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GLACIOLOGICAL STUDIES OF TWO OUTLET GLACIERS NORTHWEST GREENLAND, 1953

BY

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WITH 14 FIGURES IN THE TEXT

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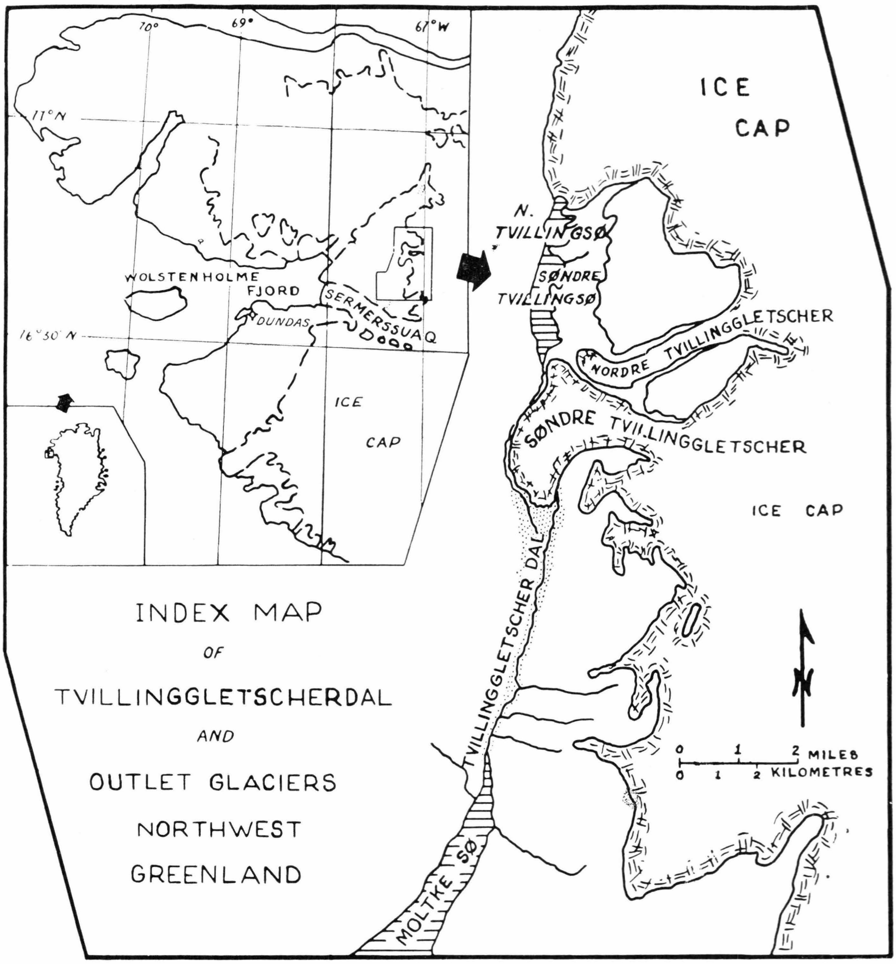

Fig. 1. Index Map of Tvillinggletscher Dal and Outlet Glaciers, Northwest Greenland.

INTRODUCTION

Glaciological studies of two outlet glaciers, Nordre Tvillinggletscher and Søndre Tvillinggletscher, 47 km northeast of Dundas (the former Thule) Greenland, indicate two periods of maximum melting for 1953, the first in late June and early July primarily due to solar radiation, and the second in late July and early August primarily due to warm winds and warm rains. Average amount of melting off both glaciers during 8 weeks of record was 77 cm (water equivalent — 62 cm). Approximately 5.8 million cubic meters of water was discharged from the two glaciers during the same period.

Nordre Tvillinggletscher is relatively free of crevasses, but the shorter, wider, and faster moving Søndre Tvillinggletscher has numerous areas of crevasses 2 to 8 m wide which eventually reseal by pressure and by refreezing meltwater, or melt out.

Nordre Tvillinggletscher moved an estimated annual 15.7 m (16.7 m also in 1954) and Søndre Tvillinggletscher 32.5 m (30.2 m in 1954). Nordre Tvillinggletscher, measured hourly for 24 hours, jerked with a pulsation similar to that known for other glaciers.

Examination of glacial deposits adjacent to the two glaciers reveals a sequence of moraines which indicate overall retreat of the main Greenland Ice Cap margin with successive shorter advances during the past thousand years. Position, shape, and lithology of moraines, outwash deposits, ice cored moraines, former lake levels, varved lake sediments, and also botanical evidence determined 8 stages of advance and retreat.

These studies were conducted under the leadership of Richard P. Goldthwait, Ohio State University, whose capable help and guidance, both in the field and office, are greatly appreciated. Gratitude is here given to Lawrence Goldthwait, St. Georges School (Newport, Rhode Island), for his energetic and willing field assistance. Thanks are due to T. N. Beard, formerly of Ohio State University, and to W. E. Riffelmacher, both of whom accompanied the author in the field on several occasions. W. S. Benninghoff, U. S. Geological Survey, helped in the dating of the recent glacial recessions.

L. F. KOEHLER, Transportation Research and Development Command, assisted in the measurement of the base line. L. H. NOBLES, Northwestern University, measured the amount of melting on the two glaciers on 29 August 1953. R. P. GOLDTHWAIT and NOBLES on 19 August 1954 determined the positions of six stakes on the two glaciers. This gave a welcome addition to the 1953 glacier motion record. R. P. GOLDTHWAIT kindly provided many constructive comments during the writing of this article.

GENERAL DESCRIPTION

The two outlet glaciers studied, here named Nordre Tvillinggletscher and Søndre Tvillinggletscher, extend west from the main inland Ice Cap into a deeply excavated north-south valley, Tvillinggletscher Dal (Fig. 1). The Tvillinggletscher Elv flows south from the main Ice Cap and from the two outlet glaciers into Moltke Sø. This lake is dammed on the south by the great outlet glacier Sermerssuaq at the head of Wolstenholme Fjord. This glacier was studied by J. W. Wright (1939) in 1937 and 1938 as the Moltke Glacier.

The area of Nordre Tvillinggletscher and Søndre Tvillinggletscher together is approximately 13 sq. km. An east-west divide separates the ice at the head of the glacier, the area of Søndre Tvillinggletscher being twice that of Nordre Tvillinggletscher (Beard, 1954, p. 36).

Nordre Tvillinggletscher expands 5.3 km from the Ice Cap into the center of Tvillinggletscher Dal. Its width varies from 1 km at its head to $^1/_2$ km at its terminus (Fig. 2). The ice surface of the center portion of the glacier has a slope of 5°. Near the glacier head where it merges with the Ice Cap, the surface slope increases from 10° to 15°. The terminus of this glacier is deflected to the north by the ice mass of Søndre Tvillinggletscher. Several small glaciers cascading from the steep rock wall along the south side are inset into the main glacier (Fig. 3). The medial moraines produced by these cascading glaciers are melted 2—3 m below the level of the adjacent ice surfaces, and meltwater flows in these troughs during most of the melt season. The sparse debris of these moraines coalesces into one wide medial moraine near the glacier terminus (Fig. 4).

Søndre Tvillinggletscher is 5.8 km long, and with bulbous shape, is 1.8 km wide where it occupies the full width of Tvillinggletscher Dal (Fig. 1, 2). The terminus has a steep slope of 40° to 50° in the first 90 m. Beyond the first 150 m the ice surface has a gentler slope of 6°. In an area of many crevasses near the middle of the glacier the slope increases to 8°. To the east is a flatter, less crevassed area where stakes for melting and motion measurements were placed. At the junction of the glacier with the Ice Cap, the surface slope is 10°. The greater size of Søndre Tvillinggletscher enables it to push the ice of Nordre Tvillinggletscher

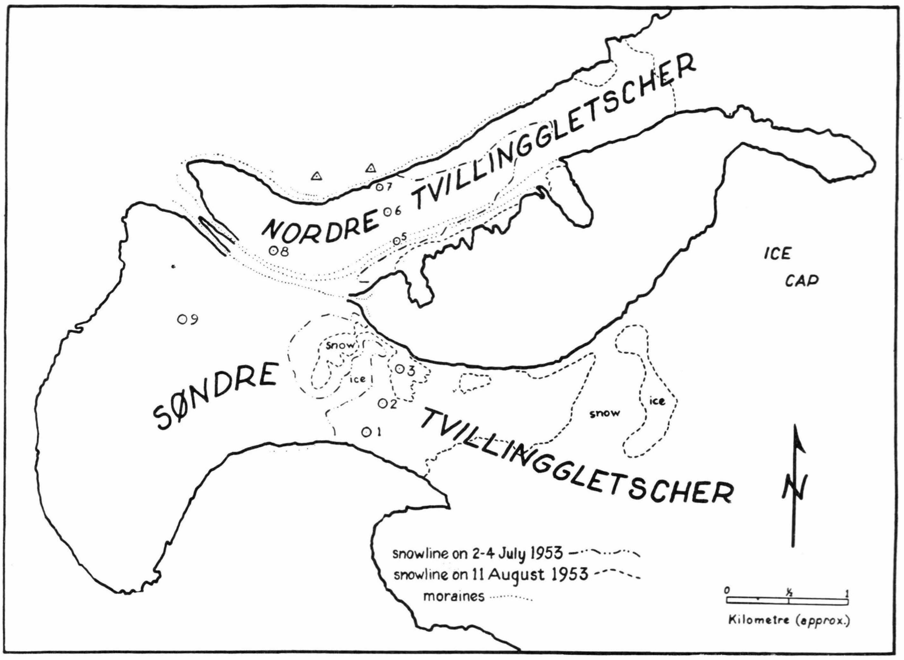

Fig. 2. Map of Nordre Tvillinggletscher and Søndre Tvillinggletscher.

aside and to abut against the vertical west wall of Tvillinggletscher Dal. Meltwater from the north is dammed by these two glaciers, and two lakes, Nordre Tvillingsø and Søndre Tvillingsø, are formed (Fig. 1, 4). The water from these lakes flows west of Søndre Tvillinggletscher against the valley wall, and then south into Moltke Sø.

Melting.

On 2 July and 4 July eight 3.2 cm diameter holes were drilled 150—165 cm into the ice of both outlet glaciers, bamboo stakes were frozen into these holes, and the level of the snow or ice surface was noted by white adhesive taped to the stakes. The positions of these stakes are indicated on Figure 2. Stake 3 was driven 154 cm into a large snowdrift, which despite its unprotected position regarding sun and rain, remained erect throughout the whole melt season; at the time of installation, the ice surface below Stake 3 was not reached. The melting of snow and/or ice around these stakes was measured only nine times during the period 4 July—29 August, inasmuch as the round trip sometimes by foot from base camp to visit the stakes during the latter part of the season when the lakes were open involved a journey of 25 km. The stakes remained in the ice all season and were used as markers also for motion study in both 1953 and 1954.

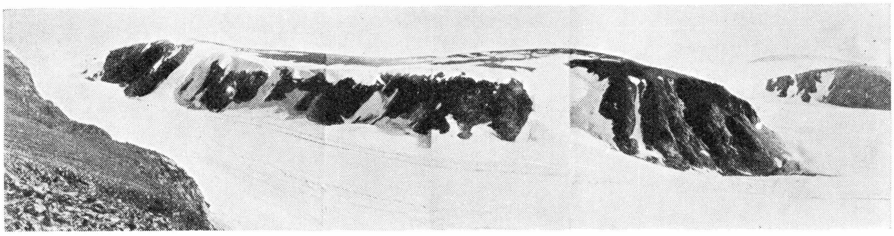

Fig. 3. Nordre Tvillinggletscher in foreground, Søndre Tvillinggletscher at right. Tributary cascading glaciers from south wall of Nordre Tvillinggletscher are inset into the glacier. Photographs by L. F. Koehler.

On Figure 2 is indicated the position of the firnline (labelled snow-line, Fig. 2) on both glaciers on 2 July and 4 July and also as shown on aerial photographs taken on 11 August 1953. The line of 11 August closely represents the limit of firn not completely melted or reformed into ice by the end of the 1953 melt season. Some of the firn which did disappear below the August line may have reformed into superimposed ice. No estimate of the amount of superimposed ice formed during the season is available.

Table I indicates the estimated daily melting of ice or snow below the original glacier surface and total water equivalent at the eight stakes in 1953. The average amount of melting at all stakes during the eight weeks of record was 77 cm (water equivalent — 62 cm).

The greatest amount of melting on the two glaciers during the time of observation occurred from 25 July through 7 August. From a study, however, of weather records made at base camp (approximately 7 km northwest of the glaciers), and of estimated daily melting during time of record, another time of great if not greater melting was late in June and through the first week in July. Maximum air temperatures at base camp, from the beginning of weather observations on 3 July to 7 July averaged 12.2° C, whereas minimum air temperatures for the same interval averaged 8.2° C; average of maximum radiation for the five days was 1.34 $G.cal/cm^{-2}/min^{-1}$. The amount of melting in the first two to four days after the stakes were set in indicates that the melt season was already well under way at that time. On Søndre Tvillinggletscher an average of 29 % of the total amount of melting recorded occurred 2—6 July, and on Nordre Tvillinggletscher 10 % took place 4—6 July. It is apparent that much of the melting record, as well as a smaller part of the meltwater volume, was missed due to the late start of these studies. Since most of the early meltwater, however, warmed the snow mass and created slush which at first did not move, few streams carried water and rather little of the meltwater volume was lost.

Warm winds and warm rains locally increased the amount of melting.

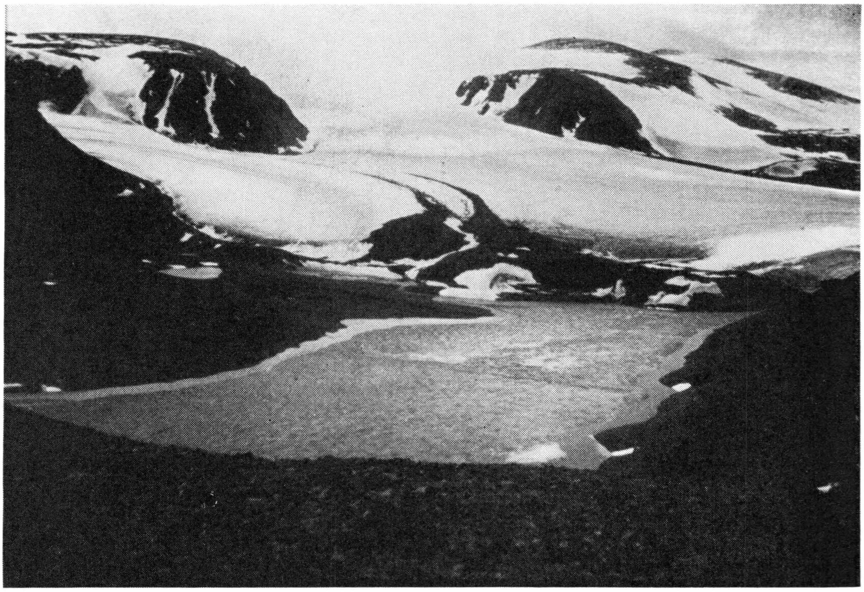

Fig. 4. View of Nordre Tvillinggletscher and Søndre Tvillinggletscher. Søndre Tvillingsø in foreground.

A warm rainstorm occurred on 26 July during which time at base camp (at an altitude of about 600 m, similar to that of the glaciers) temperature varied between 5° C and 6.6° C, with variable wind speeds from "light" to 29 km/hr, with a total sky cover, and with maximum radiation of 0.11 $G.cal/cm^{-2}/min^{-1}$. During this storm an average of 6.5 cm snow and ice (water equivalent — 4.8 cm) melted. This is 9 $^0/_0$ of the total melting recorded on Søndre Tvillinggletscher and 7.2 $^0/_0$ on Nordre Tvillinggletscher. At the protected stake (Stake 1) on the south edge of Søndre Tvillinggletscher, shielded by a high rock wall from rain driving from the southeast at a low angle, 1.3 cm ice melted (1.8 $^0/_0$ of total melting recorded at that point). This melting due to warm rain is understandable inasmuch as the specific heat of warm water is four times that of equally warm air.

Another period of rainy days ensued on 3—5 August. A continuous wind of 37 km/hr blew from the southeast on 3 August and increased in velocity throughout the night. Rain started to drive past base camp at 6.30 hr[1]) on 4 August (with an air temperature of 4.4° C) and, with wind from the southeast up to 67 km/hr, continued without more than momentary pause for more than nine hours. Rainwater flowing across the glaciers melted much of the ice, and snow bridges over deeply incised channels in the ice were inundated, uplifted and floated downice by the

[1]) All time used in this report is Eastern Standard Time.

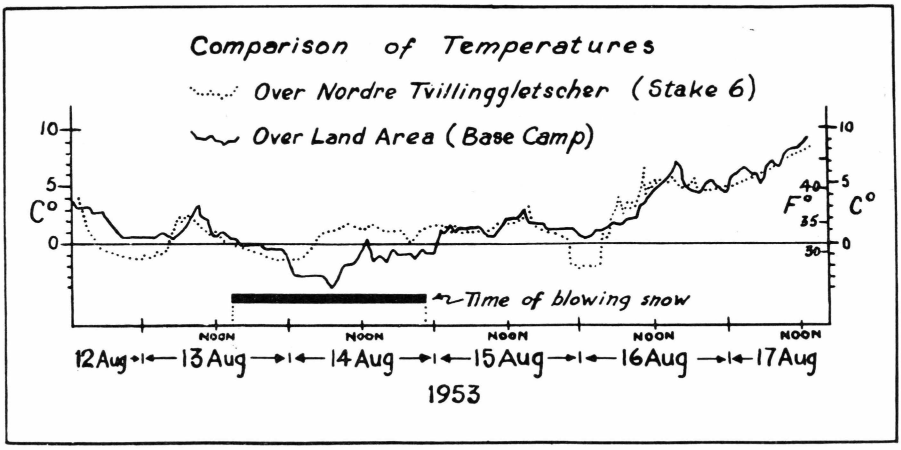

Fig. 5. Comparison of temperatures over Nordre Tvillinggletscher (Stake 6) and over land area (Base Camp), 12—17 August 1953.

runoff. Measurements made at the stakes on the two outlet glaciers encompass too large a span of time (30 July—5 August) to determine a decisive percent of melting for this storm.

After 7 August rates of melting dropped to a low level and all melting below 760 m (except at Stake 3) was that of ice. From 11 August to the end of the month, standing water on glacier surfaces froze each night and in the cryoconite (algal) holes to more than 2 cm thick. This ice remained throughout most of the following days. The nightly temperatures plus diminishing solar radiation received due to cloudiness and the low sun angle substantially reduced melting and stream flow.

The first snow that remained on the glaciers arrived during a stormy period 14—16 August. The accumulation of new snow (22.8 cm at Stake 2 and 6.3 cm at Stake 3) affected the melting record.

An attempt was made to correlate temperatures over adjacent land areas with those over one of the glaciers. An instrument shelter with a 5-day thermograph inside was set up 30 cm above the ice on Nordre Tvillinggletscher at Stake 6 from 13.00 hr 12 August to 15.00 hr 17 August. These temperatures are plotted against those recorded at base camp during the same time, and are shown on Figure 5. Wind speed, relative humidity, sky cover, and radiation over the land area (base camp) for the same period are listed in Table II.

During this period 3.2 cm ice melted (water equivalent — 2.5 cm). This is an estimated average of 6 mm ice melted per day, is 3.3 $^0/_0$ of the total at Stake 6 for the season, and indicates that the rate of melting had dropped to a low level. Snow probably blowing past Stake 6 from mid-afternoon of 13 August throughout the night and most of 14 August,

Table 1. Melting Record of two outlet

Stakes set in 2 July	Stakes set in 4 July	Altitude in metres	Average daily melting, 2—6 July	4—6 July	6—25 July	25—27 July	27—30 July	30 July—5 Aug.
								Søndre Tvilling-
1		634.3	5.08 (20.3)		0.99 (19.6)	0.63 (1.27)	—	—
2		632.5	5.58 (22.8)		0.86 (17.1)	4.44 (8.89)	—	—
3		632.5	6.35 (25.4)		1.01 (20.3)	5.38 (10.7)	—	—
	9	521.5		3.81 (7.62)	1.67 (33.6)	4.11 (8.25)	—	2.33 (23.4)[1]
								Nordre Tvilling-
	5	605.4		4.74 (9.52)	1.27 (25.4)	2.54 (5.08)	1.90 (5.71)	1.44 (10.16)
	6	606.3		3.81 (7.62)	1.52 (30.4)	4.44 (8.89)	2.10 (6.35)	1.77 (12.7)
	7	601.7		(6.98) 3.47	1.57 (31.7)	1.27 (2.54)	1.68 (5.08)	1.72 (12.0)
	8	530.0		3.47 (6.98)	—	1.70 (37.4)[2]	1.03 (3.17)	1.72 (12.0)

Figures in parentheses indicate actual total centimetres of melting below original ice or snow lev
for the period represented.
Figures here are for 27 July—5 August.

as it did over the adjacent land area, accounts in part for the small amount of melting.

Additional snow accumulation is noted in the record (*See* Table I) on 29 August with 13.3 cm at Stake 2, 6.3 cm at Stake 3, and 12.7 cm at Stake 7. "... the period from August 22 to September 4 was one of almost perfect weather, but the sun was so low in the sky that it no longer had much effect on the ice. Melting was very slow ... and by August 30, all of the streams were way down." (L. H. NOBLES, written communication, 14 October 1953)

A certain amount of meltwater is reabsorbed during the melt season. Not only the freely flowing meltwater which freezes in the many crevasses and again becomes glacier ice, but small droplets of water near the ice surface produced by melting downward of the snow above it

Glaciers, Northwest Greenland, 1953.

in centimetres				Total melting recorded in 2 months 2/4 July to 29 August cm	Water equivalent cm
27 July -7 Aug.	5/7 Aug. —12 Aug.	12—17 Aug.	17—29 Aug.		
gletscher					
1.32 (15.8)	0.33 (1.90)	0.33 (1.90)	0.68 (8.89)	69.66 7.62 snow 62.04 ice	55.62
1.62 (19.6)	0.83 (5.08)	22.86[4]	plus 13.33[4]	73.47 34.92 snow plus 36.19[4] 38.55 ice	52.70
1.85 (22.2)	0.93 (5.71)	6.35[4]	0.88 6.35[4] (12.0)	89.96 plus 6.35[4]	73.93
—	0.00 (0.00)	0.33 (1.90)	—	74.77 all ice	61.44
gletscher					
—	0.15 (1.27)	0.20 (1.27)	0.86 (11.4)	69.81 all ice	57.27
—	0.30 (2.54)	0.63 (3.17)	1.70 (2.22)[3]	93.87 all ice	77.06
—	0.48 (3.81)	0.43 (2.54)	plus 12.70[4]	64.65 all ice plus 12.70[4]	53.11
—	0.78 (6.35)	0.43 (2.54)	0.96 (12.7)	81.14 all ice	66.64

Figures here are for 6 July—27 July.
Observer stated figure not reliable; stake melted out of ice.
Accumulation of new snow.

refreeze, and thus build up the ice surface. This process of reabsorption of the meltwater, wherein it becomes superimposed ice if it refreezes just above the older glacier ice, is a feature of polar glaciers which introduces complications in the determination of annual net loss of meltwater (Schytt, 1949). Loss of meltwater as determined by measurements against stakes in the ice gives maximum estimates, because a certain amount of that lost by melting again is reabsorbed. In addition, rainwater each season runs into crevasses and there freezes; it freezes as pools on the ice surface, and it drops onto snow and is frozen again later as superimposed ice—all of which becomes eventually an undetermined amount of glacier ice and further complicates estimates of accumulation and ablation.

Two periods of maximum melting occurred during the 1953 melt

Table 2. Wind speed, relative humidity, sky cover, and radiation over land area, 12—17 August 1953.

	Wind Speed Km/hr		Hrs. of Calm	Relative Humidity %		Sky Cover Average Intern'tl Code 0–10	Radiation G. cal/cm-2/min-1	
	max.	min.		max.	min.		max.	min.
Aug. 12...	26	3	—	76	55	5	1.13	0.00
— 13...	45	—	6	93	55	9.9	0.29	0.00
— 14...	56	26	—	90	76	9.9	0.93	0.00
— 15...	51	—	3	92	77	9.8	0.80	0.00
— 16...	40	—	5	79	31	9	0.32	0.02
— 17...	40	—	4	48	30	6.8	1.19	0.03

season, the first, late June and early July due primarily to solar radiation, and the second, late July and early August due primarily to warm winds and rain. Little melting took place after early August. This short melt season from late June to early August is similar to that for the Barnes Ice Cap (P. D. BAIRD, 1952, p. 4—5) and for the Penny Ice Cap (W. H. WARD and P. D. BAIRD, 1954, p. 346), both on Baffin Island, and yet this may not be typical of the duration or timing of the melt season for northwest Greenland.

Meltwater.

Discharge measurements made by T. N. BEARD on the two outlet glaciers and the drainage area to the north indicate that Tvillinggletscher Elv had an approximate discharge of 19.8 million cu. m water from 1 July to 1 September. The actual amount of water that came from the two glaciers is considerably less than this. Runoff from the Ice Cap at the north end of Tvillinggletscher Dal (Nuna Ramp of BEARD's report) for the same period is 4.8 million cu. m. The rainy period of 3—5 August added 4—5.8 million cu. m. Other factors such as snowbank meltwater and water from frozen ground also are subtracted. Approximately 5.8 million cu. m of water, then, was derived from the two glaciers during the 1953 melt season (BEARD, 1954, p. 37—38).

Water started flowing in Tvillinggletscher Elv late in June. The runoff peak occurred 3—4 August when rainwater was added to water from melting ice and snowbanks. More than 28 cu. m/sec is estimated for the total discharge during this short period. Average velocities as high as 3.3 m/sec occurred. After this discharge peak, runoff decreased sharply and probably ceased or became insignificant after 1 September (BEARD, 1954, p. 38—39).

On 10—11 August a series of observations were made by BEARD to determine diurnal fluctuation in discharge of Tvillinggletscher Elv. The daily fluctuation of the river was regular, but a sharp rise to peak runoff was not so pronounced as on the Ice Cap at the north end of the valley (BEARD, 1954, p. 39). Time of high water was between 15.00 hr and 16.00 hr with low water at 9.00 hr. Maximum temperatures occurred near 13.00 hr and minimum at midnight. This lag between temperature and runoff undoubtedly is due to the time required for water to gather and move to the gaging station (BEARD, 1954, p. 39—40).

If an average figure of 64 cm of ice (water equivalent — 52.3 cm) be taken as representing the minimum amount of ice removed by melting across the lower half of Nordre Tvillinggletscher, then approximately 498,080 cu. m of ice (407,520 cu. m water) was melted from the lower half of the glacier. Using these figures and those in Table I, BEARD in his report calculated that approximately 6.3 million cu. m water melted off the two glaciers during his period of record (1954, p. 40). This figure is on the same order as but slightly more than his calculated estimate of runoff from the glaciers as observed in Tvillinggletscher Elv.

Drainage.

Figure 6 is a map of the meltwater streams on the surface of the two outlet glaciers as observed on the aerial photographs of 11 August 1953, but also as determined in a few special cases by fluorescein color tracing. Except in a few instances, no streams flow where crevasses exist. The absence of streams on the upper part of Søndre Tvillinggletscher, for example, is due to meager amount of melting and to the great number of crevasses in that area. Some water flowing into crevasses eventually freezes and crevasses thus are sealed. In areas of small crevasses 30 to 60 cm wide, the crevasses draw off meltwater, and the glacier surface is drained. Most streams are not more than $2^1/_2$ km in length on Søndre Tvillinggletscher. Where not controlled by old healed crevasses, the drainage pattern is parallel to dendritic. A few streams take rectangular patterns where controlled by partially healed and melted out crevasses, as on the east side of the north lobe of Søndre Tvillinggletscher. One stream bifurcates only to join itself again 1.1 km farther along on the north edge of the ice lobe (Fig. 6). Portions of some streams are truly antecedent as the channels continue to be occupied and melt sinuous miniature canyons into the ice as the glacier surface is elevated and domed over some bedrock protuberance on the valley floor beneath.

One stream where the two outlet glaciers join flows east on Søndre Tvillinggletscher into a lake between the valley wall of rock and the glacier ice. Early in June this lake had no visible outlet although several

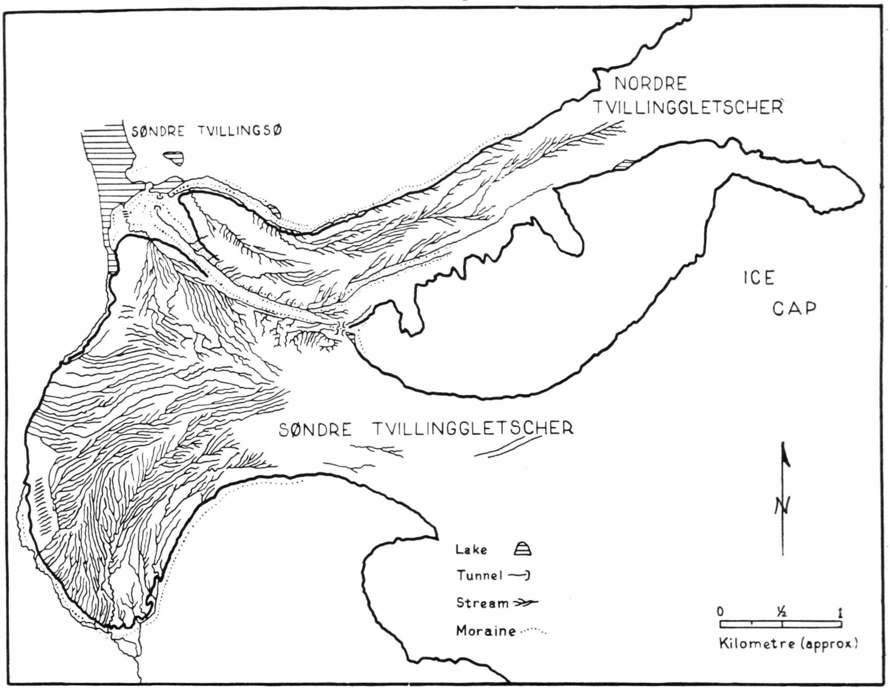

Fig. 6. Surface streams on Nordre Tvillinggletscher and on Søndre Tvillinggletscher, 1953.

streams flowed into it from both adjacent glaciers. By mid-August a part of the lake next to Nordre Tvillinggletscher was completely drained, and the part of the lake next to Søndre Tvillinggletscher had lowered several metres. Stream water flowed across the floor of the former lake and dropped vertically into a tube melted out of glacier ice 3 m in diameter and about 5 m deep. This water disappeared at the bottom of the tube, presumably entering a tunnel within the ice. The exact point of emergence of this water is not determined, although fluorescein color tracing was attempted. Figure 6 is drawn to show this mid-August condition, with streams flowing into the tunnel from several directions. Observations from the air and on the ground indicate that the same events took place during the summer of 1954.

Meltwater from Nordre Tvillinggletscher and the north one-fifth of Søndre Tvillinggletscher flows north into Søndre Tvillingsø (Fig. 6) and then south around the west edge of Søndre Tvillinggletscher. The lake ice surface on Søndre Tvillingsø on 20 June had fallen in the center of the narrow south arm of the lake. It was evident that water had started to drain from the lake over or under a barrier of stream ice along the west edge of Søndre Tvillinggletscher. Later in the season most of this stream water disappears under the west ice edge and emerges from a large tunnel in the ice 1 km farther south (Fig. 6). This tunnel also may emit some of the meltwater that flows in crevasses on Søndre Tvillinggletscher. On the day that fluorescein dye was put into the tube that had drained the small lake between the glaciers, the water from this tunnel was examined, but no trace of color was detected. This meltwater and that which drains from the south end of Søndre Tvillinggletscher cuts channels with overhanging walls into the 5—7 m thick perennial river ice (aufeis) of Tvillinggletscher Dal.

Only a few streams drain the surface of the longer, narrower Nordre Tvillinggletscher. The longest stream on this glacier is 3.8 km in length. In many places the meltwater leaves the glacier surface immediately, flowing along the sides or in troughs on the medial moraines.

At the termini of both glaciers, the larger streams have melted permanent meandering canyons into the ice. Some are 5—12 m deep and 15 m wide; the stream surface at the bottom is 2—3 m wide, the water a metre deep and flowing at high speed. These canyons are reoccupied each season by the meltwater and constitute a major barrier and danger in crossing these glaciers.

Crevasses.

Nordre Tvillinggletscher is relatively free of crevasses (*See* Fig. 7), whereas Søndre Tvillinggletscher is heavily crevassed in several areas. The steep gradient of Søndre Tvillinggletscher, the undulating bedrock surface beneath the ice, the expansion from a narrow confined glacier to a bulbous shape, and a higher speed than that of Nordre Tvillinggletscher accounts for the greater number of crevasses. The middle and upper part of Søndre Tvillinggletscher is broken by several hundred crevasses. Some of these are 30—60 cm in width, especially the many short ones oriented approximately 45° to the confining rock walls along both north and south edges. Others in the middle of the glacier, parallel to and nearly normal to the direction of glacier flow, are $1^1/_2$ to 8 m wide (*See* Fig. 8). Those indicated on Figure 7 in the upper portion of the glacier where it merges with the Ice Cap were not studied in the field but aerial photographs show them to be 3—10 m wide. Others may exist in that same region but are not visible due to the snow cover. During the season sharp reports were heard as crevasses opened up or widened. One small crevasse in the center of Søndre Tvillinggletscher widened during the season from 10 to 35 cm along its surface trace.

The great majority of crevasses in the middle and upper part of Søndre Tvillinggletscher form angles of more than 45° to the margins, although some form angles of 45°, some less than 45°, some parallel

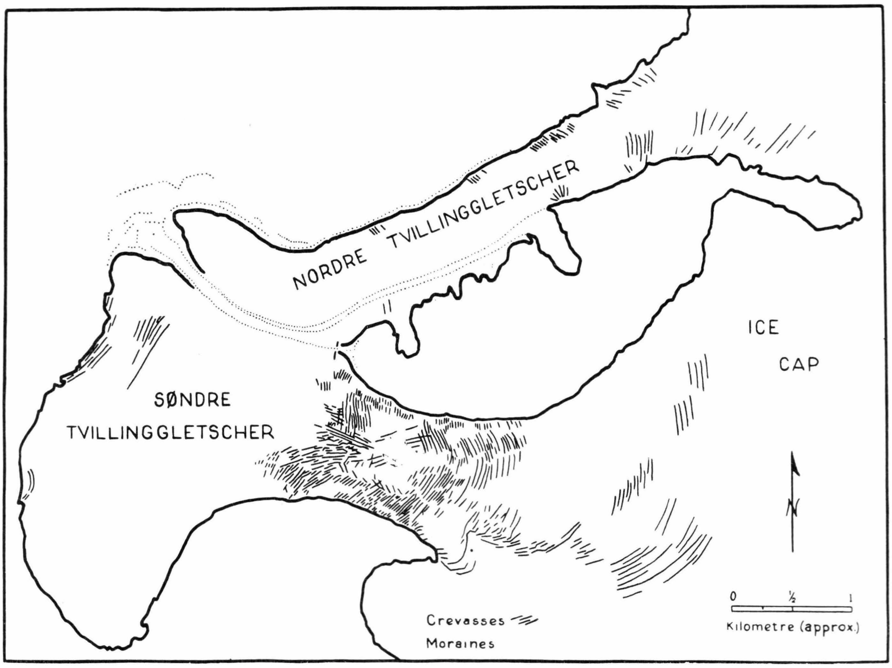

Fig. 7. Crevasses on Nordre Tvillinggletscher and on Søndre Tvillinggletscher 1953.

flow direction, and some are transverse to flow direction (Fig. 7). It might be feasible here to apply to these crevasses J. F. NYE's theory of crevasse patterns which developed out of his study of the mechanics of glacier flow (1952, p. 89—91). According to NYE, a longitudinal tensile stress within the ice will swing the direction of maximum tension towards the direction of flow and crevasses would form angles at the edges greater than 45°. Among the conditions producing the longitudinal tension (NYE, 1952, p. 91) that fit the situation at the upper part of this glacier are accumulation and a convex bed. The upper part of the glacier where these crevasses exist is in the lower zone of accumulation. The configuration of the bedrock floor is not known, but one would expect it to be convex at the point where the glacier leaves the Ice Cap. Accompanying this, a transverse tensile stress might be developed, and both principal stresses in the central part of the glacier might be tensile. It could then follow that "In this central strip one might expect to see crevasses not only transverse to the direction of flow but in many other directions as well; . . ." (NYE, 1952, p. 91). In the middle of the glacier, where the crevasses are oriented in many directions, the transverse crevasses and the wide longitudinal crevasses might thus be explained. Those crevasses parallel to flow direction probably are due to widening of the valley, resulting in longitudinal tensile stresses within the ice.

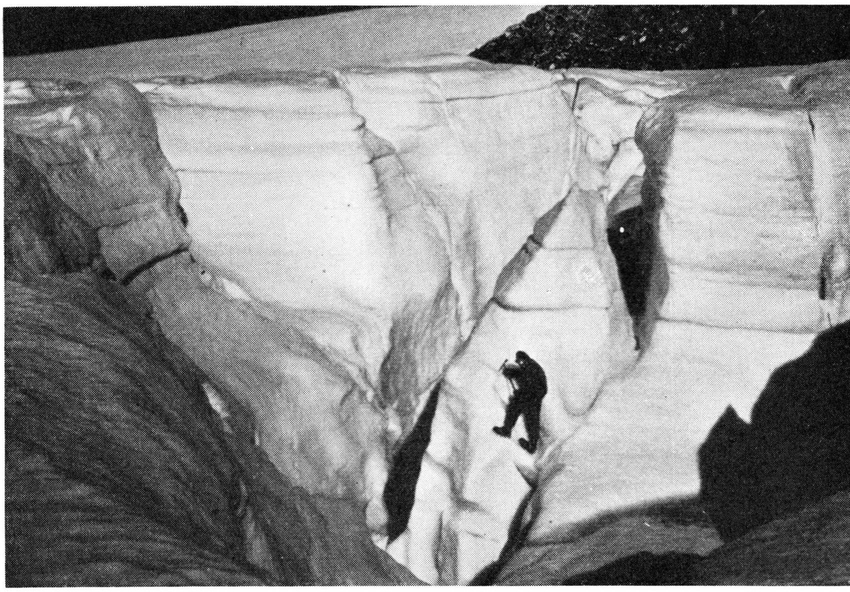

Fig. 8. Wide crevasses in middle part of Søndre Tvillinggletscher, oriented normal to direction of glacier flow.

The crevasses at 45° and less, the effect of longitudinal compressive stresses, might be due, as Nye states (1952, p. 90), to ablation and to being on the inside of a bend, inasmuch as the area where those crevasses do exist is well within the zone of ablation and near the inside of a corner.

Crevasses are eliminated in the lower part of Søndre Tvillinggletscher by transverse compressional stresses in the ice as the flatter bedrock floor of Tvillinggletscher Dal is reached. Some compression also may be exerted as the west side of the glacier presses against the west valley wall. In addition, crevasses which open in the middle part of the glacier, described above, will have at least 60 cm of ice removed at their top during each melt season. At 32.5 m of travel per year (the estimated average movement of Søndre Tvillinggletscher), when the section of glacier with the crevasses in it flows onto the flatter valley floor, a 30 m thickness of the wide upper part of the crevasses will be melted away. Unless tensile stresses are renewed as the ice mass progresses, old crevasses melt to nothing or they seal up by compression or by refreezing of meltwater.

Several parallel crevasses are a short distance from the west edge of the lower part of Søndre Tvillinggletscher where a loss of support exists due to meltwater undermining or steepening the edge of the ice cliff. These crevasses vary in width from one to two metres. At the ice edge the sections of the glacier between crevasses are pushed and undermined until they fall into the streambed.

Narrow tension craks (2—30 cm) exist along the north edge of Nordre Tvillinggletscher; a few longer and much wider ones are near the head of the glacier along the south edge. One set of crevasses radiating from a point on the south wall probably is due to an abrupt drop in the valley floor at that point.

Glacier Motion.

From high cliffs overlooking both outlet glaciers (Fig. 3), the positions of all stakes were noted on 16 July 1953 with a Wild T-2 theodolite (*See* triangulation markers, Fig. 2). On 28 July 1953 the base line was measured, and on 6 August and on 17 August the relative positions of some of the stakes again were determined. As a supplementary study, the relative positions of Stakes 5, 6, and 7 across the middle of Nordre Tvillinggletscher were recorded every hour for 24 hours, 29—30 July 1953, by using a theodolite placed on a narrow rock shelf on the near-vertical rock cliff at the north side of the glacier. On 19 August 1954, the positions of the stakes again were noted, more than one year after the measurements made in 1953. In all measurements, four to six observations were recorded, and, in some instances where all observations did not agree, two to four more were taken to obviate errors induced by possible instrumental deviations or human error.

Motion made by seven of the eight stakes on the outlet glaciers is shown in Table III.

The estimate of annual motion for 1953 is determined by projecting the motion of the period of 32 days, from 16 July through 17 August, to that of a year, and assuming that the rate of motion is uniform throughout the year. Søndre Tvillinggletscher moved an estimated average of 32.5 m for 1953, and 30.2 m for 1954, double that for Nordre Tvillinggletscher which moved an estimated average of 15.7 m for 1953 and 16.7 for 1954.

The study of the history of these two outlet glaciers reveals that their margins have been retreating haltingly with lesser readvances for the past thousand years or so. If this is still continuing, it logically follows that despite the forward glacier movement of 16 m to 31 m each year, more ice melts away than is supplied. Rough figures suggest that this is true. By comparison with alpine glaciers of similar size and by projecting the thickness of Nordre Tvillinggletscher of 200 m at Stake 8, obtained from a gravity measurement (D. F. BARNES, written communication, October 5, 1954), the ice should be at least 120 m deep at Stakes 5, 6, and 7. Since the glacier is 0.6 km wide here, the probable area of cross section is on the order of 51,000 sq. m. If the average motion, including slower moving ice next to the bottom and side, is 10 m per year, then 466,950 cu. m of new ice is supplied each year. Actual net

Table 3. Motion of the Two Outlet Glaciers, 1953 and 1954

	16 July —6 Aug. cm	6—17 Aug. cm	16 July —17 Aug. cm	29—30 July for 24 hrs. cm	Daily average for Period of Record cm	1953 Estimated Annual m	1954 Estimated Annual m
			Søndre Tvillinggletscher				
Stake 1....	173.7	85.3	259.0	..	8.1	c 29.5	c 28.7
— 2....	c 238.0	c 111.0	c 349.2	..	c 10.9	c 39.8	c 33.8
— 3....	c 200.0	c 54.2	c 254.3	..	c 7.8	c 28.3	c 28.1
			Nordre Tvillinggletscher				
— 5....	108.8	64.0	172.9	2.29	5.3	c 19.0	c 20.1
— 6....	96.0	50.9	147.0	3.13	4.5	c 16.7	c 20.6
— 7....	c 56.1	c 27.1	c 83.2	2.85	c 2.5	c 9.5	c 9.6
— 8....	c 118.9	c 37.8	c 156.7	..	c 4.8	c 17.8	..

c — approximate or estimated.

loss of ice measured in 1953, with at least a minimum of 65 cm for the whole 743,200 sq. m of glacier surface from the stakes to the terminus, is 481,100 cu. m. Compared to the estimate of the new ice supplied annually, ice coming down the valley does not quite equal the ice melting away.

The cumulative distance that Stakes 5, 6, and 7 moved on Nordre Tvillinggletscher for the 24 hours of observation 29—30 July, and the hourly movement of each stake is shown in Figure 9. The meticulous repetition of all measurements with the theodolite, previously mentioned, insured against possible diurnal instrumental wanderings, so rightfully deplored by R. P. Sharp (1954, p. 832).

The center of Nordre Tvillinggletscher moved fastest, 3.13 cm for the 24 hours, but this is slow compared to the daily movement of South Crillon Glacier in Alaska in 1934, 60—86 cm (Washburn and Goldthwait, 1937, p. 1663), and slow compared with some of the glaciers of West Greenland, such as Upernaviks Isström in 1931, the center of which traveled 18.2 to 20.5 m per day (Carlson, 1939, p. 247). Upernaviks Isström, however, terminates in the sea. W. R. B. Battle's observations on the movement of Frejagletscher, Clavering Ø, East Greenland, at nearly the same latitude as Upernaviks Isström, in 1949 indicate a speed of 17 cm a day diminishing later in the season to 1 cm per day (1951, p. 560—561; 1952, p. 13—16). Frejagletscher terminates on land. L. H. Nobles (1954, p. 1290) states that large outlet glaciers in northwest Greenland (one of which is known to be Sermerssuaq glacier) move "... a few feet per day, ..." This daily motion is recognized here as approximately 90—150 cm.

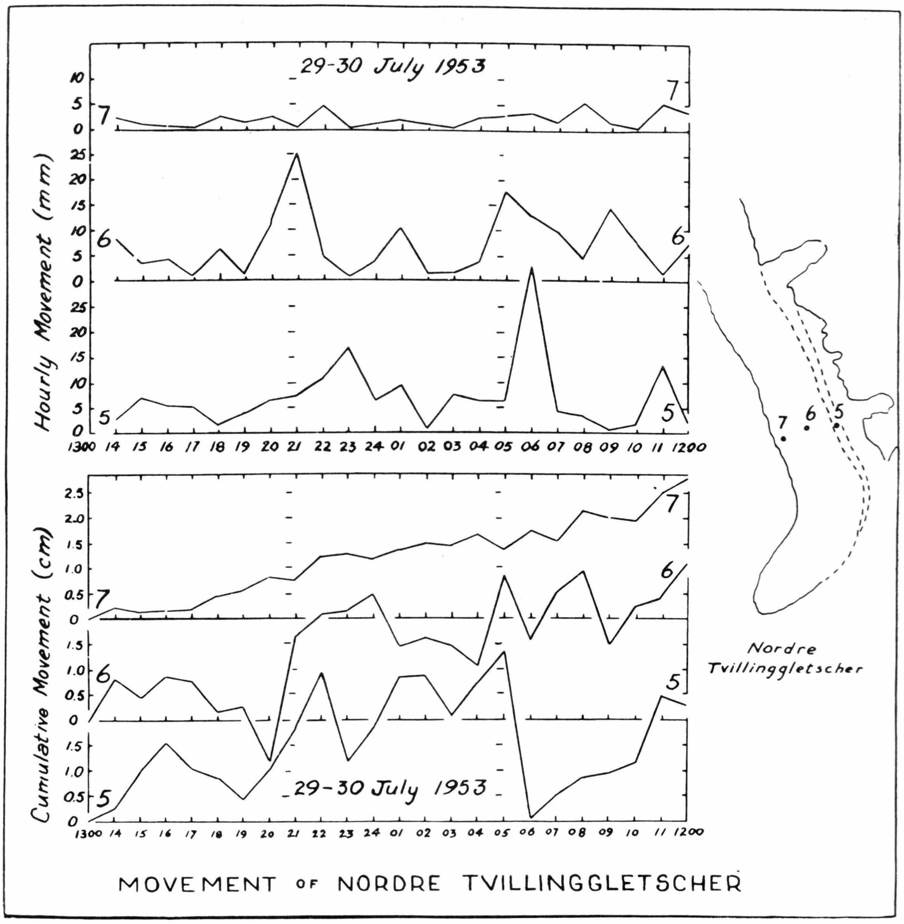

Fig. 9. Movement of Nordre Tvillinggletscher, indicating Hourly Movement (mm) and Cumulative Movement (cm), 29—30 July 1953.

Although each part of Nordre Tvillinggletscher, as measured at the stakes, advanced a definite distance downvalley, the forward motion of the glacier ceased a number of times, and also backed up to nearly its original position at the beginning of the 24 hour record (Fig. 9, Stake 5 at 6.00 hr). In one instance, Stake 6 was farther upvalley at 20.00 hr than it was at the initiation of the observations. BATTLE noted the same type of pulsation, and recognized the same difficulty in its explanation (1951, p. 560). M. F. MEIER, G. P. RIGSBY, and R. P. SHARP also noted that for 3 days during a 17 day period of observations, the Saskatchewan Glacier in Alberta, Canada receded upvalley farther than it was at the beginning of their period of record (1951, p. 10—11). The forward motion of Nordre Tvillinggletscher was greatest late at night, from 19.00 hr to midnight, and again at midday from 10.00 hr to 14.00 hr.

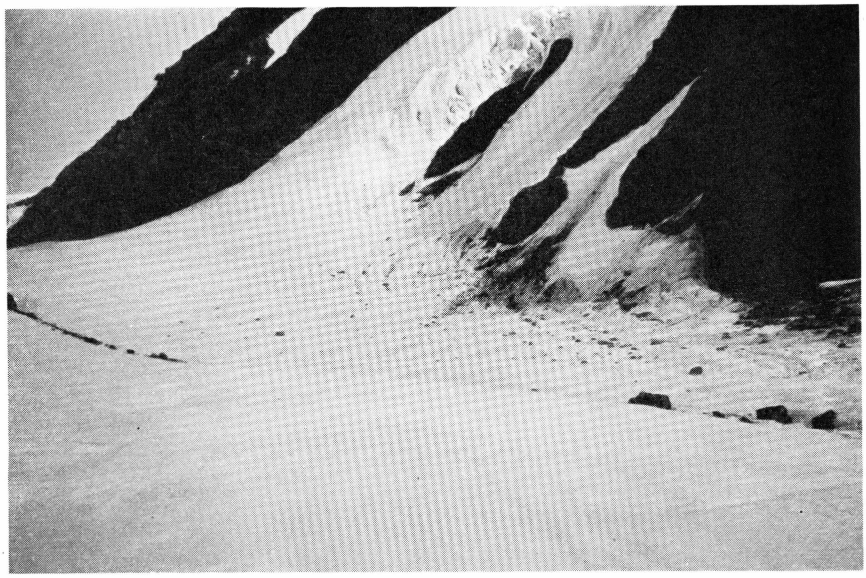

Fig. 10. Tributary glacier cascading from south wall to Nordre Tvillinggletscher.

The ice jerked with a vibration similar to that of South Crillon Glacier and Frejagletscher, varying from a maximum amplitude of 6 mm per hour at Stake 7 to 24—27 mm per hour at Stakes 5 and 6 (Fig. 9). This is slightly more than that of South Crillon Glacier with maximum amplitudes of 12—17 mm per hour (Washburn and Goldthwait, 1937, p. 1660), and of Frejagletscher with maximum amplitudes of 10—20 mm per hour (Battle, 1952, p. 16). The periods of greater jerkiness were in the late evening, 19.00 to 22.00 hr, and early morning, 4.00 to 9.00 hr; jerkiness appeared at a minimum during the late afternoon and shortly after midnight. The period of lesser variations in the rate of motion on South Crillon Glacier also was during the afternoon hours, but instead of being quieter during the hours shortly after midnight, South Crillon Glacier was quite active then (Washburn and Goldthwait, 1937, p. 1660—1661). The periods of greater jerkiness of Frejagletscher also were in the late evening hours and during the early morning hours; jerkiness was at a minimum, however, not during the afternoon hours, but during mid-morning hours (Battle, 1952, p. 15—16). No crevasses exist on Nordre Tvillinggletscher in the vicinity of any of the stakes; Battle states that none were present between his theodolite and the stakes on Frejagletscher (1952, p. 16). The irregular motion cannot be explained by crevasses despite the fact that South Crillon Glacier is severely crevassed. The periods of jerkiness of the Greenland glaciers correspond to a degree, and this correspondence may have some significance. It is entirely possible that this jerky motion and the erratic backward movement experienced in Greenland and in Canada is due to the Block-Schollen type of movement postulated by R. FINSTERWALDER (1950).

Distance between several ogives (annual white ice ridges and dirty ice hollows) on the upper part of the center of Nordre Tvillinggletscher indicates an annual motion of approximately 30 m. At Stake 6 farther downice at the center of the glacier, annual motion was 16.7 m. The distance between ogives on a tributary glacier cascading from the south wall to Nordre Tvillinggletscher (Fig. 10) exhibits movement of approximately 26 m per year. At Stake 5 in the ice from the tributary glacier, annual motion was 19 m. The faster movement of 26—30 m upglacier is expected, inasmuch as the ogives were measured closer to the area of accumulation and where the ice surface slopes 3° to 8° steeper than that near Stakes 5 and 6.

The faster motion of the ice near Stake 5 may be explained in several ways. The glacier ice along this south side may be deeper than that in the center at Stake 6 and may thus move faster, or the ice contributed from the cascading glacier, inset into the main glacier, forces this inset ice to move differentially faster than the rest of the glacier. BATTLE (1951, p. 560) observed the Frejagletscher to have "... two zones of greatest speed separated by a zone of slow moving ice." He suggests two explanations. The ice would move at different speeds if it were derived from two different sources, or if a rock ridge extended into the ice from the valley floor. The faster moving ice at Stake 5 is from a different source than that at Stake 6.

Glacial History of Tvillinggletscher Dal.

The study of glacial deposits in Tvillinggletscher Dal reveals a sequence of moraines which indicate overall retreat of the Ice Cap margin with successively shorter readvances. Initially it filled the valley but as it thinned it separated into individual ice lobes. Each of these retreated separately, resulting in the present position of the Ice Cap and the two outlet glaciers.

The sequence of retreatal stages is based upon the position of, shape of, and lithology of end moraines, lateral moraines, meltwater channels, outwash deposits, and former lake levels. These stages, as related to Tvillinggletscher Dal and the part of the valley north of Nordre Tvillinggletscher including Nordre Tvillingsø and Søndre Tvillingsø, are shown in part on Figure 11, as follows:

Stage 1. — Overall glaciation by the Ice Cap, which advanced from the east and was channeled to the south down Tvillinggletscher

Dal. It covered the mountaintops, leaving glacial till, now brown due to slight oxidation.

Stage 2. — Retreat, to some unknown position.

Stage 3. — Advance, from the north end of Tvillinggletscher Dal southward, and from the east westward, to form gray, fresh-appearing, bouldery glacial deposits, situated today high on the walls of Tvillinggletscher Dal.

Stage 4. — Retreat, with melting apart of the ice in the north end of Tvillinggletscher Dal, forming at first a stagnation zone between the ice lobes.

Stage 5. — The Ice Cap at the north end of Tvillinggletscher Dal and Nordre Tvillinggletscher appeared as separate ice lobes. The moraine now separating Søndre Tvillingsø from Nordre Tvillingsø was formed, and a single lake occupied the space between the ice lobes.

Stage 6. — Retreat, to the outer lateral moraines and end moraines which are morainal peninsulas now extending into both Nordre Tvillingsø and Søndre Tvillingsø.

Stage 7. — Continuing retreat, with a possible short readvance to or halt at the prominent inner lateral moraines within 5—10 m of all the present day glaciers (*See* Figs. 12 and 13).

Stage 8. — Continuing retreat, to youngest end moraines and lateral moraines forming along present ice edges.

The positions of Stages 3 and 5 in Tvillinggletscher Dal south of Søndre Tvillinggletscher (Fig. 11) were determined by examination from the air and from study of aerial photographs, whereas all other positions of the glacial stages were examined on the ground as well as from the air and by means of aerial photographic study. The scale of Figure 11 does not permit delineation of Stage 8.

C. D. Holmes and R. B. Colton (Written communication, November 30, 1954) state that the gray drift of Stage 3 at the south end of Tvillinggletscher Dal may be divided into deposits of slightly different age wherein a series of younger moraines, according to their interpretation, cut across older gray drift moraines. Such a readvance was not observed in the field by the author, and this possible subdivision of the gray drift cannot be made here at this time.

Almost all end moraines and lateral moraines of Stages 5, 6, 7, and 8 have cores of glacier ice beneath a thin morainal protective cover. The presence of this ice within the moraines today undoubtedly is due to the rigorous climatic environment, effective insulation of the bouldery cover, and freshness of the moraines. Because of the shape of the ice cores, some moraines are narrow ridges 15—25 m high (Fig. 14). For a

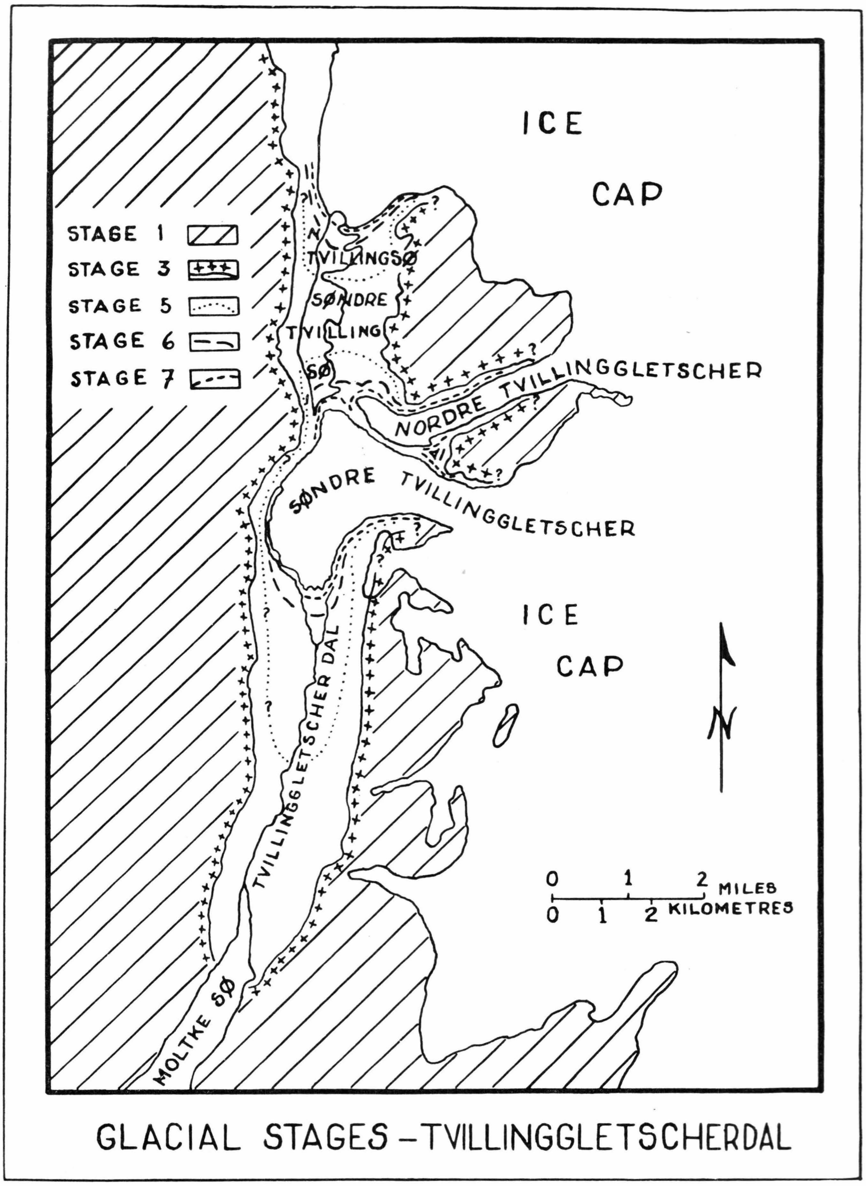

Fig. 11. Glacial Stages, as related to Tvillinggletscher Dal and the part of the valley north of Nordre Tvillinggletscher including Nordre Tvillingsø and Søndre Tvillingsø.

few weeks each year, some ice beneath the bouldery morainal cover melts. This allows blocks and boulders to slide across the exposed ice core and to slump into small irregular piles of debris. The melting of ice cored moraines and subsequent emplacement of end moraines as

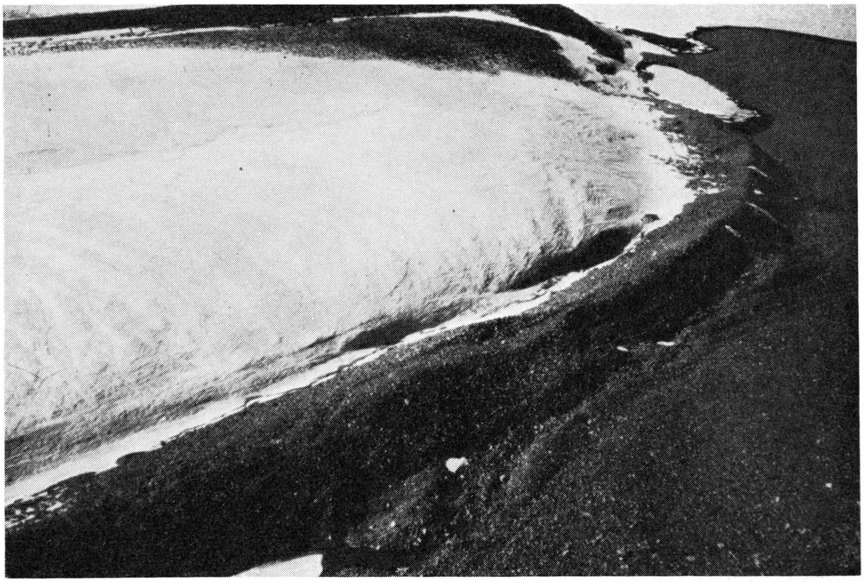

Fig. 12. Terminus of Nordre Tvillinggletscher with prominent lateral moraines and end moraine of Stage 7.

low mounds is described more completely by R. P. GOLDTHWAIT (1951, p. 573—576) on the Barnes Ice Cap on Baffin Island. The morainal material of Stages 1 and 3, in so far was observed, is so old that it no longer contains ice cores, and now consists of reduced, undulating hills and ridges of bouldery till.

A series of 18 old beaches or shorelines, varying from 0.8 to 5.3 m apart vertically and from 1 to 6 m wide in places, are cut into glacial debris and talus along the west side of Tvillinggletscher Dal between the lobe of the Ice Cap at the north end of the valley and Nordre Tvillinggletscher. These old shorelines indicate a more or less progressive lowering of a single larger lake to the levels of the present two lakes. A delta is built at the northwest corner of the valley to more than 41.5 m above lake level. Shorelines are cut into this delta from its top to the lowest level at the water's edge. Shorelines on the west side of the lake are clear and distinct. Those on the east side are not well developed and are difficult to discern. The distinct beaches along the west side suggest that today, even as in the past, winds blow from the southeast, and, when the lakes are relatively free of floating ice, waves produce wider beaches only on that side.

Finely layered silts and clays or varves were obtained by R. P. GOLDTHWAIT by drilling through the ice on both Nordre Tvillingsø and Søndre Tvillingsø and coring into the bottom sediments in the lakes.

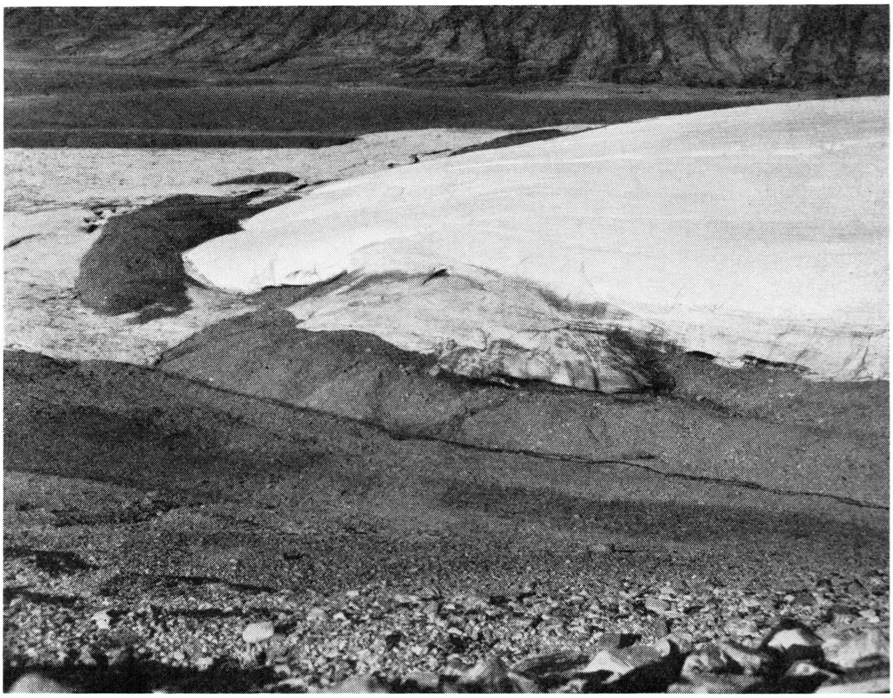

Fig. 13. Terminus of Søndre Tvillinggletscher with lateral moraine and end moraine of Stage 7. Photograph by R. B. COLTON.

More than 140 varves were recovered, so that it is probable that these lakes are more than a century old. Since the lakes came into existence after separation of the ice lobes (Stage 4) and before the deposition of moraines of Stage 5, then Stage 5 is well over 100 years old.

Moraines of Stage 5, 6, and 7 on the northwest shore of Nordre Tvillingsø and along the east side of both lakes have narrow shorelines eroded into them. A lake with a shifting water level has existed ever since Stage 5. Above the highest shoreline where a distinct lichen line exists is the complete flora one would expect to find in an arctic upland area. W. S. BENNINGHOFF (Written communication, December 21, 1954) estimates the age of that highest shoreline to be of the order of 30 to 50 years. Then the age of Stage 5 is probably not more than 140 years and not less than 30 years.

It takes many centuries to form the felsenmeer, soil structures, and patterned ground so prevalent on the adjacent mountain slopes, and since the shorelines are not too greatly affected by the movements of intense frost action, Stage 6, with its water-washed and wave-eroded moraines extending into the lakes as peninsulas, probably occurred

Fig. 14. Ice cored moraine adjacent to southeast edge of Søndre Tvillinggletscher.

within the last century. According to botanical evidence reported by BENNINGHOFF, a difference in vegetation exists on the shorelines above and below the 6 m level. The age of the 6 m shoreline is estimated to be about 20 to 30 years. This may date Stage 6 to be a minimum age of 20 to 30 years (1923—1933).

A study of the Stage 7 moraines reveals that these moraines have primitive-appearing plant communities and that the shorelines on the east side of the lakes up to about 6 m have vegetation of similar composition and arrangement. Fifteen-year-old willows occur at 4.5 m above lake level, but below that level they are less than 15 years old. BENNINGHOFF therefore concludes that the lake level has not been above the 4.5 m level, at least for more than a few days at a time, for 15 years or more. This dates Stage 7 to be less than 15 years old (1938).

According to WRIGHT (1939, p. 23—24), the Sermerssuaq glacier retreated considerably from 1932 to 1937. Inasmuch as the lake level lowered from the 6 m shoreline to the 4.5 m shoreline between Stage 6 (with a minimum date of 20 years ago or in 1933) and Stage 7 (with a date of 15 years ago or in 1938), it is apparent that the two outlet glaciers also receded during the same interval.

The two outlet glaciers and the lobe of the Ice Cap at the north end of Tvillinggletscher Dal, consequently, appear to have been retreating and slightly readvancing for the past thousand years. The ice margins may have stood at positions represented by Stage 5 more than 140 years ago and not less than 30 years ago, at positions represented by Stage 6 less than 100 years but more than 20 years ago, at positions represented by Stage 7 less than 15 years ago, and Stage 8 began only a few years ago. The net result through the years is retreat.

New Names.

The following new names have been authorized by the Danish Board of Geographic Names.

Nordre Tvillinggletscher	North Twin Glacier
Søndre Tvillinggletscher	South Twin Glacier
Tvillinggletscher Dal	Twin Glacier Valley
Tvillinggletscher Elv	Twin Glacier River
Nordre Tvillingsø	North Twin Lake
Søndre Tvillingsø	South Twin Lake
Moltke Sø	Moltke Lake

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