Institute of Polar Studies

Report No. 65

Internal Drainage of Stagnant Ice: Burroughs Glacier, Southeast Alaska

by

Grahame J. Larson

Institute of Polar Studies
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Department of Geology and Mineralogy
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Dr. Grahame J. Larson is now at:
Department of Geology
Michigan State University
East Lansing, Michigan

Copies of this and other reports of the Institute of Polar Studies are available from:

Institute of Polar Studies
The Ohio State University
125 S. Ovan Mall
Columbus, Ohio 43210
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ABSTRACT

Burroughs Glacier is a temperate glacier in Glacier Bay National Monument, southeastern Alaska. Presently, it is rapidly wasting away leaving behind several remnants of stagnating glacier ice which have become detached or semi-detached from the main glacier body. A detailed hydrologic investigation of one glacier remnant has shown that the internal drainage system developed within stagnating ice is, in many respects, similar to karstic drainage systems developed in limestones.

Meltwater produced on the stagnant surface appears to infiltrate into the ice via "vein-like" channels between disintegrated ice crystals and along fracture and shear planes that cut the ice. Within the ice, meltwater is temporarily stored in a saturated zone and eventually discharges into moulins. The coefficient of transmissibility, storage, and permeability of ice in the saturated zone were measured by pump testing and were found to average 6.64 $m^2 day^{-1}$, 6.9 x 10^{-3}, and 2.21 m day^{-1}, respectively. From the moulins, drainage is routed through a system of englacial channels which successively join together downstream forming a main englacial drainageway in semi-lateral position.

ACKNOWLEDGEMENTS

Thanks are extended to Dr. Wayne A. Pettymohn and Dr. Richard P. Goldthwait, Professors of Geology at The Ohio State University, for their help throughout the course of this project; to David Mickelson for handling logistics and offering advice in the field; to the U. S. National Park Service for logistic support; to Leonard Harstine of the Ohio Dividion of Water for loan of Water-level recorders; and to Bob Ward and John Rose for invaluable assistance in the field. Funds for this study were made available through National Science Foundation Grant GA12300 to the Institute of Polar Studies and The Ohio State University Research Foundation.

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INTRODUCTION

The research discussed in this report explores the drainage that can develop in stagnating glacier ice. Such knowledge is of fundamental importance to glacier geomorphologists and geologists involved in mapping and interpreting glacio-fluvial systems formed along modern and ancient wasting ice margins.

Burroughs Glacier, in southeastern Alaska, was chosen as the site for this investigation because it is rapidly wasting away and is not unlike much of the stagnating ice that covered parts of New England during Wisconsin deglaciation (Goldthwait, 1966). The terminus of the glacier is characterized by several detached and semi-detached masses of ice and is fringed by recently formed eskars, kames, kame terraces, and outwash deposits. This study focuses on one of these masses of ice and the drainage developed therein.

Most of what is now understood of the internal drainage of ice comes primarily from a few field studies made over the past eighty years. The earliest of these studies was concerned primarily with the transit time of meltwater passing through glacier ice. Forel (1898), for example, measured the drainage rates from two moulins on the Rhonegletscher (Switzerland) using flouresein dye and found the mean rate of drainage between location of injection and site of measurement to be 0.54 meters per second. Later, Vallot (1900) made a similar study on the Mer de Glace using the same dye and noted drainage rates of about 0.20 meters per second.

At Styggedalsbreen (Norway), Lindskorg (1928) used fuchsin to trace englacial drainage and found flow velocities to average 0.25 meters per second. He also recorded meltwater run-off response from the glacier and concluded that daily retardation of the drainage during the summer can range from one to seven hours, depending on climatic conditions. Tritium analyses of water draining from Kesselwandferner and Wintereisferner (Austria) have also shown that meltwater runs off ablation areas without much delay (Behrens and others, 1971).

Stenborg (1969) recently investigated the internal drainage of Mikkaglaciaren and Storglaciaren (Sweden) using salt solutions. He found that surficial crevasse patterns in the ablation areas of both glaciers effect the direction of meltwater flow within the ice. The average optimal flow velocities in both glaciers were found to lie between 0.5 and 0.7 meters per second. Salt solutions and dyes have also been used by Krimmel and others (1973) on South Cascade Glacier (Washington). Their studies indicate that the water flow through ice is mainly in large open conducts.

Several theoretical studies, mainly by Rothlisberger (1972) and Shreve (1972), have approached glacial drainage from the viewpoint of thermal and hydraulic physics. Their studies suggest that water in glaciers must flow in an arborescent network of arteries that gradually increase in size at the expense of smaller ones.

PHYSICAL SETTING OF BURROUGHS GLACIER

Location

Burroughs Glacier lies in a tributary valley to Wachusett Inlet in the north-central part of Glacier Bay National Monument, southeast Alaska (Fig. 1). The glacier covers an area of approximately 52 square kilometers and flows in two opposite directions from a central divide 425 meters above sea level.

The eastern tongue of the glacier is nearly 6 kilometers long and terminates at an elevation of 60 meters (Fig. 2). At its highest part, the tongue is about 2 kilometers wide, but at its lower southern end, it flares out to a width of about 3 kilometers. The tongue is surrounded on three sides by bedrock ridges and hills with summits ranging from 200 to 900 meters. Minnesota Ridge, which is the highest summit, lies on the north side of the tongue. On the south side are the Bruce Hills and to the southeast the Curtis Hills.

Surface Drainage

The eastern end of the glacier is drained by four streams: Burroughs River, Gull Creek, Bob Creek, and John Creek (Fig. 2). The Burroughs River is by far the largest of the four streams. It emerges from the south side of a semi-detached mass of stagnant ice and flows southward into Wachusett Inlet. A considerable amount of meltwater also flows down Gull Creek. It drains from the south edge of the glacier and flows westward into Wachusett Inlet. Along its course are several large and irregularly shaped stagnant masses of ice which have become totally separated from nearby Plateau Glacier. The remaining two streams, Bob Creek and John Creek, both flow from the eastern end of Burroughs Glacier into Burroughs River.

Climate

The climate at Burroughs Glacier is of West Coast Maritime type. During the summer, there are long periods of cloudiness, rain, and mist. Temperatures range generally around 10° centigrade. On occasion, there are a few days of clear skies and higher temperatures.

During the summer of 1970, meterological conditions were recorded both at the field camp and on the glacier (Fig. 2). At the camp, meterological measurements were made twice a day, at 7:00 a.m. and 7:00 p.m. Wind velocities were measured with an anamometer, temperatures with a sheltered max-min thermometer, and cloud cover was estimated in percent of overcast. A standard non-recording rain gauge was used to measure precipitation.

At the meterological station on the ice, temperature and humidity were recorded by means of a sheltered hydrothermograph. A standard rain gauge, as well as a dipping-bucket rain gauge, were used to record precipitation. The meteorological data collected at the two stations from early June to late August are summarized in Figure 3.

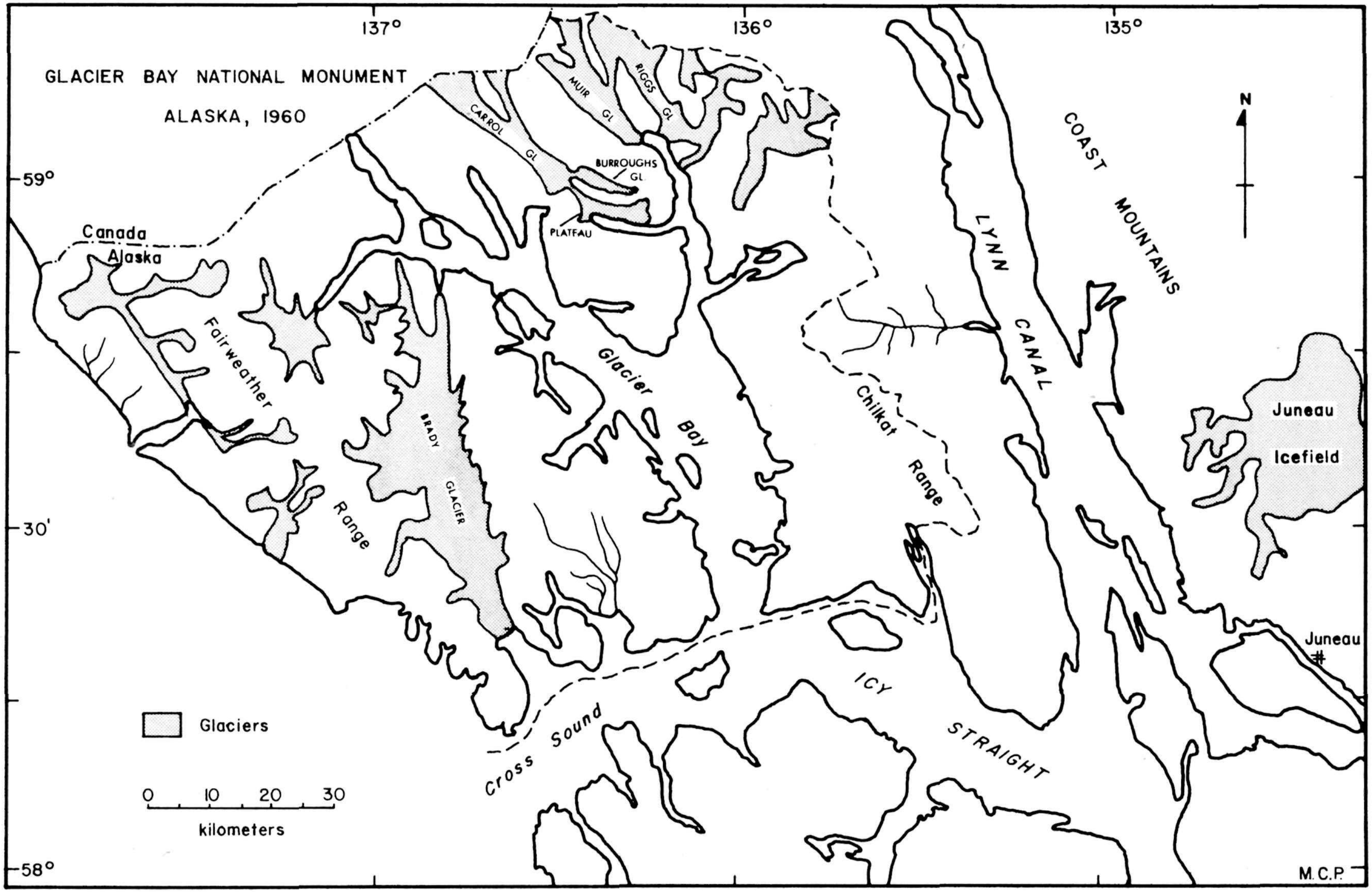

Figure 1. Location of Burroughs Glacier.

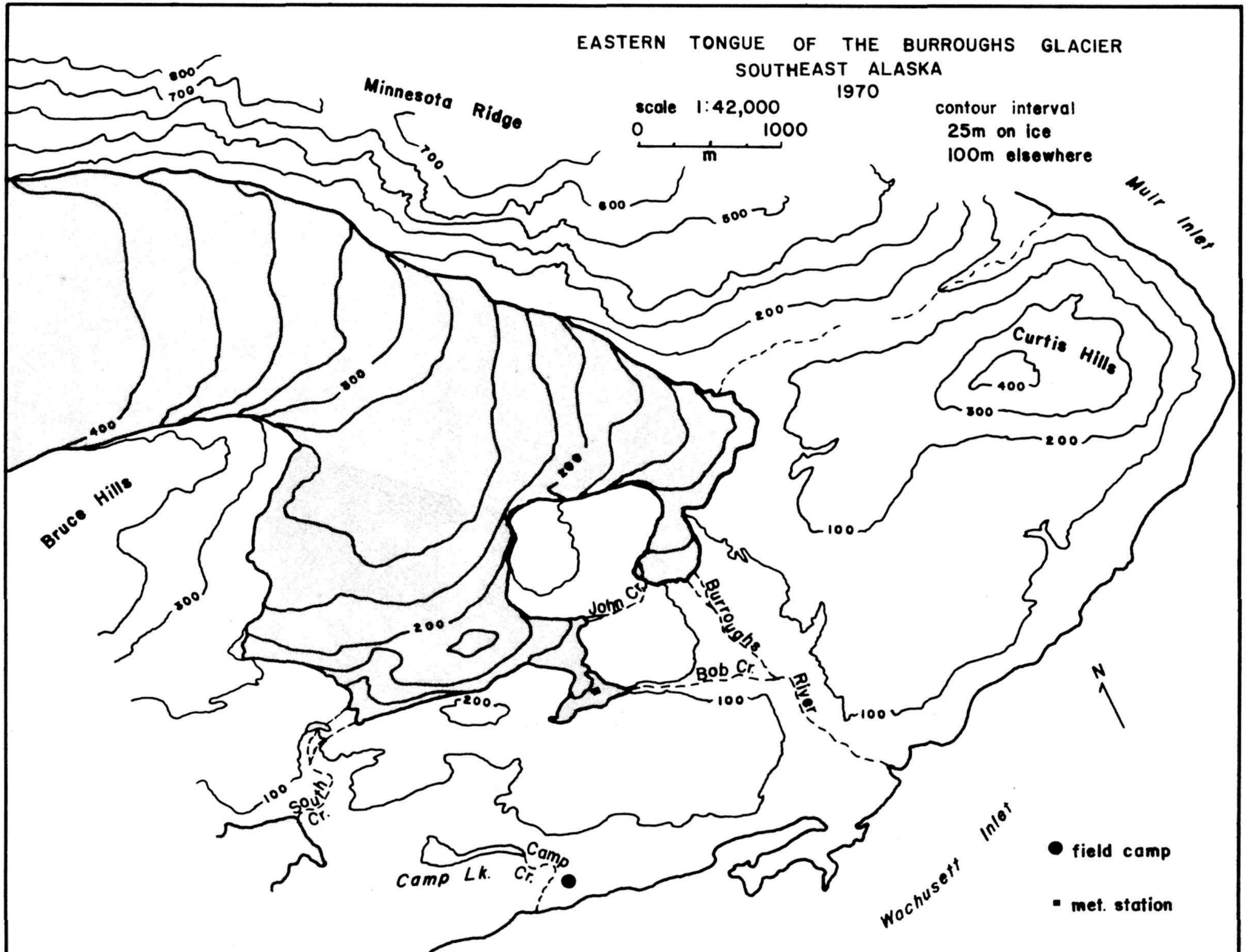

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Figure 2. Eastern tongue of Burroughs Glacier, 1970.

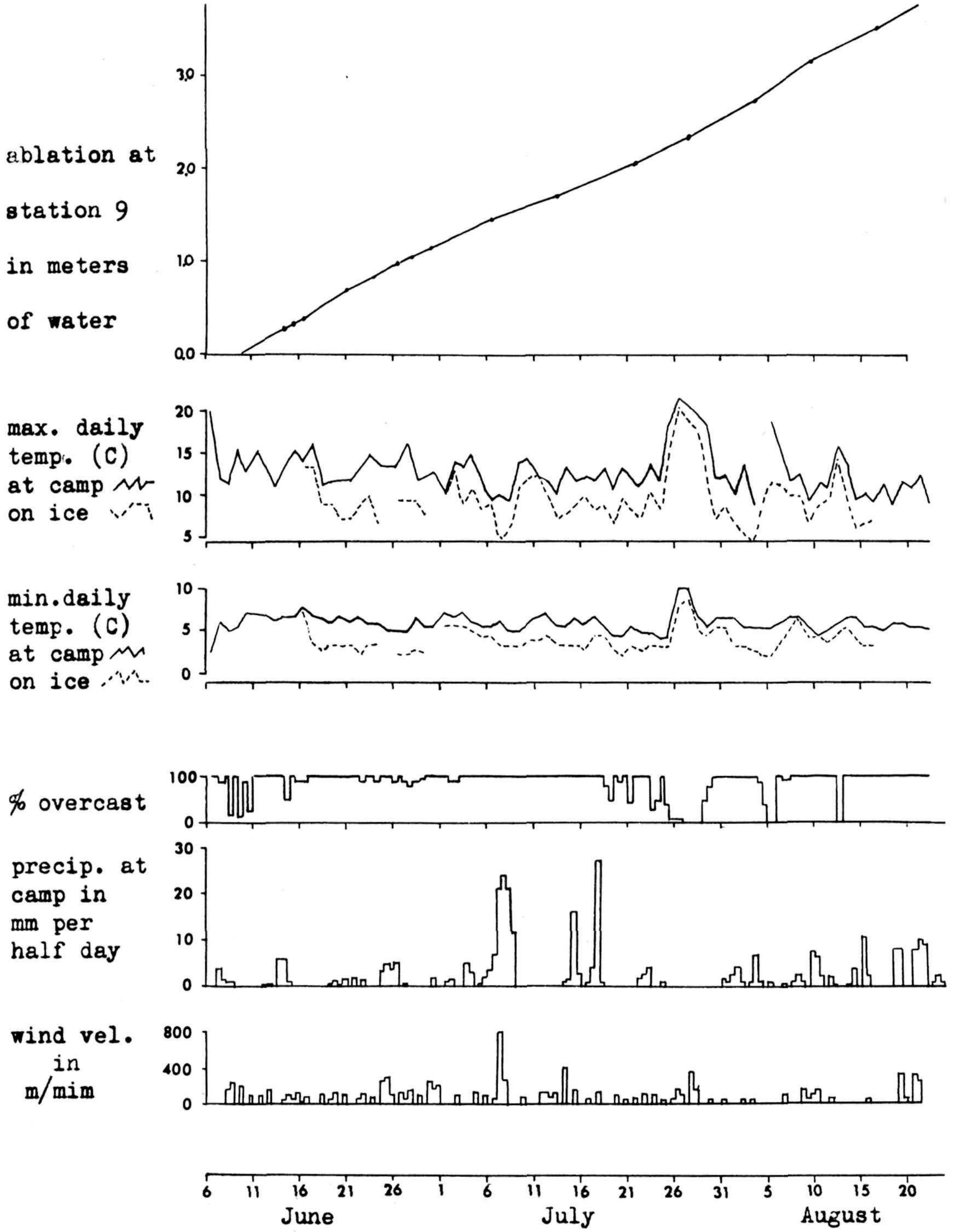

Figure 3. Meterological conditions and ablation recorded on Burroughs Glacier during the summer of 1970.

Geology

Figure 4 is a map prepared by Mickelson (1971) showing the surficial geology near the eastern end of Burroughs Glacier. The surficial deposits are principally till, sand, and gravel. The till is calcareous, light gray to olive gray, and has a dense, blocky structure. Its thickness ranges from exceedingly thin (scattered boulders) to greater than 25 meters. Particle size analysis (Mickelson, 1971) shows a mean distribution of 57 percent sand, 36 percent silt, and 7 percent clay for most of the till. Some of the fines, however, appear to have been removed from much of the till lying upon stagnant ice.

The sand and gravel deposits shown in Figure 5 were mapped either as kame terraces or outwash. The kame terraces generally occur on slopes near the base of hills and extend laterally no more than a half kilometer. They consist chiefly of sand with some gravel-size pebbles intermixed. The outwash deposits, on the other hand, are present only in the center of stream valleys draining the ice. These sinuous deposits are generally better sorted than the kame terraces and contain mostly sand and fine gravel.

Hypsithermal age gravel (Van Horn member) underlies some of the surficial deposits below an altitude of 150 meters. This gravel is medium to coarse and, in places, may be as much as 100 meters thick. It has been interpreted both as kame terrace deposit (Cooper, 1939) and as remnant of outwash that once filled Wachusett Inlet (Goldthwait, 1966).

The bedrock at the eastern end of Burroughs Glacier consists predominantly of a series of metamorphosed shales and limestones, intruded by diorite and granodiorite stocks. The metasediments are Paleozoic in age (Twenhofel, 1946) and underlie the eastern sections of Minnesota Ridge and the Bruce Hills. The Curtis Hills, the western end of Minnesota Ridge, and the remainder of the Bruce Hills are underlain by stocks of Cretaceous Age (Rossman, 1963; MacKevett and others, 1971). Intruding both the metasediments and stocks are many diabase dikes of varying composition.

General characteristics of Burroughs Glacier

According to Ahlmann's (1948) morphological, dynamic, and geophysical classification, Burroughs Glacier is a temperate, dead, valley glacier. Although well below these equilibrium line, the ice in the glacier still flows. Taylor (1962) measured the surface velocity of the glacier from 1959 to July 1960, and found movement to be between 6.7 meters at the upper part of the glacier to less than 0.5 meters near the eastern terminus. The radial outward flow of the glacier, however, has not kept pace with melting at the terminus. From 1960 to 1970, the rate of marginal retreat has ranged between 9 to 60 meters per year. During this same time period, downwastage has ranged from 4.6 meters at the glacier divide to 9.5 meters at the eastern terminus.

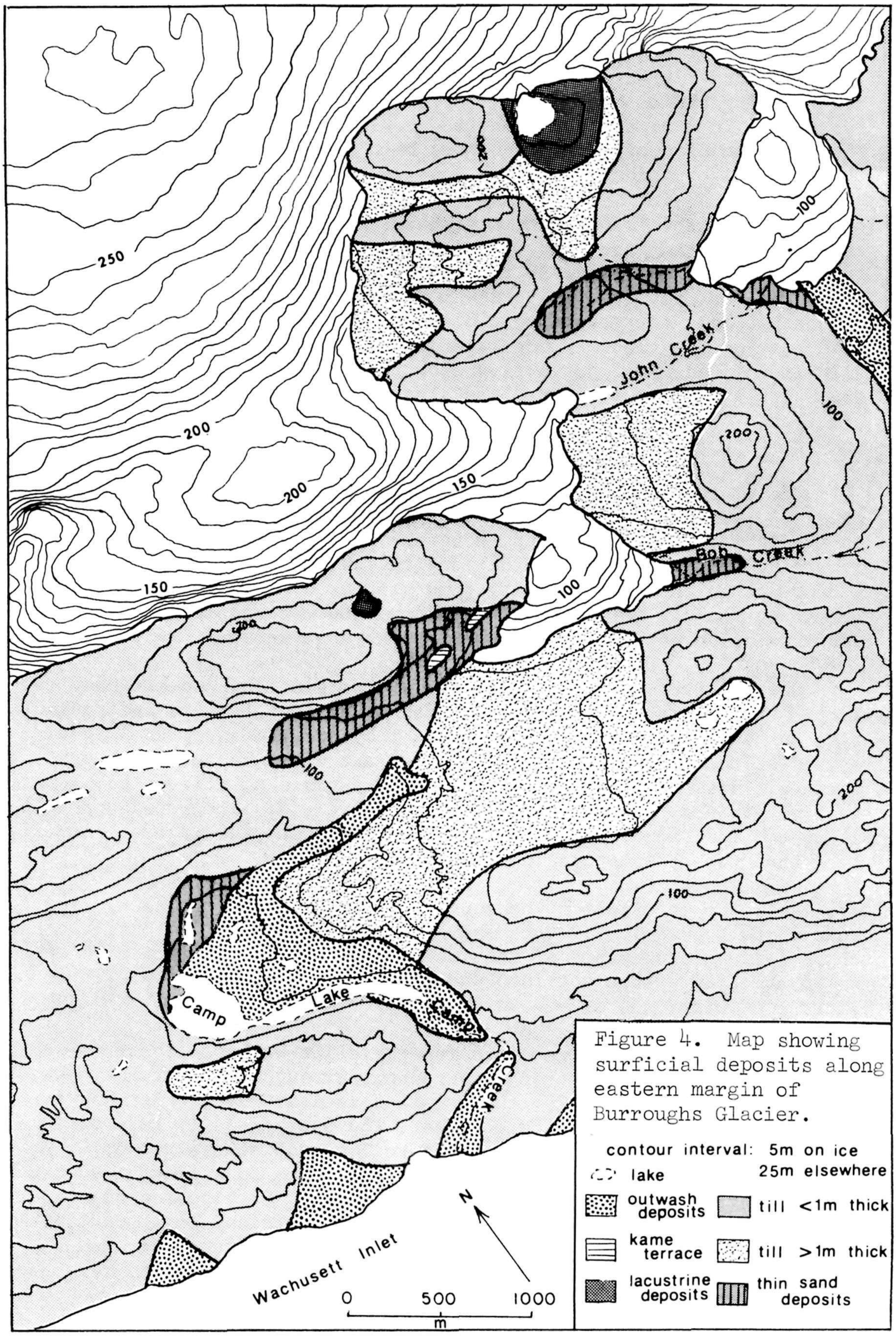

Figure 4. Map showing surficial deposits along eastern margin of Burroughs Glacier.

The shaded areas in Figure 5 show the general extent of the stagnant ice fringing the eastern end of Burroughs Glacier. Most of the stagnant ice occurs in a zone one-fourth to one-half a kilometer wide and lies the lee side of nunataks, which have been recently exposed by downwasting of the ice surface.

A plane table map of ice structures observed in one of the stagnant areas is shown in Figure 6. The map indicates a series of shear planes that dip up-glacier 15 to 30 degrees and one principal set of east-west fractures that dip steeply to the north and to the south. The shear planes probably correspond to similar structures mapped by Taylor (1962) elsewhere on the glacier. He identified tham as thrust faults of Nye's slip-line fields for compressive flow (Nye, 1952). A steeply, dipping east-west system of fractures was also recognized by Taylor. He attributed their origin to local shear deformation generated by the sub-ice topography.

The most dominant structures up-glacier are longitudinal crevasses (Fig. 5). These crevasses are nearly vertical and less than 30 centimeters in width. Their depth, however, can range from one to ten meters. According to Taylor (1962), the longitudinal pattern is associated with a decrease in the flow velocity down-glacier so that the principal stress in the ice is compressive. Above 300 meters elevation the longitudinal crevasses grade into a transverse pattern.

The texture of the ice varies over the glacier. On stagnant surfaces, the crystals are generally coarse and equigranular and range from five to ten centimeters in diameter. They sometimes appear slightly melted at their boundaries so that they are often loose, which gives the surface a disintegrated appearance. The surface of active ice, however, is fine grained, foliated, and does not have a disintegrated appearance. Also, the individual crystals are irregularly shaped and are generally less than two centimeters in diameter.

Ablation recorded on the southeastern end of Burroughs Glacier from June 15 to August 16, 1970 is shown in Figure 7. The contours are based on periodic measurements of the lowering of the ice surface with respect to 15 ablation stakes set into the ice. The values are reported in centimeters of water and assume an average ice density of 0.88.

The total ablation recorded for the eight weeks is about 45 percent of the total annual ablation measured on Burroughs Glacier in 1959-1960 (Taylor, 1962). Generally, the ablation is least up-glacier and is greatest along the lower ice margins. The average daily rate of ablation recorded during 1970 ranges from 1.6 to 2.6 centimeters per day. A straight line fitted by least squares regression to a plot of average daily ablation versus elevation of points (Fig. 8) suggests that, during the summer months, the slope of the ablation gradient is approximately -0.0075. The scatter of points about the line is presumably due to local variances in ice density, albedo, surface gradient and roughness.

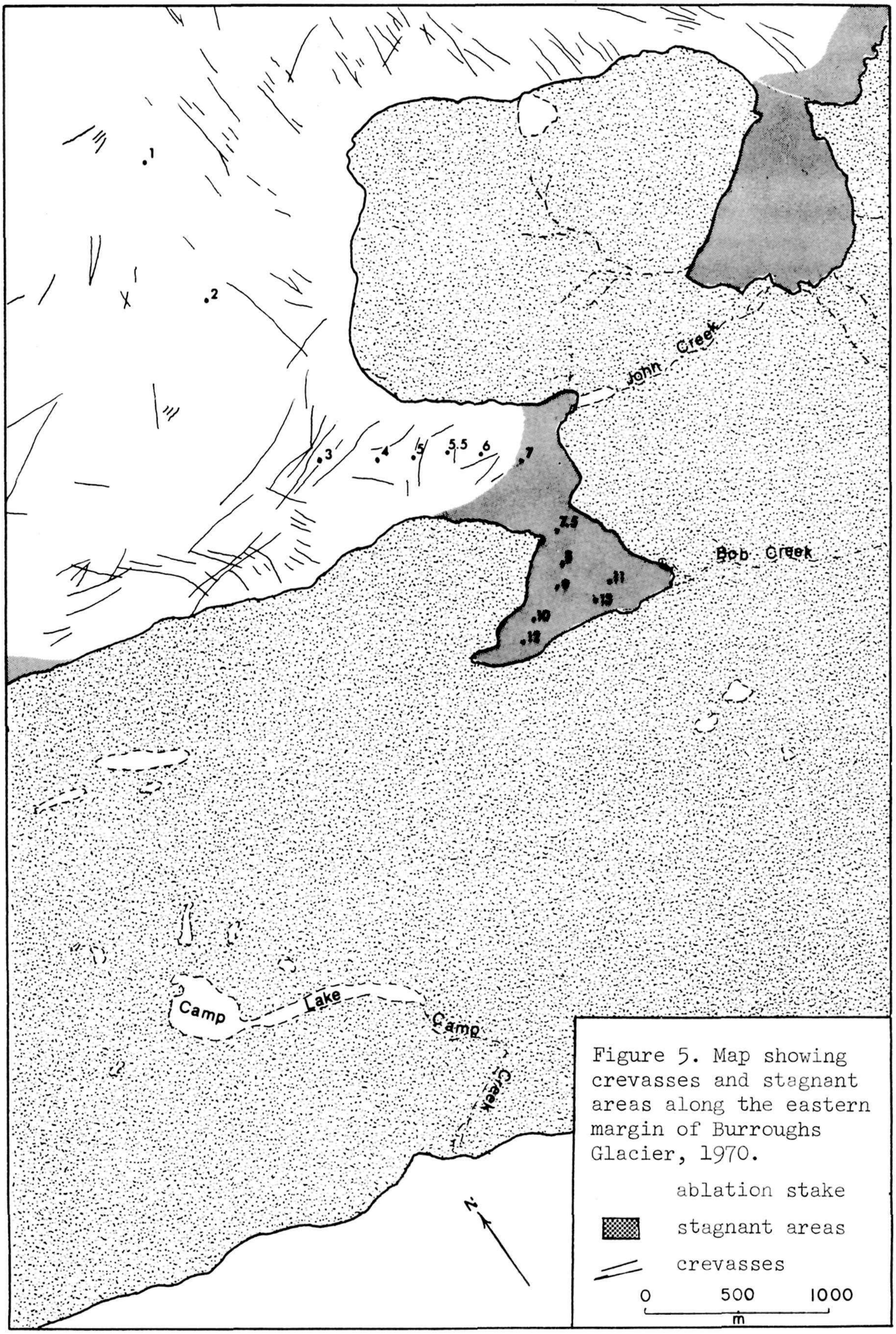

Figure 5. Map showing crevasses and stagnant areas along the eastern margin of Burroughs Glacier, 1970.

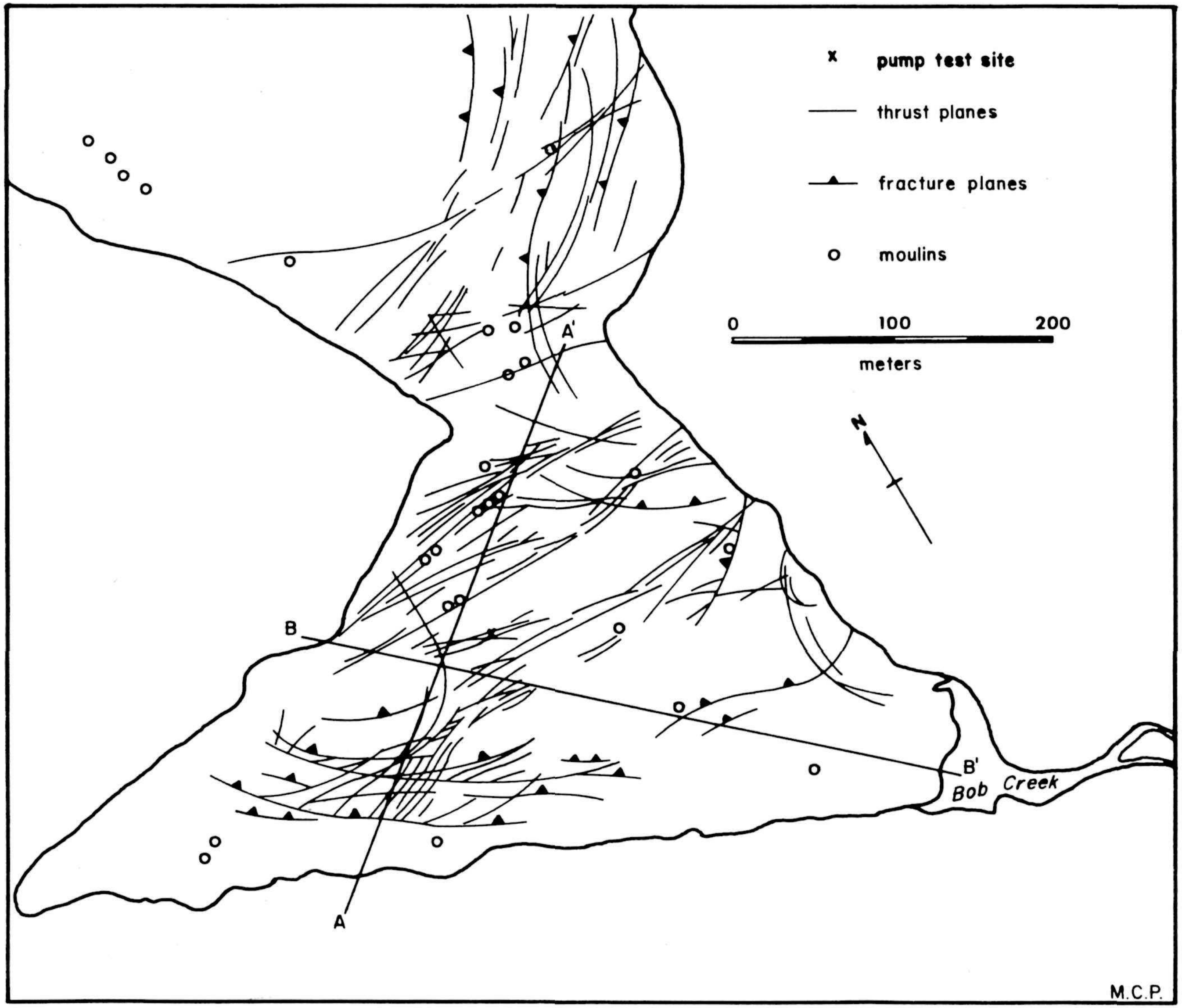

Figure 6. Plane table map of thrust planes, fracture planes, and moulins developed in stagnant ice, Burroughs Glacier.

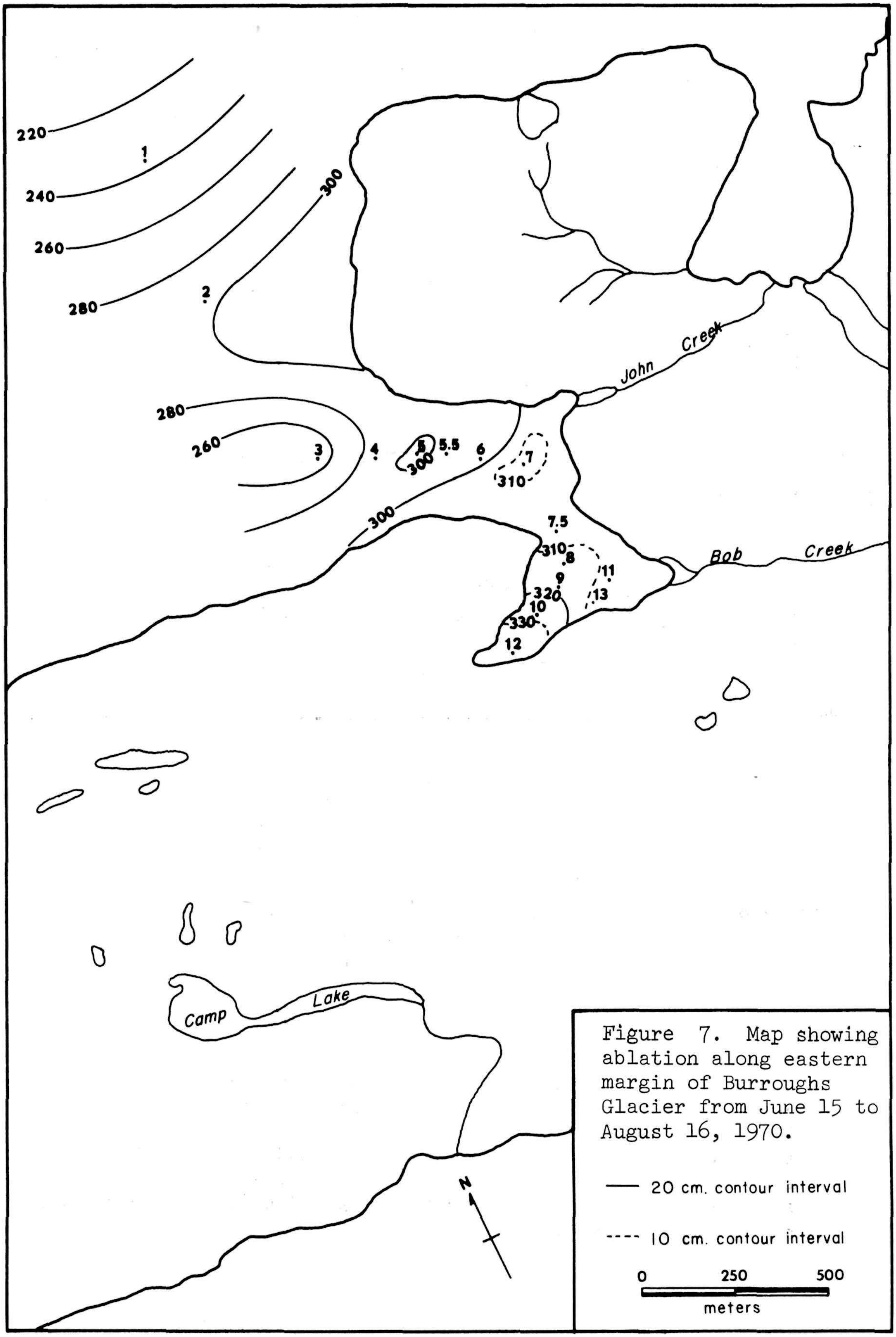

Figure 7. Map showing ablation along eastern margin of Burroughs Glacier from June 15 to August 16, 1970.

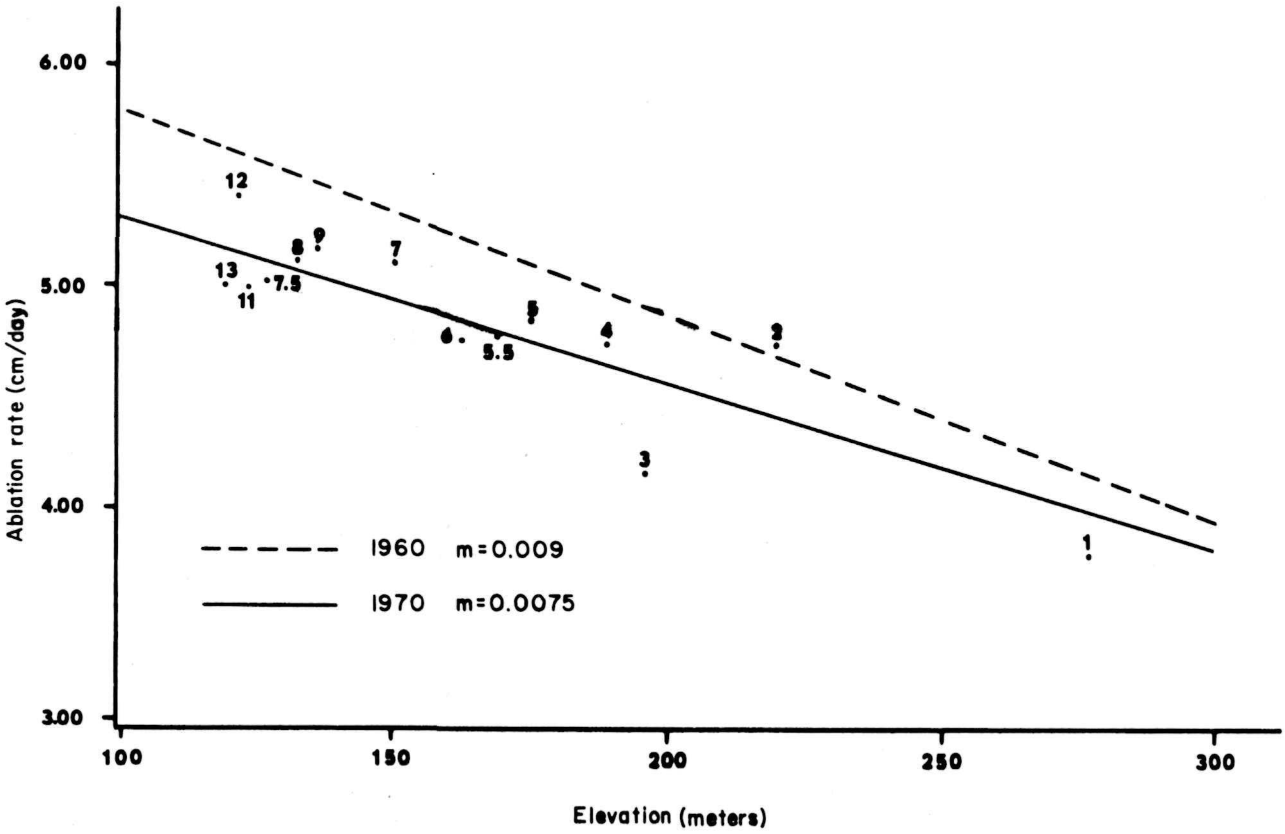

Figure 8. Plot of average daily ablation (cm/day) vs. elevation of ablation stake, Burroughs Glacier, 1970. Dashed line is ablation gradient calculated by Taylor (1962).

Cumulative ablation recorded at stake No. 9 from June 9 to August 22, 1970 is shown in Figure 3, together with meterological conditions observed over the same period. A comparison of the data clearly indicates that variations in summer weather effect the rate of ablation on the glacier. This is particularly evident during the period of July 6 to July 16, when relatively low temperatures, overcast conditions, and rain reduced the rate of ablation enough to produce a slight decline in the cumulative ablation curve for stake No. 9.

MELTWATER MOVEMENT IN STAGNANT ICE

During the summer of 1970, hydrologic investigations were made of the stagnant area shown in Figure 6. The investigations included: (1) monitoring water levels in wells drilled into the ice; (2) pump testing one of the wells and calculating ice transmissibility; (3) tracing the system of meltwater channels draining the ice; and (4) measuring the run-off from the ice. A photograph of the study area is Figure 9.

Figure 9. Stagnating ice along eastern margin of Burroughs Glacier, 1970.

The Glacier Water Table

Figure 10 shows the location of sixteen wells drilled along lines A-A' and B-B' in Figure 6. Each of the wells was drilled with a SIPRE ice auger and measured four meters deep and 10 centimeters in diameter. Water levels in the wells were measured either with a steel tape or with a Stevens automatic water level recorder. The construction of the recording wells is shown in Figures 11 and 12.

The two broken lines in Figure 10 represent the position of water levels observed in the ice at 6:00 a.m. and 6:00 p.m. on July 23. It is apparent from the profiles that the water table within the stagnant ice lies close to the ice surface and fluctuates throughout the day. Around moulins, the water table appear to be locally depressed.

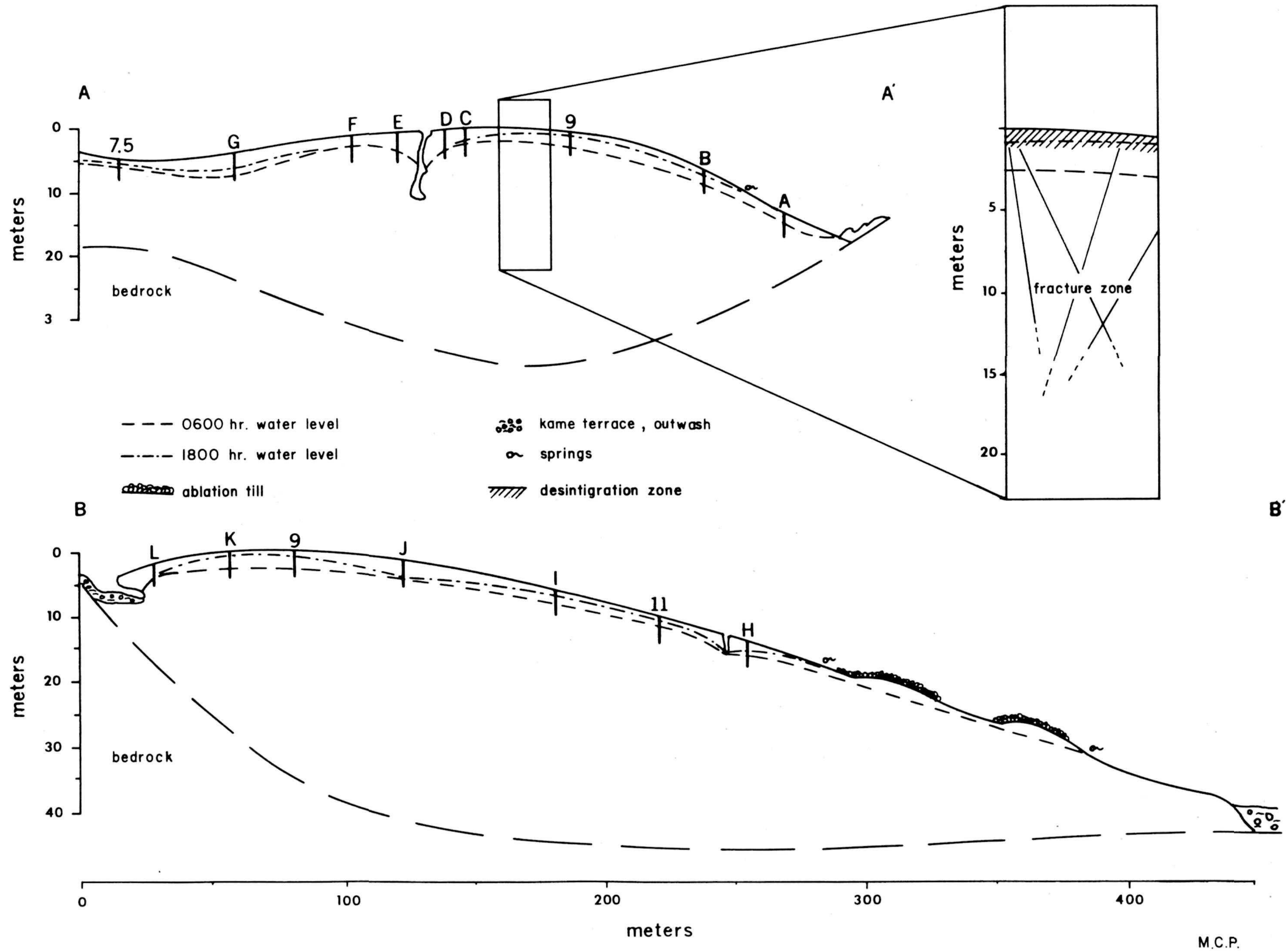

Figure 10. Cross sections showing position of water table in stagnating ice.

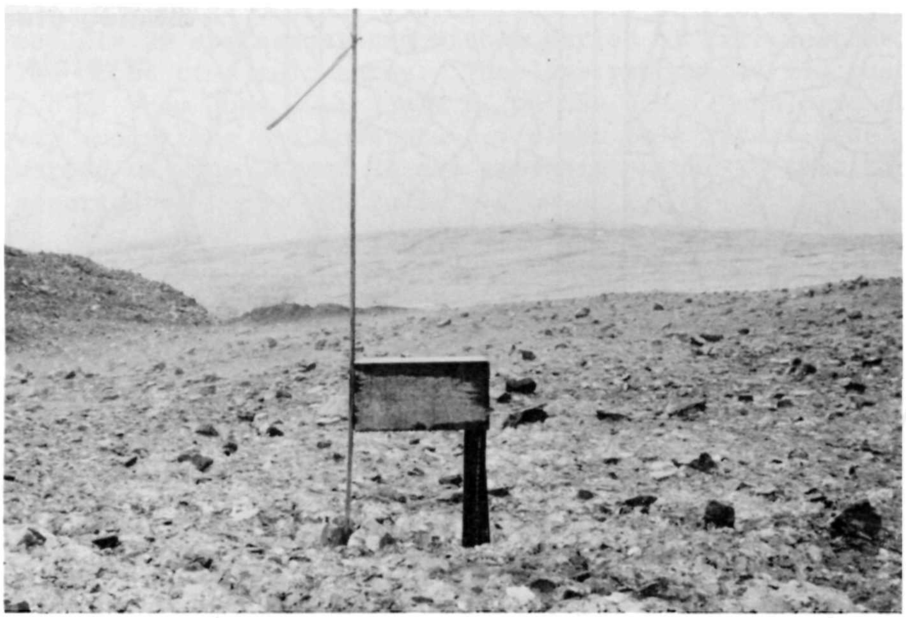

Figure 11. Photograph of well No. 9 showing construction of housing for automatic water-level recorder. Note surficial debris on stagnant surface.

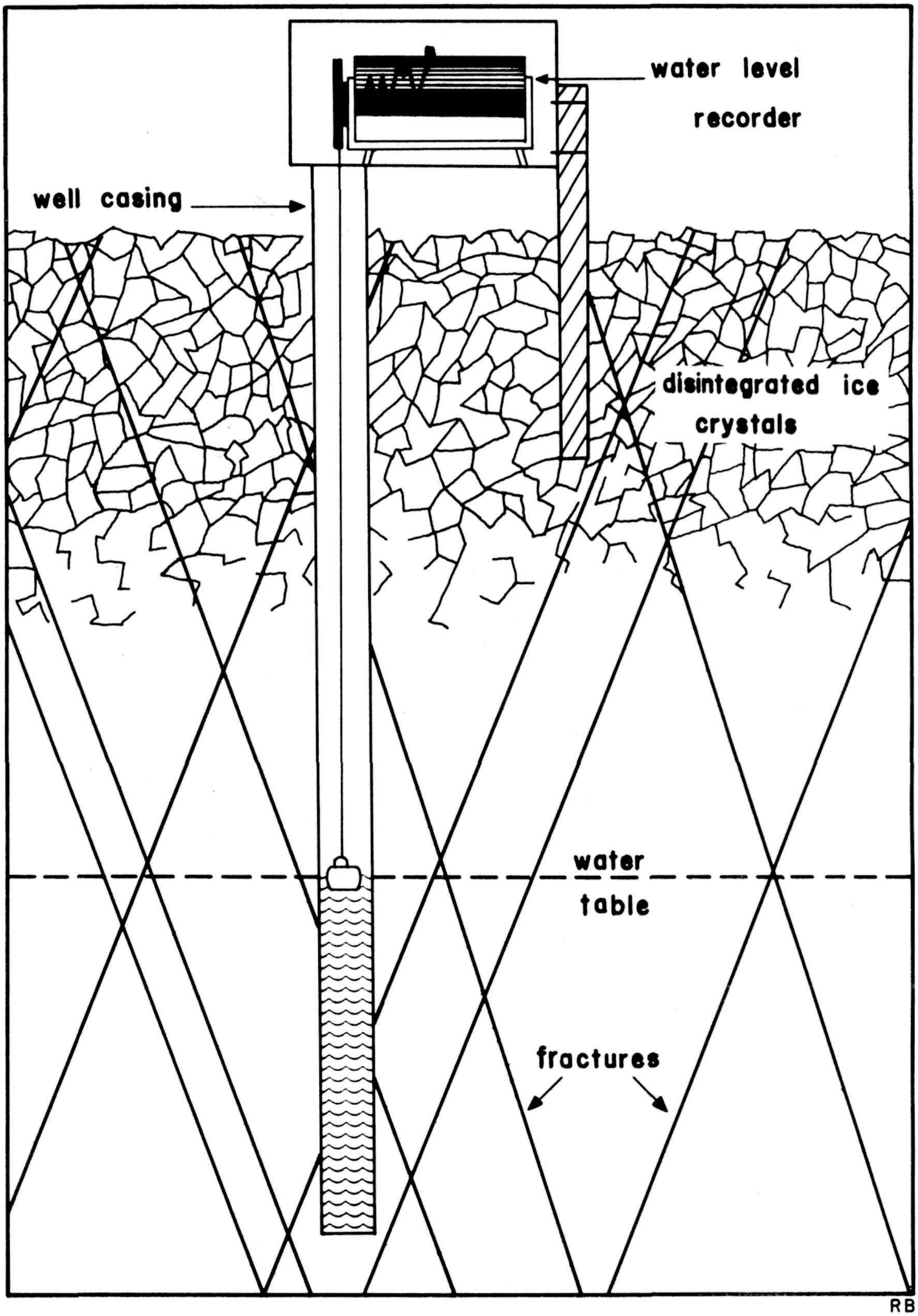

Figure 12. Diagram showing construction of well and housing for automatic water-level recorder.

Continuous records of water-levels observed in wells No. 9 and 11 are presented in Figure 13. The records cover the period from June 24 to July 6 and clearly reveal a diurnal pattern in fluctuations of the glacier water table. Each day, water levels in the wells appear to rise steadily throughout the morning and early afternoon, and to crest between 3:00 and 6:00 p.m. Through the evening and night, however, water-levels appear to fall off and are lowest around sunrise.

The magnitude of the diurnal fluctuations shown in Figure 13 seems to be related to both the melt rate and climate at the glacier surface. For example, the large diurnal fluctuation (0.9 to 2.2 m) recorded from June 26 to July 29 are associated with a period of fair weather and high daytime/low night time melt rates. The less pronounced fluctuations (0.4 to 1.6 m) from June 30 to July 6, on the other hand, are associated with cloudy conditions and moderate day/night melt rates. The fluctuations recorded on June 24 and 25 are somewhat unique in that they reflect a period of heavy rainfall.

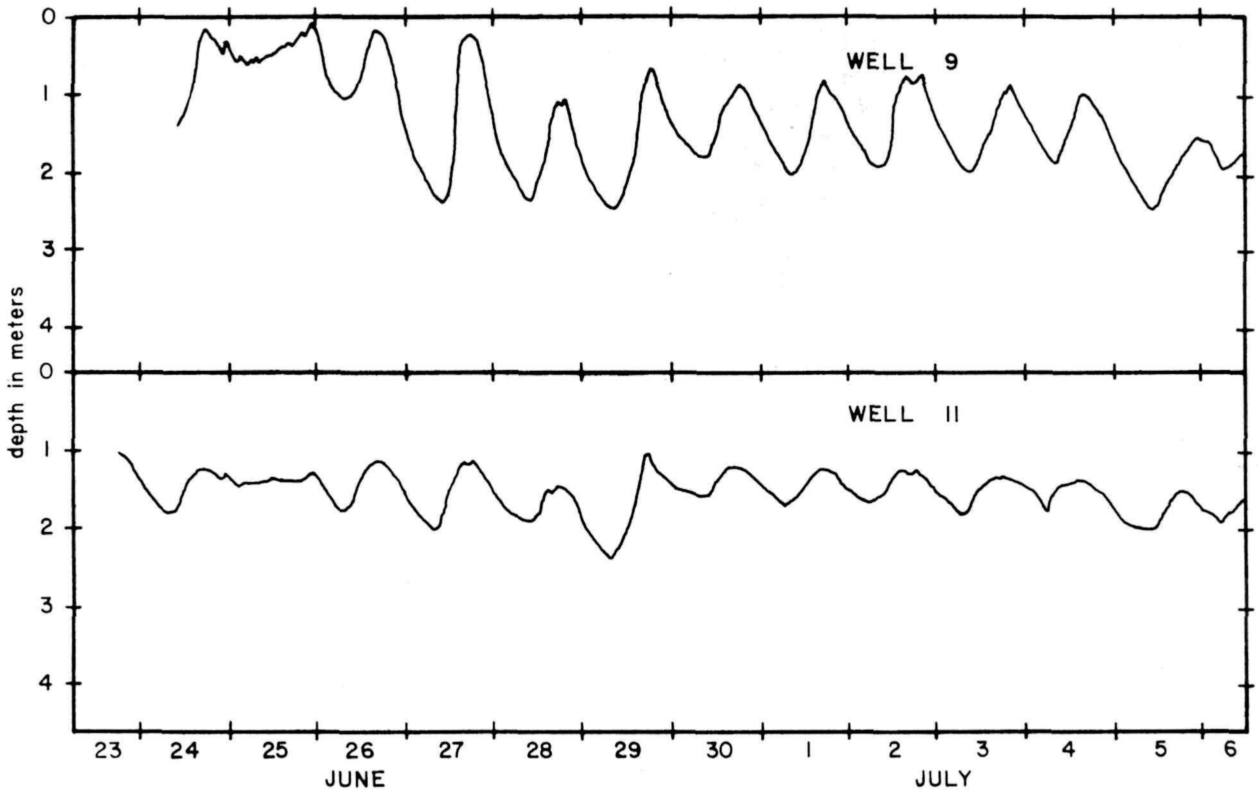

Figure 13. Hydrograph showing diurnal fluctuations recorded in wells No. 9 and 11.

Ice Transmissibility

Meltwater (and rain) from the glacier surface infiltrates into the ice and recharges the saturated zone via "vein like" passageways between disintegrated ice crystals and along fracture and shear planes that intersect the ice surface (see detail in Figure 10). The passageways between disintegrated crystals are the result of subsurface radiation melting along crystal boundaries. They extend normally no more than one meter into the ice surface and rarely exceed a few millimeters in diameter. The fracture and shear planes cutting the ice are generally less than a millimeter or two wide. They extend 10 to 15 meters into the ice (Figure 14) and provide much of the pore space within the ice for the storage of meltwater.

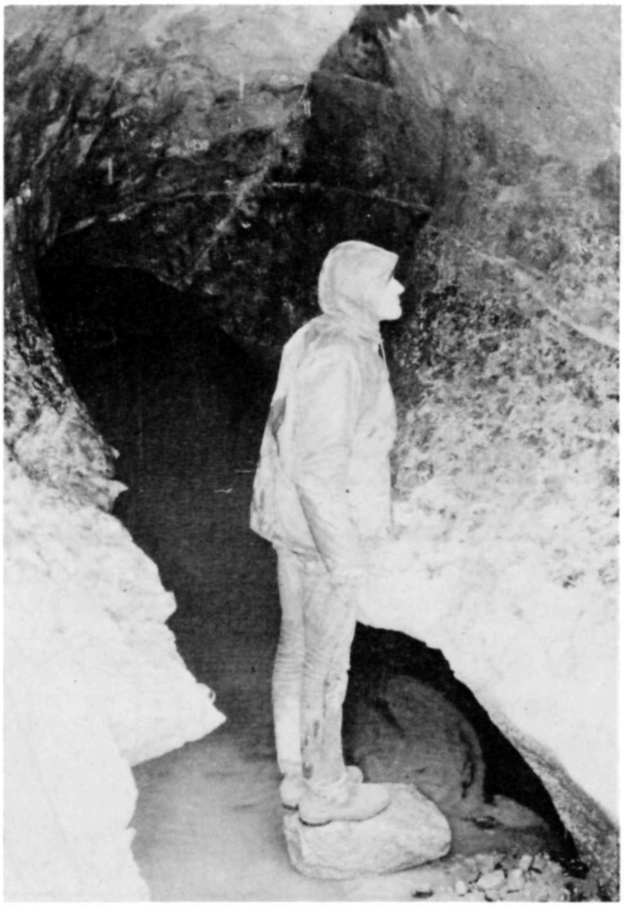

Figure 14. Fracture and shear planes within wall of moulin. Photo was taken five meters below ice surface.

On July 2, a pump test was made within the saturated zone to determine the coefficient of transmissibility and storage of the stagnant ice. The test well was located near well No. 9 (Fig. 6) and measured three meters deep and 10 centimeters in diameter. Four observations wells, each three meters deep, were also drilled 1.5 to 2.5 meters from the test well. The arrangement of the five wells is shown in Figure 15.

Pumping of the test well began at 3:30 p.m. when the glacier water table was at its highest level for the day and momentarily static. The test lasted for 16 minutes and ended when water levels in wells several hundred meters from the test well began declining for the day. The rate of pumping was kept constant at 2.3 liters per minute throughout the entire test period. The drawdowns observed in the observation wells during the test are shown in Table 1. They have been corrected for effects of decrease in saturated thickness and partial penetration losses (Jacob, 1963).

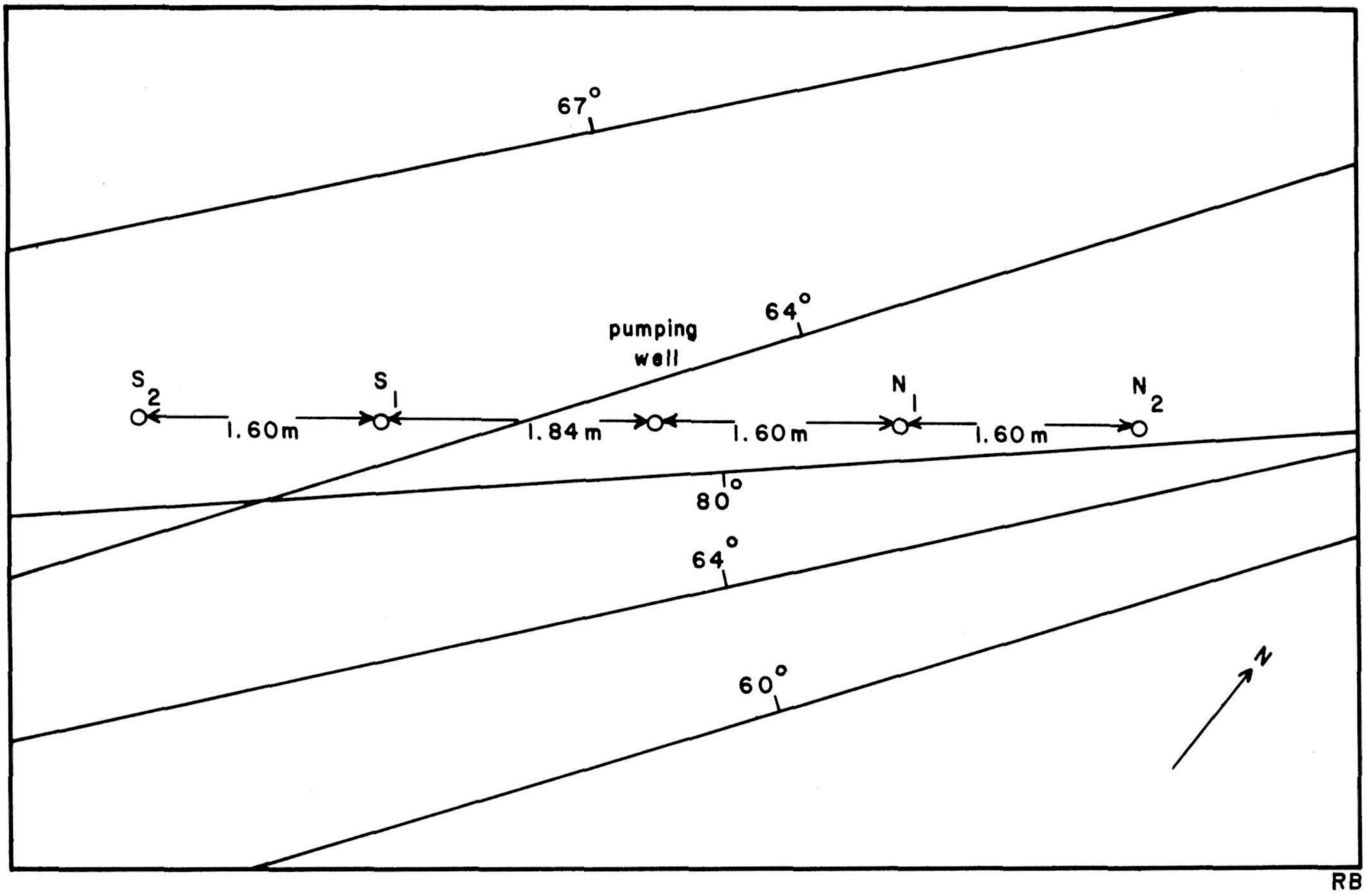

Figure 15. Fracture planes and observation wells in the vicinity of pumping well.

Table 1

Drawdowns In Observation Wells

Pumping Began (minutes	Drawdown In Observation Wells (cm)			
	N_1	N_2	S_1	S_2
0	0	0	0	0
0.5	0.3	0	0.3	0
1.0	0.6	0.3	0.6	0
1.5	0.9	0.6	1.4	0.3
2.0	1.2	0.9	2.1	0.3
2.5	1.5	1.2	2.7	0.3
3.0	1.8	1.5	3.1	0.3
4.0	2.1	1.8	3.6	0.6
5.0	2.4	2.1	3.9	0.9
6.0	2.7	2.4	4.6	1.2
7.0	3.0	2.7	5.8	1.4
8.0	3.6	3.4	7.0	1.5
9.0	4.3	3.9	8.2	1.8
10.0	4.7	4.3	9.1	2.1
12.0	5.5	4.8	10.6	2.8
14.0	6.1	5.2	11.9	3.4
16.0	6.7	5.5	12.5	3.6

The coefficients of transmissibility T and storage S were calculated by the type curve graphical method divised by Boulton (1963). The time-drawdown field-data curves in Figure 16 were superposed on a family of water table, fully-penetrating, constant-discharge, time-drawndown type curves. Selected match-point coordinates were then substituted in the equations to the right of the curves in Figure 16 for computation of the coefficients T and S.

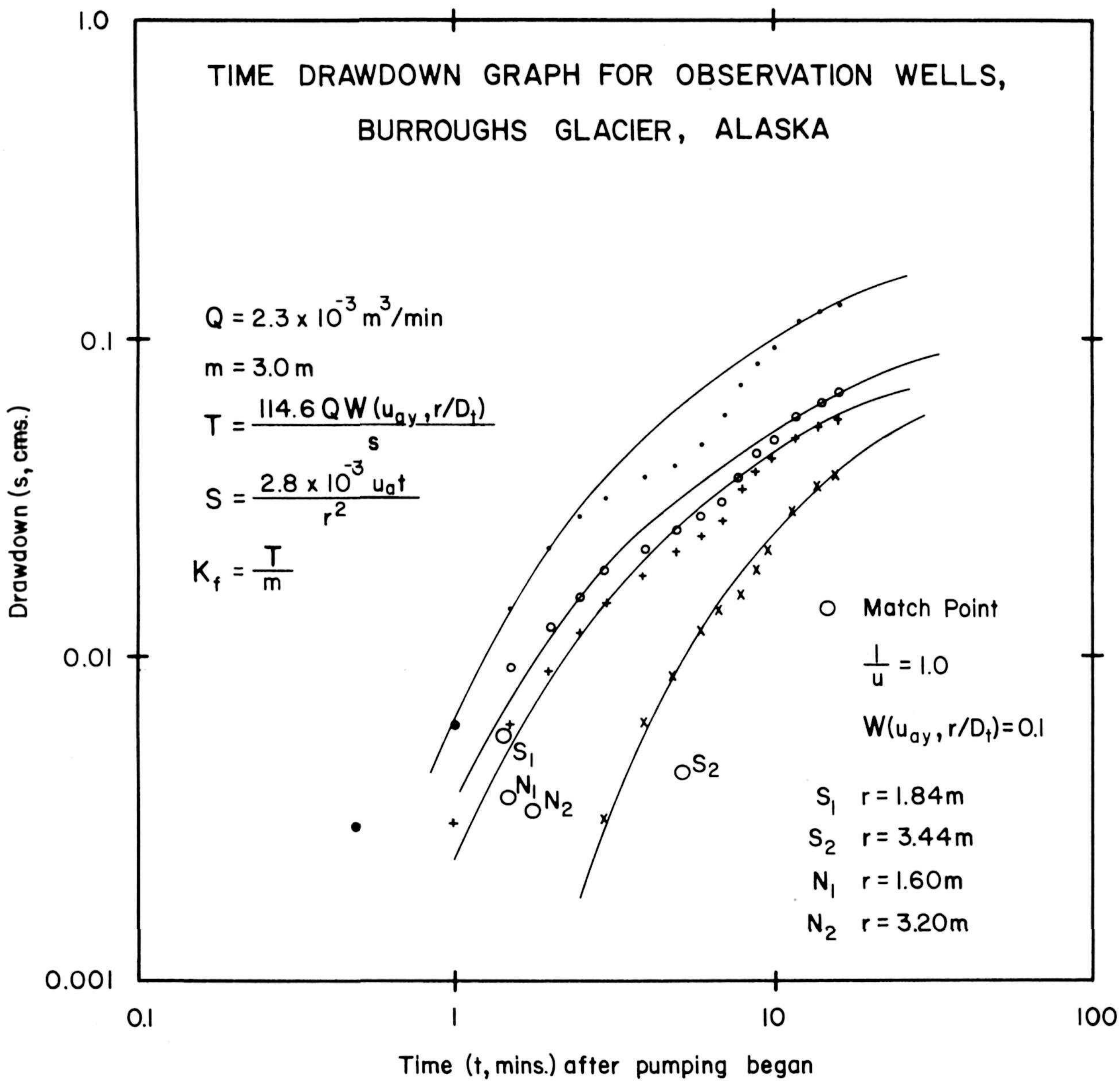

Fig. 16. Time drawdown graphs for observation wells N_1, N_2, S_1 and S_2, Burroughs Glacier, Alaska.

The values of T and S computed from the drawdowns observed in the observation wells are listed in Table 2 together with calculated ice permeabilities K_f. From the data it appears that the average values of T, S, and K_f for stagnant ice are 6.64 m^2 day^{-1}, 6.9 x 10^{-3} and 2.21 m day^{-1}, respectively. It should however be recognized that the coefficients computed represent the average hydraulic properties of the ice within the cone of depression; outside the cone the hydraulic properties may be quite different. Furthermore, the coefficient of storage computed from the test results apply largely to the part of the ice above the cone of depression and may not be representative of the ice as a whole.

Table 2

Calculated Coefficients or Transmissibility (T), Storage (s), and Permeability (K_f) for Stagnant Glacier Ice

Observation Well	Transmissibility (m^2 day^{-1})	Storage (x 10^{-3})	Permeability (m day^{-1})
N_1	7.53	10.2	2.51
N_2	8.24	4.1	2.74
S_1	4.39	5.4	1.46
S_2	6.43	7.8	2.14
Average	6.64	6.9	2.21

Englacial and Surficial Streams

Figure 17 shows the major stream systems developed within the stagnant ice during the summer of 1970. The streams were traced by periodically injecting flourescein dye into moulins and ice marginal streams and noting points along the edge of the ice where the dye emerged. In a few instances, transient times for the dye was also recorded.

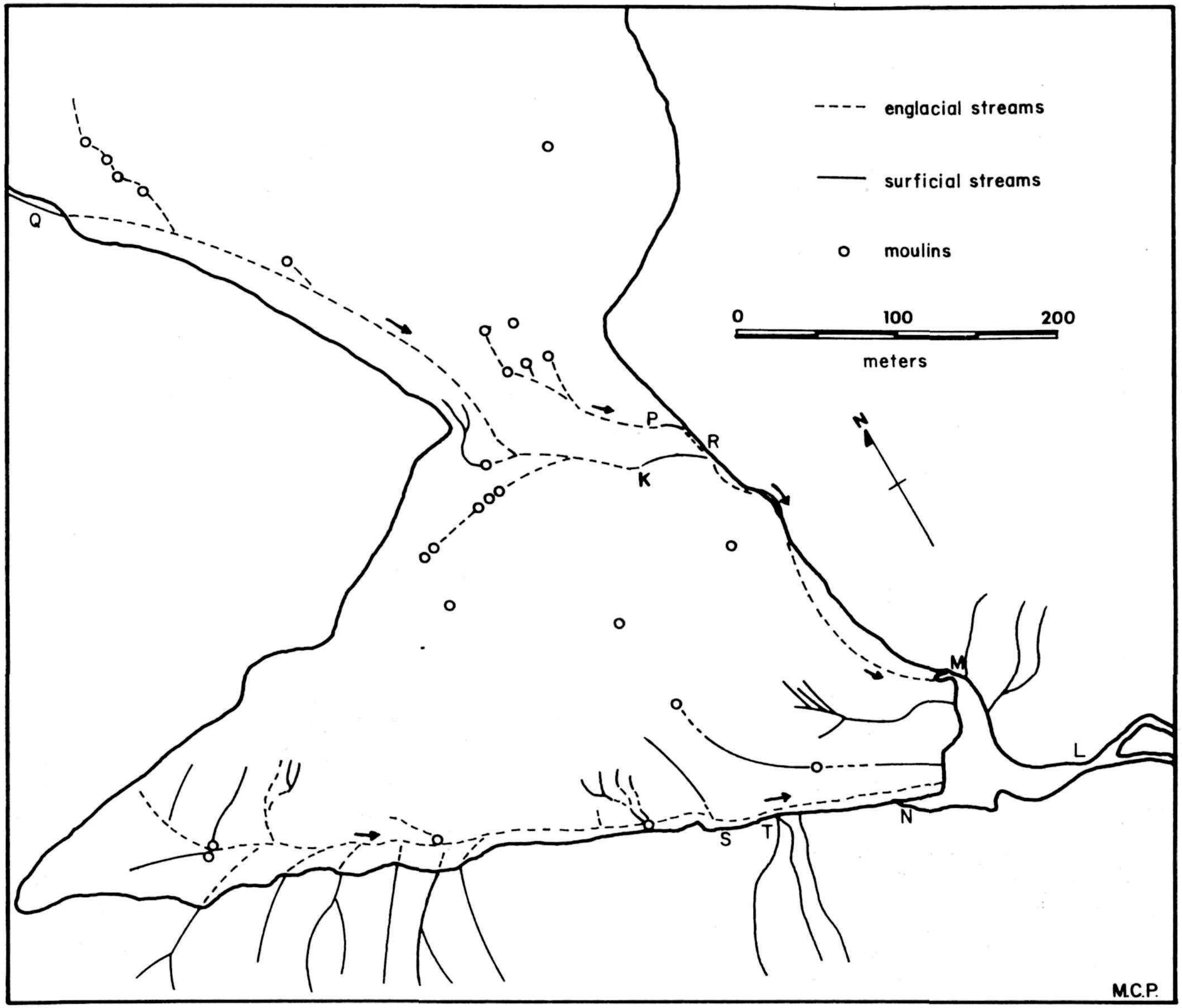

Figure 17. Englacial and surficial streams draining stagnant ice along eastern margin of Burroughs Glacier, 1970.

It is evident from the map in Figure 17 that the stagnant ice is drained by two separate systems of surficial and englacial streams. The larger of the two systems occurs within the northern part of the map area and consists of a semi-lateral trunk stream with several small tributary streams. The system within the southern part of the map area also includes a semi-lateral truck stream, but some of its tributaries also drain till deposits and kame terraces along the edge of the ice.

Some of the streams draining the ice appear to alternate between being surficial and englacial along their reaches. For example, the truck stream within the northern part of the map disappears into the ice at point Q (Fig. 18) and re-emerges 300 meters dwon stream at point K (Figure 19). After flowing on the ice surface for about 100 meters, the stream again disappears into the ice at point R (Fig. 20) and reappears again 200 meters to the south at point M (Fig. 21). The transcent time for the passage of the dye from point Q to point R averaged five centimeters per second.

Figure 18. Ice marginal stream disappearing into ice (Point Q in Fig. 17.

Meltwater Run-Off

Meltwater run-off in Bob Creek was recorded at a gaging station set up approximately a quarter kilometer downstream from the stagnant ice margin (Figure 22). The station was equipped with a Steven water-level recorder and was located along a reach of the stream underlain predominantly by bedrock.

Figure 19. Englacial stream emerging through ice (Point K in Fig. 17).

Figure 20. Englacial stream (Point R in Fig. 17). Note deposits of sand and gravel along channel banks.

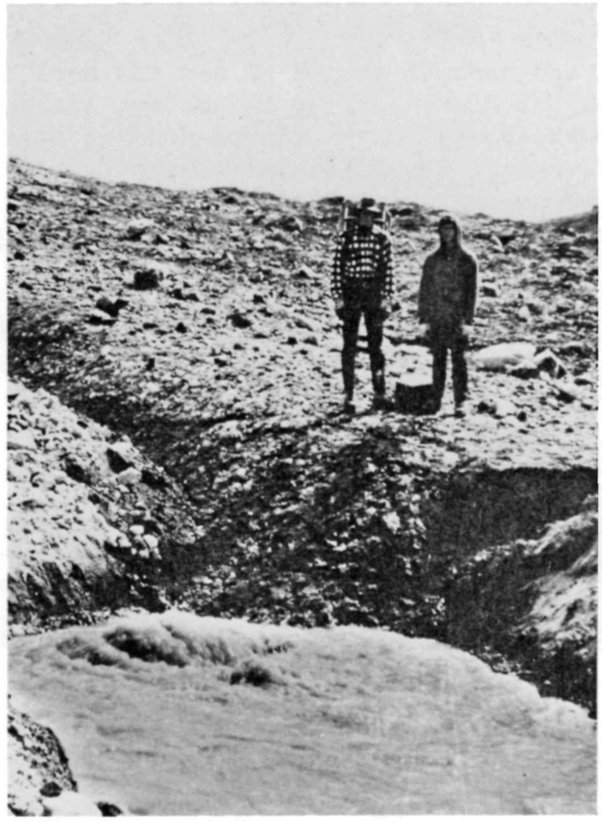

Figure 21. Englacial stream emerging from ice edge (Point M in Fig. 17).

Figure 22. Gaging station on Bob Creek. Note stagnant ice in background.

The run-off recorded in Bob Creek from June 23 to July 6 (Fig. 23) clearly shows a diurnal pattern in stream flow with maximum discharges occurring between 3:00 and 6:00 p.m. and minimum discharges occurring between 6:00 to 7:00 a.m. Superimposed on the diurnal curves are short term variation in discharge caused by both rapid changes in the surface melt rate and by rainfall augmenting meltwater run-off.

A comparison of the stream flow record in Figure 23 with the water-level records from well No. 9 and 11 (Fig. 13) shows a definite relationship between run-off from the ice and meltwater storage within the ice. The maximum and minimum values in both records appear to occur at approximately the same times. Also, the magnitude of diurnal water-level movements within the ice closely match the diurnal variations in meltwater run-off from the ice.

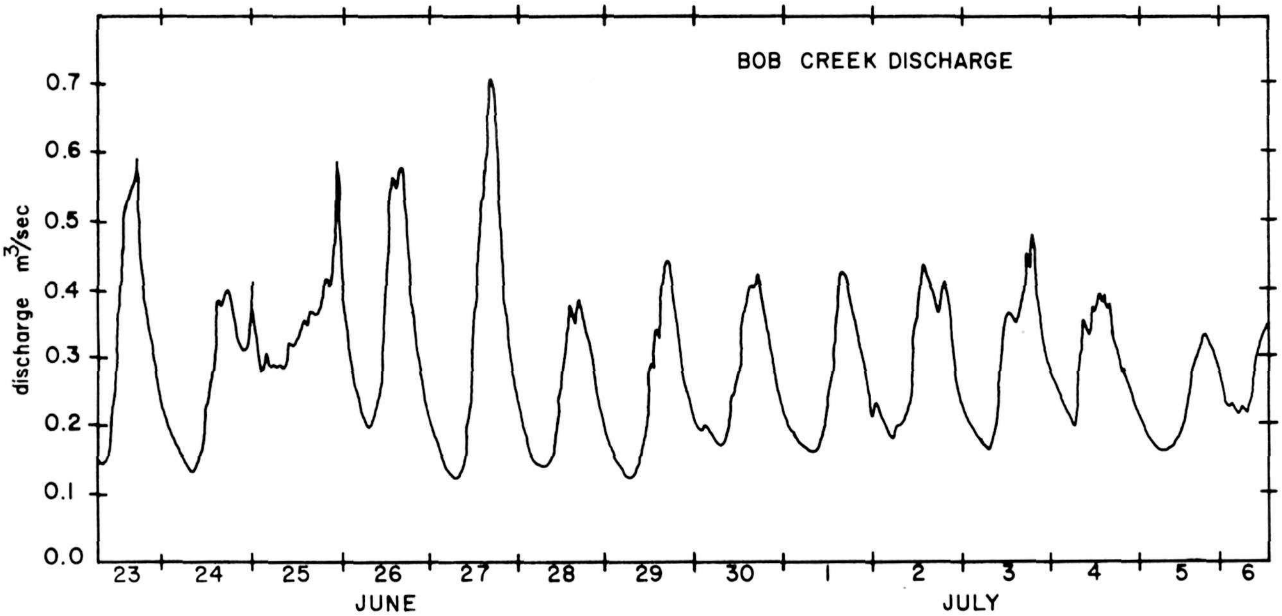

Figure 23. Hydrograph showing run-off in Bob Creek from June 23 to July 6, 1970.

SUMMARY AND CONCLUSIONS

Burroughs Glacier is a temperate valley glacier in south-eastern Alaska. It lies entirely below the equilibrium line and is rapidly wasting away. Fringing the eastern tongue of the glacier are several areas of stagnating ice that have become detached or semi-detached from the main glacier body.

Detailed investigations of the drainage developed in one of the stagnating areas have shown the following results:

(1) Meltwater produced on the surface of stagnating ice during during the summer season infiltrates into the ice via "vein like" channels between dis ntegrated ice crystals, and also along fracture and shear planes that intersect the ice surface.

(2) Within the stagnating ice lies a saturated zone. The zone is normally within a few meters of the ice surface and extends downward as far as fracture openings within the ice.

(3) The upper boundary of the saturated zone conforms closely to the ice surface and fluctuates diurnally, being furthest from the surface in the early mornings, and closest to the surface during the late afternoons.

(4) The coefficients of transmissibility, storage and permeability calculated for ice within the saturated zone are 6.64 m^2 day^{-1}, 6.9×10^{-3}, and 2.21 m day^{-1} respectively. These values are averages and apply only to ice near the pump test site.

(5) Around moulins draining the ice, the upper surface of the saturated zone is often depressed. In most cases the moulins feed into small englacial streams which successively join to form main englacial channels, normally in semi-lateral position. The transcent time of meltwater flow along a main englacial channel in stagnant ice appears to be on the order of five centimeters per second.

(6) Run-off from stagnating ice varies diurnally and conforms closely to fluctuations in the glacier water table. High run-off rates normally reflect high water levels within the ice, whereas low run-off rates correspond to lower water levels within the ice.

The above results suggest that the drainage developed in stagnant ice is, in many respects, similar to the drainage found in many limestones. In both cases, water infiltrates downward through a decayed mantle and passes along fractures and shear planes, until it reaches the water table. In glacier ice the fracture and shear planes are open only to a limited depth, hence the water table in ice appears "perched."

Moulins extending vertically through the ice are analogous to "sink holes" commonly found in karstic areas. The moulins drain meltwater from the ice and consequently draw the glacier water table down into cones of depression. The flow of water than passes through a system of englacial channels which are strikingly similar to solution passages developed in carbonate rocks. As might be expected, the flow through the channels is directly related to the surface infiltration rate and to the volume of meltwater in storage.

As is common in many limestones, the pattern of drainage channels is related in part to structural weaknesses in the ice. When meltwater passes along an open fracture or shear plane some melting will occur owing to frictional heat produced in running water. Eventually, some planes will become so enlarged that they develop into main drainage conduits.

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