ABSTRACT

NÉVÉ STUDIES ON THE JUNEAU ICEFIELD, ALASKA, 1961
WITH SPECIAL REFERENCE TO
GLACIO-HYDROLOGY ON THE LEMON GLACIER

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A detailed abstract can be found in Chaper V, pages 76 - 81, under the title, SUMMARY AND INTEGRATION OF RESULTS.

Owing to the broad and varied scope and significance of this dissertation, a chaper summarizing and integrating the results is necessary. Due to the same causes an abstract would tend to be quite comprehensive, indeed very similar to the summary. Therefore, in the interest of avoiding repetition, the author has taken the liberty of designating Chapter V as the abstract in addition to its function as the summary.

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By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1962

PREFACE

The following study was conducted as a part of the instructional field program of the Glaciological Institute, of the Department of Geology at Michigan State University, in cooperation with the Juneau Icefield Research Program of the Foundation for Glacier Research, Seattle, Washington.

The author is indebted to the Glaciological Institute and the Foundation for Glacier Research for providing the opportunity and means by which this study was carried out.

Compilation of the data would have been impossible without the generous cooperation and aid of Mr. Ralph E. Marsh of the U.S. Geological Survey Water Resources Division, Juneau office, Mr. Joseph Bower and Mr. C. E. Watson of the U.S. Weather Bureau, Juneau and Anchorage offices, and the members of the 1961 J.I.R.P. expedition...especially Mr. James H. Anderson, Mr. Douglas K. Bingham, Mr. Theodore F. Freers, Dr. Theodore R. Haley, Mr. Walter B. Lockwood, Jr., Mr. Jon Lundberg, Dr. Maynard M. Miller, Mr. Michael Porter, and Mr. Barry W. Prather.

The author wishes to express the deepest appreciation to his chairman, Professor Maynard M. Miller, for his constant guidance and encouragement during the field work and throughout the preparation of this dissertation. Further appreciation is extended for his helpful suggestions with respect to integrating the present study with details of previous research activities on the Juneau Icefield. Particularly valued is his generosity in making available unpublished data and interpretations from some of his own investigations in this area. The writer would also like to thank Professors William J. Hinze and James W. Trow for serving on his committee.

In addition, the author is grateful to his wife, Claire, for her patience and efficiency in typing the manuscript.

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I. PURPOSE AND PHYSICAL SETTING

The following study is inter-disciplinary in scope involving the fields of glaciology, meteorology, and hydrology. As suggested by the title the problem is two-fold. The first is concerned with the main accumulation sector of the Juneau Icefield in Southeastern Alaska (Fig. 1). In this there are three prime nourishment zones with mean elevations of 3900 feet, 4600 feet, and 5900 feet. A fourth lesser plateau lies at a mean elevation of 6500 feet. All are on the main southerly draining outlet of the Juneau Icefield and as such comprise the névé of the Taku Glacier (Fig. 2). The existence of the fourth plateau was recognized in the summer of 1961, however time and logistic limitations in this field season precluded more than preliminary reconnaissance assessment of its extent and character. Emphasis in this study is, therefore, on the main crestal névé at 5900 feet where the nature and magnitude of propagated surface water and the influence of subsurface glaciothermal conditions are investigated, with special attention given to the problem of melt-water percolation and the genesis of secondary stratigraphic structures in the firn-pack. The basic purposes in this aspect of the study are to delineate more precisely than heretofore, the glaciothermal character of the main névés of the Juneau Icefield; and to outline the effects on the glacio-hydrologic budget which are occasioned by factors of elevation, geographic position, and associated climatic conditions. The second aim is closely interrelated with the first in that it concerns investigation of factors producing runoff from the lowermost névé in the vicinity of the regional névé-line, in contrast to the uppermost névé where conditions opposing runoff are involved.

Two months were spent on the Juneau Icefield in the summer of 1961 gathering control data for this study. Other statistics embracing the full year of 1961 are also used, both from the Taku Glacier system and the adjoining Lemon Glacier[1] (Fig. 1). The Lemon Glacier lies southwest of the Taku Glacier system and has an area of approximately 7 square miles. This glacier, however, comprises a totally separate drainage system with a well-delineated catchment basin (12.1 square miles) not infiltrated by drainage from any other area. This circumstance lends itself to quantitative study of the effects of climate on the glacier, particularly with respect to hydrologic consequences. The névé of the Lemon Glacier corresponds to the lower (3900-foot) névé on the main icefield. To some extent this permits extrapolation of data from the Taku system. Ten years of pertinent hydrologic reports from a stream gauging site at the glacier terminus on Lemon Creek are in hand. These have been made available to the author by the regional

1. In this dissertation it was found to be simpler and less cumbersome to use the term "Lemon Glacier", rather than "Lemon Creek Glacier" as it is sometimes called. The word "Creek" is restricted to the stream (Lemon Creek) itself.

office of the U.S. Geological Survey in Juneau, Alaska. U.S. Weather Bureau climatologic reports and icefield records of the Juneau Icefield Research Program embracing the last decade provide further statistics for analysis of the glacio-hydrologic problem. Although the stream-gauge data are for the Lemon Glacier only, the results can be significant with respect to regime considerations for the icefield as a whole.

In view of this broader implication the results of the study and related statistics over the past 10 years are tabulated not only to support the conclusions drawn, but to make them available in summary form for future reference in other investigations of the long-term Juneau Icefield Research Program. To render the data most useful for further evaluations beyond the scope of the present purpose, special care has been taken in their compilation. Also in the interest of future perspectives the author's aim has been to veer in the direction of conservatism in the interpretations.

II. MAIN ICEFIELD RELATIONSHIPS

The first consideration is the geographic-orographic relationship between areas investigated on the main branch of the Juneau Icefield. Following this the relationship of Lemon Glacier will be considered. Also to be examined are differences in the ablation-accumulation ratio and in the nature of glaciothermal conditions, as well as related aspects of surface water propagation, the transmission and storage of unfrozen water, firn density, stratigraphy, and salinity, and, of course, pertinent factors in the basic glacio-meteorology of the icefield as a whole.

A. Orographic, Area, and Elevation Factors

In general, the névés critical to this study are wide and flattish with surfaces gently sloping toward the maritime flank of the Alaskan Boundary Range and, specifically, toward the central lower branch of the Taku Glacier system. The areal configuration is also relatively simple (Fig. 2). There are a number of broad platforms separated by slightly steeper zones of increased crevassing. At a mean gradient of 2.5 percent, however, they grade into each other almost imperceptibly and, hence, may be considered as continous. With the mean névé-line close to 3200 feet, the zone of nourishment extends from this level to that of the crest of the uppermost plateau...i.e. close to 7000 feet. The elevation range is thus about 3800 feet. Essentially, there are two prime névés which will hereafter be referred to as the lower (maritime) and the crestal (or upper) névés. The elevation range of the lower névé extends between 3200[1] and 5000 feet; and the crestal névé between 5000 and 6500 feet. The lower névé comprises approximately 110 square miles of the overall area in the Taku Glacier system; with the crestal névé occupying about 100 square miles. About 20 square miles of the glacier surface lies in the zone of dissipation below the névé-line. The two main névés cited above are separated geographically by a narrow section of the north branch of the Taku Glacier (mean elev. 4600 feet) in the vicinity of Camp 9 (v. Fig. 1). As has been shown by Miller (1956) any significan changes or shifts in positive regime from the lower prime névé to the crestal, or vice versa, can have important bearing on the subsequent mass behavior of the main outlet glacier below the névé-line. In turn, measurements and trends found at the two sets of research sites, 8A-8B (5900 feet) and 10A-10B (3650 feet), may be considered as representative of conditions at these respective névés.

With the total area of the Taku Glacier system being close to 230 square miles, the accumulator-dissipator ratio is roughly 10 to 1. In comparison, the Lemon Glacier, with a slightly higher mean névé-line (approximately 3300 feet),

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1. It is noted, however, that the semi-permanent névé-line on the Taku Glacier in 1961 rested at or slightly below 3000 feet. Its 1961 late-summer position on the Lemon Glacier was 3100 feet.

has a total area of only 7 square miles. Thus, its accumulator-dissipator ratio under present conditions is about 5 to 1. Since the mean elevation of the Lemon Névé is at 4000 feet, with an upper limit in the vicinity of 5200 feet, it is subjected to climatologic conditions comparable to those of the lower maritime névé of the main icefield. Its gradient is slightly steeper, however, (approximately 4°) and its terminus lies at 1500 feet rather than at sea level. Also, it is much more confined in an orographic setting of more mountainous character and its geographic position is somewhat more maritime, factors which explain the slightly higher névé-line which has been cited (v. footnote on P. 5).

B. Glaciothermal Conditions

In the sub-surface investigation of the crestal névé both hand auger and thermal drilling equipment were used for the insertion of temperature-sensing cables. With these, englacial temperatures were measured, upon which determination of the geophysical character of the upper névé was made close to 6000 feet on the Taku-Llewellyn divide. Similar equipment was employed in the higher névé zone (6500 feet) northeast of Mt. Ogilvie (Fig. 2). This highest névé, which is a distinct unit in itself, requires distinction from the main crestal névé, and so will hereafter be referred to as the Gilkey Névé. The results from each of these locales will be compared with the known temperature conditions found in the ice and firn of the lower névé which, as has already been pointed out, is geophysically comparable to the Lemon Glacier Névé.

1. Electro-Thermal Boring

At Camp 8A on the névé at an elevation of 5950 feet (Fig. 2), an electro-thermal boring rig was used to penetrate the firn to a depth of 151 feet. This drill was of a design previously used for investigation of the thermal character of the summit glaciers on Mount Rainier (Miller, 1959) and at Camp 8B (5900 feet) where similar drilling was accomplished in 1952 and 1953. Dimensional and wiring details of this unit are shown in Figure 3. In the present study it was used for melting a 2 inch bore-hole with power supplied by a portable, 2.5 kilowatt, 120 volt, 1 cylinder, 4 cycle, Onan generator.

The drill unit was suspended by a 7/16 inch manila rope, marked with tape at selected intervals. Conductor wires were G.E. insulated cord (NP-1300) of 0.58 inch (1.5 cm.) O.D., consisting of double copper leads, embedded in composition and sheathed with black rubber. The electrical leads were connected to the drill through a water-tight coupling, as noted in the figure. The drill unit could also be configurated with an outside heater coil (No. 12 wire) for drilling in exceptionally cold ice, an arrangement which is diagrammed in the extractor heating element of the figure. This accessory, which requires special care in its use, was not attached in the deeper drill hole at site 8A and, as will be shown, almost resulted in loss of the unit.

Vertical alignment of the bore-hole was established at the outset of drilling by means of the inclinometer on a Brunton compass. The general techniques in this type of drilling have been successfully tested and employed in earlier seasons of the Juneau Icefield Research Program. Details have been previously documented by Miller (1952a).

Because of the low power and consequent slow penetration rate of the closed-head drill unit in this field work the rate of advance, as logged in Appendix 1, can be used for interpreting sub-surface ice structures and density differences.

The thermal borer and generator were operated from 1815 hrs. on 29 August to 1115 hrs. on 4 September 1961. This comprised a total of 136.5 hours of nearly continuous drilling. During this period, there were short intervals, totalling 6 hours, during which the generator was not running; and, therefore, when the thermal borer was not penetrating the firn-pack (for these breaks in the record also refer to the drill log in Appendix 1).

At three different depths during the drilling a knot in the suspension line at a point 20 feet above the borer appeared to freeze into the bore-hole (v. position of small triangles in Fig. 4). This occurred on two occasions while the generator was running; the first of these at the 29-foot depth and the second at 131 feet. The third freeze-in occurred at 120 feet while the generator was stopped for repairs. On each occasion extraction of the unit was only possible after pouring anti-freeze into the hole. The reasons for this freeze-in were the bulkiness of the knot bringing it in close contact with the wall of the bore-hole. Also, as substantiated by the englacial thermal measurements discussed later, the entire 151-foot section of firn-pack penetrated by the borer was characterized by sub-freezing conditions. Although Miller (1955a) has reported sub-freezing conditions at shallow depth in this high névé the freezing of the knot at the cited depths represents the first empirical evidence that relict cold exists in the crestal névé at great depth. This finding is of critical significance to to other interpretations to be dealt with later.

By reference to the 1961 thermal drill plot (v. solid line in Figure 4A) it is seen that the first 22 feet of the bore-rate curve is hypothetic, having been extrapolated from the measured changes in density given in Figure 4C. Thus, electro-thermic drilling commenced in the bottom of a 22-foot section drilled by means of a S.I.P.R.E. 5 inch O.D. hand auger (Fig. 5).[1] For purposes of plotting, the reference datum is the top of the hole...i.e. the level of the 1961 late-summer ablation surface.

The marked variation in drill rate, as shown in Figure 4A, requires explanation. This will be considered after

1. Designed by the Snow, Ice and Permafrost Research Establishment of the U. S. Army Corps of Engineers; a model of which was manufactured for the Juneau Icefield Research Program by the General Mechanical Company of Chicago, Illinois.

review of the glaciothermal and sub-surface percolation and stratigraphic measurements obtained at the 8A and 8B sites.

2. 1961 Thermistor Measurements and Englacial Temperature Conditions

Glaciothermal measuring equipment was provided by the Foundation for Glacier Research on specifications designed and manufactured for this program by the Geophysics Laboratory of the U. S. Geological Survey. The applicability and use of this type of equipment for englacial temperature measurements has also previously been described in detail by Miller (1955a). The thermal sensors are thermistors, embodied in vulcanized cables (v. Fig. 6). The thermistors are manufactured by the Western Electric Company (type 17A) and consist of "small discs of sintered manganese and nickel oxide, 0.2 inches in diameter and 0.04 inches thick. An axial copper lead, 0.02 inches in diameter, is secured to each with an intermediary spot of ceramic silver paste. The resulting alloyed semi-conductor provides a 4.4 percent negative change in electrical resistance per degree Centigrade change in temperature at room temperatures and a 6 percent change per degree Centigrade in the vicinity of -30°C. Measurements can be made to an accuracy of 0.01°C by means of an appropriate Wheatstone Bridge" (Fig. 6).

Fifty to 180-foot cables of spaced thermistors were employed. Two cables, designated as Nos. 332 and 333, were installed in Bore-holes III, IV, and V, at the locations noted in Figure 2. This provides information supplemental to that obtained in Bore-holes I and II during the preceding ten years by Dr. Miller (also v. Fig. 2). Thus, englacial temperature measurements were obtained on the crestal névé at Camp 8A (5950 feet) and on the Gilkey Névé at Camp 19A (6500 feet). Each cable was 180 feet in length, embodying 18 thermistors with a 10-foot spacing. Both cables were recalibrated by the U.S.G.S. Geophysics Laboratory in the spring of 1961 and therefore are considered to have suffered insignificant drift and to be accurate to the limit cited above.

Cable No. 333 was placed in the 151-foot bore-hole at Camp 8A (designated as Bore-hole III in Figure 2). Cable No. 332 was placed in a 60-foot hand-auger hole (Bore-hole IV) approximately 40 feet west of Bore-hole III. Later this cable was moved to another 60-foot hand-auger hole (Bore-hole V) at Camp 19A. In each case the cables after installation were sealed at the top of their respective bore-holes and left to stabilize for periods of 24 to 72 hours before measurements were commenced. Successive thermal readings were then obtained at all thermistor levels on a 6 to 24-hourly basis. The dates and hour of installation, and the recorded measurements on each cable are given in Appendices 2-7. The thermal profiles, plotted for stabilized conditions, are shown in Figure 4B.

An examination of Figure 4B reveals the presence of the 1960-61 winter's cold wave in the 8A-8B sector, as well as in the Gilkey firn-pack. This is well demonstrated by the marked decrease in temperature between the surface and the depth of 50 feet, with minimum, -0.9°C, noted at 30 feet. Below 60 feet a relatively constant temperature (-0.05°C) exists. The curve indicates another zone of relict cold at a depth of 120-140 feet. It was at this level that the deeper freeze-in of the haul-rope occurred.

It appears significant that the temperature profiles obtained from the 60-foot Bore-hole IV at site 8A, and to the equivalent depth in Bore-hole V at site 19A, are almost identical. Additionally there is the fact that these follow the trend of the deeper thermal curve in Bore-hole III. The measured temperature depression in each of the shorter bore-holes, however, is considerably less than in the deep bore-hole. Although this could be the result of lateral temperature differences in the firn-pack, it is more likely due to size differences in the bore-hole. The shorter holes were bored with a S.I.P.R.E. auger drill which through frictional erosion produced a 5-inch diameter hole to the depths involved here as opposed to the 2-inch diameter of the thermal bore-hole. Such a larger hole may be expected to create a poorer side-wall contact with the temperature sensors, as well as to permit more air circulation than in the smaller bore-hole. These factors would tend to equalize the recorded temperatures and minimize the detection of variations. Thus, the data from Bore-hole III are considered as most representative.

The fact that, in spite of reduced magnitude, the same trends are indicated in Bore-holes III and IV...i.e. at both the 5900 and 6500-foot elevations — implies that thermal conditions are similar at least to 60 feet in both of these high névés. With this interpretation in mind the curve for the 151-foot bore-hole at 8A may be used as a guide curve to indicate the thermal conditions to be expected in the higher névé at site 19A. Therefore, the 1961 measurements on the crestal and Gilkey Névés, coupled with data from August, 1960, at Camp 8B (v. Fig. 4B) corroborate the suggestion that these upper reaches of the Juneau Icefield are sub-Temperate (Miller, 1956). This is in contradistinction to the fully Temperate condition which has been previously reported on the lower elevation névés and which characterizes most of the ice masses on the periphery of the icefield, such as the Lemon Glacier.

In Figure 4B is also plotted another temperature profile obtained by M. Miller and B. Prather (Personal communication) in late August, 1958, at site 8Y (Fig. 2). This record site lies at 6700 feet elevation on a névé apron a quarter mile north of Camp 8. Here the profile appears isothermal, its temperatures ranging so close to 0°C.[1]

The slight sub-freezing condition at the 2-foot depth on the 8Y profile may be explained by the fact that the thermistors were implanted during a sub-freezing blizzard.

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1. Because of consistantly positive readings in this set of data (v. Appendix 7) the plotted zero degree line has been moved 0.02°C to the left. Air circulation in the bore-hole may explain these slightly above-zero readings. This procedure is justified since a glacier can not be warmer than the limiting value of 0°C.

The generally Temperate condition indicated below this level seems anomalous in view of the data at nearby sites 8A and 8B discussed above. When considering the physiography of the location where the readings were taken, however, an explanation for the anomaly is suggested. The 8Y site is on the flanks of the bedrock nunatak upon which Camp 8 is situated. Bergschrunds in this vicinity indicate the glacier to be thin (80-150 feet). Thus, geothermal heat emanating from the bedrock could create warming of the ice-cover at this position. Also, crevasses which are found in this sector and which, in some cases, penetrate the glacier, permit a great deal of propagated water penetration to depth, as well as air circulation. Each of these aspects would temporize the ice. In addition, the test site is situated on an isolated massif protruding above the main névé surface, and at a position on the northwest flank of the nunatak readily influenced by westerly component maritime winds. Finally, the proximity of this portion of the névé to exposed sections of the nunatak enables it to receive a substantial amount of radiant and convective heat from adjoining bedrock outcrops. This also results in a greater propagation of melt-water, with attendant downward percolation helping to warm the ice. Such sectors of the névé, therefore, being thinner and on the flanks of the main glacier, need not exhibit the same geophysical characteristics as the main body of the ice beneath the névé of the crestal plateau.

In summary, a sub-Temperate condition in the upper Taku, Gilkey, and Llewellyn Névés is not surprising when consideration is given to the substantially colder climate and greater net accumulation that are presently encountered here. This is, of course, relative to the even more temporized climatic character of the lower névé at the level of Camps 10A and 10B, and indeed of the Lemon Glacier in the vicinity of Juneau.

C. <u>Ablation and Melt-Water Percolation</u>

The magnitude of surface melting and rainfall, and the resulting percolation of propagated water through the firn were also studied on the main icefield. Emphasis was placed on extending previous ablation records with respect to the lower névé, while the effects of water migration were more closely studied on the higher reaches.

1. <u>Main Crestal Névé</u>

On the crestal plateau at site 8A a test pit was excavated in the firn to a depth of 20 feet in order to investigate melt-water percolation and to record the firn stratigraphy. Four melt-water funnels were placed 3 feet into recesses in the west wall of the pit at depths of 5 inches, 28 inches, 58 inches, and 88 inches below the 1961 late-summer ablation surface (v. Fig. 10). From each, rubber tubes extended into collection pans in the pit for the periodic measurements of propagated water. The mouth of each funnel used is 12 inches in diameter and is covered by a wire-mesh screen to prevent contamination by loose snow or firn. This equipment has also been described in detail in previous reports of the Juneau Icefield Research Program. Each installation was completely covered with firn to insulate against atmospheric influences. Thus, secondary melting due to heating of the metal funnel by air circulation or solar radiation could be eliminated.

In Appendix 8, the amount of percolated water captured per day is tabulated. The record, taken from 25 August to 13 September 1961, shows relatively little melt-water generated during the days previous to 8 September. Contemporaneous meteorologic records obtained at Camps 8 and 8A reveal that over this period the temperature hovered around the freezing point; with atmospheric conditions varying from blizzards to CAVU. On and after 8 September, and especially after 10 September, significant increases in melt-water percolation were detected. This is considered related to the first substantial accumulation of autumn...i.e. a 12-inch snowfall on 7 and 8 September succeeded by clear skies and a strong rise of ambient temperature persisting from 10 to 12 September. The combination of moisture-laden snow with subsequent above-freezing temperatures and brilliant sunshine resulted in significant melt-water drainage in the uppermost funnel, positioned 5 inches below the 1961 ablation surface. The second, third, and fourth funnels, however, received little melt-water through this entire period of record. This suggests that the increase of surface percolation reached hardly deeper than the first funnel and did not penetrate significantly to the 28-inch, 58-inch, and 88-inch depths.

The above is not surprising in view of the englacial thermal conditions which have been recorded. Since the firn was characterized everywhere by temperatures below 0°C, the melt-water was apparently reclaimed by freezing before it could percolate to any great depth. The existence of various ice strata and related diagenetic structures bear this out. Details of this process will be discussed in section IID under the heading, Firn Stratigraphy and Structure.

Ablation stakes were also set out across the crestal névé. The alignment of these stakes was westward from site 8A to the junction with the Vaughan Lewis Névé (Fig. 2). Subsequent measurements on these stakes revealed a total gross lowering of the névé surface by ablation during the full month of August to be in the order of 11 inches of firn. Most of this ablation occurred during daylight hours, the effects being negligable at night. A review of project records from previous summers indicates that this statistic is minimal compared to ablation effects on the lower névé. The 1961 statistics from Camp 10B further bear this out, as discussed below. Precise diurnal records were not obtained because of the periodic snowfalls on the upper névé, the effects of which nearly balanced out the surface reduction by ablation (v. Appendix 9).

2. <u>Main Lower Névé</u>

On the lower névé in the Camp 10B area (3650 feet) a 1.3 mile traverse line was set out, along which 9 ablation stakes were positioned 300 yards apart. This traverse originated at the base of the Camp 10 nunatak and extended in a west-southwest direction (Figs. 2 and 8). The resulting gross ablation record for each point is plotted in Figure 7 for the period 25 July through 26 August 1961. The daily records for each stake are referenced in Appendix 10.

Total ablation for this interval averaged 48 inches of firn with respect to the broad central segment of the névé. This is more than 4 times the ablation for a comparable period in August on the crestal névé. Up to 72 inches of firn surface lowering was recorded over the same interval in the ablation moat adjacent to the Camp 10 nunatak. In the Camp 8 sector, 2500 feet higher in elevation, no ablation moat occurs, probably due to a much smaller area of exposed bedrock as well as to the factor of much less ablation. In contrast the névé area adjacent to the extensive exposures of bedrock on the Camp 10 nunatak is subjected to air convection currents and radiation from the rock. This provides adequate explanation for the greater amount of ablation observed in the marginal zones. Throughout the lower névé, especially below 5000 feet, moat features are visible wherever nunataks protrude through the icefield.

The broad central parts of the lower névé experienced less ablation not only because of their distance from rock outcrops but also due to their subjection to diurnal movements of cold katabatic air draining from the crestal sector.

Figure 8 shows the ablation per day measured at each of the stakes during the period of record. The curves are similar in each case, differing mainly in magnitude. This correspondence of peaks and troughs in spite of the erratic nature of the individual curves, suggests regional significance. By examining Figure 9 we have quantitative proof of the relationship to key meteorologic parameters. In this figure a plot is shown of the mean ablation of all the stakes for each day of record.[1] It can be seen that the ablation curve follows, fairly closely, the temperature curve; and, to much less extent, parallels the histograms of precipitation. Such a condition is due to the minimal melting effect of rainfall in the névé zones of the Juneau Icefield because of the less-than-40°F temperature condition of liquid precipitation in these areas. This corroborates the conclusion of previous investigators on the Juneau Icefield Research Program and of Wallén (1948) in his studies of climatologically comparable Scandinavian glaciers that the main control of ablation in the regions studied is ambient air temperature, even during periods of rainfall.

Specific melt-water studies on the lower névé were not conducted during this field season, however reference is made to the measurements of Leighton (1952) who, during the summer of 1949, found that melt-water was readily generated during all hours of the day, and to a lesser degree, throughout the night. He too observed direct correlation

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1. The dashed area of the ablation curve represents averages over the days involved, since daily synoptic measurements at Camp 10 were not obtained during these intervals.

between daytime melt-water production and diurnal rise and fall of ambient temperatures. Also, with similar melt-water recording equipment he noted increased concentrations of melt-water in the firn-pack with depth.

This is in contrast with the crestal névé where it is clear that far less melt-water is generated, and this only during the warmest hours of daylight. Also, in the Camp 8A firn-pack, no concentration with depth was observed during the period of August-September. In this regard the difference between the crestal and lower névés may be explained by the glaciothermal conditions discussed in section B2 of this chapter. A good share of the melt-water in the Temperate névé at lower elevations passes into the glacier at depth (Miller, 1962). This drains toward the terminus through englacial and subglacial channels, eventually emptying into Taku Fiord. In contrast, the englacial thermal conditions in the sub-Temperate névé of the crestal zone blocks the drainage of most water generated at the surface by reclaiming it through freeze-immobilization in the sub-freezing firn and firn-ice, and possibly even in bubbly glacier ice which, according to the reduction in thermal drill rate (Fig. 4A), might prevail below about 110 feet.

In the Camp 9 area ablation measurements were taken from 8 stakes on an east-west traverse across the intermediate (4600-foot) névé. A total lowering of approximately 10 inches of firn over a 10-day period was measured in August, 1961. The data are recorded for future reference in Appendix 11.

3. Mode of Percolation

The percolation of melt-water through the firn is not entirely vertical, nor is it uniform. As noted above, percolation water can become concentrated with depth under conditions where melt-water is generated in copious quantities and where conditions are sufficiently Temperate to allow it to coexist in a firn-pack or in ice without freezing. This concentration at depth may be attributed to the increase in density and consequent decrease in permeability in deeper firn. Also, planar and cross-cutting ice structures which so readily form in Temperate glaciers (Leighton, 1952) affect the concentration of mobile water. These features, once they develop, divert the normal vertical flow that would occur in homogeneous firn, and cause it to move downward in all directions...i.e. varying from horizontal components to diagonal and vertical. Therefore, the impression that a uniformly descending melt-water front exists in the firn of a Temperate glacier is in many cases erroneous. Instead, localized concentrations of melt-water occur in irregular zones where percolation is either guided or impeded by restrictive ice structures. Such selectivity in paths of flow, when coupled with repeated refreezing of melt-water in the firn, tends to accentuate diagenetic ice structures already formed (Miller, 1962a). This fact can explain the presence of unusually thick ice strata and related ice glands, particularly at the deeper levels. In the 1961 season such were observed dramatically exposed on crevasse walls at the 5700-5800-foot level in the Camp 8 sector, and especially at site 8A as noted below. Lesser ones were also found in a test pit on the 5200-foot névé at Camp 9.

D. <u>Firn Stratigraphy and Structure</u>

Firn stratigraphy deals with the annual accumulation or yearly firn increments found in a firn-pack. In each such segment freshly fallen snow of a density 0.1 has suffered destructive alteration followed by constructive crystal metamorphism before it has changed into firn at a density of 0.50-0.75. With increasing depth these segments grade into firn ice (0.75-0.88), and at the deepest levels into bubbly glacier ice (0.88-0.90). The agents of this metamorphism are primarily compaction and regelation with melt-water percolation having a supporting affect.

Incorporated within the firn-pack on this icefield, an extensive development of varied ice structures has been previously reported in publications of this long-range program. These have been described as various thicknesses of ice strata, and various forms of lenses, pods, columns, dikes, etc. But regardless of morphologic differences they are all the result of surface water percolation and refreezing of liquid water at depth. On the lower névés where Temperate conditions prevail they can only serve as an indicator of the magnitude and extent of melt-water generation during the spring amelioration period. On the highest névés, however, they represent development during the whole of the ablation season. Hence, an extrapolation of the volume of these secondary ice structures at the 8A-8B sites will be attempted.

1. Main Crestal Névé Firn-Pack

The data on accumulation and stratigraphy serve as a continuation of and supplement to records at sites 8A, 8B and 8X in 1951, 1952, 1953, 1958, and 1960.[1] The 1961 records were obtained in bore-holes and from the walls of test pits and crevasses. Tabulations of these measurements, including those from the Gilkey Névé, are given in Appendices 12, 13 and 16. By reference to this set of statistics delineation of the annual sequence of firn accretion is attempted for the period 1951-61.

a. Primary Stratification: Some of the data in 1961 were obtained through gross examination of the S.I.P.R.E. auger cores from the 60-foot bore-holes at 8A and 19A. The resulting information is plotted in Figure 11, with provisional correlations suggested by dashed lines. Additional information may be derived from the 151-foot bore-hole at 8A by interpretation of the 1961 drill-rate curve given in Figure 4A. The measurements obtained from test pit and crevasse walls were at sites noted in Figure 2. Of particular importance are the crevasse data from the 5700-foot level 2 miles south of Camp 8. These records are presented in Figure 12. Correlation of the data obtained from the same sites in the 1958 and 1960 summer seasons (Miller, Personal communication) has given credence to the time sequence depicted in this figure.

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1. The 1951-53 records can be found in J.I.R.P. file reports, Foundation for Glacier Research.

Figure 10 depicts the wall structure in the test pit at Camp 8A. This represents a detailed picture of the stratigraphy and structure in the annual firn-pack, as of 9 September 1961. On this date the stratigraphic thickness of the 1960-61 accumulation stratum was 17.5 feet; with a density range of 0.52 to 0.59. This is in considerable contrast to the 7 feet of retained 1960-61 firn-pack (v. next section) measured at site 10B on 14 September 1961. Each of these dates may be considered as close to the end of the 1960-61 budget year. The excessive difference in thickness between these accumulation segments further substantiates the existence, under present climatic conditions, of a zone of maximum net accumulation on the higher reaches of the Juneau Icefield (Miller, 1956). This is both a factor of greater snowfall received on the crestal névé (in spite of the fact that higher mountains exist farther east) and greater ablation affecting the lower névé on the maritime side of the cordillera. In other words, elevation, geographic position, and orographic influences are together the prime factors controlling the magnitude of retained accumulation.

b. <u>Density Determination:</u> Density profiles of the firn in the Camp 8 sector are plotted in Figure 4C. The data were obtained in early September using a 500 cc. hand corer in the 8A test pit, and the S.I.P.R.E. auger corer in Borehole IV. The bore-hole densities were determined at irregular intervals to a depth of 58 feet below the 1961 ablation surface (v. Appendix 17). The test pit curve represents the record at 12-inch intervals through the 1960-61 firn-pack (v. Appendix 18). The bore-hole cores represent single samples. All density values in the test pit sequence represent averages of two or more readings. This is one of the reasons why the bore-hole curve varies over a greater range of densities than the pit wall curve. Another is the occasional presence of ice strata or laminae[1] in the bore-hole samples, as opposed to the test-pit cores where more caution could be used in the sampling of uncontaminated firn.

Mention is made of the greater bulk density indicated at site 19A, compared to 8A, as suggested by the stratigraphy in Figure 11. Later discussion of this anomalous indication will be made. Density measurements were also obtained in an 11-foot test pit (elev. 5200 feet) at Camp 9. Although these data are not plotted, they are referenced in Appendix 19. Generally, the densities at the Camp 9 site were higher than at Camp 8A.

As for the lower névé, a bulk density value has been estimated from comparable late-summer surface firn thicknesses measured over the past decade by earlier expeditions of this program. Each profile is, in detail, irregular, but as expected exhibits a relatively linear trend of increasing density with depth. By projecting the average line of linear increase over a profile, a bulk density value is derived. The bulk density value in the crestal névé sector (site 8A) for

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1. Defining an ice stratum as relatively thick...i.e. greater than 3 mm. — and an ice lamina as thin...i.e. less than 3 mm.

the 1960-61 firn-pack is 0.56. This is generally lower than that found at Camp 9, and much lower than that for the 10A-10B sector as recorded at the end of the ablation season in earlier years (J.I.R.P. reports). The upper névé bulk density of 0.56 compares closely, however, with the 0.55 bulk density of the 1951-52 firn segment recorded in the surface firn at the same site 10 years ago (Miller, 1956, Fig. 40). These relatively lower values and their general similarity may manifest the consistantly more Polar glaciothermal character indicated in the higher firn over the past decade. This inter-relationship is reasonable since colder englacial conditions would tend to minimize compaction and also restrict the development of capillary water; factors which substantially affect density increases in surface firn.

c. Secondary Englacial Structures: In conjunction with the foregoing measurements, the nature and extent of diagenetic ice structures in the crestal firn were also investigated. A diversity of ice structures was observed including strata, laminae, lenses, columnar masses and annual "dirty" layers.

In the test pit at Camp 8A only the 1960-61 firn-pack was observed. No "dirty" layers were present but extensive diagenetic structures were found. These are illustrated in cross-section in Figure 10. Keeping in mind that this cross-section involves only young firn, relatively thick ice strata are a surprisingly dominant structure. Many of the thinner, less extensive strata thinned out to lamina size. This group of structures ranged in thickness from 0.2 inches (intermittent) to 4 inches. The thickest strata were continous and extensive.

In the 8A sector only a very few ice columns were observed. The largest measured 2 feet in height and 3 inches in diameter. On the névé plateau at site 19A, however, a very extensive array of ice columns, 2 inches to 10 inches in diameter, were found pimpling the névé surface in late August. This was just before the first winter snows obscured this feature. The greater abundance of these features on the Gilkey Névé, compared to the crestal névé, may ally to the greater bulk density value suggested at the 19A site. These facts suggest a slightly more maritime condition for this highest névé, further corroborated by an increased salt content as discussed in section IIE. The probable reason for this anomalous condition points toward an orographic control which allows maritime winds to sweep unimpeded into this particular sector via the Berners Bay Trench.

For the 5900-foot level, the relative proportion of ice structures to the volume of firn is estimated from the wall profile in Figure 10. The figure derived is about 4 percent, which is comparable to the proportion of diagenetic ice in 1960-61 firn exposed on the crevasse walls at the 5700-foot site. On these same crevasse walls the volume percentage for the 1959-60 and 1958-59 firn segments appeared to be 6 percent or more of discrete diagenetic ice. The structures involved were also primarily ice strata. A number of associated "dirty" layers, however, connoted annual ablation surfaces (Fig. 12). The term "dirty" layer is used to denote a layer of mixed dirt and firn, the dirt being primarily composed of dust and including organic particulate matter blown onto the névé by wind. Concentration of this material at the surface occurs by the end of summer through ablation. Special consideration of these as annual accumulation strata indicators has been made by Miller (1955b).

2. Main Lower Névé Firn-Pack

The 1961 firn-pack accumulation statistics for both the intermediate and main lower névés are tabulated in Appendices 14 and 15.

a. Primary Stratification: On 14 September, a date close to the end of the annual ablation season, examination of crevasse walls in the vicinity of ablation stake E on the traverse (v. Fig. 8) showed approximately 7 feet of the 1960-61 retained accumulation. From the record plotted in Figure 9, it is seen that in this sector an average of 1.5 inches of firn ablation per day occurred during the late July-August period. This is borne out by an earlier observation on 25 July of approximately 13 feet of firn for the segment of 1960-61 retained accumulation. Assuming comparable ablation from May to mid-July of 1961...i.e. a minimum of 5 feet of old snow (roughly equivalent to 4 feet of firn) — the total solid precipitation for 1960-61 on the lower névé is in excess of 17 feet of firn. Using a bulk density of 0.60, which approximates late-summer firn density, the 7 feet of firn yet retained on 14 September is equated to 4.2 feet of positive accumulation, water equivalent. By using the 1.5 inch per day gross ablation figure, and extrapolating to the end of the ablation season (to approximately 25 September as discussed in section IIG) the net accumulation on the lower névé for the 1960-61 budget year is calculated to be 3.4 feet water equivalent.

Since 17.5 feet of firn remained on the crestal plateau — which at a bulk density of 0.56, approximates 9.8 feet water equivalent — it might at first be considered that the gross accumulation at the higher level was greater. Another explanation of this relative difference, however, is the retention of frozen surface water in the crestal firn-pack as well as reduced ablation on this névé. In other words, the considerable difference in observed firn-thickness may largely be due to excessive ablation and runoff on the lower névé.

b. Secondary Englacial Structures: The diagenetic structures in the firn of the lower névé, described by Leighton (1952) and Miller (1952b) during the 1949 field season are of similar morphology to those in the firn of the crestal plateau. The lower elevation structures, however, appear in greater profusion than do the crestal counterparts. This is expected since the combined rainfall/melt-water effects are maximum in spring and autumn when the lower névé is changing to or from a completely isothermal condition. A few statistics are cited to bear out this conclusion. In the 1949 firn-pack, Leighton calculated that ice strata constituted 8 percent of a test pit wall in the Camp 10B sector. In 1950, 1951, and 1952 Miller (1962a) determined respective proportions of 10 percent, 10 percent and 7 percent in the 10B surface firn-pack of each designated year. Correspondingly the proportion in the 8A-8B firn-pack in 1951 was 5 percent by volume; and in 1952 again 5 percent. This compares with a 4 percent proportion of ice strata in the 1961 firn-pack at 8A.

In addition, it is to be remembered that all liquid water generated on the sub-Temperate crestal névé is reclaimed by freezing, so that some diagenesis must occur at all times during the ablation season. This is distinct from the lower névé where most of the ice structures contained in the firn form mainly in the early part of the melting season while the winter cold wave is still present. Propagated surface water percolates downward releasing its latent heat to the colder firn in the process of freezing into the various ice structures. After the winter cold wave is dissipated (on the névé usually prior to July 1st) the propagated water no longer freezes but percolates to greater depths and eventually passes into subglacial drainage channels where it drains off. Hence, a great deal of liquid water is lost from the lower névé while most, if not all, is recovered on the crestal plateau. Further information on this phenomenon may be provided by the glacio-chemical investigation cited below.

E. Glacio-Chemical Analysis

To provide supplemental information on the provenance of precipitation on the icefield various samples of firn and ice have been taken in the summers of 1950, 1960, 1961 and in the winter of 1951.[1] These samples have each been subjected to

1. See Miller, M.M. (1953) for listing of saline records, 1950 and 1951. The 1960 and 1961 records are referenced in Appendix 20.

chemical determination of their NaCl content.[1] Decontaminated plastic bottles were used to hold the samples, and great care was taken to collect samples in the natural state.

1. Significant Icefield Variations

a. Areal Distribution of Salines: Figure 13 contains a plot of the NaCl content on the late-summer névé surface from the 3500 to 6500-foot levels (i.e. Camps 10B to 19A). The data are not yet sufficiently extensive for firm conclusions, but they reveal some general facts suggesting provisional interpretations. It is noted that the data are not from one year but from several years, and that all but one set of data were obtained at the end of summer; the exception being the record in mid-winter.

In the figure it is apparent that winter surface salinity is distinctly lower than that observed under summer conditions. This is expected, since summer ablation and resultant percolation tend to concentrate the salines. Perhaps more importantly, a winter-to-summer increase in salinity may represent an increase in wind-blown oceanic vapors over the icefield during the highly humid summer months; with colder, drier, and relatively salt-free continental air being the rule in winter. It is of significance that the NaCl-rich 5100-foot and 6500-foot samples indicated on the plot were

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1. Procedure used for these analyses is the official method as described in "Standard Methods for the Examination of Water and Sewage" published by the American Public Health Association, 1936. The determinations for these icefield samples were made by H. Kothe.

collected just after southerly (maritime) storm winds passed over the icefield. Although the data are insufficient, they point the way to future fruitful measurement of this type.

Another potential climate indicator may be the testing of firn for salines carried to the icefield by terrestrial winds, as opposed to those of marine origin.[1] The p.p.m. content may be extremely low, as compared to that of salines brought in by wind-blown oceanic vapors. Areal relationships over the icefield of contrasting terrestrial and marine-derived salines may prove to be significant in glacio-climatologic studies. Much work is needed, however, to prove the validity of this concept.

Traverses over the icefield should be made both at the beginning and end of the field season to obtain saline samples for the glacio-chemical studies; and this should be done over a period of consecutive years. An assembly of such data should make possible further interpretation of storm track patterns and possibly reveal in detail cyclic shifts in maritime vs. continental air mass effects on this icefield from season to season and year to year.

b. Depth Distribution of Salines and Interpretation of Anomalies: Figure 14 plotted on a semi-log scale, shows the variation of saline content with depth in the firn and underlying ice of the lower névé in 1950 and 1951 at Camp 10B. Figure 15 com-

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1. It should be noted that salines carried by terrestrial winds are of an entirely different chemical composition than those of marine transport.

pares the saline variations in the crestal névé firn-pack as recorded in 1961 at Camps 8A and 19A. In each of these figures the data are similar and show insignificant variation in chloride content at shallow depths. Even in the Camp 10B area, the 1951 data reveal no detectable change between mid-winter and summer. This suggests the dominance of maritime storms in this sector regardless of season, and the probability that saline dispersion at depth, as a result of water percolation, had not yet begun by 11 June in this particular year. The corollary of this is that the winter cold wave was still intact at the sample level, a fact borne out by thermal observations in that same year.

The deeper analyses from Camp 10B as shown in Figure 14 were obtained from rotary drill cores. There is much more variation and a greater proportion of salines in these samples than of their shallower counterparts. Although this may in part be the result of secondary concentration through blockage of percolation water by diagenetic ice, one is tempted alternatively to invoke the mechanism of cyclic storm-track shifts to provide an explanation. This consideration is discussed more fully in the following section on climatologic implications.

At least one anomaly in the foregoing statistics may be explained by orographic controls. This is the previously cited record from site 19A on the high-level Gilkey Névé. As shown in Figures 13 and 15 we find a suggestively higher saline content from that in the shallow depth samples at site 8A. One must bear in mind, however, that site 19A is situated in the nourishment zone of the Gilkey Glacier at the head of the Berners Bay Trench. Here maritime winds are channeled directly up from the coast unimpeded by any barrier of mountains or bordering ridges. Hence, an increase in salinity should be expected in this particular locale, compared to the more continental positions found on the crestal plateau to the south and east. Concurrently, a reduced salinity should be expected in samples in the vicinity of Camp 20 and in the névé of the Llewellyn Glacier to the east (Fig. 1).

Also an anomalously high value of 7.4 p.p.m. was determined from a surface sample at Camp 10B in August, 1951. The meteorologic records[1] show a prevelance of maritime westerly and north-westerly winds over the 3-week period preceding the sampling date, which may account for this relatively high value. An alternative or supplemental explanation may lie in the excessive ablation occurring during that season, which resulted in the highest névé-line[2] of the past 20 years. At the 10B site this would mean superposition of the 1950 and 1951 ablation surfaces (multiple ablation surface) with excessive concentration of salines.

In general whatever interpretations are made with respect to saline concentrations the available data are too limited to allow definite conclusions. They do, however, provide some corroboration of other interpretations in this

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1. Juneau Icefield Research Project, Report No. 8, 1951 field season.

2. Receded up-glacier to a position well above Camp 10B...i.e. to 3800 feet.

study; and they indicate a useful direction for future measurement. For example they may provide a further means of analysing the selective modes and extent of melt-water percolation. Another possibility, indicated by the above, is the identification of saline concentrations on ablation surfaces or multiple ablation surfaces. This could be a most useful criteria for identifying such horizons on crevasse walls, in test pits or in bore-hole core samples in sub-Temperate to Polar firn where the effects of melt-water diffusion are minimal.

2. <u>Climatologic Implications</u>

The Juneau Icefield is located, meteorologically speaking, in the coastal interaction zone between a dominantly maritime climate toward the southwest and a dominantly continental climate to the northeast. Being geographically so positioned, the icefield is subjected to both climates depending upon what fluctuations or controls cause one or the other to dominate. According to the Solar Control hypothesis (Miller, 1956, 1958), reduced solar radiation of the corpuscular type will cause the maritime climate to be dominant while a high corpuscular radiation causes the continental climate to move south-westerly and force the maritime climate seaward. Also, in the winter season, the continental climate appears to dominate in the crestal plateau area subjecting it to northerly and north-easterly prevailing winds.

It can be postulated what effects such fluctuations would have on saline percentages in the névés over the icefield. The maritime climate when dominant, may be expected to bring in the NaCl-rich vapors with associated rain and snowfall from the ocean; while a lack of chlorides would characterize rain and snowfall over periods of continental dominance. But the problem remains whether or not the salt concentrations over the icefield and their variations in each accumulation year are sufficiently distinctive to indicate conclusively such climatic shifts during any particular period.

It is of interest, therefore, that in terms of present depth and measured creep rate of the glacier between the upper and lower névés, material from which the deep core samples were taken (Fig. 14) accumulated in the general vicinity of Camp 8 approximately 45 years ago. At that time the radiation cycle was at its minimum position...i.e. low sunspot number. According to the corpuscular mechanism the climate in this region 45 years ago would have been more dominantly low pressure and maritime, therefore, subjecting the crestal névé to oceanic, saline-laden winds. At the present time, with sunspot activity close to an 80-90 year peak, a theoretically high pressure, drier, and more continental climate should prevail, particularly over the upper reaches of the icefield. The theoretical consequence would be a displacement of maritime air masses coastward, so that they would influence primarily the lower and peripheral névés. Thus, in this decade the crestal névé should be receiving less salines than the lower névé, or for that matter the Lemon Névé, and relatively far less than a half solar cycle ago...i.e. 40-45 years. Such a relationship is tantalizingly suggested by the higher proportion of salines at depth as illustrated by the data in Figure 14.

In order to obtain any conclusive results of the foregoing type broader and longer-term analyses are needed, with a far more extensive collection of samples obtained in each year. For example comparative samples should also be collected from the Lemon Névé. In this way sufficient data can be accumulated to determine the use of saline analyses as a criterion for the reconstruction of accumulation and storm-track trends, and for the further understanding of related glaciothermal variations.

To explore another set of corroborative data, we now turn to the analysis of data in Appendix 1,...i.e. the drill log of the electro-thermal bore rig used for deep penetration of the crestal firn.

F. Interpretations of the Crestal Névé Thermal Bore-Hole Data

Reference is once again made to Figure 4A. The high penetration velocity indicated in the first few feet of thermal drilling is undoubtedly the result of low density in the young surface firn. The much reduced drilling rate from 5 to 39 feet, at first thought might suggest a logical increase in density with depth. This slowing down, however, is attributed at least partially to another cause. Englacial temperature measurements, made upon completion of the bore-hole, show consistently sub-freezing conditions.[1] Negative temperatures (-0.13 to -0.89°C) were encountered from 5 to 50 feet in the

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1. As discussed in section IIB2.

firn and are believed to represent the previous winter's cold wave (Fig. 4B). This encompasses the very depths at which the reduced drill-rate occurred. The increased bore-rate between 41 and 65 feet suggests attenuation of the relict cold zone; with the firn down to the 151-foot level being slightly sub-freezing, at a relatively constant temperature of -0.05 to -0.10°C.

While drilling in a "colder" zone, it is to be expected that a thermal borer will be less effective and therefore slower than when operating in "warmer" firn. According to Miller (1952a), the impediment in drilling through a relict cold zone is not believed to be by virtue of significant losses of heat in warming the firn to its melting point (since only 0.5 calories would be required to raise the temperature of one gram of ice 1°C). Instead, the colder firn surrounding the borer creates a freezing condition along the unheated upper portion of the bore shaft causing masses of loose, partially melted firn and snow to stick to the shaft and thereby increase its frictional drag.

The much more gradual decrease in bore-rate from 67 feet downward can be attributed to the normal density increase in the firn and at greater depths to the gradual transition to firn-ice. By projecting an average line of increase through the density curve (Fig. 4C) the bulk density at approximately 100 feet is indicated as 0.80 grams/cc.

Sudden large decreases in bore-rate (e.g. at the 36, 38, and 50-foot levels) are attributed to substantial ice strata ...i.e. 3 inches or more thick. Most of these are probably associated with annual ablation surfaces. Conversely, noteworthy temporary increases in bore-rate would seem to indicate "depth-hoar" strata. It would be safe to assume, however, that below the 100-foot level no depth-hoar could be detected by this method since the effects of aging and extensive compaction would destroy the softness of such zones.

The 151-foot bore-hole at site 8A may not have completely penetrated the firn-pack of the crestal névé since a deeper, 171-foot bore-hole in 1952 at site 8B was provisionally indicated as bottoming in firn-ice (Miller, 1952a). Such interpretation is supported in the present case by a fair constancy of drill-rate below the 109-foot level at a density, extrapolated from the Figure 4C curve, not greatly in excess of 0.80. As previously suggested in section IIC2, however, this reduction in bore-rate may connote bubbly glacier ice. In such event the firn-pack could be interpreted to be roughly 110 feet thick at site 8A. Actual core samples obtained at this depth in a subsequent season would clarify this point.

Superimposed on the 1961 bore-rate curve of Figure 4A is the 1952 drill-rate curve at the 8A site. This is a smoothed curve based on the detailed plotting of Miller (1952a). Although the 1952 bore-hole (3.0 inch diameter) was produced by a faster borer (2.0 KW), the drill-rate curve coincides fairly well. In fact it exhibits detail quite similar to the 1961 characteristics below the 40-foot level. This comparison, spanning the last 10 years, implies a consistancy in climatologic and meteorologic conditions over the past decade. Such relationships are significant to the long-term analyses of the

Juneau Icefield Research Program, but they are somewhat beyond the scope of the present report. Details of the glaciometerology of the summer, however, are reviewed below.

G. Glacio-Climatology

To provide basic meteorologic data for the present study and to extend the long-range climatologic record of the program, meteorologic stations were set up at the various research camps on the lower, intermediate and higher névés. At each site temperature, dew point, humidity, precipitation, wind, sky condition, radiation (Camp 10), and duration of sunshine (Camp 8) records were obtained on a 3-hourly to daily basis. Such data are essential to the climatologic interpretations in the main icefield sector. Comparative records from the Camp 10 nunatak station and from Mt. Juneau[1] (elev. 3576 feet) are available for extrapolating the Lemon Névé meteorology since these three locations are geographically adjacent and lie at approximately the same elevation.

1. Temperature and Precipitation Measurements

On the crestal névé continous records were maintained during the period of field work at the glaciologic station at Camp 8 (6800 feet). Semi-continuous records were maintained at site 8A (5950 feet). These data are listed in Appendices 21 and 22.

As may be expected, temperatures at the higher station (8) are consistantly lower than those at the lower site (8A). A mid-summer lapse rate of 3.7°F between these two sites

1. A field station on a ridge 1.2 miles northeast of the city of Juneau.

pertains. This closely agrees with the mean lapse rate of 3.5°F per 1000 feet usually cited for wet adiabatic conditions.

Precipitation was dominantly rain from late July through mid-August, with sporadic snow sometimes falling at Camp 8. From late August on, snow was the dominant form of precipitation in the Camp 8 sector; with rain persisting till mid-September at Camp 9 (5200 feet) and Camp 10 (4000 feet).

In the 1960-61 crestal firn-pack, the ablation season ended on 25 August 1961. On the lower névé, as extrapolated from the Juneau temperature records, the ablation season terminated a month later...i.e. about 25 September.

The data from Camp 9, situated above and on the eastern edge of the intermediate névé (mean elev. 4600 feet), are minimal since the camp was occupied for only two continuous weeks in the 1961 summer field season. These data are given in Appendix 23. Over the period of record in August the daily mean temperatures are distinctly higher than on the crestal névé. On this névé sub-freezing autumn conditions developed in mid-September as opposed to the last week of August on the crestal névé. In August all precipitation at Camp 9 was rain, with persistant snowfall observed in the second week of September.

On the lower névé meteorologic records were maintained at Camps 10 (4000 feet) and 10B (3650 feet). In Figure 9 the mean daily and minimum daily temperatures for the period 25 July - 27 August at Camp 10 are plotted using data referenced in Appendix 24. Comparison is also made with the minimum daily temperatures at Camp 10B.[1] The minimum temperatures at the latter site vary from 2° to 20°F lower than at Camp 10. As indicated these remained close to but consistently above freezing throughout the period of record (7 July - 14 September 1961). It was also noted that the ablation season had not yet ended on the glacier surface at 10B as of the date of evacuation, 14 September. By reference to the full seasonal march of temperatures plotted in Figure 16 the terminal date for the ablation season on the lower névé is indicated as 25 September. This is interpreted from the curves for the sea-level stations at Annex Creek and Juneau Airport, using the standard lapse rate adjustment for the 4000-foot level. It is mentioned again that the terminal date for the ablation season recorded at the crestal névé camps was a month earlier. By further reference to the Juneau and Annex Creek curves initiation of the ablation season is interpreted as 25 April at the 4000-foot level. Thus a 5-month ablation season is indicated for the lower névé. On the same lapse rate basis an ablation season of 2.7 months is suggested for the crestal névé...i.e. 5 June through 25 August. Each of these values correspond roughly with ratios observed over the past 16 years.

Also as shown in Figure 9 for the lower névé, summer precipitation was almost entirely in the form of rain. For the period of record, the amount of precipitation at Camp 9 and 10 appear similar; however, longer periods of record are

1. Ambient temperatures measured by alcohol thermometer at a position 4 feet above the névé surface.

needed to evaluate this.

2. Duration of Sunshine Records

At Camp 8, duration of sunshine records were kept from 15 August to 13 September 1961. These data were obtained by means of a Campbell Stokes recorder, and are tabulated in Appendix 25 for future reference. The total hours of sunshine recorded is considered a minimum value, since the instrument could not begin recording at the actual time of sunrise. This was due to obstruction by the summit of Mt. Moore, east of Camp 8, which blocked out the sun for the first hour of daylight. No such obstruction existed in the west. On clear days, therefore, a one-hour correction factor must be applied in any analysis of these records. In general, as has been shown in previous seasons of the icefield program, duration of sunshine can be directly interpreted with respect to solar radiation measurements obtained at a nearby master station.

3. Solar Radiation

Continuous radiation records were obtained at Camp 10 over the period 21 July - 14 September. The instrument used was a Belfort Recording Pyrheliometer. The readings, in Langleys (gram calories per cm^2 per hour), are also listed for possible future reference in Appendix 26. These data exhibit close diurnal correlation with sky (cloud) conditions, as would be expected. As with the sunshine data, detailed analysis of the radiation records lies outside of the scope of this present treatment.

4. Lemon Glacier Meteorology

During the summer field season, the concentration of efforts on the main icefield névés precluded occupation of the program's field station on the Lemon Glacier. Therefore, the general meteorologic condition of the Lemon Névé in the 1961 budget year is interpreted from data obtained on the comparable elevation névé of the adjoining Taku Glacier system. Additionally useful in the extrapolation of conditions are the Juneau Airport radiosonde records from 1949 through 1953.[1] Also pertinent are the precipitation records from the comparable elevation site on Mt. Juneau, these being obtained by U. S. Weather Bureau personnel over the summer months of 1961.[2] In view of the proximity of these locations and their similarity in elevation fair agreement may be expected. It has been shown by Miller (1956) that a high correlation coefficient (0.88 - 0.94) exists between these upper air data and corresponding data obtained at icefield nunatak stations. For example, by reference to Figure 17, the Camp 10 and Juneau Airport radiosonde mean monthly temperatures may be seen to agree quite closely for the months plotted. On this basis lapse-rate evaluations of the Juneau Airport records have been applied with some degree of confidence in the present analyses. Caution, however must be used when extrapolating these data to the actual névé surface. As an illustration, the 1961 August minimum record for Camp 10B (3650 feet) averages 10°F colder than that at Camp 10 (4000 feet). This undoubtedly

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1. Upper air temperature data not recorded after 1953.

2. The Mt. Juneau site is geographically proximal to the Lemon Glacier, as shown by its position just northeast of Juneau in Figure 1.

reflects the katabatic chilling of the broad névé below and west of Camp 10, since this order of mean monthly temperature difference has been cited between these two sites in previous summers (JIRP reports).

The temperatures on the comparable elevation Lemon Glacier Névé have roughly corresponded to those on the Camp 10B névé although a little warmer, presumably through lack of a significant katabatic effect and by virtue of the closer geographic position to the coast. On this basis the ablation season on the Lemon Névé is inferred to be of slightly longer duration than on the lower Taku Névé...i.e. essentially from April into October.

With respect to precipitation during the 5-week period of 21 July through 26 August 1961, Camp 10 (4000 feet) received 14.5 inches of rain (v. Appendix 24). The Mt. Juneau site, at an elevation of 3576 feet, during the same period, experienced almost 3 times as much, or 40.6 inches of rain (v. Appendix 27). Review of the shorter term records at Camp 8 reveals that only half as much rainfall occurred at Camp 8 as at Camp 10. Therefore, recognizing that the Lemon Névé and the Mt. Juneau site are in the same general locale and at comparable elevations, it may be concluded that the Lemon Névé receives nearly 3 times as much rainfall as the main lower névé of the icefield 20 miles inland and approximately 6 times as much rainfall as the main crestal névé. The exact amount received by the névé of the Lemon Glacier is probably very close to that measured on Mt. Juneau. These statistics, therefore, well illustrate the extreme maritimity of the Lemon Glacier sector. Concurrently they help to demonstrate the relative sub-continental climatic condition which pertains on the higher névés of the main icefield.

The reason behind the far greater liquid water precipitation in the Lemon Glacier area is orographic as well as geographic. Cyclonic summer winds sweep moisture-laden clouds inland from the Gulf of Alaska. Upon meeting the mountain barrier of the Boundary Range they drop their contained moisture as precipitation. As these air masses pass farther inland over the main icefield area the already partially drained air masses have less and less moisture to release, until finally on the lee side of the range the climatologic conditions become semi-arid. This relationship is well manifested by the sub-Temperate englacial condition of the crestal névé; by the relatively higher névé-line on the Llewellyn Glacier (Miller, 1956); and by the dry climate with characteristic pine and other sub-arid vegetation found in the Atlin sector on the Canadian side of the icefield.

H. Composite Considerations

Some overall considerations of the specific observations and data from the main icefield sector are now discussed to facilitate future reference.

Higher elevation combined with a position geographically farther from the sea, are the prime factors responsible for a generally colder and more continental climate on the 5900-foot axial névé of the Taku-Llewellyn Glacier Complex.

Englacial temperature investigations have shown that the crestal sector of this glacier system is geophysically sub-Temperate in character. In the firn of the highest plateaux the winter cold wave is partially retained through the summer months without being dissipated by seasonal increases in radiation, duration of sunshine, temperature, and summer melt-water percolation. This is in sharp distinction to the fully Temperate (isothermal) character of the glacier on the lower névés.

Sub-surface temperature investigations in the crestal sectors also corroborate the recognition of a shortened ablation season and the effective reclaiming, at depth, of most if not all percolated surface water. The ablation season on the crestal névé, relative to the lower névé, is of less intensity as well as shorter duration. In 1961 it extended from approximately 5 June to 25 August, thus permitting propagated water to develop on the névé surface over a period of 2.7 months. The 1961 ablation season on the lower névé of the Taku Glacier extended from 25 April to 25 September...i.e. 5 months duration, or nearly twice as long as pertains on the crestal névé of this same glacier. A slightly longer ablation period is involved on the Lemon Névé due to its more maritime position...i.e. a little over 5 months duration. These ratios are roughly equivalent to those reported in previous records of the Juneau Icefield Research Program, over the years 1948-60, and therefore are considered representative.

Liquid water percolation in the crestal firn is of much less volume than that produced on the lower névé, and does not find its way to the bottom of the glacier and drain off in subglacial drainage channels. Instead, it is largely reclaimed by freezing in the sub-freezing firn of the crestal zone. Therefore, on the upper plateaux, certainly above 5800 feet, there is little effective loss. On the Temperate, lower névé a substantial portion of the gross accumulation (estimated from 60 to 90 percent) is reduced to runoff.

From these considerations, it is clear that seemingly gradational climates can produce striking local differences in the regime of this icefield wherever it is characterized by multiple névés. Added to this is the probability that the gross meteorology of this entire region changes cyclically in 20-year to 90-year shifts, as suggested by Miller (1956, 1958). This would be revealed either by a warming trend or, conversely, by a cooling trend with its consequent lowering of freezing level. Thus by closely observing and delineating these trends through sequential and systematic study of each component of the multiple névé, fairly accurate forecasts may be possible in terms of the changes taking place in the physical characteristics of any sector of the icefield.

For illustration one may visualize full glacial conditions...i.e. the general climate becoming significantly colder for an extended length of time. This would mean that the whole geophysical character of the icefield would change. The lower névés would become sub-Temperate, sub-Polar, or even Polar depending upon the intensity and duration of the colder conditions. In like manner, the geophysical character of the intermediate and crestal névés would also change to more Polar conditions. With the glacier becoming colder its creep rate would materially decrease. If the intensity of the cold phase increased to extreme Polar conditions moisture could not precipitate except by minimal hoar-frost sublimation, as under present conditions at the center of the Greenland Ice Cap (Victor, 1950). In such circumstances a corresponding decrease in accumulation would take place in those parts of the icefield so affected. The intensity and duration of the cold hemi-cycle could be of sufficient magnitude to diminish the mass transfer of ice from all of the main glaciers emanating from the icefield, and hence reduce the present névé regions to a state of equilibrium.

The above hypothetic illustration of a complete change in climate is, of course, an extreme. It is not so extreme, however, that it could not happen; since it has happened in the glacial maxima of the Pleistocene. It is a condition which even today dominates the higher latitudes of the continent of Antarctica.

The other extreme case would be a warming trend resulting in complete ablation and destruction of the icefield. Through the development of local glacier conditions and inter-glacial landscapes, this also has happened. The present retracted icefield condition is but one link in the long chain between the cited extremes. In this the present regime of the Lemon Glacier is also considered part of the overall icefield condition.

Gross accumulation for 1960-61 on the crestal plateau has been shown to exceed 19 feet of firn while that on the lower névé was in the vicinity of 17 feet. Net accumulation on the upper plateau at the end of the 1961 ablation season was measured at 17.5 feet of firn (at density 0.56, or 9.8 feet of water equivalent) while that on the lower névé was found to be approximately 5.7 feet of firn (at density 0.60, or 3.4 feet of water equivalent). Since 1950 recorded annual net accumulation on the crestal névé at the 5900-foot level has varied between 13 feet and 19 feet of late-summer firn (averaging 14 feet). This suggests that the 1961 data represent somewhat higher than average values — not being exceeded in fact since 1948-49. These statistics are also compared with the crevasse-wall stratigraphy obtained in 1961. Thus, the suspected positive accumulation gain (not including diagenetic structures) over the past 15 years on the crestal plateau is in the order of 200 feet of firn-pack, or minimally 150 feet water equivalent. By including a 15-20 percent bulk increase due to diagenetic effects this figure may be advanced tc around 175 feet of water.[1]

1. The total covering approximately the 16 years since the inception of this field research program in 1946.

III. GLACIO-HYDROLOGIC INVESTIGATIONS ON THE LEMON GLACIER

The information described from the névé studies in the main icefield area are now combined with available hydrologic statistics for an assessment of the dynamics and magnitude of runoff from the Lemon Glacier.

Reference is made to runoff records for the decade 1951-61 from a stream gauging site at the glacier terminus on Lemon Creek. By additional reference to the U.S. Weather Bureau climatologic data from coastal stations in the Taku District, and to the 1951-61 meteorologic records from icefield stations, an analysis is made of the effect of regional and local climatic factors on the glacio-hydrologic regime. This is followed by brief consideration of related geomorphic consequences.

A. The Lemon Glacier Problem

The Lemon Glacier, one of the smallest and most accessible glaciers of the Juneau Icefield, has been selected for this study because of its unique physiographic character. Although a distinct unit in itself, this glacier is juxtaposed to and southwest of the Taku-Norris Glacier system (Fig. 1), and has a catchment basin not influenced or contaminated by drainage from this other system. The glacier is in a slowly recessional state with a trend in the decade of the 1950's toward an equilibrium condition (Crary, et al., 1962).

1. Total Runoff vs. Refrozen Percolation

As we have already seen, the crestal plateau is characterized by sub-Temperate geophysical conditions; while the lower névé is fully isothermal at 0°C. Thus, the great majority of liquid water propagated during the effective ablation season at elevations below 5000 feet eventually is discharged as runoff. The Lemon Névé is essentially all below this elevation. In fact elevation-wise it is a small-scale counterpart of the lower névé of the adjacent Taku system. The mode and effects of liquid water generation on the Lemon Névé are thus similar to those on the lower névé of the main icefield. In consequence the overall geophysical character of the Lemon Glacier is also Temperate.

In theory, most of the propagated surface water on a Temperate glacier percolates through the firn and drains to the base of the glacier through crevasses and fractures. It then eventually will pass off at the terminus via englacial and subglacial drainage channels. It may be assumed, therefore, that the volume and variation of free water discharged at the Lemon Glacier terminus is directly affected by the volume and variation of liquid water generated on its névé.

2. Areametric Relationships

The relative position of the Lemon Glacier with respect to the main body of the Juneau Icefield is shown in Figure 1. Since the glacier is a separate system, being connected to the main icefield by a narrow divide, it has been regarded as a complete physiographic unit. This unit encloses an elongated basin 12.1 square miles in area (v. map, Fig. 27). It represents an orographically simple catchment basin with practically all of the drainage derived from the Lemon Glacier Névé. Only a small fraction comes from surrounding valley walls.

The Lemon Glacier and its surrounding area have been mapped to a scale of 1:63,360, again as shown in Figure 27. Its prime névé lies roughly between the 3300 and 4500-foot contours; with a mean elevation of about 3900 feet. This mean level corresponds with the mean elevation of the lower accumulation névé on the main icefield.

3. <u>Meteorologic Implications</u>

As previously noted, the 1961 summer temperature and precipitation records from U.S.Weather Bureau sites at Annex Creek, Juneau City, Juneau Airport, and from the field site on the upper ridges of Mt. Juneau (precipitation only) have been plotted to provide comparison with the main icefield records in this reference year. Records encompassing the interval 1941-61, as obtained from the same stations, are also used to evaluate climatic fluctuations and trends, and to compare with fluctuations and trends in the runoff records.

The coastal meteorologic stations are all within 20 miles of each other and bracket the Lemon Glacier on the west, south, and east (Fig. 1). Although all but one (Mt. Juneau) are near sea-level, this does not detract from the usefulness of the records.. In the present analysis the coastal station data are interpolated, using correlative icefield data, so that reference to the 3900-foot névé of the Lemon Glacier can more effectively be made.

The mean daily temperatures for Annex Creek, Juneau City, and Juneau Airport have been presented in Figure 16 covering the period 15 April through 10 October 1961.[1] The mean daily temperatures for Camp 10, and the minimum daily temperatures for Camp 10B, are also shown covering the respective periods of field occupation of these sites from July through September. The full scope of data graphed in Figure 16 represents a longer period than the 5-month ablation season inferred for the lower icefield névé, but for reasons previously noted it may be considered close to the duration of effective ablation on the Lemon Glacier Névé. This may be cited as 5.8 months in 1961.

Daily precipitation recorded at an elevation of 3576 feet on Mt. Juneau (Fig. 19) for the summer of 1961 is 3 to 5 times greater than that recorded at the coastal stations (Fig. 18), and 3 times that noted at Camp 10 in the equivalent period (Fig. 9). The apparent reason for this has already been discussed in section IIG1. Since the Mt. Juneau data are considered representative of statistics from the adjacent Lemon Glacier Névé, these precipitation records will be referred to with respect to that névé.

Mean monthly temperature and precipitation (Fig. 20) are plotted for the period 1951-61. In addition, mean annual temperature (Fig. 21) and precipitation (Fig. 22) are plotted for the period 1940-61. These diagrams reveal the temperature and precipitation trends of the coastal stations and their

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1. The original daily temperature and precipitation records are referenced in Appendices 28-30 for the coastal stations.

variations with respect to each other.[1]

By reference to Figure 21, the 11-year running mean of annual temperatures, commencing in 1950, show a slight but steadily decreasing trend continuing through 1956. This then reverts to a steadily increasing trend up through 1961. The 11-year running mean of January temperatures over the same years (also Fig. 21) reveals a decreasing trend continuing up to 1959 and then reverting to a possibly significant trend of increasing temperatures. From these two sets of data it would appear that the low temperature years out of the past decade were in the interval 1956-59 — a seemingly paradoxical relationship in view of the maximum radiation intensity during the 1957-58 period of the International Geophysical Year. The mean annual temperatures (Fig. 21), however, show an increase during this period. Further discussion of this matter will be made at the end of this section, after consideration of the total precipitation trends over the decade of the '50's.

As for the precipitation records, the annual fluctuations and trends remain generally similar for Juneau City and the Juneau Airport from 1940 through 1961 (Fig. 22). Juneau City, however, is consistently 63 percent higher, as illustrated by the plot of 11-year running means of annual precipitation. Such differences in precipitation over distances of less than

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1. The mean monthly temperature and precipitation data for the interval 1951-61 at the coastal stations, from which records these diagrams have been prepared, are given in Appendices 31-33. The mean January and mean annual temperature and precipitation records for these stations are listed also in Appendices 34 and 35.

10 miles are strictly orographic. This factor is further illustrated by the Annex Creek data. The Annex Creek record over the comparable period of 11 years, in fact, shows a good deal more differentiation than the record from the Juneau and Juneau Airport stations. The mean annual precipitation curve (Fig. 22) dipped the lowest in the years between 1950 and 1955, and shows a marked rise from 1956 to 1961. The 11-year running mean of annual precipitation for Annex Creek (also Fig. 22) indicates a similarly pronounced decreasing trend continuing from 1950 through 1957, with a subsequent leveling off up through 1961. These data reveal dramatically that Annex Creek receives a considerably greater percentage of precipitation than Juneau City; the percentage decreasing steadily, however, from 33 percent in 1950 to 4 percent in 1956 through 1961.

By again consulting the mean annual curves in Figure 22, one can see that precipitation at the Juneau coastal stations has been steadily increasing since 1957, with this same increase reflected at Annex Creek since 1955. It is noteworthy that this trend continues to rise through 1961. Also by considering the mean monthly precipitation plots (Fig. 20) it is evident that beginning with 1956 the fall and early winter months experienced generally increased precipitation with a most prominent rise taking place in 1961. This correlates with the culmination of the increasing trend of mean annual precipitation during the referenced 5-year interval (Fig. 22). It also correlates with the general rise in mean annual temperature shown in Figure 21, and with the pronounced downward trend in mean January temperature indicated in this same figure. The long-term seasonal trends thus appear to be complex, possibly involving a lag correlation, the discussion of which is beyond the present purpose.[1]

4. Discharge Statistics

Because the Lemon Glacier and its drainage basin are a complete physiographic unit, essentially all of its drainage is channeled into Lemon Creek above the stream gauging site.[2] The glacier terminus rests at an elevation of 1500 feet above mean sea-level. The gauge elevation is at 600 feet above mean sea-level. Its position is 6000 feet down-valley from the point where in 1961 the subglacial drainage channel discharged water from the terminus. Therefore, this volume of water passing through the hydrograph station represents essentially complete drainage from the glacier basin.

The topography of the basin and glacier itself, and the position of the gauging site, are indicated on the map of Figure 27. This map has a contour interval of 100 feet.

Figure 23 diagrams the mean monthly discharge at the

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1. Miller (1956) has pointed out the problem of thermal lag effects in the climatic cycle. He suggests that they may relate to the retention of heat in the oceanic waters along a coast. Some degree of lag is of course a natural consequence of the considerably higher specific heat of water when compared to the atmosphere.

2. Established by the U.S. Geological Survey in the summer of 1951, on recomendation of the Juneau Icefield Research Program.

gauging site, in cubic feet per second. The plotted record extends over the 10-year interval between October 1951 and September 1961, and is based on the original data listed in Appendix 36. The form of this discharge curve is generally sinusoidal. Particularly notable are the rapid increases and decreases in discharge rate between summer and winter.

In the annual segments of the Figure 23 curve occasional jogs occur, representing minor but notable fluctuation during October and November (note especially the curve segments for the years 1956-57 and 1957-58 as well as the interval 1960-61). A prominent fluctuation can be noted in November 1954 matching that of November 1956, and January 1958. The autumn anomalies are probably due to surges of increased rain and melt-water resulting from the violent autumnal storms which characterize this coast. Furthermore, by comparing Figures 20 and 23, the autumn anomalies are seen to correspond with significant increases or decreases in temperature and precipitation during the corresponding months of October and November in these particular years. The January 1958 anomaly, however, deserves special consideration. This month was characterized by considerably higher temperature and precipitation than its bracketing months of December and February. It is significant that such increases do not normally occur in the January records. The causal factor would appear, therefore, to be primarily the occurrence of unusually high temperatures in January of this year (Fig. 20).

The period of greatest liquid-water generation indicated by the period of maximum flow in the mean monthly discharge curve (Fig. 23) extends from mid-April to mid-October. This suggests a 6-month interval of significant drainage which agrees closely with the 5.8 month effective ablation season inferred for the Lemon Glacier.

The mean monthly and mean annual discharge rates plotted for 1951 through 1961 (Figs. 23 and 24) indicate unquestionable trends. Figure 24 shows the mean annual trends based on the water year (October to September) as well as the calendar year. The discharge is seen to increase from 1951, with a drop-off to reduced discharge in 1954-55, and then an irregular rise continuing from 1955 up through the period of this study in 1961. These trends are shown even more strikingly in the plottings of mean annual maximum and minimum discharge given in Figure 25.[1] Here the minimums exhibit only a slight increase from 1952 through 1956, corresponding to the reduction in annual discharge cited above. From 1956 through 1961 the mean minimum values increase dramatically, again corresponding to the marked increase in annual discharge noted above. The mean annual maximums express a more varied picture but, overall, show an increasing trend which parallels the mean annual discharge curves of Figure 24.

The noteworthy upward discharge trend in recent years is not unexpected. It has already been demonstrated that temperature and precipitation trends since 1955 have been significantly

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1. The original data of Lemon Creek on mean annual maximum and minimum discharge rates, 1952-61, are tabulated in Appendix 37.

upward. In a strongly maritime climate where melting and rainfall are intimately related to temperature, runoff trends should also show a comparable increase.

Consideration is now given to the mean daily runoff curve (Fig. 26) graphed from the data for 1961 listed in Appendix 38. In this, comparison can be made with the histograms of daily precipitation for Juneau City, Juneau Airport, and Annex Creek (Fig. 18), and for Mt. Juneau (Fig. 19).

It is immediately apparent that the peaks of discharge in the 1961 record correlate almost directly (a slight but expected lag is apparent) with peaks of rainfall. We are reminded, however, that the main icefield investigations have shown that melt-water also plays an important role in the propagation of available liquid water. By comparing the ablation record at Camp 10B (Fig. 9) with the mean daily runoff curves, however, the correlation is found to be extremely poor. The ablation curve does not trend to a significant peak or trough during the period of record. Daily fluctuations may be detected, but these are not as notable as in the precipitation curves. It is possible that comparison with ablation measurements made directly on the Lemon Névé would show a closer relationship, but regardless the conclusion appears unavoidable ...i.e. that on the Lemon Glacier precipitation dominates in governing the form of the mean daily runoff curve. A plot showing runoff from melt-water alone (without being contaminated by precipitation) would in all probability be much smoother than the one shown in Figure 26. Another implication of this conclusion is that the capillary retention capacity of the firn-pack is sufficient to impede the development of strong surging at the volume levels involved in melt-water generation.

Support for the preceding conclusion is given by some pertinent statistics. The total runoff for the month of August 1961 is 68.4 inches of water.[1] Over the same period the total rainfall on the Lemon Glacier basin (as interpolated from the Mt. Juneau records) was 52 inches.[2] Ablation over a comparable 31 day period in the mid-summer of 1961, as measured on the lower névé of the main icefield, is calculated as 25 inches water equivalent. When extrapolated to the Lemon Glacier basin, the total precipitation plus ablation for the month of August 1961 would be 77 inches, a figure remarkably close to the measured runoff, 68.4 inches.[3] On the assumption that this is close to a true value, the difference may be explained by the amount retained in the firn-pack through capillary force. Miller (1962a) has shown that up to 15 percent of the density increase in the summer firn on the Juneau Icefield is due to capillary retention. Thus, these figures, representing a difference of 12 percent, may be corroborative.

The foregoing analysis can be extended into the preceding

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1. Calculated in inches to compare with the water equivalent statistics for ablation and precipitation.

2. 49.7 inches plus two days of missing record approximates 52 inches. See Appendix 27, for the Mt. Juneau precipitation records.

3. Measured value obtained from the Lemon Creek 1960-61 discharge data office file of the U.S. Geol. Survey Water Resources Division, Juneau, Alaska.

month of July 1961, in which the monthly precipitation was 33.9 inches. With the extrapolated ablation again being 25 inches, the total calculated volume of available propagated water equals 58.9 inches. The measured value of discharge at the stream-gauge site for July was 53 inches. The difference in this case is 10 percent, which is also in line with the aforementioned ratio of capillary retention.

For other reasons too, calculated values should be higher than measured values. Not all of the precipitation falling on the side-wall sections of the Lemon Glacier basin is going to result in runoff. A portion will be assimilated by vegetation and soil, just as in firn of the glacier. Evaporation, although probably slight, also claims a share of the precipitation, particularly from bedrock exposures. But most important is that volume retained in liquid form by capillarity of the firn and by impoundment in crevasses and other open fractures. The combined effect of all of these various factors would seem to explain the differences which have been cited between total volumes of propagated water and total measured runoff.

From the above statistics the total propagated melt-water through ablation on the Lemon Glacier Névé may be assumed to account for anywhere from 30 percent of the total runoff in the summer to nearly 100 percent in the winter (see discussion below). Furthermore, the form of the runoff curve (Fig. 23) demonstrated how approximately 80 percent of the total annual runoff occurs during the ablation season; with the remaining

20 percent taking place in late fall, winter, and early spring. Thus, the combined effect of ablation and rainfall on the annual discharge pattern is well substantiated.

The thesis that melt-water constitutes most of the runoff during winter is of special interest and deserves further discussion. Winter precipitation of the solid form...i.e. snow—contributes little to the runoff so long as temperatures remain below freezing. On the other hand, melt-water, stored in a glacier during the summer percolation period, and permitted to remain in liquid form by the Temperate geophysical condition, appears to be steadily discharged in small volumes (Miller, 1956). In this situation one must assume that there is slow continuation of percolation to greater depths from the capillary retention zone which is penetrated by the winter cold wave. This percolation, abetted by increased compaction squeezing of interstitial water from between the firn crystals, provides a continuous source of drainage throughout the winter months. It is also probable that continuous and discontinuous movements within the glacier produced by the stresses of a thickening winter snow-pack release water trapped during the summer by layered and diagenetic ice structures. In addition, some melting at the base of the glacier from the effects of geothermal heat may contribute minor amounts of liquid. Even though the ambient air temperatures are below freezing in winter a glacier can act as a thermal insulator and thereby keep itself, and its deep englacial reservoirs of liquid water, protected from seasonal atmospheric extremes.

It is significant that the winter runoff, in contrast to the summer's, is not laden with glacial sand and silt. This further connotes the presence of a static capillary reservoir rather than a supply by flushing of rain-water.

Such clear water discharge in winter may, in fact, provide excellent opportunities in the future for direct use of untreated runoff in commercial and municipal applications, such as would not be possible during the summer months.

B. <u>Special Considerations</u>

1. <u>Potential Effects of Climatic Change</u>

As far as the dominant factor, climate, is concerned most of the records appended in this dissertation are of insufficient duration to serve as a basis for specific forecasts of hydrologic changes or fluctuations. Sufficient data are given, however, to verify the trend in the past decade toward increasing maritimity in the coastal sectors of the Juneau Icefield and, by inference, in all of coastal Southern Alaska. The continuing rise of annual temperature and precipitation during the most recent decade is causing, as has been shown, an increase of runoff in the area affected. If this trend were to continue for many decades (in effect raising the mean freezing level higher than the névé itself) the ultimate result would be complete removal of the firn-pack and reduction in total area of the Lemon Glacier. Attending this would be a decrease or even eventual disappearance of the propagated melt-water component of runoff, which would in turn diminish or even totally eliminate the discharge over the winter months.

At present, runoff along the periphery of the Juneau

Icefield may be near its 20th century maximum, or possibly will attain this maximum within the next few years. With warmer climate and increased precipitation always comes the prospect of worsening flood conditions in these mountainous districts. Typical danger spots in the region of this study are the Tulsequah, Taku River, and Berners Bay sectors east and north of Juneau. Another well-known locality is Lake George on the Knik Glacier of the Chugach Range. These sites are prototypes of catastrophic seasonal glacial floods. Other districts too may develop flood problems as runoff reaches its peak. Thus, recognition of relationships of the kind here considered have practical value in addition to their academic geomorphic and climatologic implications.

The present trend appears to be due to change within the next several years, since the thermal curve plotted over many decades has been seen to be sinusoidal. This suggests a correlation with the sunspot cycle which has a dominant wave length of 80-90 years, with nodes of high and low sunspot activity separated by approximately 45 years (Miller 1958, 1962b). Reference is made to the 1958 paper cited above in which a comparison of sunspot numbers, climate, and glacier behavior is shown. In 1917 the mean January temperature curve recorded at Juneau was at its low point and has been on the rise up through 1961. This corresponds with the current hemicycle of increased sunspot activity. In terms of the 45-year half cycle, climate should presently be ready to revert to colder trends, as in the next few years we enter a period of lesser sunspot activity. The resultant lowering of freezing level to minimal limits in alternate 40-50 year periods would cause a thinning of glaciers nourished at high elevations and a thickening of glaciers with prime névés at low elevations. This should also reduce total annual runoff by lengthening the winter season and by shortening the effective ablation season in the warmer months. Abetting this condition we might anticipate contemporaneous reductions in precipitation and ablation, such as have been demonstrated to accompany colder conditions.

2. Hydrograph Anomalies

On a number of the daily hydrograph curves for Lemon Creek which were examined in the files of the U.S. Geological Survey Water Resources Division office in Juneau some surprisingly sharp short-term peaks were observed, indicating sudden high-velocity surges of runoff. Little indication of these abnormal peaks is found in the published daily records, such as have been plotted in Figure 26. This is, of course, the result of averaging runoff values over a 24-hour period. Other peaks are also seen on the curves of daily record, but these are of longer duration...i.e. lasting up to several days. They are presumably the result of significant increases in precipitation over intervals greater than 24 hours.

The abnormal short-term peaks, however, show no direct correlation with ablation or meteorologic fluctuations. As such they are an anomaly worthy of special consideration. It is furthermore doubtful that they are the direct reflection of precipitation changes, since precipitation in this region could not cause such large increases in volume over such short periods of time. The slow build-up of ablation melt is also not considered sufficient to produce such effects. In fact, a minor catastrophic event is believed essential to explain these short-lived and greatly-increased volumes of flow.

Indirectly, the combined effects of rain and melt-water could be a cause...i.e. through the impounding and storage of rain and melt-water. It is a unique characteristic of Temperate glaciers, through rainfall and copious melt-water generation in the summer season, that they become saturated at depth and develop what is essentially a water table relationship. Such a water table has been measured by Miller (1962a) on the lower névé of the Juneau Icefield. Because of this, crevasses extending below the water table and pinching out at depths of 90-120 feet often hold large quantities of impounded water. It seems quite possible, therefore, that a single large crevasse, or a system of such crevasses, could rather suddenly be extended by the periodic strain release of englacial stress.

The relatively steep gradient of the Lemon Glacier terminal area (Fig. 27) with slopes of 5° to 20°, should lend itself to spasmodic surges in strain-rate. In shallow or thin ice this might even be expressed by crevasses extending themselves to the base of the glacier. With impounded water in such fissures the consequence could be catastrophic. Upon extension of even one such fracture into the basal zone of the glacier, impounded water could be suddenly released as torrential runoff. The nature of this release, however, would be such as to increase the volume of flow of Lemon Creek over only a very short interval. The sudden release of impounded water by the extension of fissures at the bases of crevasses has been observed in the Camp 10 sector of the Taku Glacier, and also reported on the Skautbreen in Norway (McCall, 1952).

In the present case, of course, a tectonic mechanism must remain hypothetic since it would be difficult to witness the event taking place. Such, however, does provide a plausible explanation of the completely anomalous surges indicated by the stream-gauge record. In this record the possibility of an alternative climatologic cause is minimized when comparison is made between the plotted curves of temperature, precipitation, and runoff. In no wise do these suggest that even the most abnormal climatic fluctuations of the region can directly produce such instantaneous peaks. It is reiterated that these peaks are not the same as the patterned cycles of discharge, which have been previously discussed, but are aperiodic surges of drainage of short duration. Regardless of the cause of the sudden small-scale outbreaks, it is clear that Temperate glaciers exhibit a self-releasing capability whenever hydrologic stresses reach certain critical limits.

3. Periodic Large-Scale Floods

Mentioned earlier were several locales where catastrophic floods of large size occur. In the Taku District the Tulsequah[1] flood is the best known (Kerr, 1934). Forty miles northeast of Juneau on the eastern margin of the Juneau Ice-

1. The glacier, river, and lake named "Tulsequah" are also sometimes known by the name "Talsekwe," a form, however, no longer used in official Canadian publications.

field in British Columbia, an ice-dammed lake is formed against a lobe of the Tulsequah Glacier (Fig. 1). This lake periodically drains each summer, sometimes twice a summer, in July or August. The lake drains in 4 or 5 days, discharging some 60 billion gallons of water on the Tulsequah River and Taku River flood plains. Most of this drainage occurs during a 48-hour period (Marcus, 1960).

The lake itself is the result of seasonal impounding on a far grander scale than the fissure-type discussed in the previous section. But the catastrophic outflows are a result of geomorphic and hydrologic controls. What happens at the ice dam to cause sudden releases of the lake water into the Tulsequah River is still not clear. Several hypotheses have been put forward but it seems none have been satisfactorly proved. Yet, this problem is of economic importance since for many years the flood washed out a $15,000 bridge, which had to be re-erected annually across the Tulsequah River by the Consolidated Mining and Smelting Company of Canada, Ltd.

The meteorologic, ablation, and runoff data from the Juneau Icefield give no direct hint as to why the drainage of Tulsequah Lake is in the form of catastrophic bursts. The volume of rain and melt-water forming the lake appears to reach a critical stage at which time the flooding takes place. It is apparent that a gradual build-up of hydraulic head occurs as a result of the impounding of these waters behind the ice dam. The mechanics of the release of this stress, resulting in the sudden out-flow of water apparently through tortuous subglacial channels, is the unresolved problem on which detailed on-the-spot observation is needed. Once the mechanics are satisfactorily understood, then ablation, precipitation, and runoff measurements may be conducted in the Tulsequah sector of the icefield to permit forecasting of future floods. This potential research could also point the way to corrective action in controlling such outbursts in districts where human habitation, mountain highways, and other lines of communication may be threatened.

It is of interest in this connection that a large number of other self-discharging glacial lakes are present in the Alaskan Boundary Range about which glacio-hydrologic information is completely lacking. Other examples of these in the Taku District are two large ice-margin lakes located northwest of the icefield and dammed by the Gilkey Glacier in the Berners Bay Trench (Miller, 1952b). Without any obvious outlet these waters are suddenly released late every summer to crest in substantial floods in the Antler River Valley 15 miles down glacier from the impounding locale. Across the Antler River, as well as in the valley of the Taku River, highways eventually will be constructed to reach Alaska's capital city of Juneau. In this district alone much information will be required on the nature and periodicity of large-scale glacier-born floods.

IV. OTHER GEOMORPHIC CONSIDERATIONS

The unique internal constitution of glaciers and their related hydrologic regime involves other characteristics of potential economic importance. For example, there is the potential reservoir capacity of future significance, not with respect to liquid water but to the considerable volume stored in frozen form. Then there are aspects of erosion and sedimentation produced by the glacio-hydrologic forces which can have practical value. Some of these are now briefly considered.

A. Potential Glacier Reservoir Capacity

A glacier, being a body of water in the form of firn, ice, and varying amounts of the liquid component depending upon its geophysical character, is a natural open system relinquishing part of its substance in summer and replenishing the supply in winter. In effect it is a huge mass-energy-time system, the economic potential of which has hardly yet been exploited by man.

The reservoir capacity of a glacier can be determined by measuring its surface area and the thickness and physical characteristics of both firn-pack and ice. Firn and ice depths and related information can be revealed by test-pit, bore-hole, and geophysical measurements. As we have seen, consideration can also be given to the liquid-water content of the firn-pack. By these means, volumetric limits of the glacier, its water storage ability, and its total water equivalent can be readily calculated.

Of course, a glacier in a given region is controlled largely by meteorologic conditions and therefore, may shrink or grow depending upon fluctuations of climate. Since, as far as man is concerned, these are relatively long-term changes, we need not be unduly concerned whether the glacier in question is in a fairly healthy or an unhealthy state. But by obtaining systematic quantitative data on the annual budget through yearly measurements of accumulation, ablation, and meteorologic data such as have been dealt with in this dissertation, it is possible to prognosticate the hydrologic behavior of glaciers, upon which economic planning can be based.

B. Practical Aspects of Erosion and Sedimentation

An actively advancing glacier with substantial forward movement causes a great deal of erosion along its bed. This erosion is exemplified by direct plucking and abrasion of the rock surfaces over which the glacier moves. Some erosion is also produced by the torrential subglacial drainage streams, and by side-wall frost shattering in open spaces. The ultimate result is the deepening and molding of the glacier's bed into a trough of usually U-shaped form. Most of the rock directly eroded from the bed is reduced to rock flour...i.e. glacial silt and clay. This material is eventually washed out by the subglacial and proglacial streams and deposited somewhere down valley.

In the case of the Lemon Glacier, rock flour is transported by Lemon Creek directly into the adjacent fiord (Gastineau Channel, Fig. 27). This presents a problem since the silt brought in by Lemon Creek and other glacial streams

(e. g. the adjacent Mendenhall River) is filling in the northern section of this channel. In recent years continuous dredging has been required to keep the channel clear, even for small boats to navigate. Furthering this condition is the post-Wisconsinan epeirogenic uplift of the Juneau area at the mean rate of 1.5 centimeters per year; a total of 500 feet since maximum glaciation (Twenhofel, 1955). The resultant uplifted and poorly drained silt beds are now the locations of many farmlands along the Alaskan Coast. In the Juneau area they serve as grazing grounds for the only herds of dairy cattle in this region. The geomorphic and tectonic processes involved in the production of these features insure an increase in the use of such lands for farming purposes in the years ahead.

Another sedimentation problem is the silting in of natural and man-dammed lakes. An illustration in the Taku District is Salmon Creek Reservoir, about three miles north of Juneau (Fig. 27). This lake is used by the city of Juneau for a hydro-electric power source and municipal water supply. It is gradually being filled in with glacial fines by feeder streams from two small local glaciers. Theoretically, this process could cause the lake to eventually overflow its boundaries, thereby jeopardizing the municipal and hydro-electric water programs. This type of sedimentation process is of little concern at present but in the future could become a major problem in the expanded development of hydro-electric power and municipal water reservoirs along the Alaskan coast.

Another economic aspect of these studies bears on glacial erosion. The mountains of the Boundary Range and adjoining districts of Alaska and northwestern Canada are famous for their gold mines of years ago. Glaciers, by down-cutting and eroding into the metamorphic bedrock, originally exposed gold veins and lodes. Through mechanical weathering and glacial corrasion the gold was separated from the country rock and because of its high density, settled into the beds of glacial streams and became concentrated in glacially-eroded depressions. Upon retraction of the glacier it awaited discovery by the ever-searching prospector.

In the Alaska-Juneau gold belt it was such placer gold deposits which were initially discovered, leading to the extensive mining of the parent lodes in the early decades of this century. In effect the glaciers were the first miners. No doubt, there are other significant deposits yet to be found in the auriferous sediments washed out and deposited by runoff from these glaciers.

C. <u>Water and Hydro-Power Projects</u>

The Salmon Creek Reservoir discussed earlier is in truth, a man-modified tarn, impounded in an early Wisconsinan glacial cirque (Miller, 1961). There are many of these natural basins in the Boundary Range of Southeastern Alaska. Some contain tarns fed by glacial streams, others are dry. The potential can be seen for low-cost development of such basins and tarns as local reservoirs providing future power and water. Such has been a problem with respect to the recent multi-million dollar pulp mills at Ketchikan and Sitka, and may arise as a future problem with respect to a large pulp development which may be considered at Juneau and elsewhere in this region of Alaska and Canada. In such cases the silt problem can become an especially important consideration. This, not only as an infillent of the reservoir but also as a contaminant of the water itself.

Lake Atlin, which lies 65 miles north of Juneau, is a prime example of a potential major source of hydro-electric power. This lake, which lies entirely within Canada, is nourished by the runoff from the continental flank of the Juneau Icefield. It fills a deep glacier-carved valley 75 miles long and from 2 to 5 miles wide. If jointly developed by the United States and Canada this lake could supply the low-cost power and water needed to attract large-scale industry to this region. What this would do for the future of Southeastern Alaska and Northwestern Canada is obvious. Unfortunately, however, Lake Atlin is in a region sparsely populated, completely undeveloped, and not even fully explored. The future, however, will see changes in this situation, since such vast hydro-resources cannot forever remain undeveloped. When that happens the potential power and water supply of Atlin and its sister lakes will be high on the list, just as the Hoover, Grand Coulee, and Niagara-St. Lawrence power projects became necessities for continued municipal and industrial development. Thus, looking ahead to such a time, glacio-hydrologic studies on the Juneau Icefield will be given similar priority.

V. SUMMARY AND INTEGRATION OF RESULTS

A final compendium of the results of this study is given below. This summary may be considered as a detailed abstract of the 1961 results where they concern investigations of the main crestal névé and related aspects of propagated surface water and runoff. Statistics particularly significant to the long-term studies of the Juneau Icefield Research Program are underlined.

A. Brief of the Névé Investigations

1. During 1961 the crestal névé of the main Taku Glacier on the Juneau Icefield was found to be sub-Temperate in geophysical character, as compared to Temperate conditions prevailing in the main lower névé. At 5800 feet to 6500 feet the magnitude of sub-freezing was measured at -0.4° to -0.9°C at depths of 10 to 40 feet beneath the 1961 ablation surface, and -0.05°C to -0.10°C at depths from 50 to 150 feet.

2. Net accumulation for the 1960-61 budget year on the crestal névé was found to be 17.5 feet of firn, and on the lower névé, 5.7 feet of firn (water equivalents noted below). The 1960-61 crestal firn-pack ranged in density from 0.50 gm/cc. at the surface, to 0.58 at 15 feet. The basal depth-hoar stratum was of a density 0.52 at 17 feet. The resultant bulk density, including the addition of diagenetic ice, was determined as 0.56. The resultant water equivalent for the 1960-61 firn-pack was 9.8 feet of net accumulation on the upper névé. The corresponding water equivalent for the lower névé firn-pack (bulk density 0.60) was 3.4 feet for the 1960-61 budget year, including the proportion of diagenetic ice.

3. The 1961 ablation and temperature records bear out previous reports of a much shorter ablation season on the crestal névé than on the lower névé. The duration of the effective ablation season for 1961 was 2.7 months (5 June-25 August) on the crestal névé at the mean elevation of 5900 feet; and 5 months (25 April - 25 September) on the lower névé at the mean elevation of 3900 feet. The Lemon Névé ablation season at a comparable mean elevation of 3900 feet was found to be of 5.8 months duration in 1961.

4. Minimum values of gross ablation in the 1961 budget year at the mean elevations of the crestal and lower névés were calculated respectively to be 1.5 feet and 6.3 feet water equivalent.

5. Propagated surface water percolating into the crestal firn was found largely to be reclaimed at depth in consequence of the observed sub-freezing glaciothermal conditions. This verifies under present conditions the findings of the early 1950's that gross ablation on the upper névé must be considered as recaptured accumulation. Therefore, net ablation on the crestal névé is reported as essentially zero. On the lower névé most of the propagated surface water percolates through the glacier becoming runoff at its terminus. A small amount of this water, however, freezes in the firn-pack during the early part of the ablation season while the winter cold wave is still present. Thus, annual net ablation on the lower névé by volume is slightly less than gross ablation.

6. The mode of melt-water percolation involves concentration of water in "channelized" zones...i.e. selective infiltration in which the direction and rate are guided by ice structures, rather than being characterized by a uniformly descending front.

7. The 1960-61 crestal and lower névé firn-packs contain similar diagenetic ice structures (strata, laminae, lenses, and columns) but on each névé these differ in volume percentage.

a. Diagenetic structures constitute a 5 percent increase in density in the crestal firn and an approximately 8 percent increase in the firn-pack of the lower névé. A component of diagenetic ice comprised of vertical "columns" was abundantly noted in the firn of the lower névé while being relatively scarce in the 5900-foot crestal firn. On the 6500-foot plateau of the Gilkey Névé, however, these were found in even greater abundance than on the lower (3900-foot) névé. This is attributed to the stronger maritime influence exerted on this sub-temperate névé by air masses sweeping up the Berners Bay Trench into which the Gilkey Glacier drains.

b. Diagenetic ice structures are formed by the freezing of propagated surface water. Those found in the firn of the lower névé are formed only during amelioration of the firn at the beginning of the ablation season, and to a far lesser extent during the brief interval of transition at the onset of the cold wave in early autumn. Because of the persistent sub-Temperate englacial conditions those of the crestal névé form throughout the ablation season.

8. Glacio-chemical analyses made of the Juneau Icefield firn reveal a gradual decrease in NaCl inland from the coast. The sampling, however, was insufficient in areal extent and time to corroborate the working hypothesis concerning shifts in climatologic and accumulation effects. But they do bear out the relative continentality of the crestal névé and maritimity of the lower and Lemon Névés. Also, they point the way to fruitful future results in the interpretation of firn profiles from depth.

9. Interpretation of the Lemon Glacier meteorology is

permitted by access to continuous weather records from stations at adjacent locations.

a. The temperature range on the Lemon Névé (mean elev. 3900 feet) is found to be similar to that on the lower névé of the main icefield; although somewhat warmer due to its slightly more maritime position and lesser influence by katabatic icefield winds. By extrapolation from available data the Lemon Névé was found to experience a 5.8-month effective ablation season during the 1960-61 regime year. Assessment of the runoff data over the decade since 1951 corroborates this as a representative value.

b. Total precipitation (water equivalent) on the Lemon Névé is considered to correspond to that at the rain-gauge site (3576 feet) on Mt. Juneau. This is approximately triple the precipitation recorded at equivalent elevations on the lower névé of the main icefield. Orographic factors, coupled with geographic position, account for this difference.

B. Brief of the Glacio-Hydrologic Investigations

1. Consideration was given to climatic trends covering essentially the past decade; and using data from the Annex Creek, Juneau City and Juneau Airport stations.

a. The 11-year running mean of annual temperatures for these stations exhibits decreasing temperatures from 1950 to 1956; with the trend increasing from 1956 through 1961. The 11-year running mean of January temperatures reveals a marked decrease from 1950 through 1958. In 1959 the trend reversed to increasing temperatures continuing through 1961. It should be noted, however, that the overall trend of January temperatures at Juneau since the 1917 low point has shown a general increase through the present period of record; with the reversal of the past decade probably representing a superimposed fluctuation. Since this study is primarily concerned with regime changes over the interval 1951-61, consideration of the longer-range upward trend is beyond the scope and purpose of the present treatment.

b. With regard to precipitation the 11-year running mean of annual total precipitation at Juneau City and Juneau Airport shows generally little change over the period 1950 through 1961. The 11-year running mean of annual precipitation for Annex Creek, however, reveals a pronounced decrease from 1950 through 1957, the curve then levelling over the 5-year interval 1957-61.

c. Comparison of the mean annual precipitation records, however, shows a gradual increase since 1957. Also, the mean monthly precipitation data reveal an increase in autumn and early winter precipitation since 1956. These trends are of importance in the analysis of Lemon Glacier discharge data.

2. Hydrograph records of mean annual discharge rates of runoff from the Lemon Glacier basin show a gradual increase over the decade 1951-61. The trend parallels the previously cited increase in annual temperature and precipitation values

since the mid-1950's. It may reflect as well the longer-term warming shown by the upward trend of winter temperatures over the past 44 years.

The mean monthly discharge rates tend to corroborate a 5.8-month ablation season on the Lemon Névé, since in the period April-October approximately 80 percent of the yearly discharge occurs.

Precipitation and not ablation generally governs the magnitude of fluctuation in the mean daily runoff curve. The greatest peaks of runoff are due to fluctuations in precipitation; ablation being characterized by relatively small variation throughout the summer months.

3. Calculated runoff from the Lemon Névé for July and for August, 1961 was respectively 58.9 and 77 inches. This is compared to a measured runoff of 53 and 68.4 inches for these two months. The significant differences between calculated and measured runoff are considered due to retention of some melt-water and precipitation by the capillary intercrystalline forces in the firn, by impounding in crevasses and to a much less extent by absorption in the soil and vegetation of the basin rim, and by evaporation.

4. The preceding summer's rain and melt-water is considered to be indirectly responsible for runoff during the winter period. Most of this is stored in the glacier during the ablation season, then subsequently discharged in small and steady volumes. The discharge is relatively free of glacial silt during the winter months, which further implies origin in the preceding ablation season.

5. Meteorologic data covering the decade 1951-61 indicate a trend toward a slightly more maritime climate in the Juneau area.

6. Based on Lemon Glacier hydrologic records since 1951, runoff in this decade has steadily increased and, through analysis of the climatic trends, should peak in the next few years. After that the trend should reverse, paralleling decreases in temperature and precipitation associated with an indicated short-range reversal in the climatic cycle.

7. Discharge anomalies in glacier runoff are characterized on the Lemon Creek hydrograph charts by notably sharp peaks of brief duration (a few hours or less). These peaks are probably the result of sudden releases of impounded water held in crevasses and associated fissures in the Lemon Glacier at depth. The events may be triggered by normal glacier creep, or associated discontinuous movements causing deepening of crevasses or extension of fissure systems into the basal shear zone of the glacier. Here further drainage is probably aided by fracture permeability and the presence of related subglacial channels.

8. The annual <u>Tulsequah floods</u>, originating on the eastern margin of the Juneau Icefield, as well as similar glacier bursts in the Berners Bay sector to the north, are considered direct results of geomorphic, glaciologic, and hydrologic controls. Once the mechanics of associated stress-strain in the impounding ice is understood, forecasts of future ice-released floods which threaten site of human activity may be made by application of selective meteorologic and runoff data of the type considered in this present report. Remedial measures may also be taken to release the lake waters slowly.

C. Review of Practical Glaciologic Considerations

1. A glacier may be considered as a natural reservoir of co-existing liquid (in the Temperate case) and frozen water. Its liquid storage capacity and total water equivalent can be calculated through area and thickness measurements of the snow-pack and firn-pack, and of the underlying mass of bubbly and dense glacier ice. Allied measurements can be made of its structural and glaciothermal character and of the volume of stored liquid water. The evaluation of related meteorologic and glacio-hydrologic data may aid in the assessment of reservoir capacities and the forecast of discharge volumes for future commercial and municipal use.

2. Sedimentation of glacial erosional products under certain circumstances have costly effects. The eroding power of an advancing glacier is great. Abrasion at the sole of a glacier produces vast quantities of rock flour. As illustrated by the Lemon and Mendenhall Glaciers, such fines are carried by discharge streams into the Gastineau Channel. Deposition there has in-filled the northern section of this fiord, so that dredging has become necessary to keep it navigable. Abetting this effect has been 500 feet of post-glacial upwarp in this sector of the Boundary Range since maximum glaciation in the Pleistocene.

3. One beneficial aspect of glacial erosion and sedimentation is the depostion of placer gold in outwash streams, in depressions of the floor of glacial valleys, and in abandoned cirques at low and intermediate level. The gold, originating in veins and lodes, has been extracted from the country rock by shattering, plucking, and abrasion by periodically advancing and receding glaciers. Because of its high density, the gold has separated from the country rock and by fluvial action has accumulated in local depressions. Such sites have been and may again become the loci of gold mining operations.

4. Glacial lakes for power and water supplies are abundant in coastal Alaska. In-silting of both natural and dammed lakes is thus a problem to take in account. Many of these lakes are excellent sites for hydro-electric programs. As power requirements grow, a careful study of the glacial-lake phenomenon will become necessary in many areas of Alaska.

Salmon Creek Reservoir, 3 miles north of Juneau, is a dammed glacial tarn, impounded in an abandoned cirque and fed by two glacial streams. It provides a municipal water supply for Juneau. Since the Boundary Range of Southeastern Alaska contains many such natural basins where clear water is available, the potential for development of relatively small low-cost water supply projects is also evident. The need for a practical understanding of related glacio-hydrologic problems will have increasing importance in this area of interest. It is hoped that the present study may provide some guidelines for future glacio-hydrologic assessments.

5. Lake Atlin, 65 miles north of Juneau, represents what someday may be the site of a large-scale hydro-electric power and water project. Fed by glaciers of the Juneau Icefield this lake lies in Canada, and is the ultimate headwater of the Yukon River. It occupies a glacier-carved valley 75 miles long, varying from 2 to 5 miles in width. Once tapped it would serve as a strong incentive for joint U.S.-Canadian industrial development in this part of North America.

VI. SIGNIFICANCE OF THE 1961 STUDY

The investigations described in this dissertation have been conducted as part of the long-term Juneau Icefield Research Program under the sponsorship of the Foundation for Glacier Research. The névé, meteorologic, and glacio-hydrologic observations and measurements add to the aggregate of data which has been assembled annually on this icefield since 1946. The present discussions have dealt only with regime aspects covering the decade 1951-61, and with special emphasis on the 1961 records. It is hoped, however, that the new information provided and the related evaluations will serve the broader purposes of the long-range program. The writer believes that with respect to the study of the icefield system as a whole it has helped to clarify several previously hidden relationships, and also has solidified the foundation of regime statistics covering the last decade. This cannot help but serve as useful reference for future investigators. In addition, it is hoped that this study will prove helpful in furthering the methodology of field measurements and interpretative techniques in the glaciology of this icefield. From such sequential effort will come the eventual understanding of the true causes and manifested effects in the birth, life, and death, and indeed in the multiple re-incarnation, of this huge glacier system.

From the examples which have been cited as to the practical uses of glaciologic data, the value of continuing investigations in glacial regions should be obvious. This should be particularly so in the Juneau area, where huge and spectacular glaciers and snowfields lie so close to a significant center of population. The increasing potential of this type of research is germane in other sectors of Alaska too. Along this whole coast it may be expected that future activities will develop where glaciers and their summer névés can provide important recreational facilities, and where impounded glacial water can be used as an unlimited natural resource for important municipal and industrial water management and hydro-electric programs. Glaciers are already being tapped for such purposes in Switzerland, Austria, and France. Glacio-hydrologic plans are underway in the south Argentine Andes and are being given serious consideration in the Cascade Mountains of Washington state. In fact even on the flanks of the Himalayas Communist China is working on the problem of glacial runoff as a source of water for irrigation projects and future hydro-power developments. Today, the world-wide recognition of the potential and practical use of glaciers for water and power supplies is strongly evident.

VII. SUGGESTIONS FOR FURTHER INVESTIGATION

It is stated again that because of the widely integrated nature and long-term aspect of the separate phases of the Juneau Icefield Research Program the study here presented must not be considered complete. It is but a segment of the continuing investigational program now in its 17th consecutive year. Thus it is in order to provide suggestions for further research that has been brought to light by the present treatment. This, of course, does not ignore the continuing need to pursue future measurements using similar and already established lines of investigation.

The first suggestion is that more detailed névé studies, and particularly further geophysical, ablation and water percolation measurements must be made on the crestal névé. Particular attention should be paid to the higher Gilkey Névé because of its apparently anomalous character, and also to the highest névé of the adjoining Llewellyn Glacier on the continental side of the icefield. These studies should be much more extensive than was possible within the time-limits of the 1961 summer field season. Ideally the period of investigation should be planned to encompass completely the effective ablation season. This means from early June through August on the upper névé; and from mid-April through September on the lower névé. Consideration should also be given to special observations during the winter-to-spring amelioration period, particularly over the months of February through May.

In this connection the Camp 9 or intermediate névé should also be fully developed as a research locale. Here, investigations similar to those on the crestal and lower névés should be conducted. The Camp 9 sector is the link between the crestal and lower sectors. In this sector, comparative studies could permit the establishment of a long profile of geophysical and glacio-climatologic parameters for the Juneau Icefield as a whole.

From the 1961 and previous saline content analyses, it would appear that here is a useful criterion for determining cyclic storm track shifts. Furthermore, the analyses should prove useful for the detection of ablation horizons and for differentiating retained segments of annual accumulation in deep firn profiles. Due to the dearth of data gathered to date, more systematic and complete surface sampling should be conducted on the key central névés, as well as on peripheral glacier névés such as the Lemon. Added to this should be complete sampling at depth across the same three main accumulation zones. In this way sufficient data should be obtained to make this technique useful, and to provide enough background statistics to make future comparisons valid.

Also, in order to make more effective the study of glaciohydrology for possible commercial exploitation a full ablation season should be spent at selected observation sites on the Lemon Névé as well. As part of this program a first hand examination of the direct effects of ablation on propagated water percolation, and of the pertinent meteorologic controls, should be carried out. In this, a continuation of the hydrograph record at the Lemon Glacier terminus will be invaluable.

Here and on the 6500-foot névé of the main icefield precise glacier thickness, firn-pack and deep ice structural measurements should be made, using seismic and core-drilling equipment. In other words, surface and subsurface studies should be conducted to parallel those being carried out on the main névés of the icefield, but directed more fully to the problems of reservoir capacity and to the factors producing runoff. In this the U.S. Geological Survey should be encouraged to continue their hydrologic data collection at the Lemon Glacier site; and the U.S. Weather Bureau should be urged to establish a precipitation gauge on the Lemon Glacier Névé to permit a closer evaluation than has been possible using the data obtained at the Mt. Juneau site during the summer of 1961.

Although in this dissertation an attempt has been made to explain the hydrograph anomalies of the Lemon Glacier discharge, actual field research is required to determine whether the provisional explanations provided are fully valid, or whether the anomalies are the result of still unrecognized effects.

Much more work should be carried out on mechanics of the periodic floods from ice-dammed lakes such as the Tulsequah and unnamed lakes impounded along the Gilkey Glacier in the Berners Bay Trench. This problem appears to require as much a geomorphic-hydrologic approach as it does the climatologic.

Field work should be carried out directly at the scene of these glacier bursts during the height of the ablation season. This should be done in the interest of providing effective methods of arresting these and other such floods elsewhere in Alaska, or for that matter in other parts of the world, such as the Andes or Himalayas where similar catastrophic events have resulted in much loss of life and property in recent years.

Lastly, from this present study it has become quite clear that a continuous record of temperature, precipitation, ablation, and runoff should, if at all possible, be kept over the full season of activity on all future field operations in this critical glacier region so close to Alaska's capital. To this end the present field research facilities and stations should be improved and consolidated, so that an even more complete and systematic observational program can be developed on the Juneau Icefield. In this way much more sophisticated and refined evaluations will become possible. And in this way the details of long-term climatic trends can be more adequately recognized and made more useful to the public in terms of actual forecasts of climatic events and their glaciologic and hydrologic results.

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IX. ILLUSTRATIONS

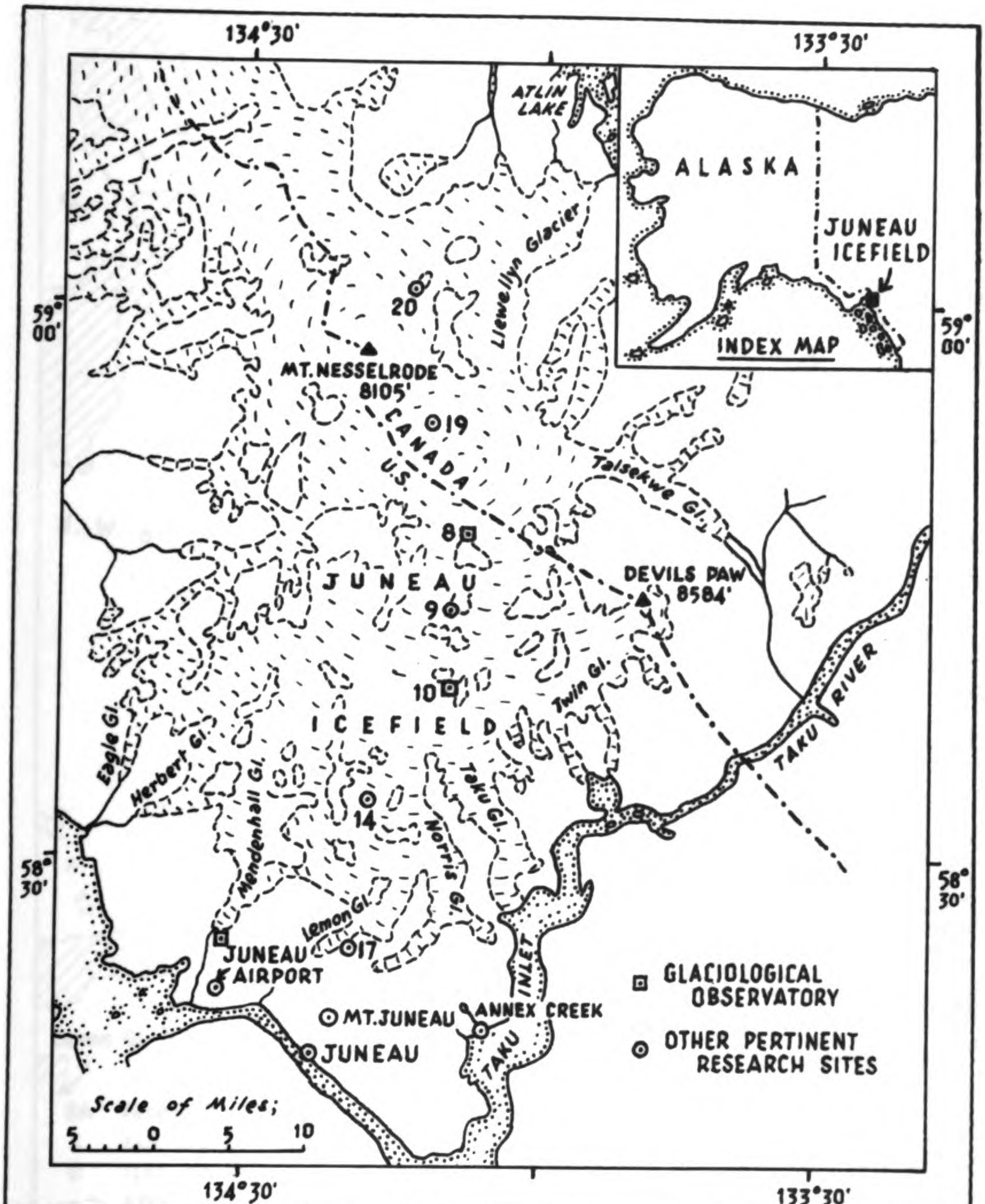


Fig.1 Sketch map of the Juneau Icefield and vicinity showing main meteorological and glacier research stations pertinent to the investigations of 1960 and 1961. Summer Institute headquarters at Camp 8 (elev. 6,800 ft.) and Camp 10 (elev. 4,000 ft.)

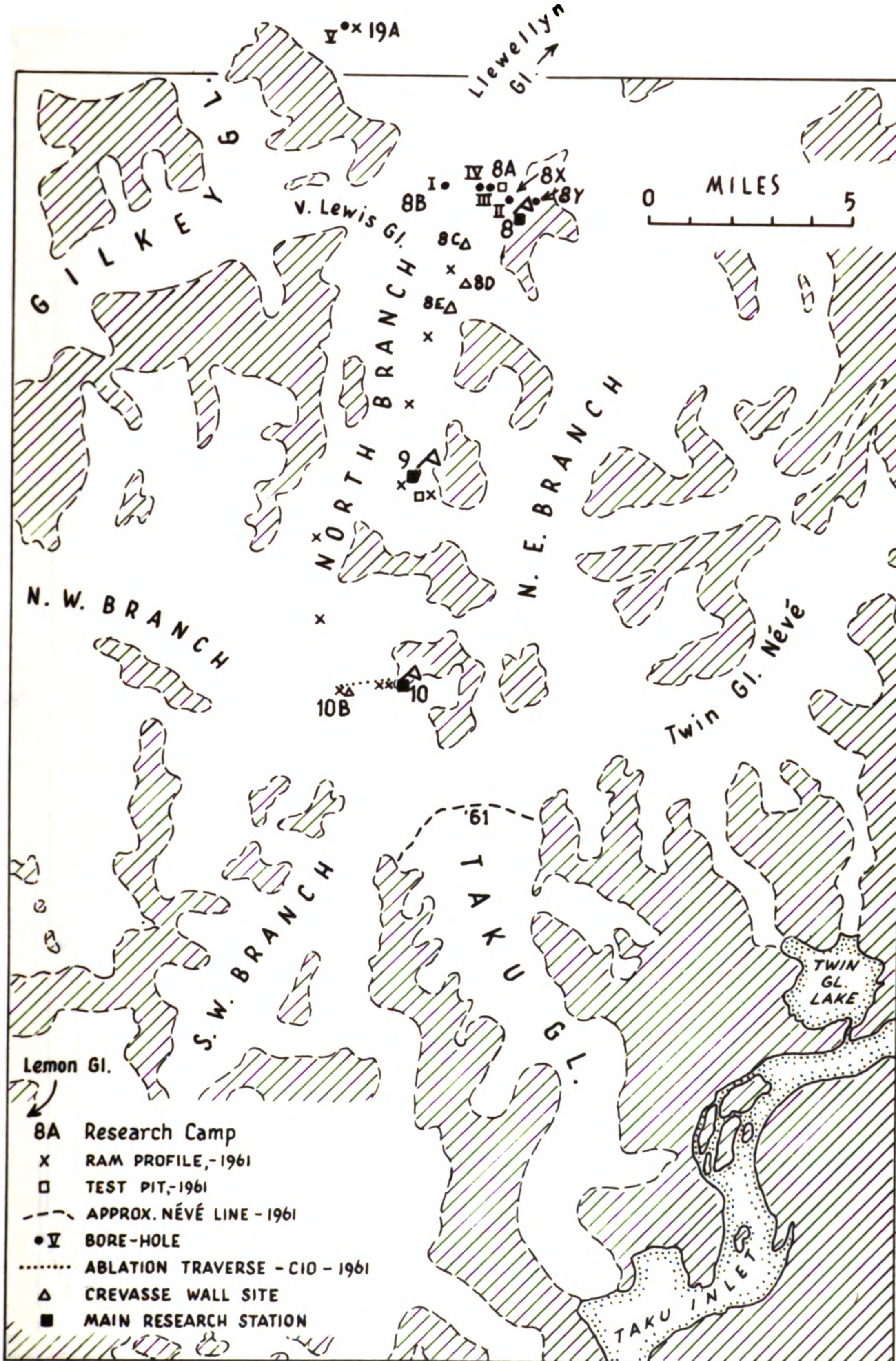


FIG 2 SKETCH MAP OF TAKU GLACIER SYSTEM SHOWING RESEARCH SITES, 1961.

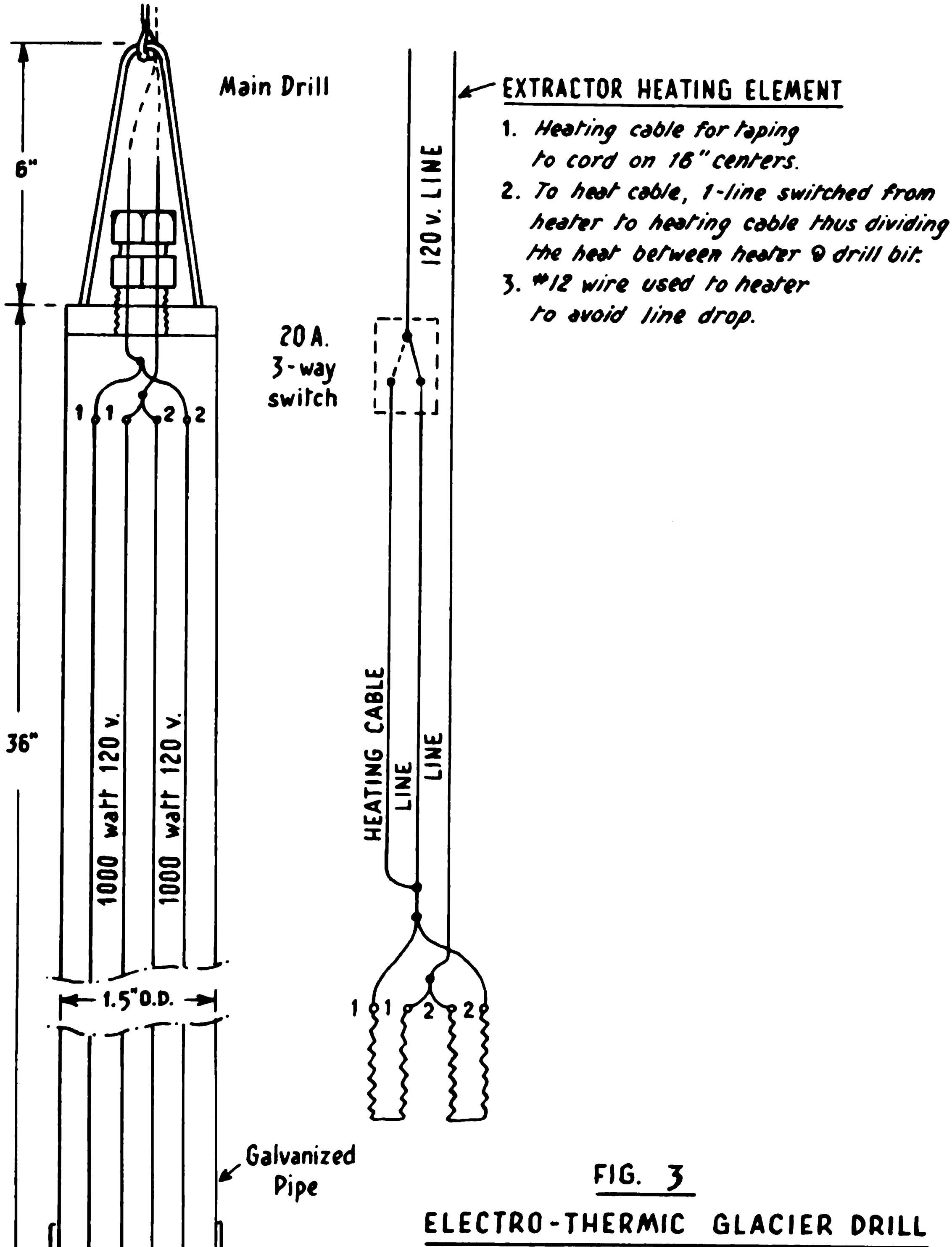


FIG. 3

ELECTRO-THERMIC GLACIER DRILL

2000 watt element; 120 volt wiring detail as used at Site 8A, Upper Taku Glacier, elevation 5900 ft., August - September, 1961.

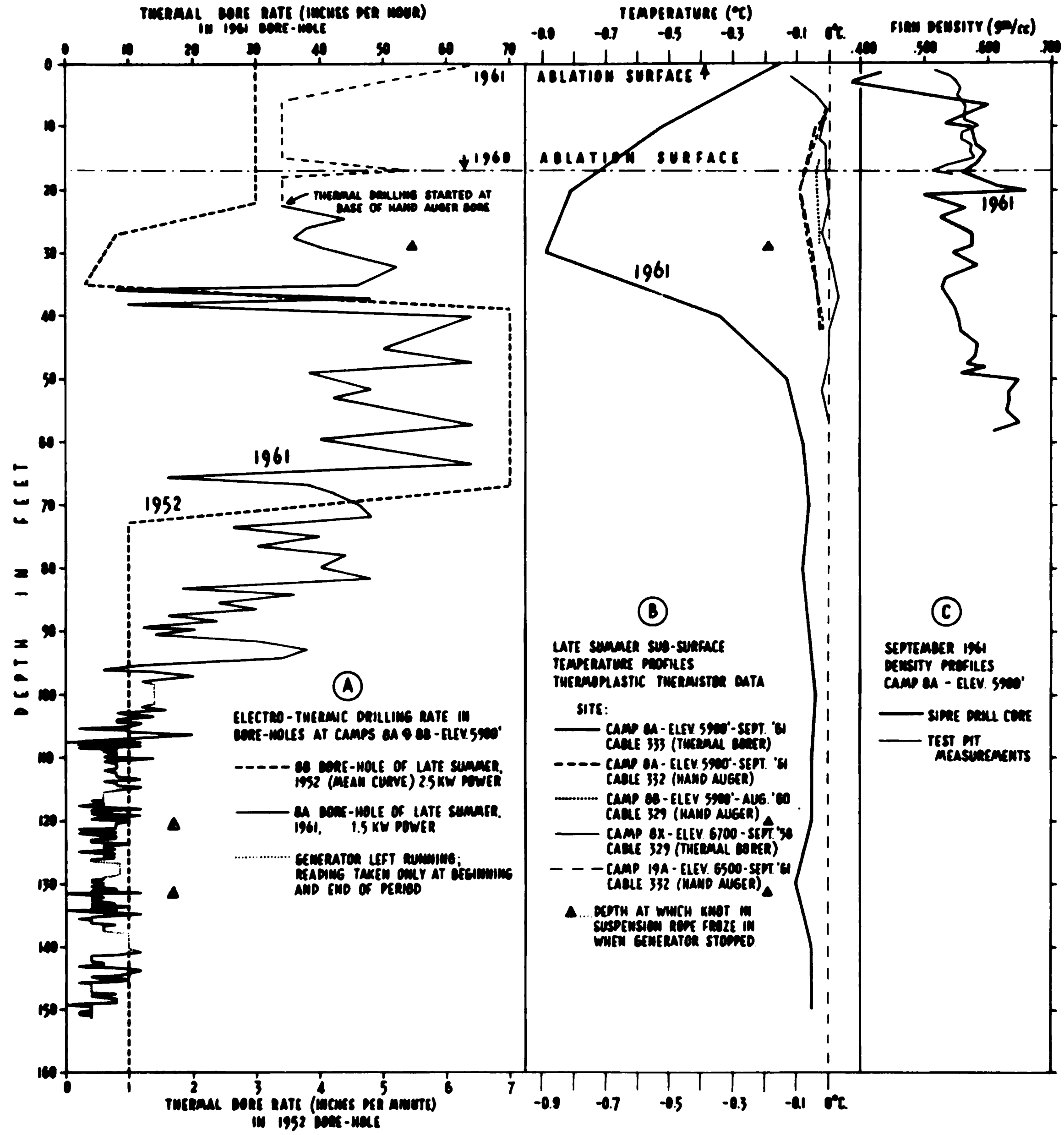


FIG. 4 COMPARATIVE PROFILES OF THERMAL BORE-RATE, ENGLACIAL TEMPERATURE AND DENSITY IN THE CRESTAL NÉVÉ, TAKU-LLEWELLYN GLACIER SYSTEM, JUNEAU ICEFIELD, ALASKA
(emphasizing field data of September, 1961)

FIG.5 S.I.P.R.E. 5 INCH O.D. HAND AUGER.

FIG.6 WHEATSTONE BRIDGE, SELECTOR SWITCH AND THERMISTOR GLACIO-THERMAL CABLES USED ON THE JUNEAU ICEFIELD RESEARCH PROGRAM, 1960 AND 1961.

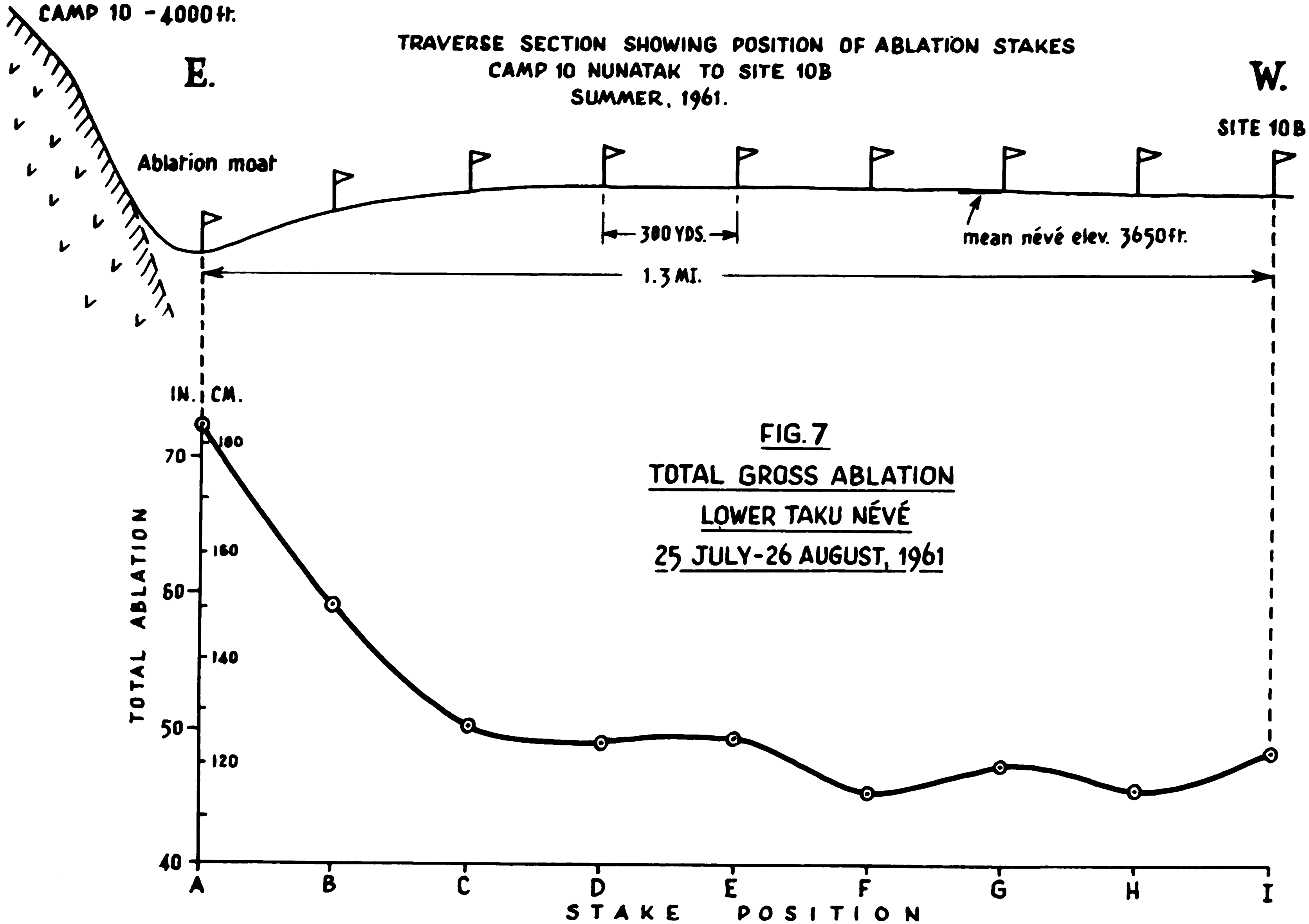
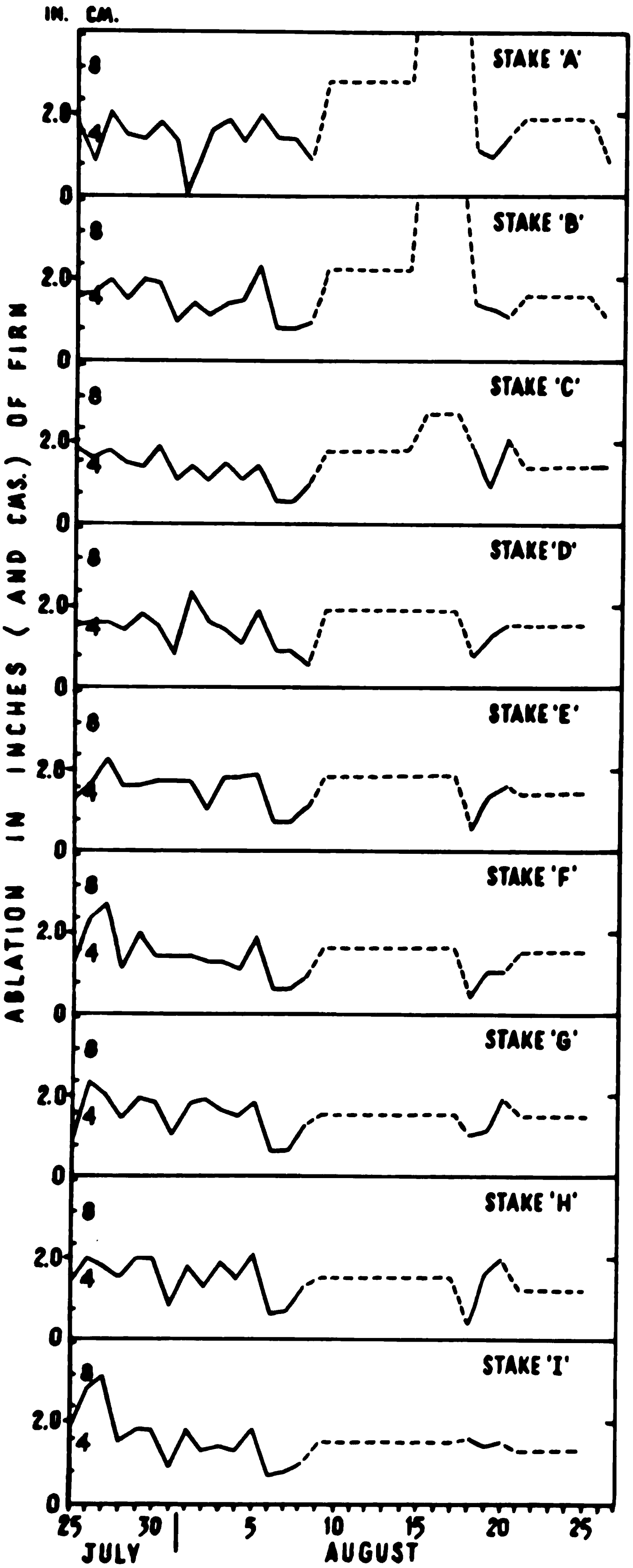
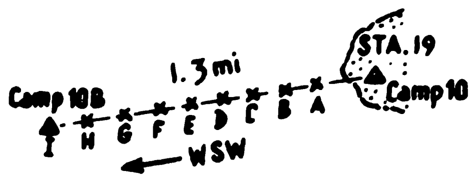


FIG. 7
TOTAL GROSS ABLATION
LOWER TAKU NÉVÉ
25 JULY-26 AUGUST, 1961





TRANSECT LOCATION
WITH RESPECT TO CAMPS 10 & 10B.

FIG. 8

ACROSS-GLACIER ABLATION PROFILE SHOWING RELATIVE GROSS ABLATION IN EASTERN THIRD OF LOWER NÉVÉ.

PERIOD OF RECORD;-
25 July - 26 Aug. 1961

MEAN ELEVATION OF TRANSECT;-
3650 ft.

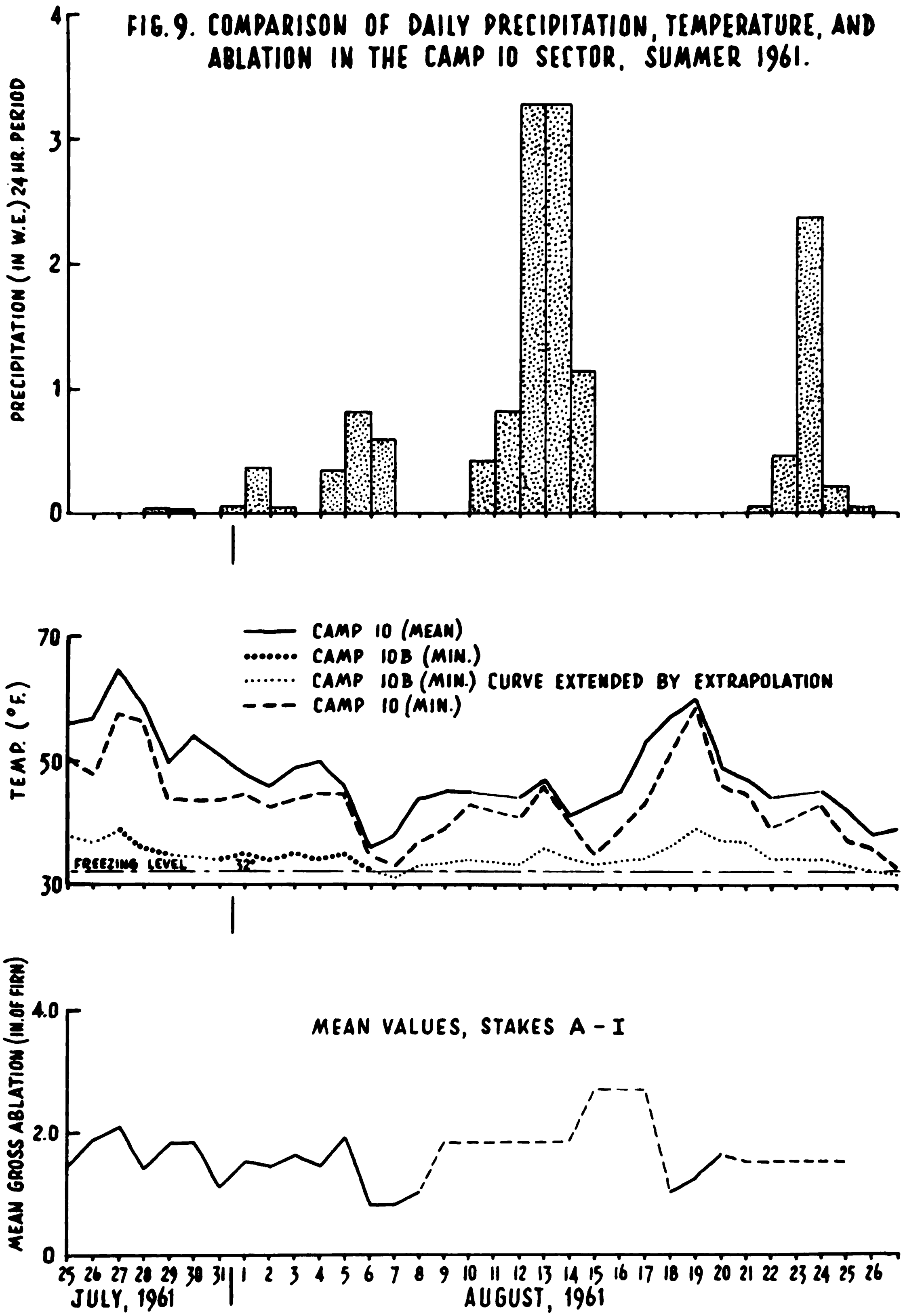


FIG. 9. COMPARISON OF DAILY PRECIPITATION, TEMPERATURE, AND ABLATION IN THE CAMP 10 SECTOR, SUMMER 1961.
PRECIPITATION (IN W.E.) 24 HR. PERIOD
0
1
2
3
4
TEMP. (°F.)
30
50
70
CAMP 10 (MEAN)
CAMP 10B (MIN.)
CAMP 10B (MIN.) CURVE EXTENDED BY EXTRAPOLATION
CAMP 10 (MIN.)
FREEZING LEVEL 32°
MEAN GROSS ABLATION (IN. OF FIRN)
0
2.0
4.0
MEAN VALUES, STAKES A - I
25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
JULY, 1961
AUGUST, 1961

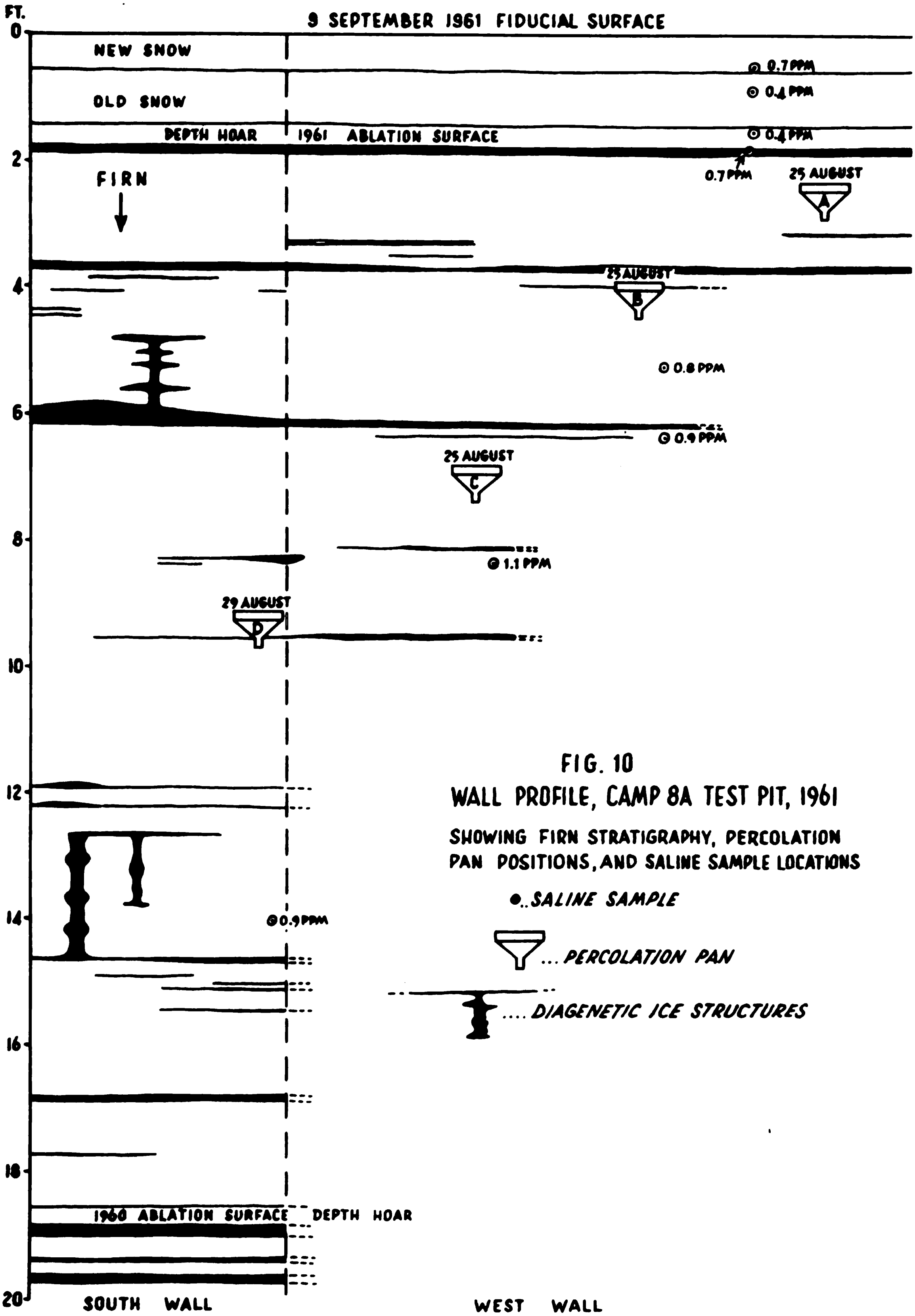


FIG. 10
WALL PROFILE, CAMP 8A TEST PIT, 1961
SHOWING FIRN STRATIGRAPHY, PERCOLATION PAN POSITIONS, AND SALINE SAMPLE LOCATIONS

FIG. 11
STRATIGRAPHY FROM SIPRE-DRILL CORES
AT CAMPS 8A & 19A, 1961

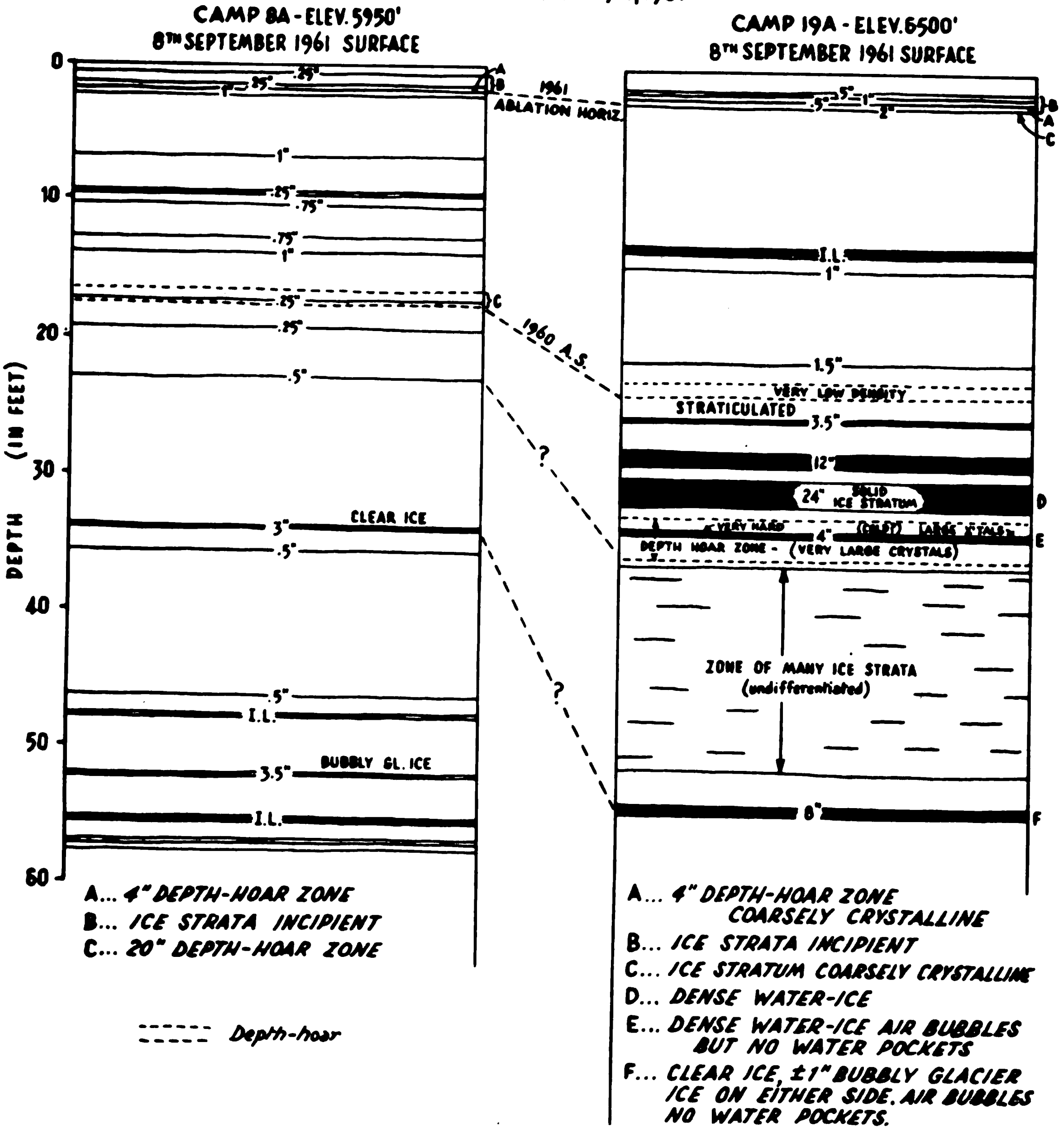
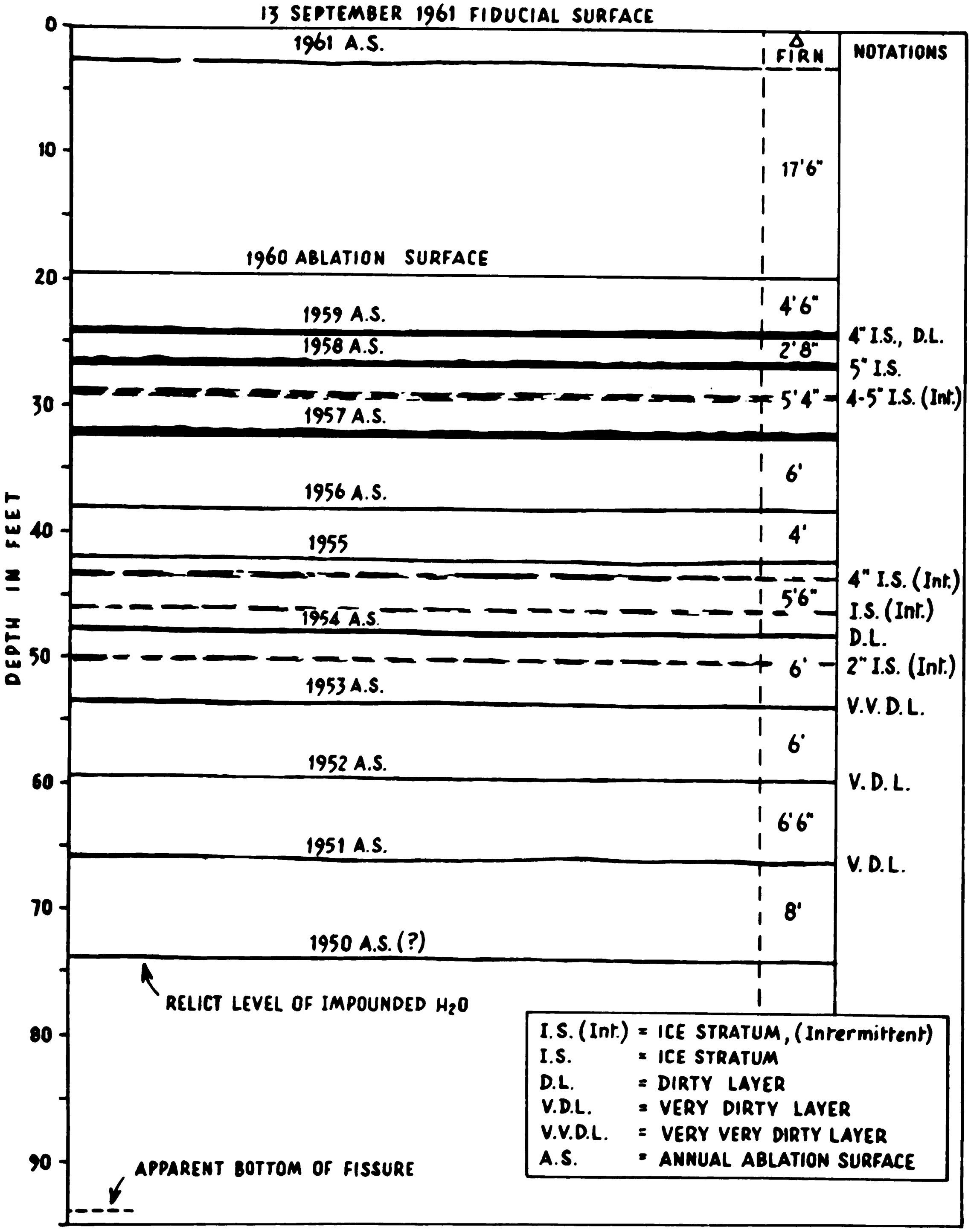


FIG. 12 STRATIGRAPHY OF CREVASSE WALL, UPPER TAKU GLACIER SITE 8D, ELEV. 5700', SOUTH OF CAMP 8, 1961.



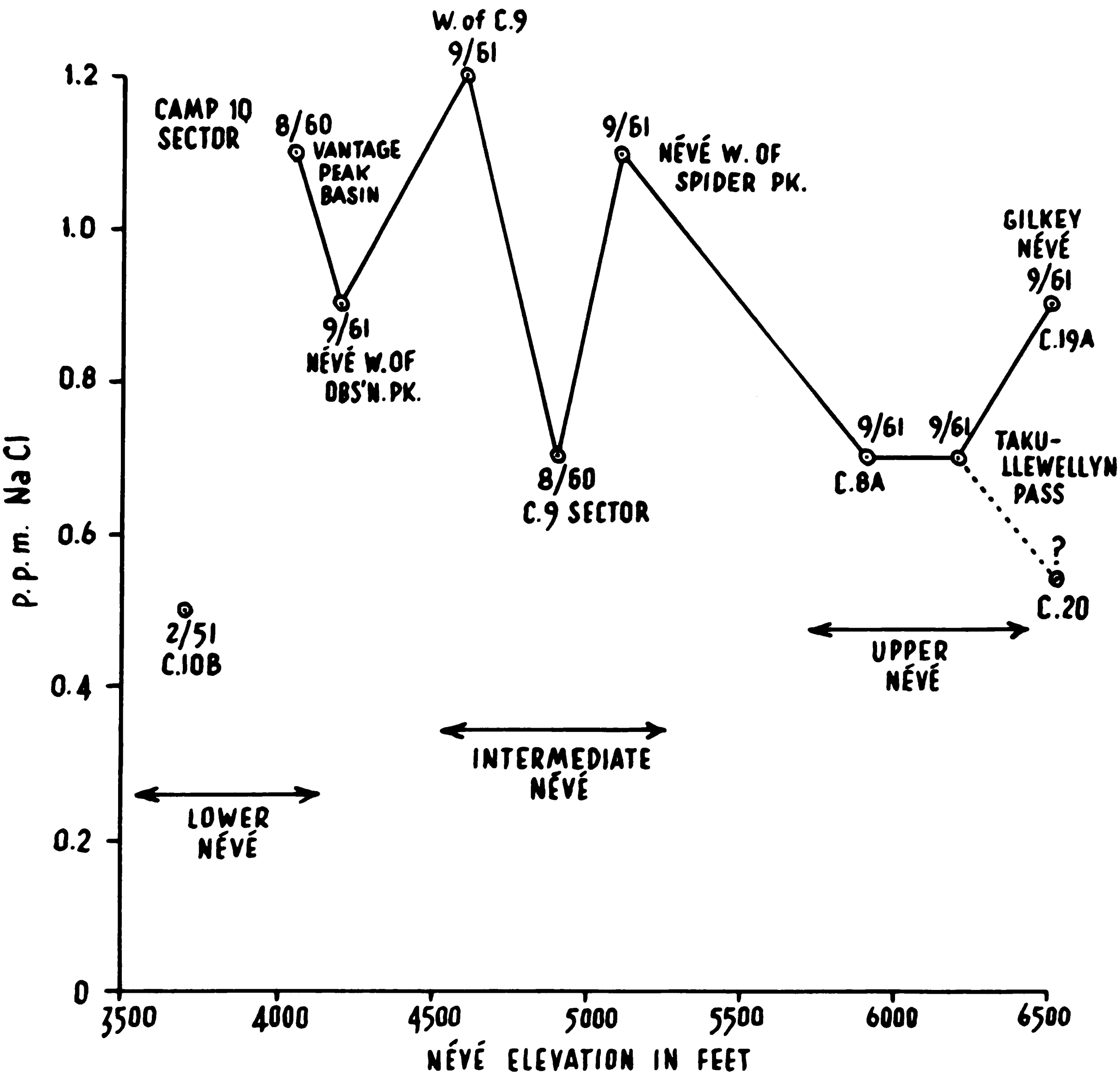


FIG. 13

DISTRIBUTION OF NaCl CONTENT
AT SURFACE
OVER JUNEAU ICEFIELD, ALASKA

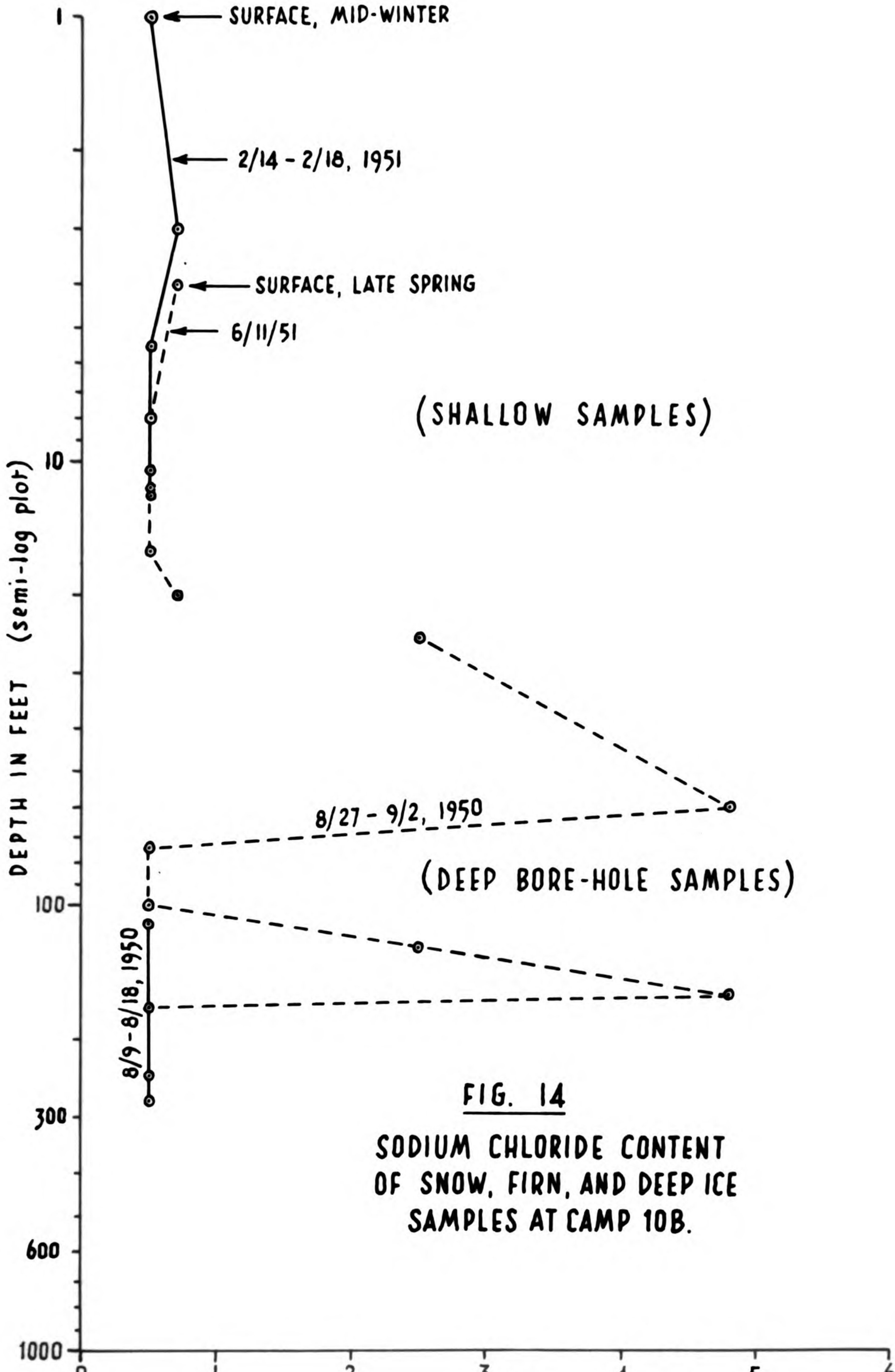


FIG. 14

SODIUM CHLORIDE CONTENT OF SNOW, FIRN, AND DEEP ICE SAMPLES AT CAMP 10B.

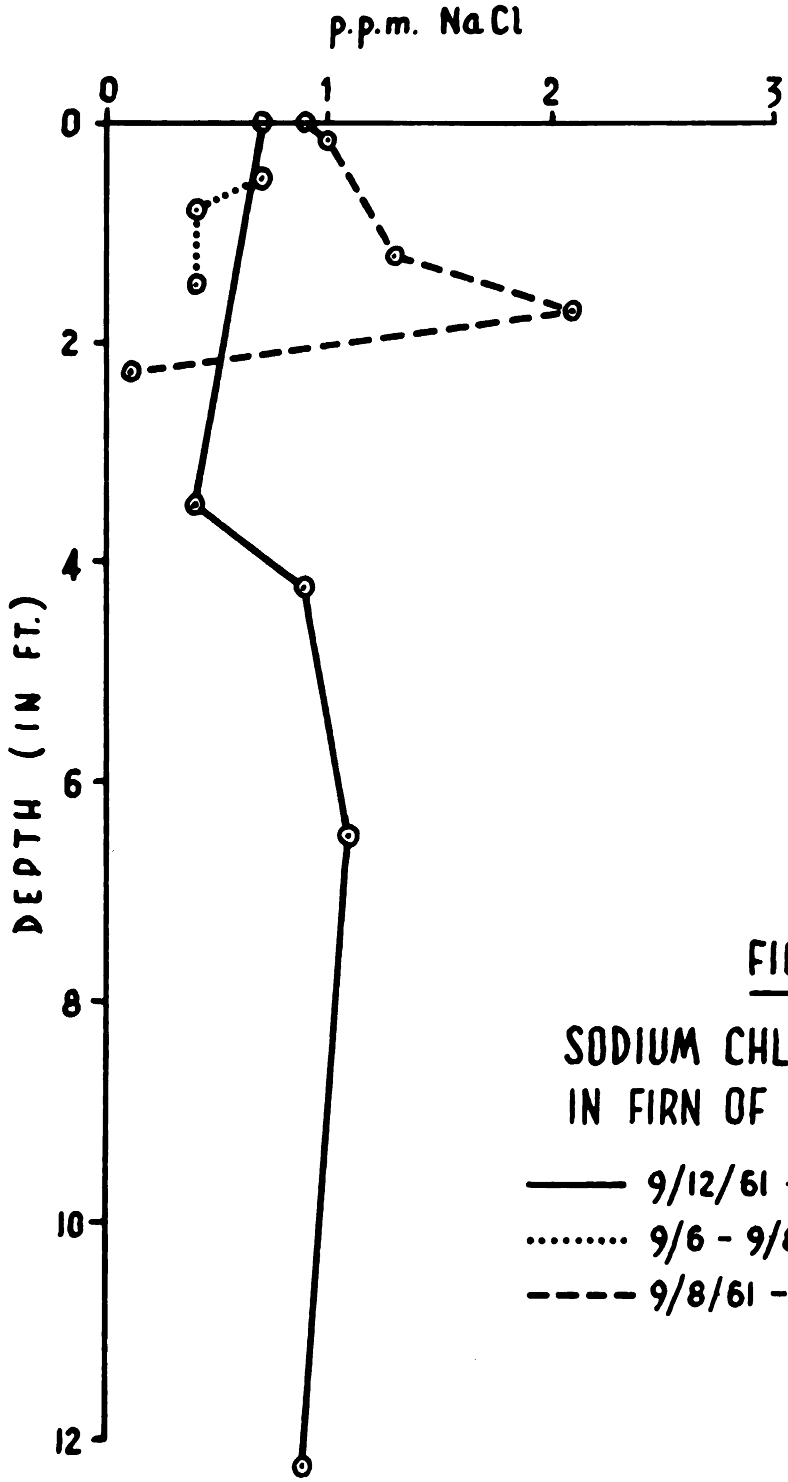


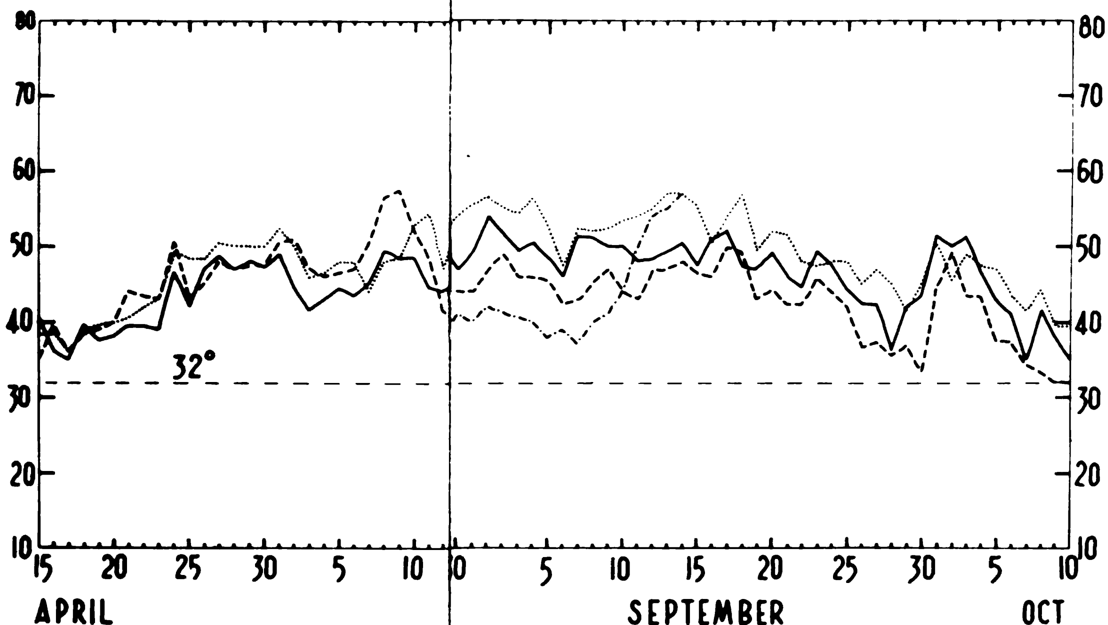
FIG. 15

SODIUM CHLORIDE CONTENT IN FIRN OF CRESTAL NÉVÉ

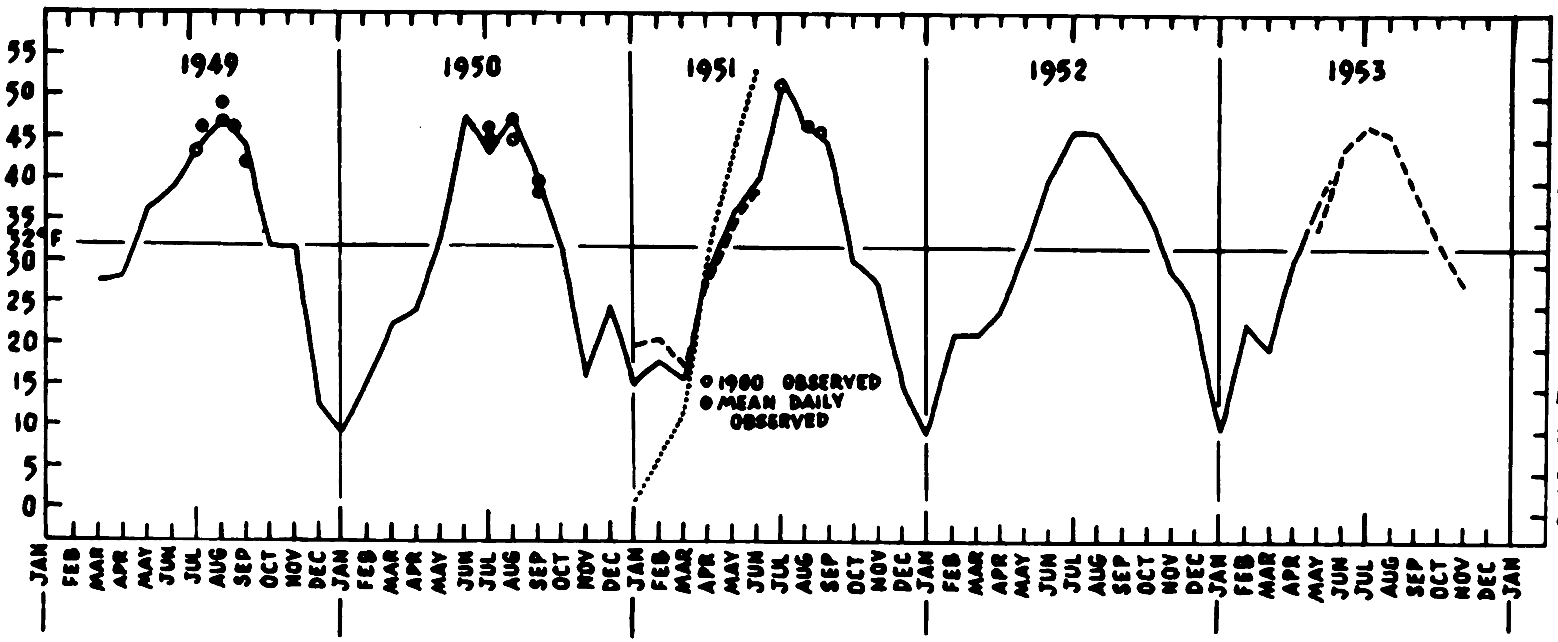
——— 9/12/61 - CAMP 8A - 5950'

········ 9/6 - 9/8/61 - CAMP 8A - 5950'

- - - - 9/8/61 - CAMP 19A - 6500'



80
70
60
50
40
30
20
10
32°
15
20
25
30
5
10
10
5
10
15
20
25
30
5
10
APRIL
SEPTEMBER
OCT



Legend;

Juneau Airport Upper Air

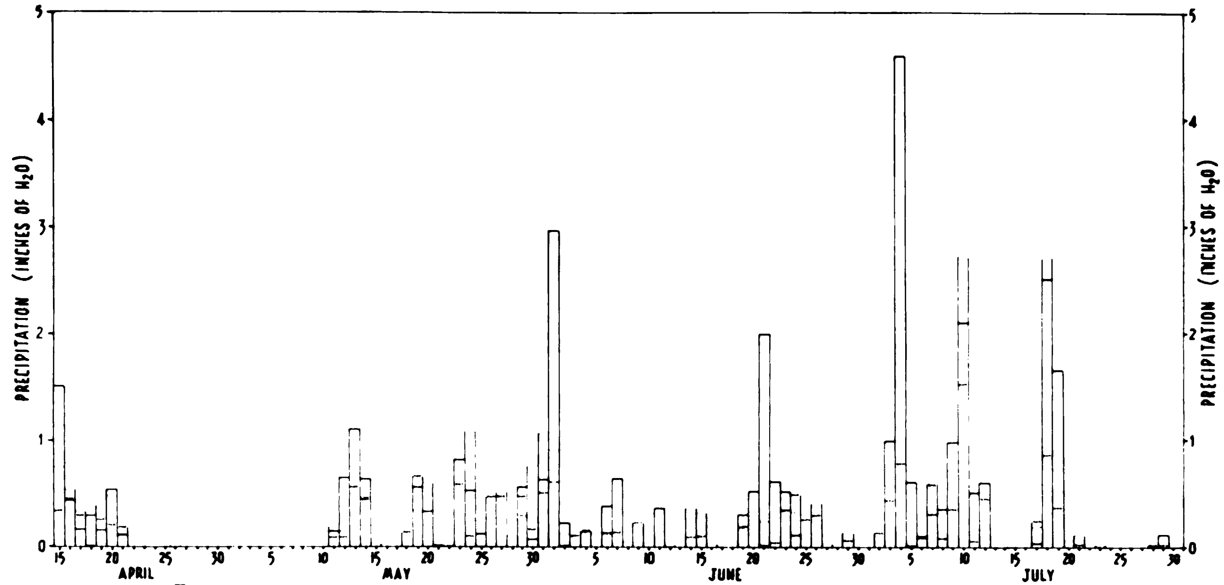
Yakutat Upper Air

Whitehorse Upper Air

o ● Icefield Station, Camp 10. (elevation 3862')

FIG. 17

MEAN MONTHLY TEMPERATURES AT ELEVATION OF CAMP 10, ACCORDING TO RADIOSONDE RECORDS AT JUNEAU. DATA FOR 5-YEAR PERIOD 1949-1953 SHOWING RECORDS FROM ICEFIELD AND COASTAL STATIONS. (after Miller)



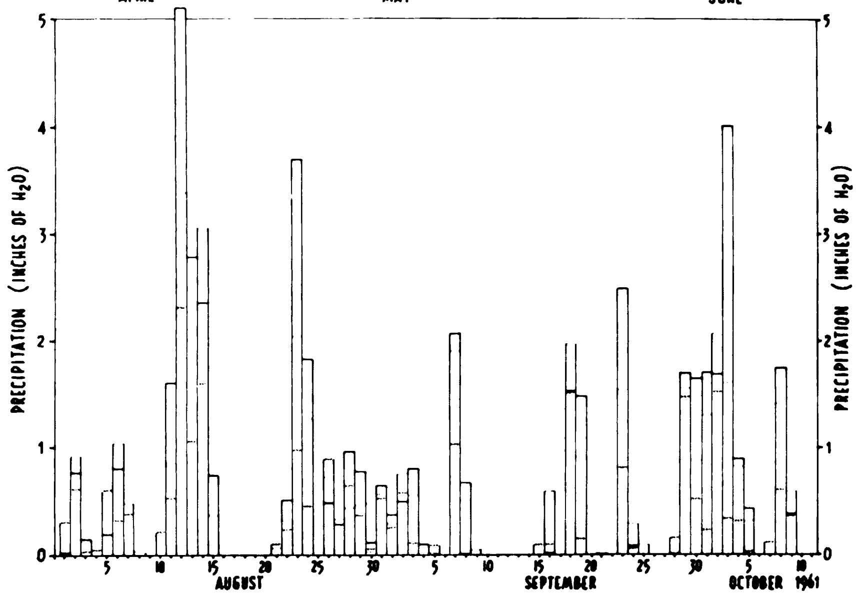
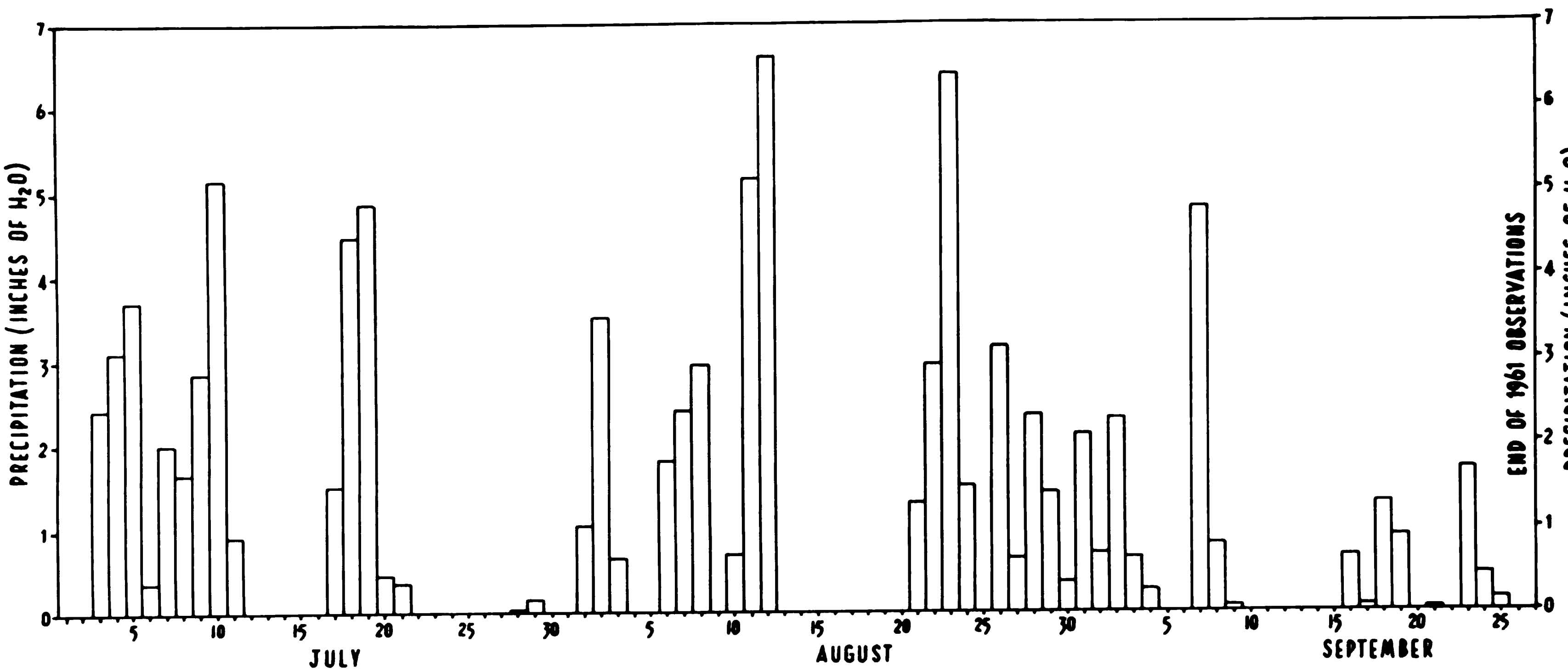


FIG. 18

DAILY PRECIPITATION,
TAKU DISTRICT

---JUNEAU (CITY) - ELEV. 72'
···JUNEAU AIRPORT - ELEV. 17'
—ANNEX CREEK - ELEV. 24'

PERIOD: 15 APRIL - 10 OCTOBER, 1961



<u>FIG. 19</u> DAILY PRECIPITATION, MT. JUNEAU SITE, ELEV.-3600'
PERIOD: 1 JULY - 27 SEPTEMBER, 1961

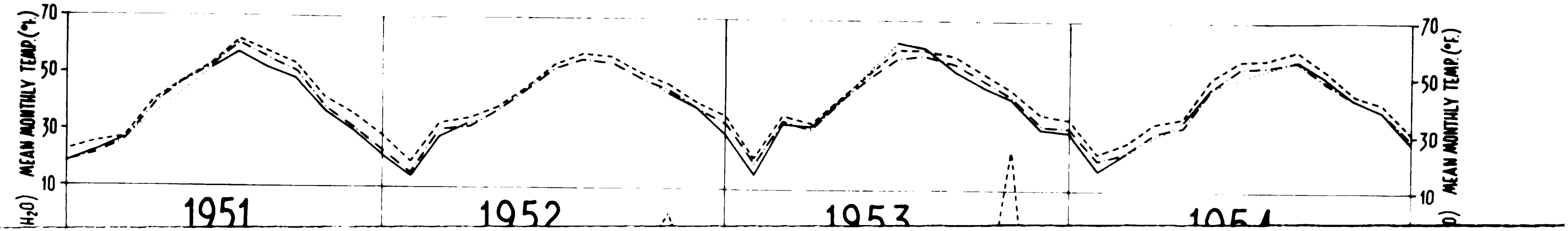


FIG. 20 MONTHLY MEAN TEMPERATURE AND PRECIPITATION
TAKU DISTRICT, ALASKA, 1951-1961.

JUNEAU (CITY) - ELEV. 72'
JUNEAU AIRPORT - ELEV. 17'
ANNEX CREEK - ELEV. 24'
Extrapolated

FIG. 21

ANNUAL MEAN and JANUARY MEAN TEMPERATURE CURVES for ANNEX CREEK, JUNEAU, and JUNEAU AIRPORT, ALASKA, 1940-1961

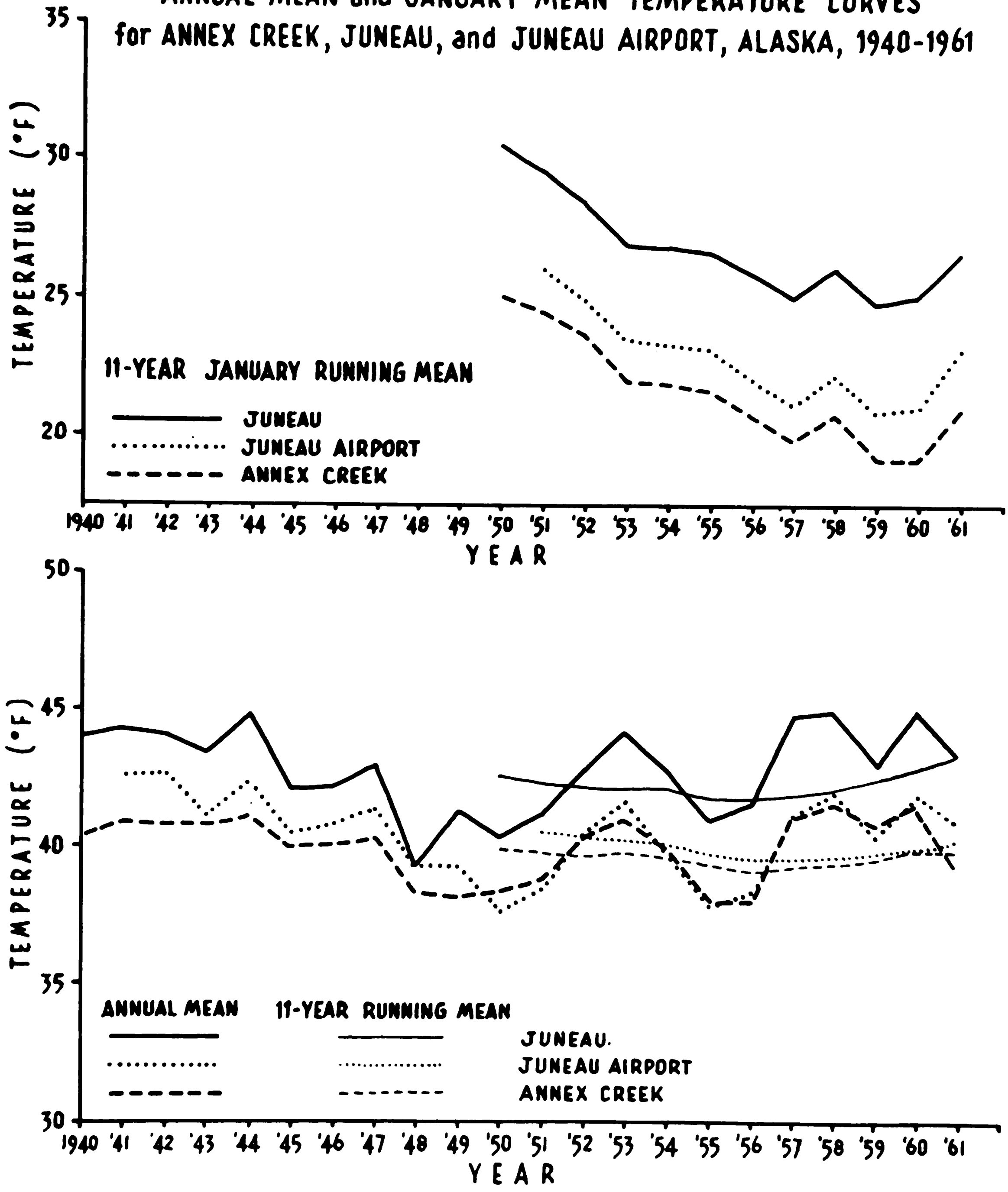
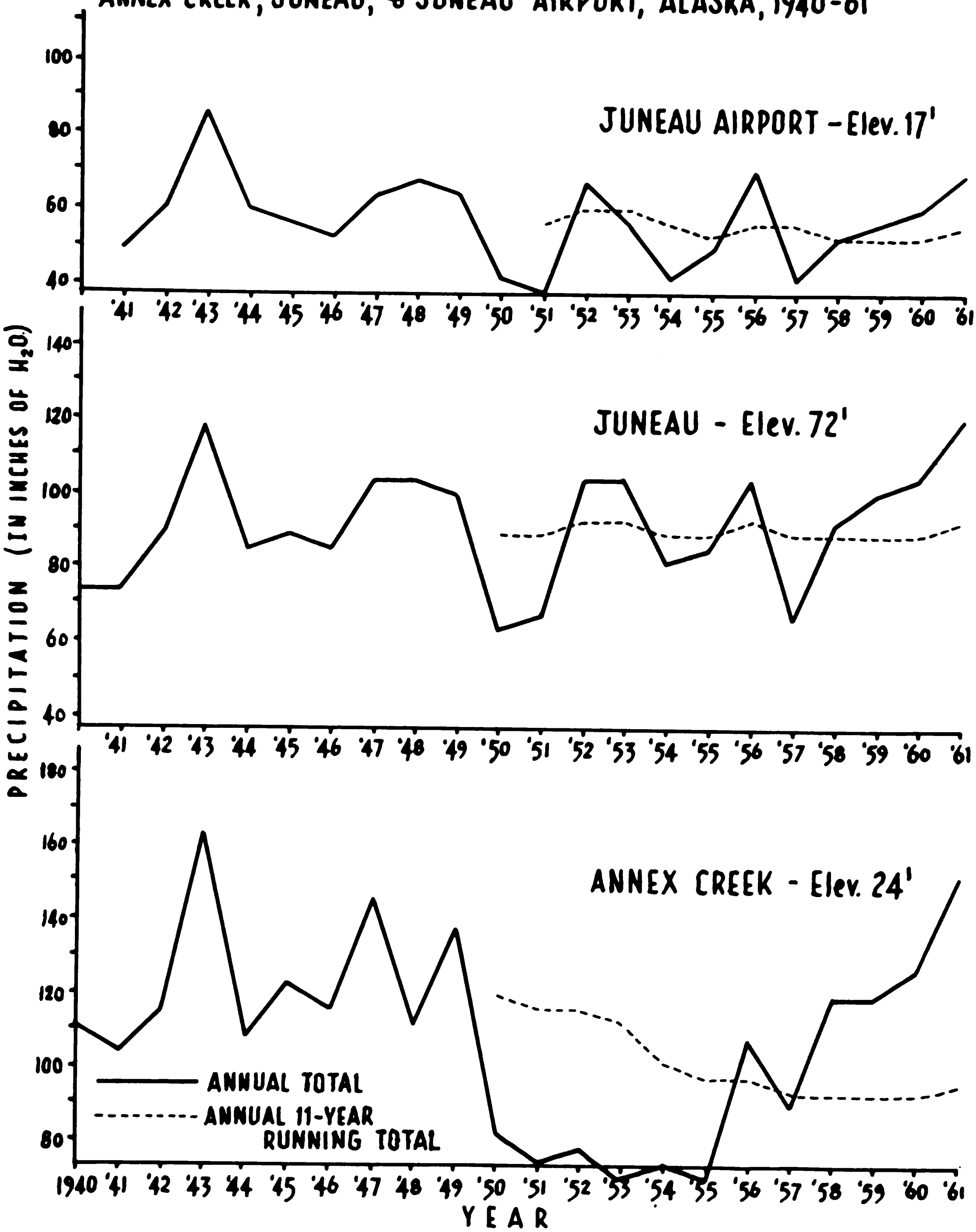
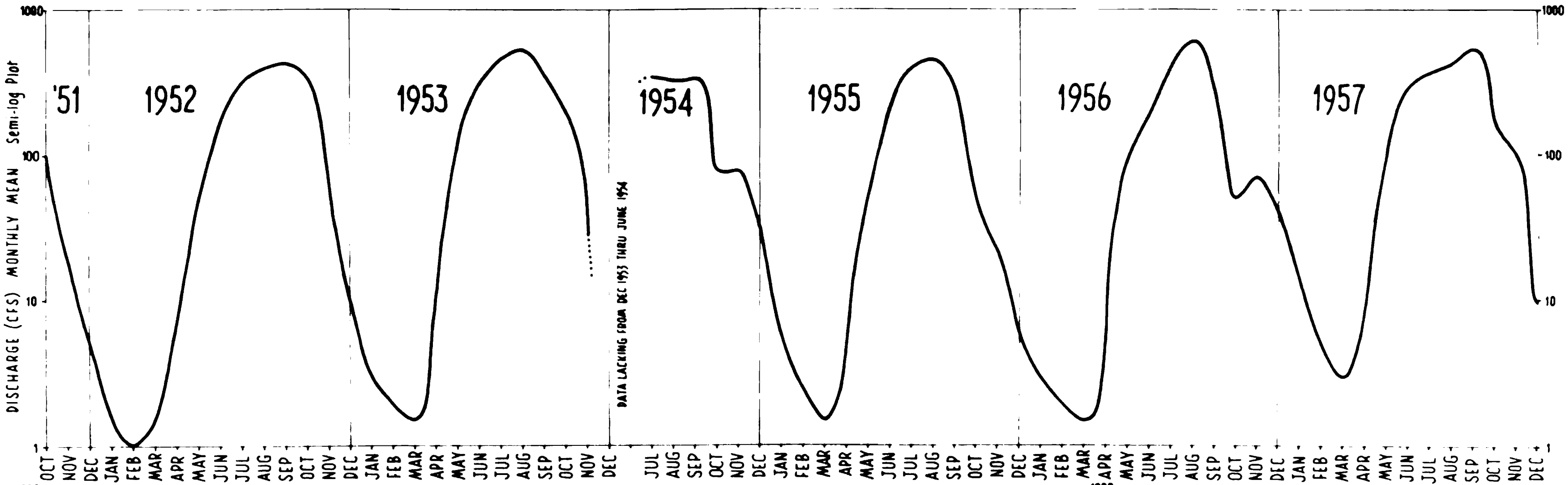


FIG. 22

ANNUAL TOTAL PRECIPITATION
ANNEX CREEK, JUNEAU, & JUNEAU AIRPORT, ALASKA, 1940-61





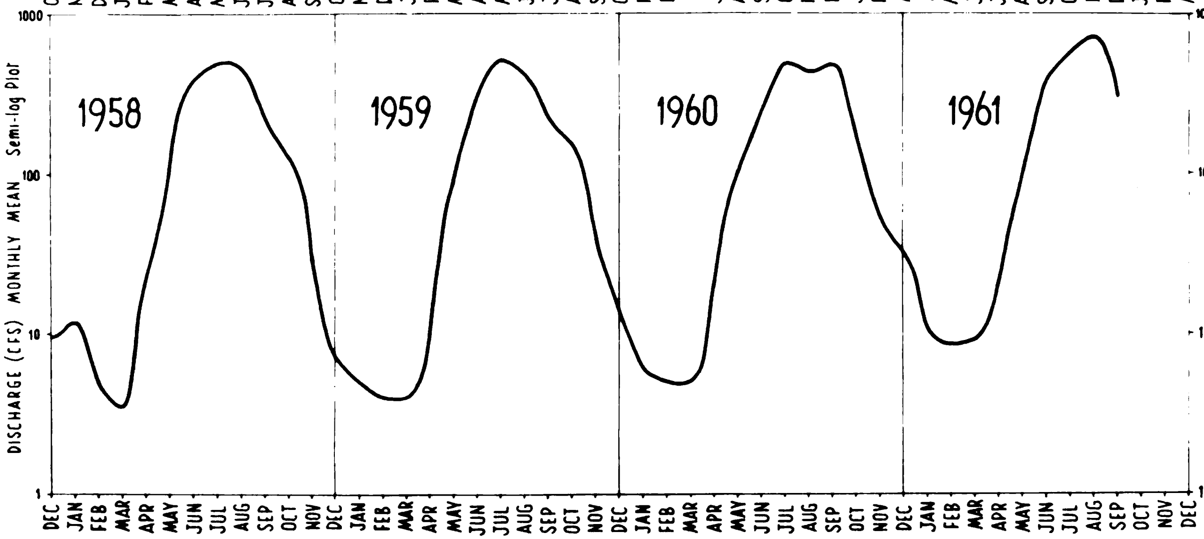


FIG 23

10-YEAR RUNOFF CURVE FOR LEMON CREEK
SHOWING MONTHLY MEAN DISCHARGE RATES

FOR PERIOD: OCTOBER, 1951 THROUGH SEPTEMBER, 1961

LEMON CREEK GAGING STATION, USGS
Elev. 600 feet
JUNEAU ICEFIELD, ALASKA

FIG. 24

MEAN ANNUAL DISCHARGE

LEMON CREEK (Glacier Gaging Site) JUNEAU ICEFIELD, ALASKA, 1951-1961.

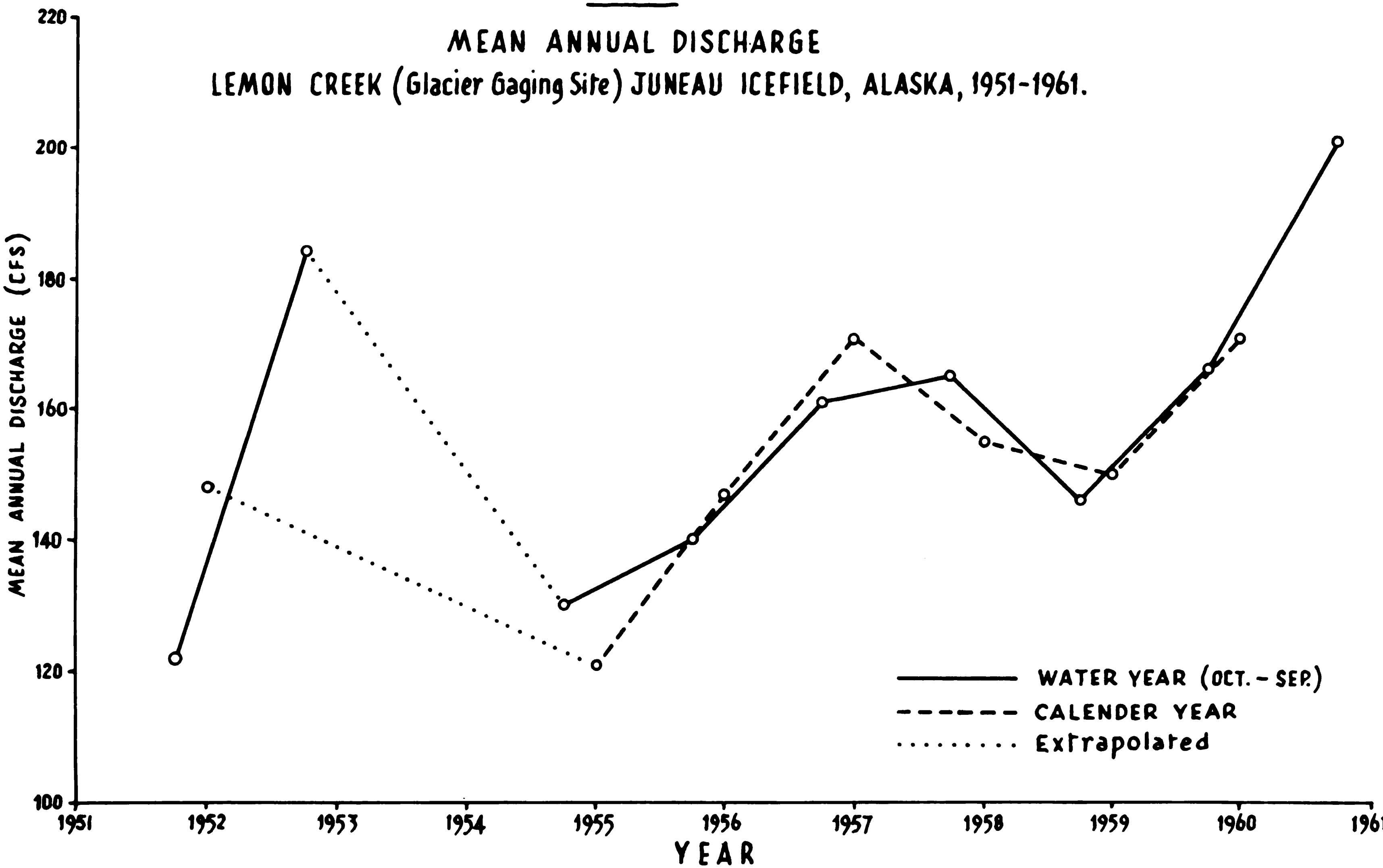
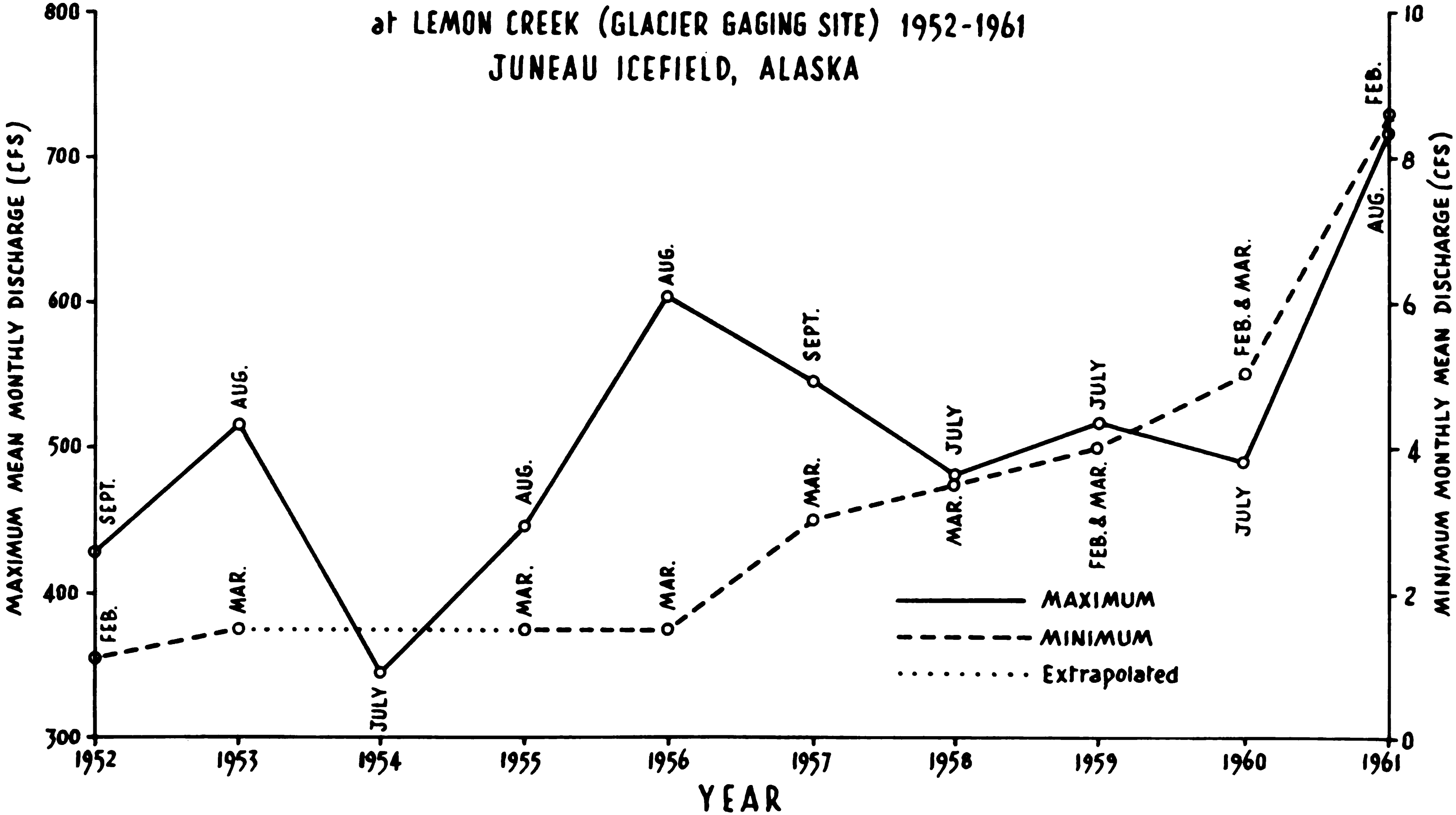


FIG. 25

MAXIMUM and MINIMUM ANNUAL MEAN DISCHARGE RATES
at LEMON CREEK (GLACIER GAGING SITE) 1952-1961
JUNEAU ICEFIELD, ALASKA



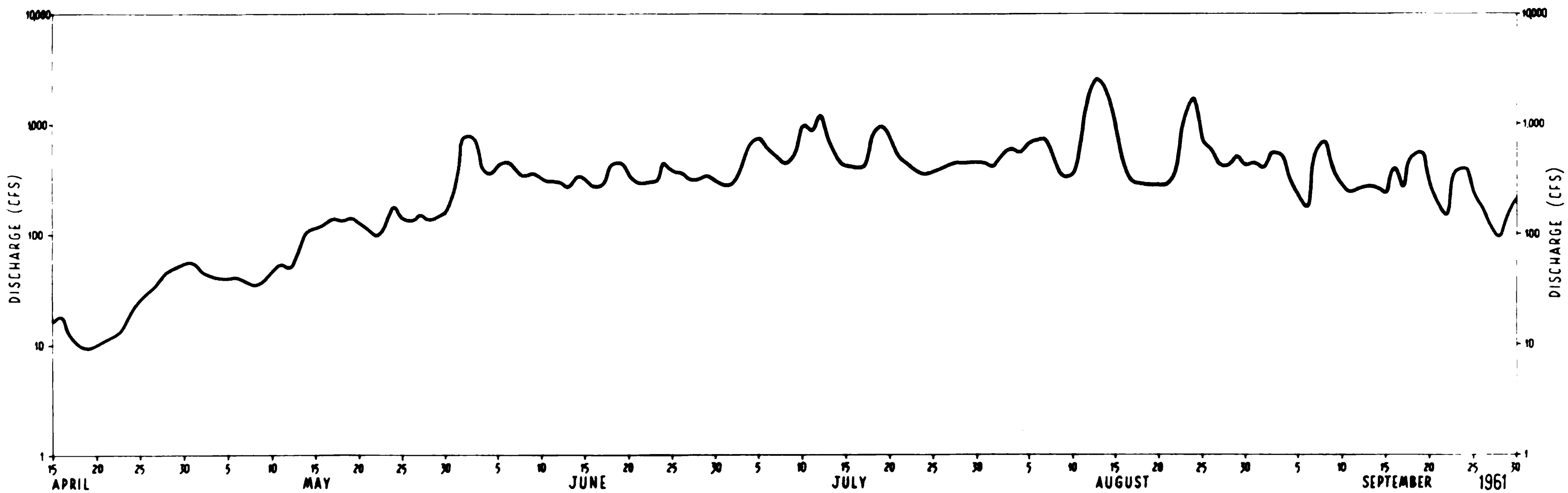


FIG.26

LEMON CREEK RUNOFF, SPRING-SUMMER, 1961
DAILY MEAN DISCHARGE RATES
FOR PERIOD 15 APRIL - 30 SEPTEMBER
Data from Lemon Creek Gaging Station, Elev. 600'
JUNEAU ICEFIELD, ALASKA

Fig. 27 Juneau, Alaska B-1 and B-2 Quadrangles (1:63,360) showing the Lemon Glacier, the Boundary of its Drainage Basin, and the Lemon Creek Gauging Site.

X. APPENDED DATA

APPENDIX 1

Camp 8A - Thermal Bore Drilling Rate Readings, 1961

elev. 5950 feet

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
8/29/61	1815			22	00	Starting point in bottom
	1845	1	05	23	05	of hand auger hole.
	1915	1	10	25	03	
	1945	1	07	26	10	
	2015	1	06	28	04	
	2045	1	08	30	00	
	2115	1	11	31	11	
	2145	2	02	34	01	
	2215	1	11	36	00	
	2245	0	04	36	04	
	2315	2	00	38	04	
	2345	0	05	38	09	
8/30/61	0015	2	08	41	05	
	0045	2	05	43	10	
	0115	2	01	45	11	
	0145	2	08	48	07	
	0215	0	07	49	02	These two readings obscured
	0245	3	00	52	02	by rope being caught.
	0315	1	09	53	11	
	0345	2	02	56	01	
	0415	2	08	58	09	
	0445	1	08	60	05	
	0515	2	02	62	07	
	0545	2	08	65	03	
	0615	0	08	65	11	
	0645	1	07	67	06	
	0715	1	09	69	03	
	0745	1	11	71	02	
	0815	2	00	73	02	
	0845	1	01	74	03	
	0915	1	08	75	11	
	0945	1	03	77	02	
	1015	1	10	79	00	
	1045	1	08	80	08	
	1115	2	00	82	08	
	1145	0	09	83	05	
	1245	1	00	85	11	
	1315	1	03	87	02	

Camp 8A - Thermal Bore Drilling Rate Readings, 1961 (cont.)

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
8/30/61	Brought forward			87	02	
	1345	0	08	87	10	
	1415	1	01	88	11	
	1445	0	06	89	05	
	1515	0	10	90	03	
	1545	0	07	90	10	
	1615	1	03	92	01	
	1645	1	07	93	08	
	1715	1	05	95	01	
	1745	0	06	95	07	
	1815	0	05	96	00	
	1845	0	03	96	03	
	1915	0	07	96	10	
	1945	0	10	97	08	
	2015	0	06	98	02	
	2045	0	07	98	09	
	2115	0	07	99	04	
	2145	0	07	99	11	Generator left running, no
	2215	0	07	100	06	reading taken, for a total
	2245	0	07	101	01	advance of 4 ft.
	2315	0	07	101	08	
	2345	0	06	102	02	
8/31/60	0015	0	00	102	02	Generator not running
	0045	0	00	102	02	during this period.
	0115	0	08	102	10	
	0145	0	04	103	02	
	0215	0	07	103	09	
	0245	0	04	104	01	
	0315	0	04	104	05	
	0345	0	06	104	11	
	0415	0	05	105	04	
	0445	0	01	105	05	
	0515	0	05	105	10	
	0545	0	05	106	03	
	0615	0	10	107	01	
	0645	0	04	107	05	
	0715	0	00	107	05	
	0745	0	06	107	11	
	0815	0	01	108	00	
	0845	0	06	108	06	
	0915	0	01	108	07	
	0945	0	04	108	11	
	1015	0	03	109	02	

Camp 8A - Thermal Bore Drilling Rate Readings, 1961 (cont.)

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
8/31/60	Brought forward			109	02	
	1045	0	04	109	06	
	1115	0	04	109	10	
	1145	0	03	110	01	
	1215	0	06	110	07	
	1245	0	03	110	10	
	1315	0	04	111	02	
	1345	0	04	111	06	
	1415	0	04	111	10	
	1445	0	03	112	01	
	1515	0	04	112	05	
	1545	0	04	112	09	
	1615	0	04	113	01	
	1645	0	06	113	07	
	1715	0	03	113	10	
	1745	0	04	114	02	
	1815	0	04	114	06	
	1845	0	06	115	00	
	1915	0	04	115	04	
	1945	0	03	115	07	
	2015	0	03	115	10	
	2045	0	03	116	01	Generator left running
	2115	0	03	116	04	for total advance
	2145	0	03	116	07	of 1' 8".
	2215	0	03	116	10	
	2245	0	02	117	00	
	2315	0	00	117	00	Generator not running
	2345	0	00	117	00	during this period.
9/1/61	0015	0	03	117	03	
	0045	0	03	117	06	
	0115	0	01	117	07	
	0145	0	01	117	08	
	0215	0	03	117	11	
	0245	0	06	118	05	
	0315	0	02	118	07	
	0345	0	03	118	10	
	0415	0	02	119	00	
	0445	0	06	119	06	
	0515	0	03	119	09	
	0545	0	02	119	11	
	0615	0	05	120	04	
	0645	0	04	120	08	

Camp 8A - Thermal Bore Drilling Rate Readings, 1961 (cont.)

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
9/1/61	Brought forward			120	08	
	0715	0	04	121	00	
	0745	0	04	121	04	
	0815	0	01	121	05	
	0845	0	03	121	08	
	0915	0	04	122	00	
	0945	0	01	122	01	
	1015	0	02	122	03	
	1045	0	04	122	07	
	1115	0	04	122	11	
	1145	0	02	123	01	
	1215	0	02	123	03	
	1245	0	02	123	05	
	1315	0	05	123	10	
	1345	0	03	124	01	
	1415	0	03	124	04	
	1445	0	04	124	08	
	1515	0	03	124	11	
	1545	0	01	125	00	
	1615	0	04	125	04	
	1645	0	03	125	07	
	1715	0	04	125	11	
	1745	0	02	126	01	
	1815	0	02	126	03	
	1845	0	04	126	07	
	1915	0	05	127	00	
	1945	0	04	127	04	Generator left running
	2015	0	05	127	09	for total advance
	2045	0	04	128	01	of 2' 6".
	2115	0	04	128	05	
	2145	0	04	128	09	
	2215	0	00	128	09	
	2245	0	00	128	09	Generator not running
	2315	0	00	128	09	during this period.
	2345	0	00	128	09	
9/2/61	0015	0	03	129	00	
	0045	0	03	129	03	
	0115	0	02	129	05	
	0145	0	02	129	07	
	0215	0	02	129	09	
	0245	0	03	130	00	
	0315	0	03	130	03	

Camp 8A - Thermal Bore Drilling Rate Readings, 1961 (cont.)

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
9/2/61	Brought forward			130	03	
	0345	0	02	130	05	
	0415	0	03	130	08	
	0445	0	04	131	00	
	0515	0	02	131	02	
	0545	0	06	131	08	
	0615	0	00	131	08	
	0645	0	02	131	10	
	0715	0	03	132	01	
	0745	0	02	132	03	
	0815	0	02	132	05	
	0845	0	02	132	07	
	0915	0	02	132	09	
	0945	0	04	133	01	
	1015	0	02	133	03	
	1045	0	05	133	08	
	1115	0	02	133	10	
	1145	0	04	134	02	
	1215	0	00	134	02	
	1245	0	03	134	05	
	1315	0	06	134	11	
	1345	0	03	135	02	
	1415	0	02	135	04	
	1445	0	02	135	06	
	1515	0	01	135	07	
	1545	0	02	135	09	
	1615	0	02	135	11	
	1645	0	02	136	01	
	1715	0	02	136	03	
	1745	0	04	136	07	
	1815	0	03	136	10	
	1845	0	03	137	01	
	1915	0	03	137	04	
	1945	0	03	137	07	
	2015	0	05	138	00	
	2045	0	05	138	05	
	2115	0	05	138	10	Generator left running
	2145	0	05	139	03	for total advance of
	2215	0	05	139	08	2' 11".
	2245	0	05	140	01	
	2315	0	05	140	06	

Camp 8A - Thermal Bore Drilling Rate Readings, 1961 (cont.)

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
9/2/61	Brought forward			140	06	
	2345	0	00	140	06	Generator not running.
9/3/61	0015	0	00	140	06	No advance, rope
	----	-	--	---	--	frozen in hole.
	0745	0	00	140	06	
	0815	0	06	141	00	
	0845	0	04	141	04	
	0915	0	02	141	06	
	0945	0	02	141	08	
	1015	0	02	141	10	
	1045	0	02	142	00	
	1115	0	02	142	02	
	1145	0	02	142	04	
	1215	0	02	142	06	
	1245	0	03	142	09	
	1315	0	03	143	00	
	1345	0	01	143	01	
	1415	0	04	143	05	
	1445	0	06	143	11	
	1515	0	05	144	04	
	1545	0	04	144	08	
	1615	0	02	144	10	
	1645	0	05	145	03	
	1715	0	04	145	07	
	1745	0	01	145	08	
	1815	0	01	145	09	
	1845	0	02	145	11	
	1915	0	02	146	01	
	1945	0	03	146	04	Generator left running
	2015	0	02	146	06	for total advance of
	2045	0	03	146	09	1' 4''.
	2115	0	02	146	11	
	2145	0	02	147	01	
	2215	0	00	147	01	Generator not running
	2245	0	00	147	01	during this period.
	2315	0	00	147	01	
	2345	0	04	147	05	
9/4/61	0015	0	02	147	07	
	0045	0	02	147	09	
	0115	0	03	148	00	
	0145	0	04	148	04	

Camp 8A - Thermal Bore Drilling Rate Readings, 1961 (cont.)

Date	Time	Advance Ft.	Advance In.	Depth Ft.	Depth In.	Remarks
9/4/61	Brought forward			148	04	
	0215	0	04	148	08	
	0245	0	04	149	00	
	0315	0	01	149	01	
	0345	0	01	149	02	
	0415	0	00	149	02	
	0445	0	02	149	04	
	0515	0	02	149	06	
	0545	0	02	149	08	
	0615	0	02	149	10	
	0645	0	02	150	00	
	0715	0	02	150	02	
	0745	0	02	150	04	
	0815	0	01	150	05	
	0845	0	02	150	07	
	0915	0	01	150	08	
	0945	0	02	150	10	
	1015	0	02	151	00	
	1045	0	02	151	02	
	1115	-	--	---	--	Rope frozen in hole; drilling completed.

APPENDIX 2

Camp 8A - Thermistor Measurements - 151-Foot Bore-Hole

Elev. 5950 feet   Cable 333   T = °C, R = ohms

	DATE	9/5/61				9/6/61				9/8/61			
	TIME	1600 hrs.		1900 hrs.		0900 hrs.		1900 hrs.		1230 hrs.		1830 hrs.	
	Therm. No.	R	T	R	T	R	T	R	T	R	T	R	T
1	4300	2580	+4.16	5070	-8.35	1512	+15.49	3903	-3.57	1741	+12.52	2809	+2.80
2	4301	3207	-0.42	3218	-0.49	3340	- 1.21	3303	-1.00	3134	+ 0.02	3138	-0.01
3*	4302	3865	-1.41	3785	-1.01	3831	- 1.24	3727	-0.71	3633	- 0.22	3633	-0.22
4	4303	3491	-1.57	3434	-1.25	3381	- 0.95	3352	-0.79	3311	- 0.55	3310	-0.55
5	4304	3663	-2.18	3595	-1.81	3492	- 1.26	3465	-1.11	3431	- 0.92	3430	-0.92
6	4305	3713	-2.77	3638	-2.38	3494	- 1.60	3466	-1.44	3399	- 1.06	3392	-1.02
7	4306	3445	-1.28	3399	-1.02	3315	- 0.55	3310	-0.52	3285	- 0.36	3284	-0.36
8	4307	3311	-0.74	3270	-0.50	3210	- 0.14	3212	-0.16	3207	- 0.13	3206	-0.12
9	4308	3423	-0.68	3377	-0.41	3319	- 0.09	3321	-0.10	3315	- 0.07	3314	-0.06
10	4309	3351	-0.69	3303	-0.42	3241	- 0.05	3244	-0.06	3242	- 0.05	3242	-0.05
11	4310	3387	-0.75	3333	-0.43	3275	- 0.09	3279	-0.11	3274	- 0.08	3273	-0.08
12	4311	3452	-0.71	3396	-0.40	3335	- 0.05	3337	-0.06	3334	- 0.05	3334	-0.05
13	4312	3331	-0.72	3275	-0.40	3216	- 0.05	3214	-0.04	3216	- 0.05	3213	-0.03
14	4313	3374	-0.73	3330	-0.48	3259	- 0.05	3264	-0.08	3256	- 0.04	3257	-0.04
15	4314	3352	-0.72	3316	-0.51	3233	- 0.04	3238	-0.07	3235	- 0.05	3234	-0.04
16	4315	3537	-0.74	3501	-0.55	3420	- 0.09	3424	-0.11	3416	- 0.07	3420	-0.09
17	4316	3496	-0.75	3457	-0.51	3372	- 0.04	3375	-0.05	3374	- 0.05	3373	-0.05
18	4317	3355	-0.75	3301	-0.44	3232	- 0.03	3238	-0.07	3234	- 0.04	3234	-0.04

* Top of bore hole.

Camp 8A - Thermistor Measurements - 151-Foot Bore-Hole (cont.)

	DATE	9/9/61				9/10/61				9/11/61			
	TIME	0900 hrs.		1850 hrs.		1100 hrs.		1800 hrs.		1130 hrs.		1805 hrs.	
	Therm. No.	R	T	R	T	R	T	R	T	R	T	R	T
1	4300	2148	+8.18	3876	-3.44	0896	+27.05	1738	+12.55	1203?	+20.44	1731	+12.64
2	4301	3135	+0.01	3140	-0.02	3092	+ 0.28	3129	+ 0.05	3043	+ 0.59	3124	+ 0.08
3*	4302	3632	-0.22	3626	-0.19	3618	- 0.15	3618	- 0.15	3616	- 0.13	3606	- 0.08
4	4303	3307	-0.53	3326	-0.64	3301	- 0.49	3303	- 0.51	3296	- 0.47	3302	- 0.50
5	4304	3422	-0.87	3414	-0.83	3407	- 0.79	3408	- 0.79	3403	- 0.76	3405	- 0.77
6	4305	3381	-0.96	3377	-0.94	3366	- 0.88	3364	- 0.87	3356	- 0.82	3357	- 0.82
7	4306	3282	-0.35	3281	-0.35	3280	- 0.34	3278	- 0.33	3276	- 0.31	3280	- 0.34
8	4307	3208	-0.13	3208	-0.13	3208	- 0.13	3206	- 0.12	3207	- 0.13	3211	- 0.15
9	4308	3317	-0.08	3317	-0.08	3317	- 0.08	3315	- 0.07	3316	- 0.07	3319	- 0.09
10	4309	3243	-0.06	3243	-0.06	3243	- 0.06	3242	- 0.05	3243	- 0.06	3246	- 0.08
11	4310	3274	-0.08	3273	-0.08	3274	- 0.08	3273	- 0.08	3274	- 0.08	3278	- 0.11
12	4311	3338	-0.07	3336	-0.06	3338	- 0.07	3335	- 0.05	3336	- 0.06	3340	- 0.08
13	4312	3214	-0.04	3215	-0.04	3215	- 0.04	3215	- 0.04	3216	- 0.05	3218	- 0.06
14	4313	3257	-0.04	3258	-0.05	3258	- 0.05	3259	- 0.05	3259	- 0.05	3262	- 0.07
15	4314	3236	-0.06	3234	-0.04	3236	- 0.06	3235	- 0.05	3236	- 0.06	3238	- 0.07
16	4315	3421	-0.09	3421	-0.09	3423	- 0.11	3423	- 0.11	3422	- 0.10	3426	- 0.12
17	4316	3375	-0.05	3373	-0.05	3375	- 0.05	3374	- 0.05	3374	- 0.05	3377	- 0.07
18	4317	3235	-0.05	3234	-0.04	3235	- 0.05	3235	- 0.05	3235	- 0.05	3238	- 0.07

* Top of bore hole.

Camp 8A - Thermistor Measurements - 151-Foot Bore-Hole (cont.)

	DATE / TIME	9/12/61 1500 hrs.		9/13/61 1100 hrs.	
	Therm. No.	R	T	R	T
1	4300	1359	+17.78	1561	+14.82
2	4301	3021	+ 0.73	3041	+ 0.60
3*	4302	3600	- 0.05	3598	- 0.04
4	4303	3306	- 0.52	3293	- 0.44
5	4304	3394	- 0.71	3391	- 0.71
6	4305	3349	- 0.78	3341	- 0.75
7	4306	3277	- 0.32	3274	- 0.30
8	4307	3209	- 0.14	3207	- 0.13
9	4308	3318	- 0.08	3316	- 0.07
10	4309	3244	- 0.06	3242	- 0.05
11	4310	3276	- 0.09	3274	- 0.08
12	4311	3338	- 0.07	3336	- 0.06
13	4312	3217	- 0.05	3215	- 0.04
14	4313	3260	- 0.06	3259	- 0.05
15	4314	3237	- 0.06	3235	- 0.05
16	4315	3426	- 0.12	3423	- 0.11
17	4316	3376	- 0.06	3374	- 0.05
18	4317	3236	- 0.06	3235	- 0.05

* Top of bore hole.

APPENDIX 3

Camp 8A - Thermistor Measurements - 60-Foot Bore-Hole

T = °C
R = ohms

Elev. 5950 feet

Cable 332

	DATE / TIME	9/5/61 1600 hrs.		9/5/61 1900 hrs.		9/6/61 0900 hrs.		9/9/61 1850 hrs.		9/10/61 1130 hrs.	
	Therm. No.	R	T	R	T	R	T	R	T	R	T
9	4259									2642	+ 3.65
10	4260									1509	+14.74
11*	4261	4394	-5.26	4037	-3.67	1432	+17.26			1825	+12.11
12	4262	3269	+0.38	3944	-3.23	3043	+ 1.77	3338	-0.04	3338	- 0.04
13	4263	3528	-0.25	3501	-0.10	3503	- 0.12	3500	-0.10	3499	- 0.09
14	4264	3441	-0.21	3415	-0.06	3411	- 0.03	3414	-0.06	3412	- 0.03
15	4265	3222	-0.20	3196	-0.05	3196	- 0.05	3192	-0.03	3192	- 0.03
16				8.980		8.671		2.401		2.77	
17				8.960		8.645		2.414		2.78	

* Top of bore hole.

Camp 8A - Thermistor Measurements - 60-Foot Bore-Hole (cont.)

	DATE / TIME	9/10/61 1730 hrs.		9/11/61 1300 hrs.		9/11/61 1730 hrs.		9/12/61 1530 hrs.		9/13/61 1030 hrs.	
	Therm. No.	R	T	R	T	R	T	R	T	R	T
9	4259	2975	+1.30	2289	+ 6.53	3041	+0.89	2819	+2.37	2924	+1.65
10	4260	2819	+1.98	1906	+ 9.85	2947	+1.12	2704	+2.80	2221	+6.73
11*	4261	3102	+1.40	936	+26.69	3044	+1.78	2457	+6.02	2171	+8.53
12	4262	3336	-0.03	3338	- 0.04	3340	-0.05	3336	-0.03	3336	-0.03
13	4263	3497	-0.08	3500	- 0.10	3501	-0.10	3500	-0.10	3499	-0.09
14	4264	3412	-0.03	3416	- 0.07	3416	-0.07	3415	-0.06	3414	-0.06
15	4265	3190	-0.01	3193	- 0.03	3193	-0.03	3193	-0.03	3193	-0.03
16		2.502		4.34		3.381		3.192		3.56	
17		2.508		4.35		3.365		3.172		3.57	

* Top of bore hole.

APPENDIX 4

Camp 19A - Thermistor Measurements - 60-Foot Bore-Hole

Taku-Gilkey pass
Elev. 6500 feet

Cable 332

T = °C
R = ohms

	DATE / TIME	9/6/61		9/8/61					
		1830 hrs.		1430 hrs.		1615 hrs.		1700 hrs.	
	Therm. No.	R	T	R	T	R	T	R	T
9	4259	3991	-4.32	1631	+13.53	2355	+5.95	2792	+2.57
10	4260	3925	-4.38	1835	+10.64	2528	+4.13	2784	+2.23
11*	4261	4192	-4.37	3315	+ 0.10	3323	+0.06	3327	+0.03
12	4262	3428	-0.54	3336	- 0.03	3337	-0.03	3338	-0.04
13	4263	3593	-0.60	3496	- 0.08	3498	-0.09	3500	-0.10
14	4264	3508	-0.58	3413	- 0.05	3415	-0.06	3414	-0.06
15	4265	3289	-0.60	3192	- 0.03	3191	-0.02	3191	-0.02
16		8.200		5.550		4.910		3.080	
17		7.731		5.520		4.900		3.050	

* Top of bore hole.

APPENDIX 5

Camp 8B - Thermistor Measurements - 30-Foot Bore-Hole

Elev. 5900 feet — Cable 329 — T = °C, R = ohms

DATE / TIME		8/13/60 1900 hrs.		8/13/60 2230 hrs.		8/14/60 1800 hrs.		8/16/60 1700 hrs.	
Depth	Therm. No.	R	T	R	T	R	T	R	T
2 ft.	4255	3066	+0.16	3085	+0.04	2823*	+1.79	2758	+2.26
12 ft.	4256	3243	+0.02	3237	+0.06	3105*	+0.84	3253	-0.04
27 ft.	4257	3269	+0.01	3272	-0.01	3274	-0.02	3275	-0.03

* Shifted vertical position slightly downward due to opening of hole.

APPENDIX 6

Camp 8X - Thermistor Measurements* - 58-Foot Bore-Hole

T = °C

Elev. 6500 feet | Cable 329 | R = ohms

DATE	9/27/58
TIME	1500 hrs.

Therm. No.	Depth	R	T
5	1'	2964	+1.11
6	4'	3411	-1.01
7	8'	3285	-0.87
8	12'	3086	+0.04
9	14'	3244	+0.02
10	16'	3271	0.00

* Site (bore-hole II) in ice 1000' northwest of Camp 8 on ice shoulder; cable jammed in spirally.

Depth is below 1958 ablation surface upon which, on 9/27/58, lies 1.5' of new snow.

APPENDIX 7

Camp 8Y - Thermistor Measurements - 90-Foot Bore-Hole*

Elev. 6700 feet — Cable 329 — T = °C, R = ohms

	DATE	9/24/58				9/25/58			9/26/58				9/27/58	
	TIME	1700 hrs.		2000 hrs.		1900 hrs.			1300 hrs.		1630 hrs.		1000 hrs.	
Therm. No.	Depth	R	T	R	T	R	T	Depth**	R	T	R	T	R	T
1	2'	3328	-0.44	3330	-0.45	3270	-0.10	7'	3251	+0.02	3254	0.00	3255	-0.01
2	5'	3483	-0.09	3411	+0.31	3470	-0.02	10'	3465	+0.01	3467	0.00	3469	-0.01
3	8'	3164	-0.05	3155	+0.01	3154	+0.01	13'	3153	+0.02	3154	+0.01	3153	+0.02
4	12'	3317	-0.04	3312	-0.01	3310	0.00	17'	3308	+0.01	3308	+0.01	3310	0.00
5	17'	3141	-0.03	3136	+0.01	3134	+0.02	22'	3135	+0.01	3135	+0.01	3136	+0.01
6	22'	3236	+0.01	3235	+0.02	3240	-0.01	27'	3233	+0.03	3235	+0.02	3235	+0.02
7	27'	3142	-0.01	3140	0.00	3140	0.00	32'	3137	+0.02	3139	+0.01	3141	-0.01
8	32'	3087	+0.03	3085	+0.04	3083	+0.05	37'	3082	+0.06	3082	+0.06	3084	+0.05
9	42'	3245	+0.01	3244	+0.02	3243	+0.02	47'	3243	+0.02	3244	+0.02	3243	+0.02
10	52'	3270	0.00	3270	0.00	3270	0.00	57'	3268	+0.02	3268	+0.02	3269	+0.01

* Site (bore-hole D) 1000' north of Camp 8 station; cable installed at 1200 hrs. on 9/23/58.

** Cable lowered 5' at 1930 hrs. on 9/25/58.

Depth is below 1958 ablation surface; 9/21/58 snow surface is 5' above 1958 ablation surface.

APPENDIX 8

Camp 8A - Daily Melt-Water Percolation Record, 1961

Elev. 5950 feet (Measured in ml.)

Depth* / Date	Pan A 5 inches	Pan B 28 inches	Pan C 58 inches	Pan D 88 inches
8/25/61	Pans A, B, and C Installed			
26	0	0	0	
27	32	0	0	
28	34	0	0	
29	14	4	0	Pan D Installed
30	0	0	0	0
31	0	0	0	0
9/1/61	14	0	0	0
2	15	3	0	0
3	10	0	0	0
4	7	0	0	0
5	4	0	0	0
6	No Record			
7	No Record			
8	1	3	2	1
9	1	12	4	11
10	125	1	3	1
11	1256	8	1	0
12	1175	6	5	5
13	1074	4	0	0

Date	Time	Pan A	Pan B	Pan C	Pan D
9/4/61	0900	0	0	0	0
	1000	0	0	0	0
	1100	0	0	0	0
	1200	0	0	0	0
	1300	0	0	0	0
	1400	7	0	0	0
	1500	0	0	0	0
	1600	0	0	0	0
	1700	0	0	0	0

* Depth, below 1961 ablation surface.

APPENDIX 9

Camp 8A - Ablation Measurements, 1961

Elev. 5950 feet (in inches of snow or firn)

Date	Stake A	Stake B	Stake C
8/23/61	Installed (late-summer firn)		
25	3.9	3.6	4.0
26	Snow		
9/10/61	Re-marked Stakes (new snow)		
11	1.8	1.5	
12	1.0	0.5	
13	0.4	0.6	

APPENDIX 10

Camp 10 - Ablation Measurements, 1961

Elev. 3650 feet (in inches of firn)

Date	A	B	C	D	E	F	G	H	I
					Stake				
7/24/61	Emplacement of stakes.								
25	1.8	1.6	1.8	1.5	1.3	1.1	0.8	1.4	1.8
26	0.9	1.6	1.6	1.6	1.6	2.3	2.3	2.0	2.8
27	2.1	2.0	1.8	1.6	2.3	2.6	2.0	1.8	3.1
28	1.5	1.5	1.5	1.4	1.6	1.1	1.4	1.5	1.5
29	1.4	2.0	1.4	1.8	1.6	2.0	1.9	2.0	1.8
30	1.8	1.9	1.9	1.5	1.7	1.4	1.8	2.0	1.8
31	1.3	0.9	1.1	0.8	1.7	1.4	1.0	0.8	0.9
8/1/61	0.0	1.4	1.4	2.4	1.7	1.4	1.8	1.8	1.8
2	1.6	1.1	1.1	1.6	1.0	1.3	1.9	1.3	1.3
3	1.9	1.4	1.5	1.4	1.8	1.3	1.6	1.9	1.4
4	1.3	1.5	1.1	1.1	1.8	1.1	1.5	1.5	1.3
5 (morn.)	1.0	1.4	0.6	1.0	1.0	1.0	1.0	1.3	0.9
5 (even.)	1.0	0.9	0.8	0.9	0.9	0.9	0.8	0.8	0.9
6	No measurements taken.								
7 (morn.)	1.8	1.1	0.8	1.4	0.9	0.9	0.9	1.0	1.1
7 (even.)	0.9	0.5	0.4	0.4	0.5	0.3	0.3	0.3	0.4
8	0.9	0.9	1.0	0.6	1.0	0.9	1.3	1.3	1.0
9-13	No measurements taken.								
14	16.9	13.0	10.6						
15-16	No measurements taken.								
17	21.4	12.8	8.1	16.8	16.5	14.4	13.4	13.1	13.8
18	1.2	1.4	1.8	0.8	0.5	0.4	1.0	0.3	1.6
19	1.0	1.3	0.9	1.3	1.3	1.0	1.1	1.5	1.4
20	1.5	1.1	2.1	1.5	1.6	1.0	1.9	2.0	1.5
21-24	No measurements taken.								
25	9.3	7.8	6.9	7.6	7.0	7.5	7.6	6.0	6.4
26	0.8	1.0	1.4						

APPENDIX 11

Camp 9 - Ablation Measurements, 1961

Elev. 4600 feet (in inches of firn)

	Stake							
Date	A	B	C	D	E	F	G	H
8/17/61	Emplacement							
8/27	11.4	9.9	10.0	10.9	10.3	9.1	7.9	10.9

APPENDIX 12

15-Year Firn-Pack Accumulation Statistics for the Crestal Névé, Juneau Icefield Vicinity of Research Sites 8A (5950 feet), 8B (5900 feet), 8D (5700 feet), and 8E (5600 feet) for 1946-61

Budget Year	Annual Increment of Positive Firn Accumulation (feet)		Mean Bulk Density (gm/cc)	Mean Water Equiv. (inches)	Ann. Precip. Total (Sept. -Aug.) Juneau Airport Station (inches of water)
		1961 Data 8A	1961 Data	1961 Data 8A	
1960-61		17.5	0.56	118	71
1953-60:	1960 Data 8E	1961 Data 8D		1961 Data 8D	
1959-60	5.0	4.5	0.55*	30	52
1958-59	2.0	2.7	0.60*	19	58
1957-58	6.0	5.3	0.60*	38	47
1956-57	6.0	6.0	0.62*	45	50
1955-56	2.0	4.0	0.65*	31	54
1954-55	3.0	5.5	0.80*	53	53
1953-54	3.0	6.0	0.85*	61	45
1946-53:	1953 Data 8B	1961 Data 8D	1953 Data	1953 Data 8B	
1952-53	15.0	6.0	0.61	100	62
1951-52	16.0	6.5	0.55	106	46
1950-51	13.5	8.0	0.60	97	39
1949-50	17.0	-	0.61	124	51
1948-49	18.0	-	0.65	140	70
1947-48	11.0	-	0.80	106	49
1946-47	7.0	-	0.88	74	61

* Estimated values based on extrapolated curve similar to that of 1946-53. These figures are to be subjected to refinement during the 1962 summer season.

Statistics previous to 1961 based on field data from M. M. Miller.

APPENDIX 13

Annual Primary Stratification on the Crestal Névé as Measured in 1960-61

Strat. Thickness (in feet of firn)

Strat. Year	Site 8X* 6500 Feet 8/12/60	Site 8C* 5850 Feet 8/13/60	Site E* 5600 Feet 8/13/60	Site 8D* 5700 Feet 9/13/61
1960-61	-	-	-	17.5
1959-60	5.1	11.5	5.0	4.5
1958-59	3.0	3.3	2.0	2.7
1957-58	9.0	6.0	6.0	5.3
1956-57	3.3		6.0	6.0
1955-56	1.3		2.0	4.0
1954-55	2.7		3.0	d.l. 5.5
1953-54	6.0		3.0	v.d.l. 6.0
1952-53	1.3		3.5	v.d.l. 6.0
1951-52	4.0 —— 6*		3.0	v.d.l. 6.5
1950-51	4.5 —— 11*		4.0	8.0 ?
1949-50	6.3 —— 3*		1.5	
1948-49	3.8		d.l. 2.3	
1947-48	3.0		2.3	
1946-47	2.0		4.0	
1945-46	-		1.0 ?	
1944-45	-		1.0 ?	
1943-44	-		1.0 ?	

—— ice stratum

d.l. dirty layer
v.d.l. very dirty layer

* Each site is on a relatively level névé.

APPENDIX 14

Annual Primary Stratification Statistics
for the Intermediate Névé as Measured in 1960-61

Strat. Year	Strat. Thickness (in feet of firn) 5300 Feet* 8/16/60	4900 Feet* 8/17/60	5300 Feet* 1961	4900 Feet* 1961
1960-61	-	-	12.0 (est.)	10.0 (est.)
1959-60	4.0	4.0	-	-
1958-59	4.0	5.0	-	-
1957-58	-	2.0	-	-
1956-57	-	3.0	-	-

* Each site is on a 2° down-glacier gradient.

APPENDIX 15

Annual Primary Stratification Statistics for the Level 3650-Foot Surface on the Lower Neve as Measured in 1950, 1958, and 1960-61

Strat. Year	Strat. Thickness (in feet of firn) 8/19/60	Mean Bulk Density (gm/cc) 8/19/60	Water Equivalent (in inches)	Strat. Thickness (in feet of firn) 6/28/58	Strat. Thickness (in feet of firn) 9/15/50	Water Equivalent (in inches)
1960-61	5.7(meas. 1961)	0.60	41	-		
1959-60	6.3*	0.57	43*	-		
1958-59	3.7	0.61	27	-		
1957-58 d.l.	3.7	0.70	31	11.0**		-
1956-57	2.1	0.80	20	2.5		-
1955-56	2.3	0.80	22	3.5		-
1954-55	1.8	0.91	20	2.0		-
1953-54	3.0	0.84	30	4.5		-
1952-53	2.0	0.80	19	2.5		-
1951-52	2.2	-		2.0+		-
1950-51(neg. year)	0***	-		0		-
1949-50	1.8	-			1.0±	6
1948-49	1.0	-			8.0±	80
1947-48	2.3	-			4.8	34
1946-47	1.0?	-			2.4	22
1945-46	2.0?	-			1.8	14
1944-45					3.9	38
1943-44					2.3	22
1942-43					3.0	30
1941-42					3.0	30

* Measured 8/19/60; subtract ablation after 8/19...i.e. approx. 4 feet of firn.

** Approx. 2 feet remained at end of 1958 ablation season.

*** Multiple ablation surface.

APPENDIX 16

Firn-Pack Statistics for the Gilkey Névé, Site 19A
6500-Foot Level Surface North of Mt. Ogilvie, 1961*

Strat. Year and Firn Increment	Structure	Depth (in feet)	Remarks
Beginning of 1961-62 Accumulation	New Snow	0-1	
	1" Ice Stratum		
	Old Snow	1-2	
	4" Depth-Hoar Stratum		
	1-2" Ice Stratum	2	1961 Ablation Surface
1960-61 21.5 Feet**	4 Thin Ice Strata	13	
	1" Ice Stratum	15	
	1.5" Ice Stratum	21	
	Depth-Hoar Stratum	23	1960 Ablation Surface
1959-60 6.0 Feet	3.5" Ice Stratum	26	Notably Straticulated
	12" Ice Stratum	28-29	Notable Feature, Continuous. Probably 1959 Ablation Surface
1958-59 4.5 Feet	Depth-Hoar Zone, Thin	33	Much Diagenetic Ice at 30 Feet and Below
	4" Ice Stratum	34	Large Xtals, Hard Ice (cold?) with Diagenetic Quality: Many Air Bubbles; No H_2O Pockets
	Pronounced Depth-Hoar Stratum	35	Very Large Xtals. 1958 Ablation Surface
	Numerous Ice Strata	36-53	
	Dominant 8" Ice Stratum	55	Water Ice (clear), Few Bubbles. 1" Core with Dense Water Ice on Either Side; No Air Pockets; No Water Sacks. Typifying Polar-Type Thermal Conditions

* Data recorded 9/6 - 8/61.

** As opposed to 17.5 feet on the crestal (8A-8B) névé.

APPENDIX 17

Camp 8A - Firn Density Measurements (S. I. P. R. E. Corer),*
September, 1961

Elev. 5950 feet

Depth (inches)	Density (gm/cc)	Englacial Features
14-22	0.434	
33-41	0.384	
77-85	0.600	1 Inch Ice Stratum
115-117	0.531	2 Small Ice Layers
120-128	0.572	.75 Inch Ice Stratum
148-156	0.580	" " " "
161-169	0.596	1 " " "
187-195	0.580	
204-212	0.560	.25 " " "
228-236	0.616	" " " "
240-248	0.660	
248-250	0.497	
270-278	0.564	.50 " " "
291-299	0.528	
320-328	0.576	
343-351	0.576	
359-361	0.544	
378-386	0.583	
406-408	0.532	3 " " " (not weighed) Very Clear Ice
423-431	0.528	.50 " " "
460-468	0.549	
483-491	0.553	
507	0.557	
534	0.583	
556	0.580	.38 " " "
569	0.566	2 Ice Laminae
577	0.597	Homogeneous
592	0.557	"
604	0.649	"
624	0.631	3.5 Inch Ice Strat. -Bubbly-Grades into Firn
643	0.631	Homogeneous
661	0.629	3 Ice Laminae
682	0.650	Ice. Strat. and Ice Laminae (not weighed)
701	0.608	Homogeneous

* Density samples obtained from 60-foot bore hole.

APPENDIX 18

Camp 8A - Firn Density Measurements (500 cc Hand Corer),*
September, 1961

Elev. 5950 feet

Depth Inches	Density (gm/cc)	
12	0.518	
24	0.540	
36	0.550	
48	0.556	
60	0.551	
72	0.558	
84	0.565	
96	0.563	
108	0.563	
120	0.586	
132	0.560	
144	0.558	
156	0.574	
168	0.572	
180	0.578	
192	0.534	Depth-Hoar Zone
204	0.516	
207	2'' Ice Layer	(1959-60 Ablation Surface)
209	0.542	

* Density samples obtained from east and west walls of test pit.

APPENDIX 19

Camp 9 - Firn Density Measurements, August 1961

Elev. 5200 feet

Depth (inches)	Density* (gm/cc)
12	0.508
24	0.530
36	0.496
48	0.561
60	0.621
72	0.596
84	0.568
96	0.598
108	0.555
120	0.568
132	0.665

* Density samples taken from the wall of a test pit using a 500 cc hand corer. Each value is an average of 3 measurements.

APPENDIX 20

Juneau Icefield Saline Content Record, 1960-61

Date	Location	Depth	PPM* of Chloride
8/17/60	Camp 9 - 4900'	0	0.7
8/60	Vantage Pk. Basin - 4050'	0	1.1
8/60	Camp 8	0	0.6
8/60	Camp 10B - 3500'	0	1.4
8/60	Camp 9	0	0.5
8/60	Camp 9	0	0.3
8/60	Camp 10 ?	0	0.3
9/8/61	Camp 19E - 6500'	0(new snow)	0.9
		15''(new snow)	1.0
		20''(new snow)	1.3
		30''(new snow)**	2.1
		34''(60-61 firn)	0.1
9/8/61	6200'	0	0.7
9/6-9/61	Camp 8A - 5950'	6''	0.7
		10''	0.4
		18''	0.4
9/12/61	Camp 8A - 5950'	0	0.7
		3.50'	0.4
		4.25'	0.9
		6.50'	1.1
		12.25'	0.9
9/9/61	5100'	4''	1.1
9/9/61	4600'	4''	1.2
9/9/61	4200'	2''	0.9

* PPM = parts per million or milligrams per liter.

** Depth-hoar.

APPENDIX 21

Camp 8 - Daily Temperature and Precipitation Record, 1961

Elev. 6800 feet

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
7/27/61	58		54*	
28			48*	
29			39*	0.01
30	54	39	47	
31	42	36	39	
8/1/61	37	30	34	
2	40	36	38	0.30
3	37	34	36	0.28
4	39	35	37	0.09
5	38		35*	0.58; 0.71 snow
6	29		25*	12.0 (snow)
7	32		27*	
8	40	27	34	
9	39	31	35	
10	34	32	33	0.03
11	36	32	34	0.12
12	37	35	36	1.32
13	40	33	37	1.87
14	32		30*	0.35; 0.47 snow
15	41		32*	
16	45		34*	
17	51		42*	
18	54		46*	
19	56		49*	
20	43		38*	
21	34	33	34	
22	33	32	33	0.08
23	36			0.18
24	35		34*	1.68
25	31	25	28	
26	28	26	27	
27	30	23	27	
28	32	27	30	
29	30	27	29	
30	30		30*	
31	32	30	31	

* Extrapolated from Camp 10 records using a delta difference of -11°F...i.e., A ±3.7°F lapse rate per 1000 feet of elevation.

Camp 8 - Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
9/1/61	34	28	31	
2	30	29	30	
3	31	26	29	
4	28	24	26	
5	21	19	20	
6	28	23	26	
7	32	24	28	
8	30	26	28	
9	29	26	28	
10	43		33*	
11	53	41	47	
12	40	38	39	
13	41			(End of 1961 summer field season at Camp 8)

APPENDIX 22

Camp 8A - Daily Temperature and Precipitation Record, 1961

Elev. 5950 feet

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)	
7/27/61			57*		
28			51*		
29			42*		
30			50*		
31			42*		
8/1/61			37*		
2			41*		
3			39*		
4			40*		
5			38*		
6			28*		
7			30*		
8			37*		
9			38*		
10			36*		
11			37*		
12			39*		
13			40*		
14			33*		
15			35*		
16			37*		
17			45*		
18			49*		
19			52*		
20			41*		
21			37*		
22			36*		
23					
24			37*	3.3 (rain)	(start of Camp 8A
25	38		31*		summer field
26	32	30	31	3.0 snow	season)
27	37	26	32	0.5 "	
28	44	30	37	5.5 "	
29	35	29	32	3.0 "	
30	33	26	30		
31	36	31	34	0.7 "	

* Extrapolated from Camp 8 records using a delta difference of +3.4°F... i.e., A±3.7°F lapse rate per 1000 feet of elevation.

Camp 8A - Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
9/1/61	41	30	36	
2	37	31	34	3.5 snow
3	38	28	33	5.0 "
4	37	22	30	
5	25	19	22	
6	38	13	26	
7		26	31*	6.0 "
8		26	31*	6.0 "
9		27	31*	
10		24	36*	
11		42	50*	
12		34	42*	(End of 1961 summer field season at Camp 8A)

APPENDIX 23

Camp 9 - Daily Temperature and Precipitation Record, 1961

Elev. 5200 feet

Date	Temp. (° F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
7/27/61	64	48	56	
28	56	51	54	
29		39	46*	
30			50*	
31			47*	
8/1/61			44*	
2			42*	
3			45*	
4			46*	
5			42*	
6			32*	
7			34*	
8			40*	
9			41*	
10			41*	
11				
12			40*	
13			43*	
14			37*	
15			39*	11.45 (7/29-8/15)
16	49	33	41	
17	56	37	47	
18	72		53*	
19	59		56*	
20	47		45*	
21	52	40	46	
22	43		40*	0.18
23	43	39	41	1.30
24	41	40	41	2.50
25	42		38*	
26	35	32	34	0.08
27	42		35*	
28	38	33	36	0.59
29	35	32	34	0.49
30	38		37*	(end of 1961 summer field season at Camp 9)

* Extrapolated from Camp 10 records using a delta difference of -4°F...
i.e., ± A 3.7°F lapse rate per 1000 feet of elevation.

Camp 9 - Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
8/31/61			36*	
9/1/61			38*	
2				
3				
4			36*	
5			34*	
6			35*	
7			33*	
8			36*	
9			37*	
10			40*	
11			46*	
12			50*	
13			51*	
14			53*	

APPENDIX 24

Camp 10 - Daily Temperature and Precipitation Record, 1961

Elev. 4000 feet

Date	Temp. (in °F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
7/21/61	48	38	43	(start of 1961 summer field season)
22	49	38	44	
23	51	34	43	
24	59	42	51	
25	61	51	56	
26	66	48	57	
27	72	58	65	
28	60	57	59	
29	55	44	50	0.04
30	64	44	54	0.03
31	57	44	51	
8/1/61	50	45	48	0.06
2	48	43	46	0.38
3	53	44	49	0.05
4	55	45	50	
5	46	45	46	0.35
6	37	35	36	0.82
7	42	33	38	0.60
8	50	37	44	
9	50	39	45	
10	47	43	45	
11	45			0.41
12	47	41	44	0.83
13	47	46	47	3.30
14	42	40	41	3.30
15	50	35	43	1.16
16	50	39	45	
17	63	43	53	
18	62	51	57	
19	61	59	60	
20	52	46	49	
21	48	45	47	
22	48	39	44	0.05
23	46			0.47
24	47	43	45	2.37
25	47	37	42	0.21
26	39	36	38	0.05
27	45	33	39	

Camp 10 - Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (in °F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
8/28/61*	41	39	40	**
29 *	39	37	38	
30 *	44	38	41	
31 *	41	38	40	
9/1/61 *	45	38	42	
2	No record taken.			
3	No record taken.			
4 *	42	38	40	
5 *	42	34	38	
6 *	43	34	39	
7 *	40	34	37	
8 *	43	36	40	
9 *	45	36	41	
10 *	48	40	44	
11 *	57	42	50	
12 *	59	48	54	
13 *	61	48	55	
14 *	63	50	57	(end of 1961 summer field season)

* Taken from thermograph charts.

** No record kept from 8/28-9/10/61, camp not occupied.

APPENDIX 25

Camp 8 - Duration of Sunshine Record, 1961

Elev. 6800 feet

Date	Duration (time)	Total Hours	Total Possible Hours
8/15/61	0945-2030	10.50	15.5
16	1015-2030*	10.25+	15
17	0810-2000	11.80	
18	0650-0710; 0825-2030	12.40	
19	0815-1930	11.25	
20	0820-2000	11.66	
8/21-9/2	No Record	-	
9/3/61	0725-0745; 0910-0915; 1205-1220	0.66	14
4	1155-1830	6.60	
5	1130-1140; 1235-1340; 1355-1740	5.00	
6	0730-1345; 1620-1645	6.66	13.5
7	0955-1040; 1320-1445	2.10	
8	0640-0710; 0840-0930; 0940-1750	9.50	
9	No Record	-	
10	0840-1800	9.30	
11	0815-1900	10.75	
12	0835-1855	10.30	
13 (up to 1500 hrs.)	0840-1500	6.30	13

* Not recorded from time of sunrise.

APPENDIX 26

Camp 10 - Daily Peak Solar Radiation Record, 1961

Elev. 4000 feet

Date	Peak Radiation (in langleys)**	Date	Peak Radiation (in langleys)
7/21/61	1.72	8/15/61	*
22	1.60	16	*
23	1.50	17	*
24	1.46	18-24	No chart record
25	1.44	25	0.53
26	1.44	26	1.00
27	1.40	27	1.04
28	1.41	28	1.50
29	1.21	29	1.36
30	1.30	30	1.52
31	1.55	31	1.60
8/1/61	1.10	9/1/61	1.01
2	1.11	2	0.73
3	1.42	3	0.95
4	1.85	4	1.20
5	0.82	5	1.58
6	0.92	6	1.16
7	*	7	0.66
8	*	8	1.18
9	*	9	1.20
10	*	10	1.16
11	*	11	1.14
12	*	12	1.10
13	*	13	1.11
14	*	14	1.06

* Chart indicates instrument was not recording properly, hence values are probably erroneous.

** Langley = Gram calories per cm^2 per hour.

APPENDIX 27

Mt. Juneau Daily Precipitation Record, 1961

Elev. 3576 feet (Ppn. in inches)

Day	July	August	September
1	0	1.05	0.70
2	0	3.50	2.30
3	2.42	0.65	0.65
4	3.10	0	0.25
5	3.70	0	0
6	0.35	1.80	0
7	2.00	2.40	4.80
8	1.65	2.95	0.80
9	2.85	0	0.05
10	5.15	0.70	0
11	0.90*	5.15	0
12	M?	6.60	0
13	0	Misg.	0
14	0	Misg.	0
15	0	0	0
16	0	0	0.67
17	1.50	0	0.06
18	4.45	0	1.30
19	4.85	0	0.90
20	0.45	0	0
21	0.35	1.30	0.02
22	0	2.95	0
23	0	6.40	1.70
24	0	1.50	0.45
25	0	0	0.15
26	0	3.15	0
27	0	0.63	0
28	0.03	2.35	End of program for 1961
29	0.15	1.42	
30	0	0.35	
31	0	2.10	

* Estimated

APPENDIX 28

Annex Creek Daily Temperature and Precipitation Record, 1961

Elev. 24 feet

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)	
7/21/61	60	44	52		(start of 1961 summer field season)
22	60	44	52		
23	76	41	59		
24	75	39	57		
25	70	40	55		
26	72	41	57		
27	74	47	61		
28	73	50	62		
29	63	44	54	0.11	
30	73	40	57		
31	66	41	54		
8/1/61	64	44	54	0.01	
2	60	41	51	0.77	
3	66	48	57	0.15	
4	66	48	57		
5	65	41	53	0.19	
6	52	43	48	0.81	
7	55	38	47	1.10	
8	67	39	53		
9	65	39	52		
10	58	39	49		
11	54	47	51	1.62	
12	51	48	50	5.11	
13	62	51	57	2.79	
14	58	45	52	2.36	
15	60	38	49	0.75	
16	68	38	53		
17	66	35	51		
18	64	36	50		
19	66	36	51		
20	66	38	52		
21	62	44	53		
22	54	48	51	0.51	
23	52	50	51	3.71	
24	58	48	53	1.83	
25	58	36	47		
26	48	43	46	0.48	
27	52	36	44	0.28	
28	50	38	44	0.97	

Annex Creek Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
8/29/61	48	40	44	0.79
30	50	38	44	0.11
31	48	40	44	0.65
9/1/61	58	36	47	0.37
2	50	48	49	0.50
3	54	38	46	0.81
4	54	38	46	0.10
5	52	37	45	
6	56	29	43	
7	48	38	43	2.08
8	53	38	46	0.67
9	56	38	47	
10	56	32	44	
11	54	32	43	
12	56	38	47	
13	56	38	47	
14	60	36	48	(end of 1961 summer field season)

APPENDIX 29

Juneau Daily Temperature and Precipitation Record, 1961

Elev. 72 feet

Date	Temp. (in ° F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)	
7/21/61	63	50	57	0.11	(start of 1961 summer field season)
22	65	50	58		
23	70	51	61	0.02	
24	74	47	61		
25	77	42	60		
26	77	52	65		
27	80	54	67		
28	80	54	67		
29	70	55	63	T	
30	72	51	62		
31	72	52	62	T	
8/1/61	71	56	64	0.01	
2	60	53	57	0.93	
3	65	53	59	0.13	
4	65	*		U	
5	*	50		U	
6	*	*		1.05	
7	56	49	53	0.48	
8	64	46	55	0.04	
9	66	48	57		
10	66	53	60	T	
11	63	54	59	0.87	
12	59	49	54	3.38	
13	58	54	56	2.11	
14	57	53	55	3.07	
15	64	46	55	0.37	
16	68	49	59		
17	65	45	55		
18	68	48	58		
19	70	48	59		
20	71	49	60		
21	69	52	61	0.06	
22	59	52	56	0.32	
23	55	52	54	2.05	

T - Trace, an amount too small to measure.

U - Amount included in following measurement, time distribution unknown.

* No record.

Juneau Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (in °F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
8/24/61	58	49	54	1.28
25	62	47	55	
26	56	49	53	0.73
27	59	48	54	0.33
28	61	46	54	0.44
29	56	48	52	0.47
30	58	50	54	0.04
31	59	52	56	0.57
9/1/61	61	52	57	0.29
2	61	49	55	0.76
3	62	47	55	0.56
4	60	53	57	
5	60	45	53	0.02
6	57	38	48	
7	55	50	53	1.91
8	56	48	52	0.51
9	58	47	53	0.05
10	65	42	49	
11	65	43	54	
12	67	43	55	
13	69	45	57	
14	69	45	57	

(end of 1961 summer field season)

APPENDIX 30

Juneau Airport Daily Temperature and Precipitation Record, 1961

Elev. 17 feet

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)	
7/21/61	61	46	54	0.02	(start of 1961 summer field season)
22	63	47	55		
23	71	46	59		
24	73	44	59		
25	76	45	61		
26	77	47	62		
27	79	49	64		
28	70	48	59	0.02	
29	68	50	59	0.02	
30	78	46	62		
31	67	47	57	T	
8/1/61	62	51	57	0.30	
2	57	49	53	0.62	
3	71	51	61	0.03	
4	70	50	60	0.05	
5	61	50	56	0.61	
6	52	49	51	0.32	
7	59	45	52	0.38	
8	66	44	55		
9	66	44	55		
10	64	49	57	0.21	
11	57	53	55	0.53	
12	59	55	57	2.32	
13	61	57	59	1.07	
14	58	47	53	1.61	
15	64	41	53		
16	63	44	54		
17	69	41	55		
18	72	41	57		
19	71	43	57		
20	68	48	58		
21	60	47	54	0.10	
22	55	49	52	0.23	
23	59	53	56	0.98	
24	62	46	54	0.45	
25	59	43	51		

T - Trace, an amount too small to measure.

Juneau Airport Daily Temperature and Precipitation Record, 1961 (cont.)

Date	Temp. (°F) Max.	Min.	Avg.	Ppn. (inches in 24 hrs.)
8/26/61	52	42	47	0.90
27	60	41	51	T
28	53	45	49	0.65
29	53	47	50	0.36
30	55	39	47	0.06
31	54	45	50	0.53
9/1/61	63	45	54	0.25
2	53	45	49	0.58
3	55	44	50	0.11
4	60	41	51	
5	58	39	49	0.09
6	59	33	46	T
7	57	46	52	1.04
8	56	46	51	0.01
9	58	42	50	T
10	62	38	50	
11	60	36	48	
12	61	36	49	
13	61	38	50	
14	64	37	51	

(end of 1961 summer field season)

APPENDIX 31

Mean Monthly Temperature and Precipitation Record for Annex Creek, 1951-61
Elev. 24 feet

Mean Temp. (°F)

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
Jan.	18.6	13.9	15.0	17.2	28.8	20.4	18.9	28.8	14.6	24.5	29.4
Feb.	22.2	28.1	33.5	23.5	29.2	22.1	26.0	26.3	29.8	33.3	28.5
Mar.	26.9	33.1	32.4	*	29.2	31.6	35.8	36.1	35.5	32.0	32.9
Apr.	*	*	41.8	35.0	38.2	42.6	40.5	44.0	40.8	42.0	40.6
May	*	*	*	47.3	42.6	46.2	48.2	48.3	47.3	50.4	48.5
June	51.1	*	62.1	*	51.4	49.0	54.8	56.1	54.7	51.4	53.6
July	57.1	*	60.2	53.8	57.1	52.8	55.0	56.8	53.8	52.8	53.4
Aug.	51.8	*	52.2	56.7	51.9	47.4	55.6	52.8	52.9	52.0	50.1
Sept.	48.1	*	46.7	50.6	47.5	47.0	51.6	47.6	49.6	49.0	43.9
Oct.	36.7	43.9	42.2	42.6	39.0	38.9	43.4	41.5	41.7	43.6	35.8
Nov.	29.9	38.5	31.8	38.4	29.9	38.0	37.0	32.8	33.8	34.9	29.1
Dec.	20.7	29.5	31.0	27.3	17.8	20.3	25.6	27.8	34.3	33.3	19.5

Mean Precipitation (inches in 24 hrs.)

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
Jan.	0.17	0.11	0.17	0.17	0.20	0.13	0.04	0.34	0.08	0.32	0.27
Feb.	0.19	0.22	0.33	0.17	0.09	0.25	0.27	0.20	0.29	0.16	0.38
Mar.	0.27	0.22	0.30	0.17	0.11	0.19	0.06	0.10	0.30	0.33	0.23
Apr.	0.27	0.23	0.16	0.06	0.08	0.17	0.26	0.14	0.17	0.18	0.32
May	0.12	0.26	0.15	0.15	0.24	0.39	0.15	0.25	0.22	0.06	0.20
June	0.33	0.19	0.10	0.10	0.15	0.09	0.09	0.16	0.07	0.19	0.29
July	0.10	0.15	0.07	0.17	0.14	0.13	0.12	0.27	0.54	0.34	0.50
Aug.	0.15	0.20	0.14	0.06	0.33	0.61	0.11	0.42	0.45	0.33	0.81
Sept.	0.22	0.22	0.17	0.38	0.26	0.32	0.50	0.41	0.30	0.60	0.48
Oct.	0.31	0.26	0.24	0.32	0.34	0.50	0.36	0.61	0.47	0.68	0.85
Nov.	0.14	0.20	0.10	0.33	0.12	0.32	0.63	0.40	0.49	0.36	0.30
Dec.	0.12	0.25	0.25	0.35	0.13	0.37	0.32	0.48	0.46	0.52	0.33

* Daily record insufficient for calculation of monthly mean value.

APPENDIX 32

Mean Monthly Temperature and Precipitation Record for Juneau, 1951-61

Elev. 72 feet

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
Mean Temp. (° F)											
Jan.	22.6	19.0	20.6	23.0	34.3	25.1	25.8	35.9	20.6	31.3	34.1
Feb.	25.6	33.2	36.2	26.8	33.1	24.7	29.1	30.6	32.7	36.7	33.1
Mar.	27.2	34.7	33.8	34.6	32.0	32.0	38.2	36.5	35.6	34.1	36.9
Apr.	40.2	38.6	*	36.2	39.5	42.0	41.9	45.8	41.0	44.0	41.8
May	47.3	45.6	50.9	50.3	43.8	48.1	50.8	50.3	48.2	53.3	50.6
June	52.9	53.8	59.7	56.5	52.9	52.6	58.1	59.2	58.1	53.7	54.6
July	61.8	57.7	59.7	57.1	59.3	59.9	58.4	60.4	56.3	58.0	58.9
Aug.	57.3	56.4	57.5	60.0	53.4	55.6	61.7	55.8	54.9	57.0	56.1
Sept.	53.5	50.9	51.4	53.1	50.9	50.9	55.3	50.0	50.9	51.2	51.4
Oct.	41.3	47.0	45.5	44.5	41.3	39.6	45.8	43.4	43.4	45.5	41.5
Nov.	36.1	40.4	37.2	41.4	27.8	39.8	40.0	36.6	36.7	37.0	33.3
Dec.	28.1	36.2	35.9	30.7	23.3	27.2	32.0	33.7	37.0	36.8	25.0
Mean Precipitation (inches in 24 hrs.)											
Jan.	0.14	0.21	0.12	0.17	0.29	0.09	0.09	0.25	0.03	0.23	0.17
Feb.	0.15	0.20	0.41	0.42	0.27	0.21	0.23	0.09	0.37	0.16	0.25
Mar.	0.28	0.22	0.29	0.14	0.31	0.16	0.08	0.05	0.31	0.20	0.17
Apr.	0.33	0.26	0.24	0.12	0.18	0.15	0.29	0.17	0.21	0.18	0.25
May	0.12	0.34	0.14	0.14	0.32	0.29	0.12	0.27	0.19	0.08	0.21
June	0.20	0.12	0.14	0.07	0.11	0.10	0.09	0.11	0.06	0.19	0.17
July	0.13	0.13	0.11	0.15	0.09	0.11	0.09	0.26	0.38	0.26	0.39
Aug.	0.12	0.26	0.30	0.15	0.33	0.46	0.08	0.28	0.31	0.26	0.60
Sept.	0.18	0.47	0.36	0.29	0.28	0.24	0.31	0.30	0.33	0.43	0.40
Oct.	0.18	0.56	0.67	0.34	0.40	0.42	0.20	0.52	0.35	0.56	0.64
Nov.	0.22	0.41	0.18	0.36	0.13	0.59	0.44	0.27	0.43	0.28	0.37
Dec.	0.17	0.18	0.45	0.45	0.11	0.48	0.19	0.38	0.33	0.43	0.26

* Daily record insufficient for calculation of monthly mean value.

APPENDIX 33

Mean Monthly Temperature and Precipitation Record for Juneau Airport, 1951-61

Elev. 17 feet

Mean Temp. (°F)

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
Jan.	18.5	14.4	18.7	20.7	32.1	19.8	20.6	32.8	18.0	27.8	30.5
Feb.	21.6	30.6	34.3	23.6	29.3	21.8	25.3	27.1	28.2	33.4	31.5
Mar.	26.0	31.5	31.4	30.8	27.8	28.0	32.8	32.9	33.8	31.9	34.5
Apr.	39.0	37.5	41.0	33.1	38.0	38.7	38.6	42.5	38.8	40.9	39.9
May	46.8	44.7	49.2	46.3	42.9	45.2	47.9	48.1	46.0	49.5	47.4
June	52.2	52.2	56.3	53.8	50.5	50.0	54.9	56.5	55.2	51.1	52.4
July	60.3	55.5	57.3	54.3	56.8	56.3	55.5	57.4	54.1	54.4	56.3
Aug.	55.5	54.1	54.9	56.1	52.0	54.0	57.6	54.5	52.6	53.3	53.9
Sept.	50.6	48.7	49.1	49.2	47.0	48.2	52.4	47.4	48.2	49.2	47.7
Oct.	38.0	44.9	43.2	42.8	38.7	37.5	41.9	41.1	40.3	43.5	40.3
Nov.	31.1	38.4	33.1	38.4	21.8	38.4	37.9	33.9	34.4	34.3	30.6
Dec.	22.4	33.3	32.3	28.1	18.1	23.5	29.4	30.0	34.9	33.9	24.6
Mean Precipitation (inches in 24 hrs.)											
Jan.	0.07	0.11	0.05	0.07	0.13	0.09	0.04	0.16	0.04	0.13	0.12
Feb.	0.07	0.10	0.22	0.15	0.12	0.14	0.14	0.07	0.13	0.07	0.15
Mar.	0.12	0.11	0.12	0.05	0.15	0.15	0.04	0.04	0.15	0.15	0.09
Apr.	0.11	0.12	0.10	0.06	0.08	0.10	0.12	0.07	0.11	0.11	0.13
May	0.07	0.20	0.08	0.09	0.16	0.16	0.08	0.13	0.12	0.05	0.15
June	0.13	0.08	0.10	0.05	0.07	0.11	0.05	0.09	0.04	0.12	0.11
July	0.09	0.12	0.10	0.11	0.08	0.10	0.09	0.14	0.24	0.14	0.19
Aug.	0.09	0.19	0.18	0.04	0.21	0.32	0.05	0.13	0.17	0.15	0.40
Sept.	0.12	0.36	0.21	0.17	0.18	0.15	0.19	0.17	0.19	0.27	0.23
Oct.	0.12	0.43	0.40	0.20	0.24	0.21	0.13	0.30	0.19	0.29	0.33
Nov.	0.15	0.24	0.09	0.19	0.09	0.37	0.28	0.14	0.23	0.17	0.20
Dec.	0.08	0.09	0.16	0.17	0.09	0.31	0.12	0.24	0.19	0.24	0.13

APPENDIX 34

Mean January and Mean Annual Temperature Record
for Annex Creek, Juneau, and Juneau Airport, 1940-61

Temp. (in °F)

Date	Annex Creek				Juneau				Juneau Airport			
	Mean		Running Mean		Mean		Running Mean		Mean		Running Mean	
	Jan.	Ann.	Jan.	Ann.	Jan.	Ann.	Jan.	Ann.	Jan.	Ann.	Jan.	Ann.
1940	25.0	40.4			32.8	44.0						
1941	23.7	40.9			31.2	44.2			27.7	42.6*		
1942	33.4	40.8			38.0	44.0			34.0	42.7		
1943	18.2	40.8			23.6	43.4			22.8	41.2*		
1944	31.6	41.1			36.4	44.8			34.8	42.4		
1945	30.8	40.0			34.6	42.1			32.0	40.5		
1946	28.8	40.1			33.8	42.2			30.4	40.8		
1947	19.1	40.3			23.9	43.0			21.0	41.4		
1948	31.3	38.3*			34.6	39.3			32.6	39.3		
1949	24.6	38.2			28.4	41.3			25.6	39.3		
1950	9.7	38.4*	25.1	39.9	18.0	40.3	30.5	42.6	7.9	37.7		
1951	18.6	38.8*	24.5	39.8	22.6	41.2	29.6	42.3	18.5	38.5	26.1	40.6
1952	13.9	40.3*	23.6	39.7	19.0	42.8	28.4	42.2	14.4	40.5	24.9	40.4
1953	15.0	41.0*	22.0	39.8	20.6	44.2*	26.9	42.2	18.7	41.7	23.5	40.3
1954	17.2	39.9*	21.9	39.7	23.0	42.8	26.8	42.2	20.7	39.8	23.3	40.2
1955	28.8	38.0	21.6	39.4	34.3	41.0	26.6	41.8	32.1	37.9	23.1	39.8
1956	20.4	38.0	20.7	39.2	25.1	41.5	25.8	41.8	19.8	38.4	22.0	39.6
1957	18.9	41.1	19.8	39.3	25.8	44.8	25.0	42.0	20.6	41.2	21.1	39.6
1958	28.8	41.6	20.7	39.4	35.9	44.9	26.1	42.2	32.8	42.0	22.2	39.7
1959	14.6	40.8	19.1	39.6	20.6	43.0*	24.8	42.5	18.0	40.4	20.8	39.8
1960	24.5	41.6	19.1	40.0	31.3	44.9	25.1	42.9	27.8	41.9	21.0	40.0
1961	29.4	38.8	20.9	40.0	34.1*	43.1	26.6	43.1	30.5	40.8	23.1	40.3

* Interpolated from Annex Creek, Juneau, and Juneau Airport records.

APPENDIX 35

Mean Annual Precipitation Record for Annex Creek, Juneau, and Juneau Airport, 1940-61

(Ppn. in inches)

	Annex Creek		Juneau		Juneau Airport	
Date	Ann. Mean	Running Mean	Ann. Mean	Running Mean	Ann. Mean	Running Mean
1940	0.30		0.20		-	
1941	0.28		0.20		0.13*	
1942	0.31		0.24		0.16*	
1943	0.44		0.32		0.23*	
1944	0.29		0.23		0.16	
1945	0.33		0.24		0.15	
1946	0.31*		0.23		0.14	
1947	0.39		0.28		0.17	
1948	0.30		0.28		0.18	
1949	0.37		0.27		0.17	
1950	0.22	0.32	0.17	0.24	0.11	
1951	0.20	0.31	0.18	0.24	0.10	0.15
1952	0.21*	0.31	0.28	0.25	0.18	0.16
1953	0.19*	0.30	0.28	0.25	0.15	0.16
1954	0.20*	0.27	0.22	0.24	0.11	0.15
1955	0.19*	0.26	0.23	0.24	0.13	0.14
1956	0.29	0.26	0.28	0.25	0.19	0.15
1957	0.24	0.25	0.18	0.24	0.11	0.15
1958	0.32	0.25	0.25	0.24	0.14	0.14
1959	0.32	0.25	0.27*	0.24	0.15	0.14
1960	0.34	0.25	0.28	0.24	0.16	0.14
1961	0.41	0.26	0.32	0.25	0.19	0.15

* Interpolated from Annex Creek, Juneau, and Juneau Airport Records.

APPENDIX 36

Lemon Creek Mean Monthly Discharge Record, 1951-61

Elev. 600 feet

Monthly Mean Discharge (cfs)

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
Jan.		1.5	3.0	*	5.5	3.0	14.0	12.0	5.0	6.0	10.7
Feb.		1.0	2.0	*	2.5	2.0	5.0	5.0	4.0	5.0	8.6
Mar.		1.5	1.5	*	1.5	1.5	3.0	3.5	4.0	5.0	9.2
Apr.		7.0	12.0	*	4.5	5.5	9.5	21.1	9.6	20.7	21.4
May		47.0	115	*	44.4	93.3	107	102	85.5	103	102
June		158	310	*	180	186	293	371	292	233	375
July		310	446	346	391	406	367	480	518	490	557
Aug.	406	383	515	324	447	602	421	461	428	437	718
Sept.	369	429	358	338	290	291	544	228	224	483	320
Oct.	101	350	200	78.6	51.1	50.8	169	130	155	179	
Nov.	18.9	66.9	28.0	77.8	22.0	70.3	101	28.0	38.5	54.2	
Dec.	5.0	10.0	*	30.3	6.0	41.9	9.7	7.0	13.8	32.5	

August, 1951 - Installation of gauging station on Lemon Creek.

* No record taken.

APPENDIX 37

Lemon Creek Mean Annual, and Mean Annual Maximum and Minimum Discharge Record, 1952-61

Date	Mean Ann. Disch. (cfs) Calendar Year	Mean Ann. Disch. (cfs) Water Year**	Mean Ann. Max. Disch. (cfs)	Mean Ann. Min. Disch. (cfs)
1951				
51-52		122		
1952	148		429 (Sept.)	1.0 (Feb.)
52-53		184		
1953	*		515 (Aug.	1.5 (Mar.)
53-54		*		
1954	*		346 (July)	*
54-55		130		
1955	121		447 (Aug.)	1.5 (Mar.)
55-56		140		
1956	147		602 (Aug.)	1.5 (Mar.)
56-57		161		
1957	171		544 (Sept.)	3.0 (Mar.)
57-58		165		
1958	155		480 (July)	3.5 (Mar.)
58-59		146		
1959	150		518 (July)	4.0 (Feb. & Mar.)
59-60		166		
1960	171		490 (July)	5.0 (Feb. & Mar.)
60-61		201		
1961			718 (Aug.)	8.6 (Feb.)

* Discharge records insufficient to calculate these values.

** Water year represents the period from 1 October - 30 September.

APPENDIX 38

Lemon Creek Daily Mean Discharge Record, * 1961

(discharge in cfs)

Day	April	May	June	July	August	September
1		56	779	280	418	400
2		46	764	287	530	560
3		42	422	432	606	535
4		41	355	680	555	331
5		40	436	740	674	236
6		41	470	590	722	173
7		37	386	515	746	565
8		35	339	445	500	716
9		38	355	495	335	396
10		46	319	987	339	284
11		54	301	875	626	242
12		50	294	1210	1750	261
13		73	267	740	2660	270
14		108	335	500	2130	267
15	16	116	315	418	980	236
16	18	124	267	414	445	400
17	12	140	274	414	301	264
18	10	136	432	786	290	515
19	9	142	455	966	287	560
20	10	126	343	798	280	294
21	11	111	294	525	284	192
22	12	98	294	440	418	148
23	14	123	301	386	1090	374
24	20	180	450	355	1730	400
25	26	138	378	373	722	242
26	30	134	355	391	595	175
27	37	150	315	436	427	119
28	46	136	319	445	422	94
29	50	146	343	440	520	146
30	55	161	304	450	427	209
31		280		445	450	

* Stevens A-35 water-stage recorder used to measure stream discharge.

XI. GLOSSARY

Ablation. The wasting or surface-lowering of a glacier by the combined processes of melting, evaporation, and sublimation.

Amelioration. The total or partial dissipation, in the spring and early summer, of the previous winter's cold wave in the surface zone of the firn-pack of a glacier, a result of the warming effect of the downward percolation of rain and melt-water.

Bergschrund. The crevasse occurring at the head of a glacier or margins of an icefield, which separates the moving firn and ice of the glacier from the relatively immobile firn and ice adhering to the headwall or nunatak. This crevasse commonly penetrates to the headwall or bed of the glacier.

Bubbly glacier ice. The main material of glaciers variably containing air pockets and entrapped water bubbles, and having a density approximating 0.88-0.90 gm/cc.

CAVU. Clear and visibility unlimited. A meteorologic term used to describe atmospheric conditions.

Cirque. A deep, steep-walled "amphitheatre" recess in a mountain, caused by glacial erosion.

Dense glacier ice. Solid, unaerated ice at a density of 0.917 gm/cc., denoting great age and/or metamorphism.

Depth-hoar. Stratum of relatively softer autumn snow lying just above the annual ablation surface, characterized by low density, cupshaped crystals.

Diagenetic. A result of changes which take place in firn due to accumulation above it, or percolation of rain and melt-water through it; e.g. compaction and recrystallization.

Epeirogenic. Designating the broad uplift or depression of extensive areas of the earth's crust.

Firn. Compacted, granular, but still pervious "snow" in transition to glacier ice, characterized by a density approximating 0.50-0.75 gm./cc.

Firn-ice. A mixture of partially altered firn and bubbly glacier ice (not a separate stage of metamorphosis), characterized by a density approximating 0.75-0.88 gm/cc.

Firn-pack. The volume of retained firn accumulation of a glacier for any particular year or series of years. The total firn component of a glacier.

Glacier. A mass of snow, firn, and ice with definite lateral limits, with motion in a definite direction, and originating from the compaction of snow by pressure.

Isothermal. Having equal degrees of temperature.

Katabatic wind. A wind that flows down slopes that are cooled by radiation, the direction of flow being controlled topographically. Such a wind is the result of downward convection of cooled air.

Local glacier condition. The end phase (or initial phase) just before complete disappearance of glaciers in cordilleran glaciation as depicted in the Taku District, Alaska-B.C. This condition is characterized by disconnected glaciers or small icefield systems only at the highest elevations.

Mean névé-line. The average elevation of the névé-line taken over a period of 10 years.

Melt-water. Water resulting from the melting of snow, firn or glacier ice.

Multiple ablation surface. A surface resulting from the complete ablation of the annual accumulation each year for two or more successive years.

Névé. The accumulation area of a glacier.

Névé-line. The elevation of the most stable position of the lower limit of firn or the névé. The demarkation dividing the areas of accumulation and dissipation.

Nunatak. A hill or mountain which protrudes through the surface of a glacier.

Polar glacier. A geophysical classification, characterized by perennially sub-freezing temperatures (-20°C or lower) within the glacier, except for a shallow surface zone wihich may be warmed for a few weeks each year by seasonal atmospheric variations.

Propagated surface water. Rain and melt-water produced on the surface of a glacier.

Regelation. The refreezing of ice which has melted under momentary pressure.

Regime. The material balance of a glacier involving the total accumulation and the gross wastage in one budget year. The state of health of a glacier.

Retracted icefield condition. A stage of local proportion in cordilleran glaciation, with névé areas restricted to intermediate and high elevations. This condition applies to the Juneau Icefield at present.

Semi-permanent névé-line. The elevation of the most stable position over a several year period.

Snow-pack. The total snow component of a glacier from the current accumulation year.

Sub-Polar glacier. A transitional phase in the geophysical classification of glaciers in which the penetration of seasonal warmth is restricted to a relatively shallow surface layer, but extends to greater depths than in the Polar glacier. Characterized by sub-freezing temperatures around -10°C.

Sub-Temperate glacier. A transitional phase in the geophysical classification of glaciers in which the penetration of the winter cold wave is relatively deep, and may not be completely dissipated during the summer warming period.

Tarn. A small mountain lake or pool that occupies an ice-gouged basin on the floor of a cirque.

Temperate glacier. A geophysical classification, characterized by an isothermal temperature at the pressure melting point (0°C), below a recurring winter chill layer.

Wisconsinan. The fourth and last stage of the Pleistocene epoch, extending from approximately 70,000 to 11,000 years ago, and including the last advance of the Pleistocene ice sheet.