Technical Report 39

OCTOBER, 1960

Study of Ice Cliff in Nunatarssuaq, Greenland

U. S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
Corps of Engineers

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by R. P. Goldthwait

U. S. ARMY SNOW ICE AND PERMAFROST RESEARCH ESTABLISHMENT
Corps of Engineers
Wilmette, Illinois

PREFACE

This constitutes the final report on Contract DA-11-190-ENG-19 with the Ohio State University Research Foundation. The work was done under SIPRE Project 22.1-24, Ice cliff studies (CE Project 24) for the Snow and Ice Basic Research Branch, J. A. Bender, chief. The Ohio State University provided working space and certain items of equipment and service under Project 636 of The Ohio State University Research Foundation. Field support was provided by the U. S. Army Engineer Arctic Task Force and the U. S. Army Transportation Corps. Field work was accomplished during June, July, and August of 1955 and 1956 with a brief visit in March 1956. Civilian personnel in the field parties, and their principal assignments, were as follows:

Dr. R. P. Goldthwait, Project leader (Summer 1955, 1956)
Mr. W. Blake, Jr., Motion (March 1956; Summer 1956)
Mr. W. R. Farrand, Ablation (Summer 1955; March 1956)
Mr. J. F. Gregory, Geomorphology (Summer 1955)
Mr. R. E. Hilty, Ice physics (Summer 1955, 1956)
Mr. H. L. Jury, Photogrammetry (Summer 1955)
Mr. R. E. Mase, Ablation (Summer 1956)
Dr. W. M. Merrill, Structure (Summer 1955, 1956)
Mr. R. Sanderson, Camp manager (Summer 1955)
Dr. S. E. White, Ice motion (Summer 1955)
Dr. J. N. Wolfe, Botany (Summer 1955)

Sp-3 J. E. Sater and Pfc Hugh Dresser, USAEATF, assisted with the Photogrammetry and Mapping projects, respectively. Other USAEATF personnel provided field support.

Personnel of CE Projects 24.2 and 28, located at Red Rock camp for varying periods of time, contributed to the discussion of problems considered in this report. The thickness of the ice sheet and contour of the bouldery floor beneath was determined by geophysical teams under the supervision of Mr. Charles Bentley and Mr. David Barnes, as a part of CE Project 28.

This final report was prepared by Dr. Goldthwait from figures, tables, and analyses supplied by each scientist and from the 1955 Annual Report (Goldthwait et al., 1956). Each section has been read and criticized by the appropriate scientific co-workers.

This report has been reviewed and approved for publication by the Office of the Chief of Engineers.

W. L. NUNGESSER
Colonel, Corps of Engineers
Director

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SUMMARY

During the summers of 1955 and 1956, a detailed study was made of an ice cliff 500 m long and up to 40 m high on the east margin of North Ice Cap near its junction with the main Greenland Ice Cap. Glaciological and meteorological measurements were extended from the cliff northward for 2 km up the rolling surface of the glacier, which forms an ice drainage basin. Geomorphological and botanical studies were extended southward over 6.5 km^2 of land in northern Nunatarssuaq. From these studies, details of the present activity of the ice cliff are known, and the past history of the ice cliff and adjacent glaciers is outlined.

The recent geological history of the area starts with complete coverage by the main Greenland Ice Cap, which moved from the southeast in the Wisconsin (Wurm) glacial stage. The ice retreated farther back toward the interior than it is now, perhaps 8000 or more years ago. Evidence consists of V-shaped inner valleys cut without restriction but now blocked by glaciers, patterned soils or rubble developed by long permafrost conditions, and well smoothed and grooved ventifacts. The very youthful nature of the vegetation in northern Nunatarssuaq raises some question that this area has been exposed such a long time.

Long after the exposure of the land, the main Greenland Ice Cap readvanced to a position from 300 m to well over a kilometer beyond its present edge. This may have coincided with the general advance known elsewhere about two centuries ago. Poor, subdued end moraines and patches of kame terrace, and, to the south, a prominent gray drift, are left as evidence of the advance. The continuing retreat from this last advance, in the last few decades, is marked by trimlines above the present glacier and in every hollow, by vegetation zones on a nunatak 15 km to the south, and by former higher lake shores and channels above Red Rock Lake or along Red Rock Creek.

There is no evidence in the glacial deposits that North Ice Cap existed before or during this readvance of the main Greenland Glacier, and there is much evidence that it is now as far forward as it has ever been. Well developed large-patterned soils can be traced right in underneath the toe ice of North Ice Cap; aeolian sands developed at an earlier stage from outwash of the main Greenland Ice Cap are being plowed up and brought out as ablation moraine under one section of North Ice Cap; and vegetation less than 200 years old (carbon-14) has been removed from the rocky floor 23 m back beneath the glacier.

The condition of present vegetation next to this ice cliff indicates deterioration due to recent advance to one botanist, but indicates simply the adverse conditions near any ice margin to another. Careful photogrammetric surveys twice in 1955 and 1956 made possible 25 cm contour maps which show that the vertical white ice cliff near Red Rock Lake made a net advance of 0.53 m in 1 year in spite of the extra heavy ablation and dry calving that year. In general, the photogrammetric surveys agree with sample measurements of ice motion and ablation (below) over the 14-month period of observation, but they afford many more measuring points.

Motion stakes on top of the glacier and in the upper part of the ice cliff moved approximately 12 mm/day, but they were by no means uniform in either amount or direction. Ice on the east slope of Survey Hill moved more slowly and more obliquely eastward. Near the ice cliff, a downward com-

ponent due to slow failure in the cliff face produced an outward bulging (extra-fast motion) in the middle parts of the cliff face. Ice masses are converging from the north and northwest toward the east-central parts of the high ice cliff, resulting in upward motions 1 km or less back from the ice cliff.

Variations in the motion of any one stake are not well understood. Over 14 months there was more than a 20% variation in the average rate for all stakes. The fastest motion came during the spring. In all periods of measurement, certain individual stakes had retrograde motion to the north and others varied greatly in rate to the south. When measured by continuous recording and by supplementary triangulation in half-day intervals, individual stakes showed a very jerky motion, but with a tendency toward fastest daily motion either early (0400-1000 hr) or late (1000-1300 hr) in the morning.

Stakes near the bottom of the vertical ice cliff moved at approximately half the speed of the top surface of the glacier (Fig. 52). Here was the zone of greatest shearing motion, involving as much as a millimeter a day of differential motion in ice masses less than a meter thick. The sloping toe of dirty ice below the cliff lay on a very slowly moving prism of dirt-banded ice approximately 5 m thick. Pegs in a tunnel extending 30 m into this ice under the cliff and a carefully constructed mechanical strain gage on the bottom 28 m back indicated that the greatest differential shear motion farther back was right next to the ground; ice 5 m above the ground moved 2.7 mm/day. No visible failure or fracture was observed in the zones of shearing.

Structures due to motion of the glacier were carefully mapped and studied in thin sections. Hundreds of small fractures a few meters deep, many meters long, and a few centimeters wide lie at all azimuths, but dominantly parallel to ice motion and radiating from high points. Vertical blue bands of ice are found more or less parallel to these cracks and appear to be old cracks filled with bubble-free ice.

Where all components of motion were measured, the motion was parallel to the foliation. Foliation (bands of bubbles) in the ice is steepest (approximately 40° N) at the ice cliff and gentlest (less than 20° N) upglacier. Two years' observation in the tunnel showed, however, that the bubble bands change in shape and orientation, apparently with shifting directions of motion in the ice. Most bubbles were elongated into filaments subparallel with the ice motion, but sometimes they cut at low angles across the foliation as though adjusting to changing motions. Cores of dye-colored ice emplaced in the tunnel wall during the first summer were squeezed from circular to elliptical cross sections with the long axis of greatest strain parallel to foliation. Dirt bands occur in the heavy shear zone at the very bottom of the glacier 28 m back, and as high as the top of the stagnant ice prism just beneath the ice cliff. Dirt bands were squeezed into recumbent isoclinal folds, often cross-cut by younger foliation. Since the rock surface at the bottom of the glacier was undisturbed by ice motion, most of the dirt in the bands is material which melted out below the ice cliff on sloping toe ice, was inundated by growing snowdrifts, and raised again by shearing in the advance of the over-riding ice.

Crystal grains in the moving ice masses showed a strong preferred orientation which was not quite normal to the plane of shear motion and foliation, but tipped on the order of 15° forward. Lesser concentrations of optic axes appeared to indicate new lines of motion to which the crystal axes were adjusting or relics of old directions of motion.

Since the tunnel represents a void under more than 30 m of ice, there was constant hydrostatic pressure, producing closure of approximately 0.75 mm/day. This increased where the wall was large and unsupported and decreased where it was narrow or supported by an adjoining wall. Creep varied also with the temperature, which was both more variable and warmer near the mouth of the tunnel. It is not certain why the creep rate increased over 13 months of observation, but the average rate of creep fits well with that for temperate glaciers expressed in formulas by Nye. The deep ice had a temperature of -14C and the surface outside the tunnel shifted from nearly -40C to 0C. Between June and August of each year there was a rapid change in temperature of the surface ice to 3 or 4 m depth.

The melt season lasted for 70 to 80 days. The average rate of ablation was about 35 mm/day near the ice cliff (Fig. 52), where the mean July temperature (for two summers) was 1.9C and decreased regularly upward to snowline between 900 and 920 m altitude, where July temperatures ran 1.2C. The mean monthly temperatures in summer 1956 were nearly twice as high above freezing as those of 1955, and the ablation rate was nearly double. Radiation appears to be a much more important factor on the ice cliff than elsewhere. The actinograph indicated approximately equal radiation in the two summers and a 550 cal/cm^2-day maximum in early July. Ablation on the vertical ice cliff was only 30% greater in the second summer than in the first and a large part of the melting was at crystal boundaries. Crystals loosened and fell without being completely melted on the cliff face. A second major loss on the cliff face occurs during May and June of each year by the avalanche ("dry calving") of sheets of ice a hundred or so meters long, 25 m high, and 1 to 2 m thick. This represents a part of the accumulated over-extension during the winter months when sublimation and erosion losses total only 31 cm.

Sloping toe ice at the bottom of the ice cliff is mostly banded with dirt or covered with ablation moraine, and so absorbs much radiant energy and melts nearly twice as fast as the vertical white ice above it. Unlike the white ice, however, it is covered by accumulated winter snow and dry calving, so that its melt season is shorter and there is frequent net addition in a year. Here and there the toe is deeply cut by the waters of some of the many melt-water streams coming over the cliff, and kinetic energy is a recognizable source for the loss of toe ice.

The volume of these small issuing streams varies by 300% from day to night, with a lag of some $1\frac{1}{2}$ hr behind the climax of melting on the ice surface above. There is a delay of 4 hr from the period of greatest melting until the time all of this water is collected in Red Rock Lake. The daily flood wave is attenuated, so that the common variation of discharge from day to night is only 25%. Total discharge measured from Red Rock Lake was nearly 3,000,000 m^3 in 1955 and over 4,000,000 m^3 in 1956, both some 500,000 m^3 more than the water calculated as produced by the known ablation and rain. The amount of runoff per square kilometer is approximately double that characteristic of land in warmer climates; this is the contribution of the accumulated snowfall preserved in the ice cap.

The net changes observed on the ice cliff are summarized in Figure 52. During these 14 months the toe ice base maintained its position by accumulations of snow and calved ice which equal total ablation. But the cliff above moved 4.8 m during the year and even with two seasons of calving and melting, it made a net gain and became steeper and more overhung.

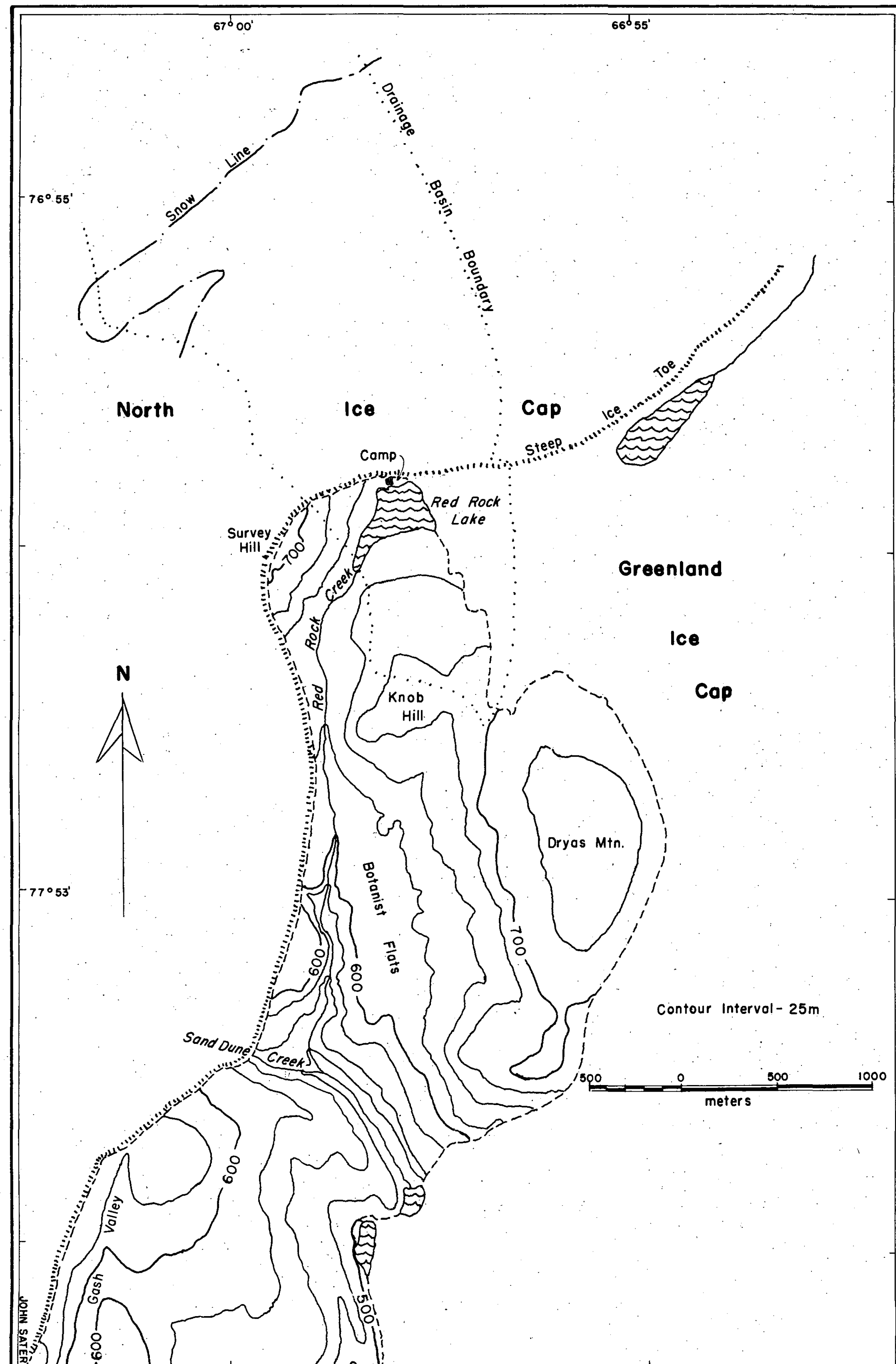

Figure 1. Red Rock area, northern Nunatarssuaq, Greenland.

DEVELOPMENT OF AN ICE CLIFF IN NORTHWEST GREENLAND

by

R. P. Goldthwait

I. INTRODUCTION

Objectives

The form and activity of one sample ice cliff along the margin of the Greenland Ice Cap was studied in an attempt to learn in detail how the glacier moves and how the calving of ice masses and ablation during the melt season counteract this motion to produce a balanced ice cliff. The factors in this balance are considered with reference to the recent history of this ice edge in order to arrive at logical hypotheses for the origin and elimination of such ice cliffs.

There has been little, if any, recorded study of ice cliffs hitherto. Casual observations have been made (e.g. Victor, 1955), especially concerning ice cliffs in northeast Greenland. A brief aerial survey of the ice edge through northwest Greenland in 1954 (Goldthwait, 1954) indicated that at least 45% of the ice edge terminating on land consists either of a very steep incline, which is impossible for ordinary travel, or of vertical ice cliffs. These do not include the vertical cliffs of rather obvious origin wherever an outlet glacier touches the ocean or a lake. It appears that these land-bound ice cliffs represent some sort of an undermining or extra trimming-back of the ice edge which exposes a cross section of the interior of the glacier. This presented an unexplored possibility for gathering basic scientific information concerning motion, bottom activity, and structure near the edge of a continental glacier.

Information regarding ice motion, the nature and amount of ablation near the ice edge, recent changes of the position of the ice edge, and the physical characteristics of the ice itself is needed as a basis for further engineering research. The rates of motion of the ice, the dry calving of ice masses from the cliff, and changes in the cliff form and position from year to year control the location of roadways, tunnels, tramways, storage depots, and transfer points. The nature of the differential summer ablation on various ice structures and the location and form of accumulation of snow in the winter determine the feasibility of surface routes and of aircraft landing areas near the ice margin. The physical nature of the ice and the pattern and rate of its deformation under stress are critical for excavations, pipelines, and use of tunnels.

Field work was accomplished during June, July, and August of 1955 and 1956 with a brief visit in March 1956. All field studies were based at Red Rock Camp (Fig. 1, 2).

Mapping methods

A precise baseline of about 420 m length was laid out east and west 100 to 150 m south of the ice cliff. Base stakes were placed in the frozen ground to 1 m depths. A 1.5 m long "two-by-four" was set in cement and rocks were piled loosely around. These 15 stakes were measured precisely for use in photogrammetry. A second baseline was established by two flagged poles, approximately 275 m apart, drilled 2 m deep into the sloping ice surface some 250 m north of the cliff. Exact positions of the ends of this baseline were determined by triangulation with a Wild T-2 theodolite from the main baseline on the ground.

Within the ice basin studied in detail, which is approximately 1.25 km , each ablation stake and level stake was located at the scale of 1:2,000 on a 38 x 38 cm plane table sheet with a telescopic alidade. Drainage divides were located by pouring chemical dye into tiny rivulets during the height of the melt season. Together with streams, these divides appear on Figure 55. Five-meter contours were sketched in the field on the basis of 130 occupied rod stations. In the same fashion, with stations along the drainage divide, the outer perimeters of the drainage basin flowing into Red Rock Lake were mapped up to snowline on the scale of 1:10,000.

The air photographs of greatest use were taken for the Army Map Service between 11 and 17 August 1953. No ground control was available at that time. From these photographs a mosaic of the land area and ice basin in the northern 2.6 km of Nunatarssuaq was prepared and enlarged to 1:10,000 for field use. From stereoscopic pairs of photographs across this land area, rough form lines were drawn with the Kelsh plotter (Fig. 56).

Two means were used to determine the position and depth of land or bedrock beneath the ice cap. The seismic method provided the basic control. Measurements were made with a complete Houston Technical Laboratories 7000B seismograph system (1955) or a Midwestern high resolution seismograph (1956). Twelve vertical geophones were laid out in one straight line and shot charges of from one blasting cap to $\frac{1}{2}$ lb of TNT or C-3 were set off at both ends. Reflections were obtained from all points more than 80 m north of the cliff face. The compressional-wave velocity was carefully determined to be 3780 ±5 m/sec. This value was consistent for all shot-detector distances and at all depths where checks could be made. Ice thickness was calculated from the triangular relationship of shotpoint, detector, and an elliptical surface defining the nearest point on the bottom. A homogeneous one-layered condition was assumed. One profile of points (A-A', Fig. 53) was nearly normal to the cliff, following level stakes to Shelter 3; a second was completed from the high slopes of the ice cap to the west across the Red Rock Basin at level stake 4 (B-B', Fig. 53).

A more detailed supplementary survey was made by gravimeter. All observations were made with a Worden meter which has a scale of 84 milligals and sensitivity of 0.011 milligals/scale division. At each site the gravimeter was carefully leveled on a small wooden stand. To reduce the drift produced by age, temperature change, and tidal force, some stations were reoccupied in loops running from 1 to 6 hr from a single base. Errors due to drift were great owing to rough travel and a sensitive instrument, but never more than 1.0 milligal, which is the equivalent of 13 m of bedrock in terms of depth. Terrain corrections were made only at stations very near the ice cliff since elsewhere the ice slopes were generally less than 5° and corrections were less than 0.1 mg. The precision of the anomaly used in calculating depth of ice depends upon the precision with which altitude measurements may be made. A relative altitude of most ablation stakes* and other markers above the east end of the baseline (base stake 15) was determined by telescopic alidade or leveling, so may be correct to within a few centimeters. The absolute altitude is not well known since no precise determination of the altitude of Red Rock Lake has been made. The Army Map Service sheet "Nunatarssuaq 1" (1954) scale 1:50,000 shows Red Rock Lake (unnamed) between the 2075 and 2100 ft contours or about 630 m above sea level. On five trips by helicopter to Thule (Dundas) Air Base, differences in altitude were read on Paulin and Wallace & Tiernen altimeters; when corrected for the average temperature of the air column, the average altitude at Red Rock east base is 630 ±3 m. Since the earth gravity decreases by about 0.27 milligals/m of elevation when on ice, a 2 m error in the measurement of surface elevation will result in a 7.4 m error in bedrock elevation, or possibly 5.4 m in the indicated thickness of the ice. Variations in the geologic structure probably cause variations in bedrock gravity up to 1.0 mg or 13 m elevation. In spite of these possibilities the surveyors believe that the relative ele-

* Except 10, 20, 30, 40, 50 which were sketched in, in 1956.

vations on the detailed contour map of the rock floor beneath the glacier should be accurate to ±13 m. The value of observed gravity at Red Rock Camp is 982.8112 g/cm.

Beyond the area of detailed study, two long traverses were made from the land area northeast of North Ice Cap to the high surface of the ice cap 2.6 km west of Red Rock Lake (points on Fig. 53). One other traverse was made westward directly up the highest surface of the ice cap for over 6 km, and a short traverse (2 km) was made from the north ridge of Dryas Mountain along an ice ridge attached to the main Greenland Ice Cap and up the east side of the detailed study area. Altogether more than 120 measurements of the depth of the ice were made by gravimeter.

Character of region

The independently operating North Ice Cap is about 61 km long east and west and 38 km wide north and south. Near the western sector there may be several centers, as low mountains divide the ice cap. At the high broad surface, 6 km from the east end, the top is smooth, unbroken, and the maximum depth measured was 330 m. This thickest high "feeding" area is 3 km northwest of Red Rock Ice Cliff (Fig. 53). The highest altitude measured on underlying surface is 800 m and the exposed mountains northeast and southeast of this eastern tip reach 750 and 850 m, respectively. A large ice dome with crevassed slopes seen south of the high traverse is like those east of Thule (Barnes et al., 1956), and may cover a bedrock hill 1000 m high. It is probable that this is a highland ice cap generated by snows accumulating on ice between 880 and 1200 m altitude and draped over a rolling hill topography generally at 450 to 1000 m altitude.

The ice drainage basin studied in detail is on the southeast side of the eastern tip of North Ice Cap (Fig. 1). It heads above a snowline at 910 m (1955) or 940 m (1956) elevation on the south side of a broad high ridge which forms the eastern Ice Cap. The upper area drops away steeply from the ridge above 950 m and flattens out to a broad smooth basin at 830 m. Here the uppermost discrete courses of the longest streams may be discerned (Fig. 55). Below 800 m, stream channels become more abundant and the slope gradually steepens from 3° to over 14° near the cliff. The streams all converge toward the central region of the high ice cliff. To the west of the basin is a steep ice surface formed into a series of two "steps," 500 m broad, with steep "risers" (5° to 29°) dropping to the top of Survey Hill at 725 m. The lower step at 830 m forms the western boundary of the melt-water drainage basin.

Southwest of this drainage basin the surface contours swing southward parallel to the 13 km-long ice cliff which is draped over hills similar to Survey Hill. East of this drainage basin the contours swing northeastward and then north around the eastern tip of North Ice Cap (Fig. 53). The ice cliff at Red Rock Lake extends in a broad arc east and northeast as a very steep ice slope (Fig. 3). Above the ice slope is a narrow ice ridge with backslope which appears to be the turned-up edge of the North Ice Cap where it rides up onto the main Greenland Ice Cap or its superimposed ice.

Geophysical work indicates that the whole area from Red Rock Lake northeastward to the high land beyond North Ice Cap is a broad valley near the 600 m contour, sloping southeast to 520 m or less (Fig. 53). A large frozen lake (Angiussaq Lake) with many arms, beginning 9 km northeast of Red Rock Lake, seems to represent tributaries to this main valley from the north. Red Rock Lake is at the western tip or headwater of a short, shallow western tributary to this main valley. Another parallel small tributary valley lies under ablation stakes 45 and 46 or level stake 3 where gravity values are low. This may explain the terrace or step of ice west of level stake 4. The main valley is blocked by the 15 km-wide lobe of the main Greenland Ice Cap which presses northwest up this valley and abuts North Ice Cap moving into the head of the valley.

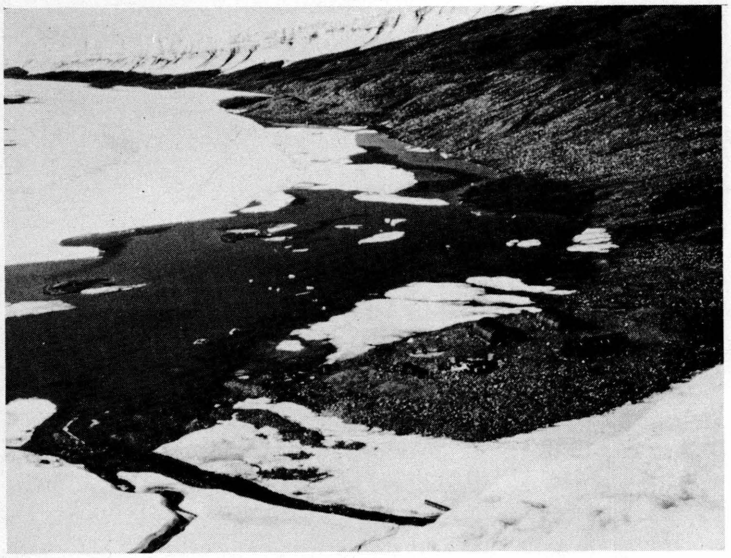

Figure 2. Red Rock Lake and camp, from the ice cliff, showing the outlet and North Cap in the background.

Figure 3. The ice cliff in August 1955, looking west along the cliff from below stake row 13.

There is no suggestion in the shelves and basins in the Red Rock ice drainage area of the contours of the rocky land beneath. The surface due north of Red Rock Lake under the tunnel and stakes is almost perfectly flat for 3 km or as far as the snowline (A-A', Fig. 53). The rise in the ice surface is due entirely to thickening of the ice sheet northward, and its irregularities must result from phenomena of accumulation and motion. Toward the west the rocky surface rises slowly but nowhere as steeply as the exposed east slope of Survey Hill.

II. REGIMEN

Climatology

Weather shelters. A general program of weather observations was maintained from 18 June to 28 August 1955 and from 7 June to 28 August 1956. A standard weather shelter (shelter I, see Fig. 10), approximately 60 cm^3, was situated on the snowdrift about 100 m northwest of the Red Rock Camp buildings and 40 m from the high ice cliff. The long legs of the shelter were dug down into the snow and reset twice each summer as ablation exposed them, so that the instrument height above the snow surface varied between 50 and 150 cm. On top of shelter I was set an Italian actinograph, which had been carefully calibrated at SIPRE prior to use in Greenland, and which was checked occasionally for zero reading by covering with a black cloth. Recording was by a 24-hr drum in 1955 and an 8-day drum in 1956. In summer 1955, a 7-day recording hygrograph was kept at this station, and calibrated twice daily by a sling psychrometer. The hygrograph did not check consistently. A Cassell thermograph with 7-day recording drum was calibrated daily by dry-bulb temperature reading; a minimum thermometer reset here each day provided additional check. In a separate shelter (no. IV) over bare ground next to the camp, 150 m from the ice cliff, a Bendix-Friez microbarograph was housed from 7 July to 29 August 1955. A standard U. S. Weather Bureau anemometer with recording dials was mounted on a pipe at 2 to 3 m above the snow surface at shelter I (1955) and over the ground low on the side of Survey Hill 230 m southwest of camp (1956). A standard galvanized rain gage with 10:1 measuring ratio was maintained at the camp. Twice daily, within the first hour after 0800 and 2000, visual observations were made of the percentage of sky cover, the types and levels of clouds, the direction of wind, and the wet and dry bulb temperatures as recorded by sling psychrometer.

During both summers two stations were maintained on the surface of the glacier above the ice cliff. Shelter II was approximately 20 m north of the high ice cliff near "the gallows" and over the ice tunnel. Shelter III was 1425 m north of the ice cliff in the upper part of the ice basin in June 1955, but it proved to be well below snowline; for this reason it was moved to 2175 m north of the ice cliff in summer 1956. Both were standard weather shelters with doors opening toward the north and long legs drilled into the ice to 1 m depth. The lower station (shelter II) had to be reset twice each summer owing to ablation, so its height above the surface varied between 1 and 1.5 m. The only recording instruments maintained continuously at each shelter were 8-day Cassell thermographs. Calibration was done with a sling psychrometer. During the summer 1955 a barograph was kept at the upper shelter for comparison to that at base camp (I). In 1955 a totalizing anemometer was set on an iron pole at each shelter and read every 6 days or less, as visited. A wind vane 2 m above the ice surface was maintained at shelter II for visual observation from camp with field glasses.

In order to get more detailed records of temperature differences in the ice cliff area, supplementary small weather shelters were placed on the cliff for limited periods during each summer. In 1955 just one (shelter V) was located right at the base of the vertical cliff near row 10 of the cliff stakes (272 x 78 grid position, Fig. 57). In 1956 three small shelters were installed on 3 July and maintained intermittently until 28 August. Shelter VII was at the base of the ice toe (grid position 369 x 74); shelter VI was in amber ice just under an overhang at the bottom of the vertical cliff (grid position 384 x 76), and shelter V was about 2/5 of the distance up the vertical cliff (grid position 358 x 85). Each shelter, approximately 30 x 20 x 20 cm, was mounted on an iron pipe which was sunk 1.5 m or so into the ice. These melted out on some occasions, allowing the shelter to overturn with subsequent loss of record.

Temperature. Since observation was limited to two summers, no year-round climatic averages are available. However, every attempt was made to capture the full

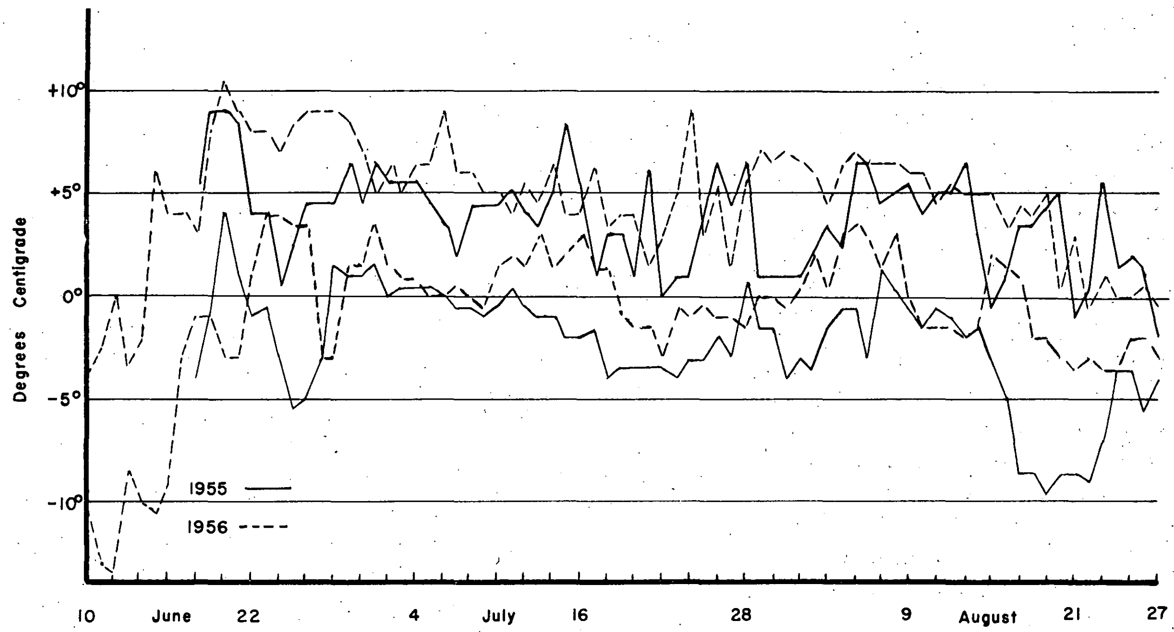

Figure 4. Daily temperature maxima and minima, shelter I.

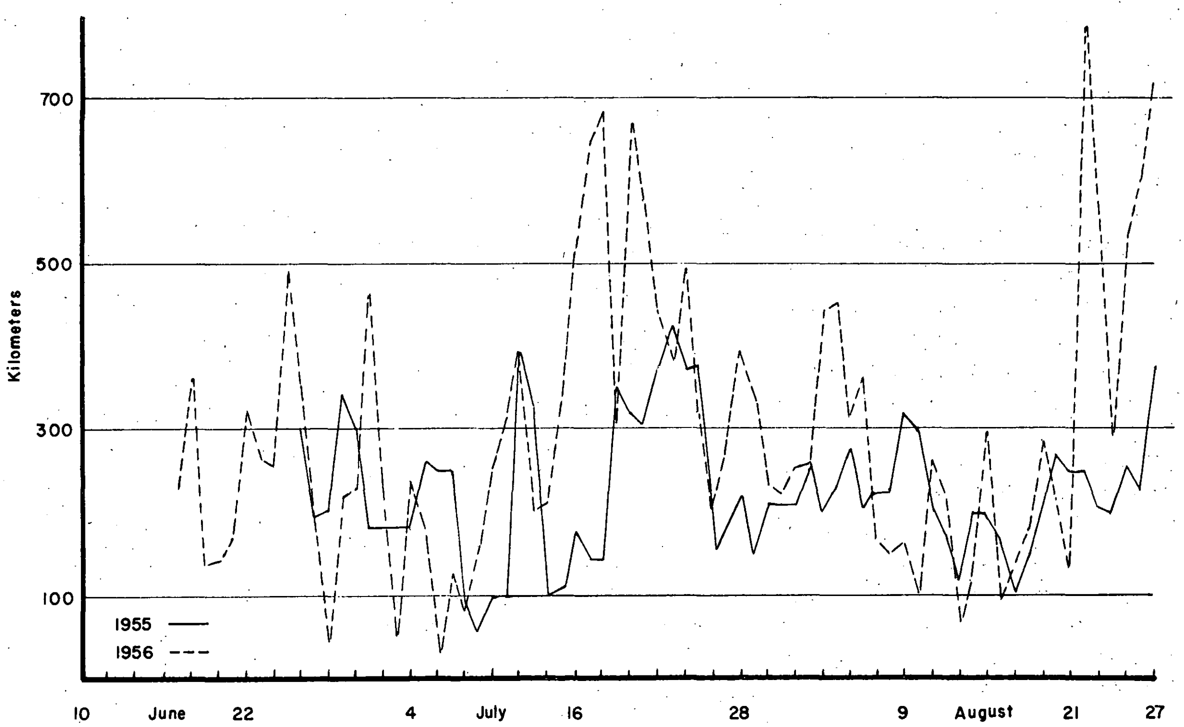

Figure 5. Wind velocities, shelter IV.

record of each melt season. This was not fully achieved in 1955 because of unusually early heavy melt between 6 and 10 June before the field party arrived. The field party arrived on 5 June 1956 and no significant melting occurred until 15 June. In both years after 21 August the temperatures fell to below freezing and stayed there most of the day. Undoubtedly radiation produced some important effects prior to the arrival of the field party in both years, for loss of snow is indicated by cupping of the surface in some spots.

Mean temperature for the last half of June was 2.9C in 1955 and 4.3C in 1956.* The same contrast carries through July with mean monthly temperature 1.8C warmer in 1956 than in 1955, and through August, which was 2.0C warmer in 1956 than in 1955. Based upon the accumulation of superimposed ice on the ice toe, it is fair to surmise that this second season was abnormally warm, but one can only guess than the first season was normally cool since some superimposed ice did collect.

The curve for daily maximum and minimum temperatures (Fig. 4) shows that the maximum thermal peak occurred between 20 June and 4 July with noonday temperatures mostly between 5 and 10C. The absolute maximum was 10.5C on 20 June 1956. These noon temperatures declined irregularly but slowly through the melt season to between 3 and 7C from 10 to 20 August. Minimum temperatures also declined slightly but irregularly throughout the melt season so that the lowest temperatures during the melt season occurred early (-5.5C on 25 June 1955) or late (-9.5C on 18 August 1955). Prior to 20 June there was rapid rise in all temperature curves; after 20 August there is a rapid fall. The mean daily range between maximum and minimum temperatures at shelter I was 5.8C, which was surely tempered by the near presence of the glacier. The gradual decline of temperature throughout the melt season was certainly a function of insolation.

Table I. Mean monthly temperatures (C) for melt seasons 1955 and 1956 at principal weather stations.

Date	Station I Base of ice cliff	Station II Top of ice cliff	Station III Near snowline
Last half June 1955	2.88	1.11	0.66
Last half June 1956	4.35	4.51	3.64
July 1955	1.00	1.50	0.22
July 1956	2.84	2.58	2.34
August 1955	-0.44	-0.33	-1.05
August 1956	1.59	1.34	0.43

The difference between temperatures at the base station and other shelters (Table I) are largely due to altitude. For example, the overall mean during the melt season was 0.33C more at the top of the ice cliff (shelter II) than at the base of the cliff (shelter I). Station III near snowline was 0.72C colder than station II for the same period. This amounted to a difference of 0.92C/100m of altitude between the lower two stations, and 0.47C/100 m between the upper two. Evidently some of the difference between the lower two stations may be ascribed to the topographic effect of the cliff on winds and insolation at the lower shelter I.

* The mean for all of June 1956 is much lower (0.4C) because of the cool first half of June.

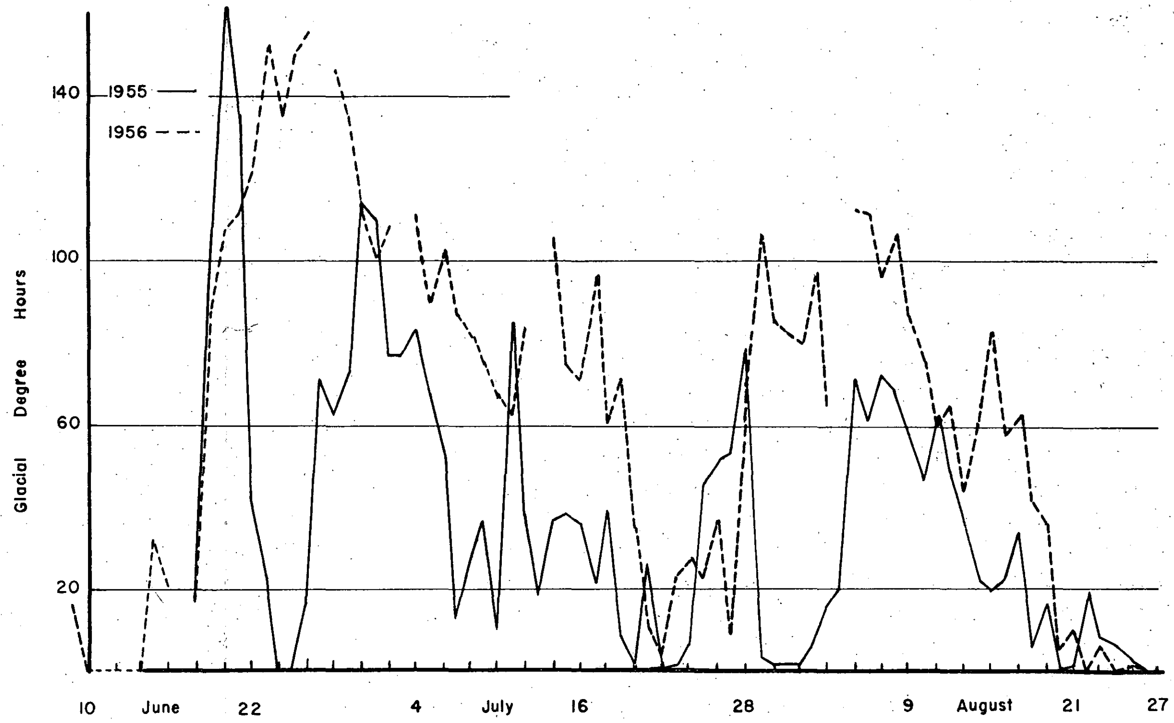

Figure 6. Glacial-degree hours, shelter I.

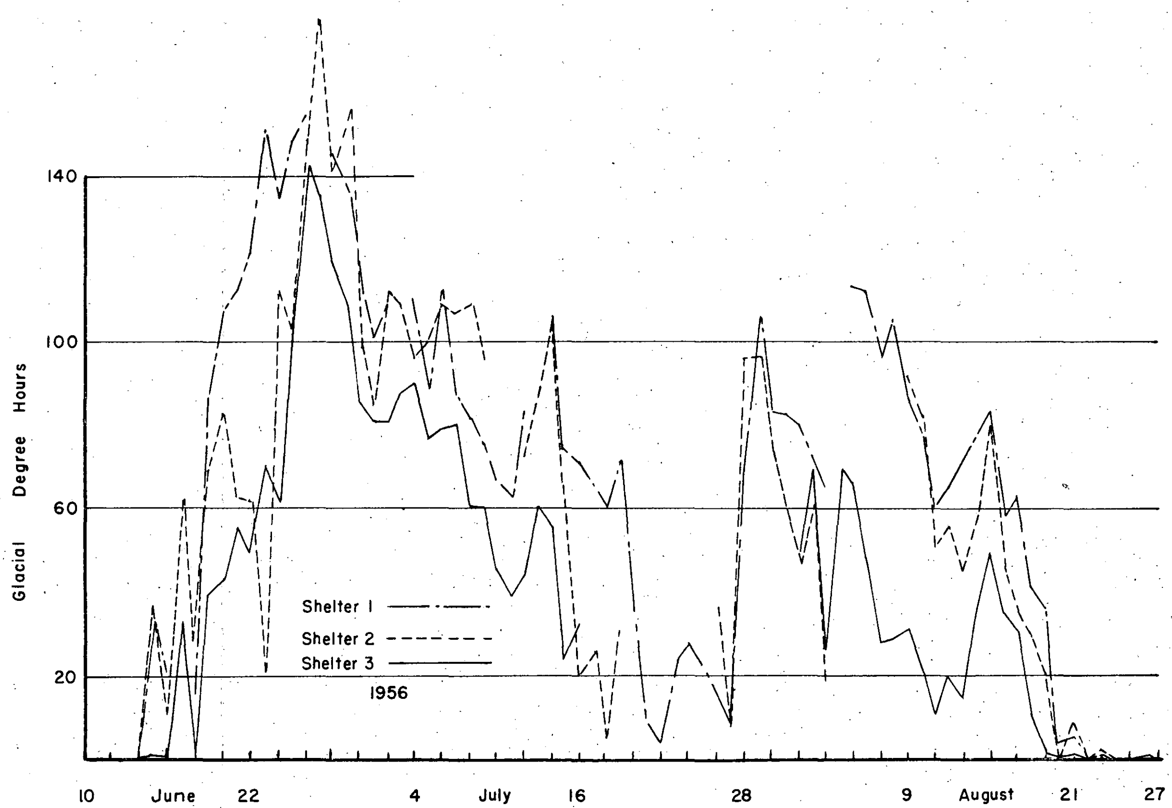

Figure 7. Glacial-degree hours, shelters I, II, and III.

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We have very little knowledge of the winter temperatures. Assuming that the temperature of the deeper ice (-14C) represents the mean annual temperature and knowing the mean maximum temperature of the warmest month to be 4.5C, then the mean minimum of the coldest month should be near -38C. The minimum thermometer which was buried in storage in camp registered -39C. This probably represents the coldest spell of the winter. During the visit for winter observations from 22 to 24 March 1956, daily maximum temperatures ranged from -26C to -20C and daily minima were from -31C to -35C.

A very useful expression for the potentialities of warm air for ablation is a "glacial-degree hour" introduced in work in 1953. (Goldthwait et al., 1954, sect. IVB). Glacial-degree hours are the sum of hourly temperature readings (C) for 1 day, 24 readings from 0100 hr to 2400 hr inclusive. All temperatures below freezing are considered to be zero. At the base camp, from 18 June to 28 August, there were 2606 glacial-degree hours in 1955, and 4919, nearly twice as many, in 1956. It is clear (Fig. 6) that in 1956 the temperatures went higher and remained higher throughout the season than in 1955. Each summer was characterized by notable cold spells, however. In 1956 there was really just one mid-season cold spell from 21 to 27 July during which glacial-degree hours dropped to generally less than 30/day. In 1955, there were at least 3 such spells (24 to 25 June, 19 to 24 July, and 29 July to 4 August) with virtually no glacial-degree hours on several days. Small streams and algal pits stayed frozen.

For the three different levels (Fig. 7), the period of glacial-degree hours through the summer is about equally long (63 days), but the intensity differs. Just above the ice cliff (shelter II) there are only 77% as many glacial-degree hours as at the base, and at shelter III near the snowline the total is only 62% as great. However, on at least 12 days both early and late in the 1956 season, the thermograph at the top of the cliff (shelter II) recorded significantly more glacial-degree hours than did the thermograph at the bottom of the cliff (shelter I). Inspection shows that these were always sunny days with a moderate to strong wind, which probably reduced the baking effect of the ice cliff on station I below.

A comparison of conditions on the face of the cliff (shelter V, 1955) with those below the cliff 40 m away indicates that the ice cliff received higher maximum daily temperatures on sunny days but has only 86% as many total glacial-degree hours. This was true also in 1956.

Radiation and cloud cover. The curves for radiation (Fig. 8) are very similar for both summer seasons. Perhaps this attests the accuracy of the instrument, for there are some who doubt the absolute meaning of specific figures from such an instrument. It appears likely now that the quantitative figure for the area under the curve is reasonably close to the amount of energy received during a significant period of time such as one day. In any case, the relative values must be correct. This means that in both years there were marked ups and downs from clear to cloudy days involving more than 350 cal/cm^2-day. The absolute maximum was 736 cal/cm^2-day on 1 July 1955. In the last week of August the highest recorded was 395 cal/cm^2-day. The mean of the ups and downs shows a slight rise in late June to a peak of 550 cal/cm^2-day in the first few days in July, a gradually increasing dropoff to 500 late in July, and a steep drop to less than 300 by late August. It happens that there were long clear spells near the maximum radiation period on each year: 25 June to 5 July 1955 and 23 June to 10 July 1956. In 1956 this had devastating results, coming at the height of the warm season, for it created a sea of slush 75 cm deep around the camp area and backed water up into the tunnel in the ice cliff.

Cloud cover, in percent of sky covered, was noted twice each day and averaged over 6-day periods from 20 June to 25 August 1955 (Fig. 9) This shows variation from 75%

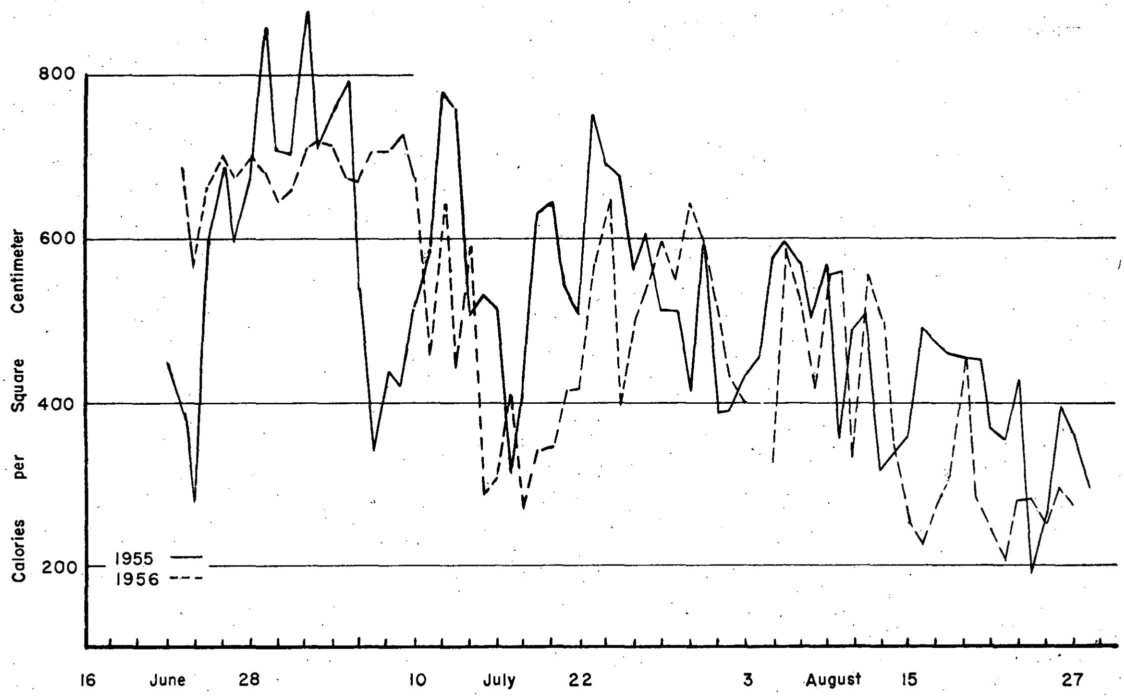

Figure 8. Radiation.

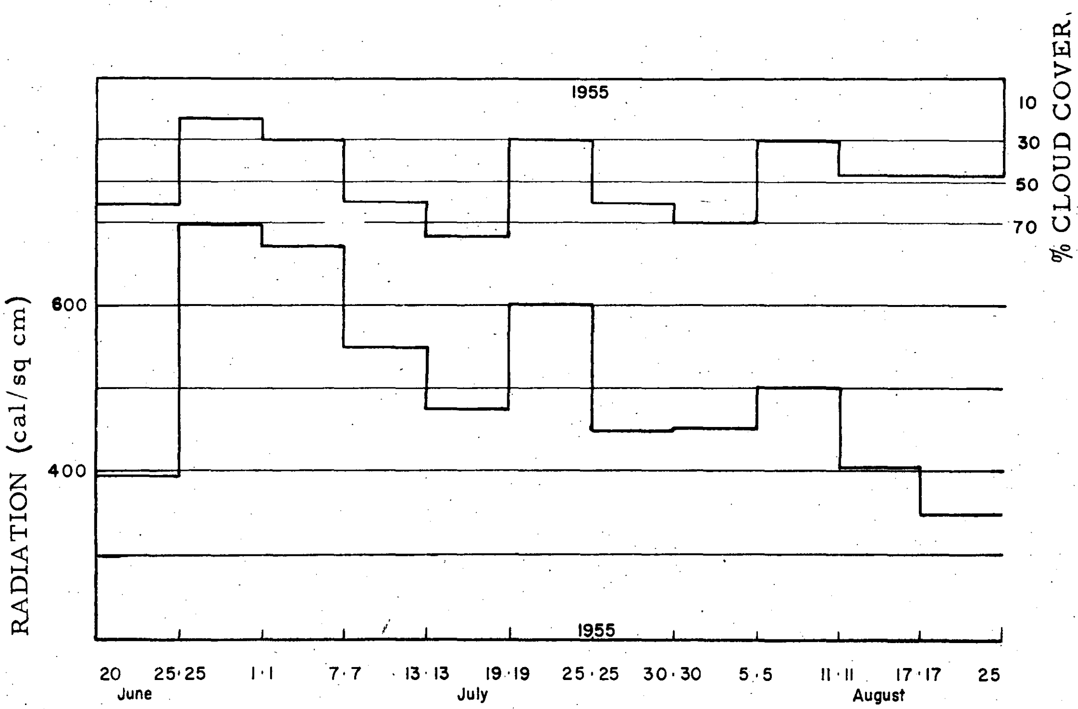

Figure 9. Percent of cloud cover and radiation.

sky cover to as little as 20 during the clear spell at the end of June. Similar fluctuations occurred throughout the summer. Radiation combined in 6-day units on a bar graph shows the exact reciprocal of these ups and downs, i.e., radiation was high when the cloud cover was low. With the lowering sun in the later part of the season, radiation shows a major dropping-off which is not correlated with cloud cover. Mean cloud cover is about 45%. There is no reason to believe that the sky cover or radiation differed materially at the upper weather station, although it was noted on many days of low blowing cloud cover that the uppermost weather station (III) was in the clouds. Nothing is known of the winter cloud conditions in this area except that visitors to Nunatarssuaq in each of three winters have encountered long clear spells during the last week of March.

Table II. Summer precipitation (cm).

1955			1956		
Storm begins	Storm ends	Total precip	Storm begins	Storm ends	Total precip
			10 June*	11 June	0.33
7 July	11 July	0.49			
15 July	18 July	0.18	15 July	23 July	2.74
29 July	31 July	0.25			
2 Aug.	5 Aug.	1.63	1 Aug.	5 Aug.	0.38
15 Aug.	16 Aug.	0.23	14 Aug.	18 Aug.	0.28
22 Aug.	25 Aug.	0.05	20 Aug.*	31 Aug.	4.51 ?
31 Aug.	2 Sept.	?			
Total measured		2.83			8.24

* All as snow.

Precipitation and humidity. Fortunately all of the precipitation which arrives as rain comes in the summer months, when it may be measured. Even then, there is more snow than rain. In 1955, summer precipitation totaled 2.83 cm and in 1956, 8.24 cm (Table II). During the arctic winter, 25 August 1955 to 7 June 1956, the average depth of snow accumulated on open ground south of Red Rock Lake (ablation area XV) was 130 cm; in the area near camp and along the cliff where drifting occurs (XIII) the average depth was 250 cm. When reduced to equivalent water (probable density of wind-packed snow: 0.39), this amounted to 50.7 cm over the 10 winter months, which together with 2.8 cm during the previous summer totaled 53.5 cm/yr, 18 June 1955 to 18 June 1956. Based on measurements of new snow at all of the ablation stakes between 25 August 1955 and 24 March 1956, only 1,502,000 m^3 had arrived over the whole drainage basin in those 7 months, whereas in 2.5 months between 24 March and 7 June 1956, 2,302,000 m^3 arrived. It is not known whether it is abnormal to have half again as much snowfall in these 2.5 months as arrives in the preceding 7 months. It is obvious that the summer precipitation is small by comparison (one-tenth?) and varies by at least 300%.

The storms in 1955 were more frequent (6) but shorter (average 2.7 days) than in 1956 (4 storms over a similar period; average 5.6 days). Perhaps the average duration lies between these two values. Six storms during July and August 1955 brought an average precipitation of 0.46 cm/storm, whereas the four rain-snow storms in the same months in 1956 brought an average of 1.98 cm. This difference is due in part to the final long stormy period from 20 to 31 August 1956 which brought snow calculated to be the equivalent of 4.5 cm of water, whereas a final storm on 31 August to 2 September 1955 was not measured. In 1953 one storm in August brought more than 7.5 cm of rain at Nuna Lake. In general each summer is punctuated by one big rainstorm (2 to 5 August 1955; 15 to 23 July 1956) which brings one-quarter to one-half of the summer precipitation.

The hygrograph did not agree well with the sling psychrometer as to relative humidity; however, it is believed that averages from the hygrograph which do agree with the sling psychrometer are reliable. They indicated an average relative humidity of 75 ±5% near the ice cliff (shelter I). Observed humidities ranged from 50 to 100%. Observations with the sling psychrometer at the top of the cliff (shelter II) indicated relative humidity there was similar to that at the base.

Barometer and wind. Barometric pressure at Red Rock Lake was approximately 700 mm Hg. It was checked against the barometer at Thule Air Base and corrected for altitude. It moved slowly from lows of 695 mm to highs of 715 mm and no significant difference was noted at the upper shelter (III).

The prevailing winds at Red Rock Lake were from the west and northwest. However, near the face of the cliff (shelter I) the winds were predominantly from the southwest, so evidently the local configuration of the cliff turned the regional winds. During some stormy periods the winds shifted to the south and became more easterly as the storm began to pass over. Storm frequency cannot be detected in the wind velocities measured (Fig. 5) since moderately high winds were characteristic of many afternoon and evening hours and some clear days. The frequency of high winds after noonday on fair days suggests katabatic winds were generated locally on North Ice Cap and flowed down over Survey Hill. Mean maximum storm velocities during the summer were on the order of 64 to 80 km/hr. After the anemometer was taken down on 29 August 1955 an estimated velocity of 120 km/hr occurred during one storm. In general this is a windy climate with only 9 summer days in 1955 and 7 in 1956 when wind at the base totaled less than 113 km (4.7 km/hr avg).

Ablation

Observations. Melting accounts for about 93% of all ice loss in the Red Rock ice basin of North Ice Cap. This was measured by the simple expedient of setting poles into the snow or ice and measuring the changing position of the snow or ice surface against the pole. Ablation varies greatly in individual situations, so a statistical study of stakes was made. Results are analyzed according to rough altitudinal zones (areas I through XII, Fig. 10).

Thirty-nine stakes were set in June 1955 in the lower drainage basin of North Cap just above the ice cliff. These were arranged 200 m apart in six parallel rows each about 150 m farther north of the ice cliff than the last. The stakes are bamboo poles 3 m long set in holes 3.1 to 3.8 cm in diam made with a brace, Carr bits, and bit extensions. Bailing powdered ice from the hole when deep and dry, or keeping the bit from freezing in a wet hole were time-consuming problems. The poles in the lower basin had to be reset as they melted out late in the summer 1955; most of the stakes were replaced again in July 1956 but all records were made continuous from 24 June 1955 to 31 August 1956. West end stakes in most rows (nos. 10, 20, 30, 40, and 50) were not put in until June 1956, when mapping revealed inadequate sampling of the west part of the basin. To account for high areas of little melting (IX to XII) two rows of four stakes each (81 to 84, 91 to 94) were added northwestward across snowline on 23 to 26 July 1955.

The original level of snow or ice against each stake was marked by adhesive tape. Every 6 days from 22 June to 25 August 1955, on 24 March 1956, and from 7 June to

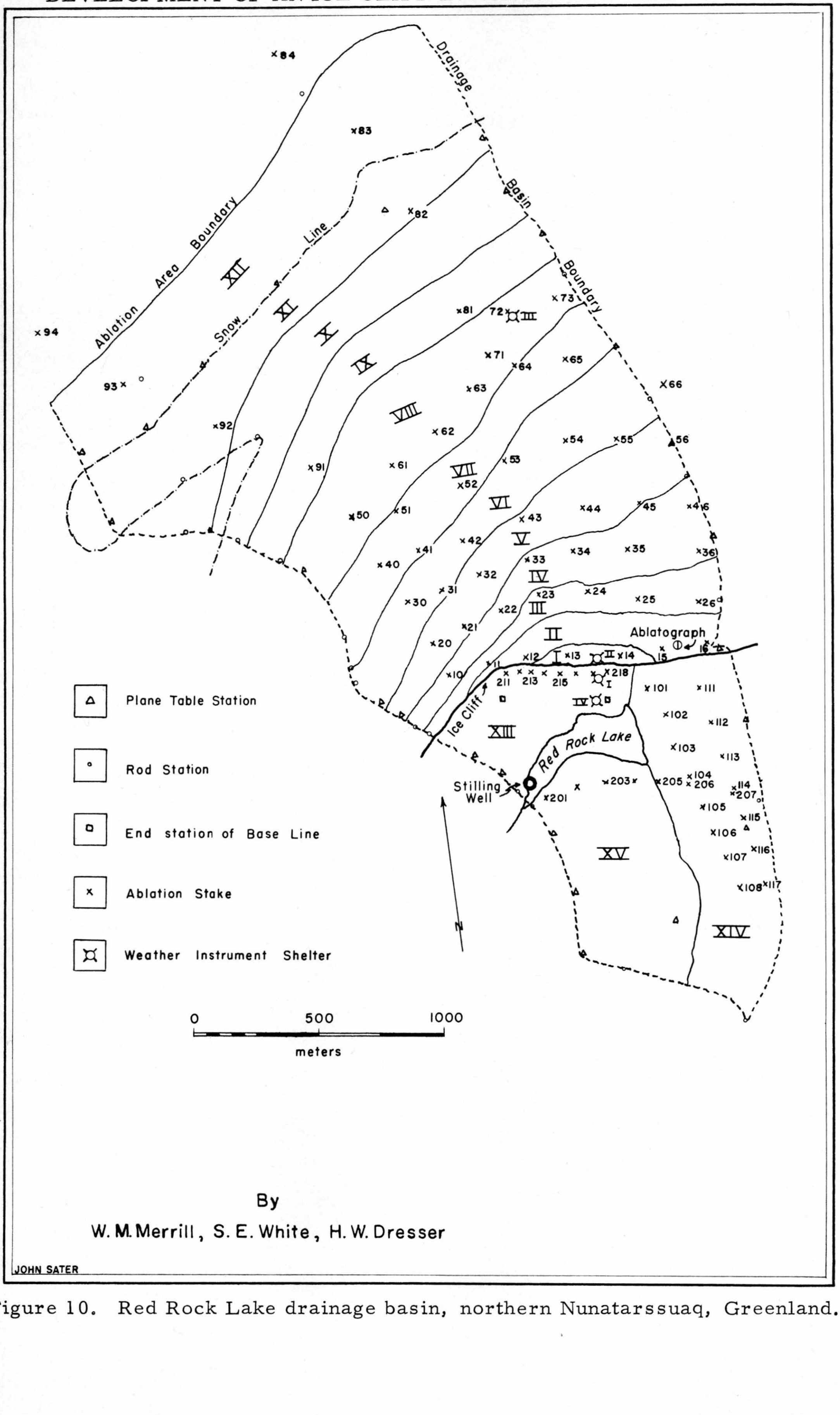

Figure 10. Red Rock Lake drainage basin, northern Nunatarssuaq, Greenland.

Figure 11. Typical ablation stake with taped initial level of ice at left hand. Measurement actually made vertically.

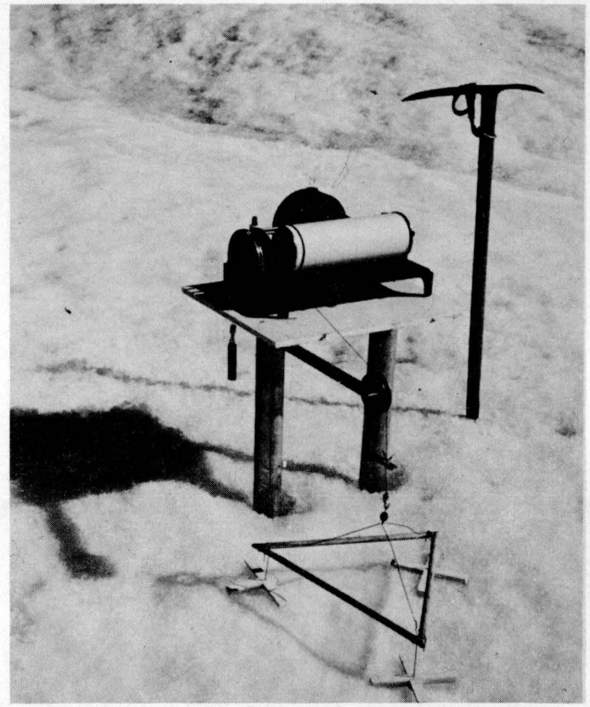

Figure 12. Ablatograph with top removed showing drum and clock. White crosses lower as the ice melts.

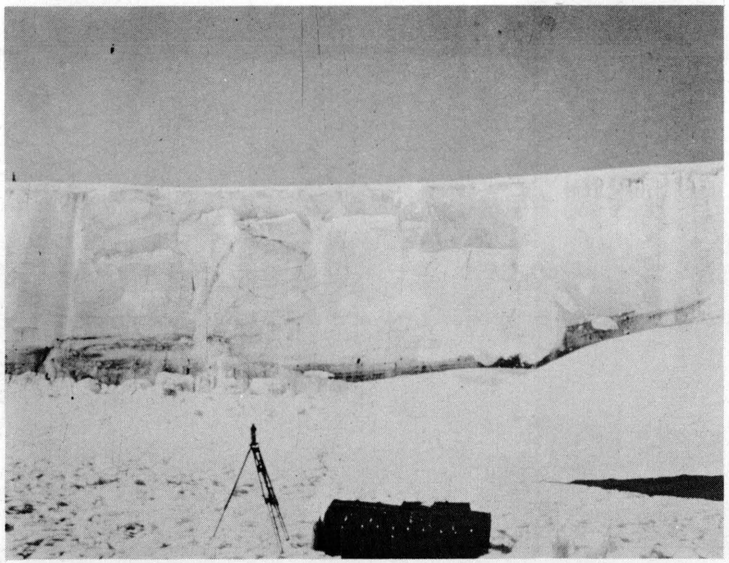

Figure 13. Dry calving of large section of cliff face, 20 June 1956.

24 August 1956, the distance from the top of each stake to snow or ice surface was measured (Fig. 11).

To compute water equivalents, the nature of the ice surface was noted, i.e., whether it was composed of loose grains, solid hard ice, a filigree of thin crystals, or shell ice. The depth of any new snow was measured by ruler near the stake. Occasional samples taken with 500 cc standard snow tubes gave a density of 0.13 g/cm^3 for new snow.

The melting of the ice cliff was handled somewhat differently. Fifty-six ash dowels 183 x 2.5 cm were painted every other centimeter with a red stripe; black stripes were added every 10 cm. These were drilled horizontally into the face of the cliff (37 in 1955 and 19 in 1956) as motion targets. Every 3 days, from 1 July to 25 August 1955 and from 11 June to 25 August 1956, the position of the ice to the nearest centimeter was read by field glasses. The rate of ablation proved so great that all stakes were replaced several times and new positions made the record discontinuous; dry calving demolished most remaining 1955 stakes prior to mid-June 1956. There were enough stakes at all times to give reasonably accurate average rates (±0.1cm) in the upper and lower parts of the cliff. (Placement of the stakes is described in section III.)

Both the ridge east of camp, which is superimposed ice contiguous with the main Greenland Ice Cap, and the semipermanent snowdrifts in the land basin west and south of Red Rock Lake register ablation and contribute to runoff. To determine the contribution, bamboo stakes were set on the ridge (ablation stakes 101-117; 205-207, Fig. 10) and birch dowels 1.3 x 79 cm were set into the snowdrifts (stakes 201-204; 211-218). During both summers these were measured every 6 days. Samples (500 cm^3) from a snow pit dug near stake 115 on 22 June 1956, from near the surface, give a firn density of 0.39 ± 0.10 g/cm^3.

An ablatograph was used to fill in the record of fluctuating ablation rates between visits to the stakes. Ideas tried out by others (Liestøl, 1954) were adapted to a Stevens water level recorder, Type F, with 8-day movement and 1:1 recording ratio. The recorder was mounted on a table supported by 2 aluminum pipes drilled 2 m into the glacier just northeast of the main ice cliff (between stakes 15 and 16). In lieu of the usual water float, 3 wooden crosses hung on a triangular wood or wire frame rested against the melting ice (Fig. 12). The arms of the crosses were 15 x 1.3 cm, rounded on the bottom, and pinned in place by a wire projecting through the center. To reduce absorption, they were painted white in 1955 and covered with aluminum foil in 1956. In spite of this, the wooden crosses melted a few centimeters into the ice in 1955 and possibly 0.5 cm in 1956. Error was minimized since the depth became stable in a few hours. However, this lesser entrenchment in 1956 meant that the crosses blew loose more often during high wind. Six days records were lost in 1955, and 8 in 1956. Records were attempted from 1 July until 24 August 1955, when snow covered the crosses, and from 23 June to 25 August 1956, when they were again covered. Summer snows produced short stable gaps in record while they melted off. The ablatograph table was set 30 cm above the ice on 1 July 1955 and ended up 150 cm above on 25 August 1956 even after one resetting. A typical ablatograph record is shown in Figure 14.

Toe of the ice cliff. The fastest melting by far occurred on the 10 to 40 m long toe below the ice cliff. The warmest measured position melted back as much as 42.4 cm in 6 days (stake 8J on 1 to 7 July 1955). Of course, the two summers differed greatly; 1955 averaged 32 mm/day whereas 1956 probably reached 38 mm/day.

One of the sources of energy to dispose of toe ice is the water falling from above. All parts of the toe receive some dribbling water on warm days, but the great gorges and plunge pools 1 to 10 m deep below each of the 10 larger waterfalls indicate unique concentration of energy here. Extrapolating from 1955 measurements of the stream at the

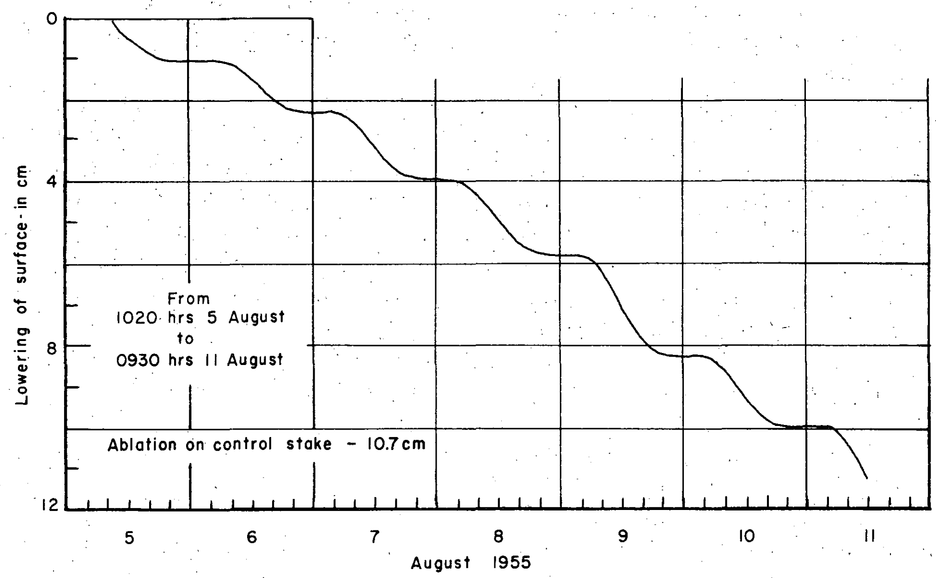

Figure 14. Typical ablatograph record.

cliff base (p. 25), 6740 m³ of water/day fall over the cliff; in 45 days 2.1 x 10^6 kcal of kinetic energy is expended, or enough to melt 30 m³ of ice (50 or 60 m³ in 1956). Actually these plunge pits are estimated at about 700 m³, so most of the heat energy is available from other sources.

Significantly, the areas of lowest melt rates during warm weeks (stakes 4J, 5J, 6J) are right below areas with some of the highest measured rates on the cliff above (4A, 5G, 6I). This appears to happen when the toe ice becomes covered by thousands of loosened ice grains which fall from above. On toe slopes of 35° to 50° a covering of loose ice grains as much as 10 cm thick was observed after some sunny days.

Much of the heat of melting is expended on drifted snow. In early June, snow covers all except patches of the toe ice; little by little more ice is exposed until in warm seasons like 1956 all energy in August is effective in melting glacier ice or superimposed toe ice. In cooler years like 1955 some melt is refrozen as it soaks into deep cold drifted snow and becomes added to the glacier as patches of superimposed ice. In still other areas of toe ice, great masses of ice-snow breccia fallen from the cliff above in May or June cover the toe and prevent melting of original glacier ice for a year or more.

The average total melt for 1955 (projecting rates for two unmeasured weeks in June) was 2.5 m; for 1956 the extrapolated total is 3.0 m.

Vertical ice cliff. Melt rates on the vertical cliff (Table III) were only slightly less than those on the toe. Actually they consist of two very different rates: (1) in amber ice containing disseminated dirt in the lower 0 to 4 m of cliff, and (2) in white ice making the upper 5 to 25 m. Because it absorbes some 50% of incident radiant energy in the summer, the amber ice melted at 31 mm/day in 1955 and 37 mm/day in 1956. The white ice, which absorbes only 20% of incident energy, melted at 24 mm/day in 1955 and 30 mm/day in 1956. This meant a total season's loss of 2.5 m and 3.0 m of amber ice for the two melt seasons, in contrast to 1.9 m and 2.4 m for white ice above.

There is no protection of the vertical cliff by a cover of winter's snow, melting granules, or avalanche breccia. The recorded melting represents a total seasonal loss. Melting begins in May as soon as temperatures climb near freezing and the sun is high enough to affect radiational melt.

Table III. Average total ablation (m) on the cliff face.

Stakes	Number	All summer 1955 (80 days)	All summer 1956 (80 days)	6 of the warmest days* 1955*	6 of the warmest days* 1956*
In upper white ice	12 or 9	1.90	2.56	0.18	0.33
In lower white ice	10 or 7	1.88	2.26	0.17	0.35
In amber ice vertical	9 or 3	2.46	2.97	0.22	0.39
In sloping toe ice	6 or 0	2.53	3.05**	0.22	—

* 1 to 7 July 1955 and 5 to 11 July 1956
** Extrapolated

The manner of ablation on an ice cliff differs markedly from that on the toe or ice above. The unique processes are tied up with direct summer radiation; a south-facing vertical surface receives 60% more energy than a horizontal one because the angle of incidence is more nearly perpendicular (calculated for 75° N latitude from 21 June to 21 September). Thermographs on the cliff face verified the "baking effect"; on quite sunny days like 19, 21, and 26 July 1955 or 12, 23 and 28 July 1956, they recorded an average maximum of 7.2C, which is 2C more than on shelter II above or I below. Especially on cool sunny days like 17, 18, 19 July 1955 the glacial-degree hours on the cliff were nearly 7, 3, and 5 times those below.

Differential melt rates are further evidence of the role of radiation on the cliff. During sunny spells in early July 1956, cliff melt rates in amber ice (64 mm/day) were 33% greater than those for the white ice just above (48 mm/day); in protracted cloudy spells like 17 and 21 July 1956, ablation was only 23% greater in amber ice than in white, although mean daily air temperature was about the same.

An important adjunct to radiation loss was the dropping of granules from the cliff face. Ever since Tyndall's studies in the Alps a century ago, it has been recognized that radiation first melts crystal boundaries and so loosens the crystals. On a vertical cliff, these fall as soon as interlocking spurs are reduced. Wind may hasten their detachment. This produced a continuous hail of ice particles at the base of the cliff on sunny warm days; obviously, the ice is removed from the cliff without expending the 25% to 50% more heat needed to melt the remaining grain.

Running water was effective in melting some ice. Whereas kinetic energy of fall was most effective in pitting the toe ice, and circulation of heat was most effective above the cliff, both have some effect on the vertical cliff. Any stream position more than a year old has a trench inset 0.5 to 5 m. In the photogrammetric survey of changes on the ice cliff during summer 1955, it can be shown that 327 grid points along the stream channels deepened an average of 0.53 m, while grid points over the whole surface changed an average of only 0.45 m. This difference is a measure of the small loss on the vertical cliff due to falling water alone.

In the winter, when melting ceased and streams stopped flowing, the only forms of ablation were sublimation and wind erosion. The high gloss on the ice surface noted in March and early June 1956 suggests significant abrasion. By March 1956 an average of 17.9 cm had gone; by June 1956 it totalled 31.1 cm. Theoretical calculations (Table VII) show that sublimation may account for well over half the total (22 cm).

Cliff calving. One very substantial loss of ice substance from the glacier was not concentrated in the melt season nor can it be measured by ablation stakes; this was the peeling of large sheets of ice from the cliff face in avalanches, here called "dry calving" (Fig. 13). In order to appraise the total quantity, the area of each loss was noted by sketching (1956) and by photography. Thickness of the sheet calved was estimated by measuring calved blocks. Some check was possible through net loss measurements by photogrammetry corrected for winter motion.

Table IV. Record of dry calving from ice cliff.

Date of ice fall	Grid position of center	Total area of scar (m^2)	Estimated average thickness (m)	Avg vol. lost (m^3)
19 June 1955	390	509	1.5	764
10 Aug. 1955	380	142	1.5	213
? winter 1955-56	360	127	1.0	127
? winter 1955-56	260	571	1.5	857
? May 1956	330	1179	1.5	1768
19 June 1956	330	432	1.0	432
19 June 1956	230	526	1.5	789
20 June 1956	400	479	2.0	958
20 June 1956	500	400	1.5	600
2-year total		4365		6508

Nearly all dry calving in both years took place in May or June (Table IV). All falls were preceded by the opening of a deep curved crevasse, concave to the ice cliff face, which widened in a few days from a few centimeters to as much as 2 m at the top. However, some cracks 2 to 10 cm wide lasted from July to the following May before the ice sheet fell off. In all cases the fall was preceded by 10 min to 4 hr of intensified loud cracking noises; random cracking occurred through the year. In several instances the final fall seemed to be triggered by artificial vibrations: dynamite 10 August 1955, helicopter landings on 20 June 1956. In two years, areas totaling 82% of the high cliff studied (Fig. 57, 58) had collapsed.

Typically a whole sheet of ice covering 480 m^2 of the cliff face and up to 2 m thick collapsed downward at once. As it hit the sloping ice toe, it crumbled into blocks 2 m^3 or less. As it slid down the toe, it threw up a cloud of pulverized snow or sprayed slush. It slid and rolled 30 to 100 m up over the flanking high snowdrift. Each whole episode was over in 3 to 5 seconds.*

In 1955 we became convinced that calving was only a secondary means of ice disposal; in 1956 it took on double importance (Table V). For the whole length of cliff studied, the equivalent of 0.3 m thickness was lost in 1956. In each year this constituted only 11% of all ice loss on the cliff.

Glacier surface above. Most glacier melt rates are proportional to air temperature: the more degree-hours, the more melting. The ablation curves (Fig. 15, 16) are very

* Areas above and below where cracks opened were staked as "off limits." When cracking was heaviest no person was allowed near the cliff.

Table V. Estimated loss of ice on the vertical ice cliff face (grid 160 to 420 only).

	Area affected (m^2)		Thickness removed (m)		Vol. ice removed (m^3)	
	1955	1956	1955	1956	1955	1956
Calving loss (ice fall)	778	3587	1.30	1.50	1011	5381
Granulation loss (grains detached)	5308	5308	0.16	0.20	849	1061
Radiation loss*	5308	5308	0.42	0.40	2229	2123
Convection loss †	5308	5308	1.38	1.86	7325	9873
Falling water loss (kinetic heat)	248	300	0.16	0.30	40	90
Sublimation loss**	5308	5308	0.22	0.20	1168	1062
Total					12622	19590

* Calculated from sun's energy measured assuming an average albedo on the ice of 75%.
† Measured ablation loss minus calculated radiation and sublimation, measured falling water loss, and estimated granulation.
** By formula assuming rates in Table VII.

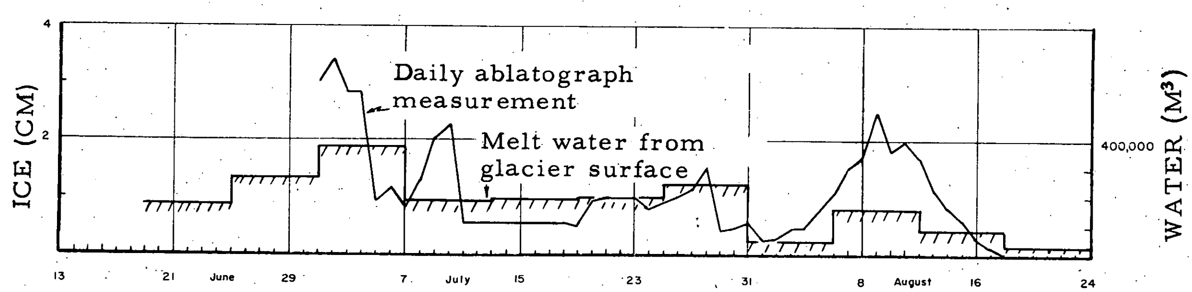

Figure 15. Ablation during 1955.

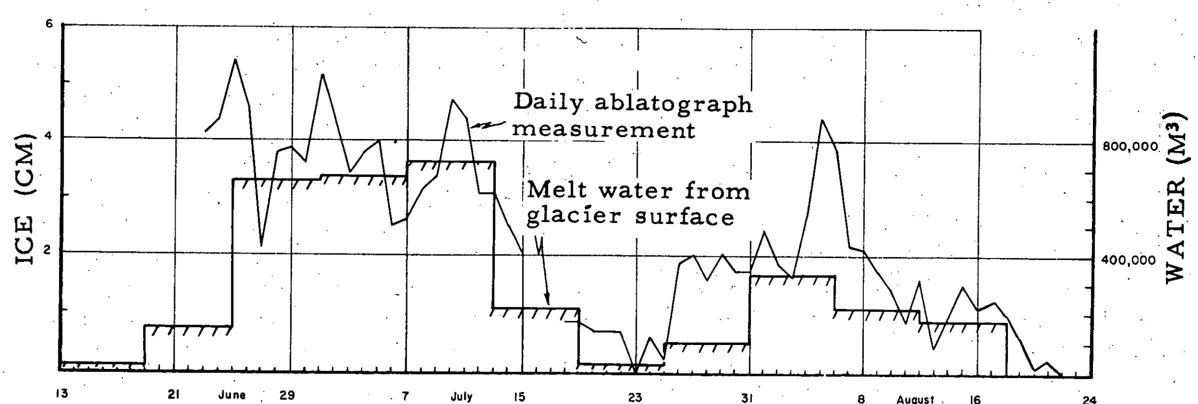

Figure 16. Ablation during 1956.

Table VI. Average ablation (cm) of glacier surface at various altitudes.

Area	Altitude above sea level (m)	1955 July	1955 Aug	1956 June	1956 July	1956 Aug
I	670 to 692	45.2	25.2	48.0	76.1	49.5
II	692 to 712	38.4	21.0	45.9	69.7	40.5
III	712 to 732	37.7	19.9	37.7	55.7	33.3
IV	732 to 752	33.2	19.1	43.1	54.7	32.6
V	752 to 772	35.2	15.7	27.1	55.5	35.0
VI	772 to 792	36.5	16.8	28.2	65.0	32.3
VII	792 to 812	34.0	13.9	29.7	63.7	33.1
VIII	812 to 832	28.7	10.6	24.9	62.0	30.6
IX	832 to 852	—	10.2	21.4	20.5	12.5

similar to smoothed temperature curves such as degree-hours (Fig. 6). They do not follow the sharp fluctuations of the daily maximum and minimum temperatures (Fig. 4). Three warm days in a row like 1, 2, and 3 July 1956 take off far more ice (126 mm) than three isolated warm days like 14, 17, and 19 July 1956 (66 mm). Eighty percent of the total annual surface loss occurred in three warm periods in 1955 (26 June to 16 July, 25 to 28 July, 5 to 14 August) and in two long periods in 1956 (20 June to 17 July, 27 July to 13 August).

The average seasonal lowering of surface in 1956 (110 cm) was twice that for 1955 (54 cm). This is not surprising since glacial-degree hours in 1956 totaled 3 times those in 1955. The radiation was 5% less in 1956 than in 1955 which may explain why ablation on the cliff - most affected by radiation - increased only 31% rather than 2 or 3 times. Assuming only 2 cm melting prior to 19 June, the 1955 average rate of lowering of the glacier surface was 6.8 mm/day for 80 days and the measured rate in 1956 was 15.7 mm/day for 70 days.

The amount of melting decreases regularly with altitude (Fig. 17, Table VI). Averages of stakes in each altitudinal zone show 100 to 160 cm melting for the summer at the cliff edge (680 m), 60 to 120 cm at 800 m altitude, and 10 to 30 cm at 900 m. Irregularities are due to drifting and rough zoning. This places the snowline between 900 m and 920 m elevation on the glacier surface; it was mapped at about 892 m in 1955 and observed still higher in 1956. The lines for the two seasons converge (Fig. 17), indicating that the seasonal fluctuation of snowline was not as great as the variation in ablation at lower levels.

Surface melt water seeps in between grains; it oozes out of freshly drilled holes at 1 to 10 cm down. It can be seen percolating irregularly between grains along the surface until it reaches a rill or creek. Most probably melt water serves as an agent to carry heat a few centimeters downward or, when collected in streams, to increase the melt rate of the stream bottom. Experimental measurements at one low stream (area II, stake 15) indicate extra deepending of from 15 to 20 cm below the surrounding interfluves between 1 July and 18 August 1956, even though the interfluves lowered at the normal regional rate (21.2 mm/day). This stream deepening, observable everywhere below 800 m, is a rough measure of excess energy applied to stream bottoms.

The detailed topography of the ice surface is the product of ablation eating into complex structures for decades. In the lower basin (670 to 740 m) there is a zone 60 to 800 m wide in which melt water is confined to relatively few well developed subparallel channels; these melt to 3 m deep so that the dominant surface form is a series of "whaleback" ridges about 5 by 20 m between streams. These cut across most structures so that only a subdued sawtooth effect is expressed by ice foliation

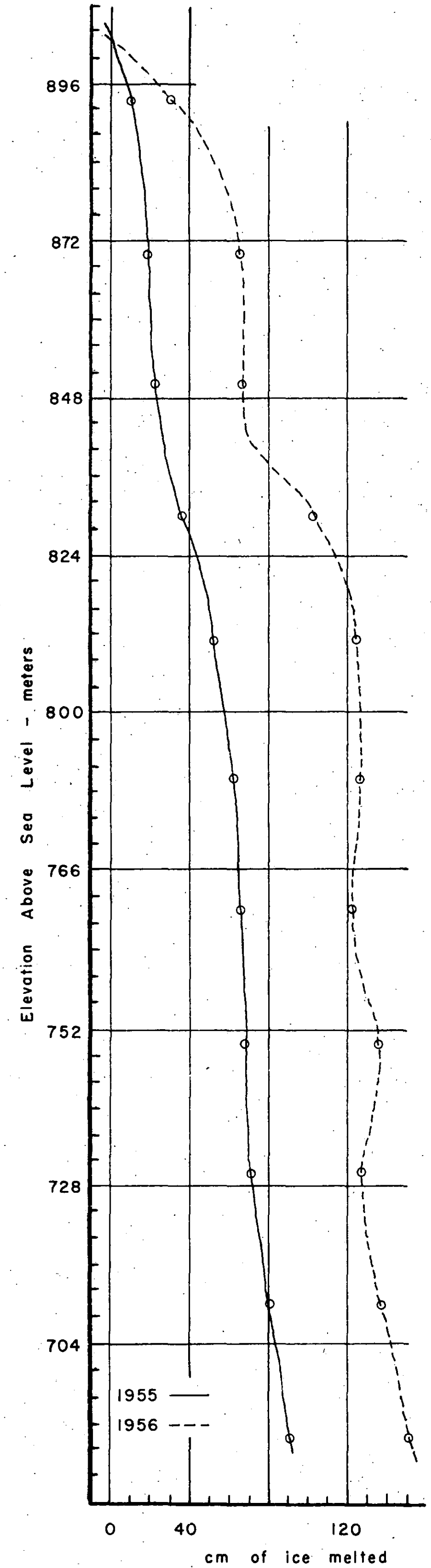

Figure 17. Effect of elevation on melting.

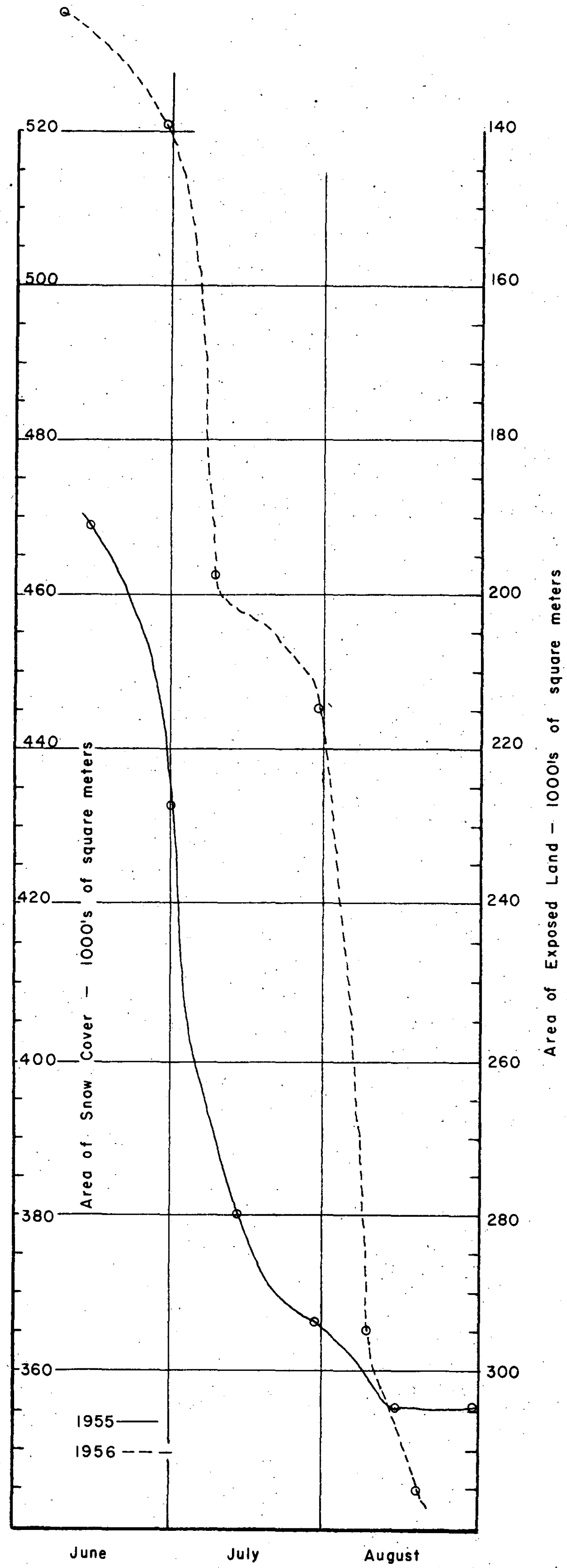

Figure 18. Decrease in area of snow cover.

along the ridge crests (Fig. 55). It is this lower surface which is sprinkled liberally every few meters with algal pits mostly 5 to 200 cm in diameter and 10 to 50 cm deep. Each unit is cylindrical, although many coalesce in complex groups. A thin film of dark brown algae covers the bottom and deepens the hole during the summer by absorbing radiation. By melting ahead of the main ice surface, these undoubtedly accelerate total ablation rate. Still higher up (to 780 m) is a belt 80 to 200 m wide in which stream channels are not more than a few centimeters deep and flow among many isolated hummocks which may be up to a meter high or 5 m in diameter. Most of these hummocks are asymmetrical with the steeper side to the south across the dip of bubble foliation, and they become higher as the melt season progresses. Still higher (above 780 m to snowline) is a smooth ice surface in which very few streams flow in discrete channels. Evidently these forms are produced one from another - smooth ice to hummocks to ridges and channels - as the ice takes from 15 to 200 years to move through these three zones.

Evaporation. Evaporation was estimated on a theoretical basis since there was no adequate instrumentation. Fitzgerald's (1886) formula:

$$E = \frac{(V - v)\left(1 + \frac{W}{2}\right)}{60}$$

E = rate of evaporation (in. /hr)
V = maximum vapor pressure (in. Hg) of vapor-producing surface
v = vapor pressure in air above (in. Hg)
W = wind velocity (mph)

was used since he showed experimentally that it applied to ice. For the entire 80 days of summer 1955 this yields 2.32 cm loss, which is 4% of the total loss recorded;

Table VII. Calculation of probable evaporation rate (mm/day)*

Season	Mean air temp (C)	Wind, 1/2 that at 3 m (km/hr)	Evaporation rate (mm/day)
Summer 1955	0.7	2.88	0.29
Winter 1955-56	-18.0	12.00	0.30†
Summer 1956	1.6	2.88	0.73†

* Assuming average barometric pressure of 700 mm Hg and average relative humidity of 75%.
† Approximate only.

for the 70 days of 1956 it is 5.1 cm which is 5%. This rate is probably high since it does not apply equally to snow which covers much ice in June and early July. It may become relatively very important in spring, however. If the values adjudged to exist from September to May inclusive are correct, exposed ice surfaces such as the

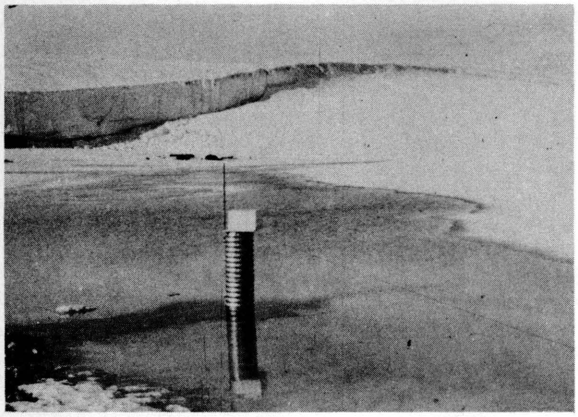

Figure 19. Stilling well and water-level recorder box at south end of Red Rock Lake. Camp and ice cliff in background. Late June 1956.

cliff would lose 8.1 cm of ice. As pointed out already, actual measured loss on the cliff over the winter averaged 31 cm, which may be in small part wind erosion and early melting from radiation.

Drifted snow. Wherever winter winds drift snow, a semipermanent snowdrift develops at the summer's end. On the glacier these snowdrifts represent irregularities along the snowline; on the land they diminish all summer and contribute to runoff. Total melting on drifts is much like that for ice: (1) 19 mm/day on the ice ridge (area XIV) east of Red Rock Lake at altitudes equal to the lower glacier surface (2) 23 mm/day for the snowdrift (area XIII) along the ice cliff right next to the dirty toe ice, and (3) 22 mm/day for drifts on the north slope of Knob Hill (area XV). These melt fast because snow offers more grain surface to melt than ice, but the rates did not exceed that in dirty toe ice.

The feathered edges of these drifts shrink regularly through the season. Starting at 450,000 m^2 cover on 10 June 1955, the combined areas of snowdrift decreased to near 300,000 m^2 by 10 July and levelled off near 210,000 m^2 just after 10 August. In 1956, 100,000 m^2 more land was covered to start with, but the long warm season reduced drifts even further than in 1955, to 180,000 m^2 by 25 August (Fig. 18).

Rainfall is popularly thought to induce rapid melting. It is forgotten that it takes 79.8 cal/g to melt snow or ice. Thus, the 2.28 cm of rain on 15-19 July 1956 at 3.2C or the 1.14 cm of rain on 4 to 5 August 1955 at 1.6C would melt less than 1 mm of ice or 3 mm of snow at density 0.39 g/cm^3.

Discharge of melt water

Lake level. Melt-water discharge from the ice basin at the east end of North Ice Cap and from the ice cliff studied can be measured at Red Rock Lake, where all melt water is temporarily impounded before entering Red Rock Creek (Fig. 19). Allowances must be made, however, for water coming from the superimposed ice ridge attached to the main Greenland Ice Cap to the east, from snowdrifts over the land basin surrounding Red Rock Lake, and from summer precipitation.

A continuous lake-level recorder was installed at the west shore of the lake near the outlet. A stilling well was made of an upright length of corrugated culvert pipe 244 x 38 cm. In late June 1955 the pipe was set in water on the only ice-free lake bottom near the west shore. As submerged plants had indicated, however, this position proved too high for water levels during the latter half of the summer. On 8 July 1955 the pipe was moved to a point below the lowest water level, held in place by a high pile of boulders all around, and guyed to two large boulders on the shore. On 26 June 1956 water rose as much as 30 cm above the top of the stilling well.

A Stevens water-level recorder, type F, with 2-day clock-driven pen movement and 2:1 gear ratio between the float and drum was situated in a housing on top of the stilling well. Water entered a 6-mm hole at the bottom of the well to actuate a 20-cm diam float counterbalanced by a 1-kg weight. Every 2 days when the record was changed, the marking on the chart was calibrated against a gaging stick wired to the stilling well.

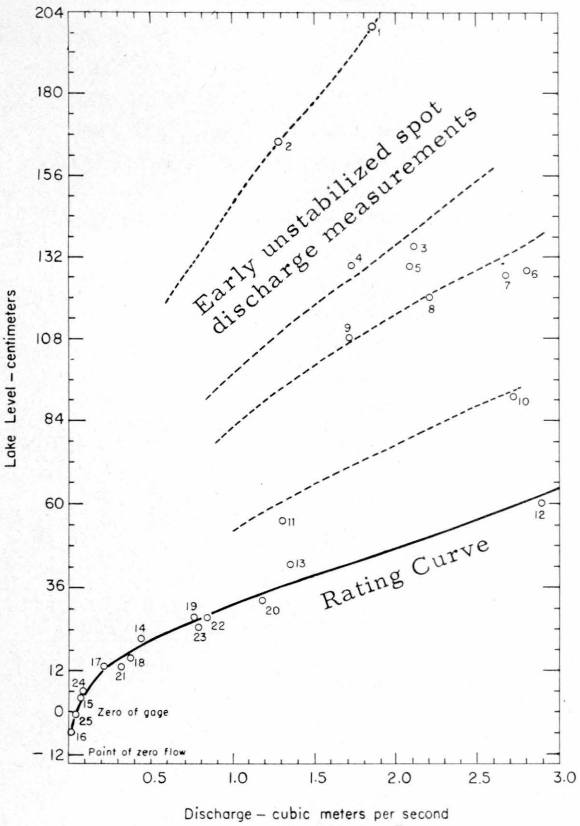

Figure 20. Rating curve.

Records were begun on 21 June 1955, when the stilling well was set at its first position, and continued with short interruptions for accidental troubles until the lake froze over for the winter on 26 August 1955. In 1956 records were begun on 23 June, when the melt water flooded over lake ice and ice inside the stilling well could be melted by pouring in buckets of boiling water. On 22 August 1956 the lake again froze over.

Outlet flow. Discharge down Red Rock Creek was metered by determining the velocity and cross section of the water in the outlet for various stages of lake level. The procedure used is outlined in U. S. Geological Survey Water Supply Paper 888. A tagline with beads 2 ft (61 cm) apart was suspended across the outlet perpendicular to the flow. A standard Gurley current meter with 1 and 5 revolution contacts was mounted on a graduated vertical rod and placed successively at the bead stations 61 cm apart along the tagline. A pygmy meter was used in shallow water in 1956. At each station the depth of the water was read. If the water was less than 46 cm deep, one velocity was read at 0.6 of the total depth; if more than 46 cm, two velocities at 0.2 and 0.8 depths were read. The observer stood in waders downstream from each position. The product of average depth (cm) and velocity (cm/sec) at each pair of adjacent stations multiplied by the distance between stations (cm) yielded the rate of discharge (cm^3/sec) for the cross sectional area between the stations. The sum of discharge figures for all intervals across the stream is the total discharge at the time of observation.

The situation for discharge measurement was far from ideal. Greatest accuracy is achieved where there is a fixed flume. Not only was the channel irregular, but initial flow was over a deep winter drift of snow and ice. As the melt of late June raised a deep blue lake behind this drift, a ditch more than 100 m long was dug across the suspected site of the outlet to initiate overflow at a controlled time and in an outlet of known proportions. However, the walls of snow and ice were rapidly undermined by the swiftly moving water and the overhanging snow had to be cut away before each measurement. On 2 July 1955 the initial trench superimposed itself upon the sloping side of the underlying boulder channel so that the outlet stream migrated southeastward; it was necessary to change the site of measurement. Only after 15 July 1955 and after 12 July 1956 did channel conditions become more or less stabilized.

From 15 June to 15 July 1955 and from 19 June to 12 July 1956, melt water flooded into the Red Rock Lake basin and was ponded against the snowdrifts which closed the natural outlet. The conspicuous slope of the winter ice surface from deep portions of the lake up to the outlet area indicates that, beneath the winter ice, the lake had actually drained below its own outlet by slow seepage. Total storage until overflow begins is estimated at 950,000 m^3. Since the size of the first artificial overflow channel was constantly changing, this early discharge was measured 21 times in 2 summers; intermediate rates of discharge must be interpolated between the nearest preceding and following measurement. Plotted against lake level (Fig. 20), the early discharge measurements

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fall on a series of dashed lines suggesting a lowering outlet. The maximum measured rates of discharge occurred in this period: 1.27 m^3/sec for a few hours on 5 July 1955 and 2.95 m^3/sec as stability was reached on 10 July 1956. In each case the highest water in the lake occurred long before the maximum discharge: 102 cm above the zero-flow level on 21 June 1955 and 213 cm above the level of zero flow on 25 June 1956. During this early period, there was a steady decline of daily maximum level from near 200 to less than 60 cm above the point of zero flow, which probably registers the deepening and widening of the outlet since ablation continued to be heavy.

Rating curve. Stability of outlet flow and water-level relations began when the outlet reached its maximum width and became completely bedded upon the bouldery channel. This stability is indicated when the measurement of discharge first falls upon a repeatable rating curve established by all subsequent measurements of discharge (Fig. 20). The curve is dependable if all points fall on a single parabola whose vertex is the point of zero flow. The 14 points for 10 July to 21 August 1956 fall on a rather smooth curve. Most of the discharge points after 15 July 1955 fall very close to this curve also, so that these data must represent a fair key to the stabilized discharge. By using values on this curve, the actual fluctuations of discharge during the stabilized two-thirds of the melt season are directly traceable to long-term fluctuations in ablation due to the cumulative effects of 3 or more days of persistent weather. For example, lake level and discharge were high from 25 to 27 July 1955, 9 to 11 August 1955, 4 to 6 August 1956, and 16 to 18 August 1956 (Fig. 21, 22).

Diurnal cycling. It is well-known that glacially-fed streams vary tremendously in volume during any one day of heavy summer melting. Superimposed upon the declining early lake level are the daily ups and downs in response to high and low sun. In general, the maximum lake levels came at 1700 hr, some 4 hr after the peak of warmth for the day. Water level declined very rapidly through the early morning hours to reach a mean minimum about 20 cm below the maximum at 0800 hr. As nearly as can be interpolated, this represents a daily change in the rate of discharge of 0.5 m^3/sec or fluctuation by more than 25%.

This diurnal cycling is even more apparent on the smaller streams feeding Red Rock Lake. They flood faster by day, drop more rapidly at night, and do not have the attenuating influence of the lake. The flow of three small tributary creeks was measured, using the same procedure as at the outlet of Red Rock Lake except that during 1956 a pygmy current meter was used. The stream on ice along the base of the high ice cliff, which collects water from the many falls over the ice cliff, was measured on 27-28 July and 9-10 August 1955. The stream flowing into the southeast corner of Red Rock Lake from snowdrifts on Dryas Mountain and Knob Hill was measured on 9-10 August 1955. The stream coming down the lower east slope of Survey Hill from western sections of the ice cliff was measured on 10-11 August 1956. To record the rapid daily fluctuations of discharge, measurements were made every 2 hr for a 24-hr period in 1955, or every hour in 1956. Water level was measured with a steel tape against a metal stake driven into the stream bed.

The times when very modest fluctuation of discharge occurred down the outlet of Red Rock Lake were picked for measurement of these small streams; nevertheless, variations of more than 300% from day to night occurred in each of these streams. The minimum stream level and discharge came near 0500 hr, which is 2 to 3 hr before the lowest level in Red Rock Lake. This period of low flow is fully 6 hr after any appreciable ablation was recorded on the ablatograph (Fig. 23). Apparently it takes 6 to 8 hr for water percolating between ice grains to filter out slowly into the nearest stream. With the more remote parts of the ice basin more than 2 km from the gaging station, and average stream velocities of 78 cm/sec, the flow of some water to the lake takes on the

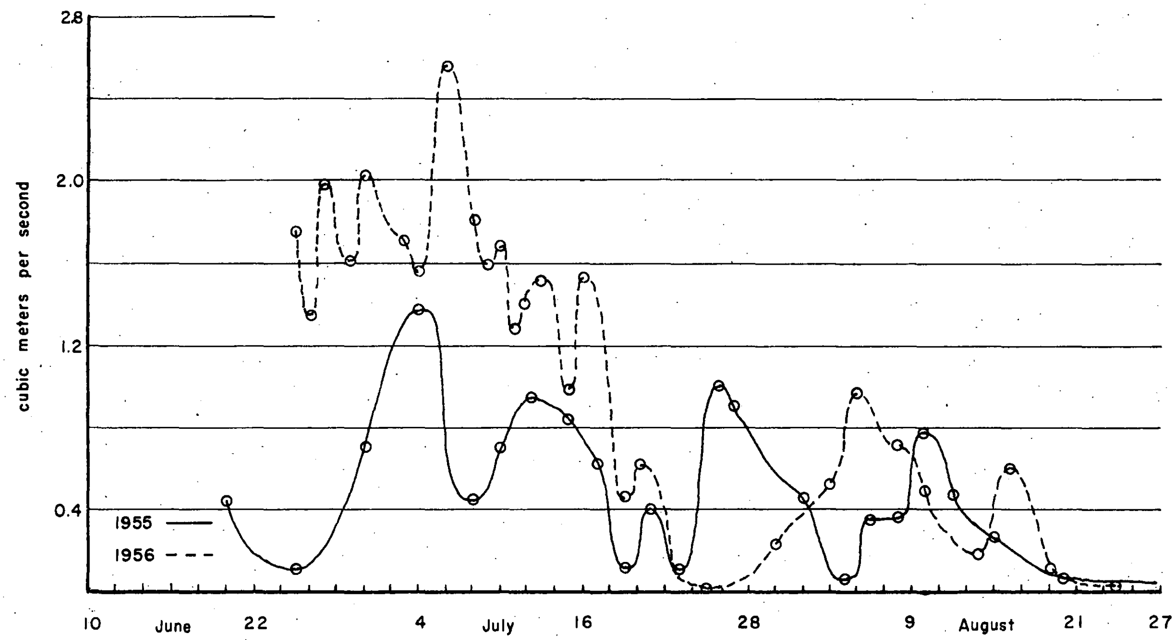

Figure 21. Average discharge calculated from Red Rock Lake levels.

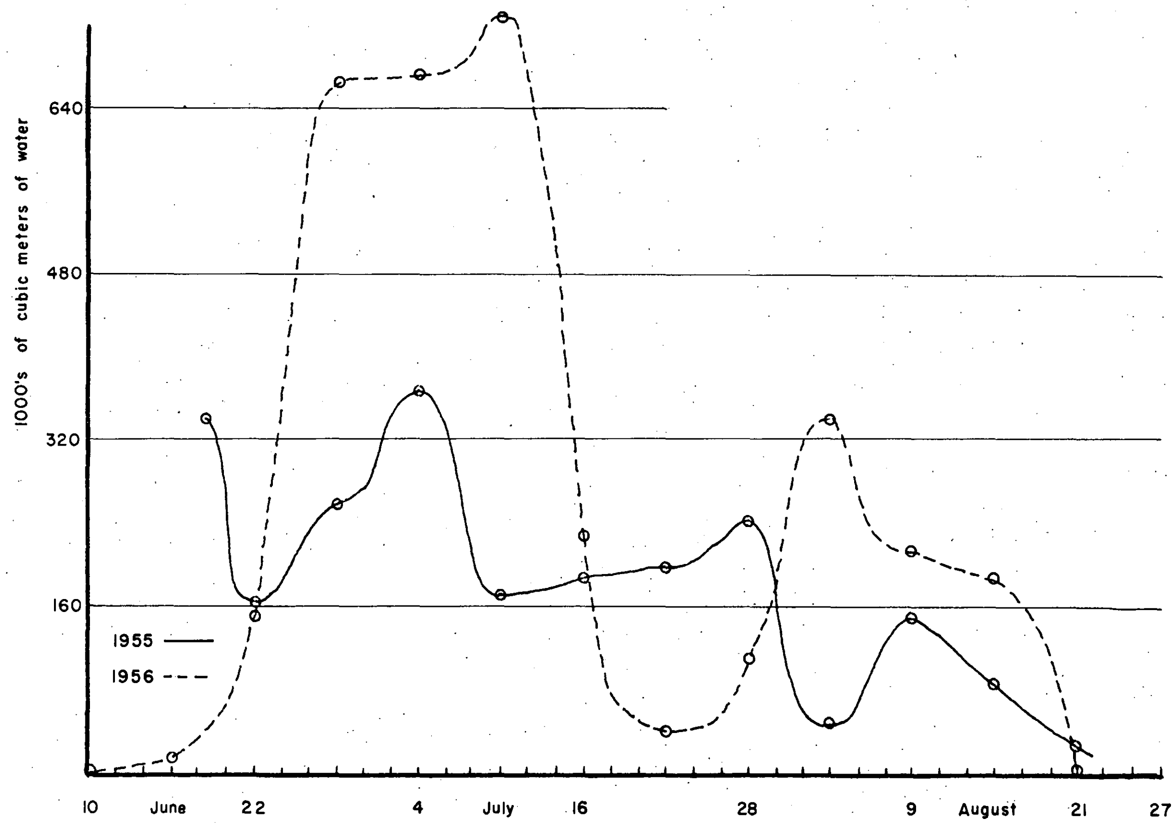

Figure 22. Ablation, all stakes above cliff.

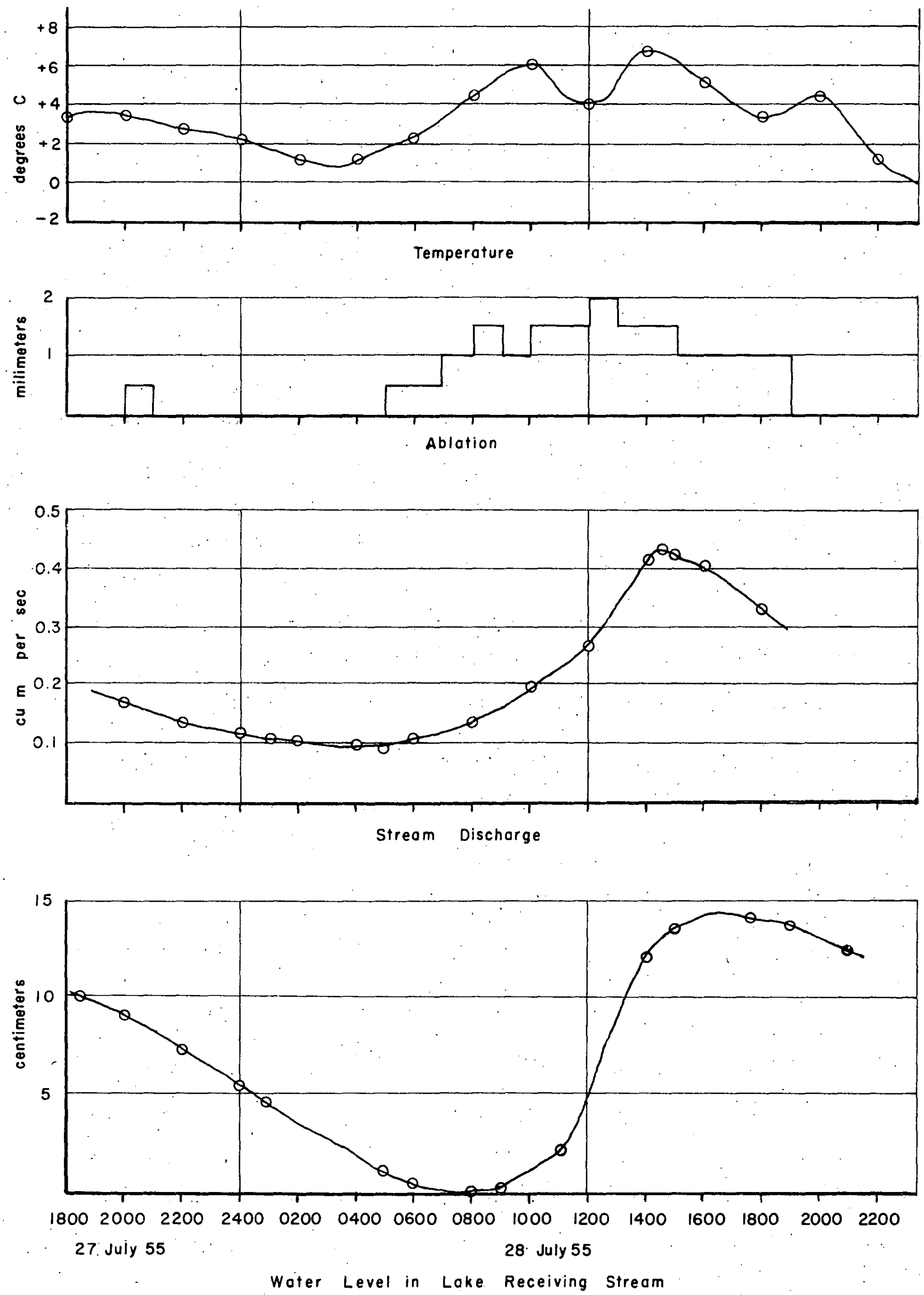

Figure 23. Comparative diurnal fluctuations.

order of 1 hr. Flow builds up rapidly from 0800 to 1430 hr on sunny days. The rate of ablation reaches its peak at 1300 hr, roughly 1.5 hr earlier than maximum flow, and the level of Red Rock Lake reaches its peak 2.5 hr later, at 1700 hr. Thus, the transit from the climax of ablation to storage in Red Rock Lake involves an average delay of 4 hr.

Total discharge. The area under the curve for discharge (Fig. 21) is a measure of the total discharge. For 1955, 17 July divides the summer almost evenly into two halves of 1,400,000 m³ discharge apiece. In 1956, the discharge before 17 July was almost double that during the first half of 1955 or equal to the total 1955 discharge. This is the obvious consequence of many more glacial-degree hours and double the ablation rate in 1956.

A comparison of curves for ablation (Fig. 22) and for measured discharge brings out interesting relationships. In the third week of June, discharge is nonexistent so that large amounts of water must be absorbed by snowdrifts, especially those covering the lake. During the last week in June, or the first few days in July, the outlet rushes into action, causing the discharge curve to jump suddenly upward, but, because of the restriction by snowdrifts at the outlet, all of the melt water being produced cannot escape, so ablation exceeds discharge. Then in the first and second weeks of July the situation is reversed: the channel is enlarged and reduced in level so that discharge exceeds ablation and the amount of stored water decreases. Finally, a sort of balance is reached between 15 and 25 July after which time the ablation and discharge curves fluctuate slightly, sometimes crisscrossing each other. Freezing nights and days below 5C occur and discharge drops rapidly with reserves in the lake being quickly used up.

Table VIII. Total runoff (m³) measured in Red Rock drainage basin by 6-day periods.

Period ending	1955 lake discharge	1956 lake discharge
25 June	155,520	0
1 July	295,488	970,272
7 July	606,528	993,600
17 July	357,696	817,344
19 July	264,384	606,528
25 July	207,360	111,456
30 July	380,160	27,648
5 Aug.	103,680	281,664
11 Aug.	295,488	321,408
17 Aug.	108,864	174,528
25 Aug.	27,648	73,440
Totals	2,802,816	4,316,544

In the 1955 report (Goldthwait, 1956, p. 109) it was pointed out that the actual measured discharge of the lake exceeded the amount of water created by measured ablation and precipitation by some 563,500 m³ of water during the summer. In the 1956 season there was an excess of 439,504 m³ of discharge over ablation. Many errors are possible. (1) The single most sensitive figure is the scale used in calculating the area over which each ablation figure is to be applied. Assuming that error from this source might be as much as 2%, the total error would be 68,900 m³, added or subtracted. (2) The calculation of runoff from snowdrifts melting over the land was based on sketches on aerial photographs. If there were a 5% error, this might add or subtract 21,500 m^3 of the ablation. (3) Failure to assign a high enough average density (say 0.5 instead of 0.39) to the snow which melted might add 89,500 m^3 to the ablation. (4) The melt for area X near snowline was interpolated since there were no stakes in this area. If this is off by 5%, the resulting error in the ablation totals would be ±7,700 m^3. (5) A little early rain and melt may have refrozen in the ice below and become superimposed ice. Since no more than 13 or 14 cm of this newly formed material was observed in the latter part of the 1955 season and none in 1956, it may be fair to estimate that no more than 5 cm of such material formed within the snow-covered areas during 1955. This would subtract 53,100 m^3 from the 1955 ablation total. (6) Sublimation and evaporation were taken into account only by the lowering of ice on stakes. If evaporation from the flowing melt water in the streams, the ponded water in Red Rock Lake, and exposed land areas amounted to 3.5 cm this might subtract 19,100 m^3 from the total figured for ablation. (7) The precipitation in the summer was assumed to fall as snow on the glacier, rain on the land. If most of it did not show up in ablation measurement, this might add another 170,678 m^3 to the ablation. (8) Standard rain gages are rough measuring instruments; therefore, since one gage was used to average the whole area this figure might be 25% off. This would introduce an error of ±12,800 m^3. (9) The early season measurements of runoff are subject to particular error since no rating curve was possible. It might be 120,000 m^3 or less. Added together these possible errors could account for 491,000 m^3 more ablation or 303,000 m^3 less. Although many of these possible errors may be compensating, certainly the reason why ablation and runoff totals do not agree is among them.

Compared to normal runoff in temperate regions, this total discharge of 3 or 4 million cubic meters is high. This figures to 725,000 m^3/km^2 as contrasted with 305,000 m^3/km^2 for the Ohio valley, where annual rainfall is twice as heavy as the total annual precipitation at Red Rock Lake. This tends to indicate that the absorption by the ice or snow or ground around Red Rock Lake is very small or nil compared to melting of the glacier, and that almost all of the seasonal precipitation runs directly off. In addition, this means that there is a very significant contribution to the runoff of this area by precipitation in snow areas high up on the North Ice Cap, from where ice flows down as ice and is contributed as melt water to the Red Rock Basin.

These sources which contribute runoff may be appraised. In 1955, the contribution of drifted snow (areas XIII, XIV, XV) plus the early season snow cover in the higher areas (I to XII) amounted to 2,727,200 m^3, which resulted in approximately 1,063,600 m^3 of meltwater. In 1956 the net accumulation was about 1.4 times as great, or 3,804,100 m^3 of snow, which made 1,483,600 m^3 of meltwater. The summer precipitation amounts to only 0.8 and 1.1% of the discharge in 1955 and 1956, respectively. Barring any semipermanent change in the total amount of water trapped in the ground, this leaves about 63% attributable solely to the melting of the inner mass of the North Ice Cap. In actuality, this is old precipitation which fell many years ago outside the Red Rock drainage basin.

Summary of glacier budget

Mean monthly temperatures for June, July, and August ranged from -0.44C to 2.84C, although the later half of June 1956 had a mean of 4.35C when taken alone. Mean daily range was 5.8C. Summer 1956 averaged 1.4C to 2.0C warmer than what is believed to be the more normal summer, 1955. Expressed in glacial-degree hours (sum of degrees above freezing for each hour), the summer 1956 was twice as effective in producing melt water. This was expressed in the average rate of melting of the glacier surface: only 6.8 mm/day in 1955 but 15.7 mm/day in 1956. The white ice of the ice cliff at the very edge of the glacier melted 24 mm/day in 1955 and 30 mm/day

Table IX. Calculated sources for melt water discharged through Red Rock Lake.

Year	Last winter snow		Summer precipitation		Old ice melted	
	m^3	%	m^3	%	m^3	%
1955	1,063,600	38	23,300	1	1,715,900	61
1956	1,483,600	35	51,100	1	2,781,844	64

in 1956. The darker lower ice mostly on a sloping toe averaged 32 mm/day in 1955 and 38 mm/day in 1956. The actual discharge measured in 1956 was 54% greater than that in 1955 (2,802,816 m^3). Each summer had its cold periods near the freezing point when ablation and discharge dropped nearly to zero.

The temperature differential between the base and the top of the cliff (0.92C/100 m) is due largely to the "baking effect" of the cliff. On the glacier surface above, the average temperature gradient was only 0.47C/100 m of elevation. Thus in a 63-day period there were only 77% as many glacial-degree hours at the top of the cliff as there were at the bottom. At snowline they totaled only 62% as much. Convectional heat was shown to be the most important source for melting of the glacier surface. The amount of melting decreased regularly upward at a gradient enough steeper in 1956 so that snowline in both years was between 900 and 920 m above sea level. Old glacier ice contributed 61 to 64% of the volume of melt water produced; some 35 to 38% was produced by snowdrifts which accumulate on the ice and on the land. These show melt rates of 19 to 23 mm/day during the melt seasons.

During both summers the cloud cover averaged 45%. In each season radiation reached the peak early in July at about 550 cal/cm^2-day and dropped regularly to 300 cal/cm^2-day on clear days in late August. Radiational melting was particularly effective on the vertical face of the ice cliff, as illustrated by the fact that melting on the ice cliff was only 20 to 30% greater in 1956 than in 1955. Glacier ice melts first along the grain boundaries when in bright sunlight. The loosened grains are then blown free or fall onto the toe of ice below. This process reduces the calories required to remove a given thickness of ice on the face of the ice cliff. Another loss which accelerates the disposal of ice from the ice cliff is the calving of great sheets of ice 10 to 300 m long from the face of the cliff. Almost all calving occurred in May and June of each year and was preceded by a few hours of loud cracking noises.

Streams falling over the cliff actually deliver kinetic energy to the toe of glacier ice at the base of the cliff and, while this kinetic energy may be only enough to melt 30 m^3 of ice, great plunge pits with volumes totaling nearly 700 m^3 were excavated in 1956. Elsewhere the cascade of ice granules from the cliff above, along with a mass of breccia which fell in ice avalanches, covered the toe ice and effectively reduced melting. Certainly in some years, as in 1955, patches of refrozen superimposed ice are formed here and there on this ice toe. The small streams along this ice toe, headed for Red Rock Lake, fluctuated more every day (300%) than does the outlet of Red Rock Lake (25%) and the peaks and troughs of flow are delayed by only about 1.5 hr behind the maximum and minimum of ablation whereas Red Rock Lake, absorbing many streams, reaches its daily extremes 4 hr after ablation is greatest or least.

The total annual precipitation measured at ablation stakes and rain gage during the summer was 53.8 cm for one year. Only about 1/10 of this amount arrived during the melt season. This summer rain constitutes less than 1% of the discharge from Red Rock Lake; the winter snow constitutes more than 35%. Together with melting of the glacier itself, these produced more than double the amount of runoff per square kilometer that is yielded by rains in moist temperate regions.

III. MOTION

Ice cliff surface

Observation stakes. Forty ash dowel stakes were set horizontally into the cliff early in July 1955. Because unexpectedly rapid ablation loosened them, 30 of these were reset and observed anew in August. Nineteen of the reset stakes remained for a March 1956 observation and 10 remained for observations early in June 1956. A completely new set of 33 stakes was added in June 1956.

All stakes were set out in systematic vertical rows. In 1955, 10 rows were emplaced with the seventh row (row 13) containing the largest number (10) of closely spaced stakes.* In 1956 a series of new target stakes, lettered U, was set vertically at the top within 2 m of the edge of the ice cliff and opposite each of the base stakes from 4 to 15. The other new stakes in 1956 were closely spaced vertically in rows 8, 13, and 17.

Each 1955 motion stake was set 170 to 180 cm deep into the ice by drilling a 2.5 to 3.2 cm diam hole. The high holes (A, B, C) on the cliff face were drilled from cable ladders suspended from a deadman back of the cliff edge. Long rows of stakes (row 13 in 1955; rows 8, 13 and 17 in 1956) were drilled from a bosun's chair suspended on a rope and pulley system from an overhanging "gallows"(Fig. 24). Most lower cliff stakes (H and I) were set from an aluminum ladder placed on an ice platform chopped in the glacier toe. Stakes in the toe (J and K) were emplaced by standing on crampons. Working in these several precarious positions meant that the design and sharpening of the drill was of utmost importance.

Ample stakes were prepared before each field season. Each stake was an ash dowel 182 cm long turned down to 2.54 cm diam in 1955 or 2.35 cm diam in 1956. Hollow aluminum tubes 92 cm long and 2.54 cm diam were affixed to the ash dowels in 1956, so that the stakes could be set more deeply into the cliff. The same stakes were used for ablation measurements, and the upper and lower ones (U, A, J) were used as targets for the photogrammetry.

All triangulation readings were made with a Wild T-2 theodolite supplied from government sources. The standard procedure of the U. S. Coast and Geodetic Survey was employed. Three sets of direct and reverse readings were made on each stake until readings agreed within 10 sec of arc.

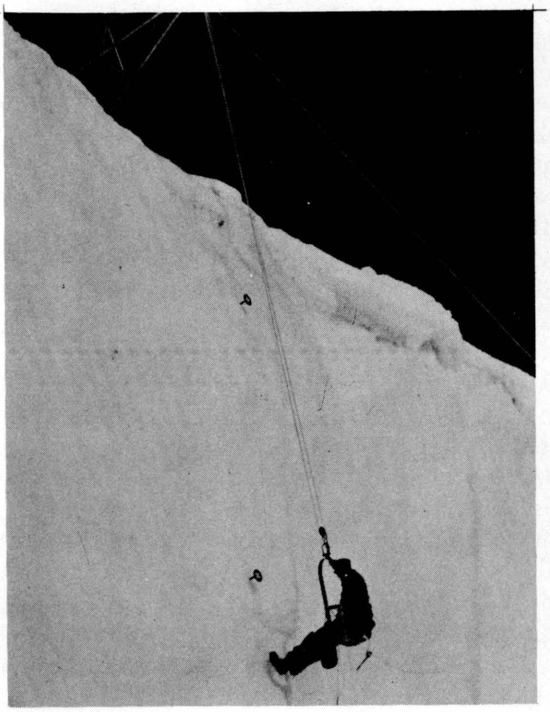

Figure 24. Preparing to drill stake target in ice cliff. Sitting in bosun's chair hung from "gallows" above.

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*Numbers used do not agree with the 1955 Annual Report (Goldthwait et al., 1956). The earlier stake rows were numbered in sequence (1, 2, 3, 4), but were renumbered in 1956 to match the baseline stake point most directly opposite. Stakes in each vertical row are labelled A, B, C, etc., from the highest down (see Fig. 26).

All readings were made by swinging from a base stake at either end of the baseline (1 or 15) to the target points and back to the baseline. Base stakes 1, 9, and 15 seemed to provide the best angular intersections to the target stakes. Two internal horizontal angles were determined for each triangle each time. In order to make a complete check of three-dimensional motion, three vertical angles on both right and left circles, usually agreeing to within 10 sec, were read on all target stakes (A and J) used in photogrammetry in 1955 and on all stakes in 1956.

Since each set of observations required several days, observation periods approximately 2 weeks apart were chosen. To get the maximum detail possible, a special survey was conducted from 13 to 19 July 1956. Fourteen sets of observations were made twice daily at 0800 and 2000 hr by two observers with two theodolites working simultaneously from base stakes 9 and 14. In order to do this within the allotted time, only the 8 targets of row 13 were observed.

Abstracts were made in the field for each set of angles in each period of survey. In the autumn of each year the positions were calculated by standard procedures from 7- or 8-place trigonometric tables. The X axis was established east and west parallel with the baseline, the Y axis north and south normal to the baseline, and the Z axis up and down or vertical. The X and Y coordinates were computed from the two observed angles and the included (baseline) side by using the law of tangents. For each reading, the actual distance moved was determined on a separate form by using the law of square roots. This was checked occasionally by using the law of sines. Most errors in machine calculation were detected by doing two self-checking computations, but any especially large forward motions or erratic backward motions were double-checked from the beginning of the procedure to the final results. Since the periods between observations were of slightly different lengths, most comparisons are made in terms of the rate of motion per day.

Cryokinegraph. Following the lead of several Swiss observers (Mercanton, 1935), a wire recording instrument was designed to make a continuous record of the glacier motion at the ice cliff. A Stevens water-level recorder, type F, with a 2- or 8-day pen movement and a 1:1 ratio of cable movement to record trace was arranged on a fixed platform some 40 m from the ice cliff (Fig. 25). In neither summer could ground be reached; therefore it was necessary to fix the table by pipes 3 m long drilled into ice beneath the stationary snowdrift opposite stake row 13. In 1955 the one instrument used was activated from a stake at the top edge of the ice cliff by a piece of spring steel no. 9 music wire, 0.55 mm diam, 56.8 m long. Results were so important that in 1956 three such instruments were mounted on one table and attached to stakes at the very top edge (354, 97), upper middle (354, 80), and lower parts (355, 70) of the face of the ice cliff by separate pieces of 0.762 mm cold drawn Invar wire (53.9, 44.2, and 40.0 m long). At the instrument end, each wire was held taut over a grooved steel pulley by an 8- or 11-kg (1955) or 5-kg (1956) weight. After experiencing trouble in 1955 in preparing a hole below to receive the weight, hooks were arranged in 1956 which could be moved up on a chain attached to the wire. The regular beaded cable of the water-level recorder was clamped to the wire leading to the glacier approximately 4 m from the recorder and held taut by a 1-kg (1955) or 171-g (1956) weight.

The first wire, attached on 10 July 1955, was secured to an ash wood dowel which bent very rapidly under the constant stress, so it was replaced by an iron pipe. The positions of most stakes or supporting pipes under stress were checked by placing two separate small stakes on either side and stretching a wire between them, so that check measurements might be made from the wire to the pipe. In 1955 the pipe adjusted at a rate of 1 mm/day for the first 3 days and thereafter at less than 0.4 mm/day. No reliable data on this adjustment are available for 1956, but the figures are probably somewhat higher than those for 1955 because of the weak pipe available.

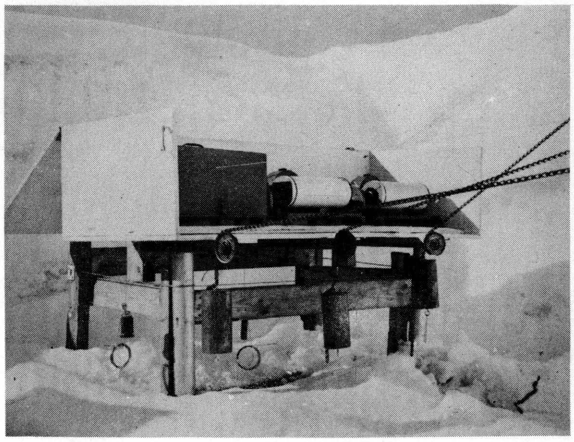

Figure 25. Cryokinegraph, 1956. Adjustable weights attached to chains in front; 3 water-level recorders on top of table (left one covered).

Motion as recorded on the cryokinegraph was reduced in two operations to actual horizontal movement of the iron pipe embedded in the cliff. First, motion at the cryokinegraph was corrected for expansion and contraction of the wire caused by temperature change. The coefficient for this spring steel was 10.5×10^{-6}/C from 0C to 100C; thus, the wire changed in length by 0.596 mm per degree change in its temperature, or 8.1 mm for the maximum diurnal change (13.6C). Temperatures were read from the thermograph at shelter I a few meters away. In 1956 the coefficient for the Invar wire was only 0.63×10^{-6}, giving a change of only 0.045 mm/degree change in temperature for the longest wire. Consequently, no adjustment was necessary. Second, motion in the slant line of the wire was converted to horizontal motion perpendicular to the cliff. In 1955 the wire from cliff top to the cryokinegraph formed a catenary curve at an average angle of 40° from horizontal; in 1956 the 3 wires sloped at 36°, 18°, and 8°. These were adjusted by a right triangle computation.

A long period was required in 1955 to set the table securely, to adjust the wire, and to allow all fixed positions to become balanced. The continuous records, therefore, extend from 1900 hr on 18 July to 2130 hr on 17 August, a total of 30 days. In 1956, great difficulties were encountered in setting the table supports securely into solid ice; therefore, records begin on 9 July on 2200 hr and continue to 0730 hr on 27 August, a period of 48 days.

Annual motion. Only 13 stakes could be observed repeatedly over the larger part of one year (295 to 370 days). With one exception all of these, both high and low on the cliff, had net motion principally southward toward the baseline and slightly eastward toward base stake 15. This totaled from 1.5 and 1.8 m in the lower ice near the top of the toe to 4.1 and 4.2 m in some of the highest ice (A stakes). Projected to 365 days the total motion is 4.8 m at the cliff top, 2.3 m at the base. The exception was 13J (grid position 360, 68), which retreated northward and slightly west and up away from the baseline by 0.3 m in 370 days just as it had previously during the summer 1955. These figures are far too large and well-checked for several periods to be explained as instrumental, observational, or computational errors. Since the periods of observation necessarily differ a great deal, the fairest comparison of motion is that of the average rates of motion (Table X). Over the year all of the top "A" stakes averaged 12.1 mm/day whereas the six lowermost stakes in the upper ice toe (H-J) averaged 6.6 mm/day. Thus, the ice at the top thrust ahead (south-southeastward) about twice as fast as any of the dirty ice near the base.

The middle part of the high ice cliff showed a tendency to bulge out even a little faster than the white ice at the very top of the cliff. Over 219 days (17-18 August to 23 March) the upper (A) or lower (E, F) white ice of row 13 showed motion of 13.1 to 13.7 mm/day, while stakes C and D recorded average daily motions of 15.6 and 14.5 mm/day, while stakes C and D recorded average daily motions of 15.6 and 14.5 mm/day.

Table X. Motion of stakes over almost one year in the direction of actual displacement.

Stake no.	Grid position (m) x	Grid position (m) z	Rate (mm/day) 17-18 August to 23 March 218-219 days	Rate (mm/day) 23 March to 8 June 77 days	Rate (mm/day) 8 June to 19 June 11 days	No. of days	Total motion (m)	Avg rate (mm/day)
1A	2	123	8.9	17.0	7.5	306	3.340	10.9
3A	62	116	9.7	11.1	7.5	306	3.060	10.0
5A	122	108	10.0	11.0	9.1	306	3.124	10.2
7A	181	99	11.2	12.6		295	3.409	11.5
7J*	185	87				364	1.850	5.1
9A	240	96	12.9	14.6	12.5	306	4.088	13.4
9G	232	83	11.6	12.4	9.1	321	3.740	11.7
11A	300	95	15.4			218	3.362	15.4
13A	370	97	13.2			219	2.886	13.2
13C	370	90	15.6			219	3.408	15.6
13D	370	86	14.5			219	3.177	14.5
13E	370	84	13.7			219	3.004	13.7
13F	370	80	13.1			219	2.866	13.1
13G	367	77	12.2			219	2.672	12.2
13H*	366	75	10.5			219	2.329	10.5
13I*	363	72	7.0			219	1.532	7.0
13J*	360	68				370	-0.334#	-0.9#
15A	418	96	13.3	15.1	15.7	307	4.244	13.8
15G	416	75	12.4	13.4		296	3.759	12.7
15H*	418	73	10.7	12.5		296	3.302	11.2
17A	510	106	11.4	13.3	11.1	307	3.642	11.9
19I*	574					358	2.474	6.9
Averages:								
16 white A-G			12.4	13.4	10.4			12.7
6 dirty H-J*			9.4	12.5				6.6
All 22 A-J			12.0	13.3	10.4			11.1

*Stake in dirty lower ice
#Retrograde motion to the north

The summer rates measured in several vertical rows in 1955 and 1956 (Tables XI, XII) show the same effect: (row 1 in 1955; row 13 in 1956). At still other sections of high cliff, there were regular, if small, decreases in rate from the top down (row 13 in 1955; rows 8 and 17 in 1956). The vertical motions of cliff stakes in 1956 confirm this sagging in the middle (Table XIII). All stakes on the high cliff from rows 7 through 13 had net movement downward at rates of 0.3 to 7.4 mm/day. Fastest lowering (2.9 to 7.4 mm/day) was in middle-lower stakes C and D of row 8; D, E, F of row 13; and D of row 17.

It seems likely, then, that this is not a demonstration of extrusion flow (Demorest, 1943). On a vertical boundary of an ice cliff, where there is no support for the ice, there may be a greater sagging or creep down low because the pressure of overlying ice is greater there. In the lower part of the vertical cliff, this is masked by less forward thrust of the main ice mass.

Where the ice is thicker and the cliff is higher (13A, 15A, and 17A) the net motion of the top of the cliff seems to be a little faster than where the ice is not nearly so thick (1A, 3A, 5A), even though the thinner ice rests on a steep easterly slope of Survey Hill. The A stakes on the high cliff (300 to 510) moved 25% faster over the year than stakes on the lower cliff (0 to 300). Actually the thinner sloping ice also was moving upward (stakes 4U, 5U, 6U) at 0.8 to 1.1 mm/day in the summer 1956, when all other cliff stakes moved downward. This follows the well-known principle - the thicker the ice, the faster the motion.

Table XI. Motion of stakes during summer 1955 in the direction of actual displacement.

Stake no.	Grid position (m) x	Grid position (m) z	Rate (mm/day) July 1st half 12-13 days	Rate (mm/day) July 2nd half 12-$15\frac{1}{2}$ days	Rate (mm/day) August 1st half $14\frac{1}{2}$-16 days	No. of days	Total motion (cm)	Avg rate (mm/day)
1A	2	123	12.0	9.0		$28\frac{1}{2}$	29.6	10.5
1G			10.6	12.6		$28\frac{1}{2}$	39.6	11.6
1J*	1	114	7.0	6.7		$28\frac{1}{2}$	19.4	6.8
3A	62	116	10.9	9.0		$28\frac{1}{2}$	28.0	9.9
3G			9.5	8.1		$28\frac{1}{2}$	24.9	8.8
3J*	57	104	4.3	3.6		$28\frac{1}{2}$	11.3	3.9
5A	122	108	10.6	9.2		$28\frac{1}{2}$	28.1	9.9
5G			10.3	9.1		$28\frac{1}{2}$	27.6	9.7
5H*			10.2	8.8		$28\frac{1}{2}$	27.0	9.5
5J*	116	96	4.5	4.0		$28\frac{1}{2}$	12.1	4.2
7A	181	99	12.3		11.2	28	32.8	11.7
7H*			341.7	10.0		28	442.7	15.8
7J*	185	87	7.7	2.3	4.8	43	20.6	4.9
9A	240	96	14.1	17.6		27	43.4	15.8
9G	232	83	14.8	-81.1#		27	-103.9#	-3.8#
9H*			12.8	12.0		27	33.3	12.4
9K*	233	84	12.1	10.5		27	30.2	11.3
11A	300	95	14.8	13.0		27	37.3	13.9
11H*			13.3	11.5		27	33.2	12.4
11I*			12.2	9.5		27	28.9	10.8
11J*	297	73	5.6	4.2		$26\frac{1}{2}$	12.8	4.9
13A	370	97	14.2	13.5		25	34.5	13.8
13B	370	94	13.2	12.8		25	32.4	13.0
13C	370	90	14.1	12.8		25	33.2	13.4
13D	370	86	13.0	12.7		25	32.1	12.8
13E	370	84	12.6	13.0		25	32.1	12.8
13F	370	80	13.6	12.0		25	31.6	12.8
13G	367	77	12.9	12.4		25	31.5	12.6
13H*	366	75	13.4	11.8		$26\frac{1}{2}$	33.0	12.6
13I*	363	72	10.2	9.4		$25\frac{1}{2}$	24.9	9.8
13J*	360	68	5.2	-11.0#		$26\frac{1}{2}$	-10.5#	-4.0#
15A	418	96	14.5	12.7		$23\frac{1}{2}$	31.7	13.6
15G	416	75	14.3	10.2		$23\frac{1}{2}$	27.9	11.2
15H*	418	73	13.3	11.3	13.4	$38\frac{1}{2}$	48.6	12.7
15J*	419	67	5.5	7.6		$21\frac{1}{2}$	14.4	6.5
17A	510	106	16.1	13.4		$23\frac{1}{2}$	34.1	14.7
17G			16.2	9.5		$23\frac{1}{2}$	28.7	12.8
17H*			13.4	9.0		$23\frac{1}{2}$	25.3	11.2
19A			19.3		8.3	$25\frac{1}{2}$	31.6	13.8
19I*	574		-18.7#		6.0	$25\frac{1}{2}$	-8.1#	-3.2#
Averages:								
22 white A-G			14.2	12.4	9.8			11.6
18 dirty H-J			26.3	7.1	8.1			7.6
all 40 H-J			11.8	10.3	8.7			9.9

*Stakes in dirty ice
#Retrograde motion to the north

Table XII. Motion of stakes during the summer 1956 in the direction of actual displacement.

Stake no.	Grid position (m) x	Grid position (m) z	Rate (mm/day) Early to mid-July 14-21 days	Rate (mm/day) Late July to early August 10-25 days	Rate (mm/day) Mid-August 11-15 days	No. of days	Total motion (cm)	Avg rate (mm/day)
4U	89	115		13.9	2.0	29	27.2	9.4
5U	119	112		12.1	3.4	29	25.4	8.8
6U	152	108		13.1	4.7	29	28.7	9.9
7U	178	104		12.4	7.7	29	28.8	9.9
8U	209	101		9.9	15.1	29	36.5	12.6
8A	212	98	13.2	11.9		35	44.4	12.7
8B	212	95	12.6	11.1		35	42.0	12.0
8C	212	92	12.5	11.5		35	42.4	12.1
8D	211	89	12.0	11.5		35	41.2	11.8
8H*	210	87	10.0	9.4	10.9	50	50.4	10.1
9U	237	100		-25.9#	13.2	34	-45.1#	-13.3#
10U	264	99		4.3	13.9	34	25.3	7.4
11U	297	99		16.6	8.8	30	41.2	13.7
12U	326	99		8.3	13.5	34	33.9	10.0
13U	358	100		13.6	13.2	36	48.4	13.4
13A	357	96	13.1	7.7		24	25.0	10.4
13B	357	93	12.6	13.2	13.1	39	49.6	12.7
13C	357	90		13.2		10	13.2	13.2
13D	357	85	12.4	15.3	10.9	50	64.8	13.0
13E	357	82	17.6	13.3	12.8	50	71.8	14.4
13F	357	78	11.9	11.9	13.3	39	48.6	12.5
13H*	358	75	11.6	10.9	11.5	39	44.0	11.3
13I*	358	73	8.7	8.2	8.9	39	33.8	8.4
13J*	370	69		7.7	5.6	25	16.1	6.4
14U	384	100		15.2	17.0	25	40.7	16.3
15U	417	100		11.9	13.5	34	42.2	12.4
16U	447	103		12.7	12.3	34	42.6	12.5
17A	505	105	14.1			15	21.2	14.1
17B	505	101	13.8	11.0		35	42.6	12.2
17C	505	98	13.9	11.1	12.8	50	62.2	12.4
17D	505	94	13.3			15	20.0	13.3
17E	504	91	12.1	10.7	12.5	50	58.1	11.6
17H*	502	85	12.8	10.7	13.0	40	49.4	12.4
Averages:								
28 white	U-F		13.2	11.8	12.6			11.1
5 dirty	H-J		10.8	9.4	10.0			9.7
all 33	U-J		12.7	10.3	11.0			10.9

*Stakes in dirty ice
#Retrograde motion to the north

Seasonal variation. If temperature were the controlling factor, one would expect faster rates of motion in summer 1956. Instead, we find that the average for all stakes in the white ice was 11.6 mm/day in 1955, and 11.1 mm/day in 1956 (Tables XI, XII). The A stakes at the top averaged 13.3 mm/day for 1955; 12.4 mm/day for 1956. However, the average for all stakes in dirty ice in the lower parts of the ice cliff was 7.6 mm/day for 1955 and 9.7 mm/day for 1956. This reversal may be no more than an accident of stake selection.

Differences between parts of the year are more strongly marked than the differences between the two seasons. During each summer, motion was distinctly faster during the early part of July than during the latter part of July. For example, all of the stakes averaged 11.8 mm/day during the first half of July 1955, but slowed down to an average of 10.3 mm/day during late July. In 1956 all stakes averaged 12.7 mm/day

Table XIII. Downward motion of stakes during the summer 1956.

Stake no.	Grid position (m) x	Grid position (m) z	Rate (mm/day) Early to mid-July 15-21 days	Rate (mm/day) Late July to early August 10-20 days	Rate (mm/day) Mid-August 11-16 days	No. of days	Total motion (cm)	Avg rate (mm/day)
4U	89	115			0.9#	11	1.0#	0.9#
5U	119	112			1.1#	11	1.2#	1.1#
6U	152	108			0.8#	11	0.9#	0.8#
7U	178	104		0.6	0.0	29	0.8	0.3
8U	209	101	1.8	0.0	0.6	50	4.6	0.9
8A	212	98	5.0			21	10.5	5.0
8B	212	95	1.9	5.6		35	11.7	3.3
8C	212	92	4.6	11.7		35	26.0	7.4
8D	211	89	5.0	8.4		35	22.3	6.4
8H*	210	87	1.3	5.9	9.4	50	25.1	5.0
9U	237	100			1.6	11	1.8	1.6
10U	264	99			1.5	11	1.6	1.5
11U	297	99			1.3	11	1.4	1.3
12U	326	99			1.9	11	2.1	1.9
13U	358	100			1.5	11	1.6	1.5
13A	357	96		1.8		10	1.8	1.8
13B	357	93	1.3	1.4	2.6	40	7.3	1.8
13D	358	85	2.2	3.6	5.9	50	19.3	3.9
13E	357	82	2.7	2.3	4.3	50	15.1	3.0
13F	357	78	4.3	1.8	2.3	40	11.7	2.9
13H*	358	75		1.6	2.9	25	5.9	2.4
13I*	358	73	1.0	0.4	2.5	40	5.6	1.4
13J*	370	69		1.0*	0.9*	25	2.3*	0.9*
14U	384	100	0.9	0.8	2.4	43	6.1	1.4
15U	416	100			2.2	11	2.4	2.2
16U	447	103			1.4	11	1.5	1.4
17A	505	105	6.1			15	9.2	6.1
17B	505	101	5.7	3.0		35	14.4	4.1
17C	505	98	4.2	2.8	3.7	50	17.4	3.5
17D	505	94	5.2			15	7.8	5.2
17E	504	91	2.0	3.9	5.3	50	18.6	3.7
17H*	502	85	5.5	0.8	2.7	40	13.0	3.3
Averages: 27 white A-F			3.5	3.4	1.8			2.6
5 dirty* H-J			2.6	1.5	3.3			2.2
all 32 A-J			3.4	2.9	2.2			2.5

*Stake in dirty ice
#Upward motion (others down)

in mid-July, but slowed down to 10.3 mm/day in late July and August. As nearly as can be judged, the minimum rate of motion during the summers came at just about the end of July.

The middle of August brought an increase in glacier motion. Only two stakes were observed continuously in 1955 but they show a speeding up by more than 20%. In 1956 average motion of 24 stakes increased from 10.3 mm/day in late July to 11.0 mm/day in August, and stakes in the white ice increased from 11.8 to 12.6 mm/day.

In the autumn-winter period (Table X) motion was a little faster (12.0 mm/day) than average August motion for all stakes, although still not as fast as that for early July.

The fastest motions of the year occurred sometime during the spring period of late March to mid-July. Between 23 March 1956 and 8 June 1956 average motion was 13.3 mm/day for all 10 stakes*, and 13.4 mm/day for those in the upper white ice alone.

* Nine stakes were lost by calving from the ice cliff during late May and June.

It is not clear why the mean monthly velocity of forward thrust of the upper part of the glacier varies by nearly 30% from season to season. This may be an irregular and aperiodic function associated with the volume and thickness of ice arriving at the ice cliff edge, but the fact that the same pattern of change was repeated during each of the two summers of observation suggests that it may have a more fundamental seasonal cause. As shown later, there is some correlation during the diurnal period with rising and lowering sun; if this were effective on a longer basis, one would expect the lowest rates of motion during the winter night, November to February. Possibly there was a slowing down which has been thoroughly masked by faster motion in the autumn and in March, but, if so, one would not expect a drastic and clear-cut slowing down in late July when the sun is still high. Certainly the variation is not a reaction to the amount of external energy applied to the glacier because that varies tremendously between the summer and the winter. Air pressure, wind, and humidity seem to show no causal relationship.

An analysis of just the top A stakes, giving the two horizontal dimensions of motion in comparable average daily rates (Table XIV) shows that the far western stakes (1A, 3A) have a relatively slow southward component of motion (10.0 mm/day) but a surprisingly strong eastward component of motion down the hill slope (5.6 mm/day). In the high central and eastern part of the ice cliff (13A, 15) the southward motion is on the order of 36% greater (13.6 mm/day) but the eastward component is less (4.4 mm/day). It is very clear that the main high ice cliff represents the area of convergence between ice flowing southeastward obliquely across the north slope of Survey Hill and that flowing almost southward down the broad buried bedrock valley toward Red Rock Lake.

This convergence does not result in upward motion, for all the stakes from row 7 east through 19 were moving down (Table XIII). On the other hand, stakes on the hill slope to the west (4U to 7U) and where North Ice Cap meets the Greenland Glacier to the east (stake R, Table XIX) were moving up, suggesting that the ice was piling up on either side, forcing converging ice flow down the central valley to Red Rock Lake.

Table XIV. Motion of upper (A) stakes parallel (X-axis E-W) and perpendicular (Y-axis N-S) to baseline.

Stake no.	Position (m)	Rates of daily motion (mm/day) along vectors: 3-4 July 1955 to 25-27 Aug 1955 Y(⊥)	X(∥)	18-19 Aug 1955 to 21-24 March 1956 Y(⊥)	X(∥)	21-24 March 1956 to 7-8 June 1956 Y(⊥)	X(∥)
1A	2	8.3S	6.1E	9.4S	6.2E	15.6S	6.7E
3A	62	8.1S	4.7E	8.4S	4.9E	9.9S	5.0E
5A	122	12.5S	2.3E	9.4S	3.4E	10.3S	3.7E
7A	181	8.2S	2.8E	10.8S	2.9E	12.2S	3.1E
9A	240	8.7S	3.7E	12.5S	3.4E	14.1S	4.0E
11A	300	10.0S	3.8E	15.2S	2.7E		
13A	370	15.1S	4.9E	12.9S	2.7E		
15A	418	12.1S	3.5E	13.0S	3.0E	15.1S	7.8E

<u>Diurnal variation</u>. It is abundantly clear that individual stakes adjacent to one another move quite differently. One stake (7H) moved 427.12cm in 12.5 days during the first part of July 1955 and yet showed normal motion (10 mm/day) for the remaining 15.5 days in July. Three stakes out of 42 (9G, 13J, and 19I, Table XI) actually moved backwards, that is, northward, at rates varying from 11 to 81 mm/day during different parts of July 1955. Since these motions total 16.5 to 121.5 cm, they are well beyond

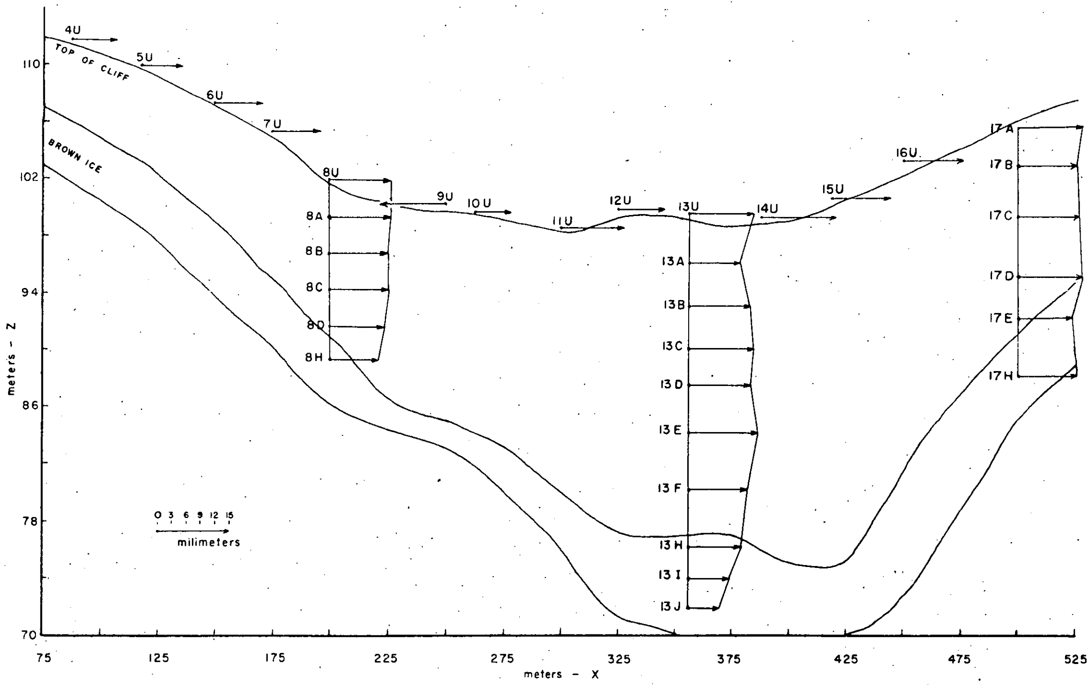

Figure 26. Average daily motion of stakes at cliff face, summer 1956.

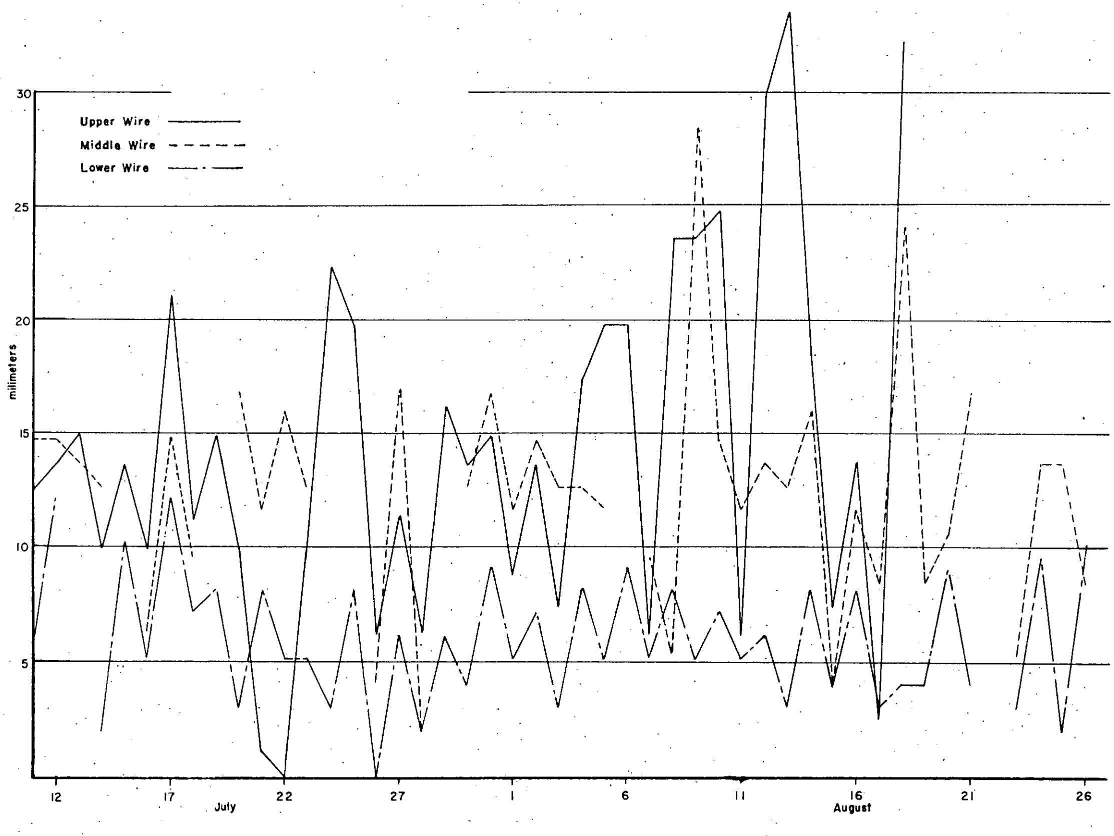

Figure 27. Daily motion recorded by cryokinegraph, 1956.

the probable limits of error in measurement and all figures were carefully double-checked from beginning to end. One stake (13J) continued to move northward during the intervening winter, but a new stake at the same place moved slowly southward in summer 1956 (6.4 mm/day). These very erratic motions were concentrated in the lower part of the vertical cliff and the upper part of the ice toe (stakes G-J), but in 1956 one stake at the top of the cliff (9U) showed rapid retrograde motion (25.9 mm/day) between 19 July and 11 August. Evidently the ice has attenuated turbulent motion concentrating where the shear couple is greatest.

Examination of the continuous record of motion (cryokinegraph) for one point at the cliff top (13U) for 30 days during the summer 1955 indicates a great range of daily motion from 6.8 to 18.0 mm/day. Similar variation is noted in the 3 curves for three different levels in the same stake row (U, E, and I-J) for 1956 (Fig. 27). The average daily motion at the cliff top was 12.1 mm/day for 1955 and 14.3 mm/day for 1956, which corresponds reasonably to measured motion on nearby stakes for similar periods (13A at 13.5 mm/day, 13U at 13.4 mm/day in 1956).

The individual records for 1955 show distinct repeated diurnal changes, principally a faster and jerkier motion during the early morning hours (0400 to 1000) when temperature is increasing suddenly. Little or no motion occurred in the evening hours (1700 to 0200), when temperatures were decreasing. In summer 1956 the periods of fast motion are somewhat different. Fastest motion at the top of the cliff occurred between 1030 and 1330 hr; slowest motion was between 0130 and 0430 hr. During long periods of steady weather conditions, as for example 13 to 19 July 1956 when temperatures rarely reached above 0C and a strong steady wind was blowing, the ice cliff advanced at an even pace of 13.4 mm/day. It is quite clear that, over very short periods of time, the motion of the glacier is very jerky (0.5 to 1.0 mm/hr) and that even in units as long as one day there is a 100% variation in the amount of motion.

The three instruments operating simultaneously during July-August 1956 show that day-to-day variations in rate of motion at one level in the glacier are not reflected more than 8 m above or below that point. In other words, these speedings up and slowings down are independent differential motions in adjacent parts of the glacier. Yet in long intervals of time, such as a year, they average out into a smooth curve. That this is fundamentally a shearing motion of upper ice over lower ice is quite apparent from the fact that the curve for 13U lies above that for 13E and both in turn above 13 I-J (Fig. 27).

A great deal of doubt was expressed after 1955 concerning the possible effects of temperature on the cryokinegraph recording wires or possible instrumental effects in the smoothness of recording. Therefore, a motion survey with two theodolites and two observers was made at 12-m intervals from 13 to 19 July 1956. In the vertical row 13, 12-hr motions varying from 11 mm northward (retrograde) to 17 mm southward were recorded (Table XV). While these did not follow in a perfectly regular pattern, there was a concentration of reverse motion in the lower stakes (13 E to I) between 2000 hr on 13 July and 0800 hr on 14 July. Slow or retrograde motion was recorded on all stakes between 0800 and 2000 hr on 18 July. The reversals in stakes on the lower cliff on 13-14 July were compensated for by fast motion averaging 14 mm/12-hr between 0800 and 2000 on 14 July. Some individual periods, such as 0800 to 2000 hr on 16 July, showed rapid motion at nearly all levels. Large segments of cliff face tend to speed up or slow down together.

The average motion for night and day over the 6.5 days showed a distinct diurnal change in rate and direction. At every level except the very bottom (I) and top (U), the motion was 25% or more greater during the day (from 0800 to 2000 hr) than during the night (between 2000 and 0800 hr). Furthermore it is clear that at every level, including the top stake (13U), the motion was strongly to the east of south during the day but definitely west of south (to a lesser degree) during the night. On all of the cryo-

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Table XV. Motion of stakes in row 13 over 12-hr intervals (mm) in the direction of actual displacement, 13-19 July 1956.

	U	A	B	D	E	F	H*	I*
13-14 July								
Day	6	8	7	7	9	12	9	10
Night	11	7	3	2	-6	-10	-11	-9
14-15 July								
Day	-4	3	6	8	13	17	16	13
Night	9	7	7	5	7	5	6	5
15-16 July								
Day	7	7	6	9	7	8	6	7
Night	3	-1	3	3	2	3	3	3
16-17 July								
Day	8	12	10	7	12	14	14	4
Night	11	10	7	10	9	2	2	3
17-18 July								
Day	3		9	9	10	12	8	7
Night	7		6	3	2	5	7	6
18-19 July								
Day	-1		2	3	4	0	-2	-2
Night	6		5	7	5	6	4	16
19 July								
Day	12		11	9	9	10	8	-7
Totals								
7 days	31 SSE	30 SSE	51 SSE	52 SSE	64 SSE	73 SSE	59 SSE	32 SSE
6 nights	47 SSW	23 SSW	31 SSW	30 SSW	19 SSW	11 SSW	11 SSW	24 SSW
Avg daily motion	12.0	13.3	12.6	12.6	12.8	12.9	10.8	8.6

* Indicates stakes in dirty ice.

kinegraph records for 1956 the average daytime motion (0800 to 2000 hr) was 8.6, 6.4, and 2.9 mm at the top, middle, and bottom respectively; for the night corresponding values were only 5.8 mm, 6.2 and 3.0.

The relationships shown by short-term theodolite triangulation of the stakes seem to confirm completely the diurnal fluctuations in motion represented on the cryokinegraph day after day. It is clear that the causal relationship involves some factor which changes on a 24-hr cycle rather than a tidal force operation on a 12-hr cycle. Whatever this factor is, it seems to affect the whole mass of ice at the edge of the glacier. The movement of the glacier responding to this pulsating force is very jerky. Furthermore, large masses of ice, especially near the lower part of the cliff where shearing and differential motion are greatest, seem to move both forward and backward in a very erratic fashion as though undergoing an attenuated overturning in elongate elliptical paths. This is confirmed by the structures.

Glacier surface

Measurements. Four ablation stakes in the row 20 to 40 m from the ice cliff (stakes

11 to 14) were used for triangulation measurements since these are the only ones visible from several points on the baseline. Four additional wooden and metal poles were established in 1956: stakes X, Y, Z were placed as far up on the ice surface as possible, 100 to 125 m north of the ice cliff, and stake R was placed on the cliff edge near ablation stake 16 (see Fig. 55). Only those set in as ablation stakes in 1955 had to be replaced, with consequent loss of record.

Triangulation was done by standard procedure. Three readings (within 10 sec of arc) to the top of each stake were averaged, and the position of the stake at each time of reading was calculated on the coordinate system used for the ice cliff. The motion taking place during intervals was calculated from a right triangle representing net motion during the period, regardless of direction.

Five special stakes (level stakes 1-5) were set in on 2 and 3 August 1955 to measure precise levels further back from the ice cliff and over a longer period of time (Fig. 55). Three-meter long "2 by 4's" were set in holes at least 2.5 m deep, drilled with the 12.7-cm coring auger and repacked with cold ice. The top of each stake was covered with a copper plate and marked for the exact position of the station. No stake had to be replaced in the course of two summers, although the lowest stake (1) projected about 1.8 m above the ice at the end of the season 1956.

The level stakes were placed in one row going north from, and nearly normal to, the face of the ice cliff (Fig. 55). The uppermost stake (5) was near the upper weather shelter (III) on the east side of the ice drainage basin and 257.3 m above base stake 15 (at about 889 m altitude).

The lowest stake was referenced both horizontally and vertically to the solid ground south of the ice cliff by triangulation from the baseline. Its position for 5 August 1955 and 7 August 1956 was established by three coordinates, as were the motion stakes. The lower level stake (1) was triangulated periodically through the summer 1956, when the motion stakes were observed. Precise relative elevations of the four higher stakes were determined by standard leveling procedure with a Wild N-2 level. Since double-run leveling was performed each year, the divergence of elevation differences for the total length between the forward and backward running was 8.7 mm for the 1955 leveling and 8.6 mm for the 1956 leveling. The probable limit of error was 0.5 cm for 1955 and 11 cm for 1956.

Annual motion. Five stakes within 40 m of the edge of the ice cliff were observed for horizontal position over the interval between summers. The average rate of motion (12.5 mm/day) was close to that of the upper part of the ice cliff (12.7 mm/day). The results (Table XVI) confirm the fact that the ice behind the east end of the ice cliff is moving faster than that behind the west end; ablation stake 11 moved 12.1 mm/day, while ablation stake 14 moved at 14.1 mm/day. The motion at stake 11 was strongly southeastward down the hillside, while that of stake 14 was southward, and somewhat westward, between 8 and 19 June 1956. This illustrates the convergence of ice into the high part of the ice cliff.

The precise motion in 3 dimensions is known for level stake 1 (grid position 377, 104), lying 15 m north and east of cliff stake row 13, and for the east base stake 18 m north of 15U. In 368 days, level stake 1 moved 4.97 m southward, normal to the baseline, 0.92 m eastward parallel to the baseline, and 0.26 m downward. The east base stake moved 3.74 m southward, 0.98 m eastward and 1.32 m upward. The rate of thrust southward is similar to that for other high points on and above the ice cliff. Downward motion only occurred here and there just back from the ice cliff and is 5% of the forward thrust. It is suggested that this settling represents the same strain of the ice mass which produced a bulging in the lower middle cliff. The eastward component (2.5 mm/day) is the deflection due to topography underlying the ice.

Table XVI. Motion over the year 1955-56 for stakes in the glacier surface 15 to 40 m back from the ice cliff.

Stake	Rate (mm/day) 1955-1956 3-5 Aug to June-July 310-333 days	1956 8 June to 19 June 11 days	1956 3 July to 19 July 16 days	Total Days	Total Motion (m)	Total Rate (mm/day)
11 Abltn.	11.6	26.4		321	3.88	12.1
13 Abltn.	13.1	13.8	10.6	337	4.38	13.0
1 Level	13.8		12.6	368	5.05	13.7
14 Abltn.	12.8	42.5		321	4.53	14.1
East base stake (upper baseline)				364	3.47	9.5
Average	12.5	27.6	11.6			12.5

Level stake 2 (between ablation stakes 24 and 25) moved upward at almost as rapid a rate as stake 1 moved downward (Table XVII). Stake 2 was situated on the forward edge or riser of a step with the steepest slope lying between it and the ice cliff. Since the ground beneath the glacier was shown to be almost perfectly level (Fig. 53) the implication is that this higher ice was actually pushing up and out over the lower ice, thereby steepening the forward slope of the bulge. Northward across the step from level stake 2 the upward motion decreases until it is zero at level stake 4, and a downward motion of 24 cm/year at level stake 5. Level stake 5 (between ablation stakes 72 and 81) is just above the broad gently sloping tread, so this motion suggests that these shelves actually sink on the back side while they rise on the front. Could this step-like bulging form be moving toward the ice cliff faster, like waves, than the ice moves?

Table XVII. Vertical movement of 5 level stakes north of the ice cliff between 5-6 August 1955 and 30 July 1956.

Level stake	Distance from cliff (m)	Elev above base stake 15 in 1955 (m)	Change in one year (cm)
1	15	104.14	26 down
2	295	154.42	25 up
3	600	183.81	19 up
4	1110	227.17	00
5	1470	257.29	24 down

Seasonal motion. The 1955 summer measurements cover only 27.5 days for three stakes just back from rows 4, 11, and 15 on the cliff face (Table **XVIII**). Ablation stake 14 moved erratically at 23.8 mm/day in 1955, as did some of the stakes on the cliff face, and it repeated this in 1956 (25.7 mm/day during the summer).

Table XVIII. Motion during part of the summer 1955 for stakes in the glacier surface 15 to 40 m back from the ice cliff.

Ablation stake	Motion for 27.5 days Total (cm)	7 July to 3 August 1955 Average (mm/day)
11	27.8	10.1
13	31.0	11.2
14	65.5	23.8
Average of 3	41.5	15.0

From early June to late July 1956 the average motion accelerated from 12.3 to 14.1 mm/day. After that it did not slow down by any appreciable amount as had been the case on the ice cliff during both summers. Again the fastest motion throughout the summer was at the easternmost stakes (14 and R).

A comparison of the six surface stakes within 50 m of the cliff face to the three more than 100 m back from the cliff face (stakes X, Y, Z) shows no consistent difference (Table XIX). Both groups showed similar rates of motion. Excepting the erratic motion of stake 14 in June, the stakes near the cliff moved slightly more rapidly in late July and in mid-August, and the stakes farther back moved more rapidly. A component of motion to the west of south was noted in some stakes near the edge of the ice cliff; in general these are at either end of the cliff studied. Also the end stakes (east and west) move most rapidly upward, although most stakes back from the ice cliff have net upward motion. Nine stakes are hardly enough to make one sure that these changes in the direction of motion occur solely in the area near the face of the ice cliff but they do agree roughly with cliff motion measurements to indicate (1) that at either side of the ice basin the ice is forced upward, and (2) that motions converge on the central area of high cliff.

Base of glacier

Tunneling. The lowermost 10 m of the cliff studied is a sloping toe of glacier ice dipping south at about 45°. This was well-covered with drifted winter snow until late in July, and even then some parts of the toe had a superimposed ice layer of snow or avalanche ice which had refrozen on the cold ice beneath. To study true basal motions, it was necessary to tunnel into this toe ice. To get information well back from the cliff boundary effects, a tunnel approximately 30 m long located under the glacier at approximately 5 m above the ground surface was excavated between 7 and 28 July 1955 (Fig. 54). The original tunnel was 0.9 to 1.2 m wide, and 1.7 to 1.8 m high. Between 29 July and 4 August 1955 a vertical shaft 5 m deep was dug near the inner end of the tunnel to the floor of boulders beneath the glacier. The shaft opening measured approximately 1.5 x 1.0 m. At 9 m in from the original entrance a short horizontal opening called "The Blue Room" was made parallel with the cliff face (Fig. 54).

Table XIX. Motion of stakes in the glacier surface 0 to 125 m north of the ice cliff during the summer 1956.

a. Horizontal motion.

Stake	Rates (mm/day) Mid-June 11 days	Mid-July 16-21 days	Late July to early August 14-19 days	Mid-Aug. 13-15 days	Total days	Total motion (m)	Average rate (mm/day)
11 Abltn.	26.4	11.8		4.9#	45	0.60	13.4
X* Motion			10.1	19.7	34	0.49	14.3
12 Abltn.		7.1		13.8	29	0.29	10.1
Y* Motion			13.4	13.0	29	0.38	13.2
13 Abltn.	13.8	10.6		12.8	40	0.49	12.2
1 Level		12.6	13.8	14.7	50	0.69	13.7
Z* Motion			10.6	11.5	29	0.32	11.1
14 Abltn.	42.5	19.6#		21.4	46	1.18	25.7
R Motion			22.8#	12.8	25	0.44	17.6
Averages:							
6 near cliff	27.6	12.3	18.3	13.4			15.5
*3 to north			11.4	14.7			12.9
all 9	27.6	12.3	14.1	13.8			14.6

* Stakes 100 m or more north of ice cliff
# Motion slightly west of south (others east of south)

b. Vertical motion.

Stake	Rates (mm/day) Mid-July 18-21 days	Late July to early August 14-17 days	Mid-August 13-15 days	Total days	Total motion (m)	Average rate (mm/day)
11 Abltn.	0.2#		2.9#	34	.043#	1.3#
X* Motion		1.8	1.5	32	.054	1.7
12 Abltn.	1.9#		0.7	31	.026	0.8#
Y* Motion		0.1	0.9#	29	.013#	0.4#
13 Abltn.	0.6#		0.4	45	.019	0.4
1 Level	0.2	1.4	0.8	50	.039	0.8
Z* Motion		0.8#	1.6#	29	.035#	1.2#
14 Abltn.	0.9		2.6#	35	.019#	0.5#
R Motion			3.1#	13	.040#	3.1#
Averages:						
6 near cliff	0.3#	1.4	1.1#			0.8#
3 to north		0.4	0.3#			0.0
all 9	0.3#	0.6	0.9#			0.5#

* Stakes 100 m or more north of ice cliff
# Motion upward (others downward)

The heavy ablation during and after the excavation of the tunnel in 1955 shortened it by approximately 2.8 m. On 29 August a door was built just inside this position. The winter party found the ice toe covered smoothly by approximately 1.6 m of wind-drifted snow, and the returning party on 5 June 1956 found the area buried by approximately 3 m of mixed snow-ice breccia from dry calving of the cliff above. A week's work was required to reopen the entrance. During July and early August, however, all of the fallen covering material melted away and the original toe-ice surface melted back another 6 m. Total shortening of the tunnel in two ablation seasons exceeded 8 m.

A new sloping shaft to the bottom was dug between 29 June and 30 July 1956. This headed east from the 1955 tunnel opposite the Blue Room (originally 9 m depth) and then turned northward parallel to the old tunnel, but descended in a series of steps along a steep dirty shear plane until it reached the floor under the original 12 m position. An area 15 x 2 m was enlarged along the rocky floor.*

Peg positions. As soon as the first tunnel was completed in 1955, pegs were put into the walls, ceiling, and floor. The precise distance between pegs was measured at weekly intervals during August 1955, once on 24 March 1956, and at 10-day intervals from the middle of June through August 1956. Each peg was a 2.5-cm diam wooden dowel soaked in water and driven into a 2.5-cm drilled hole approximately 30 cm deep until it froze tight. Shallow 6-mm holes were drilled into the ends of the wooden pegs to receive the space measuring instrument. Distances between pegs were measured by a Starrett dial gage connected to extension rods of varying lengths (100, 60, 20, 10, 6, 2 cm). This dial gage recorded to 0.001 in. but proved accurate only to 0.1 mm. Steel extension rods were drilled and threaded to screw into each other for any combination of total length of up to 222 cm.

To measure net movement of the four walls of the 1955 shaft with respect to the ground beneath, a notched steel pole was firmly driven into the frozen ground near the middle of the base of the vertical pit. Wooden pegs placed in the ice of each of the four walls 10 cm and 35 cm above the rocky floor (Fig. 54) were measured every day from 10 August 1955 until 23 August 1956.

In 1956, 16 special pegs were placed 20 cm apart in two parallel vertical rows, also about 20 cm apart, extending from 20 to 160 cm above the floor on the west wall of the vertical shaft (Fig. 28, peg pairs 1-8). The pegs (2.5 cm diam, 30 cm long) were set almost flush with the ice surface and sealed in by freezing water. In the end of each wooden dowel, a 2.5 x 0.63 cm cylinder of drill rod was forced tightly into a 0.63 cm hole and a 1.6 mm hole was drilled in this metal to receive the strain gage. These were set plumb and spaced evenly at the start of the season, 19 June 1956. A 15 x 2.5 cm steel peg (peg O) was drilled in between boulders in the rocky floor for absolute reference of the grid. Measurements between these pegs were made with a Berry-type mechanical strain-gage, a fixed 20.3 cm (8") gage, and a 50.8 cm (20") gage with adjustable arm. The lever ratio on both was 5:1. Regular readings were begun on 13 and 14 July. Measurements were repeated over each interval until 3 measurements agreed to within 0.01 mm.*

Micromotion wires. A system of weighted wires attached to stakes firmly anchored in the ice and running over "frictionless" pulleys so that changes in relative position might be measured was set up both in 1955 and 1956 (Fig. 29). The original instrumentation consisted of two spring steel music wires (no. 9) attached to different

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* 1957 deformation measurements are reported in USA SIPRE Special Report 28.

levels of ice in the north wall of the Blue Room and run over scales to ball-bearing pulleys on a T-bar. Three others were attached 133 m west of the tunnel (stake row 5, grid location 233, 83) at the base of the vertical cliff. The T-bar was drilled 2 m into the ice beneath. The iron pipes set 1.6 to 2.0 m deep in the exposed lower cliff melted loose after 18 days of recording and the cascade of ice grains from the melting cliff face above made reading somewhat awkward. Therefore, all six micromotion wires were set up inside the Blue Room over one T-bar in June 1956. Two- to three-kilogram weights kept the wires taut.

Measurement was made against 0.5 mm steel rules welded at one end of each covering tube. The reference marks were nicked with a razor into a white-painted section of the wire. Positions were read every 3 to 9 days in July 1955 with a filar microscope on a special base. This proved hard to use when tipped back for steeply inclined wires. In 1956 marks were read every 15 days with a hand lens. Some small error (constant?) was introduced by depressing the wire 3 to 4 mm with a finger to the rule, to avoid parallax and get focus, but readings could be repeated to ±0.5 mm.

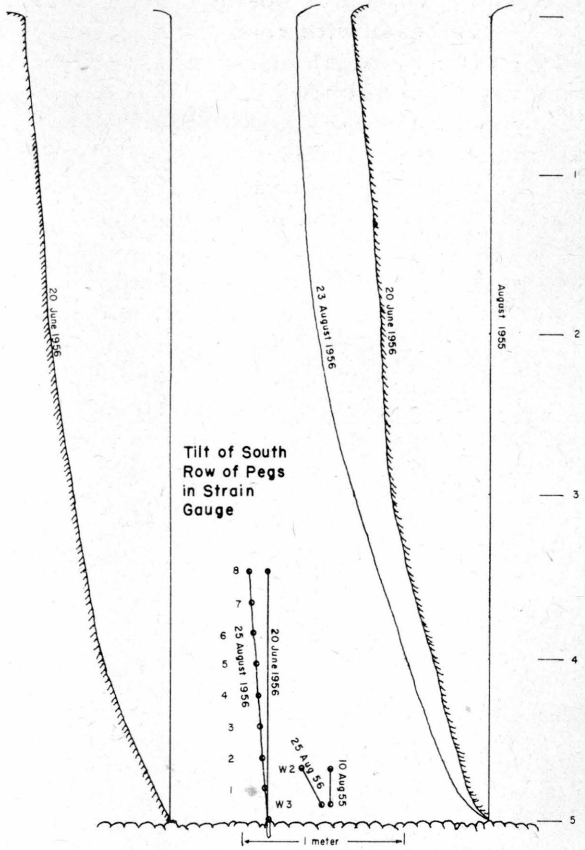

Figure 28. Tilt in shaft dug vertically in 1955.

Forward motion. At the base of the vertical shaft, and over the 30 m^2 of the 1956 tunnel floor, evidence denies the sliding of the glacier over the pavement on which it rests. Each boulder extracted was found to have a complete covering of lichen on its top side, and those lichens were not abraded even though they projected as much as a millimeter into the ice. Plant material in a bubble-free black ice between the boulders projected up into the ice for a few millimeters without being sheared off. On the other hand, air bubbles within a few centimeters of the tops of these boulders were stretched into thin filaments. Differential shear motion is distributed within the ice mass itself, but there is no evidence of a gliding plane or fracture on the rough bottom.

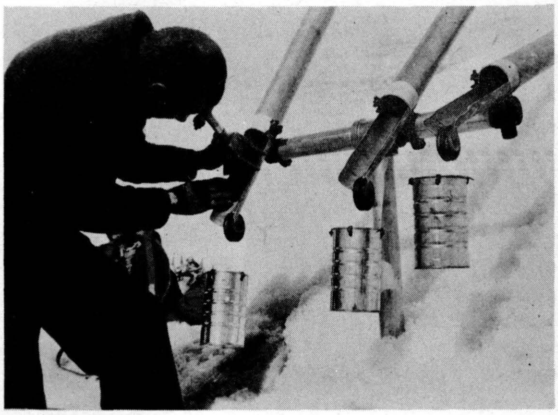

Figure 29. Micromotion wires in tubes attached to T-bar base in ice toe. Cans of rocks hold wires taut over pulley and rule. Observation through filar microscope (left).

The rectangular opening of the shaft against the bouldery ground shifted obliquely south-southeast with respect to a fixed peg (NS) in the center of the opening. This was entirely smooth differential movement of the ice above the rocky floor of the opening. Actually two sorts of motion are involved: (1) the south-eastward thrust of the whole ice mass, and (2) the creep of the plastic ice into the shaft opening from all sides, since support had been removed from the wall ice. On the south wall, plastic flow into the new opening obviously counteracted the forward thrust of the glacier to reduce the net motion over 372 days to 4.5 mm at 10 cm above the rocky floor and 93.9 mm at 35 cm above the floor. The north wall combined forward thrust and plastic creep to move 117 and 267 mm at these two respective levels. To calculate southward thrust separate from the creep, the movement of these two opposing walls was averaged (Table XX). This gives very uniform rates of motion at 0.16 ±0.01 mm/day at 10 cm above the floor, and 0.54 ± 0.03 mm/day at 35 above. Since the net motion of the south wall at 10 cm above the floor was only 4.5 mm in more than a year, it is obvious that at this level the rate of closure almost equals the forward thrust of the glacier, whereas at the 35 cm level the net forward thrust of almost 94 mm far exceeds the total closure in 372 days.

Table XX. Movement of north and south walls of vertical shaft.

Dates	No. of days	Shift southward (mm) N. wall	S. wall	Avg (mm)	Rate (mm/day)
	(at 10 cm above rocky floor)				
8/17/55 to 8/24/55	7	1.8	0.3	1.0	0.15
8/24/55 to 3/24/56	213	69.1	1.2	35.2	0.17
3/24/56 to 6/14/56	82	24.9	2.2	13.5	0.17
6/14/56 to 8/23/56	70	21.3	0.8	11.0	0.16
8/17/55 to 8/23/56	372	117.0	4.5	60.8	0.16±.01
	(at 35 cm above rocky floor)				
8/17/55 to 8/24/55	7	5.3	2.6	4.0	0.57
8/24/55 to 3/24/56	213	177.0	64.8	120.9	0.57
3/24/56 to 6/14/56	82	63.7	19.6	41.7	0.51
6/14/56 to 8/23/56	70	27.6	(6.9	14.1	0.20) *
8/17/55 to 8/23/56	372	273.6			0.54±.03

* South peg may be displaced by accident; unreliable

The walls of the vertical shaft were cut rather smooth on 4 August 1955 and checked with a crude plumbline. This made it possible to plot the distortion so obvious by 20 June and 23 August 1956. Measurements were made at each meter vertically to a plumbline (Fig. 28). Averaging the north and south wall positions on 20 June 1956, we find that in 321 days the ice 1 m above the floor moved 1.25 mm/day; 1.91 mm/day at 2 m above; 2.19 mm/day at 3 m; 2.41 mm/day at 4 m; and 2.72 mm/day at 5 m. Curves of distortion fit a parabola tangent to the bottom of the glacier. It is obvious that the greatest change in rate of motion occurs right at the bottom of the glacier; it increases by 1.25 mm/m-day, which is only 2.4% of the total increase in rate of motion from the bottom to the top of the glacier.

Shear at the base. The 16 steel pegs on the west wall of the shaft were arranged in the plane of the main forward thrust of the glacier so that any closure effects were

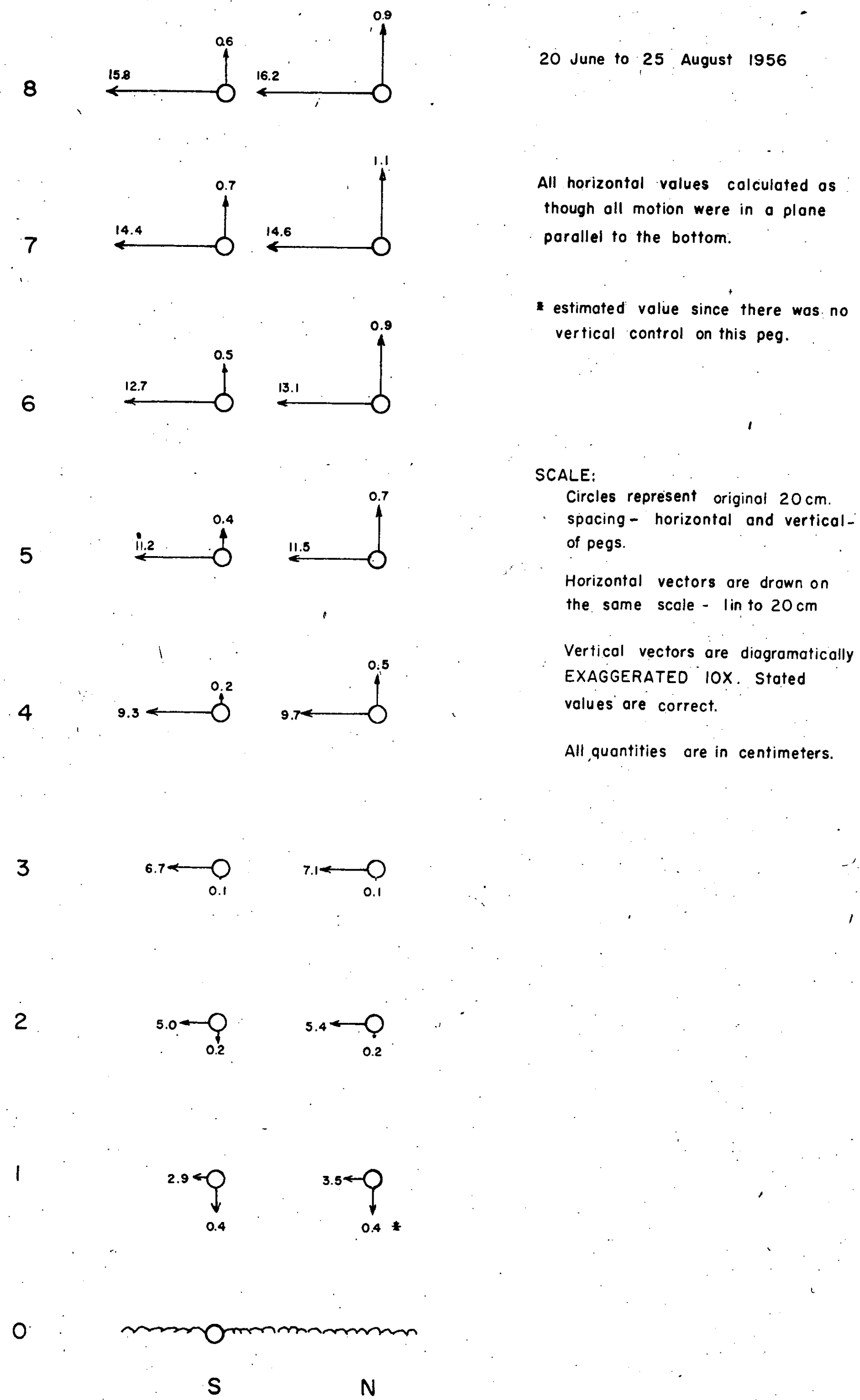

Figure 30. Approximate net motion of strain-gage pegs at glacier bottom under 41 m of ice.

Table XXI. Ten-day contraction (mm) of south-dipping (45°) diagonals between pegs in west wall of shaft (28 m back in tunnel at base of glacier). 1956

Pegs	N peg above floor (cm)	19-29 June	29 June - 9 July	9-19 July	19-29 July	29 July - 8 Aug	8-18 Aug
8N-7S	162.56	2.2199	2.0777	1.9253	2.2809	2.1691	2.1234
7N-6S	142.24	2.2098	2.1539	2.0167	2.3164	2.2098	2.2250
6N-5S	121.92	2.4485	2.3164	1.9812	2.2250	2.1234	2.1844
5N-4S	101.60	2.5654	2.4536	2.3418	2.7787	2.6365	2.6365
4N-3S	81.28	3.4899	2.9159	3.0124	3.3629	3.2207	3.2562
3N-2S	60.96	2.3977	2.2860	2.2707	2.5654	2.4841	2.4993
2N-1S	40.64	2.5501	2.6263	2.6670	3.0886	2.8244	3.1902
1N-0 peg	20.32	4.2011	3.6982	4.0690	4.4754	4.2672	4.6583

Table XXII. Twelve-hour contraction (mm) of south-dipping diagonals between pegs, west wall of shaft. 1956

	13 July		14 July		15 July		16 July		17 July		18 July		19 July	
Begin	0800	2000	0800	2000	0800	2000	0800	2000	0800	2000	0800	2000	0800	Avg
End	2000	0800	2000	0800	2000	0800	2000	0800	2000	0800	2000	0800	2000	(mm/12-hr)
Between:														
0 to 1N (0 to 20.3 cm)	.183	.142	.234	.188	.203	.203	.193	.274	.203	.203	.224	.229	.193	.206
1S to 2N (20.3 to 40.6 cm)	.168	.132	.163	.127	.117	.152	.137	.152	.132	.183	.137	.163	.102	.142
2S to 3N (40.6 to 61.0 cm)	.112	.102	.147	.127	.132	.117	.122	.163	.112	.117	.117	.127	.132	.124
3S to 4N (61.0 to 81.3 cm)	.142	.152	.183	.152	.157	.163	.132	.137	.142	.132	.178	.097	.193	.150
4S to 5N (81.3 to 101.6 cm)	.117	.157	.142	.132	.137	.112	.137	.112	.107	.127	.122	.132	.147	.130
5S to 6N (101.6 to 121.9 cm)	.118	.142	.132	.112	.147	.107	.107	.102	.107	.117	.107	.102	.132	.117
6S to 7N (121.9 to 137.2 cm)	.097	.102	.132	.127	.122	.102	.112	.102	.112	.117	.102	.137	.102	.112
7S to 8N (137.2 to 152.4 cm)	.142	.117	.091	.107	.137	.107	.076	.117	.086	.137	.097	.102	.102	.109

Table XXIII. Two-hour contraction (mm) of south-dipping diagonals between pegs, west wall of shaft.

	13 July 1956								14 July 1956				
Begin End	0800 1000	1000 1200	1200 1400	1400 1600	1600 1800	1800 2000	2000 2200	2200 2400	2400 0200	0200 0400	0400 0600	0600 0800	Average mm/2-hr
Between: 0 to 1N (0 to 20.3 cm)	.066	-.003*	.041	.038	.005	.036	-.005	.030	.043	.064	.005	.005	.027
1S to 2N (20.3 to 40.6 cm)	.066	.003	.084	-.010	.015	.008	.023	.015	.041	.023	.005	.025	.025
2S to 3N (40.6 to 61.0 cm)	.008	.023	.020	.028	.020	.015	.028	.003	.036	.015	.000	.020	.018
3S to 4N (61.0 to 81.3 cm)	.061	.020	.003	.013	.000	.046	.025	.036	.028	.028	.013	.020	.024
4S to 5N (81.3 to 101.6 cm)	.015	-.018	.074	.018	.025	-.003	.043	.013	.033	.025	.010	.036	.023
5S to 6N (101.6 to 121.9 cm)	.010	-.005	.086	-.025	.028	.015	-.015	.018	.046	.005	.025	.010	.017
6S to 7N (121.9 to 137.2 cm)	.020	.018	.005	.056	.005	-.008	.010	.020	.018	.048	.000	.005	.015
7S to 8N (137.2 to 152.4 cm)	.076	-.041	.079	.028	.000	.005	.015	.015	.015	.066	-.036	.038	.022

* Negative readings are expansions.

perpendicular to the measurements and would not affect them significantly. From the rock floor to 1.6 m above, the horizontal pairs of pegs at every level are approaching each other at a rate of 0.38 to 0.91 mm/day, whereas the 20-cm long verticals between pegs are being tilted and lengthened at rates up to 0.53 mm/day. This change from square to parallelogram indicates a regular shear motion which is perhaps best expressed and measured by the south-dipping diagonal between higher and next lower pegs. These diagonals shorten at rates between 0.21 and 0.42 mm/day.

Two figures showed anomalous overall motion during the 60 days of measurement. The lowermost triangle between peg O and pegs 1S and 1N and the uppermost square (Fig. 30) showed that normal shortening also existed between the vertical pegs. In true shear these become longer with tilting from square to parallelogram. Two explanations are suggested: (1) since peg O was drilled into the rocky floor, it may have been a little out of plumb with the vertical lines of pegs above and, therefore, closure eastward into the open pit would shorten its distance to the first peg, or (2) it may represent turbulent motion over rough bouldery floor which was seen to have a microrelief of at least 5 cm.*

The shearing motion near the floor is at least 20% faster than 1 m and more above the floor. This can be seen in the average rates of motion (Fig. 30) or in Tables XXI-

* Actual rising of the bouldery floor caused by relief of ice load seems very dubious since the pit had already been open a year and the area of relief is less than 2 m .

XXIII, which show the contraction of the south-dipping diagonals over 10-day, 12-hr, and 2-hr intervals. Pegs 1N and 1S are moving southward at a rate of 0.54 mm/day, while the next pair (2N and 2S) moves only 0.32 mm/day faster. The uppermost pair (8N, 8S) moves only 0.24 mm/day faster than the next pair below it, yet their net total cumulative motion southward is 15.99 mm/day (Fig. 30).* The increase in motion from the ground to 1.6 m above the ground is not clearly parabolic; this may be due to the shorter period of time during which strain-gage measurements were made.

Over 10-day intervals (Table XXI), the shifting of the pegs is amazingly regular. For example, the next to top diagonal (6S to 7N) shortened at 2.18± .18 mm/10 days with only 8% variation from the mean in all periods. This seems to indicate that forward motion averages out in all parts of the lower ice, so that each ice grain gets its quota of motion over several days, though shorter period measurements show very erratic movements. Over 12-hr intervals (Table XXII), the same diagonal shortened by 0.112±.025 mm/12 hr, a 23% variation. Measuring at 2-hr intervals (Table XXIII) pushes the mechanical strain-gage to its limit of accuracy (±.01 mm), so here shortening averaged 0.015±.04 mm/2 hr or more than a 200% variation. In spite of the inaccuracies in short period measurement, we can be sure that the motion during 1- and 2-hr periods is exceedingly irregular, or jerky, as has been pointed out before (Washburn and Goldthwait, 1937).

Shear nearer the cliff front. From the vertical shaft to the ice toe beneath the cliff face, gross figures for the rate of shear at the level of the tunnel are available from the measurement of horizontal displacement of a plumbline between ceiling and floor pegs (Fig. 54). The ice of the ceiling moves forward faster than ice of the floor. The one complication, again, is the amount of closure as the floor rose and the ceiling was depressed, but this is largely eliminated by measuring the horizontal component of gain of the ceiling pegs over the floor pegs. Except for peg 7, the readings for the three different periods (Table XXIV) agree as well as one could expect from ruler measurements. There does appear to be a slight decrease in rate with time which

Table XXIV. Rates of horizontal travel of ceiling peg beyond floor peg (mm/day).

Peg	Meters from first tunnel door	28 July 55 to 24 Mar. 56 240 days	24 Mar. 56 to 14 June 56 82 days	14 June 56 to 23 Aug. 56 70 days
3	6	1.9	1.8	—
5	10	2.0	1.5	—
7	14	1.7	1.2	2.1
9	18	1.6	1.5	1.7
11	22	1.3	1.2	0.9
13	26	1.4	1.0	1.0
15	30	—	(1.1)	1.0

may be the result of closure; the ceiling dropped nearer the floor by 4.0 to 11.9 cm in the 152 days. The most notable contrast in figures is between the head of the tunnel, more than 20 m in, where the foliation and shear planes dipped generally only 13°, and

* The motion of pegs 2N and 2S at 40 cm above the floor is in very close agreement with that for the north and south wall pegs 35 cm above the floor (Table XX).

the outermost parts of the tunnel under the melting ice toe, where the shear planes and foliation dip at about 45°. It is evident that the zone of greatest shear motion rises upward toward the toe and face of the glacier, so that greatest rates of shearing occur well above the bed of the glacier (5 to 10 m) in the upper parts of the toe ice. In other words, the lower toe ice is a nearly stagnant prism-shaped mass estimated to extend 15 m back under the glacier on the ground.

These motions were measured also by the micromotion wires at the top of the toe ice 133 m west of the tunnel in July 1955 (Table XXV). Together these shearing motions represent approximately half of the total motion at the top of the cliff but distributed in less than 30% of its height. They suggest also slight decrease with time as do motion figures for the ice cliff (Table X).

Table XXV. Rates of differential shear motion (mm/day) between pairs of ice layers at the base of the cliff.

	Estimated elevation (m)	17 to 20 July 3 days	20 to 26 July 6 days	26 July to 4 August 9 days
White ice	9.5			
over				
Amber ice	8.0	1.12	0.20	0.13
Amber ice	8.0			
over				
Dirty ice	6.5	1.96	2.14	3.36
Cliff ice	6.5			
over				
Toe ice	0	2.25	2.37	0.86
Average shear per estimated meter thickness		0.56	0.50	0.45

The six motion wires in the Blue Room, 9 m back in the original tunnel, gave significant results in the summer 1956. Here the strata dip 18°N; the pegs were set parallel with this dip and the motions recorded are recalculated for the component parallel to the dip (Fig. 32). The average rate of differential motion is almost exactly 1 mm/day-m of ice thickness. Rates of differential motion as high as 0.88 mm/day were measured between pegs (Table XXVI) and yet no perfectly sharp overhang or marked gliding plane appeared on the surface of the north wall. Since such overhangs and gliding planes are apparent on the cliff face 3 to 9 m away, it appears that slightly unequal zones of shear at 30 m back rise and become more and more differentiated into concentrated planes of shearing at the vertical cliff base.

Unlike shear motions measured by wire on the cliff face, the internal shearing in the Blue Room seemed to increase in rate during the summer up to 18 August or so. This is a difference in the two summers brought out by other motion figures (Table XIII). Here, also, within the uppermost ice, which is amber-colored with fine disseminated dirt, one layer seems to lag behind, for its differential motion is in opposition to the usual shear couple. This is interpreted as showing the same attenuated turbulent

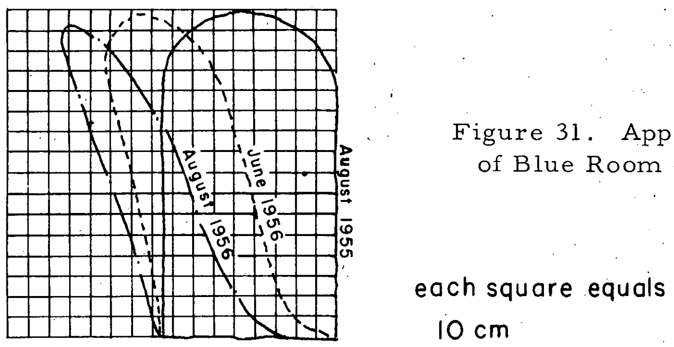

Figure 31. Approximate tilt of Blue Room doorway.

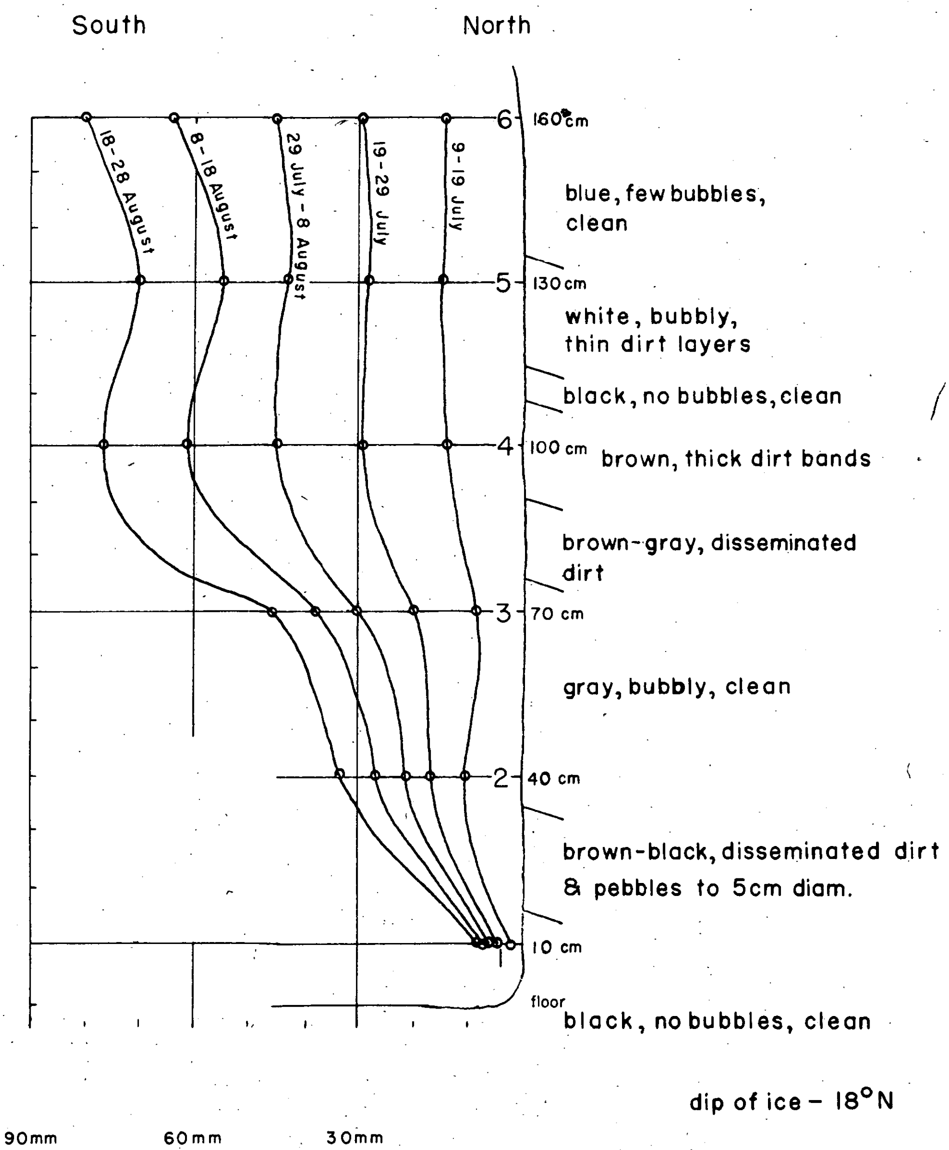

Figure 32. Cumulative micromotion on north wall of Blue Room, 1956.

Table XXVI. Rates of differential motion (mm/day) between pairs of wires in the Blue Room (Fig. 32) 1956.

Peg	Position (cm)	Ice	9 to 19 July	19 to 29 July	29 July to 8 Aug	8 to 18 Aug	18 to 28 Aug
6	162	blue, clear					
	over		-0.07	0.19	0.11	0.60	0.27
5	132	white, dirty					
5	132	white, dirty					
	over		0.10	-0.16	-0.11	-0.38	-0.16
4	102	brown, dirty					
4	102	brown, dirty					
	over		0.53	0.49	0.62	0.72	0.72
3	71	gray, bubbly					
3	71	gray, bubbly					
	over		-0.19	0.42	0.42	0.32	0.31
2	41	gray, bubbly					
2	41	gray, bubbly					
	over		0.88	0.42	0.49	0.54	0.39
1	10	black, clear					
1	10	black, clear					
	over		0.18	0.19	0.10	0.05	0.10
0	0						
Average shear per meter thickness			0.88	0.96	1.01	1.14	1.01

motion as is demonstrated by stakes on the cliff face. The greater motions from wires on the cliff face are due to the larger segments considered there.

<u>Tilting</u>. On cliff surfaces perpendicular to the thrust of the glacier, shearing motions are expressed as sharp small overhangs on discrete gliding planes. There can be little doubt that ablation alone is not responsible for this phenomenon. In contrast to this, the north wall and entrance to the Blue Room, which are perpendicular to ice motion, were deformed rather smoothly (Fig. 31). The vertical door was originally 84 cm wide with pegs inserted at the same level on opposite walls. Just about one year later, on 24 August 1956, the middle wall sections were tilted at 15° from the vertical and were only 36 cm apart horizontally. However, the two pegs had moved so that the one on the south wall was 45 cm higher than that on the north wall. Even at this short distance back into the ice mass, this same deformation is expressed as a smooth tilting.

The offset of the vertical peg sets in the tunnel also indicated the magnitude of the tilting due to shear motion at the tunnel level. It is possible to estimate how much of this is due to closure (p. 48) and so the actual tilt measured and the calculated tilt rate (disregarding closure) are both given (p. 56).

Minimum tilt rates were recorded in the upper parts of the shaft, i.e., farthest back in the glacier and above the bottom. At the top of the shaft, 3 to 5 m above the rocky floor, tilt was smooth at 6°/year, while in the lowest 10 cm it was 45°/year. Old 1955 pegs in between at 10 and 35 cm above the bottom were tilted out of vertical 26° to 35°. Since these were expressed as perfectly smooth surfaces with no offsets,

Peg	Depth into tunnel (m)	Tilt measured roof to floor in 1 yr	Tilt calculated (eliminating closure) for 1 yr
3	6	23°	19°
5	10	24°	19°
7	14	22°	20°
9	18	20°	18°
11	22	16°	14°
13	26	16°	14°
15	30	13°	12°

and only a few small surficial tension cracks, it is clear that this was plastic yielding under confining pressure caused by the forward thrust of the upper ice.*

Summary of glacier flow

The annual forward thrust of the glacier at the surface is approximately 4.8 m; the daily rate for uppermost stakes on the ice cliff was about 12.1 mm/day. The most notable variation is that the highest part of the cliff moved some 25% faster than the smaller cliff on the slope of Survey Hill. This shallower ice moves diagonally across the slope with a strong eastward component, whereas the central parts of the ice basin are moving almost due south; this means that ice is converging into the area of the high ice cliff.

The surface of the ice just above the cliff moved 26 cm/yr downward, probably as a result of the sagging of the unsupported ice on the face of the ice cliff; in several places the middle portion of the cliff face moved faster than either the top or the base. Up-glacier 295 and 600 m, on the forward slope or riser of the step which is passing down through the ice basin, upward motions of 19 to 25 cm/yr were registered. Still further up (1470 m) at the back of the step the ice was settling at the rate of 24 cm/yr. Thus the motion toward the highest ice cliff involves a series of slight rotations and major convergence from the sides of the ice basin toward the center.

The top of the glacier moves twice as fast as the bottom of the ice cliff; stakes in the lowermost amber vertical ice and in the ice toe averaged 6.6 mm/day or 2.3 m in the year. The shearing motion between upper and lower ice is largely concentrated right at the base of the vertical cliff and the top of the toe where individual shear zones moved as much as 0.88 mm/day over the adjacent ice only 30 cm below. Below this zone of great shearing is a prism of ice which moves only very slowly and pinches out under the ice cap within 25 m. At the bottom of the vertical shaft in the tunnel, 28 m in from the ice toe, ice 10 cm above the ground moved at 0.16 mm/day whereas at 35 cm above the ground it moved at 0.54 mm/day. Five meters above the ground it moved 2.72 mm/day so that the displacement of originally vertical walls was that of a parabola. Tilting in the lower part in one year amounted to 45°. Precise measurements on the strain gage pegs near the bottom indicated that square groups of pegs were pushed into parallelograms. In spite of this concentration of strong shearing motion near the bottom, the ice surrounding the rocks on which the glacier lay had not moved in less than 200 years because lichen, moss, and vascular plants which are that old were perfectly preserved without being sheared off in the ice.

Ice motion varied by 15% from season to season, although the two summer seasons averaged nearly the same on the ice cliff (9.9 and 10.9 mm/day). Fastest

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* Difference in the size of the void may explain why this fracture displacement occurred on the ice cliff where confining pressure is relieved but was not seen on tunnel walls where pressure is also relieved.

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average motions on the cliff were in early July (11.8 and 12.7 mm/day); the fastest motion of the surface above was 14.1 mm/day at the end of July. There was a marked slowing down of the cliff to 10.3 mm/day when the cliff moved fastest at the very end of July and the early part of August. The fastest long-term rates were 13.3 mm/day recorded between March and June 1956. No definite causes for these fluctuations could be detected by 14 months of observation.

The motion of the glacier is irregular from stake to stake. Certain stakes moved in retrograde fashion upglacier for intervals of 10 to 30 days even though most of the time their motion was southward; 13J moved consistently northward. This seems to suggest a somewhat turbulent or eddying motion with ice grains moving occasionally in very elongate elliptical paths.

The motion during short periods of time is very jerky. When measured over half days it moved 25% faster during the high sun hours and moved toward the southeast, whereas at night the slower motion was southwest. On the cryokinegraph the motion was fastest and most irregular between 0400 and 1000 hr in 1955 or between 1030 and 1330 in 1956. Slower smoother motions in both years came between 1730 and 0200 hr. Thus, there appears to be a diurnal variation which may not be constant and for which no likely explanation has been found.

IV. STRUCTURE

Physical properties

Temperature. Internal temperature of the glacial ice was measured principally by drilling holes as deep as possible in July 1955, inserting cables with thermocouples, and repacking to allow the whole ice mass to come to its stable temperature. This was accomplished with great difficulty because the holes had to be drilled during the months of melting, and any water which penetrated the hole refroze immediately, binding the drill. Extraction of cores over 4 m down proved very difficult. A coring auger with an 11 cm outside diameter and 7.6 cm inside diameter was used to make three vertical holes on the surface of the glacier 6 m, 6 m, and 3.5 m deep (nos. 3, 4, 5). At the head of the tunnel, 30 m in from the open face of the cliff where temperatures were constant and melt water was absent, this same auger was used to bore horizontally for 8 m (no. 6). Two holes were drilled horizontally into the face of the ice cliff, one at the base and one near the top (nos. 1 and 2), and these were made with 2.5 and 3.8 cm bits, using extensions to reach 3.5 and 5 m depths.

The thermocouple cables were prefabricated in 1953 for another project and consisted of iron-constantan thermocouples enclosed in Tygon tubing. The original spacing of the thermocouples at 0.5 m, 1 m, 2 m, 4 m, and 8 m below the ice surface from the initial end of the tube was changed at the 8 m end by doubling the tube over in places or by using only part of the cable. Thermocouples were read with a standard precision 0 to 71 mv potentiometer balanced to a cold reference junction at exactly 0C (Fig. 33). This was a vacuum bottle containing a mixture of ice and water. Readings during the stabilization period indicated that the thermocouples came to fixed temperature within a day or two after the holes had been repacked with ice.

Readings were made at approximately weekly intervals from 7 July to 18 August 1955. At the beginning of the second summer season, 1956, the cable at the highest site (no. 5) could not be found because it was covered by snow and both short cables (nos. 1 and 2) had been removed or covered by the dry calving of ice from the cliff. Measurements on cables 3, 4, 5, and 6 were made every half-month during the summer 1956, beginning with 14 June and ending with 28 August. The attempt to get winter readings failed because of improper procedure, and even the early readings on 15 and 20 June 1956 are subject to some possible question, since the cold junction vacuum bottle did not arrive until late in the month and a clumsy constant temperature bath had to be used.

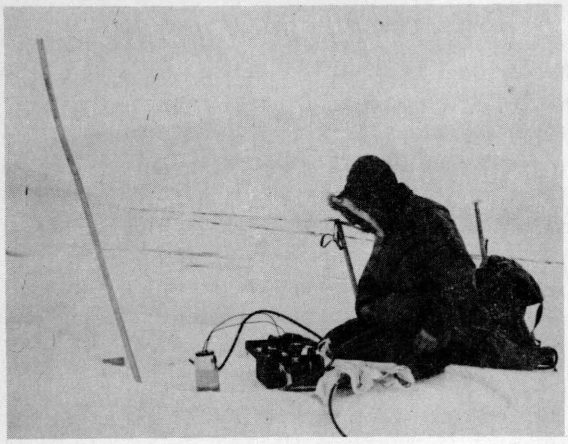

Figure 33. Measuring ice temperatures through thermocouple cable (black) with potentiometer (black box) and cold junction (vacuum bottle with wires).

The deepest and most constant temperatures measured were those at the head of the ice tunnel, 28 m in from the cliff face, the cable reaching to 36 m. This is estimated at 37 m depth below the glacier surface. In 1955 the temperature at 2 m, 4 m, and 8 m depth from the tunnel opening was -11C. When the tunnel was first re-opened on 20 June 1956, the somewhat less accurate readings at 8 m averaged -13.3±0.7C. This may be due to ice contact with cooled air in the tunnel in winter. By 30 June 1956 all the deeper thermocouples read -11.8±0.4C, and by 15 July all thermocouples read -11.4C exactly. On 28 August 1956 these had all cooled again to -12.2±0.4C. How much of this is the effect of the tunnel and to what extent is the seasonal change felt at this great depth? From formulas for conduction of heat in solids (Carslaw and Jaeger, 1947), it seems that effect of the outside air above the glacier is nil but that of air in the tunnel may be significant.

The temperature gradients to 6 m depth below the surface of the glacier (Fig. 34) suggest a convergence toward -14C or -15C approximately 7 m from the edge of the ice cliff (no. 3), and near -16C and -17C at approximately 25 m back from the ice cliff (no. 4)*. We may surmise that undisturbed ice temperatures at 6 m or below run between -12C and -16C. So far as can be judged, this is very close to the mean annual temperature existing at Red Rock Lake today.

Air temperature measurements made while digging the tunnel indicate that inside air was slightly affected by outside air temperature. The air in the outer tunnel generally ranged between -2C and -5C while the inner portion was -11C when the tunnel was opened each year and -7C at its warmest. In March 1956 it was -10.5C. At the base of the vertical shaft, it was constantly at -11C. The 0.5 m and 1 m deep thermocouples at the head of the tunnel were only -9.7C and -10.2C when deeper ice was -11C. A 1-m long thermocouple cable in the tunnel wall 8 m in from the entrance showed on 7 July 1956: outer air -2.8C; ice 6.25 cm deep -5.0C, at 12.5 cm -6.1C, at 25 cm -6.3C, at 50 cm -6.3C, and at 100 cm -7.0C. The steepest gradient as air warms is at the outer wall (17.6C/m) and it is less at 1 m depth (1.4C/m). But by 30 July, tunnel air got cooler, and ice all the way to 1 m depth was uniform (-2.6C to -2.8C). Such shallow effects hardly explain the 1.8C measured change at 8 m depth in the protected tunnel (36 m from the outside). No instrumental error of detectable magnitude was found and all readings were double checked at the time.

The temperature of the surface ice near the ice cliff fluctuates widely through the year. Measurements shown on Figure 34 indicate only the progression of temperature gradients during the summer melt season. It is evident by projecting upward the 15 June curves at nos. 3 and 4 that winter ice temperatures had reached -40C or lower, whereas summer temperatures get as high as 0C. At 2 m actual depth, temperatures appear to range from -26C to -4C. At 4 m depth they vary from -23C to -9C. It appears that the maximum warm swing of the temperature curve near the surface occurs between 17 and 28 August; on the 28th, the surface portion of each curve began to bend back sharply in

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* Temperatures of -12 to -16C were recorded at 8 m depth in Nuna Ramp in 1953.

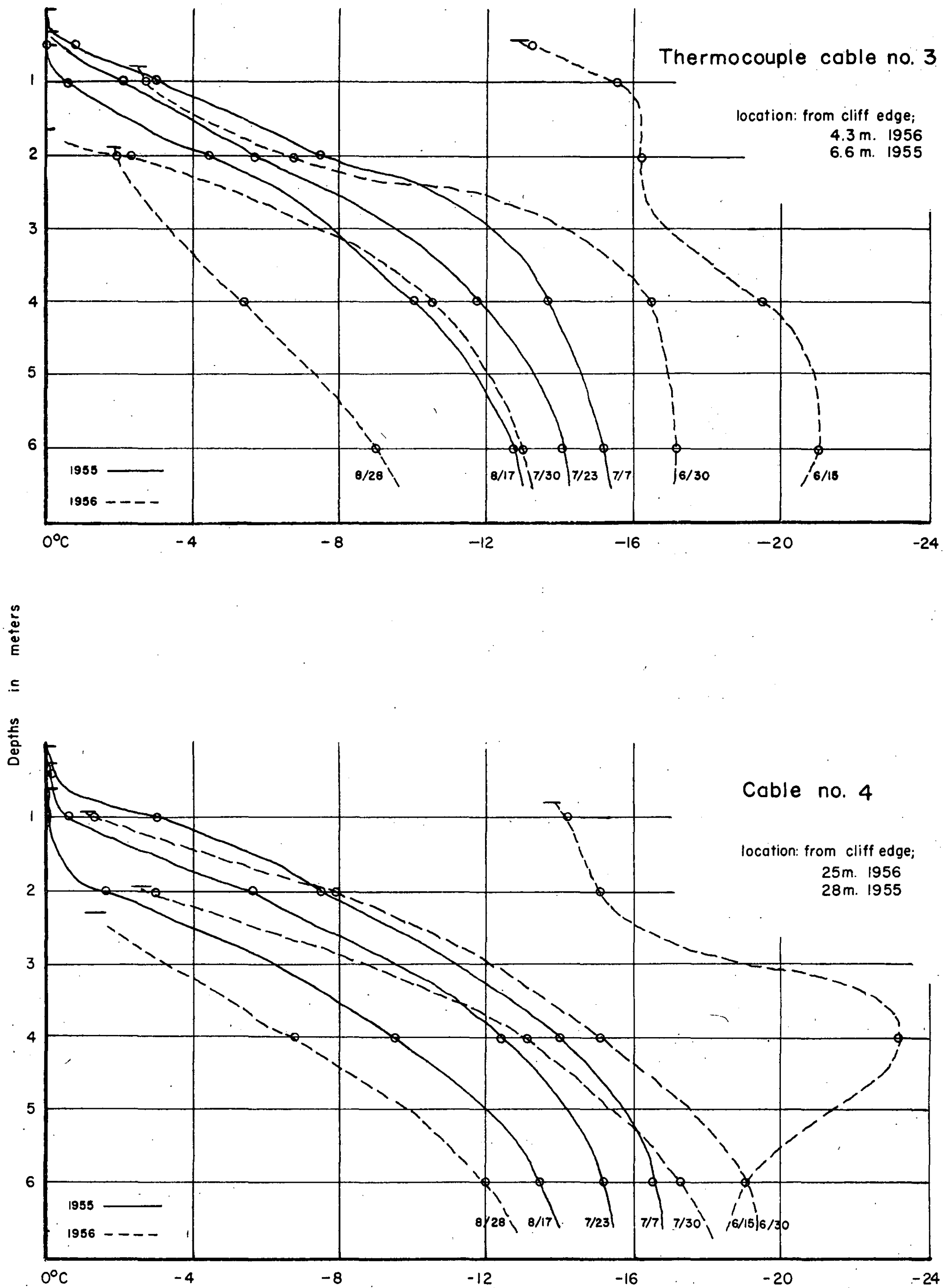

Figure 34. Ice temperatures at depth in the glacier. Horizontal tick marks indicate ice surface at time of readings.

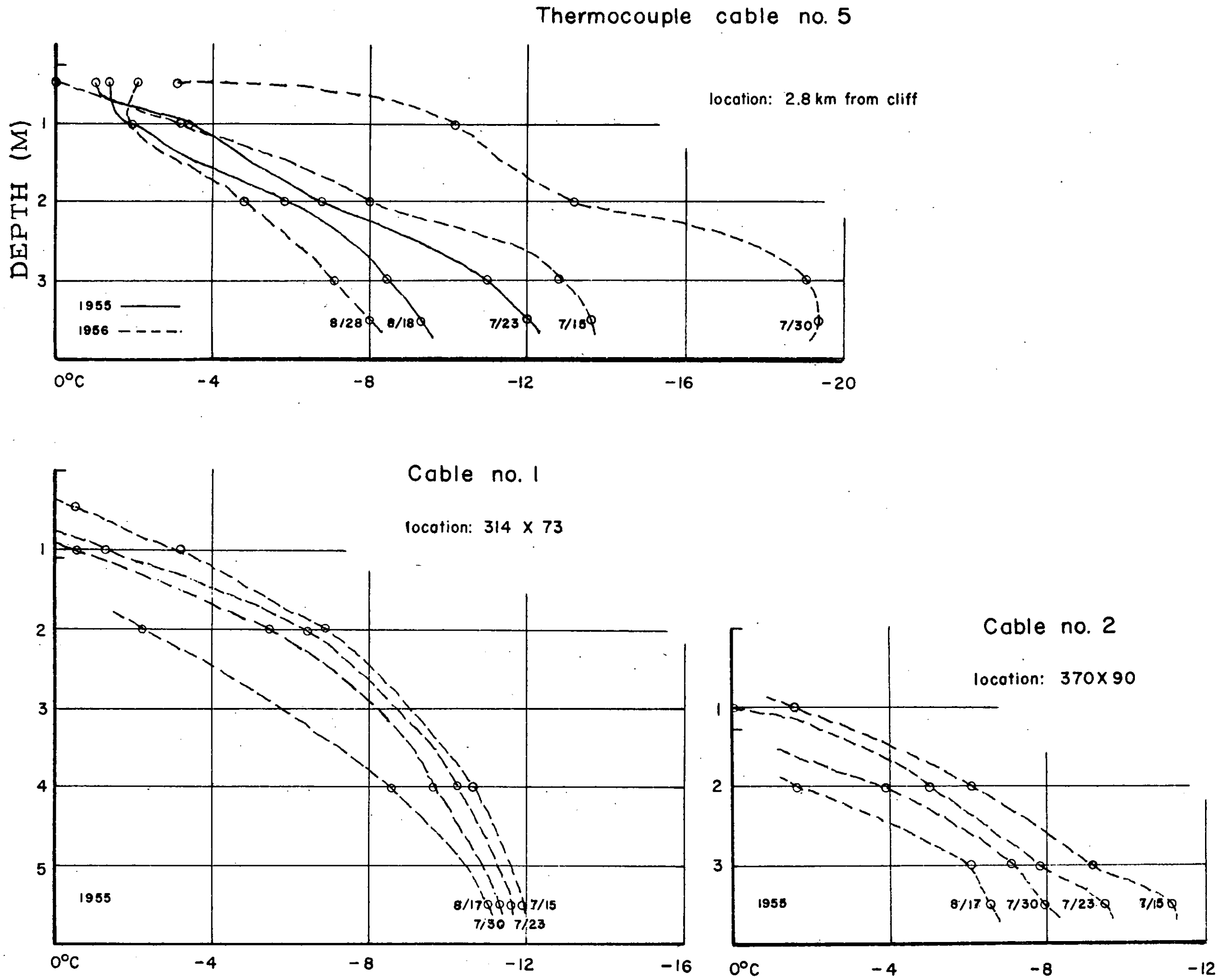

Figure 35. Ice temperatures at depth in glacier.

response to the cold nights. Undoubtedly, some time in the early part of March, there is a similar bending back of the curve for surface temperature from the extreme cold surface of the height of winter. The lag in reaching highest and lowest temperatures is nearly 2 months after the solstice and 1 month after the winter climatic extreme in the air above the glacier.

During any one summer the curves show a progression from a steep temperature drop (3.6C to 5.8C/m) extending to shallow depth at the end of June to a gentle temperature gradient (1.7C to 2.6C/m) extending to greater depth by the end of August (Fig. 34). The point of sharpest change in gradient lowers from 4 m to perhaps 8 m in that time. It is notable that the gradient in the upper 2 to 4 m of ice is steeper in July 1956 than in July 1955. This is a logical consequence of the mean monthly temperature for July 1956, which was 1.08C warmer than for 1955. This rapid warming in 1956 began suddenly on 15 June and was interrupted only once by a cold spell between 19 and 30 July.

Table XXVIII shows ice temperatures for different parts of the area. Since the ice surface lowered position by from 0 to 2.3 m during the total length of the time span involved, readings were interpolated for the 3 to 4 m depth. However, since the inte-

Table XXVII. Ice temperatures (C) at depth in the glacier.

Date	Ice surface depression	Air temp. prior 3 days	Original depth in ice ½ m	1 m	2 m	4 m	5½ m
No. 1 - Base of ice cliff at stake row 11							
1955							
15 July	0.36 m	3.1	-0.6	-3.0	-6.7	-10.3	-11.8
23 July	0.74	-0.8		-1.2	-6.2	-10.1	-11.5
30 July	1.17	1.5		(-0.3)	-5.3	-9.7	-11.2
17 August	1.93	-2.6			-2.2	-8.3	-10.9
No. 2 - 7½ m below top of ice cliff						(3 m)	(3½ m)
1955							
15 July	0.09 m	2.1		-1.6	-6.0	-9.1	-11.1
23 July	0.21	0.2		-0.1	-4.9	-7.8	-9.4
30 July	0.39	1.3		0.0	-3.9	-7.1	-7.9
17 August	0.94	-2.0		0.0	-0.7	-6.0	-6.5
No. 3 - Glacier surface to 5 m north of ice cliff							(6 m)
1955							
15 July	0.07 m	1.1	-0.8	-3.0	-7.4	-13.8	-15.2
23 July	0.13	1.1	-0.1	-2.7	-6.4	-12.6	-14.7
30 July	0.18	1.2	0.0	-2.1	-5.8	-11.7	-14.0
17 August	0.39	-1.5	0.0	-0.7	-4.2	-10.0	-12.7
1956							
15 June	0.41	-3.7	-13.4	-15.6	-16.2	-19.6	-21.0
30 June	0.63	5.1		-2.4	-6.7	-16.4	-17.0
15 July	1.16	3.6			-2.4	-10.6	-13.0
30 July	1.50	2.6			-3.6	-12.0	-16.0
14 August	1.84	1.8			-0.6	-8.8	-12.4
28 August	1.91	-1.8			-2.0	-5.4	-9.0
No. 4 - Glacier surface 25 to 28 m north of ice cliff							(6 m)
1955							
7 July	0.09 m	1.3	-0.1	-2.8	-7.5	-13.9	-16.3
15 July	0.23	1.1		-1.7	-6.6	-13.4	-15.7
23 July	0.34	1.1		-0.5	-5.5	-12.3	-15.1
30 July	0.44	1.2		-0.5	-4.8	-11.7	-14.7
17 August	0.72	-1.5			-1.7	-9.4	-13.3
1956							
15 June	0.77	-3.7		-14.0	-15.0	-23.0	-19.0
30 June	1.03	5.1		(-1.2)	-7.8	-15.0	-19.0
15 July	1.56	3.6			-1.2	-11.2	-15.4
30 July	1.90	2.6			-2.8	-13.0	-17.2
14 August	2.24	1.8				-10.2	-16.8
28 August	2.31	-1.8				-6.7	-12.0
No. 5 - Glacier surface 2.8 km north of ice cliff near snow line						(3 m)	(3½ m)
1955							
15 July	0.05 m	-0.8	-0.0	-3.0	-8.0	-11.8	-13.0
23 July	0.11	-1.8	-1.2	-3.2	-7.2	-11.0	-12.0
30 July	0.15	1.1	-0.6	-3.1	-6.7	-9.8	-11.1
17 August	0.15	-3.1	-1.0	-2.0	-5.7	-8.3	-9.2
1956							
30 June	-0.31	3.9	-3.0	-10.0	-13.2	-19.0	-19.4
15 July	0.26	2.0	0.0	-3.0	-8.0	-12.8	-13.6
30 July	0.20	3.2	-7.4	-9.6	-12.0	-16.4	-17.6
14 August	0.36	0.8	-1.4	-4.0	-7.4	-12.0	-12.6
27 August	0.15	0.0	-2.0	-2.0	-4.4	-7.0	-8.0

Table XXVIII. Temperatures (C) of ice cliff and glacier, summarized for 3-4 m depth.

Date	Cable 5 2.8 km back	Cable 4 25-28 m back	Cable 3 cliff edge	Cable 2 cliff high	Cable 1 cliff base
15 June		-23	-19		
30 June	-20	-15	-16		
* 7 July		-13½			
15 July	-14	-11	-10		
*15 July	-13½	-13	-13	-11½	-10
*23 July	-12	-12	-12	-10	-10
30 July	-17	-13	-12		
*30 July	-11½	-11	-11	-8½	-9½
14 Aug	-13	-10	-8½		
*17-18 Aug	-9½	-9	-9½	-6½	-8
28 Aug	-8	-6½	-5½		

* 1955 measurements, others 1956.

grated figures for the two years seem to agree well where both were available, this did not have an effect of more than 1C or 2C. For similar times it is obvious that the ice in the face of the ice cliff had warmed up from 1C to 3C more than the ice surface immediately above. This is probably due to lack of winter snow cover, the greater rates of melting, and the warmer temperatures on the ice cliff face (Fig. 7). The high thermocouple cable (5) ranged from 0.5C to 5C colder than near the ice cliff at any given depth and any given time. Measured summer air temperatures were at least 0.5C to 1.15C colder above (Table I); undoubtedly this is the altitude effect of more than 220 m and represents an approximate difference between mean annual temperatures at the two points.

In the Annual Report for 1955 (Goldthwait et al., 1956) the preliminary conclusion (p. 30) was that "The 0C isotherm lowered gradually from 0.7 m on 15 July to a maximum depth of 1.7 m, but because of ablation of the surface, this was only 1.1 m net depth." A straight projection of the curves for ice temperature at depths of 0.5, 1, 2, and 4 m (Fig. 34) brings the 0C position at from 0 to 1 m actual depth. However, in a heat transfer system in which very cold ice at depth is receiving heat energy from rather warm air above, there must theoretically be a curved gradient from 0C at the surface of the ice to the -15C or -16C reading at depth. If there was percolation of water in the upper centimeters of ice, either accidentally along the drilled and sealed cable hole or between ice crystals, this would transfer heat energy downward and still lower ice might also reach 0C.

During the melting season heat is transferred to the ice by two means: (1) direct radiation during the high sun hours, which affects the ice to a few centimeters in depth, and (2) conduction into the ice whenever the air is above 0C. Judging from 1956 measurements, the surface ice does not reach 0C until 20 to 30 June at the ice cliff and later above (no. 5, Fig. 35). Prior to 15 June the ablation losses were minimal and took place by sublimation which produced a glazed surface on the ice. After 15 June the heat is effective in (1) producing melt water and (2) in raising the temperature of the ice mass at depth.

The amount of heat required to produce the melt water may be calculated. Ice requires 80 cal/g to melt, so ice of density approximately 0.82 g/cm will require

65.6 cal/cm^2 to melt a centimeter thickness of ice. During July 1955 and to 17 August the ablatograph located nearby showed a daily melting of from 0.2 to 2.8 cm/day. The average was 1.19 cm/day for that melt season after the ice reached 0C. This involves 78.1 cal/cm^2-day net input of heat. In 1956, the melting reached as much as 5.3 cm in one day and averaged 2.0 cm for all days of 0C ice. Total heat input the second summer averaged 131.2 cal/cm^2-day.

This latent heat of melting is about double the amount indicated as heat flow by conduction at shallow depth within the ice. If we use the customary formula for heat flow:

$$\text{Rate of conduction } (cal/cm^2\text{-day}) = k\left(\frac{t_1 - t_2}{d}\right)$$

where k is the coefficient of conductivity, suggested as 53.5 x 10^{-4} cal/C-cm-sec by Dorsey (1940), t_1 and t_2 are temperatures (C) on either side of the layer considered, and d is the thickness of the layer. The value for heat flow into the ice amounts to 5.3 cal/m^2-sec at 25 to 28 m back from the ice edge (no. 4) and roughly 8.0 cal/m^2-sec for the cliff edge position (no. 3). This gives a minimum heat flow during the melt season of 45.8 cal/cm^2-day, or a probable maximum of about 68.7 cal/cm^2-day. Most of the measurements at either of these two stations vary between these two extremes.

If, indeed, the 0C isotherm is depressed a centimeter or more below the surface of the ice by the downward penetration of freshly produced melt water or by absorption of radiation at crystal boundaries, conduction of heat from the air cannot occur, for no gradient exists. From watching the surface of the ice and digging in it during the melt season, it would appear that this condition exists only for short periods during the high sun hours and that the penetration is only for a few centimeters of depth in spite of the apparent depression of the 0C line.

The rate of increase of the temperatures in the ice is fairly regular after 1 July (Fig. 35) until close to the end of August. Prior to July and especially during May, the most rapid temperature changes must take place in the upper ice; this may amount to as much as 0.6C/day. For the cable within 5 m of the ice cliff, the maximum change at 4 m depth was from 0.09 to 0.10C/day, whereas at the 1 m and 6 m thermocouples it was from 0.04 to 0.08C/day. At 2.8 km north of the ice cliff and at higher elevation, the maximum rate of temperature change is 0.11C/day in the zone between 3 and 3.5 m depth.

In 1956 the rates of increase in temperature were nearly double those of 1955 for the lower area near the cliff. Right at the edge of the ice cliff (no. 3) at 4 m depth, the rate of change in 1955 was 0.09C/day, whereas in 1956 it was 0.19C/day. A short distance back from the cliff edge, where it had been 0.12C/day in 1955, it was 0.17C in 1956. Far north of the cliff, where it had been 0.11C in 1955, it was 0.13C/day in 1956.

Late in each season (23 August 1955 and 22 August 1956) a discontinuous layer of new snow coupled with below-freezing air temperatures produced a drop in the ice temperatures above the ice cliff. The snow acts as an excellent insulator since its thermal conductivity is only about 1/20th that of ice, and, where there was no snow cover, the heat flow reversed into the cold air.

<u>Ice densities</u>. The sampling problem was simply one of getting a symmetrical piece of ice large enough to minimize errors due to irregularities or weighing methods. Most uniform ice samples were obtained by careful coring with the 12.7 cm coring auger. Cylinders 7.6 cm in diameter were obtained at 6 places in the tunnel in 1955. A variety of visible structures was sampled.

Specimens were trimmed carefully with a saw and measured with a steel rule, at a number of lengths and diameters. Each sample was weighed on a triple beam balance, and density was calculated by simple division of volume by weight.

Table XXIX. Ice character and densities.

Sample number	Distance from old tunnel mouth	Character of ice (bubbles)	Weight (g)	Density (g/cm^3)
Shelter I	surface	very bubbly	379.1	0.85
none	3 m	moderately	351.2	0.88
none	3 m	moderately	330.2	0.85
Y	17.5 m	very few; clear	760.7	0.91
Z	19 m	moderately	156.7	0.86
X	23 m	very bubbly	308.3	0.91
56A3	22.5 m	no bubbles	348.7	0.89
56D	22.5 m	moderately	416.0	0.90
none	27.5 m	moderately	639.0	0.88
Average 9 samples				0.88

Densities ranged from 0.85 to 0.91 (Table XXIX). The variations seem to follow the bubbly character of the ice; very bubbly white ice is near 0.85 and clear blue-black ice with few bubbles is near 0.91. These variations make up the foliation discussed later. The average of the samples, 0.88 g/cm^3, seems reasonable for the non-dirt-bearing parts of the ice cliff.

Foliation and fracture

Surface structure map. Most motions within the ice mass are expressed in the deformation of linear elements such as air bubbles in the ice itself. For a time at least, bands of dirt or streaks of bubbly white ice may preserve the trend of a strong flux of motion. Thus, the ice on the surface of the ice cliff and exposed on the glacier up to snowline reveals the recent history of ice motions within the ice mass. To detect the nature of these movements, detailed structural maps were prepared for the lower drainage basin and the tunnel (Fig. 54, 55).

The glacier surface was mapped in 1955 from a 275.46 m long subsidiary upper baseline oriented west-northwest up the west slope of the ice basin. The ends of the baseline were bamboo poles set more than 2 m into the ice. Each end was triangulated with the Wild T-2 theodolite from baseline stakes 9 and 15 on the land.

Mapping was done on a small plane table 38 cm square. The scale (1:2000) required the use of 7 plane table sheets. Some trouble was experienced in setting the pointed feet of the tripod firmly into the ice so that settling would not occur after leveling. This settling problem was partly solved by packing loose ice around the feet at the time of initial occupation of the station. Plane table stations were occupied in closed traverses and these levels always checked to within 1 m.

Specific rod-station points were mapped at or near each ablation stake, weather shelter, or level stake. From the levels of these positions as read in the field, 5 m contours were sketched. The datum plane or base of 0 reference was base stake 15, which corresponds to 59.54 m on the Z-axis of the grid system depicting the ice cliff (Fig. 57, 58). Additional rod stations were occupied at approximately 25 m distances along the lower stream courses and at about 100 m intervals on the upper stream courses to locate drainage features (Fig. 55).

All structures visible within the ice were noted carefully at each rod station and later plotted on the structure map (Fig. 55). The strikes and dips of bubbly bands (foliation) and tension cracks were the principal features mapped. The magnetic declination of approximately 74° was too large to be corrected by setting the compass, so that strikes at most stations were taken as angles to some point of known location. At many stations strike and dip readings were taken on several cracks; the length of the line on the map (Fig. 55) is proportional to the number of readings obtained on cracks having very nearly the same strike. The visibility of these structural features varies greatly from day to day. Only the lower parts of the basin revealed any structures during the summer of 1955, and these were mapped, beginning at the ice cliff and moving upward as snow was removed by ablation. In 1956 it was possible to obtain data on cracks and foliation much farther north; these were located by relating them to points which had been surveyed in 1955.

Plot of tunnel. Even more structural features such as dirt bands, shear zones, stretched bubbles, bubble bands, and tension cracks could be traced east and west along the toe ice and lower parts of the ice cliff and northward under the glacier into the ice tunnel. These are best shown in a 3-dimensional perspective diagram (Fig. 54). The level of the pegs was determined by precise leveling from baseline stake 15 in 1956 (see p. 99). Distances back into the tunnel to each peg and opening or point of observation were measured with a 30 m steel tape and the direction determined by Brunton compass.

Tension cracks. One of the simplest structures to recognize and map is the open fracture. These were found concentrated in the southeast third of the area mapped (Fig. 55), but there is some concentration in the southwest corner. No big crevasses were observed in the ice basin; most of the open fractures were only a centimeter or two wide at the top, although a few reach 10 cm in width. One at the cliff top reached 2 m in width. It was impossible to measure depth of the cracks, since they become too narrow to receive a steel tape within 1 to 5 m down. Most of the cracks were nearly vertical and those which were not dip at angles greater than 60°. The radiating lines on Figure 55, indicating the numbers of such cracks observed in each azimuth at each station, clearly show a trend from north-northwest to south-southeast. The eastward component was stronger north of shelter II and stake row 13, where motion data showed the ice moving obliquely eastward off the buried northeast slope of Survey Hill. To this extent the majority of cracks strike roughly parallel to the ice motion.

Observed over the whole area, the cracks bore no constant angular relationship to the foliation or dirty banding within the ice. They seem to have roughly radial patterns centering around the topographic highs in the ice surface; in this sense they are similar to large crevasses high on North Ice Cap observed by Barnes and attributed to an ice dome (p. 3). Near the cliff margin some of the cracks are parallel to the edge of the cliff. The longest cracks are those parallel to the majority trend, whereas those perpendicular to this are generally short and pinch out within a few meters.

Some cracks were observed to open within the two summers and others were observed to have opened within very recent time. As evidence of this, some cracks 1 to 10 cm wide were half-filled by a lining of ice crystals built perpendicularly outward from the wall; evidently the crack had opened, filled with melt water which froze normal to the surface of refrigeration, and then pulled farther apart to create a new void in the center. During the excavation of the tunnel in 1955, a few cracks developed near the opening, dipping 60° to 80° S, and became as much as 3 cm wide, or 8 cm in 1956. Two of the cracks on the east wall of the tunnel, 4 and 8 m in from the original opening, could be traced to pegs which had been drilled in during mid-July 1955. Since the longest was only 1 m long, it is suspected that these were triggered by the release of pressure in the tunneling operation; however, these lie in the plane of tension release for forward thrust of the ice (p. 46). In the vertical shaft 28 m back from the base of the vertical ice cliff, an east-west crack dipping about 10° southward became 6 cm wide and over 25 cm deep along the south wall where a peg had been placed 35 cm above the rocky floor. These suggest that the drilling of the wall pegs introduced an extra weakness which invited the release of tension.

Cutting through the foliation of bubbly ice at various angles were brilliant "blue bands" which have been described and discussed in the literature many times. These ranged from 2 or 3 cm to over a meter in width and one could be traced more than 100 m before it disappeared under snow cover (Fig. 55). Some cut across structures for a few meters and then offset along the structure a meter or two before resuming the original general trend. Each one lensed out, if traced far enough, but another one took up "en echelon." The majority had a dip of near 90° and so in all respects they fit the pattern of cracks.

Blue ice is clear bubble-free ice with no visible crystal structure. Fabric diagrams made elsewhere indicate that the ice crystals have little, if any, systematic orientation. Not every "blue band" structure was composed entirely of blue ice, however. One prominent example near ablation stake 71 had a strike northeastward and was 1 m wide (Fig. 55). In it two bands of blue ice occurred alternately with three bands of exceptionally white bubbly ice, all of which trended across the regional foliation of the surrounding ice. Toward the northeast this structure curved more northward, and recent cracks opened out to a centimeter or two, first in the central white ice and then in each of the bordering white bands.

The simplest origin which fits these facts is that of water refreezing in a crack. Because of the lack of air bubbles, which must have been eliminated before the water froze or were crowded out in the ice, this ice did not melt as fast as the white ice surrounding it, and each "blue band" made a low ridge across the ice surface in the ablation zone. In many places there were tiny rapids or waterfalls where melt-water streams passed across one of these bands.

Foliation and bubbles. The foliation of glacier ice is recognized by bands of very bubbly white ice and dark ice with sparse bubbles. In the dull light in the tunnel, bands with few bubbles appeared rather dark, but in brilliant sunlight on the ice surface they were blue owing to refraction. Banding was observed everywhere that glacier ice was fully exposed, but it was hard to discern near the snowline. Folia could be seen as a faint structural feature on the white ice cliff, although they became masked by layers of dirty ice on the ice toe below.

On the surface of the glacier the foliation roughly paralleled the edge of the ice cliff, but by no means exactly. Short lines with ticked ends (Fig. 55) show the strike at about 40° to the face of the ice cliff between stakes rows 13 and 17 (360 and 510). In the field, the folia bands could be seen intersecting the cliff and dipping down the face at low angles for short distances, flattening and continuing essentially horizontal for much of the cliff face, and then rising at low angles to reappear on the upper surface. Dips of folia were all in a northerly direction. The amount of dip was extremely variable but, in general, it was steepest (40° to 70°) at the high edge of the ice cliff and decreased westward to 20° or less on the cliff up Survey Hill or northward within 0.5 km. Going back in the ice tunnel, dips of foliation decreased from 41°N at 3 m in from the original entrance to 15°N at 15 m in, and 12°N at 23 m. On the walls of the vertical shaft 28 m in from the tunnel entrance, dips of near 10° at 5 m above the rocky floor of the glacier became less and less with depth until at 1 m above the boulders foliation was virtually parallel to the floor.

The attitude of this foliation, when compared to the zones of increasing motion already described, made it abundantly clear that the trajectory of the forward thrust of the glacier occurred approximately along the plane of foliation. At the east base stake for plane tabling, the annual motion was exactly in the plane of foliation. Just at the edge of the ice cliff where net motion was southward and downward, the foliation dipped steeply northward; probably this foliation was residual from upward motions 10 to 200 m to the north (Table XVII), but was depressed locally by failure of the cliff face.

Several bits of evidence indicate that these bubbly bands are constantly shifting and reorganizing in accordance with the vicissitudes of ice motion. For example, at 9 m in the original tunnel (Fig. 54) a thin clear ice band noted in detailed mapping in 1955 was not present in 1956. A nearby area of clear ice on the wall had changed shape near its base; and an inclusion of bubbly ice noted in 1955 intersected the boundary of the clear ice area in 1956. At 6 m depth (peg 3), the bubbly zone below the dirt band in 1955 had become a zone of clear ice in 1956 (Fig. 54). In the tunnel between pegs 1 and 2, not only foliation but also dirt bands and tension cracks had flattened out between 1955 and 1956. Some change was noted along the cliff face where foliation intersected the cliff face at an angle near 20°. Strikes read in 1956 by Merrill are generally at lower angles to the cliff face and dips are higher than those taken by Dresser in 1955.

Table XXX. Attitude of structures on the west tunnel wall 3 m in from the entrance.

Year	Open cracks tension Strike	Dip	Dirt bands shear Strike	Dip	Bubble bands foliation Strike	Dip
1955	N86° W	54°S	N79° W	61° N	N70°W	41° N
1956	N83° E	49° S	N79° W	53° N	N81° W	40° N

The surface expression of foliation, whether on the ice cliff where it was weak or on the surface of the glacier where it was strong, was one of differential melting. The hummocks and ridges, which grew more accentuated through the melt season (p. 22) and became as much as 2 m high, had a miniature cuesta and vale topography. Ridges and hummocks tended to have a gentler slope northward (downdip) than southward. Looking along the strike of foliation, one saw a series of similar small knobs a decimeter or two high in alignment on ridge after ridge. High points were generally relatively bubble-free blue zones.

Within any one band of foliation, the individual bubbles of trapped air were stretched out into elliptical form or even pulled out into a long thin thread. Here and there perfectly spherical bubbles were scattered among the elongated ones. When melting occurred on ice surfaces exposed to sunlight, these stretched bubbles popped or exploded, throwing droplets a few centimeters into the air and making a faint sizzling noise. Clearly the air is under a significant confining pressure resulting from prior deep burial under the main mass of the North Ice Cap (Bader, 1950). In addition to the confining pressure, there must have been shearing of the ice mass in order to produce and maintain elongation.

In general, rows of stretched bubbles tend to parallel foliation, but in places they cross folia boundaries. Where white bubbly ice folia thicken and thin, the rows of bubbles within them diverge and converge to make the changes in thickness, but dips of stretched bubbles do not exactly parallel the dip of the bubbly foliation band of which they are a part (Fig. 54).

In 1955 it was found that both the foliation and the contained rows of stretched bubbles passed through a dirt layer near the tunnel entrance, but were not offset along it (Goldthwait et al., 1956, p. 55). In 1956, bubble layers that were parallel to the folia bands which contained them were found reoriented so that they passed through folia boundaries. At some places bubble trends that had intersected and crossed dirt bands, and folia boundaries in 1955 were reoriented so that they paralleled either the dirt band or the folia boundary. It seems logical to conclude that foliation is very sensitive to change in ice motion and that bubbles migrate fairly rapidly as new differential pressures are developed.

Dirt bands. Near the lower part of the face of the vertical ice cliff there were parallel dirt bands traceable individually for 10 to 100 m. Since this was the zone of greatest shearing (p. 52) and there are offsets of 1 to 20 cm in a sort of inverted staircase, the dirt was associated with shear zones. Shear zones and dirt bands have long been associated, and all of the evidence gathered here would indicate that the distribution of dirt was due to the motion of a shear couple in the forward thrust of the ice.

These dirty shear zones showed a great variety of orientation and are by no means parallel to each other. Within the tunnel the dips of individual shear surfaces ranged from 43° to 76° toward the north. Within the tunnel the very dirty bands were 2, 3, 10 cm thick, and displacements were shown to be distributed throughout the zone; i.e., these are zones of active shear (p. 52). On the face of the ice cliff these shear zones rose and fell with the topography at the base of the glacier. There seemed to be an upper limit within the ice mass above which this material does not migrate. In the whole Nunatarssuaq region dirt was never found more than 31 m vertically upward on the toe and cliff face.* At the bottom of the 1956 tunnel, however, there was no dirt more than 1.3 m above the bed of the glacier. When the dirtiest shear zone found, at 6 m, inside the 1955 tunnel was followed downward in the 1956 excavation, it was not continuous to the glacier floor nor to the position of the 1955 shaft 28 m back. Each dirt band visible horizontally along the face of the cliff and each dirt band which could be followed far back into the interior of the glacier got nearer the ground but then lensed out into clean ice.

Folding has been recognized in such dirt bands for a long time. On the steep ice surface at the top of Survey Hill, dirt bands exposed late in 1955 revealed a whole series of intricate folds, all isoclinal and lying on their sides. The steep ramp-like surface of the ice edge truncated these folds approximately at right angles to the dip of the axial plane.

Within the year between observations, the folded dirt bands 8 m in from the tunnel mouth rotated forward a little, and the dirty shear bands which were relatively far apart at the purple plug in 1955 (Table XXXI) became much closer together on either side of the plug and even joined on one side by 1956. Two other dirt bands just to the north were about 0.05 m farther apart, and the top of the lower zone was greatly drawn out and attenuated at a low angle during the year.

In the broad picture there was a similarity of orientation and attitude between the bubble band folia and the dirt band shear zones. Both had a strike very roughly parallel to the ice edge. In detail, however, they crisscrossed slightly in every area where close observation was made. Close to the entrance to the tunnel in 1955, a shear surface cropped out which crossed, at 20°, the foliation and lineation of stretched bubbles. Foliation and the bubbles were neither offset nor truncated by the dirty shear surface but continued through it. In the thicker dirty zones next to the north,

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* In the area 0.5 to 4 km east of Red Rock Lake, where the ice of North Ice Cap meets a thick ice mass which is stationary or moving very slightly in the opposite (northerly) direction, the dirt may be many tens of meters higher for the gravity soundings indicate 60 m of ice (Fig. 53).

some folia and stretched bubble rows were truncated by shear surfaces. Of course, at many places all three were parallel. In the toe ice below stake row 14 (396 m), where waterfalls had scrubbed the surface, dirty shear zones and foliation bubble bands dipped at angles from 40° to 65° north, but the boundaries between zones crisscrossed at acute angles (Fig. 36). Bands of stretched bubbles parallel these boundaries in places or crisscross them elsewhere, and this imparts a crossbedded appearance to the zones.

Table XXXI. Attitude of dirt bands in 1955 and 1956 at 4 to 8 m in the tunnel on its west wall.

Dirt band measured	Attitude in 1955 Strike	Dip	Attitude in 1956 Strike	Dip
South end near floor	N83 W	76 N	N77 W	68 N
South end middle of wall	N76 W	45 N	N77 W	40 N
Floor below peg 3	N84 W	46 N	N89 W	39 N
Floor below purple plug	N74 W	51 N	N84 W	54 N
Wall above purple plug	N74 W	46 N	N59 W squeezed out	40 N
North end near floor	N79 W	43 N	N75 W	40 N
Axial plane of fold		46 to 56 N		40 N

All of these observations lead one to the question: where did the dirt in the outermost lower ice come from? It was, indeed, surprising in 1955 to find the plants and lichens at the bottom of the shaft under 40 m of ice completely intact and the surface undisturbed. On the 30 m² of surface exposed in the larger tunnel in 1956 the same condition existed. Certainly the presence of abundant plant material in the dirty shear planes themselves indicates that all of the dirt was swept once upon a time from the surface beneath the ice. Periodically, a large pod of frozen glacial drift which had moved up one of these dirty shear planes melted out near the base of the vertical cliff. These were observed at many places from 1 to 3 km east of Red Rock Lake and in other entirely different cliffs in 1954 (Goldthwait, 1954, p. 14-17). Some of these masses were outwash material and in some even the crossbedding of the original outwash deposit was preserved. This had neither been macerated nor exposed to ablation and slump. There can be little doubt that this large mass of material was removed intact from beneath the glacier and carried in frozen condition to the ice cliff. Thus, the fluxing currents of ice at the bottom of the glacier must erode or adhere to portions of the ground beneath in certain places and by this means dirt was introduced into the bottom of the ice sheet.

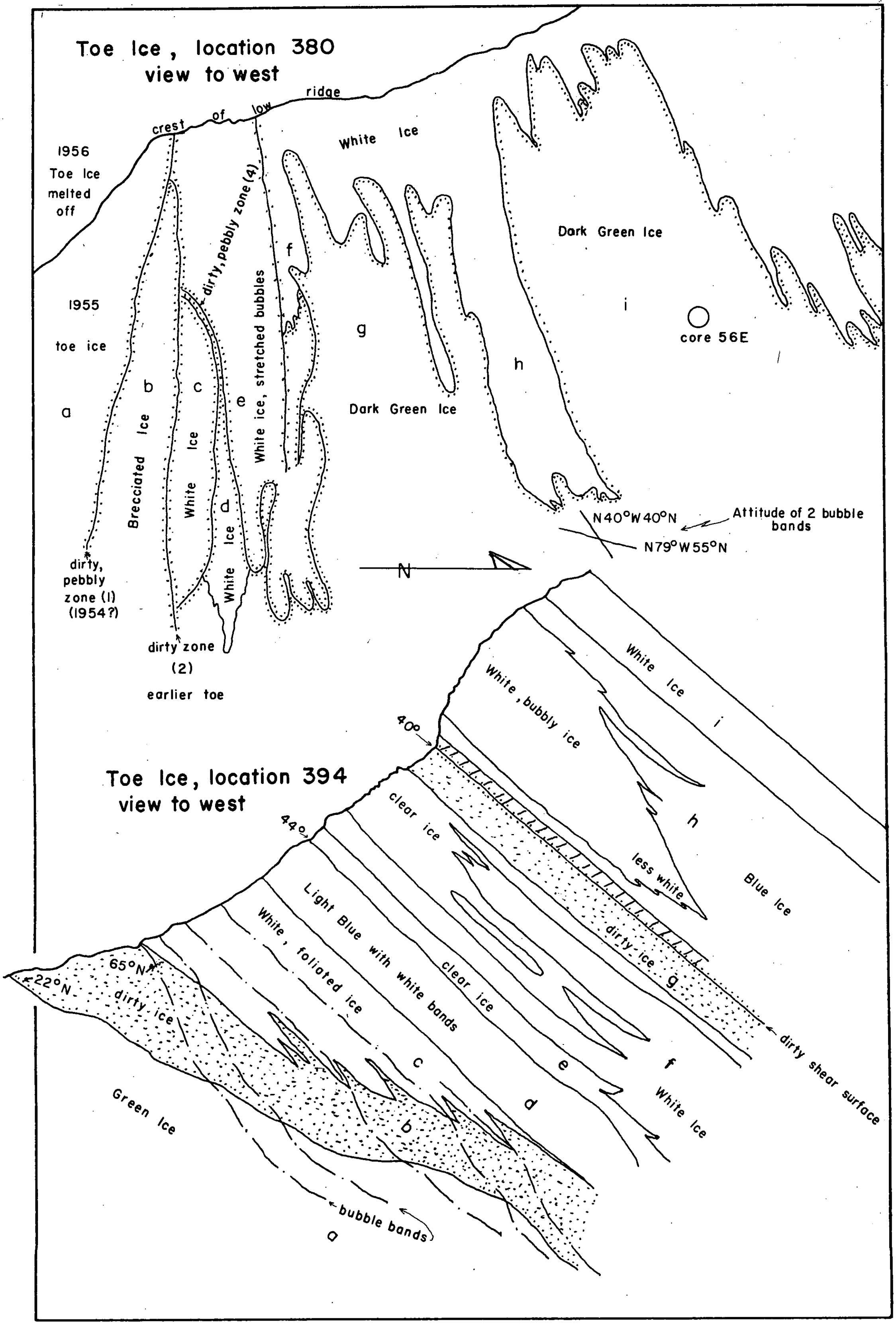

Figure 36. Section through toe ice.

It can be shown from structures in the ice toe that some or all of the dirt now circulating near the ice front is simply reincorporated in the basal layers of ice as the white ice of the glacier above advances onto its nearly stagnant dirt-covered toe ice. Fifteen m east of the tunnel entrance (380 m) a stream from the cliff above cut a cross section through the toe ice which clearly revealed the successive stages of incorporation of superimposed ice and dirt on the toe into the mass beneath the main glacier (Fig. 36, top). White bubbly ice (a) with lack of bubble orientation at the left hand (south) edge was identified as 1955-1956 accumulation by the stakes which had been emplaced in 1955. Below it, but standing at a steep angle, was a pebble dirt band (1) which undoubtedly represented the accumulation on the surface of the toe in 1954. To the right (north) was a series of steep vertical dirt bands more intensely folded and with strongly oriented crystal grains. The dips of bands and folia changed from near 70°S at the left outer toe to 40°N at the right near the vertical cliff. There are various lenses of breccia and ice with intermediate gradations between the superimposed ice (left) and compact metamorphosed glacier ice to the right. Thus, ice which accumulates in snowdrifts and as superimposed sheets covering dirt on the ice toe gradually gets squeezed into a series of folds and overturned until it forms the steep bands of dirty ice near the base of the cliff. This cycle — insertion under the glacier; up the shear plane to the face; falling down onto the toe; and incorporation back under the glacier — might take as little as 25 years or as much as 12 centuries (see Table X). That the plant material in the shear planes is much older (4760± 220 years) than mosses in place on the bottom (less than 200 years old)* indicates that this recirculation has gone on for a long time during advance. Clearly much of the dirt seen at the front of the glacier is worked and re-worked in shear planes and does not represent new material being scraped up from the bottom of the ice sheet.

Crystal distortion

Crystal fabric. Crystal structure is studied most effectively by using polarized light through thin sheets of ice. As study of each section is a 6-hour task, sampling was restricted to 21 localities (24 cores) where typical or interesting gross structures were visible or detailed motion data were available. Since the internal features found are consistent from section to section, it is felt that these represent a sufficient number for valid conclusions.

Cores were obtained by drilling in from the ice surface with the coring auger. Only buried and untouched ice was used. This was obtained from cores 7.6 cm diam and generally 8 to 10 cm long. In order to orient the core and cut section, the end of each core was marked with a knife cut after about 2 cm of hole had been drilled. The orientation of the knife cut was measured with a Brunton compass and, as the segments were removed from the hole, a single groove was cut along the side of the core parallel to its axis starting from the knife cut at the end. Seventeen cores were shipped to the SIPRE laboratories for study. All other cores were placed under cover in the tunnel until sections could be cut and studied near the mouth of the tunnel.

To make thin sections in the field, a disk about 1 cm thick was sawed normal to the core axis with an ordinary 46-cm pruning saw. One side of the ice disk was smoothed by rotary motion of the bottom of a small flat-bottomed pan filled with hot water, then immediately frozen to a plastic plate; little projecting wires prevented the section from slipping. The other side of the mounted disk was melted down by setting the pan of hot water on the disk until the pan rested on the frame around the plastic plate. This left a section about 2 mm thick. If the ice had grains finer than 1 cm in diameter, the section had to be made still thinner by using a smaller pan warmed only by radiation from the sun.

Generally, several such thin sections from any one core were studied on the 4-axis universal stage, which measures 3-dimensional orientation. This was a Rigsby-

* Samples W-408 and W-532 dated by U. S. Geological Survey, see p. 95, 96.

type stage with polaroid sheets for both the polarizer and analyzer. For uniformity, the end of the knife cut marking the orientation of the specimen was kept at the 180° position. Methods of study outlined by Bader (1951, p. 526-529) and Rigsby (1951, p. 593-594) were used. Grains were counted by traverses from left to right, starting at the top of the disk. In coarse-grained ice, where it was necessary to count more than one section to obtain a sufficient number of readings for statistical validity, sections were cut at intervals greater than the largest grain diameter in order to avoid counting the same grain twice.

All readings were corrected for the index of refraction, in accordance with unpublished data furnished by Rigsby. Some error was introduced in 1955 because all readings were recorded as though the optic axis had been rotated to the horizontal position. Later observations at the SIPRE laboratories showed that corrections for differences in indices of refraction of air and ice do not follow Snell's Law (Rigsby, 1951, p. 597-598).

The results are plotted on Figures 54 and 55. Each circle represents a plot on one hemisphere of the Schmidt equal-area net; results were contoured according to procedures outlined by Haff (1938). Lines labeled "foliation plane" on the diagrams are the traces of the intersections of the inclined folia on the hemisphere furthest from the observer. "Poles to foliation planes" are the intersections of normals to the planes with the surface of the hemisphere. Thus, the positions of the concentrated contours show where the concentration of optic axis orientations lies with respect to foliation.

All of the core studies except two (1C and 56A3) showed a marked concentration of crystal axes in 1, 2, or 3 directions. Normally this is interpreted as a result of the strains set up during differential motion in the forward thrust of the glacier. Greater concentration near one point may indicate a longer period of uniform motion, during which reorientation to this axis took place, or it may indicate a stronger motion flux in the ice. A tendency for groups of adjacent grains in a section to be oriented in exactly the same way was noted in 1956. The scattering of grain axes at other than the point of concentration may be relict from earlier orientations in other directions; or may represent the weakness of the force producing these orientations; or may represent a recent trend toward a new orientation.

The two cores showing a very weak pattern of orientation illustrate these points. Core 1C was taken from near the surface of the glacier at a point very near snowline. This may well be ice which was derived from superimposed snow only a few hundred meters away. In any case, its trajectory of motion near snowline would have carried it no more than a meter or two deep. It should have been subject only to general regional tendencies to sink and rise, and thus would not have undergone strong motion forces producing an orientation. The other weak fabric was observed in core 56A3 taken from dye-colored ice inserted into a drill hole in the tunnel in 1955. Undoubtedly the fabric in the original colored ice in 1955 was radial from the center to the boundaries of the core. When sectioned and observed in 1956, only a weak uniform fabric had developed. The weakness may be due in part to the fact that the original colored cylinder did not completely fill the hole and had to be packed in tightly with chips of ice. It does suggest that good patterns take several years to develop in ice where there are moderately strong differential motions.

Comparisons of the fabric of core X (Fig. 54), taken in 1955, with core 56A4 from the same place in 1956 show only minor differences. The first core showed two axial poles within 30° of each other; the new sample showed very similar optic axes and many grains elongated parallel to the foliation. A yellow ice plug inserted into the core hole of X in 1955 and sampled in 1956 (56A3) showed a few concentrations of axes in weak maxima resembling the other two cores. It also shows additional maxima which might be inherited from the freezing of the yellow ice.

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The optic axes of the grains were oriented neither parallel to the direction of foliation (and motion) nor exactly normal to it. In most sections the maximum concentration of the optic axes lay nearly normal to the plane of foliation but was inclined at an acute angle of 60° to 88° to it. The glide planes (0001) of the ice and the foliation plane diverged opposite to the direction of general motion.* In most ways this resembled the orientation of shear cleavage caused by drag during the folding of a sequence of competent and incompetent rock layers. Since ice is a rather uniform material, this might be of no significance; if glide planes within the crystals were sufficiently close together, the optic axes could be tilted within the plates by frictional drag. On the other hand, if glide planes were widely separated, it may be that there was tilting of large crystal segments by differential movement in the glide direction.

One specimen (56M, Fig. 55) from the east stake of the upper baseline was carefully tied to absolute motion. Between 7 July 1955 and 5 July 1956 this stake moved 3.74 m southward toward the main baseline on the ground, 0.98 m eastward parallel with the main baseline, and 1.32 m vertically upward; this motion was in a plane which strikes N 75° E and dips 19.5°N. The foliation at this point strikes N 80° E and dips 21° N, showing that foliation was essentially parallel to the motion. The optic axes here are more concentrated than in any other section but they tilt at about 25° normal to the motion-foliation plane. This lack of a consistent relationship between fabric and foliation suggests that changes in foliation and fabric do not occur exactly together.

In some of the petrofabric diagrams the concentration of optic axes was very lopsided and even extended out into a ridge or tail in one direction (E7A and X). This may be evidence of old orientation in the process of being destroyed, or axes moving along a constant path to a new orientation in the process of developing. Reorientation may lag behind or get ahead of changes in attitude of foliation, but some evidence indicates that changes in fabric occur earlier.

Individual crystals crossed foliation boundaries even if optic axes were related to them. However, many grains were elongated parallel to foliation, and the coincidence of a number of grain boundaries with bubble bands may have resulted from some differential movement between grains. In one case the elongation of the grains was parallel to a dirt zone (shear zone) and boundaries coincident with it, therefore this alignment almost certainly points to failure by fracture. This sort of shear produces failure in rocks. In general, grain boundaries crossed bubble bands with no apparent offset of either one.

One specimen from the toe ice (56L) showed a definite orientation, but a rather broad and weak concentration of optic axes. Another one (56E) showed strong concentration in three maxima (Fig. 55). Since these orientations were not far from normal to the plane of foliation, this seems to demonstrate that toe ice, even though formed from the superimposed ice of old snowdrifts, is dragged and squeezed until it has all the metamorphic characteristics of normal glacier ice.

Distortion of cores. Some motion of the ice within the tunnel has already been described (Fig. 29). However, this involved creep into the artificial opening of the tunnel as well. To study the nature of deformation in continuous ice mass, seven artificially colored ice cores were inserted into holes in the walls of the tunnel in 1955. Blue, red, green, and yellow organic dye was added to ordinary melt water and frozen in tall juice cans to make a cylinder 10 cm in diameter. Holes were made

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* Very similar fabric diagram relations with optic axes tilted (not normal) to foliation were described in Nuna Ramp 15 km south (Rigsby, 1955).

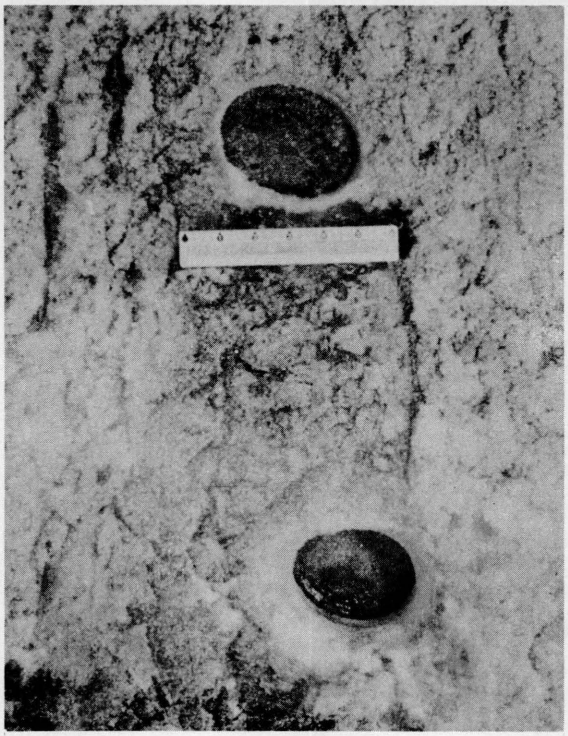

Figure 37. Distorted cores of colored ice at 19 m in tunnel on west wall.

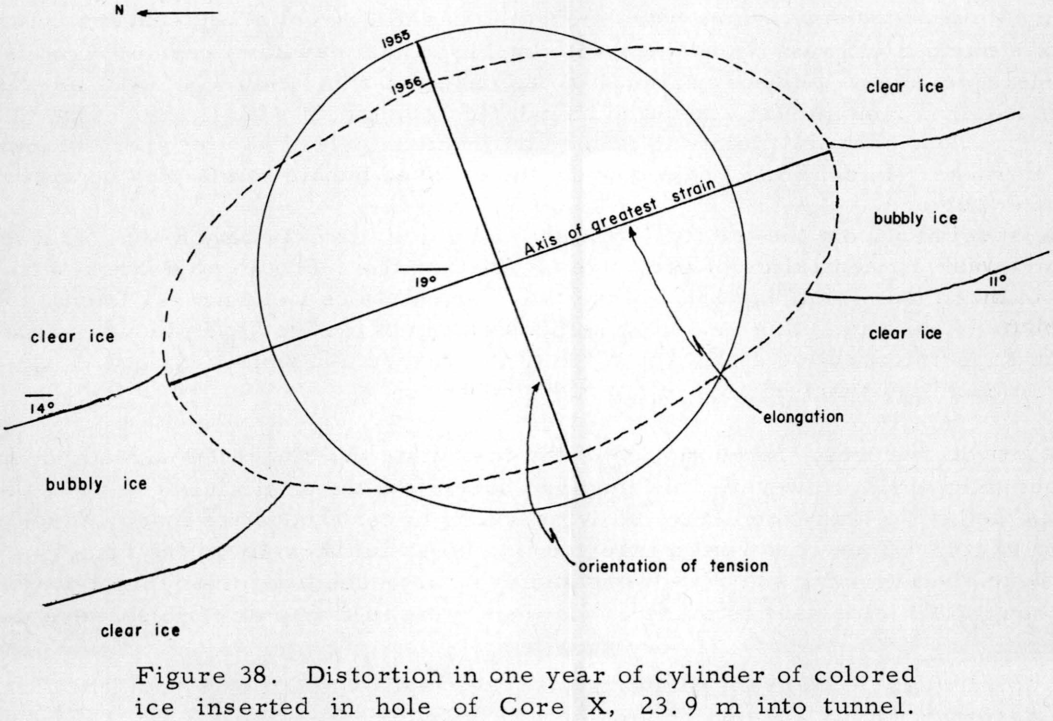

Figure 38. Distortion in one year of cylinder of colored ice inserted in hole of Core X, 23.9 m into tunnel.

in the east and west walls of the middle and inner sections of the tunnel with the 12.7 cm coring auger so that one or more 17-cm sections of this colored ice could be inserted in each hole and packed tightly with cold ice chips until it froze solid. Results might have been even better if the cores had been made to fit the hole exactly, thereby eliminating voids in the packing around the edges. In late June and early July 1956 the dimensions of the exposed ends of these cores were measured with a steel tape (see Fig. 38).

In August 1955 a niche was cut in the east wall 19 m inside the tunnel (between pegs 9 and 10); in this shelf a vertical hole was drilled with a 12.7 cm auger and then filled with antifreeze. This remained liquid and did not evaporate noticeably. In 1956 the cross section of the hole was remeasured with steel tape.

When emplaced in August 1955, every core was circular and 10 cm in diameter; when measured in July 1956, every core was elliptical and about 10.6 x 7.2 cm in cross section (Table XXXII).

Table XXXII. Distortion of cylindrical colored ice cores drilled horizontally into the walls of the tunnel along the strike of the foliation.

Number	Depth from tunnel mouth (m)	Surrounding structure	Dip of long axis	New dimension in 1956 Long axis (cm)	Short axis (cm)
56G purple	8.6 east wall	dirt bands 36°N	31°N	10.5	8.0
56I yellow	17.9 east wall	foliation 17°N	33°N	11.0	7.0
Y′ yellow	18.4 west wall	foliation 17°N	29°N	10.5	7.5
56J yellow	19.9 west wall	foliation 18°N	16°N	10.5	7.0
Z or 56K purple	19.9 west wall	foliation 18°N	21°N	10.3	7.0
X or 56A yellow	23.9 east wall	foliation 15°N	19°N	11.0	6.4
Average				10.6	7.2

There is little question but that the same forces which produced the foliation dipping 15° to 30°N also produced the distortion of cores (16° to 31°N). This is precisely the shape of distortion figured mathematically for rock yielding plastically to a shear couple. It may be checked by tension cracks since, by the same theory, these should dip 50° to 80°S. Nearly all short cracks opening up within the tunnel are in this range.

One other colored (green) cylinder of ice was placed vertically across a dirty band just north of the Blue Room. By 28 June 1956 it dipped 50°N. The vertical hole (filled with antifreeze) seemed to get tipped and the circular cross section squeezed into an eliptical section 12.0 cm NW-SE by 10.5 cm NE-SW.

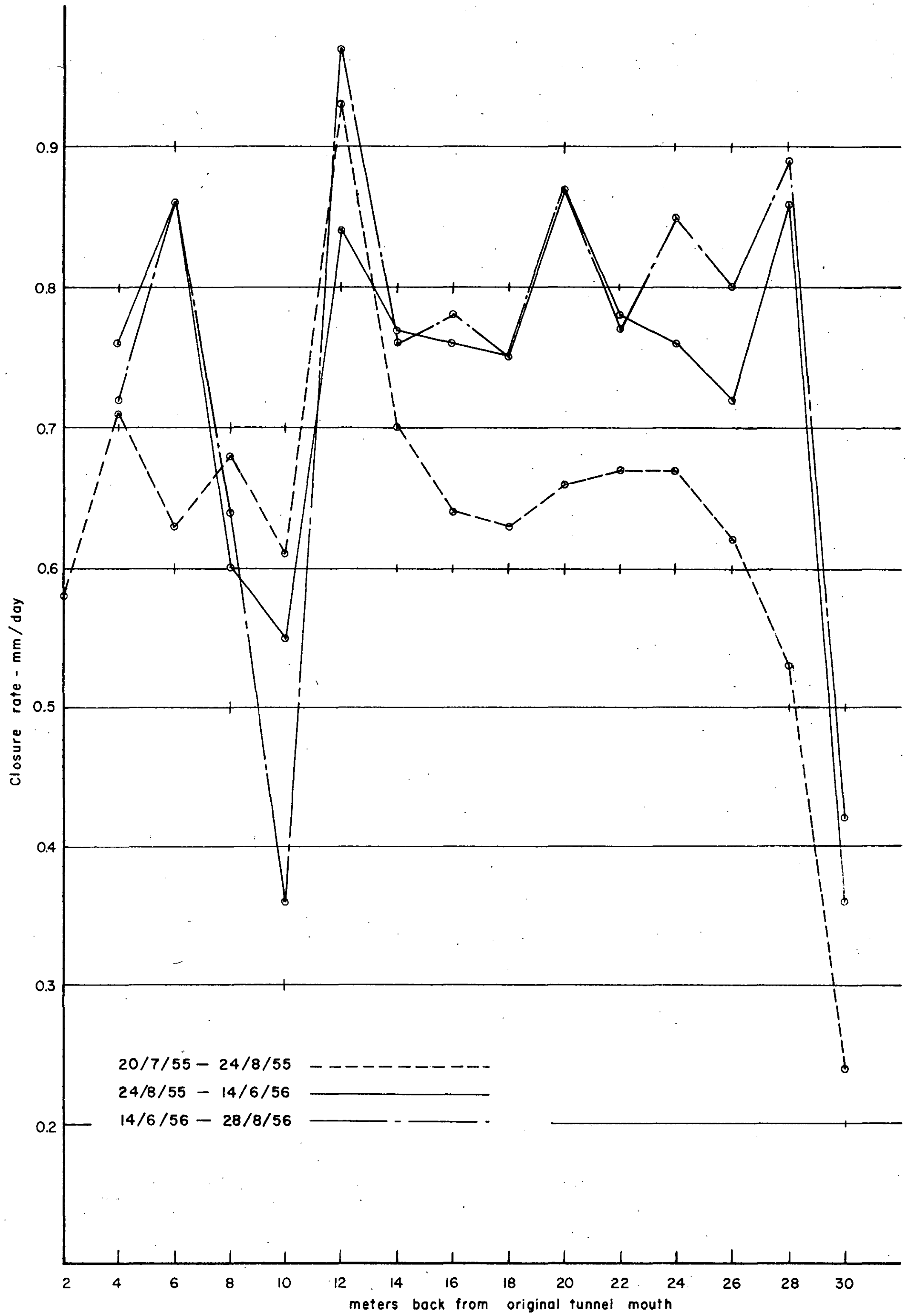

Figure 39. Horizontal closure rate by position in tunnel.

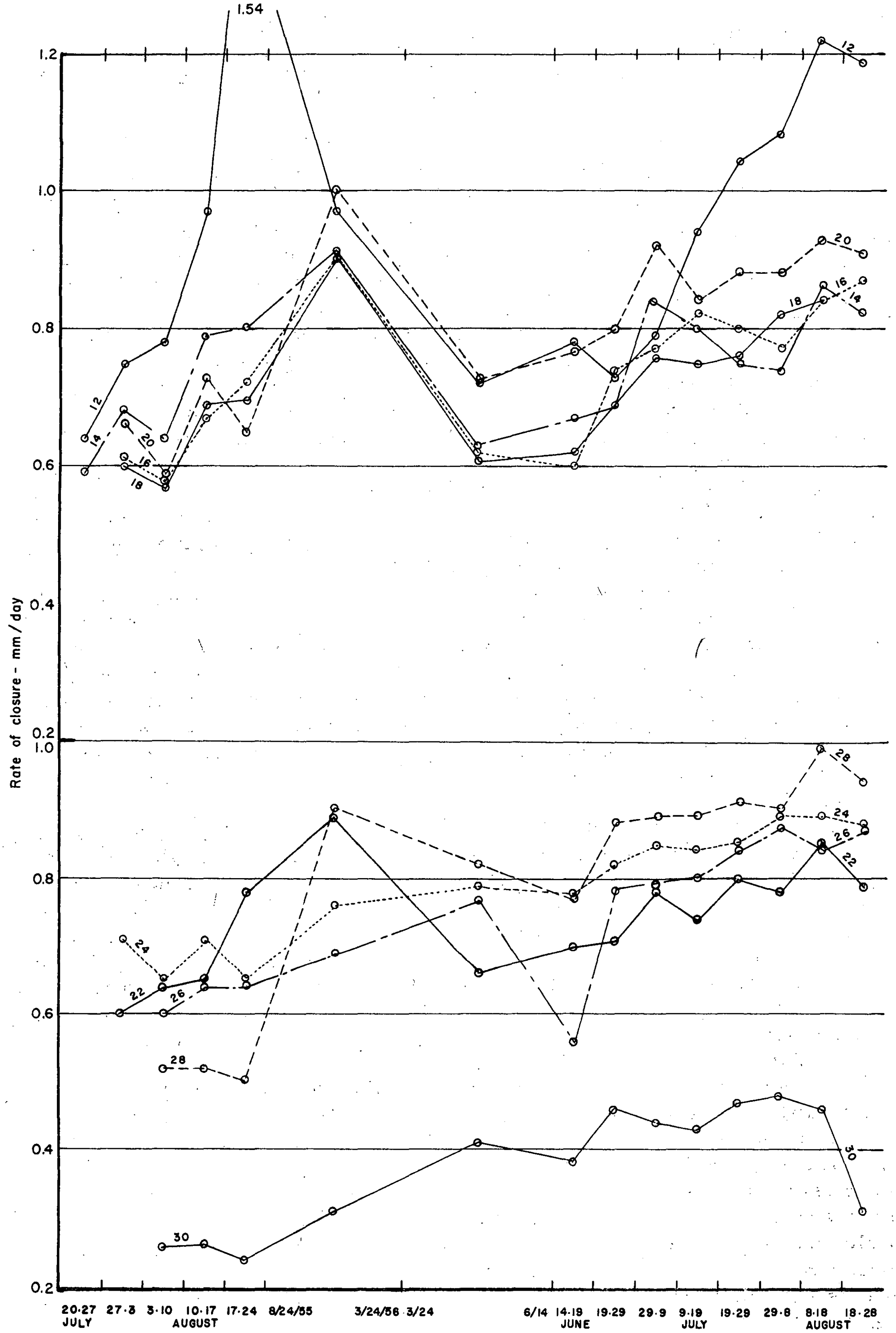

Figure 40. Horizontal closure rates for each period. Numbers give positions in meters back from original tunnel mouth.

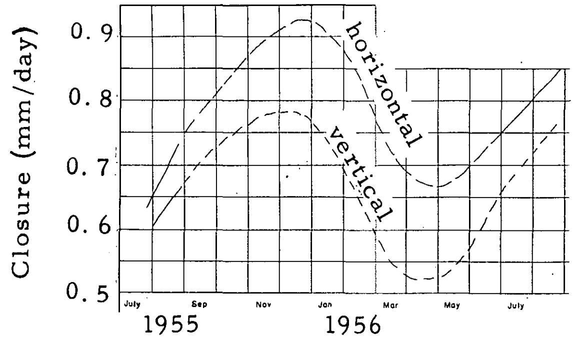

Figure 41. Average rate of closure in tunnel.

Englacial strain

Closure measurements. Deformation of the ice is stimulated artificially by opening a void such as the tunnel under 35 m of ice. Deformation takes the form of a slow creep of the walls of the tunnel toward each other. This deforms the crystals and other structures adjacent to the tunnel, and from it something may be learned of the nature of yielding to stresses in glacier ice.

Closure measurements were made between pairs of pegs in holes in the tunnel walls (p. 46). Measurements were made at weekly (1955) or ten-day intervals (1956) during each summer, using rod extensions of varying lengths attached to a Starrett dial gage. When the gage was left in the tunnel, significant amounts of moisture penetrated into the dial, occasionally freezing the indicator needle to one position. Readings could be continued only after thawing the dial.

The ice moves slightly around the pegs, which were frozen in to a depth of about 30 cm; this was most conspicuous at peg 6 on the east wall, which was recessed by at least 2 cm after 1 yr. The convergence of the pegs on opposite sides gives an average figure for the outer 10 to 30 cm of ice on either side.

Boundary effects were evident both at the mouth and head of the tunnel. The sets of pegs (1, 2, 3, and 4) that were less than 10 m from the original opening of the tunnel, and thus were under the full 31 m of ice above for little or no time showed less closure. For example, the vertical pegs 3 (6 m in) showed approximately 60% as much closure as those at depths of 10 to 26 m. The innermost pegs, at 30 m depth, differed from all of the others because of the support of the rear wall of the tunnel 25 cm away. Both vertical and horizontal closure at 30 m were on the order of 50% as much as that for peg stations through the central part of the tunnel. All these boundary effects were omitted from averages used.

Horizontal closure exceeded vertical closure by approximately 15% (Fig. 41); the walls approached each other at 0.75 mm/day and the ceiling approached the floor at 0.65 mm/day. This indicates that the size and shape of the void determines the rate of strain of the ice around the tunnel. The original tunnel, which was 107 to 140 cm wide, had shrunk more than 27 cm in one year which is 14% of the height of the wall exposed; the roof, which started at 187 to 196 cm above the floor, was nearly 24 cm nearer the floor, or 19% of the total width of tunnel. Another possible indication of the greater effect of vertical closure was the increase of vertical strain rate from the outermost to the innermost reliable pegs (pegs 5 to 13); in the outer area the strain averaged just over 0.5 mm/day, whereas at the inner stations it averaged just over 0.7 mm/day (Fig. 39). This is not true of horizontal peg pairs. This suggests that the vertical effects are just a little greater than the horizontal effect.

A circular section cut in the lower tunnel in 1956 could be measured only over a single 5-day observation in August 1956. With such an equidimensional cross section, its horizontal closure (0.41 cm) was slightly greater than its vertical closure (0.37 cm). Such variations suggest that while these stress conditions seem to approach a hydrostatic state (equal closure on all sides) another important controlling factor may be the horizontal compressive stress of the forward thrust of the whole ice mass above.

What affects vertical strain more than horizontal? Temperature seems to be ruled out, for even though it did increase in the tunnel with time it did not affect horizontal surface more than the vertical. Another possible factor is the dip of foliation, which is more than 41° N near the outer part of the tunnel and less than 12 N near the inner end. It is unlikely that this would affect closure rate directly, but foliation is a result of the forward thrust stress in the glacier obliquely up through the tunnel. It seems possible, but not proven, that this compressive stress toward the front basal edge of the glacier may supplement creep more in the vertical direction than in the horizontal.

Temperature is a definite controlling factor in the rate of strain in the tunnel. This was noticed in changes in the rate of strain while the tunnel was open for work: between 19 June and 18 August 1956 the horizontal creep rate varied by 0.12 mm/day at 26 m where temperature was rather constant, 0.14 mm/day at 22 m, 0.15 mm/day at 18 m, 0.24 mm/day at 14 m, and 1.02 mm/day at 12 m where temperature variations were greatest.

The rate of horizontal closure showed a gradual increase over the course of the full 13 months (Fig. 40, Table XXXIII). Also, the horizontal strain rate in the ice increased by something like 23% from the first to the second summer. In 1955 the significant pegs showed an average strain rate of 0.67 mm/day and in 1956 the same pegs showed a rate of 0.78 mm/day. This is not in accordance with the observations of Glen (1955, p. 526) who found experimentally that creep rate does not increase with time under low stresses. Possibly it is due to the cumulative effect of tunnel air temperature, although that fluctuated irregularly from -2C to -12C during the observation period.

In both summers the earliest measurements of closure (20 to 27 July 1955 and 14 to 19 August 1956) were generally the lowest rates for the season, and the last or next to last observation (17 to 24 August 1955 and 8 to 18 August 1956) was the highest for the summer. A plot of average closure rates against time (Fig. 41) also shows this general increase from July 1955 to August 1956, but, if correctly interpolated through the March 1956 reading, it implies that the most rapid motions of all occurred between August 1955 and March 1956 and the very slowest motions of all occurred between March and June 1956. In other words, each summer represented an accelerating rate between the lowest rate which occurred sometime before the melt season (late April?) and the highest rate near the end of the year (December?). Since the hydrostatic pressure remains constant, one might look to heat again as a cause of this acceleration, and yet it is unlikely that the heat energy stored in the ice and the air of the tunnel could have a lasting effect until December. The increase in motion and thus longitudinal compressive stress between late March and early June and the definite decrease in early August (p. 37) do not coincide with these changes in rate of closure either.

In general, horizontal closure rates between 14 and 26 m depth were rather uniform; the strain rate varied by only about 0.1 mm/day during any season. However, the creep rate at peg 6, which was not particularly fast at the beginning of each summer, almost doubled (1956) or tripled (1955) its rate by mid-August. As with other pairs of pegs a small part of the rise in strain rate must be due to increasing temperature. However, there was no concentration of heat at this one peg locality. This ice, 12 m in, is situated in a zone of high shear stresses and of dirty ice bands (Fig. 54). This may well be due to an actual zone of failure and slippage within the ice mass, since the floor of the tunnel developed a small step or offset estimated to be 4 cm high at about 10 m in from the original entrance.

Predicted closure. The rate of closure of a tunnel in ice has been expressed in a formula by Nye (1953, p. 477-489) so that we may compare these actual measurements with the predicted closure. The fact that this formula was calculated originally for an inclined tunnel is probably not too important:

$$S = \left(\frac{P}{nA}\right)^n$$

Table XXXIII. Horizontal closure rate between tunnel walls.

Summer 1955

Strain rate (mm/day)

Peg	Distance from tunnel mouth (m)	20 July to 27 July	27 July to 3 Aug	3 Aug to 10 Aug	10 Aug to 17 Aug	17 Aug to 24 Aug	Avg
1	2	0.52	0.64				0.58
2	4	0.61	0.70	0.70	0.83		0.71
3	6	0.47	0.63	0.65	0.73	0.70	0.63
4	8	0.60	0.68	0.68	0.66	0.79	0.68
5	10	0.57	0.59	0.58	0.68	0.64	0.61
6	12	0.64	0.75	0.78	0.97	1.54	0.93
7	14	0.59	0.68	0.63	0.79	0.80	0.70
8	16		0.61	0.58	0.67	0.72	0.64
9	18		0.59	0.57	0.68	0.69	0.63
10	20		0.66	0.59	0.73	0.65	0.66
11	22		0.60	0.64	0.65	0.78	0.67
12	24		0.70	0.62	0.71	0.65	0.67
13	26			0.60	0.63	0.64	0.62
14	28			0.52	0.52	0.55	0.53
15	30				0.26	0.23	0.24

Summer 1956

Peg	Distance (m)	14 to 19 June	19 to 29 June	29 June to 9 July	9 to 19 July	19 to 29 July	29 July to 8 Aug	8 to 18 Aug	18 to 28 Aug	Avg
1	2									
2	4	0.69	0.76							0.72
3	6	0.83	0.89							0.86
4	8	0.69	0.59							0.64
5	10	0.33	0.39	0.38	0.44	0.35	0.38	0.37	0.24	0.36
6	12	0.78	0.72	0.79	0.94	1.04	1.08	1.23	1.17	0.97
7	14	0.67	0.63	0.84	0.80	0.75	0.74	0.87	0.82	0.76
8	16	0.60	0.74	0.77	0.82	0.81	0.77	0.84	0.87	0.78
9	18	0.62	0.69	0.76	0.75	0.77	0.82	0.84		0.75
10	20	0.77	0.80	0.92	0.84	0.88	0.89	0.93	0.92	0.87
11	22	0.70	0.71	0.79	0.74	0.80	0.78	0.85	0.79	0.77
12	24	0.76	0.82	0.88	0.84	0.85	0.87	0.90	0.88	0.85
13	26	0.56	0.78	0.84	0.80	0.84	0.90	0.84	0.87	0.80
14	28	0.77	0.88	0.89	0.89	0.91	0.90	0.96	0.92	0.89
15	30	0.39	0.46	0.43	0.43	0.48		0.47	0.31	0.42

where $\underline{S}$ is the rate of contraction, $\underline{P}$ is the pressure of the overlying ice, $\underline{n}$ is a constant determined by Nye to be 3.07, and $\underline{A}$ is the rate of stress. Since $\underline{A}$ is the unknown factor in this application, we may transpose to get:

$$A = \frac{P}{nS^{1/n}}$$

The calculated values for A average 3.2×10^8 dynes/cm^2-sec $^{1/3.07}$

P is determined from

$$P = dgh$$

where d is the density (0.88 for glacier ice), g is the acceleration due to gravity, and h is the vertical depth of the overlying ice.

The rate of contraction S is evaluated by the equation:

$$S = \frac{V}{a}$$

where V is the rate of closure, and a is the distance between pegs.

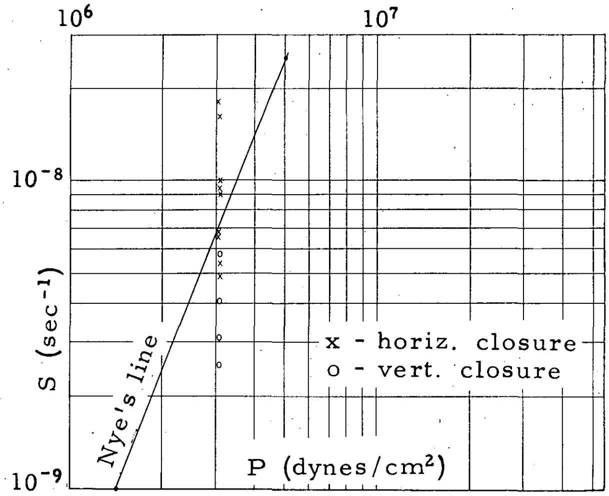

Figure 42. Effect of ice pressure on closure.

The values of P and S are plotted on Figure 42. Even using these figures from pegs unaffected by conditions existing at either end of the tunnel, there is still a wide divergence from the results of Nye because the points have a wide vertical spread. However, if one takes the average horizontal rate of closure and the calculated pressure, that point falls close to Nye's line. Since the overburden of ice varied by only a few meters from one end of the tunnel to another, a horizontal distribution of points could not be obtained. The fact that the results are at all similar to those of Nye is significant, since this cold ice (-14C) at the edge of an arctic ice cap might be expected to behave differently from the warmer ice (0C) of mountain glaciers studied by Nye.

Another physical relation follows from Nye's formula for calculation of shear stress T on the bed of the blacier (Nye, 1952, p. 83). The formula is:

$$T = d\, g\, h \sin b$$

in which b is the angle of glacier surface slope.

Values of shear stress on the subglacial floor in this marginal zone of North Ice Cap range between 0.84 and 1.42×10^6 dynes/cm^2.

Table XXXIV. Calculated values of shear stress on glacier bed.

Location (Fig. 53, 55) Seismic profile AA	h, Ice thickness (m)	b, slope of glacier surface	T, stress (10^6 dynes/cm^2)
Level stake 1	42	12° 43'	0.84
80 m north of ice cliff	64	11° 18'	1.08
Level stake 2	100	6° 57'	1.04
Midway between ablation stakes 34 and 35	123	5° 11'	0.96
West end of traverse CC'	146	6° 29'	1.42
Near ablation stake 54	147	4° 39'	1.03
110 m south of level stake 4	155	5° 01'	1.17
Level stake 4	163	5° 11'	1.27
Weather shelter III	189	4° 28'	1.27
Average value of stress			1.12

These values fall within the ranges for mountain glaciers (between 0.5 and 1.5 x 10^6 dynes/cm^2) as determined by Nye (1952, p. 86). The calculated shear stress in the marginal area of North Ice Cap, however, (average 1.12 x 10^6 dynes/cm^2) is considerably greater than the values determined for the southern lobe of Barnes Ice Cap on Baffin Island (average 0.4 x 10^6 dynes/cm^2) (Orwig, 1953, p. 242-246). This difference is accounted for mainly in the relatively steeper glacier surface in the marginal zone of North Ice Cap.

Summary of ice structure

Fractures produced by tension were generally 10 to 100 m long but only 2 to 10 cm wide. The majority ran from northwest to southeast (Fig. 55) and were concentrated in the southeast part of the map near the ice cliff with secondary concentration in the southwest part. They dipped steeply and cut across foliation. A few small short cracks opened on the walls within the tunnel. These were generally along the axis of least strain perpendicular to foliation and most passed to pegs emplaced in the tunnel wall, indicating that a weakness was produced by this drilling. In general, these cracks strike in the direction of ice motion although a secondary set widens rapidly right next to the cliff and parallel with it. Blue bands of ice a few centimeters to a meter wide are also nearly vertical and cut across the foliation, so that they seem to have originated by the filling and refreezing of former cracks.

Foliation consisted of alternating bands of very bubbly ice and ice with few bubbles. These had a strike roughly parallel to the cliff and dipped north in all cases. The dip was steepest (40° or more) on the glacier surface near the cliff and gentler (20° or less) to the north and at the bottom of the ice cap. At two places at least, the plane of ice motion was found to be almost exactly that of the foliation and all criteria indicated that foliation was due to differential motion. Individual bubbles and groups of bubbles were found to shift during the interval of a year, especially where detailed diagrams were made in the tunnel. These bubbles were under pressure; they burst and expanded as the ice surface melted down. In the ice they were stretched out generally in the plane of foliation, although in detail they were sometimes oblique to that plane or its dip. It appears that with changing directions of motion the bubbles shifted and became oriented first one way and then another. In one year these motions distorted colored cores of ice, originally circular and 10 cm in cross section, into ellipses 10.6 by 7.2 cm. The axes of elongation of these ellipses were tilted parallel to foliation.

The lower portions of the glacier (up to 31 m on the cliff face but only 2 m high back under the glacier) contained bands of concentrated dirt or dirt disseminated in amber-colored ice. This had been intricately folded in recumbent isoclinal folds. Folia and stretched bubbles were roughly parallel to these planes of dirt but also passed through them suggesting motions taking place before or after the distribution of dirt. It was shown that the immediate source for most of this dirt was the toe of sloping, dirt covered ice just below the ice cliff where ablation material collects each summer. In most summers at some spots net accumulation of winter snow or fallen ice over this toe is refrozen into superimposed ice. This ice entraps the dirt again, and as the glacier mass overrides the toe, this dirt band gradually tilts to vertical, gets folded, and is overturned. Finally it is reincorporated in the shearing action and moves up toward the low part of the cliff face to melt out once more. Thus, plant materials on some shear planes may have been recirculated several times for they dated 4760 ± 220 years old (by the radiocarbon method) whereas vegetation collected from ground surface beneath the glacier dates the local advance at less than 200 years ago.

The optic axes of the crystal grains showed strong preferred orientations except for two samples; one in the toe where snow probably accumulated recently as superimposed ice, and one very near snowline where it had never been buried very deep. Even the colored ice plug placed in the tunnel wall for just one year showed weak concentrations of crystal axes similar to those in surrounding wall ice. The optic axis is not normal to the plane of foliation or motion, as one might expect but it is tilted at angles up to 30°. This may represent a bending of the optic axis with respect to the gliding plane (0001) in the direction of shearing motion. Weak concentrations of crystal axis orientation or "tails" may indicate the initial stages of a reorientation or may be the remainder of an old orientation now largely destroyed.

The effect of creep due to the rather uniform pressures of overlying ice could be seen in the closure of the tunnel walls toward one another at 0.75 mm/day. Within 10 m of the mouth of the tunnel, where the pressure was less, the closure was less. At the head of the tunnel (30 m in), closure was 50% less because support was afforded by the end of the tunnel. The span of ice surface being supported affects the rate of closure as illustrated by the fact that the ceiling approached the floor more slowly (0.65 mm/day). Careful comparison, however, shows that the effect of vertical closure was just a little greater than that of horizontal closure when due allowance is made for the length of the span. Some non-hydrostatic horizontal compressive stresses also acted on the void.

The principal factor controlling the rate of closure appears to be air temperature in the tunnel. Closure was much more variable (1.02 mm/day) near the mouth of the tunnel; it was very slow early in each summer when the air in the tunnel was cold but faster in August after the air had warmed up. The net rate of closure in the second summer increased by 23% over the first. One pair of pegs (12) showed normal motion between the summers, but very erratic speeding up during each summer. This local spasm is attributed to shearing action in this particular portion of the tunnel.

The average rate of closure of the tunnel void corresponded fairly well to Nye's formula for the rate of stress (A). Individual points based on individual tunnel measurements vary greatly from this average, however, and no series of points could be obtained under different depths of ice. The calculation of the shear stress on the bed of the glacier, based on the slope of the surface and ice thickness, indicate 1.12×10^6 dynes/cm^2 which is within the range of figures given by Nye. It is greater than figures given for Barnes Ice Cap.

These physical similarities to temperate glaciers are of particular interest in view of the fact that temperatures 6 to 8 m down in this ice measured -11C to -13.3C and that, projecting the temperature gradient curves downward, the deep ice temperature is believed to be about -14C. In the tunnel the air affected not only the creep rate but also the temperature of the ice, which had a gradient in the summer of 17.6C/m right next to the outer wall and 1.4C/m at 1 m depth. Temperature profiles indicate that the ice surface on the glacier above moved from near -40C in the coldest part of winter to 0C during more than 1 month of summer. Warmest temperatures at shallow depths in the ice were recorded nearly two months after summer solstice. It appears that the zero isotherm may be depressed 10 cm or more below the ice surface by percolating water or absorption of radiation at crystal boundaries. The ice in the face of the cliff warmed from 1C to 3C more than the surface of the ice above due to its early exposure (no snow) and to the "baking effect" of the cliff topography. The input of heat required for known ablation of the ice surface was 78.1 cal/cm^2-day (1955) or 131.2 cal/cm^2-day (in 1956). At 2 m depth in the ice the temperature increased during the summer at rates between 0.11C and 0.18C/day.

V. HISTORY

Late glacial times

Geomorphological studies. The land area studied in detail is the triangular northern tip of Nunatarssuaq, 6.5 km^2, which lies north of North Lake and between the main Greenland Ice Cap on the east and the North Ice Cap to the west.

Prior studies by Koch (1926; 1929) do not touch upon the extreme northern tip of Nunatarssuaq. Reconnaissance geomorphological observations were made in 1953 by Chauncey Holmes and Roger Colton while mapping the whole of Nunatarssuaq for the Transportation Corps, U. S. Army (Goldthwait et al., 1954, sections II A, B). At the same time, the bedrock was studied by Arthur Fernald and Alan Horowitz (Horowitz, 1954).

The present study began with the construction of a form line map (Fig. 56) from uncontrolled stereoscopic pairs of vertical air photographs taken in 1953. The topographic expressions of possible glacial deposits were studied on these pairs in conjunction with careful field traverses over every portion of the exposed land area in 1955. Two days were spent studying the land area 3 km northeast of Red Rock Lake where the main Greenland Ice Cap and North Ice Cap separate to the east. The glacial map (Fig. 56) is based upon the combined topographic expression and internal content exposed in natural and artificial cuts.

Exposed materials were sampled in two ways. Stonecounts were made in the field to indicate the lithologies of pebbles contained in the material. One hundred pebbles between 2.5 cm and 7.6 cm diam were picked at random from the material in each of 41 locations. The pebbles were washed, broken, and classified according to:

Thule Group rocks -	Basement complex rocks -	Dike rocks -
conglomerate	granite gneiss	aphanitic igneous rocks
sandstone, red to purple	porphyritic gneiss	diabase
sandstone, white to buff	coarse schist or banded gneiss, gray	
shale, red to black	amphibolite schist	
orthoquartzite, gray to green	gray granite	
vein quartz		

Thirty-eight sack samples of materials common to the area were analyzed in the laboratory for mechanical grain size. Each sample was dry-sieved through 4.0, 2.0, 1.0, 0.5, 0.25, 0.124, and 0.062 mm sieve openings. Where the material that passed through the 0.062 mm sieve constituted more than 10% of the total sample, the percent of silt and clay was determined by standard pipette method. Material remaining on the 4.0 mm sieve was discarded since sample size precluded statistically adequate analysis of the coarse fraction of stones and boulders present in almost all drift in Nunatarssuaq. A sand-silt boundary at 0.06 mm and a silt-clay boundary at 0.004 mm were adopted to make these analyses comparable to certain tills analyzed in the United States.

Bedrock: Two major rock groups crop out in the Red Rock area. The southern one-third exposes a metamorphic basement complex composed mostly of a reddish-yellow to gray granite gneiss, which in places shows black bands of amphibole. Although highly folded and squeezed by pre-Cambrian orogeny, the only structure clearly controlling topography is a more recent probable fault trending north-northeast to south-southwest in the southwest corner of this area along the straight headwater course of Gash Valley and southward to Twin Lakes.

The northern two-thirds is underlain by a younger sedimentary series, the Thule Group, which is thought to be very late pre-Cambrian (Hoch, 1933). It lies unconformably on the basement complex and dips 10° to 15° northeast on this north limb of a broad

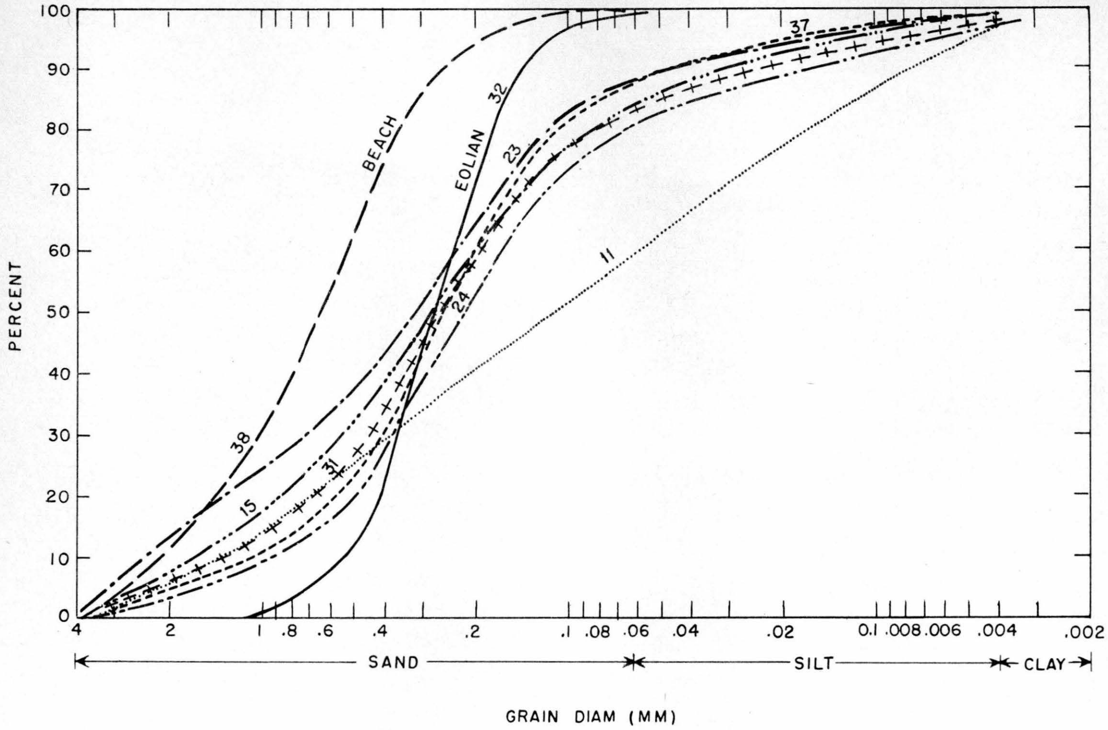

Figure 43. Cumulative percentage curves of mechanical analyses of eight sediments.

anticline. The Thule Group consists mostly of conglomerates with quartz pebbles, red to white quartzitic sandstone, and some small beds of brown and black shale.

Both the basement rock and the Thule Group are cut by late pre-Cambrian parallel intrusive diabase dikes a few tens of meters broad, extending nearly east and west across the top of Dryas Mountain and across the spur south of it. A small plug of granitic rocks 300 m in diameter intruded into the Thule Group occurs midway along the course of Red Rock Creek in the general portion of this area.

The underlying bedrock appears as the dominant rock pebble type in the overlying drift. Since this was found to be true wherever outcrops were available, it was utilized as a method of mapping where no outcrops appear. The distance of transport of the average pebble-sized piece from its outcrop can be hardly more than a few hundred meters.

Glacial drift: Eight different units of surficial drift are indicated on the map (Fig. 56). These are interpreted as follows:

(1) Ground moraine. This is unstratified till (Fig. 44) deposited directly by a glacier and covering 59% of the area. It dominates the gently rolling and sloping intermediate surfaces both east and west of Red Rock Creek down the central parts of the area. The till contains all grain sizes from subrounded boulders, estimated visually to constitute 10% to 30% of the material, to small amounts (under 10% and 20%) of silt and clay (Fig. 43). The coefficient of sorting is generally 2. 2 or more. Fifty to 75% of the pebbles are Thule Group sandstones or conglomerates except at the south end of the area. From cuts it is estimated that the thickness of this material would probably average only 2 to 3 m. On the surface of this material are developed the best patterned grounds.

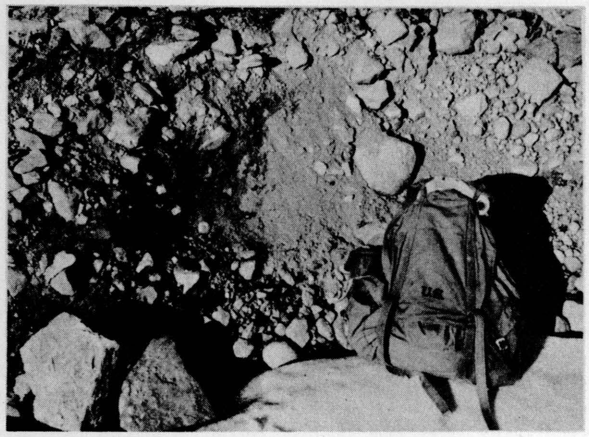

Figure 44. Typical loose coarse sandy till comprising the ground moraine and end moraine in the Red Rock area..

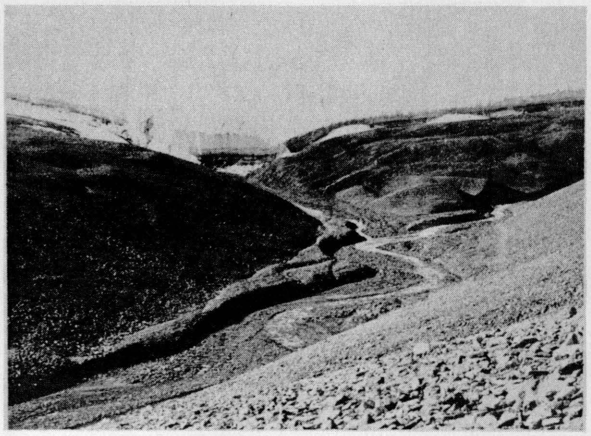

Figure 45. Valley train of Red Rock Creek just below its junction with Sand Dune Valley (center). In the Y-junction is a high kame terrace and on the left is a gravel outwash-delta aggraded to former ponding of this valley downstream. At stream level is typical valley train.

(2) End moraine. This comprises chiefly glacial till similar to that of ground moraine but occurring in morainal ridges over 1% of the area. As a combined result of the slim debris load in the adjacent glaciers, the slow motion of the ice, and the rapid attenuation of any deposit by frost-action, the only distinct belts of end moraines are two linear swells rising above the ground moraine on long slopes just south of Red Rock Lake. These lie in belts around the north end of Knob Hill, a position appropriate to an ice edge coming into the Red Rock Lake basin from either the north or east. The more than 75% of Thule pebbles, unlike nearby North Ice Cap with 50% or less, suggests that ice came from the east. The lack of lobate or sharp down-hill slopes on these ridges seems to preclude the idea that they are solifluction sheets.

(3) Valley train. Under 4% of the area, along the narrow valley floor of Red Rock Creek and its tributaries, there is medium to coarse outwash gravel (Fig. 45). In the quarter of Red Rock Valley just below the middle of the map this gravel is covered by braided stream channels which actively build the valley train each summer. In the northern half some material so mapped is spread by distributaries of modern small creeks on fans coming from slopes on either side, but it is the same sort of gravel material resting on outwash. Boulders up to 20 cm diam are common in some areas, but silt and clay particles are practically absent (less than 3%). Pebble types resemble those in till on either side. This material registers the construction by fully loaded streams of melt water continuing during the period of exposure of this land.

(4) Kame terrace. Important small areas (about 0.5%) on the west slopes of Red Rock Valley are covered by well-sorted dipping beds of sand with variable amounts of gravel. Bedding can be seen on the steep slope of one sector facing Red Rock Creek at its junction with Sand Dune Creek (see Fig. 45). Here a small terraced top stands 18 m above the present valley floor, is kettled on its west side, and would seem to indicate the former presence of ice temporarily blocking the upper courses of Red Rock and Sand Dune Creeks. If so, this was ice on the southeast, the main Greenland Ice Cap. The second area, on the south side of Survey Hill, is a series of step-like terraces that have been dissected by small streams now coming from North Ice Cap. The position of these well-bedded sands indicates ice 20 m or more deep lapping up onto the slope.

The surface of at least one of these flat terrace tops is covered by 2.8 m of till on 0.3 m of bedded gravel and 4 m of sand, suggesting overriding by the ice which contacted the deposit, after the water laid it. Again, more than 60% of "Thule" pebbles indicates this was the main Greenland Ice Cap from the east.

(5) Delta. Slightly more than 0.5% of the area consists of washed bedded gravel deposits, with sand and larger amounts of silt found wherever modern melt-water streams enter Red Rock Lake. The positions of these deposits have been controlled by three successive levels of Red Rock Lake: 5 and 2 m above, and present lake level. Whereas the largest deltas at lake level today, and 2 m above it, are in the northwest and northeast corners of the lake directly below the ice cliff; the largest delta on the 5 m level is above the mid-west shore, suggesting drainage off the top of Survey Hill.

(6) Beach sands. These are very localized deposits (0.1% of the area) of sand and gravel, apparently sorted by small waves, since they were left in strips along the contour around each of two former lakes. The coefficient of sorting is 1.75 and 80% of the grains by weight have diameters between 0.25 and 2.0 mm. At Red Rock Lake these are 2 and 5 m above the present lake, and the upper shore line connects with an abandoned outlet at the southwest corner above the present outlet. Five kilometers south of Red Rock Lake in the valley on the south side of the ventifact field is another beach about 61 m above a small present lake. Evidently the main Greenland Ice Cap just to the south lay higher on the slopes above North Lake and blocked Red Rock Creek waters at this level.

(7) Windblown sand. This likewise covers only 0.1% of the area and is found on the south wall of Sand Dune Valley. Much more sand is found scattered between boulders in the ground moraine throughout the area of ventifacts stretching 2 km south and southeast from Sand Dune Valley, but this dispersed sand was not included on the map. Eighty percent of these grains by weight lay between 1.5 and 0.5 mm diam; the coefficient 1.41 indicates excellent sorting. Based upon the lee position of the largest deposits of sand on this northerly slope, and upon well-etched grooves on hundreds of ventifacts lying in place on the ground moraine surface, it is evident that the wind which carried the sand came from the southeast. This area and the source of the sand is now covered by the main Greenland Ice Cap in a broad tongue reaching North Lake.

(8) Rubble. Angular blocks of bedrock broken up by frost action and covering all bedrock are found over approximately 35% of the area, chiefly on the gently sloping higher parts of Dryas Mountain. On the steeper slopes, such as the sides of the stream valleys where the bedrock is broken up by frost action, some steeper talus rubble exists. In general this angular material simply indicates the nature of the bedrock below, for there are few solid outcrops, and little can be deduced concerning glacial action.

Deduced glaciation. It is nearly certain that the whole of northern Nunatarssuaq was covered by ice until very late in the last (Wisconsin) stage of the Pleistocene ice age. Erratic stones are found in the rubble of every hill, and till with mixed Thule and basement rock pebbles is common to most intermediate slopes. Pieces of the Thule sandstone, found by the Baffin Island expedition of 1950 (Baird, 1950) in stratified marine glacial tills 10 miles north of Cape Christian, indicate that ice from west Greenland moved, probably as shelf-ice, most of the way across Baffin Bay. The only real indicator rocks in northern Nunatarssuaq come from one small source along Red Rock Creek: the intrusive plug of reddish granite. Pieces of this are found scattered in the ground moraine north and northwest of the outcrop along the present margin of the North Ice Cap. Right here the last ice moved northwestward; this must have been the main Greenland Glacier.

All hills are subdued and somewhat rounded in the fashion so characteristic of glaciated areas. Some of the hills to the northeast of North Lake and south of the area mapped showed shaping as rude rock drumlins by ice from the east. Gravity measurements from the 1953 gravimeter survey of Barnes (Goldthwait et al., 1954, sect. IV A)

Figure 46. Eskimo tent ring on slopes west of Dryas Mountain. These boulders have been overturned recently exposing lichen-free sides.

Figure 47. Cairn no. 2 nearest to Red Rock Lake in transect studied botanically. This area is devoid of lichens and probably was recently covered by snowbank and/or water.

suggest a rounded glaciated valley 1600 ft deep entering the region from the east-northeast under Nuna Ramp to a point somewhat south of North Lake. There is no indication that North Ice Cap existed as a separate entity or that ice flowed to the east over any part of the northern tip of Nunatarssuaq.

Deglaciation. The date of the retreat of this main Greenland Ice Cap from the northern Nunatarssuaq land area is not precisely known, and such indirect evidence as exists is not consistent. Extensive frost action, weathering, inner valley erosion, and one distant radiocarbon date indicate as much as 9000 yr of uncovering, while the great paucity of flora and the presence of lichens and willows hardly a century old suggest that the land has been exposed for only a few centuries at most.

The date of 9000 ± 350 years ago was obtained by analysis of the carbon-14 isotope in shells buried in a raised beach along the southwestern margin of Nunatarssuaq, just above Moltke glacier in the vicinity of former Beach Camp.* These shells from only 10 m above present sea level and just above the highest recent lateral moraine and outwash of Moltke glacier (Goldthwait et al., 1954, sect. IIB, p. 18, Fig. 8) may be subject to some possible question, but their age is borne out by other analyses nearby at Thule Air Base (Suess, 1954). Even if the date were in error by 100%, it would still indicate that southern Nunatarssuaq was free of ice during the warmest part of post glacial time, some 3500 to 4500 years ago.

In 1955, three approaches were made to the age of oldest vegetation in the northern tip of Nunatarssuaq. The first was a simple search for the oldest datable plant. Dwarf willows (Salix arctica) were cut and rings counted; the oldest was on west Botanist Flats with 75 annual growth rings. Many others on upper Survey Hill, Knob Hill and east Botanist Flats were as old as 25 years. Dead willow trunks found in 1956 on west Botanist Flats dated to 47 years. Thus, a minimum age for the exposure of all this land is about a century.

Second, lichens were studied for size, which is a function of age. The largest surface Umbilicaria are 30 to 35 mm in diam, although some are double-decked and a few triple-decked. Dead and decaying lichens are absent and growing foliose lichens are not

* Kulp, J. L., letter of 11 March 1954.

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dying at the center as in known old colonies. Of course decomposition is probably slow at 77°N latitude. Assuming that growing *Umbilicaria* increase at the rate of 0.5 mm in diameter per year as is true at lower latitudes*, then the largest lichens now exposed would be 80 years old; if 0.33 mm is assumed, these are a century old. Whereas lichens occur only on the upper exposed surfaces of each rock, old lichens also occur on the undersides of stones found in three eskimo tent rings (Fig. 46). Some of the *Umbilicaria* overturned in these simple shelters were 25 to 28 mm in diam. With new lichen well established on the top of one of these rings, the total time may be over a century. If the arctic growth rate is much slower, in view of the two-month "growing season," and it takes a few decades for *Umbilicaria* to pioneer into the region, the age might be increased by a factor of five. The oldest reasonably possible date is 1000 years.

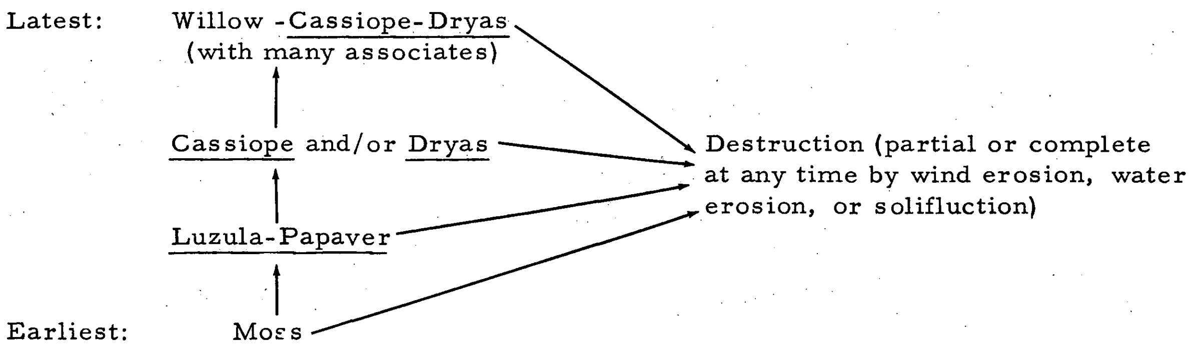
The third criterion is the extremely youthful appearance of the whole assemblage of plants even in favored spots in northern Nunatarssuaq. Where relative stability is attained on upper slopes the basic plant types are:

Luzula confusa
Papaver radicatum
Cerastium arcticum

Enrichment is by some or all of these:

Lichens	Vascular species
Stereocaulon, sp.	*Cassiope tetragona*
Dactylina ramulosa	*Dryas integrifolia*
Cladonia pyxidata	*Poa arctica*
Alectoria minuscula	*Potentilla* sp.
A. pubescens	*Ranunculus* sp.
A. jubata	*Draba* sp.
Umbilicaria sp.	*Saxifraga oppositifolia*
	Saxifraga sp.
	Hierochloe alpina
	Salix arctica
	Silene acaulis
	Antennaria sp.

The dynamic relationships of these communities might be represented diagrammatically as follows:



Taken altogether this indicates the extreme youth of the plant population.

* Wolfe, J. N., measurements on plants in Hocking County, Ohio.

The patterned soils and frost-riven ledges, as mapped in 1953 by Holmes and Colton and as noted by this author, and those mapped in 1955 in northern Nunatarssuaq do not seem to differ in magnitude or character sufficiently to indicate any time difference. Solifluction forms which were marked carefully and mapped in central and southern Nunatarssuaq have shown no significant movement in 1 to 3 years (Colton and Holmes, 1958), and the establishment of firm vegetation mats on the soil centers of patterned soils suggest that these forms were produced relatively rapidly early in the period when this area became deglaciated and have become stabilized long since. The fact that the 1.0 km^2 of land north of North Lake is covered with ventifacts in place and that the boulders of this till are arranged in gutters between polygonal soil centers or in solifluction lobes shows that all of this frost organization must have taken place prior to the cutting by the wind. This simply indicates that the whole of the Nunatarssuaq land area has been exposed, i.e., out from under glacial ice, for at least several centuries and perhaps a great deal more.

During several centuries of exposure late in the Pleistocene ice age, this area, like others further south in Nunatarssuaq, was etched deeply by a second cycle of stream action which produced sharp V-shaped cuts or inner canyons in the otherwise rather broad, rounded glacial troughs. The V-shaped cut of Red Rock Creek commences 1.2 km south of Red Rock Lake and just southwest of Knob Hill, bisecting the broad area called Botanist Flats. This sharp inner valley 20 to 60 m deep is blocked in its east-southeastward course by the broad lobe of the main Greenland Ice Cap, so it must have been formed when this ice cap was further in retreat than it is today. Since this lower Red Rock Creek valley is the one containing high knobs of kame terrace at its junction with Sand Dune Creek, it can be argued that this cutting took place prior to the last deglaciation of northern Nunatarssuaq. However, this may also relate to ice blocking further up into Red Rock Creek Valley by limited readvance at a later date. If this cutting is assignable to the early stages of the last deglaciation, it would indicate centuries of vigorous erosion by streams.

How can plants in northern Nunatarssuaq have begun only 100 to 1000 years ago when, according to carbon-14 dating, most of this land has been exposed for 4000 to 9000 years? The brief botanical work of this study has not settled this question, but three hypotheses seem possible: (1) that the exposure of southern Nunatarssuaq came long before that of the northern tip in spite of physiographic similarities, (2) that after millenia of exposure extensive snowdrifts and partial advance of the Greenland Ice Cap within the last two centuries destroyed all former vegetation, even in exposed areas, so present plants started anew, or (3) that all of northern Nunatarssuaq was covered by the main Greenland Ice Cap less than 1000 years ago but the V-valleys and patterned soils of earlier centuries of exposure were left intact.

The distance of this first retreat of the main Greenland Ice Cap following the Wisconsin (Würm) glacial stage cannot be precisely determined, since there has been subsequent advance. It is evident from northern Nunatarssuaq field conditions that the main Greenland Ice Cap was smaller than it is today and that the North Ice Cap did not exist as an influence in this drainage basin. For example, there are the wind-sorted sands on northern (lee) slopes, and the scattering of these sands between boulders up a southeast-northwest valley at neither end of which is there a sand source today.* This indicates a former source to the southeast and underneath the present main Greenland Ice Cap. By projection, the nearest likely valley with outwash was at a minimum distance of 1 km under the present ice cap.

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* The formation of ventifacts well smoothed and deeply grooved indicates a long time as well. Based upon evidence from Fristrup (1952-53) and experiments by Troelsen (1952) in Peary land, this time would be measured in centuries.

Recent glacier activity

Botanical studies. Both the geomorphological studies and a study of the plants are utilized in discerning the probable recent positions of the ice edges on either side of Red Rock Lake. These botanical studies were carried out in such a short time (14 field days) that detailed observation was restricted to selected small typical areas within the region and no attempt at complete mapping was made.

Sixteen small quadrats some 20 m apart in a line from the west edge of Red Rock Lake (630 m) to the steep edge of North Ice Cap on Survey Hill (696 m) were marked by cairns 0.5 m to 0.6 m in height. At each of these stations species lists were compiled, character of the substrate recorded, and the nature of the vegetation indicated. This transect was laid out primarily for future reference but it indicates the nature of vegetation close to the active Red Rock Lake, above and below a vague "trimline" or near the present active ice edge. Complete plant lists for future study are given in the preliminary report (Goldthwait, 1956, p. 128-131).

In the second group of detailed studies small areas of each typical habitat were selected for analysis:

Lake shores: almost devoid of vegetation
Lower rocky slopes: lichen free, some mosses.
Upper slopes: unstable steep tongues with pioneer plants and gentler ones with well established communities.
Boulder fields: black lichen, upper sides only.
Eskimo stone rings: some lichen on under sides of boulders.

Each species was listed and samples of typical vascular plants and lichens were collected. Critical plants, such as the willow, were cut so that the rings could be counted and search was made for the oldest individual in the area. At random intervals in certain of the habitats studied, temperature readings were taken by inserting a mercurial thermometer in or below mats of vegetation.

Recent readvance. Benninghoff and Robbins (Goldthwait et al., 1954b, sect. IV D, p. 8-9) found a zone of impoverished flora near Nuna Take-Off 15 km south of Red Rock Lake, and up onto First Nunatak. Along the ice margin at Nuna Ramp this impoverishment extends 200 m west of the present ice edge. The black crustose lichen Umbilicaria and Peltigera-like forms occur in this zone, together with the mosses Polytrichum and Grimmia and six species of vascular plants:

Papaver radicatum	Saxifraga cernua
Luzula confusa	Draba sp.
Saxifraga oppositifolia	Festuca brachyphylla. (8137)

Beyond the 200 m zone are found many lichens and the first Potentilla, Poa arctica, Carex nardina, and Cerastium alpinum. Another 100 m farther upslope there is added a rather dense lichen development (collection 8141) on sheltered surfaces, patches of the fruticose lichen Stereocaulon, Saxifraga nivalis (8131), Salix arctica (8130), Arenaria rubella (8132), Lycopodium selago, and several mosses (8128). The fact that the vegetation exists only on the higher inner part of Nuna Knob and that only pioneer plants have invaded the zone along the present ice edge leads to the conclusion that a snowfield associated with the Nuna Ramp has uncovered this 200 m zone relatively recently, probably within the past two decades.

In this same 1953 study, Holmes and Colton arrived at the conclusion that the ice of the main Greenland Ice Cap advanced to 500 m west of the present glacier margin just north of Nuna Ramp. The evidence is a thin cover of scattered gray drift, readily visible in air photographs, and extending in a great loop northwestward from Nuna Ramp across Gash River and northward to the moraine belts holding in North Lake. Two channels cut through the thin gray drift, showing that it lies on top of another layer of older yellow drift heavily stained with limonite.

This is probably the same readvance that carried the very active Twin Glaciers in east central Nunatarssuaq 8 km down Twin Glacier valley to Moltke Lake (White, 1956, p. 25-26). Here this advance is marked by a prominent lateral moraine and lobate terminal moraine. Below this moraine and the level of a high lake trapped by Twin Glaciers at 41.5 m above the present lake, Benninghoff and Robbins found the following plants:

Luzula confusa	Salix arctica (rare)
Carex nardina (cf. 8056)	Cerastium arcticum (rare)
Potentilla sp. (8055)	Papaver radicatum (rare)
Polytrichum sp.	

Lichens (restricted to widely scattered small colonies on boulders).

On the older moraine surface above the highest shoreline the full suite of upland plants is found:

Salix arctica	Potentilla sp. (8055)
Carex nardina (8056)	Melandryum furcatum (8049)
Saxifraga nivalis (8048)	Taraxacum sp. (8051 and 8052)
Potentilla sp. (8053)	Mosses (8060)

Lichens (8061, the usual density of forms on rocks and on the soil).

Assuming the above patterns resulted only from differences in the ages of the surfaces, these authors estimate that the retreat from the 41.5 m level took place on the order of 50 to 80 years ago.

Colton and Holmes note that both the Moltke and Rasmussen glaciers have been somewhat more extensive up to ice-cored lateral moraines which rise well above the present ice surface. These moraines contain fragments of mollusk shells in a very clay-rich till plowed up from the formerly extended floor of Wolstenholme Fjord. Moltke Glacier reached its maximum position down the fjord not far beyond the position it had when mapped in 1916 (Wright, 1939, p. 21). On the other hand, Colton and Holmes suggest that the readvance of the ice carrying the gray drift occurred about 200 years ago when Scandinavian and Icelandic glaciers became considerably larger. It may be that all these ideas indicate the same main event, a general advance two centuries ago with significant retreat within the last three decades.

End moraines in the Red Rock Lake area suggest a similar but not necessarily identical readvance of the main Greenland Ice Cap. Two low belts of probable end moraine wrapping around the northern slopes of Knob Hill just south of Red Rock Lake contain larger numbers of Thule formation rocks than do the high areas of Survey and Knob Hills (Fig. 56). This ice edge extended up at least 20 m high on Survey Hill, to produce the ice contact slope on the kame terraces above Red Rock Creek (p. 86). Three kilometers northeast of Red Rock Lake similar but more marked end moraines wrap around the south end of a hill, indicating that the same lobe of the main Greenland Ice Cap pressed northward some 20 m higher on this hill and spread its load of Thule formation pebbles.

One indication of the magnitude of this recent readvance is found in the relationships of the ventifact area south of Sand Dune Creek to the potential sources for the sand underneath the main Greenland Ice Cap. The linear distribution of this sand toward the

Figure 48. Trimline on rocky slope northeast of North Ice Cap 5 km east-northeast of Red Rock Lake. Profuse lichen above, barren area below. Ice Cap on left.

Figure 49. Abandoned outlet, 5 m above present outlet to Red Rock Lake, which established old beach level. Ice of the main Greenland Glacier or associated drifts lay on the left only a few decades ago. North Ice Cap in the background now.

north-northeast and the cutting of grooves in ventifacts indicate a source 1 km northeast of North Lake. By analogy to other active areas seen along the ice edge, this source must have been a valley train of repeatedly washed sands. It is presumed that North Lake stood at a lower level or was nonexistent when the ventifacts were made. When the readvance came, gray drift moraines blocked the lower part of the valley, raising North Lake to a level even higher than it is today, as registered by a series of shorelines from 30 to 96 m above the present lake level. Solifluction lobes which have come down through and over these shorelines may well be a century or two old; the advance is at least that old.

Continuing retreat of Greenland Ice Cap. There are many indications of progressive retreat in stages from the last advanced position of the main Greenland Ice Cap. A common, but not always sharp, "lichen trimline" between higher dark areas in which the rocks are completely covered by lichen and lower areas where both lichen and vascular plants are scarce marks the limit of snowdrifts which prevented sufficient "growing season" for the establishment of plants. Such a line may be seen from a distance across the east slope of Survey Hill, heading indistinctly into the transect line.* It is noteworthy that below the trimline (plat 5 19.5 m above lake) lichen are somewhat sparse and the common vascular plants are:

Luzula confusa	Poa arctica
Papaver radicatum	Saxifraga sp.
Cerastium arcticum	Polytrichum sp. (moss)
Draba sp.	

In the upper part of this zone near Cairns 3 and 4 a few small Salix arctica and one specimen of Potentilla sp. appear. Then at and above the trimline (Cairn 5) a much more complete assemblage occurs:

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* Wolfe noted only sporadic trimlines here at close range.

Lichens on rocks:

Umbilicaria cylindrica
U. arctica
U. vellea
Alectoria minuscula
Omphalodiscus discussatus
Caloplaca elegans
U. proboscoidea
U. hyperborea

Lichens on soil:

Dactylina

Vascular plants:

Draba 2 sp.
Potentilla sp.
Cassiope tetragona
Salix arctica

On slopes 5 km northeast of Red Rock Lake the trimline and wide expanse of vegetationless substrate below it are conspicuous (Fig. 48). Holmes, Colton, and Goldthwait noted trimlines common in the lower part of every valley in southern and central Nunatarssuaq in 1953 even where no remnants of glacier exist today. Thus, it appears that the trimlines register the fluctuating edge of formerly more extensive snows, some of which were associated directly with the main Greenland Ice Cap, and some of which were semipermanent snowdrifts well outside of the confines of the ice cap. In the area below the trimlines, the period of adequate exposure for growth of arctic plants certainly cannot amount to more than a few decades.

Red Rock Creek is impounded in small lakes at two points against the main Ice Cap within the first kilometer upstream from North Lake. During late June each of these lakes is large because it is blocked by snowdrifts, but it drops 5 m and shrinks as channelways are developed through the drifts and under the ice edge in July and August. Sixty-one meters above the final lower lake, however, there is a small, poorly developed beach on the west shore which connects to a deep outlet cut in bedrock and sloping toward North Lake. The fact that this has been abandoned for a new lower cut into the bedrock under the edge of the present ice cap suggests that the ice once stood higher over this slope. A second small upper lake was ponded back into the main Red Rock Valley where there is now a fine valley train (Fig. 44). A definite niche or small bench can be seen 23 m up on the valley walls; a gravel terrace at the junction of Red Rock Creek and Sand Dune Creek suggests the deposition of the entering Red Rock and Sand Dune creeks at this level. A deep V-shape spillway is cut southeast of this valley 23 m above the present floor of Red Rock Valley where only ice 300 m more extensive than that of today could hold an overflow stream. The spillway is cut to 20 m depth in tough granite gneiss and must represent the erosion of several decades of heavy melt-water flow.

In the basin of Red Rock Lake itself there is evidence of two retreatal stages: one at 5 m above the present lake and the other about 2 m above lake level. Each is marked by a discontinuous sandy beach deposit above the west shore. The 5 m beach level connects to an abandoned outlet cut in the till 5 m above the present outlet (Fig. 49). Since the present outlet is controlled by a semipermanent snowdrift, it seems logical that these slightly higher levels were also controlled by still larger snowdrifts associated with retreatal stages of the last advance of the main Greenland Ice Cap. Cairn 1 at 5 m above the lake is described as rocky to gravelly with rocks devoid of lichens and even of mosses between rocks. However, there are scattered clumps of Luzula confusa, Papaver radicatum, and Poa arctica. These last low level lakes may have occurred within the last decade or two to produce such a sterile area.

Advance of North Ice Cap. The complete absence of any identifiable drift sheet from the west would seem to indicate that the local North Ice Cap has never been farther over the Nunatarssuaq area. As indicated by stonecounts, all movement was toward the

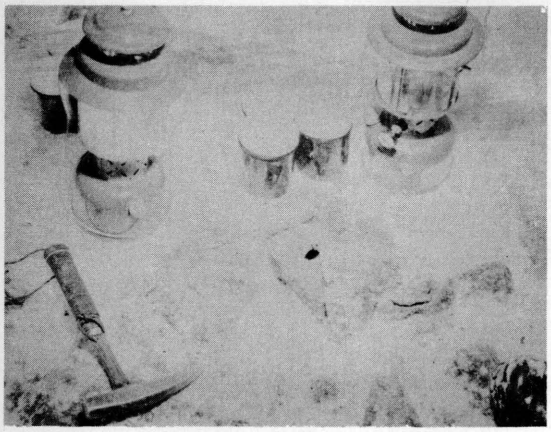

Figure 50. Rocky floor beneath 41 m thickness of North Ice Cap. Showing ice filling around boulder pavement and undisturbed plant material. Dated samples in jars.

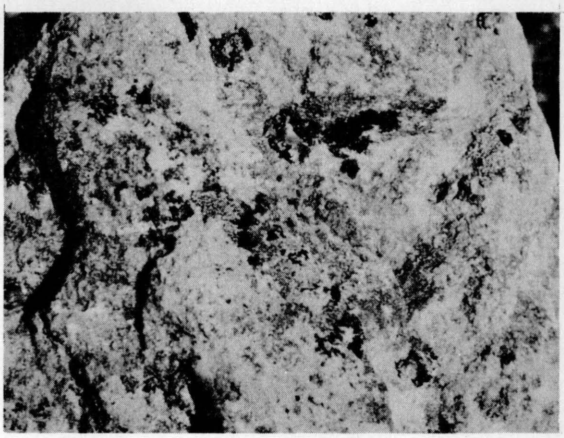

Figure 51. Lichen-covered boulder from rocky surface beneath glacier. Width of boulder on photo about 25 cm.

west, so it is doubtful that North Ice Cap existed as an entity with locally radiating ice even during Wisconsin (Wurm) time.

The patterned soils extending right in under North Ice Cap demonstrate that the last motion of the outer parts of North Ice Cap was one of advance. From the flat top of Survey Hill and along the west edge of Botanist Flats, well-developed polygonal soil centers separated by boulder gutters 5 to 30 m apart extend right up under the cliffed edge of the ice cap. Short trenches into the toe ice of the ice cap demonstrated that these forms continue under the moving glacial ice of the present ice cap. Any hypothesis for formation of these patterned soils involves exposure (Washburn, 1956). Therefore, it is evident that they must have been produced prior to this advance of the outer part of North Ice Cap and that they were covered by this ice without any significant disruption of the form.

Another indication of the advance of North Ice Cap to the east is the nature of the sandy drift being melted out of the tongue of ice which extends into the upper end of Sand Dune Creek. The shear planes are loaded with well sorted sand entirely lacking in either pebble sizes or clay and silt sizes. This material is identical with the dune material on the south wall of the same valley (84% between 0.15 and 0.5 mm diam) and is undoubtedly eolian sand once deposited in the upper reaches of Sand Dune Creek but now buried under North Ice Cap; only advancing ice could plow up these sand dunes.

Wolfe made a study of one boulder about 22 kg in weight retrieved from the bottom of the glacier in the shaft 30 m back (north) from the ice cliff and beneath 41 m of ice (Fig. 51). On its surface and sides this boulder had a continuous cover of lichens undamaged and apparently viable. Five of these lichens were:*

Alectoria pubescens (L.) Howe
Rhizocarpon chionophilum T. Fr.
Umbilicaria arctica Nyl.
Sporostatia cinerea (Schaer.) Koerb.
Lecidea auriculata T. Fr.

* Identified by J. W. Thompson, Department of Botany, University of Wisconsin, personal communication 20 January 1956.

Identification in 1956 of plant materials scraped up from between the boulders exposed 23 m back from the ice cliff indicates the following:*

Rhacomitrium lanuginosum (Hedn.) Brid.
Pogonatum brachyphyllum (Rich.) Beauv.

Since these all represent forms now growing at the edge of the ice cap, an advance of the ice out over previously exposed land is implicit.

The material scraped from the bottom of the tunnel in 1956 has been dated by the radiocarbon method, from acetylene analysis,† indicating an age less than 200 years. Other material found in transit in the shear planes of the North Ice Cap along the cliff 1 km east of Red Rock Lake has also been dated as 4760± 220 years old.** It is evident then that the North Ice Cap began to develop at least 4000 years ago and has grown at least 100 m in the last 200 years.

In 1953 Benninghoff and Robbins made plant collections in Botanist Flats, both on the east side of Red Rock Creek far from the North Ice Cap and next to the cap at the west edge. They noted 16 vascular plants which occurred on both sides of Red Rock Creek:

Luzula confusa	(7852)	Saxifraga oppositifolia	(7862)
Salix arctica	(7850, 7853, 7854)	Cerastium arcticum	(7849)
Papaver radicatum	(7856)	Saxifraga nivalis	(7851)
Carex nardina	(7860)	Draba sp.	(7863)
Hierochloe alpine	(7855)	Melandryum cf. affine	(7859)
Salix arctica	(7858)	Arenaria rubella	
Festuca brachyphylla	(7864)	Cardamine bellidifolia	
Potentilla sp.	(7857)	Mosses	(7865)
Potentilla sp.	(7861)	Lichens	(7866)

They go on to note that the flora within 100 m of the ice front resembles closely the one from the east side of Red Rock Creek with respect to species, but that the relative abundance is different. Within 15 m of the ice cap in the area largely inundated by melt water during July, there was no live vegetation except Polytrichum sp. and scattered tufts of Luzula confusa. They conclude, "From the above observations it would appear that the North Cap is advancing over long established vegetation... A rate of advance of several tens of feet per annum would be compatible with the above interpretation." (Goldthwait et al, 1954, sect. IV D, p. 6-7).

Wolfe found in 1955 that the vegetation adjacent to North Ice Cap on Survey Hill is substantially different from that of the opposing slope of Knob Hill a kilometer away because of the physical conditions of soil and climate in the zones bordered by the ice. Beginning in mid-afternoon the top of Survey Hill is in the shadow of the cliff of North Ice Cap. The melt water from the ice saturates the substrate over a large area during the growing season, resulting in poor aeration and low soil temperatures. Only a few soil temperatures were measured, but one representative set from the unsaturated mid-slope of Survey Hill indicated temperatures of 20C to 25C under Dactylina ramulosa and Alectoria jubata, and 18.3C in a Cassiope mat when the air temperature was 8.3C. At the same time, wherever water stood near the toe of the ice, it was 0C and it saturated large areas of slope but was nowhere above 4.4C. The progress of similar plants on

* Identified by R. Giesy in letter 26 December 1956.

† Sample W-532 reported by Myer Rubin of the U. S. Geological Survey by letter, February 1957.

** Sample W-408 reported from the U. S. Geological Survey, Washington Laboratory by letter of 2 May 1956.

Table XXXV. Condition of vegetation on opposing slopes, 11 August 1955.

Species	On Knob Hill	On Survey Hill
Papaver radicatum	Bud, flower, some fruit	Few buds, past peak flower, most in fruit
Potentilla	Flower and fruit	In fruit, few in flower
Silene acaulis	Past peak flower, mostly in fruit	All in fruit
Dryas	Past peak flower, mostly in fruit	All in fruit
Draba	Mostly at peak flower	Past peak flower, mostly in fruit
Cassiope	Past peak flower, mostly in fruit	In fruit
Saxifraga	Past peak flower, mostly in fruit	In fruit, none in flower
Salix	Leaves green to slightly yellowish	Leaves yellow or abscised
Poa	Few in flower	All in fruit
Cerastium	Some past peak flower	Well past peak flower.

the two sides indicated markedly greater advance on Knob Hill (Table XXXV). Wolfe believes that these differences will prevail as long as the ice front is in the area regardless of frontal fluctuations in position. Thus, the plants do not give clear proof that the ice edge is advancing right now.

Balance of present regimen

Photogrammetric surveys. To determine the present activity of the ice cliff, four photogrammetric surveys were made of the ice cliff as near the beginning and end of each melt season as possible. Vertical contour maps with 25 cm contours were prepared from these surveys. The position of the ice cliff was then compared, period by period, on a grid system of 2 m squares to determine the net change in the face of the cliff.

The precise baseline on the glacial drift, 100 to 150 m south of the ice cliff, was set up principally to give accurate positions for this survey. After the 15 base stakes at 30 m intervals along this baseline had settled, thin copper strips were nailed to the 2 x 4 tops and a small hole was pricked near the center of each strip to represent the station. The baseline measurements were made with a nickel-steel tape (K & E Lovar #9505) by standard methods (Gosset, 1950, p. 193-236). Corrections were applied for temperature, inclination, setup-setback, and reduction to station points at each base stake. A sea level reduction correction was omitted since only relative data in this localized area was required. Double-run measurements of the baseline were made three times: 4 July 1955, 12 August 1955, and 10 July 1956. In the second measurement

Table XXXVI. Probable chronology of late-glacial events, Nunatarssuaq, Greenland.

Years ago	Evidence	Event
9000 to 6000	Dated marine beach deposits above Moltke Glacier	Gradual uncovering from main Greenland Ice Cap from southwest first, to northwest last
	Most lush vegetation well established in south Nunatarssuaq	
	Glaciation from southeast	No North Ice Cap
	Young plant communities in northern Nunatarssuaq	Red Rock area covered by Greenland Ice Cap
	Well-developed patterned soils	Stabilizing slope-soil forms
5000 to 1000	Marine clays in moraines of Moltke Glacier	Sea far up Wolstenholme Fjord
	Deep inner V-shaped gorges in all major valleys	Moltke, Rasmussen, and Twin Glaciers far receded
	Active outwash, windblown sand, ventifacts made in North Lake Valley	Recessive ice tongue of main Ice Cap, northeast of North Lake
	Vegetation 4750 years old in North Ice Cap ice	Development and expansion of North Ice Cap
500 to 200	High lateral moraines 8 km down Twin Valley	Extension of Twin Glaciers system
	Gray drift cover 3 km westward Nuna Ramp to North Lake; moraines	Extension of Greenland Ice Cap into Gash Valley damming North Lake
	Kame terraces in Sand Dune Creek and Red Rock Lake; low end moraines; covered eolian sand sources	Advance of ice tongues up Red Rock Creek from North Lake and west across Red Rock Lake
200 to 50	Recessional moraines in Twin Valley, intermediate vegetation	Halting retreat of Twin Glaciers
	High lake levels in North Lake	Halting retreat of ice lobe south of North Lake
	61 m lake and spillways on lower Red Rock Creek	Retreat of North Lake lobe of Greenland Ice Cap
50 to 5	Clay-rich ice-cored lateral moraines of Moltke Glacier	Rapid recession of Moltke Glacier tongue in Wolstenholme Fjord
	Trimline above outlets of main Ice Cap and above all perennial snowdrifts	Diminishing of snow volumes associated with marginal ice everywhere
	Pioneer vegetation below lowest beaches, above Twin Lakes	Continued recession of Twin Glaciers allowing lower spillways in ice
	Eolian sand in North Ice Cap at Sand Dune Creek and patterned soils passing under North Ice Cap	General advance of ice cliff along east margin North Ice Cap
	Sandy shorelines 2 and 5 m above Red Rock Lake with sparse pioneer vegetation	Diminishing of ice-snow drift associated with main Ice Cap and controlling Red Rock Lake

the mean length of the baseline varied only 6 mm from the first measurement.* After the interval of the winter and nearly one year's time, the mean length had increased 26 mm. After the heaving actions of a full year, one individual section had changed enough to represent a substantial but correctable error: stake no. 12 moved 23 mm out of line to the south.

The relative elevations of the base stakes were determined by U. S. Coast and Geodetic Survey procedures (Rappleye, 1948). Using a Wild N-2 level and precise leveling rods (1955) or a Philadelphia rod (1956), double-run leveling was performed on 5 July 1955, 12 August 1955, and 27 July 1956. The divergence of elevation differences bebween the forward and backward running was 9.4 mm, 14.0 mm, and 85.0 mm. This last figure, giving a probable error of 1:8500, established the limit of accuracy for all of the 1956 computations. The relative settling indicated by differences between mean readings with respect to the total length of the baseline was 26.7 mm during the first summer and 28 mm during the winter between field seasons.

Control targets were established on the cliff in July 1955 and re-established as necessary for each of the four photographic runs. These were spaced at 30 m intervals along the bottom of the cliff and at 30 m (1956) or 60 m (1955) along the top, in such a way that a minimum of 3 and possibly 6 targets would appear in each stereoscopic pair of photographs or "model." Tests before the first field season showed that a 15.2 cm diam disk, painted black with a white cross in the center, was the smallest practical size. These were prefabricated of aluminum and attached to the ends of 183 cm long poles drilled in flush with the face of the ice cliff or set vertically into the top edge of the cliff.

Photography was done with a Wild phototheodolite, T-30, set in succession over each of the 15 base stakes in 1955 or over the odd numbered stakes from 5 to 15 in 1956. At each station the instrument was plumbed over the station point, leveled approximately, and checked for area coverage. The optic axis of the camera was made perpendicular to that of the theodolite; thus the camera axis could be set perpendicular to the baseline. The tilt mechanism was set on 0, except for stations 5, 14, and 15 in 1955, and stations 5, 13, and 15 in 1956, where 7 grads uptilt were used. Photographs taken under bright sunlight conditions between 0930 and 1300 hr proved best; those taken on cloudy days proved difficult to resolve during the contouring process. Gevaert topographic, Rapide-Ortho emulsion plates were used, but the tested and rated emulsion speed data (10 ASA) proved only half enough. In 1955, seven sets of photographs were taken at approximately 10-day intervals from 3 July to 26 August but because of the slow rate of change of the cliff face only two of these merited compilation: 20 July and 26 August. In 1956, two sets of photographs were taken, on 26-27 June and 26-27 August. All plates were processed at camp in a temporary dark room fabricated out of tarpaulins.

Horizontal and vertical triangulation observations were made to each target with a Wild T-2 theodolite, set up over the station point at base stakes 1, 5, 11, and 15 (1955) and 1, 9, and 15 or 5, 9, and 15 (1956). Horizontal angles were read three times, both direct and reverse, and vertical angles were read three times, circle left and right. The tolerance in readings was 5 sec (1955) or 10 sec (1956).

To insure accuracy the principal point and camera focal length were calculated by comparison of target images on the photographic plates and field survey data. Special formulas were derived† and sample plates measured. These gave a mean focal length of 166.089 mm. The mean differences in position of the computed principal point of only 0.114 mm along the right-left fiducial line (X axis) and 0.146 mm along the vertical

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* Forward and backward runnings varied by 13, 4, and 9 mm within each of the three sets of measurements.

† From Dr. B. Hallert, Institute of Geodesy, Photogrammetry, and Cartography, The Ohio State University.

Table XXXVII. Baseline deviations (m).

Base station	Section length 1955 (X)	Mean deviation by 1956 (dX)	Station elevation (Z)	Mean deviation by 1956 (dZ)	Alignment deviation by 1956 (dY)
West 1			100.000	-	-
2	29.585	0.032	95.086	0.00	-0.002
3	29.637	-0.010	90.360	0.00	0.006
4	29.588	-0.025	85.491	0.01	-0.005
5	29.751	-0.002	81.608	0.01	0.000
6	29.844	0.030	78.425	0.01	-0.005
7	29.652	0.004	73.853	0.01	-0.008
8	29.661	-0.041	69.477	0.01	0.000
9	29.961	0.010	67.816	0.01	-0.004
10	29.949	-0.047	66.513	0.03	-0.019
11	29.876	-0.019	63.819	0.03	0.008
12	29.824	0.026	60.596	0.02	0.023
13	29.997	0.022	59.792	0.09	0.010
14	30.018	0.021	59.756	0.02	0.017
15 East	30.010	0.025	59.511	0.03	-
		Plus values denote E		Plus values denote up	Plus values denote N

line (Z) axis were too small to be corrected visibly when adjusting the diapositives in the plotter. For complete discussion of measurements and data computation methods, see Goldthwait et al. (1956, p. 66-84); and Jury (1956).

Lens distortion was checked by comparing the computed X coordinate of six target images to the actual measure of the same images. Values of from -0.011 to +0.016 mm were considered too small to require adjustment of the camera focal length.

In 1956, it was assumed that the characteristics of Wild instruments did not vary enough to warrant making these checks again.

The rectangular coordinates for each cliff target at each of four observations were calculated with the baseline as the X axis, the perpendicular toward the cliff as the Y axis, and the vertical as the Z axis, using base stake 1 as the point of origin. This point was assigned the arbitrary vertical elevation (Z) value of 100 m to make all values positive. This is the same coordinate system used for motion measurements.

As the base stakes did not remain in perfectly constant position or alignment with respect to each other, corrections were to coordinate values except those for the first (20 July 1955) survey. To accomplish this it was assumed that base stake 1 was actually stationary and that the others moved small amounts with respect to it (Table XXXVII). On the Y axis, perpendicular to the cliff, it was assumed that both stakes 1 and 15 were stationary. Necessary changes were made in the values of each of the three coordinates for each target observed.

To show the topographic features of a vertical ice cliff, contours of the Y component had to be drawn on a vertical datum plane. To accommodate a vertical cliff which varies from 93 to 160 m from the baseline, it was necessary to use a datum plane rotated with respect to the baseline through an angle of 5°52'32.2" to reduce the number of contours to a minimum. To find the position of each target on this rotated plane, the X, Y, and Z values were first calculated for a plane 130 m north of the baseline and then transformed through angular rotation.

All contours were compiled on a Kelsh plotter made available by the Institute of Geodesy, Photogrammetry, and Cartography of The Ohio State University. It was not possible to maintain a 1:1 ratio between the horizontal (X, Z) and vertical (Y) scales on the instrument, because the principal distance of this projection system could not be made equal to the calibrated focal length of the camera (166.09 mm). For most of the plotting, the horizontal compilation scale was 1:155 and the vertical scale was 1:169. However, on the eastern half of the cliff, in 1956, the relief was so great that the minimum and maximum projection distances would not accommodate the full range. New scales were then adopted for this part (horizontal 1:183, vertical 1:200). The resulting product was enlarged to match the other sheets. At the scales used, the minimum projector separation of the Kelsh plotter would accommodate only pairs of photographs having a ground separation of 60 m; therefore, only every other station point was occupied for photography in 1956.

The Kelsh plotter does not accommodate the 10 x 15 cm glass plates used in the T-30 phototheodolite. Diapositives were produced by contact printing onto the center of a standard 9.5 in^2 photographic plate. Fiducial lines were scribed to the edge and the plates were then adjusted to the plateholder. On the basis of the photography and the characteristics of the Kelsh plotter, it would theoretically be possible to plot 15 cm contour intervals. However, this proved to be very difficult and a minimum contour interval of 25 cm was finally adopted. The projected image of the portions of white cliff surface without shadow detail appeared somewhat transparent and very difficult to contour.

A few models (stereoscopic pairs of photographs) covering the west end of the cliff area could not be satisfactorily oriented. This difficulty was due to the limited extent of the cliff image on the photographic plate, to tilt, and to insufficient control targets where the cliff was near the baseline. For this reason the west end of the cliff opposite base stakes 1 through 6 was not compiled in 1955 nor repeated in 1956.

The four contour maps of the ice cliff (Fig. 57, 58) have been studied carefully and a statistical analysis is presented for the net changes of the ice cliff face. Using the 20-m basic grid and an overlay of 2 m square subdivisions, the position was read to the nearest 0.1 m. Specific changes at some 1300 points between vertical grid lines 160 and 420 were added interval by interval for each vertical sector of cliff 20 m wide.

Net gain in ice. Over one full year, 26 August 1955 to 27 August 1956, the main body of the ice cliff, which is nearly vertical and exposes white ice (1054 points), shows a net gain or advance southward of 0.53 m. This is especially notable as the ablation season involved was abnormally warm and the spring interval involved the maximum of calving recorded in the 2-yr period. If, in spite of this, the net movement was more than half a meter forward, there can be little question but that this ice cliff is advancing.

Table XXXVIII. Changes in position of vertical white ice cliff.

	No. of points	Change southward (m) Max. spot	Min. spot	Average	Rate of change mm/day
Summer 1955 - 20 July to 26 Aug	1009	-0.3	-2.5	-0.45	-12.1
Winter 1955-56 - 26 Aug to 26 June	1088	+5.6	-2.9	+1.72	+5.6
Summer 1956 - 26 June to 27 Aug	1046	+4.1	-5.3	-1.01	-16.4
One year - 26 Aug to 27 Aug	1054	+6.4	-3.6	+0.53	+1.4

The gain in position occurred during the 10 winter months from late August 1955 to June 1956 and was at the rate of 5.6 mm/day. Unquestionably this figure was reduced by the calving of large sheets of ice from the face of the ice cliff (Table IV) in May and early June: this is evident in the figures for change between grid positions 280 and 300, 340 and 360, 400 and 420 (Table X). In just one of these areas (340 to 360) was there average loss over the whole area (-1.1 m). In these areas the maximum net loss or northward shifting of the cliff face at any point was 1.8, 2.9 and 2.0 m, respectively, which is larger than values for most of the other sections.

Table XXXIX. Changes in position of the dark ice anc ice toe.

	Ice area	No. of points	Change southward (m) Max. spot	Min. spot	Average	Rate of change mm/day
Summer 1955 20 July to 26 Aug	amber*	179	-0.1	-7.6	-0.72	-19.4
	toe	247	+0.7	-5.6	-1.39	-37.6
Winter 1955-56 26 Aug to 26 June	amber	112	+5.7	-1.7	+2.77	+9.1
	toe	186	+14.1	-2.6	+3.21	+10.5
Summer 1956 26 June to 27 August	amber	154	+0.8	-5.8	-1.56	-25.5
	toe	197	+1.2	-11.4	-3.80	-62.3
One year 26 Aug 55 to 27 Aug 56	amber	132	+3.5	-3.0	+0.61	+1.9
	toe	177	+5.0	-4.8	-0.41	-1.1

* Disseminated dirt or bands on vertical cliff face only; toe is sloping and also dirty.

There are enough 2 m reference points of repeated mapping on the vertical dirty ice in the lower part of the cliff and on the sloping toe of ice below the cliff (also dirty ice) to make an analysis of these. Comparing net horizontal loss in the amber ice in the cliff face (Table XXXIX) to that in the white ice above (Table XXXVIII), we note that although both were vertical, net losses were 60 to 65% greater in the amber ice. This greater loss is due both to slightly slower motion low on the cliff and to greater ablation by absorption of energy in the darker material. The toe ice which slopes at an average of almost 45° is even more nearly perpendicular to the rays of the high summer sun, so its horizontal summer loss is 300% over that for the vertical white ice above.

These high net rates of loss in the lower dirty ice would lead to an undermining of the whole lower front of the ice cliff if it were not for counteracting gains during the intervening winter months. It is obvious from the motion figures (Table X) that the slow motion of the lower ice does not explain this net gain in the winter. Two other factors do: (1) the amber ice is in an area which is not calving much and so does not suffer the spring losses of the white ice above, and (2) large volumes of ice calving from the white ice above build out the toe as much as 14.1 m (maximum) and consolidate into a series of layers of superimposed material. As a result of high loss and high gains, the net change in one year's time in the darker ice is by far the smallest average figure; the amber ice made a small gain southward, while the dirty toe represents a slight net retrogression (Table XXXIX).

Table XL. Volume of ice gained (+) or lost (-) at the ice cliff (m^2).

	Vertical white ice	Vertical amber ice	Sloping toe ice
Area (m^2)	4197	577	807
Summer 1955			
20 July to 26 Aug	-1889	-415	-1122
Winter 1955-56			
26 Aug to 26 June	+7219	+1598	+2591
Summer 1956			
26 June to 27 Aug	-4239	-900	-3067
One year			
26 Aug 55 to 27 Aug 56	2224	-352	-331

Similar conclusions may be drawn from the net volumes of ice gained or lost by the change in position of the ice cliff (Table XL). For the white ice of the vertical cliff, the net gain in the winter of 1955-56 is nearly four times the loss recorded in the summer of 1955, but this loss does not include late June and early July when the melting was fairly heavy. By extrapolation, the winter's gain was probably about 3 times (300%) the volume of the previous summer's loss. The winter gain can be compared directly to the very heavy ablation season 1956 which is almost fully recorded in the summer 1956 figures; here the winter's gain in ice volume is 71% more than the succeeding summer's loss.

In amber ice of the lower vertical cliff, the same relationships between seasons hold true, but the total volumes are very much smaller because the area is a third as much.

Check with motion-ablation measurements. The net gain of the white ice cliff may be checked by comparing the figures on motion and ablation. The net forward motion for 16 stakes in white ice was 4.64 m in 365 days of 1955-56. Subtract from this 2.41 m of ablation for 80 days in 1956 plus 0.31 m winter sublimation and 0.95 m average calving and the remainder, 0.97 m, is net gain or advance. This is greater than the net gain shown in white ice by photogrammetry, 0.53.* If a June 1955 and June 1956

* Individual stakes have interpolated values for motion and ablation and vary greatly in amount. Furthermore, they are not precisely located on photogrammetric maps so comparisons stake by stake do not agree well.

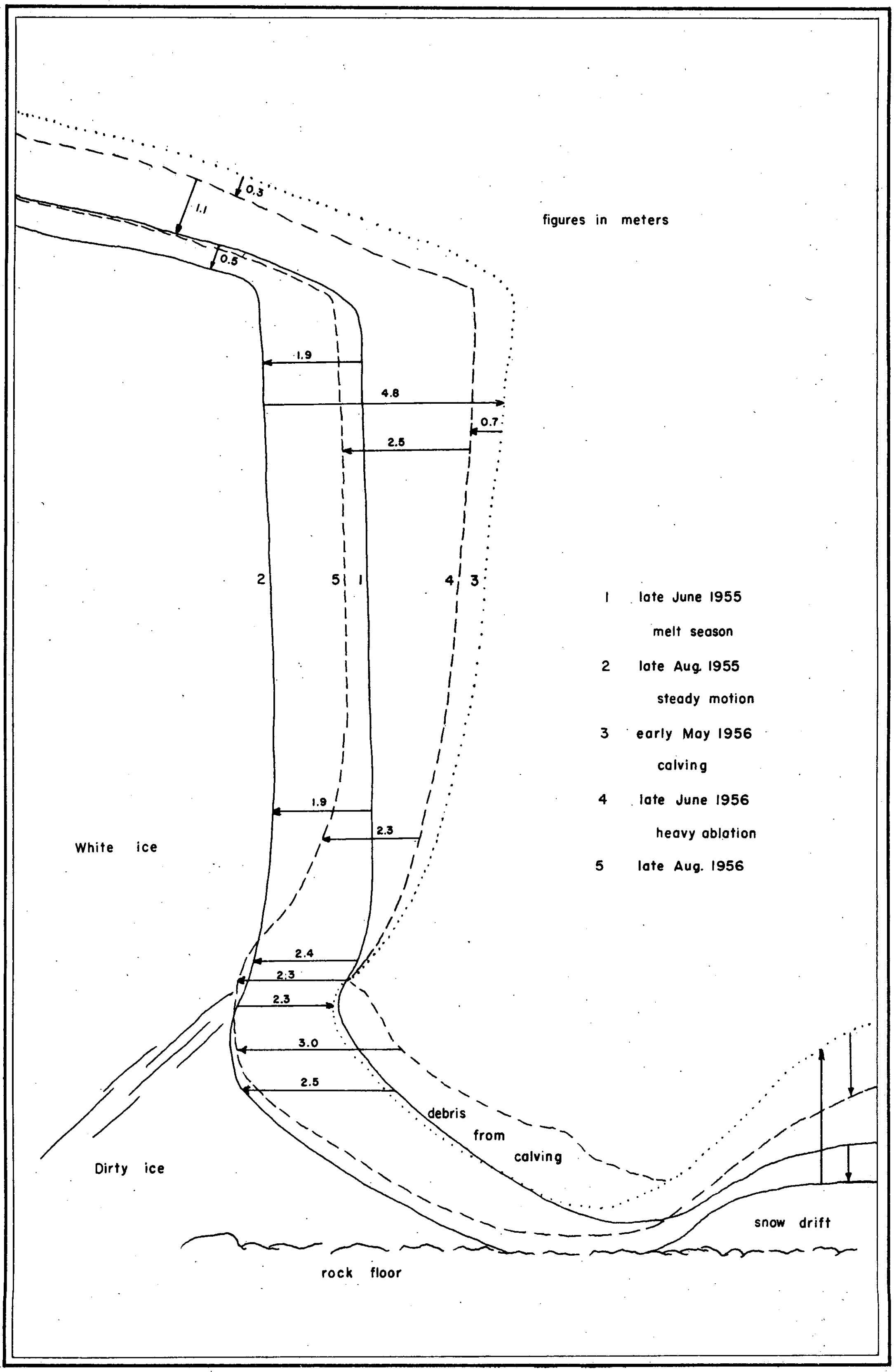

Figure 52. Average changes in Red Rock ice cliff late June 1955 to late August 1956.

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net change were available from photogrammetry it should show even greater gain; for only 1.89 m average melt plus the same calving and sublimation would leave a net gain of 1.48 m.

Values in the lower dirty ice are based on fewer positions but they agree that the surface position is nearly stable. Average motion over 365 days carries this ice 2.3 m but heavy ablation restricted to the summer 1956 is about 3.0 m which leaves a deficit or withdrawal of 0.7 m. In the year June 1955 to June 1956 melting was not so heavy so the deficit was only 0.2 m. Photogrammetry shows that the vertical amber ice above gained 0.61 m and the dirty toe ice lost 0.41 m during August 1955 to August 1956.

The figures determined by photogrammetry are in general agreement with motion and ablation figures determined in conventional ways. They are based on many more points (20 times as many) and may be more accurate averages; they afford a detailed picture of the changes in topography as well. This result is gained with only one-quarter as many man-days in the field.

Summary of cliff changes

Net changes in the ice cap are summarized in Figure 52. In the interim from August 1955 to August 1956 the vertical white ice made a net gain southward of 0.53 m in spite of very heavy ablation during the summer 1956, and very heavy calving at the end of spring 1956. The eleven more normal months from July 1955 to June 1956 registered a net gain of 1.27 m. These figures are of the same order as those derived by subtracting measured ablation and calving from measured motion over approximately the same intervals of time (0.97 m August to August; 1.48 m June to June). The amber ice near the base of the cliff had 60 to 65% greater ablation losses than the white ice above, so that net gain in the vertical amber ice was only 1.9 m and the sloping toe suffered a net loss of 1.1 m. The advance of the ice cliff is actually by annual pulsations as a result of the gain by continuous motion all winter long. Annual motion exceeded the rapid summer ablation losses by 71% in 1955 and 300% in 1956.

It is clear that the last motion of North Ice Cap was advance over deposits previously exposed. Well-developed stable soil patterns pass under the present edge of North Ice Cap and are found buried under its mass. Sandy material developed in former times from an outwash northeast of North Lake was swept northwestward by wind into the area now occupied by North Ice Cap; it is reappearing in the moraine of that ice cap at Sand Dune Creek. Tunneling at the Red Rock ice cliff exposed lichen-covered boulders and interboulder vegetation less than 200 years old overridden by the ice.

Evidence of present-day marginal vegetation is a little less clear. Botanists in 1953 felt that the dying vegetation at the west edge of Botanist Flats indicated advance of North Ice Cap. Studies on Survey Hill in 1955 indicate that the depauperate and slowly developing vegetation there may be explained simply by effect of the nearby ice and its melt water.

The main Greenland Ice Cap on the east side of Nunatarssuaq has retreated very recently. Trimlines between upper lichen-covered slopes and lower bare slopes indicated that semipermanent snows have been most extensive within the last few decades. Vegetation zones on Nuna Knob 14 km south of Red Rock Camp were reported in 1953 to show recent deglaciation there. Higher beaches and deltas (covering less than 1% of the area mapped) around Red Rock Lake and a higher outlet on the slope west of the present outlet indicate that blocking snow and ice was deeper here. Beaches were found above two small lakes along the lower course of Red Rock Creek and outlets cut deeply in the bedrock indicate that the main Greenland Ice Cap was 100 to 300 m more advanced when these higher lakes existed.

The former extension of the main Greenland Ice Cap is marked only by very poor end moraine ridges just south of Red Rock Lake which cover less than 1% of the total mapped area. Extension of the ice is implied, however, by the ice-contact slopes of kames on the south side of Survey Hill. In one case there was a covering sheet of till and stonecounts indicate that this material came from the east. For 23 km to the south of North Lake this recent extension of the ice cap was clearly outlined by fresh gray drift and end moraines. Indirect evidence suggests that this advance may have culminated some two centuries ago.

Still earlier than this the Greenland Ice Cap was far receded and North Ice Cap was somewhat smaller or absent. Inner valleys in southern Nunatarssuaq (one extending most of the way up Red Rock Creek) indicate a two-cycle development with a period of canyon-cutting prior to the existence of the present lakes and glaciers which block these valleys. The glacial drift is fairly heavily oxidized and a long period was required for the development and stabilization of frost-built patterned soils. The development of extensive eolian sands and ventifacts out of the former North Lake Valley train took some time. Thirty-five percent of the mapped surface of northern Nunatarssuaq is bedrock completely broken up to a rubble by frost action. Near Thule Air Base (Dundas) and in southern Nunatarssuaq this initial exposure of the land must have occurred at least 8000 or 9000 years ago, based upon radiocarbon age determination of marine strand line deposits in these areas. However, the oldest willow trees in northern Nunatarssuaq indicate little more than a century and the size of the lichen on the rocks indicates somewhat less than 1000 years of growth at the most. The whole plant assemblage is a very youthful population containing no decadent stumps or materials. This is hard to reconcile with the radiocarbon date of 4760± 220 years for plant material being carried up shear planes at the edge of North Ice Cap.

The earliest recorded stage of glacial history in northern Nunatarssuaq is complete coverage by the main Greenland Ice Cap. According to stonecounts and the shaping of hills near North Lake this ice moved from the southeast and deposited the coarse ground moraine of till which now covers 59% of the area mapped.