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North Greenland Glacier Velocities and Calf Ice Production

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Summary: Average velocities of North Greenland glaciers which reach the sea have been determined by comparison of aerial photographs taken between 1947 and 1978. Glaciers draining the northern margin of the Inland Ice have floating frontal portions up to 50 km in length, whose integrity is maintained by the confining effect of semi-permanent fjord ice; their measured forward velocities range from about 100 m to more than 980 m per year. Smaller glaciers draining independent ice caps have movements of generally less than 50 m per year, but occasionally as much as 150-200 m. Total calf ice production from the major glacier outlets of the Inland Ice in North Greenland is estimated at slightly under 3.5 km^3 annually. Most fjords have a semi-permanent ice cover which melts completely only at rare intervals (> 30 years); accompanying break-up and dispersal of floating glacier tongues releases large tabular icebergs resembling ice islands, some of which may reach the Arctic Ocean.

Zusammenfassung: Die durchschnittliche Geschwindigkeit der das Meer erreichenden Gletscher Nordgrönlands wurde durch Vergleich von Luftbildern der Jahre 1947 bis 1978 bestimmt. Gletscher, die dem Nordteil des Inlandeises entstammen, weisen bis zu 50 km lange schwimmende Zungen auf, deren Zusammenhalt durch die fast permanente Eisbedeckung der Fjorde bedingt wird. Die Geschwindigkeit reicht von 100 m bis 980 m pro Jahr. Kleinere Gletscher, die von isolierten Eiskappen ausgehen, haben Geschwindigkeiten von weniger als 50 m pro Jahr, gelegentlich aber auch 150-200 m pro Jahr. Die gesamte Kalbungsrate des nordgrönländischen Inlandeises durch die großen Gletscher wird auf etwas weniger als 3,5 km^3 pro Jahr geschätzt. Die meisten Fjorde haben eine fast permanente Eisbedeckung, die nur in seltenen Abständen (>30 Jahre) gänzlich schmilzt. Im Gefolge davon brechen die schwimmenden Gletscherzungen auf und geben große Tafeleisberge oder Eisinseln frei, von denen manche den Arktischen Ozean erreichen können.

1. INTRODUCTION

This report embodies the results of a systematic study of available aerial photographs of North Greenland, carried out with the purpose of determining the movement of the productive glaciers which reach the fjords. The most important glaciers drain the north margin of the Greenland Inland Ice (Fig.1). Less important glaciers include outlets from independent ice caps, and the glaciers draining the alpine terrain of Nansen Land and northern Peary Land.The region covered by this study extends from Petermann Gletscher in the west to Flade Isblink, east of Station Nord, in the east (Fig. 1).

Early observations on North Greenland glaciers go back to the voyages of geographical exploration towards the end of the 19th century, and have been summarised by KOCH (1928). Lauge Koch's own observations were made in the course of geological and topographical surveying during the Second Thule Expedition 1916-18 and the Danish Bicentenary Jubilee Expedition 1920-23. DAVIES & KRINSLEY (1962) based their conclusions of the general stability of glacier fronts in North Greenland on these early observations, aerial photographs from 1947, and their own fieldwork in the 1950's. However, these general descriptions of North Greenland glaciers, and the review of WEIDICK (1975), give little in the way of quantitative data on glacier velocities.

The earliest aerial photography of North Greenland was flown by the US Air Force in 1947. In 1953 the Danish Geodetic Institute carried out a programme of oblique aerial photography throughout North Greenland, followed up by vertical aerial photography in the period 1959-63. A commercial company, Grumman Ecosystems Corporation, flew routes of vertical photographs over a segment of western North Greenland in 1971. The most recent vertical coverage comprises wide-angle, small scale, photography of all of North Greenland, flown for the Geodetic Institute in 1978. This 30 years of photographic coverage permits calculations of average velocities to be made on floating segments of productive glaciers, where these have preserved distinctive patterns of meandering streams and melt-water pools recognisable on photographs taken decades apart. Preliminary estimates of glacier velocities arising from this study were given by HIGGINS (1988).

The floating glacier tongues of North Greenland were discussed by KOCH (1928), who attributed their preservation to the low surface slope of many glaciers, so that major crevasses were not formed at the grounding line (the boundary between grounded and floating parts), together with the constraining effect of the semi-

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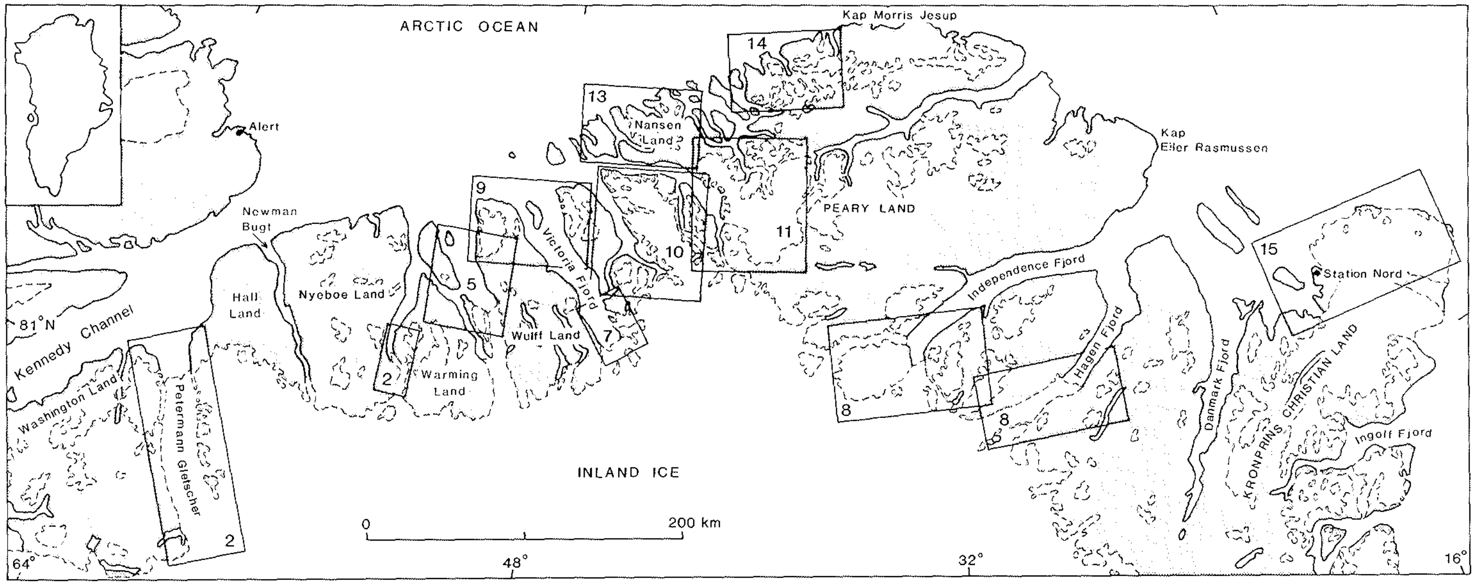

Fig. 1: North Greenland showing main glaciers draining the north margin of the Inland Ice, and independent ice caps. Frames show areas covered by detailed maps.

Abb. 1: Übersicht über Nordgrönland mit den wesentlichen vom Inlandeis und lokalen Eiskappen nach Norden strömenden Gletschern. Die Rahmen bezeichnen Detailkarten mit entsprechender Abbildungs-Nummer.

Glacier		Width (km)	Velocity range	(m/y) average	Altitude range	(m) average	Glacier thickness (m)	Calf ice (km3/Y)	
Petermann Gletscher	- west	1.3	-	855	2-7	4.0	32	0.03*	
	- central	12.0	932-988	950	4-6	5.0	40	0.46	0.59
	- east	2.2	-	890	8-10	9.0	72	0.10*	
Steensby Gletscher	- west	0.4	-	420	-	13.0	104	0.02	
	- central	3.7	410-435	430	18-25	22.6	181	0.29	0.32
	- east	0.4	-	410	-	7.0	56	0.01	
Ryder Gletscher	- main	8.2	460-535	500	18-23	20.0	160	0.66	0.70
	- east	0.8	-	500	13-15	14.0	112	0.04	
C.H. Ostenfeld Gletscher		8.0	760-805	795	8-14	11.6	93		0.54*
Harder Gletscher		3.8	84-122	100	-	10.0	80		0.03
"Brikkerne Gletscher"	- north	3.9	-	530	12-13	12.5	100	0.21	
	- central	2.5	-	500	11-14	12.5	100	0.12	0.37
	- south	1.5	-	270	8-19	12.5	100	0.04	
Academy Gletscher		8.5	50-256	140	12-30	15.0	120		0.14
Marie Sophie Gletscher		4.3	212-220	215	13-33	17.0	136		0.13
Hagen Bræ	- main	7.0	510-543	540	10-14	11.9	95	0.36	0.47
	- south	4.5	180-182	180	14-23	17.0	136	0.11	
Jungersen Gletscher		2.5	-	350	12-19	15.0	120		0.10
Navarana Fjord Gletscher		1.6	-	70	6-10	8.0	64		0.01
Henson Gletscher		2.5	-	170	-	12.0	96		0.04

Tab. 1: Potential calf ice from North Greenland glaciers draining Inland Ice. *Calculated total reduced to compensate for crevasses. Total calf ice 3.44 km^3/y.

Tab. 1: Abschätzung des Eiseintrages durch Kalbung der vom Inlandeis gespeisten nordgrönländischen Gletscher. * Berechnete Gesamtmenge korrigiert um das Spaltenvolumen. Gesamte Eismenge durch Kalbung 3.44 km^3/Jahr.

permanent fjord ice. In most North Greenland fjords the ice cover rarely melts completely, and as is apparent from the present study this is the most significant factor in maintaining the integrity of floating ice tongues, as well as preventing or slowing down the escape of tabular icebergs from the vicinity of the source glacier. While parts of some fjords may melt every summer, general ice-free summers accompanied by escape of tabular icebergs and break-up and dispersal of floating glaciers are exceptional occurrences, taking place at intervals of up to several decades.

In order to assess calf ice production of the main North Greenland outlets from the Inland Ice, photogrammetric measurements of the surface altitude of the different glaciers were made using the 1978 vertical aerial photographs. A transverse profile was measured across each of the major floating glacier tongues close to its calving front to obtain the average altitude of the glacier surface above sea level. On the assumption that seven eighths of the volume of a floating mass of ice is below sea level, the potential annual calf ice production can then be calculated knowing the measured annual velocity and the width of the glacier. The estimates for individual glaciers are discussed below, and summarised in Table 1.

The majority of the maps illustrating this account are based on 1:100 000 topographic maps with 100 m contours drawn at the Geological Survey of Greenland on the basis of ground control points and aerial photographs supplied by Kort- og Matrikelstyrelsen, Copenhagen (prior to 1989 the Geodetic Institute). Supplementary data on 1978 glacier positions have been added from individual 1:100 000 orthophotographs supplied by Kort- og Matrikelstyrelsen. Contours on Petermann Gletscher, around the head of Independence Fjord, around Hagen Bræ and on Flade Isblink are taken from other sources as noted in figure texts.

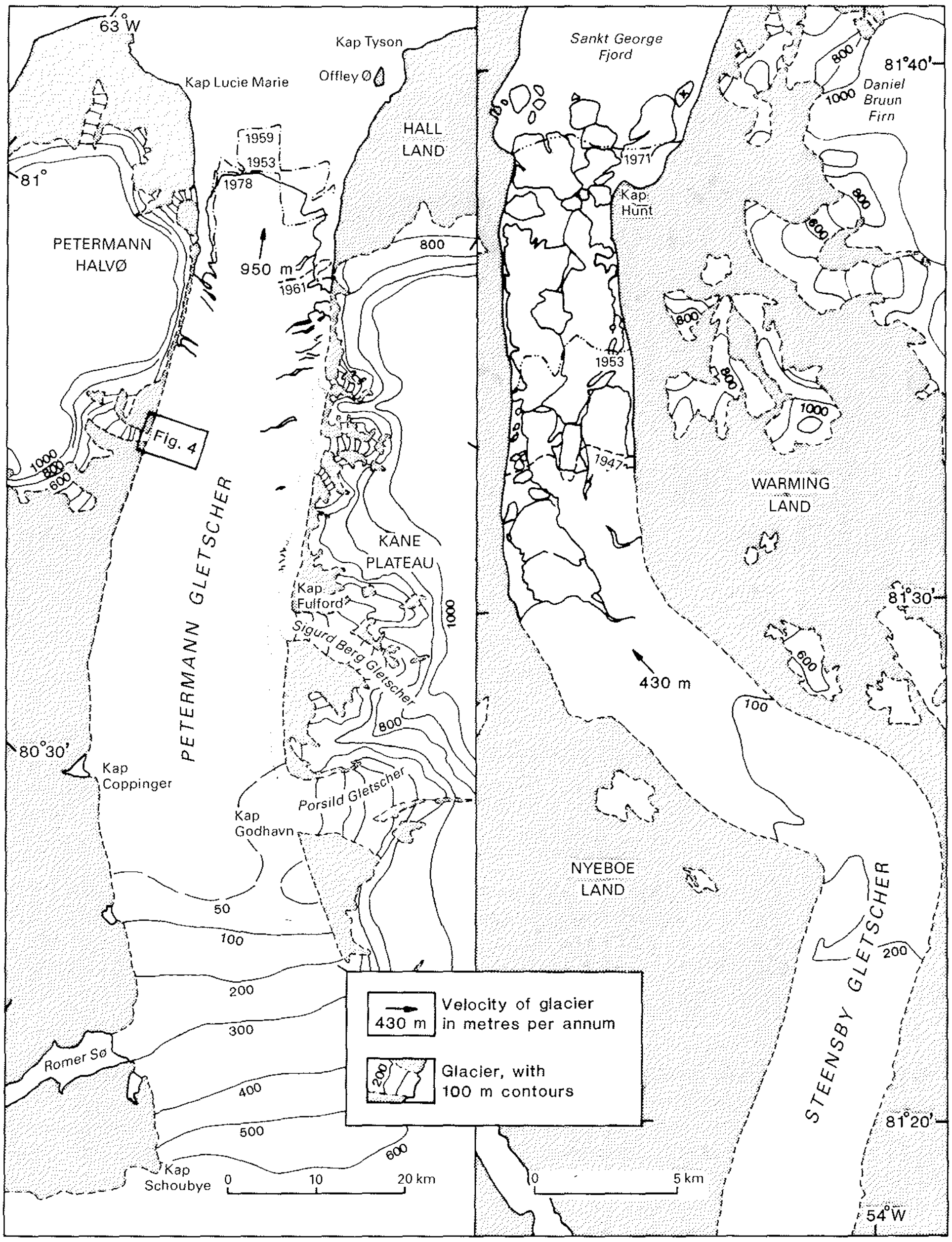

Fig. 2: Maps of Petermann Gletscher (left) and Steensby Gletscher (right), with position of glacier fronts shown for specific years determined from aerial photographs. Glacier and iceberg boundaries with full lines are 1978 positions. Contours on Petermann Gletscher constructed from new ground control positions by Kort- og Matrikelstyrelsen; contours on adjacent ice plateaus are modified from 1957 Army Map Service maps. Contours on Steensby Gletscher are from Geological Survey of Greenland map sheets. The berg in Sankt George Fjord marked with a cross was part of the 1947 glacier front.

Abb. 2: Karten vom Petermann-Gletscher (links) und Steensby-Gletscher (rechts) mit Lage der Eisfront aus Luftbildern verschiedener Jahre. Gletscher- und Eisberggrenzen von 1978 sind voll ausgezogen. Höhenlinien am Petermann-Gletscher konstruiert aus neuen Daten von Kort- og Matrikelstyrelsen; Höhenlinien auf angrenzenden Eisplateaus modifiziert nach Karten des Army Map Service. Höhenlinien auf Steensby-Gletscher aus Karten des Geol. Survey of Greenland. Der mit x markierte Eisberg im Sank-George-Fjord war Teil der Gletscherfront im Jahre 1947.

2. OBSERVATIONS AND RESULTS

2.1 Petermann Gletscher

Petermann Gletscher has the highest measured velocity of North Greenland glaciers. It is 30 km wide in the south where it merges with the Inland Ice, and narrows gradually northwards over its 110 km length, confined between Washington Land (Petermann Halvø) and Hall Land, to a width of 15.5 km near its front (Fig. 2). The surface altitude descends from 600 m at the Inland Ice margin to only 25-35 m at Kap Coppinger. North of Kap Coppinger the surface slope is very low, and crevasses on the glacier become less conspicuous northwards, to be replaced by a system of meandering streams and meltwater pools marking the sites of annealed crevasses. In the central parts of Petermann Gletscher the pools are largely transverse to the movement direction, but notably on the west side of the glacier occupy elongate depressions between movement ridges parallel to the glacier margin (Fig. 3). At least the northern 50 km of Petermann Gletscher is afloat. The grounding line cannot be located precisely due to the low gradient, but it is possible that the entire 70 km length of Petermann Gletscher north of Kap Coppinger may be floating.

No significant tributary glaciers join Petermann Gletscher on its western side, whereas five glaciers on the east side descend from Kane Plateau to merge with the main ice stream. The most important are the 6 km wide Porsild Gletscher and the 3 km wide Sigurd Berg Gletscher, whose merged representatives in Petermann Gletscher outlined by moraine trails are respectively 1250 m and 1500 m wide (Fig. 2).

The patterns of meltwater pools and meandering streams change surprisingly little from year to year, and are easily recognisable on aerial photographs taken 19 years apart, even though the floating segment of glacier on which they have developed has advanced 17-19 km northwards. Thus the stream pattern on the 1959 aerial photograph of Fig. 4 can be clearly identified on the 1978 small scale aerial photograph of Fig. 3 at the head of the 932 m arrow. Distinctive features recognised on 1959, 1961 and 1978 aerial photographs have been plotted in their relative positions on 1:100 000 orthophotographs, and velocity calculations have been made. These indicate northward movement of from 855-988 m per year (m/y) for different parts of the glacier; velocities are slightly lower in the marginal areas (Fig. 3).

The velocity difference between the centre and margin of the glacier leads to opening up of large crevasses in the marginal areas, which first become conspicuous 45 km behind the front. The crevasses, which have water in the bottom, grow in width and length as they move north, and those close to the front are up to 400 m wide and may reach almost to the centre of the glacier (Fig. 3).

The position of the glacier front, a few kilometres from where the mouth of the fjord meets Kennedy Channel (Fig. 1) appears to have remained stable within about 15 km since 1876 (KOCH 1928, DAVIES & KRINSLEY 1962). Segments of the floating glacier can be shown to break away at intervals of 5-10 years or more, to drift into Kennedy Channel where there is often open water in the summer. Oblique and vertical aerial photography shows an advance of the front between 1953 and 1959 with only minor loss from the west side. Between 1959 and 1961 a 17 km long segment of glacier was lost. The position of the 1978 front was close to the 1953 position. To judge from the distribution of crevasses in the frontal area, the largest tabular bergs lost from Petermann Gletscher reach about 12 km by 10 km in size. When they reach the open water of Kenney Channel they drift southward through Nares Strait to Baffin Bay (cf. DUNBAR 1978).

Photogrammetric measurements of the surface altitude of Petermann Gletscher along a 10 km transverse profile close to the glacier front showed the altitude of the glacier surface to lie between 4 m and 6 m above sea level on 1978 aerial photographs. As the glacier front is afloat and unrestrained by bedrock at its margins this implies a glacier thickness of between 32 m and 48 m. Photographs of the front of Petermann Gletscher in 1922 (KOCH 1928, Fig. 38) suggest the altitude of the front to be 5-6 m high, and indicate there has been no significant change in glacier thickness since the 1920's.

An approximate figure for the annual calf ice production of Petermann Gletscher can be derived using the measured velocity of the glacier and the thickness of the glacier calculated from altitude measurements of the 1978 front. Thus, the main glacier tongue about 12 km wide, 40 m thick (assuming an average altitude above sea level of 5 m) and advancing at about 950 m/y would produce 0.46 km^3 calf ice annually if calving was regular.

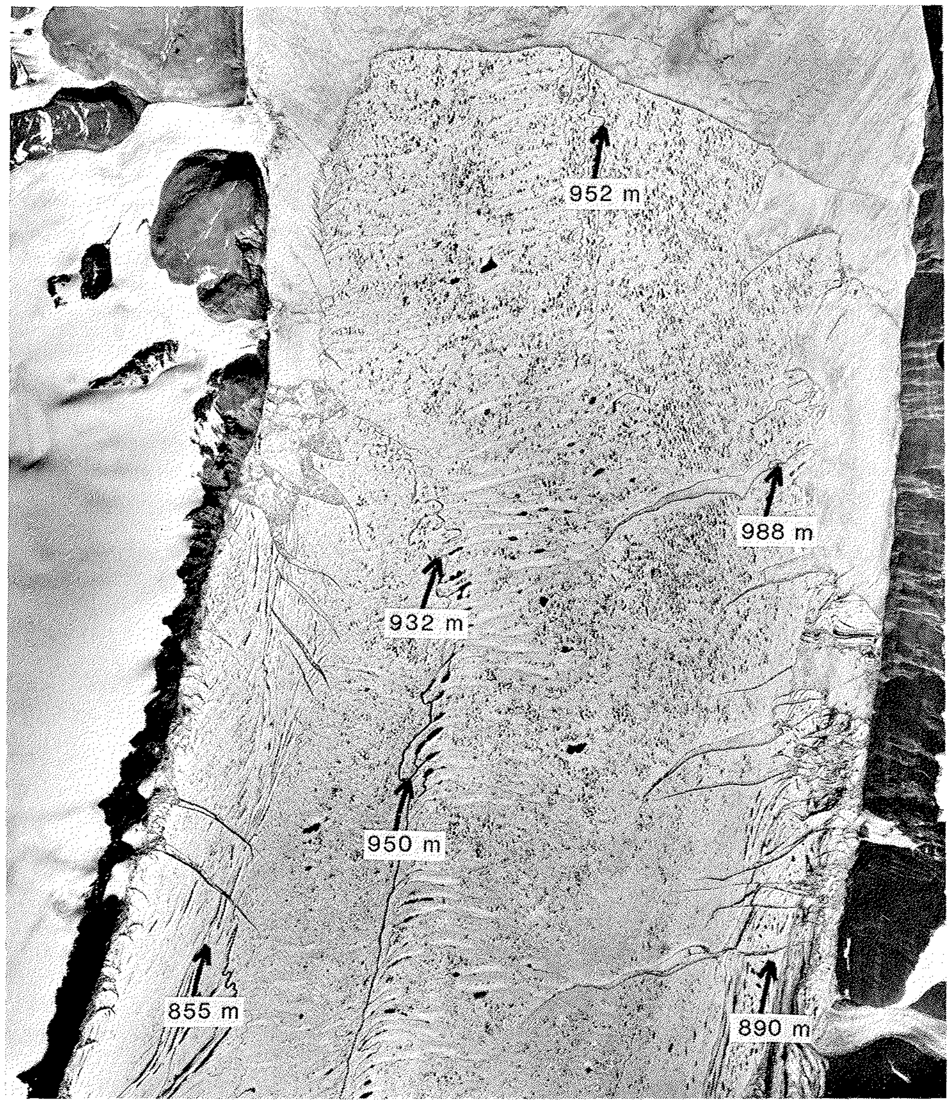

Fig. 3: Front of the 15 km wide Petermann Gletscher showing pattern of meandering streams, meltwater pools and open crevasses. Route 874 D. no 162, July 3rd 1978: copyright Kort- og Matrikelstyrelsen. Calculated annual movements averaged over 17-19 years are shown for different parts of the glacier.

Abb. 3: Front des 15 km breiten Petermann Gletschers mit mäandrierenden Strommustern, Schmelzwasserseen und offenen Spalten (Strecke 874 D. Nr. 162, 3. Juli 1978; Kort- og Matrikelstyrelsen). Für verschiedene Gletscherbereiche sind die berechneten jährlichen Bewegungen als Durchschnittswerte über 17-19 Jahre angegeben.

To this figure must be added the contributions of both marginal segments of the glacier, which as they are dissected by open crevasses tend to break away from the main tongue regularly and have a more southerly frontal position (Figs 2 and 3). It is estimated that the 2.2 km wide north-east marginal segment of the front contributes 0.10 km^3/y, and the 1.3 km wide, thinner north-west marginal segment 0.03 km^3/y calf ice annually. Total average calf ice production based on these assumptions would be about 0.59 km^3/y for Petermann Gletscher (Table 1).

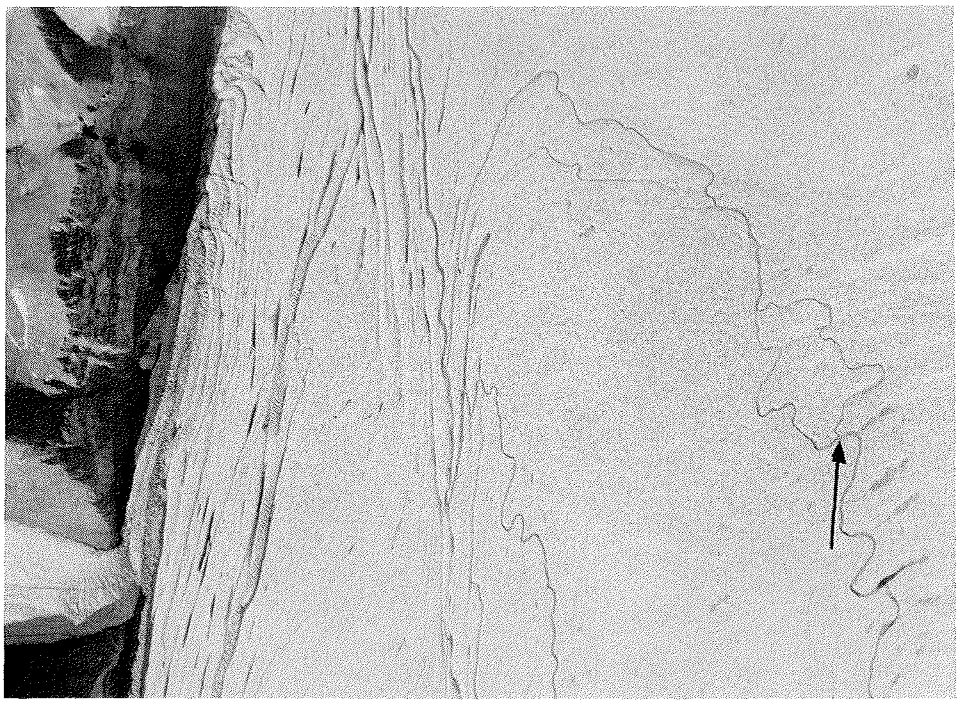

Fig. 4: Distinctive stream pattern on 1959 aerial photograph of part of Petermann Gletscher, also recognisable on the 1978 photograph of Fig. 3. Route 240 E, no 274, August 12th 1959; copyright Kort- og Matrikelstyrelsen. The location of this photograph on Petermann Gletscher is shown on Fig. 2.

Abb. 4: Luftaufnahme von 1959 mit deutlich erkennbarem Strommuster auf dem Petermann-Gletscher (genaue Lage siehe Abb. 2); ebenfalls erkennbar auf dem Luftbild von 1978 (Abb. 3). Strecke 240 E, Nr. 274, 12. August 1959; Rechte Kort- og Matrikelstyrelsen.

2.2 Newman Bugt

At the head of the long fjord between Hall Land and Nyeboe Land inappropriately known as Newman Bugt (= bay) a small unnamed glacier reaches sea level (Fig. 1). The glacier is 20 km long, and 2 km wide near the Inland Ice where it is formed by the merging of four tributary glaciers which descend steeply from the ice cap at 1000 m to about 500 m altitude. There is an even gradient down to the front, which is 1700 m wide with only the frontal 1 km afloat.

Northward movement of the glacier has been calculated at 35-45 m/y from aerial photographs. The position of the front is little changed on aerial photographs 15 years apart; the icebergs just off the front on 1978 photographs were part of the front in 1963.

2.3 Steensby Gletscher

Steensby Gletscher drains into the head of Sankt George Fjord, between southern Nyeboe Land and Warming Land (Fig. 2). It is 62 km long, and about 4.5 km wide for most of the way to its front. There are two pronounced bends in its course, and at the second bend the floating frontal portion breaks up into several lobes separated by aggregates of smaller bergs (AHNERT 1963). Ahnert's excessive estimate of an annual advance of 5.4 km to 8.7 km was based on the incorrect assumption that floating bergs were dispersed every year. Measurements of distinctive features on aerial photographs from 1963, 1971 and 1978 indicate a fairly constant average velocity for various segments of the glacier, ranging between 410 m and 435 m/y (HIGGINS 1988).

There were no floating icebergs in inner Sankt George Fjord on 1947 oblique aerial photographs, which suggests the fjord was flushed free of ice during an ice-free summer shortly prior to 1947. Since 1947 semi-permanent fjord ice has hindered the escape of bergs calved from the advancing, floating front of Steensby Gletscher. Oblique

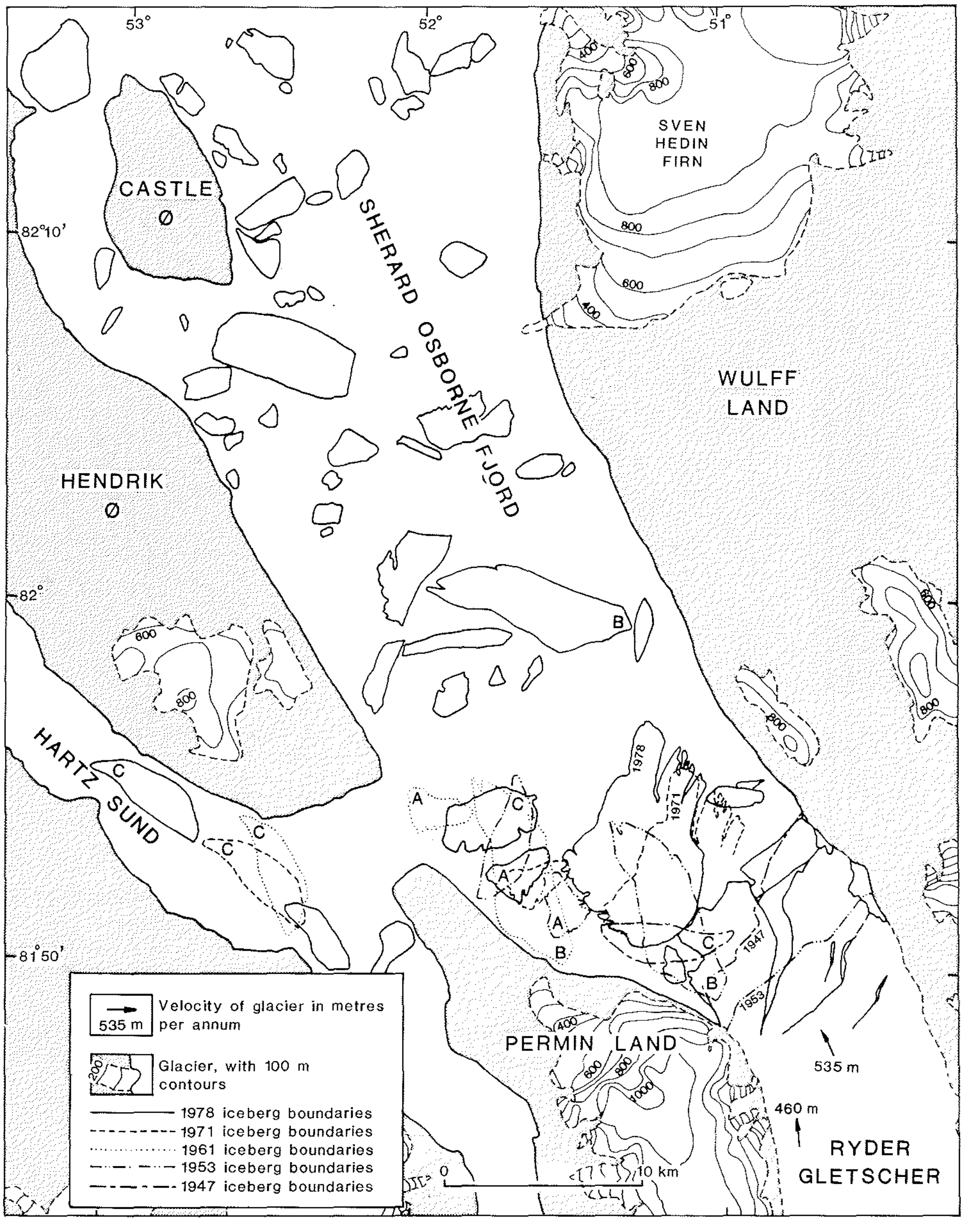

Fig. 5: Map of Ryder Gletscher and Sherard Osborne Fjord, showing glacier and iceberg positions in 1978. The glacier front position for earlier years is also shown, together with earlier positions of three icebergs (A, B, C).

Abb. 5: Karte vom Ryder-Gletscher und Sherard-Osborn-Fjord mit den Positionen von Gletscherfront und Eisbergen von 1978. Die Gletscherfronten wie auch Positionen der Eisberge A, B und C aus früheren Jahren sind ebenfalls eingezeichnet.

photographs from 1953 show advance of the front since 1947, with detachment of a few bergs from the western side. By 1971 the inner 10 km section of Sankt George Fjord was filled by detached bergs or interconnecting floating glacier segments. The most forward bergs in 1978 aerial photographs had just reached the wider section of the fjord north of Kap Hunt, and show some degree of rotation and spreading. However, the berg marked with a cross on Fig. 2 is recognisable from its pattern of meandering surface streams as the front of Ahnert's lobe III on his map of the 1947 glacier front. The surface features of the floating glaciers and icebergs show great stability over several decades. As no icebergs have drifted away from the vicinity of the advancing front since 1947, it can be concluded that the ice in outer Sankt George Fjord has not melted sufficiently to allow their escape for more than 30 years.

Photogrammetric measurements of the surface altitude of Steensby Gletscher in the inner part of Sankt George Fjord where it is afloat have been made on the basis of 1978 aerial photographs. Altitudes over much of the central part of the glacier were between 18 m and 25 m above sea level in 1978, and indicate a glacier thickness of between 144 m and 200 m. The east margin of the glacier was only 7 m above sea level, the west margin 13 m above sea level. On the basis of these figures, the potential annual calf ice production has been estimated to about 0.32 km^3 (Table 1).

2.4 Ryder Gletscher

Ryder Gletscher is more than 80 km long. At the margin of the Inland Ice where it begins at an altitude of 800 m it is more than 20 km wide, and it narrows and loses altitude as it drains northwards between Warming Land to the west and Wulff Land to the east. A minor outlet 4 km wide with a movement of 20 m/y debouches into the fjord between Permin Land and Warming Land, but the main glacier stream about 9 km wide and considerably more active drains between Permin Land and Wulff Land (Fig. 5); approximately the northern 30 km of the glacier is afloat.

Lauge Koch described how he and Knud Rasmussen unexpectedly encountered floating glacier ice in the outer part of Sherard Osborne Fjord in May 1917, and on his map (KOCH 1928) depicts the floating segment of Ryder Gletscher with a considerable more northward extent than at present. DAVIES & KRINSLEY (1962) record that this floating segment had broken up sometime prior to 1947, and that the position of the front withdrew a further 5 km by calving from 1947 to 1958. Measurements on vertical aerial photographs from 1961, 1971 and 1978 show that different parts of the floating glacier front are advancing northwards at between 460 m and 535 m annually (Fig. 5).

The numerous large icebergs found in Sherard Osborne Fjord between Wulff Land and Hendrik Ø were all derived from Ryder Gletscher. Many of those on 1978 photographs are longer than 5 km (Fig. 6), and one measured 10.5 km by 3.25 km. The photographic coverage of the region (for the years 1947, 1953, 1961, 1971, 1978) is sufficiently good that the drift of individual bergs can be charted over a period of 30 years. The shape of bergs and their pattern of surface features show very little change over three decades. The drift of bergs is largely controlled by the extent to which the semi-permanent fjord ice melts; ice-free summers are clearly exceptional events.

With respect to the drift of individual icebergs, the two marked A and B on Fig. 5 were both part of the floating glacier front in 1947. By 1953 the front of Ryder Gletscher had broken up, and both icebergs lay just off the new front. Iceberg A has shown only limited drift on aerial photographs from 1961, 1971 and 1978, and the 1978 position is in fact south of that of 1961. Berg B in the same period drifted first north-west, then about 10 km northwards to a position between Hendrik Ø and Wulff Land, a position virtually unchanged on1971 and 1978 photographs.

Iceberg C was just off the front of Ryder Gletscher in 1947, had moved 8 km north-west by 1953, and by 1961 was in Hartz Sund south of Hendrik Ø. Although Hartz Sund is one of the fjords often ice-free in the summer (pers. obs.), there were only slight changes of position between 1961 and 1978.

In an ice-free summer between 1953 and 1961 the many scattered tabular icebergs which were in Sherard Osborne Fjord between Hendrik Ø and Wulff Land on 1953 aerial photographs had drifted northwards, possibly into the Arctic Ocean. They were replaced by the bergs hitherto just off the front of Ryder Gletscher (like berg B), which drifted 10-45 km northwards. Between 1961 and 1971 many of the bergs had moved a further 5-10 km, but since 1971 there has been little change; 1971 and 1978 photographs show the bergs to have remained more or less stationary, and in 1985 many were observed to have much the same positions (pers. obs.).

Fig. 6: Part of Sherard Osborne Fjord in 1978 (cf. Fig. 5) showing distinctive shapes and surface features of large tabular icebergs. The largest berg shown here is more than 10 km long. Route 874 D, no 191, July 3rd 1978; copyright Kort- og Matrikelstyrelsen.

Abb. 6: Ausschnitt vom Sherard-Osborne-Fjord von 1978 (vgl. Abb. 5) mit deutlich erkennbaren Umrissen und Oberflächenstrukturen der großen Tafeleisberge. Der große Eisberg (Bild unten rechts) ist mehr als 10 km lang. Strecke 874 D, Nr. 191, 3. Juli 1978; Rechte Kort- og Matrikelstyrelsen.

As the front of Ryder Gletscher advances into Sherard Osborne Fjord at 460-535 m annually, the differential movements and curve of the fjord north-east of Permin Land lead to the formation of tranverse crevasses which widen from the east side, and eventually lead to detachment of large bergs. Between 1947 and 1953 a 5 km section of the front broke away, including bergs A and B. From 1953 until 1961 the front of the glacier advanced almost without loss, but by 1963 a 9 km wide and 6 km long berg had become detached. This large detached berg has since remained close to the front of the glacier, which between 1970 and 1978 photographs had advanced northwards without further major loss (Fig. 5).

The icebergs calved from Ryder Gletscher have a surface pattern of meltwater pools (Fig. 6) similar in many respects to that of ice islands calved from the Ellesmere Island ice shelves (JEFFRIES 1987). Although the semi-permanent fjord ice in Sherard Osborne Fjord may prevent their escape for several decades, in exceptional ice-free years some bergs may drift into the Arctic Ocean, where they might be difficult to distinguish from ice islands calved from the northern Ellesmere ice shelves (HIGGINS 1989).

Photogrammetric measurements of the surface altitude of Ryder Gletscher show it to be 18 to 23 m above sea level in a profile near the calving front, with an 800 m wide section on the east side of the front only about 14 m high. The greater part of the glacier is therefore probably about 160 m thick, decreasing to about 112 m on the east side. Potential annual calf ice production calculated on the basis of these figures and assuming a velocity of about 500 m per annum is of the order of 0.70 km^3, which makes it the most productive of North Greenland glaciers (Table 1). However, as is the case with Petermann Gletscher most of the potential calf ice is „stored" as segments of the floating glacier until released at intervals of a decade or more.

2.5 C.H. Ostenfeld Gletscher, Harder Gletscher and „Brikkerne Gletscher"

In May 1917 Lauge Koch drove into the mouth of Victoria Fjord by dog-sledge, but his progress was soon halted by what he initially took to be glacier ice, but later concluded must be old sea ice (KOCH 1928). His first impression appears likely to have been correct, as the inner 75 km length of Victoria Fjord is normally tightly packed with large and small icebergs emanating from the glaciers at the head of the fjord.

The glaciers draining from the Inland Ice into the head of Victoria Fjord are divided into seven main streams by the nunataks of Th. Pedersen Land and Brikkerne. Of these the largest and most productive is the 8 km wide C.H. Ostenfeld Gletscher, which is advancing northwards at a velocity of 760-805 m annually, and has a floating section extending for more than 25 km into Victoria Fjord (Fig. 7).

The surface of C.H. Ostenfeld Gletscher is characterised by a prominent pattern of crevasses; the central part is dominated by length-parallel crevasses, and the marginal parts by curved transverse crevasses inherited from differential movements of C.H. Ostenfeld Gletscher and adjacent glaciers in their descent from the Inland Ice. Where the glacier starts to float a system of open, widely spaced crevasses is formed, each crevasse up to 300 m wide; both margins of the floating glacier have a large-scale saw-tooth appearance (Fig. 7). About 5 km north of Kap Knudsen, on 1978 aerial photographs, the hitherto interconnected glacier tongue begins to divide and break up into tabular icebergs which fill the entire 16 km width of the fjord. The largest bergs are up to 15 by 5 km in size, but these seem to break up into smaller bergs within the fjord, as there are few in the outer part of Victoria Fjord longer than 2-3 km.

West of C.H. Ostenfeld Gletscher two glaciers reach Victoria Fjord, but neither appears to be particularly productive; no velocity calculations have been possible from available photographic coverage. Harder Gletscher merges with the east side of C.H. Ostenfeld Gletscher, but has a relatively low velocity of 84-122 m per annum. The contrast in velocity between the glaciers which merge with C.H. Ostenfeld Gletscher on both sides may be the major factor governing development of the transverse crevasses and the saw-tooth marginal appearance.

North of Harder Gletscher a large unnamed glacier is divided by two semi-nunataks into three branches which all reach Victoria Fjord (Fig. 7). This glacier, referred to for convenience as „Brikkerne Gletscher", has a variable velocity, documented by aerial photographs from 1947, 1953, 1963, 1971 and 1978, and has been classified by HIGGINS & WEIDICK (1990) as a surging or pulsing glacier. On 1947 and 1953 aerial photographs the glacier is apparently stationary, with a conspicuous pattern of meandering streams and meltwater pools on the three glacier lobes. Vertical aerial photographs from 1963 show dramatic changes, advance of the northern and central fronts of at least 150 m and 360 m annually respectively, and extensive crevasse development throughout the length of the glacier. Further advances are clearly discernable on 1971 and 1978 aerial photographs; the velocity figures on Fig. 7 are averages for the period 1971-78. Over the 25 years between 1953 and 1978 the northern lobe advanced 11 km and the central lobe 8 km. The surge-like movement of „Brikkerne Gletscher" is attributed by HIGGINS & WEIDICK (1990) to a kinematic wave. Photographic coverage of parts of „Brikkerne Gletscher" from the 1980's shows the fronts of the glacier lobes are still advancing, but upper reaches of the glacier show areas of collapse and stagnation implying the kinematic wave has passed.

Measurements of the surface height of C.H. Ostenfeld Gletscher have been made along two transverse profiles 15 km apart. The southern profile (Fig. 7, A-A) showed a range in height above sea level between 13 m and 29 m, on average about 19 m. The northern profile (Fig. 7, B-B) showed surface heights of the glacier between 8 m and 14 m above sea level, on average about 11.6 m. Potential calf ice production estimates based on the calculated glacier thickness along the northern profile amount to 0.54 km^3/y (Table 1).

Calf ice production estimates for Harder Gletscher and „Brikkerne Gletscher", based on measured heights of the glacier fronts and measured velocities, gave figures of 0.03 km^3 and 0.37 km^3/y. However, the figure of 0.37 km^3 annually for the three outlets of „Brikkerne Gletscher" is based on velocity calculations for the period 1971-78, during which the glacier showed unusually fast movement (HIGGINS & WEIDICK 1990).

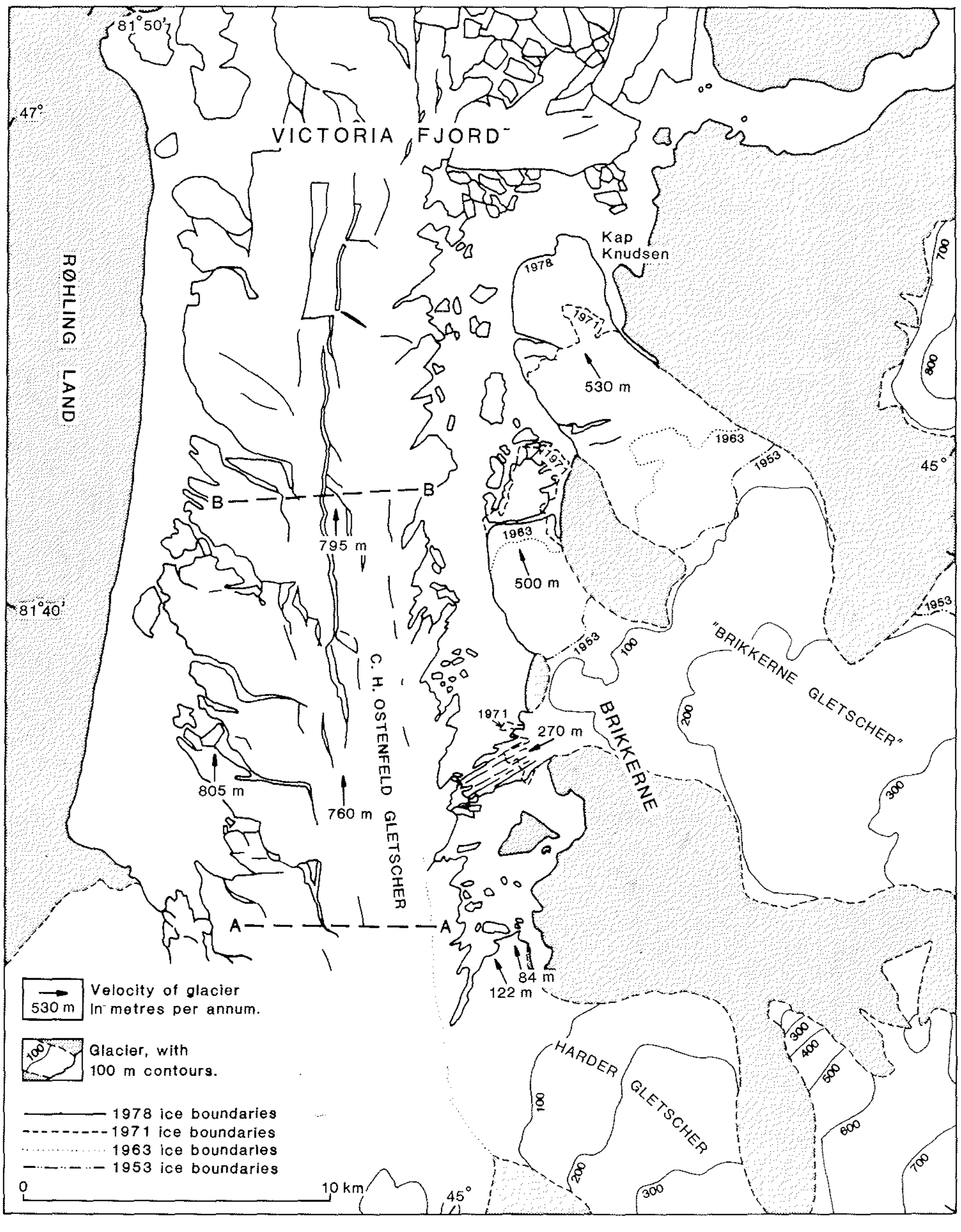

Fig. 7: Map of C.H. Ostenfeld Gletscher and Victoria Fjord. Glacier and iceberg boundaries are as in 1978, while earlier frontal positions (1953, 1963, 1971) are shown for the surging lobes of „Brikkerne Gletscher". Surface altitudes of C.H. Ostenfeld Gletscher were measured along profiles A-A and B-B.

Abb. 7: Karte vom C.H.-Ostenfeld-Gletscher und Victoria-Fjord. Gletscher- und Eisberggrenzen sind von 1978 während die älteren Lagen der Gletscherfront von 1953, 1963 und 1971 die „surging lobes" des „Brikkerne-Gletschers" beschreiben. Die Höhenlagen auf dem C.H.-Ostenfeld-Gletschers wurden aus den Profilen A-A und B-B entnommen.

2.6 Academy Gletscher and Marie Sophie Gletscher

Early observations of the glaciers at the head of Independence Fjord showed a large area of floating hummocky ice and densely packed icebergs in front of Academy Gletscher (Fig. 8). At its maximum extent this floating ice

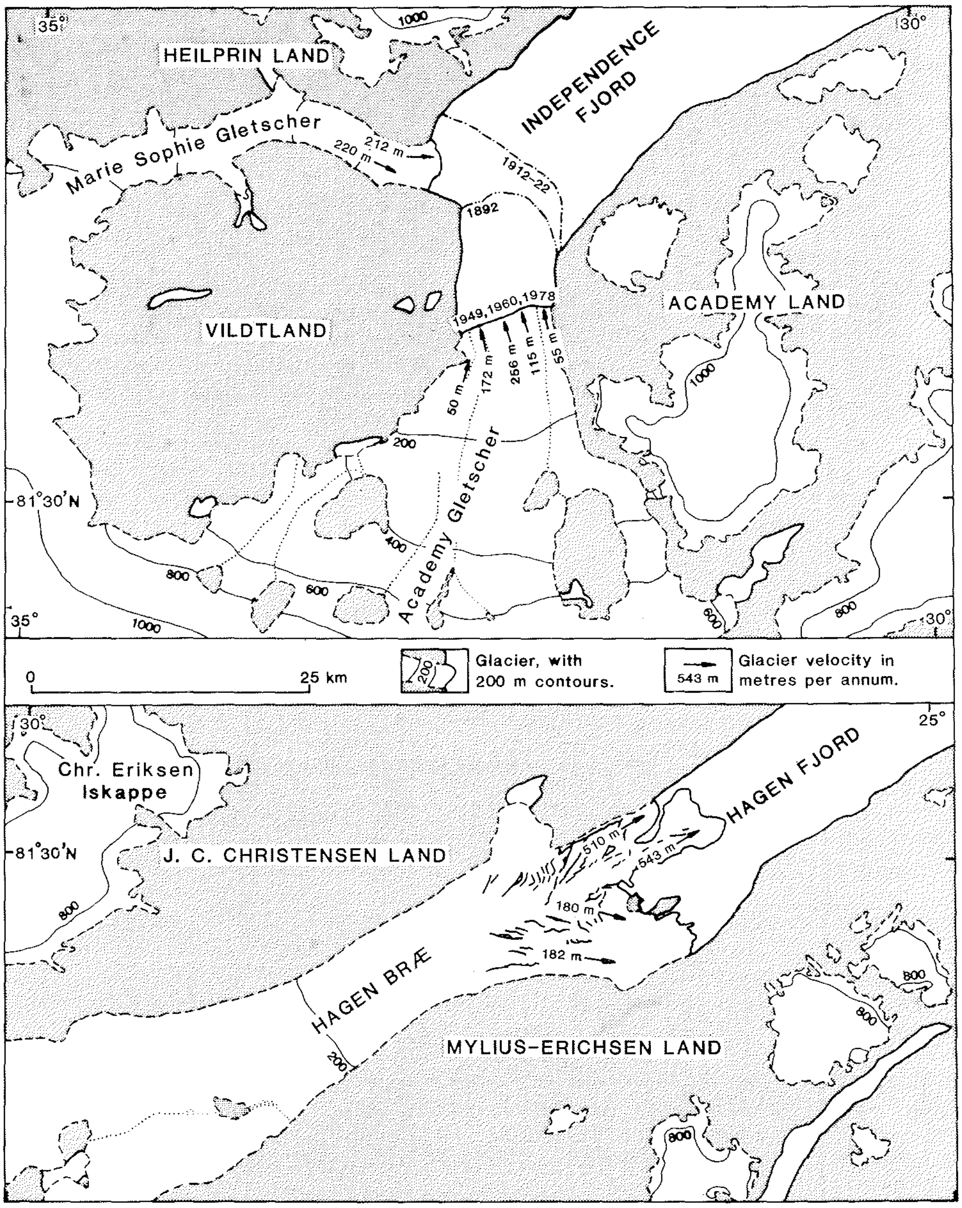

Fig. 8: Maps of the glaciers at the head of Independence Fjord (top) and Hagen Fjord (bottom). Contours on both maps are taken from 1957 Army Map Service 1:250 000 maps. The early frontal positions of Academy Gletscher are from DAVIES & KRINSLEY (1962).

Abb. 8: Karten der Gletscher am Beginn des Independence-Fjord (oben) und Hagen-Fjord (unten). Höhenlinien nach Karten 1 : 250 000 des Army Map Service; die älteren Eisfrontpositionen des Academy-Gletschers nach DAVIES & KRINSLEY (1962).

reached beyond the front of Marie Sophie Gletscher (PEARY 1898, FREUCHEN 1915, KOCH 1928). Koch described the floating ice as much crevassed, comprising large separate bergs cemented by frozen sea ice so that it presented itself as a „real glacier". He considered the ice to derive entirely from Academy Gletscher with no apparent contribution from Marie Sophie Gletscher.

The floating segment of Academy Gletscher had broken up and dispersed prior to 1956 (DAVIES & KRINSLEY, 1962), and studies of aerial photographs taken between 1962 and 1978 show no indication of re-establishment. The 1978 photographs of the highly crevassed front show no floating portion, and a scattering of small icebergs in the fjord up to 5 km from the front. It is inferred that the fjord ice in Independence Fjord since the 1950's has melted completely sufficiently regularly that the glacier front does not have the opportunity to develope a stable floating portion.

First attempts to determine the velocity of the glaciers in Independence Fjord were unsuccessful (HIGGINS 1988). A renewed study of aerial photographs from the 1960's has provided estimates of movement for both Academy Gletscher and Marie Sophie Gletscher.

Academy Gletscher is 8.5 km wide at the front. It apparently drains a broad segment of the Inland Ice, but moraine trails from the numerous nunataks which break up the ice stream show that an approximately 25 km wide wedge of the Inland Ice feeds the active front. Velocity calculations based on aerial photographs from the early 1960's taken almost exactly one year apart show a maximum of 256 m movement at the centre of the glacier, declining to 50-55 m at the glacier margins (Fig. 8).

Marie Sophie Gletscher has a constant width of about 4 km over a distance of 75 km. Minor tongues on both sides of the glacier terminate in ice-dammed lakes. Velocity calculations from aerial photographs show the entire width of the 4.3 km wide front is moving at 212-220 m annually.

Neither Academy Gletscher nor Marie Sophie Gletscher currently have a significant floating front, and the grounding line of both is probably very close to the present front. The heights of the glacier fronts where they enter the sea are somewhat variable, between 12 m and 33 m. Conservative estimates of calf ice production amount to 0.14 km^3/y for Academy Gletscher and 0.13 km^3/y for Marie Sophie Gletscher (Table 1).

2.7 Hagen Bræ

Hagen Bræ is a major outlet of the Inland Ice at the head of Hagen Fjord. It is 75 km long and 10 km wide in its central portion, widening slightly towards the front where it is partly dammed by two islands (Fig. 8). DAVIES & KRINSLEY (1962) described the front as stagnant, with a surface pattern of interlacing streams and large interconnecting ponds in parallel troughs. HIGGINS (1988) reported that parts of the front are advancing at 540 m annually.

The floating frontal segment of Hagen Bræ is up to 18 km long. Measurements of the central part on aerial photographs show it to be moving at an average of just over 540 m annually. Towards the north side annual velocities decrease to about 510 m, the difference in velocity leading to formation of a set of oblique open crevasses. The southern part of Hagen Bræ diverted south of two small islands, has measured annual movements of about 180 m.

HIGGINS (1988) observed that large tabular bergs up to 5 km by 2 km in size which formed the front of the glacier tongue in 1960 had broken free and drifted up to 45 km towards the outer part of Hagen Fjord by 1978. These and other large icebergs in North Greenland fjords were compared by HELK & DUNBAR (1953) to the ice islands calved from the Ellesmere Island ice shelves. The progress of drift of these bergs down Hagen Fjord is largely dependent on the extent to which the fjord ice melts in the summers. Studies of aerial photographs suggest bergs take several decades to reach the sea at the mouth of Independence Fjord, from where they will inevitably drift southwards with the East Greenland drift stream.

Two transverse height profiles were measured on Hagen Bræ, one close to the calving front of the northern part of the glacier where the surface of the glacier was 10-14 m above sea level, and the second 9 km west of the front where the corresponding altitudes ranged from 14-16 m. The second profile was continued across the southern, more slowly moving, part of Hagen Bræ, which showed more variation with altitudes between 14 and 23 m above sea level. Average annual calf ice production estimated on the basis of these figures, measured velocities and the width of the glacier total 0.47 km^3 (Table 1).

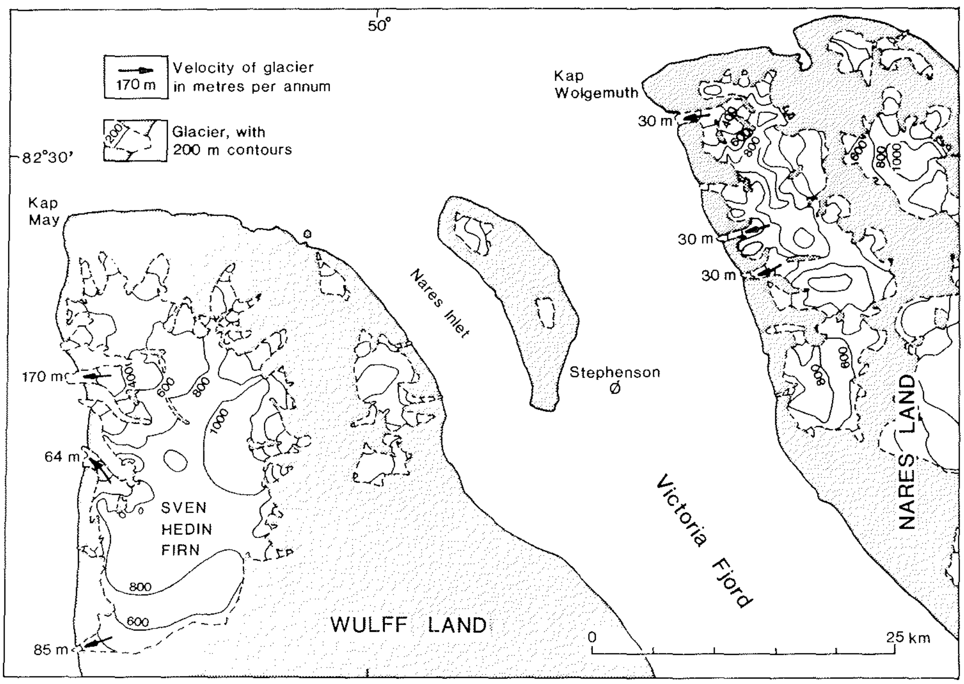

Fig. 9: Map of the independent ice caps in northern Wulff Land and northern Nares Land.

Abb. 9: Karte der isolierten Eiskappen im nördlichen Wulff-Land und nördlichen Nares-Land.

2.8 Wulff Land

The high plateaus of Wulff Land support many small independent ice caps, but only Sven Hedin Firn in north-west Wulff Land has outlet glaciers which reach the fjords (Fig. 9).

Sven Hedin Firn is 15 km wide and more than 35 km long from north to south; its summit reaches above 1000 m. Several small glaciers descend steeply from the west side of the ice cap into the outer part of Sherard Osborne Fjord. Their active fronts extend into the fjord, and although there has been some loss by calving, the fjord ice largely maintains the integrity of the glaciers from year to year. Velocity calculations from aerial photographs for three of the outlet glaciers showed annual movements of respectively 170 m, 64 m and 85 m/y (Fig. 9).

2.9 Nares Land

The plateaus of Nares Land, like those of Wulff Land, also support a number of small ice caps (Fig. 9). Most of the glacier lobes descending from them drain into the interior of Nares Land, where several have developed spectacular elephant-foot forms on the valley floors. Only the 30 km by 7 km ice cap in north-west Nares Land has outlets that reach the coast of Victoria Fjord. Velocities have been calculated for three outlets from aerial photograph studies; in each case an average figure of 30 m/y was obtained.

2.10 Freuchen Land and Jungersen Gletscher

Lauge Koch's journey towards the interior of Nordenskiöld Fjord in June 1917 was halted a few kilometres from the mouth of the fjord by a barrier of tightly packed icebergs (KOCH 1928). This observation led him to conclude the fjord was occupied by an extensive floating glacier tongue which he named Jungersen Gletscher (KOCH 1928, 1940 plates 10, 11). It is most likely that Koch's ice barrier was an accidental accumulation of icebergs calved from one of the glaciers draining the Freuchen Land ice cap (Fig. 10). The name Jungersen Gletscher is today applied to the relatively minor glacier, 2-3 km wide, draining from the Inland Ice south of Freuchen Land.

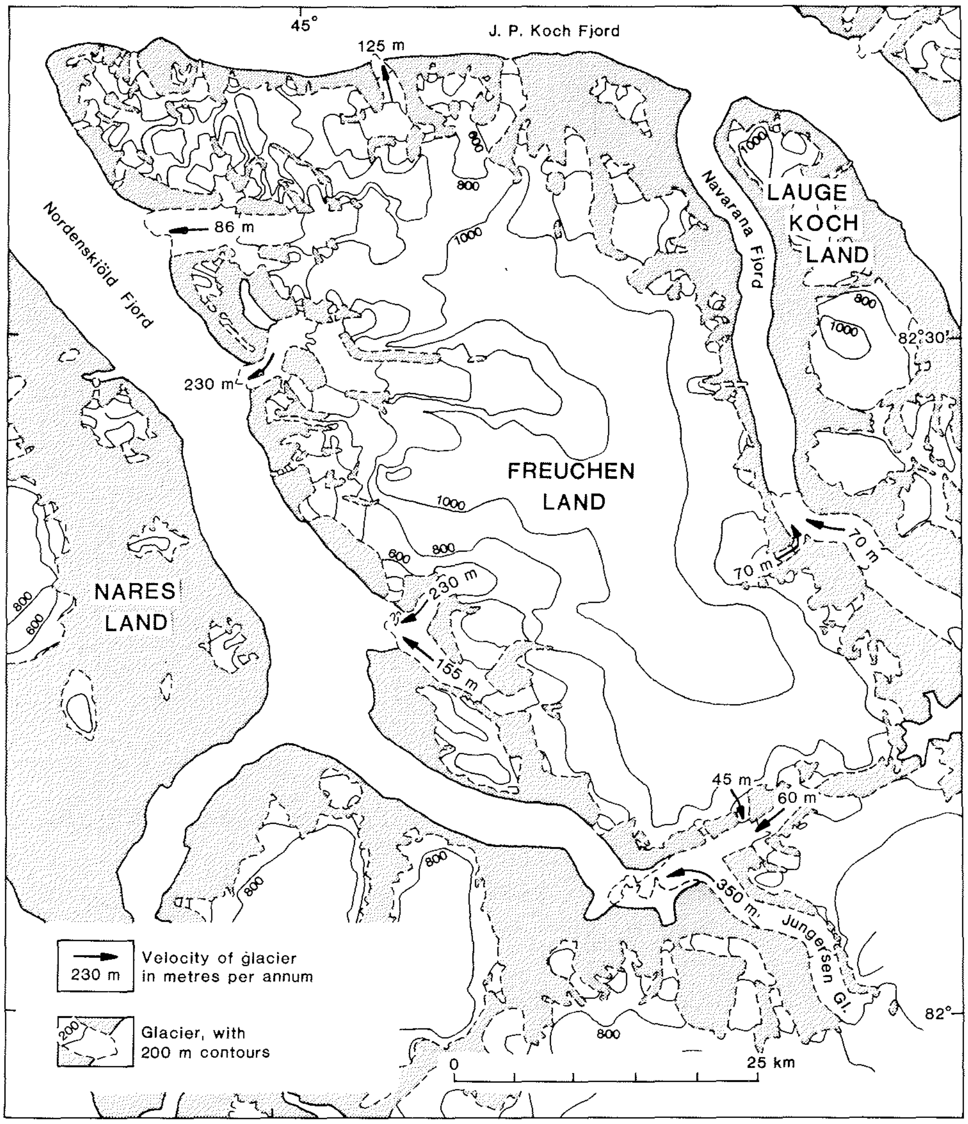

Fig. 10: Freuchen Land and its large independent ice cap. Jungersen Gletscher and the glacier at the head of Navarana Fjord drain from the Inland Ice.

Abb. 10: Karte von Freuchen-Land mit seiner großen lokalen Eiskappe. Jungersen-Gletscher und der Gletscher am Beginn des Navarana-Frjords werden vom Inlandeis gespeist.

It has a calculated movement of 350 m annually, and merges near its front with less active tributaries from the Freuchen Land ice cap.

About 80% of Freuchen Land is covered by an extensive independent ice cap, 65 km by 35 km in size and reaching altitudes above 1000 m. Outlet glaciers from the ice cap reach the fjords to the north, east and west (Fig. 10). To the south minor glaciers with movements of 45-60 m/y merge with the more productive Jungersen Gletscher.

The most important of the Freuchen Land ice cap outlets are those that drain westwards to Nordenskiöld Fjord,

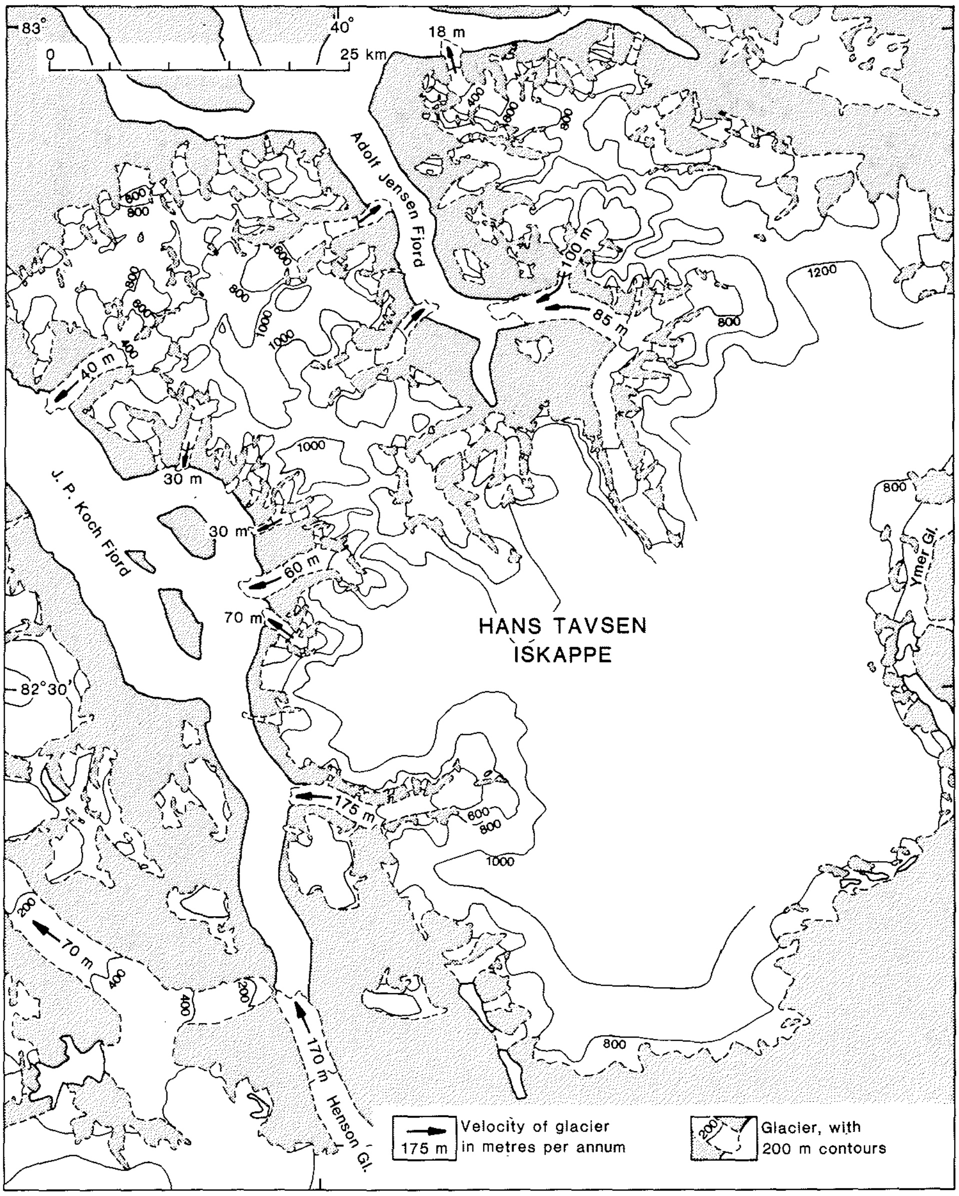

Fig. 11: Hans Tavsen Iskappe, west Peary Land, showing movement of glaciers which reach the sea in J.P. Koch Fjord and Adolf Jensen Fjord. Henson Gletscher (lower left) drains from the Inland Ice.

Abb. 11: Karte der Hans-Tavsen-Eiskappe im westlichen Peary-Land. Eingezeichnet ist die Bewegung der Gletscher, die das Meer im J.P.-Koch-Fjord und Adolf-Jensen-Fjord erreichen. Der Henson-Gletscher (unten, links) wird vom Inlandeis gespeist.

two of which are 3 km wide at their fronts. Annual velocities determined from aerial photographs range from 86-230 m. Of the two glaciers which drain north to J.P. Koch Fjord on the north coast of Freuchen Land, one has a static front and the other advances at about 125 m annually. Only one significant glacier drains eastwards. It merges with a minor outlet from the Inland Ice, and moves northwards into the head of Navarana Fjord at about 70 m/y.

Fig. 12: Small glaciers draining from Hans Tavsen Iskappe into J.P. Koch Fjord (cf. Fig. 11). Dispersal of icebergs calved from these glaciers is prevented by the semi-permanent fjord ice. Route 874 E, no 1123, July 23rd 1978; copyright Kort- og Matrikelstyrelsen.

Abb. 12: Kleine Abflußgletscher der Hans-Tavsen-Eiskappe in den J.P.-Koch-Fjord (vgl. Abb. 11). Die Ausbreitung der von diesen Gletschern kalbenden Eisberge wird durch die fast permanente Eisbedeckung des Fjords verhindert. Strecke 874 E, Nr. 1123, 23. Juli 1978. Rechte Kort- og Matrikelstyrelsen.

2.11 Hans Tavsen Iskappe and Henson Gletscher

Hans Tavsen Iskappe is the largest of several independent ice caps in western Peary Land. It is about 100 km by 80 km in size, with the highest parts above 1000 m. At the north side of the ice cap Adolf Jensen Fjord projects inland more than 25 km (Fig. 11). An ice drilling programme was carried out by GISP (Greenland Ice Sheet Programme) on Hans Tavsen Iskappe in 1975 (LANGWAY etal., 1985).

Outlet glaciers from the ice cap reach the sea in J.P. Koch Fjord (Fig. 11) and Adolf Jensen Fjord. On the east side of the ice cap several outlet glaciers coalesce to form Ymer Gletscher, but its movement is insignificant.

Most of the glaciers descending from Hans Tavsen Iskappe into J.P. Koch Fjord have widths of 1.0-2.5 km and average movements of 30-70 m/y (Fig 11 and 12). A single glacier 2.5 km wide has a measured velocity of 175 m/y.

Two glaciers on the west side of Adolf Jensen Fjord reach the sea, but while they are advancing slowly it has not proved possible to calculate the rate of movement from available aerial photographs. The 3.5 km wide glacier at the head of the fjord is formed from several tributary glaciers moving at 85-100 m/y.

Henson Gletscher is a 2 km wide glacier at the head of J.P. Koch Fjord, a minor outlet of the Inland Ice, and has a calculated velocity of 170 cm annually (Fig. 11). The glacier which almost reaches J.P. Koch Fjord on the west side of the front of Henson Gletscher is stationary.

2.12 Nansen Land

Nansen Land has an alpine topography with the highest peaks above 1200 m, and supports a network of interconnected valley glaciers (Fig. 13). It is bounded to the north-west by the Arctic Ocean.

Only few outlets from the largest glacier system reach the sea, but the two reaching Mascart Inlet do not have sufficiently distinctive surface features to permit determination of movement from 1960 and 1978 vertical photographs. However, a single glacier was found to be moving northwards at an average of 50 m/y.

2.13 *North Peary Land*

Johannes V. Jensen Land, also called north Peary Land, is an extensive alpine region with peaks reaching almost 1800 m. Interconnected valley glaciers characterise the region, but reach the sea only in the western parts (Fig.14). In the extreme north-west, slow moving glaciers on both sides of Kap Kane completely fill Hunt Fjord and partially fill Conger Sund, where they give rise to floating sheets of glacier ice with the undulating suface features characteristic of ice shelves (HIGGINS 1989). The Kap Kane ice shelves are the only features in North Greenland which compare closely with the better known Ellesmere Island ice shelves, and have clearly taken several centuries to form. Whether they are relics of more extensive ice shelves which may once have fringed the north coast of north Peary Land is another question (cf. KOCH 1923, DAVIES 1961, FUNDER & LARSEN 1982).

Average annual velocities have been determined from 1960 and 1978 aerial photographs for many of the glaciers which reach the sea. It is of interest that even glaciers with rather limited catchment areas had small, but measurable, movements of 8-23 m annually; the small glacier on northern Lockwood Ø has a velocity of 14 m per annum (Fig. 14). Glaciers draining more extensive catchment areas had generally higher velocities, the highest figure being 160 m per annum for the northern outlet of A. Harmsworth Gletscher.

2.14 Flade Isblink

Northern Kronprins Christian Land supports a large independent ice cap known as Flade Isblink, more than 100 km long and up to 75 km wide. Along much of the eastern side and the north margin the ice cap reaches close to the sea, but the only significant outlet is a 25 km broad segment east of Station Nord (Fig. 15) which extends northwards as a floating glacier up to 20 km long.

The western lobe of the outlet glacier has a calculated movement of 360 m/y as determined from 1961 and 1978

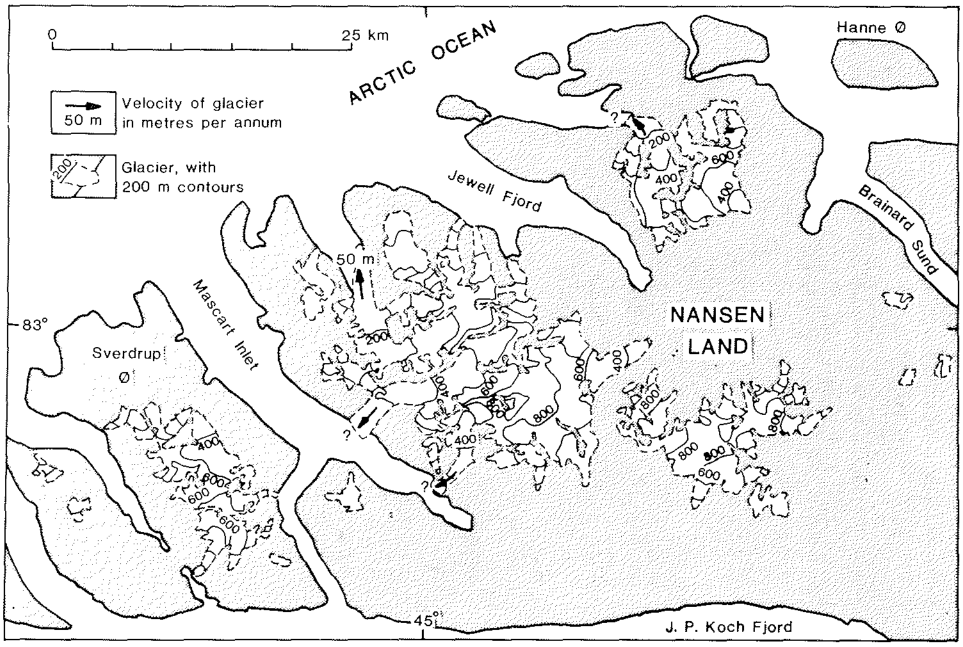

Fig. 13: Nansen Land, showing systems of interconnected alpine glaciers.

Abb. 13: Karte von Nansen-Land mit mehreren isolierten Gruppen verbundener alpiner Gletscher.

photographs. A central section of the outlet is blocked by small islands, and the eastern lobe is advancing at only 175 m a year. There was no significant loss from the floating glacier between 1961 and 1978, but on the 1978 aerial photographs extensive open-water leads are close to the front.

Parts of Flade Isblink exhibit conspicuous undulating patterns of ridges and meltwater pools, as noted by HELK & DUNBAR (1953). They are very conspicuous on the floating glacier lobes.

3. CALF ICE PRODUCTION AND ABLATION

Estimates of the calf ice production for individual North Greenland glaciers have been discussed above, and the basic data from which the calculations have been made in each case is summarised in Table 1. The critical factors in each calculation are width of glacier (measured on 1:100 000 topographic maps), glacier velocity (the main topic of this paper), and the thickness of each glacier. Surface altitudes above sea level have been measured photogrametrically along a profile near the calving glacier front at the photogeological laboratory of the Geological Survey of Greenland, using a Kern PG2 stereoplotter. Spot altitudes were determined at about 500 m intervals along each profile line with reference to sea level in the fjord bordering each floating glacier front. For each profile (or part of a profile) an average altitude has been assessed, and the average glacier thickness calculated on the assumption that seven eighths of a floating mass of ice is below sea level.

The figures for calf ice production in Table 1 are to be viewed as „potential" volumes per annum since, as documented above, much of the potential calf ice is „stored" as segments of the floating glacier until released at intervals of a decade or longer. For example, a 17 km long segment of Petermann Gletscher was lost in the period 1959-61, perhaps in a single season. It has been estimated that up to 10 km^3 of ice may have been released on this occasion, representing the stored „potential calf ice" of about 18 years.

The photogrammetric altitude measurements were made on wide-angle 1:150 000 vertical aerial photographs

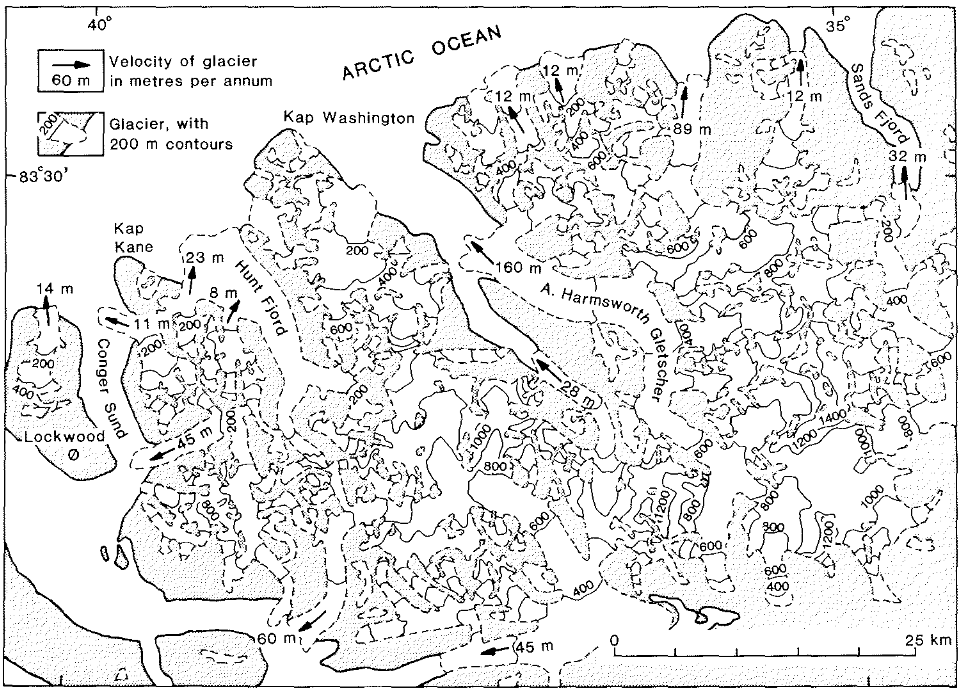

Fig. 14: Map of the west half of Johannes V. Jensen Land, showing extensive system of interconnected alpine glaciers.

Abb. 14: Karte des westlichen Teils von Johannes-V.-Jensen-Land mit einem ausgedehnten System verbundener alpiner Gletscher.

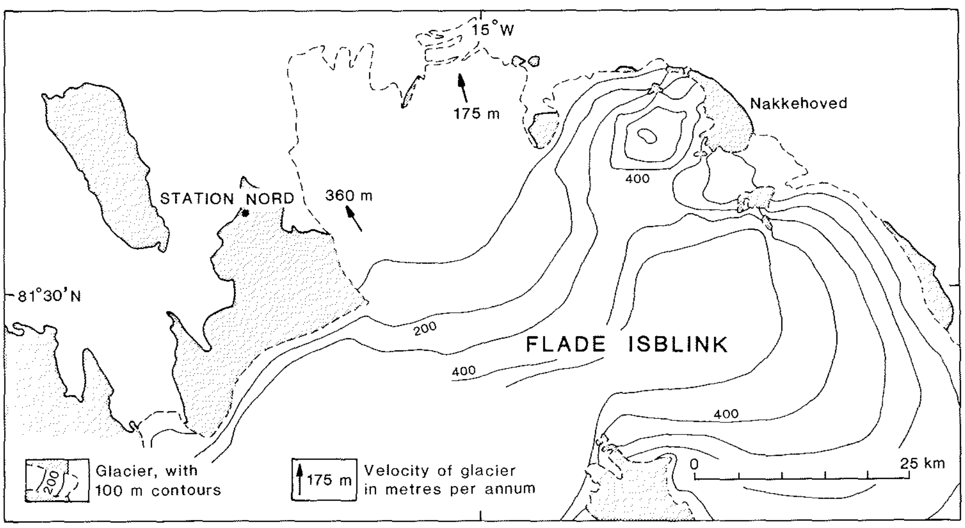

Fig. 15: Map showing the outlet glaciers of northern Flade Isblink, east of Station Nord. Contours are simplified from 1:100 000 orthophoto maps of Kort- og Matrikelstyrelsen.

Abb. 15: Karte der Ausstromgletscher von Flade Isblink östlich der Station Nord. Höhenlinien vereinfacht nach Orthophotokarten 1 : 100 000 von Kort- og Matrikelstyrelsen.

from 1978, and while the determinations were made as accurately as possible by a skilled operator, glacier surfaces are by nature irregular with hollows and ridges, and an error of plus or minus one metre is estimated as appropriate for the method. For thin glaciers this implies that calculations of the amount of calf ice may be in error by 10-20%. A further word of caution is necessary in view of the fact that nearly all altitude profiles were made on the most advanced section of the floating glacier front, that is the segment of the glacier that has been „stored" for the longest period of time prior to calving, which due to the appreciable effects of ablation (see below) will also be the thinnest parts of the glacier in question.

The figures for calf ice production in Table 1 are likely to be of the correct relative order of magnitude. The total of 3.44 km^3/y for the main North Greenland Inland Ice glacier outlets should be viewed with some reservation for the reasons given above, and also because the total includes an estimate of 0.37 km^3/y for „Brikkerne Gletscher" calculated over a period of unusually fast movement.

For three of the glaciers (Petermann Gletscher, C.H. Ostenfeld Gletscher, Hagen Bræ) the altitude profiles near the calving front were supplemented by a second transverse profile line between 9 and 17 km behind the front. Thus altitudes of the glacier surface along the profile at the front of Petermann Gletscher on 1978 photographs varied from 4 to 6 m above sea level, while 17 km behind the front altitudes along a second profile line ranged from 7 to 17 m above sea level. In respect of C.H. Ostenfeld Gletscher, two profiles 15 km apart gave altitudes of the glacier surface of respectively 8-14 m and 13-29 m. Less marked differences were noted for two profiles 9 km apart on the floating section of Hagen Bræ, which gave altitudes of respectively 10-14 m and 14-16 m above sea level (Table 2). For all three glaciers the pairs of altitude profiles were measured where the glaciers were clearly floating freely, unconstrained by fjord walls, and it is concluded that the altitude differences reflect true differences in the thickness of the glaciers.

For the three glaciers on which two altitude profiles were measured an average altitude has been assessed for each profile, and an average thickness of the glacier along each profile line has been calculated. Measured velocities of each glacier permit a calculation of the annual loss in thickness of the glacier during the time taken for it to move from one profile line to the next profile line (time lag in years in Table 2). The thickness decrease can largely be attributed to ablation, together with a possible unknown contribution arising from change at the base of the ice; for the three glaciers total loss of thickness ranges between 1.2 m and 3.1 m/y (Table 2). Calculations by Niels Reeh (pers. com. 1990) show that any decrease in thickness due to dynamic thinning for these glaciers will be very small.

There have been very few measurements of ablation and accumulation on glaciers in North Greenland. However, ice ablation of 25-50 cm of ice was recorded at the margin (ca 890 m a.s.l.) of Chr. Eriksen Iskappe (Fig. 8), north of Independence Fjord (HØJ 1970), with a net accumulation of about 10 cm water in average over major parts of the ice cap (summit at 1053 m). During the ice coring of Hans Tavsens Iskappe an average net accumulation of 13-15 cm water equivalent was reported (H. Clausen, pers. com. to A. Weidick,1989). In North-East Greenland measurements of ice ablation on Storstrømmen (ca 77°N) of 1.5-2 m ice per annum at elevations of 200-700 m a.s.l. were recorded in 1989-90 (N. Reeh, pers. com., 1990). These figures compare reasonably well with an annual thickness loss (largely due to ablation) of between 1.2 and 3.1 m ice for North Greenland floating glaciers at sea level (Table 2).

The determinations of glacier velocities and estimates of calf ice production for major North Greenland glaciers

	Upper Profile		Lower Profile		Total	Time	Annual
	altitude	ice thickness	altitude	ice thickness	thickness loss (m)	lag (years)	thickness loss (m)
Petermann Gletscher	11	88	5	40	48	17.9	2.7
C.H. Ostenfeld Gletscher	19	152	11.6	93	59	19	3.1
Hagen Bræ	14.5	116	11.9	95	21	17.6	1.2

Tab. 2: Thickness loss per annum of selected North Greenland floating glaciers at sea level, based on an average of measured surface altitudes (m) along two profile lines.

Tab. 2: Mächtigkeit des Eisverlustes pro Jahr für verschiedene schwimmende nordgrönländische Gletscher, bezogen auf Meeresspiegel. Die Werte stellen gemittelte Höhenmessungen der Oberflächen entlang zweier Profile dar.

presented here have obvious significance for mass balance studies of the northern segment of the Greenland Inland Ice, and any assessments of the response of the Inland Ice to climatic change. However, these implications lie outside the scope of this report.

4. ACKNOWLEDGEMENTS

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