GLACIOLOGICAL STUDIES IN
THE ST. ELIAS RANGE, CANADA

Thesis by

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INTRODUCTION

The glaciological and geological studies of 1948 in the St. Elias Range by a group from the California Institute of Technology were made possible by the Arctic Institute of North America and research grants from the Office of Naval Research, American Alpine Club and the California Institute. Walter A. Wood, director of the New York office of the Arctic Institute, led the entire operation, and Robert P. Sharp of the California Institute of Technology directed the scientific research.

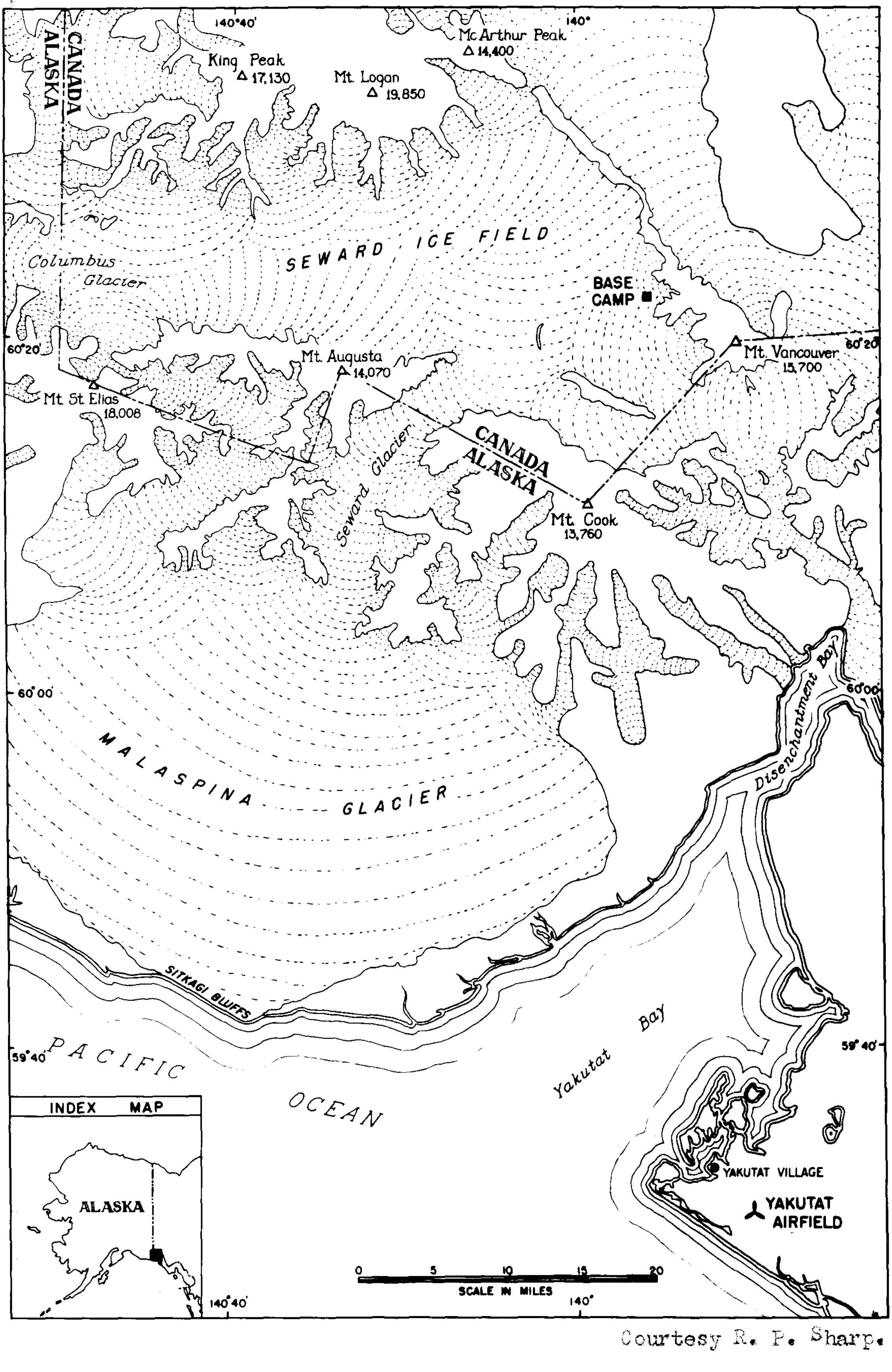
The purpose of the expedition was to make studies of the physics of ice, snow and glaciers, as well as to gather specific information on accumulation, ablation, temperature, movement, density, depth and compaction of the firn in the Seward firn field. It is also hoped that first hand study of existing glaciers will produce a better understanding of past happenings in areas from which glaciers have disappeared. Part of the program consisted of checking the published conclusions of other workers in glaciology as well as attempting to add something to this science. The possibility that radar might be a better and faster means of determining the thickness of a body of ice was investigated, and a check of the radar results by seismic methods was planned. Bernard O. Steenson, a graduate student in Electrical Engineering at the California Institute of Technology, built and operated the radar equipment. F. Beach Leighton, a graduate student in the Division of Geological Sciences at the same institution, worked with meltwater, ablation and accumulation, while the author studied temperature and density of the firn, glacier movement and bedrock geology of the area.

The seismic operations were under the direction of Donald J. Salt of the University of Toronto, Canada.

Studies reported in this paper were made on the Seward firn field just north of the Alaskan boundary in the Yukon Territory of Canada. This is a remote and unexplored part of the St. Elias Range lying between Mount Logan and Mount Vancouver and about 70 miles just west of north from the coastal village of Yakutat, Alaska (Fig. 1). Draining southward from the Seward firn field is the Seward Glacier which empties into the large piedmont Malaspina Glacier on the southern coastal plain of Alaska. The large relatively flat Seward firn field occupies an intermontane basin, approximately 6000 feet above sea level, and almost entirely surrounded by very high mountains ranging to nearly 14,000 feet higher. Many Alpine glaciers flow from the steep mountain slopes into this basin whose only outlet is the gap through which the Seward Glacier flows. The area was reached by means of a single-engine Norseman airplane with a combination ski-wheel landing gear that enabled the plane to land both on the snow and on the airport at Yakutat.

The glaciological party and equipment were landed on the firn field near Mount Vancouver on July 10, 1948. Camp for ice and snow studies was set up near the landing strip and research started immediately. This camp came to be known as the Airstrip camp, and about 2 miles to the northeast a prefabricated hut, brought in by plane in sections, was erected on a small nunatak which will be referred to hereafter as the Base Nunatak (Fig. 12).

The weather consisted of blistering sun, rain, snow, fog and freezing temperatures, as well as many beautiful days with superb rugged mountain scenery. Temperature highs were often above 60° F on clear, cloudless days giving a very hot and bright reflection from the surface of the snow, and



Courtesy R. P. Sharp.

Fig. 1. Map of area showing locations.

the lowest temperature recorded during the summer was 8° F on the early morning of August 25th.

Few open crevasses were in evidence at the beginning of the season, but by August much of the snow, accumulated during the previous winter, had melted exposing many crevasses and leaving others so thinly bridged that travel roped to a companion was often a necessary precaution. Skis and snow shoes were used for snow travel, except early in the morning after a freeze when the crust would hold under the weight of a man, and during the last week in August, when a permanent crust existed throughout the day.

The food consisted primarily of Army 5 in 1 rations and other canned and dehydrated food of good quality. Occasionally eggs and a few loaves of fresh bread were brought in by the pilot. Refrigeration facilities were more than adequate but of little use as a whole. Small single-burner gasoline stoves were used for cooking, the mess units being kept small, usually not more than four or five men each. The water supply was obtained largely by spreading snow on a tarpaulin in the sun, a system which was adequate until the last week in August when little melting occurred. Army pyramidal five-man tents were used at all the camps established away from the Base Nunatak. The tents had to be moved and reset frequently because of the rapid ablation around them.

A tribute should be given Walter Wood for his excellent leadership and efforts in providing transportation of personnel and equipment as well as rations, tents, warm sleeping bags, and other supplies. Praise should also be given Robert Sharp for his leadership and coordination of the scientific work. Acknowledgement and appreciation of help and encouragement is extended to all members of the expedition, especially to Sharp and Leighton, as they were the author's closest companions, many of the tasks being carried out together.

TEMPERATURE REGIMEN

Introduction

Ahlmann (1933, p. 213; 1948, p. 66) has classified glaciers on a geophysical basis into temperate and polar, the latter being subdivided into high-polar and sub-polar glaciers. Temperate glaciers remain at temperatures corresponding to the melting point of ice throughout except in winter, when "the top layer is frozen to a depth of not more than a couple of meters". Subfreezing temperatures prevail in polar glaciers to a much greater, but unspecified, depth even in summer, with the high-polar glaciers producing little or no meltwater at any time, and the sub-polar glaciers producing fluid water in the summer.

As so defined, a discrepancy exists between temperate and sub-polar glaciers, for many glaciers have temperate characteristics except that the winter chilled layer is much thicker than two meters. If Ahlmann's definition of temperate glaciers is enlarged to include all glaciers which reach the pressure melting point of ice during the summer, thereby having no permanent chilled layer, the Seward firn field may be classified as a temperate glacier.

Several detailed studies have been made of temperatures in névé or accumulation areas. H. U. Sverdrup (1935), a member of the Norwegian-Swedish Spitsbergen Expedition of 1934, studied temperatures in the accumulation region on Isachsen's Plateau east of Cross Bay. He found sub-zero (centigrade) temperatures in June and July down to about 10 meters, below which the temperature was at the melting point of ice. This chilled zone had completely disappeared by the end of July, and Sverdrup attributes the rise in temperature primarily to latent heat supplied by meltwater percolating downward through the firn.

Hughes and Seligman (1939, p. 617-634), members of the Jungfraujoch Research Party, 1938, made temperature studies on the Monchfirn at the head of the Aletsch Glacier, Switzerland. They recorded sub-zero firn temperatures in May and early June in some places as deep as 20 meters. The temperature below 20 meters was always at the melting-point. This chilled layer disappeared in some places as early as July 4th, but in at least one location it lasted until about August 23rd. Here also the disappearance of the chilled zone was attributed to warming by meltwater. This conclusion is supported by the temperature relations in an ice-filled hollow of the Sphinx Plateau (altitude 3460 meters). The mass of solid, glassy ice was formed by the freezing of meltwater derived from the rocks above. For many years the temperature of this ice has been known to remain below zero throughout the year. The Jungfraujoch Research Party found in early August that the temperatures fell in an almost linear manner from 0° C at the surface to a minimum of -4° C at a depth of 4.5 meters. This shows that ice can and does exist at temperatures well below zero at this altitude, provided the ice is impermeable to meltwater. The mean annual air temperature at the surface is about -7° C.

Studies of temperatures in a high-polar glacier were made by F. A. Wade (1945, p. 169-170), during the United States Antarctic Service Expedition of 1939-1941 on the Ross Shelf Ice, Antarctica. Temperatures found here were sub-zero throughout the year from the surface to 41 meters. No meltwater was produced. At depths of 15 meters and more the temperature was nearly constant at approximately -23.7° C. Wade concluded that the winter cold wave penetrates to a depth of at least 5 meters and possibly several meters farther.

Technique and Apparatus used in Temperature Measurements

Temperature measurements in the Seward firn field were made with resistance-type thermometers, in which a modified Wheatstone bridge is used to measure the electrical resistance of a wire having the property of varying resistance with changes in temperature. This equipment was designed by the Bureau of Standards for the United States Antarctic Expedition of 1939-41 (Wade, 1947).

The temperature sensitive elements, called thermohms, consisted of copper resistance coils about 3/8 inch in diameter and 2 inches long. These were wound on brass tubes and covered by closed end copper tubes about 1/2 inch in diameter and 4-1/2 inches long. The outer tubes were soldered to the inside tubes for maximum heat transfer (Wade, 1947, p. 73). This thermohm was made moisture proof by rolling the outer copper tube at three points into the rubber covering of the three wires leading from the coil (Fig. 2).

The Wheatstone bridge, used with a galvanometer, was a balanced resistance type using a sliding variable resistor of constantan and so calibrated that temperatures could be read directly in degrees centigrade, rather than in ohms resistance (Fig. 3). The instrument had two scales each 10 inches long, graduated in intervals of 0.2° C, which could be read to about one-tenth of a degree. One scale read from -70° C to -28° C and the other from -32° C to 10° C. The desired range was selected by inserting the proper resistance coil into the circuit by means of a plug type switch.

The current to operate the equipment was provided by an ordinary 1-1/2 volt No. 6 dry cell. The instrument was checked by a constant resistance test coil wound to indicate -30° C. Correction factors for each thermohm were determined by checking in a water-ice mixture, as the temperatures expected on the Seward firn field would be within a few degrees of 0° C. The equipment was very satisfactory and easy to use.

Holes for the thermohms were bored to the desired depths by means of a thermal-type "drill". This consisted of a "hot point" (Fig. 4) containing a 24-volt electrical heating coil threaded onto a one-inch aluminum drill

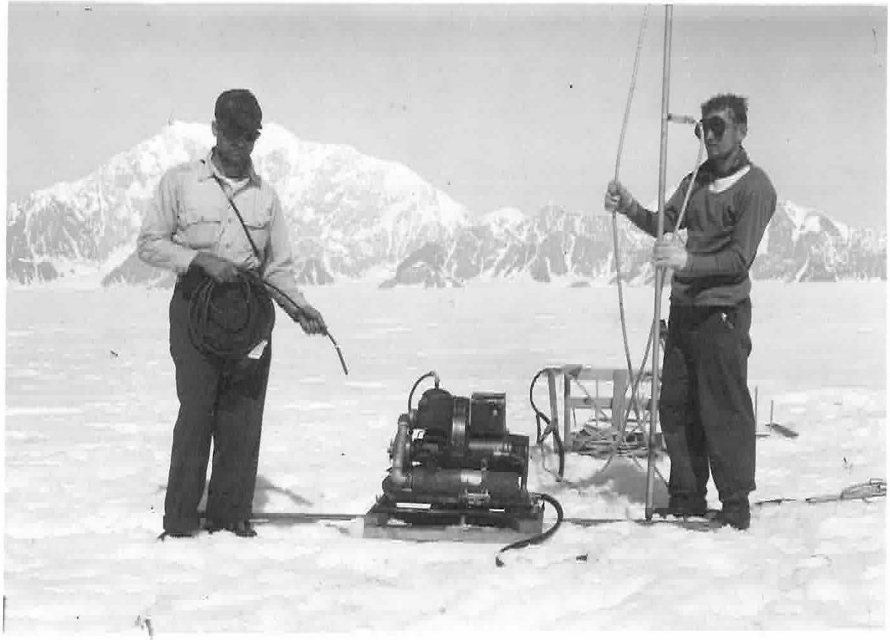


Photo by R. P. Sharp.

Fig. 2. Thermohm, engine-driven generator, drill pipe and "hot point".

Photo by R. P. Sharp.

Fig. 3. Wheatstone bridge and thermohms as installed at Airstrip Camp.

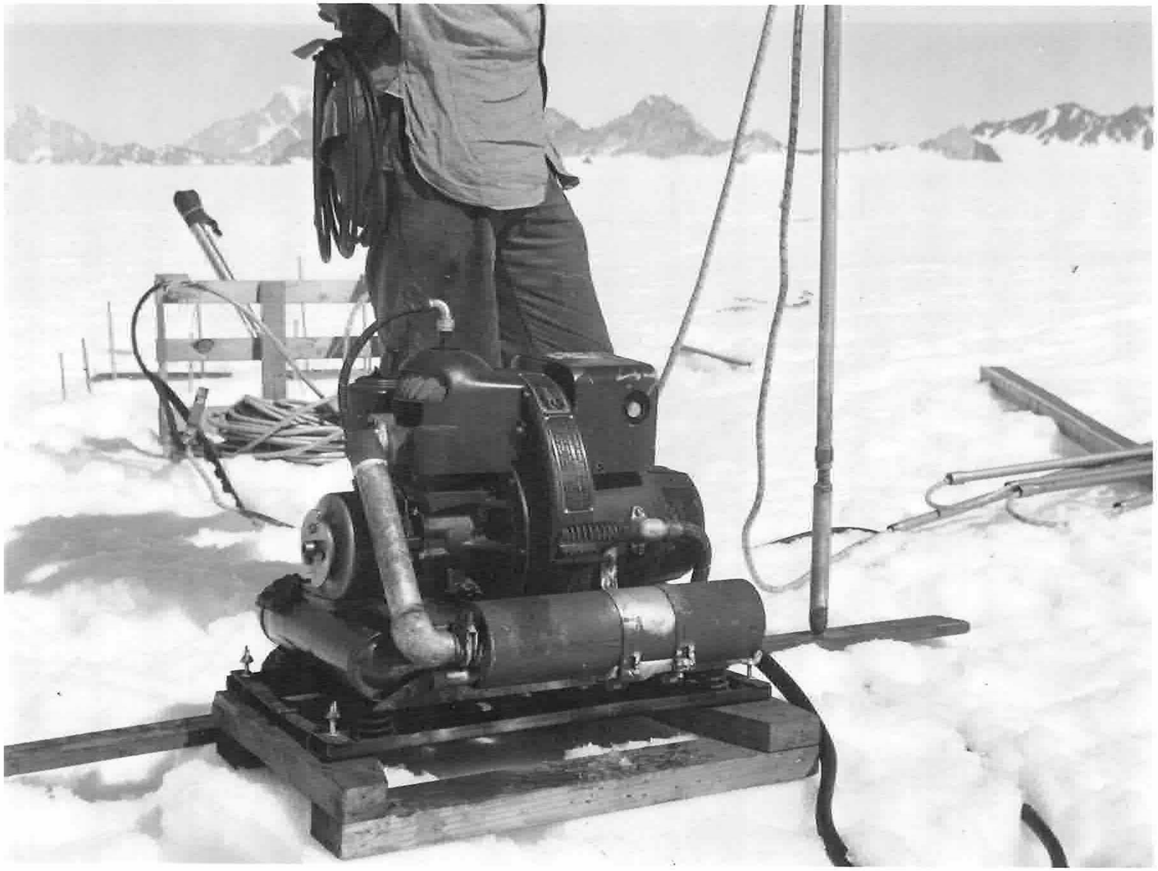


Fig. 4. Engine-driven generator and "hot point".

pipe, which served as one of the conductors. The other conductor was an insulated cable about 5/8 inch in diameter running through the pipe. The current for the "hot point" was furnished by a small power plant (Fig. 4) manufactured by Homelite Corporation, Port Chester, N. Y., which was purchased as a war surplus item. This generator, rated at 28-1/2 volts and 70 amperes D. C., was driven by a two-cycle gasoline engine.

The "hot point" equipment functioned satisfactorily. The rate of "boring" in the upper part of the firn was about 7.5 inches per minute. Below about 64 feet the drilling rate dropped suddenly to approximately 1.4 inches per minute. From data obtained in a crevasse, it was decided that this decrease was due to a water-saturated zone in the firn, and that the water was conducting the heat away from the point at an accelerated rate. Another possibility would be that the firn at this depth becomes practically impervious, and the meltwater from the "hot point" could not drain away. From personnel of the 1949 expedition, it was learned (personal communication) that much less ablation of firn took place in the 1949 season. The height of water in crevasses was lower in 1949, and no crevasse lakes were seen near the Seward outlet where they were numerous the previous year. From the above facts and from the drilling rates reported in 1949, the conclusion is drawn that a saturated zone or water table existed at approximately 64 feet in 1948.

The weld near the top of several hot points softened during the operation allowing the point to bend to one side under the weight of the pipe. This damage was attributed to the fact that the meltwater could drain away through the porous firn allowing overheating of the upper part where welded. After bending a few degrees the upper part of the point contacted the ice and it is inferred that this permitted the weld to harden. However, the bend tended to deflect the point causing a crooked hole. These damaged points were sent back to Yakutat, rewelded, and put back into operation. No hot points

Table 1. 1948 Thermohm data -- Airstrip Station.

Hole No.	Depth	Correction	Installed	Removed
1	3'5"	-0.1	12 July	29 July
2	6'8"	-0.05	12 "	29 "
3	9'7"	0.0	12 "	29 "
4	13'2"	-0.1	12 "	29 "
5	15'8½"	-0.1	12 "	29 "
6	20'4"	0.0	13 "	29 "
7	23'11"	-0.1	12 "	29 "
8	30'7½"	0.0	14 "	29 "
9	39'5"	0.0	13 "	29 "
10	61'8"	0.0	17 "	23 "
11	75'0"	0.0	17 "	23 "
12	188'0"	0.0	18 "	18 "
13	204'0"	0.0	23 "	23 "

were damaged while being used below 64 feet, further supporting the idea that meltwater could not drain away from the point below that depth. The greatest depth reached by the method of thermal "boring" was 204 feet, and the drilling stopped there only because of the lack of more pipe and cable.

Owing to delays connected with the airplane used for transportation, the glaciological party did not reach the firn field until July 10th. Some of the thermohms were installed by July 12th, and all were set in their respective holes by July 18th (Table 1). Thermohms were installed at the following depths: 3'5", 6'8"; 9'7", 13'2", 15'8½", 20'4", 23'11", 30'7½", 39'5", 61'8", 75'0", 188'0", and 204'0". Upon checking temperatures at the various depths, it was found that the winter's chilled layer had already been destroyed as all temperatures were 0° C down to 204 feet below the surface. The 1949 expedition, however, did reach the firn field in time to record part of the disappearance of the chilled layer, and through the courtesy of Dr. Sharp those data are included in this report.

Figure 5 shows the temperature at various depths from June 28 to July 9, 1949, by the end of which time the temperature of the firn was 0° C throughout. The curves have been generalized to fit the general trend of the points as the accuracy of the instrument is probably no greater than ± 0.1° C. The curious initial drop and subsequent rise of the temperature at 16'0" can be attributed to the disturbing influence of the hot point and to the possibility that some of the surface snow may have fallen into the hole requiring some time for equilibrium to be regained.

Vertical distribution of temperatures each day during the period of observation is plotted in Figure 6. This shows that on June 28th a layer at 27 feet had a higher temperature than those above and below. A similar situation developed at 21 feet on July 3rd, resulting in rapid destruction of the

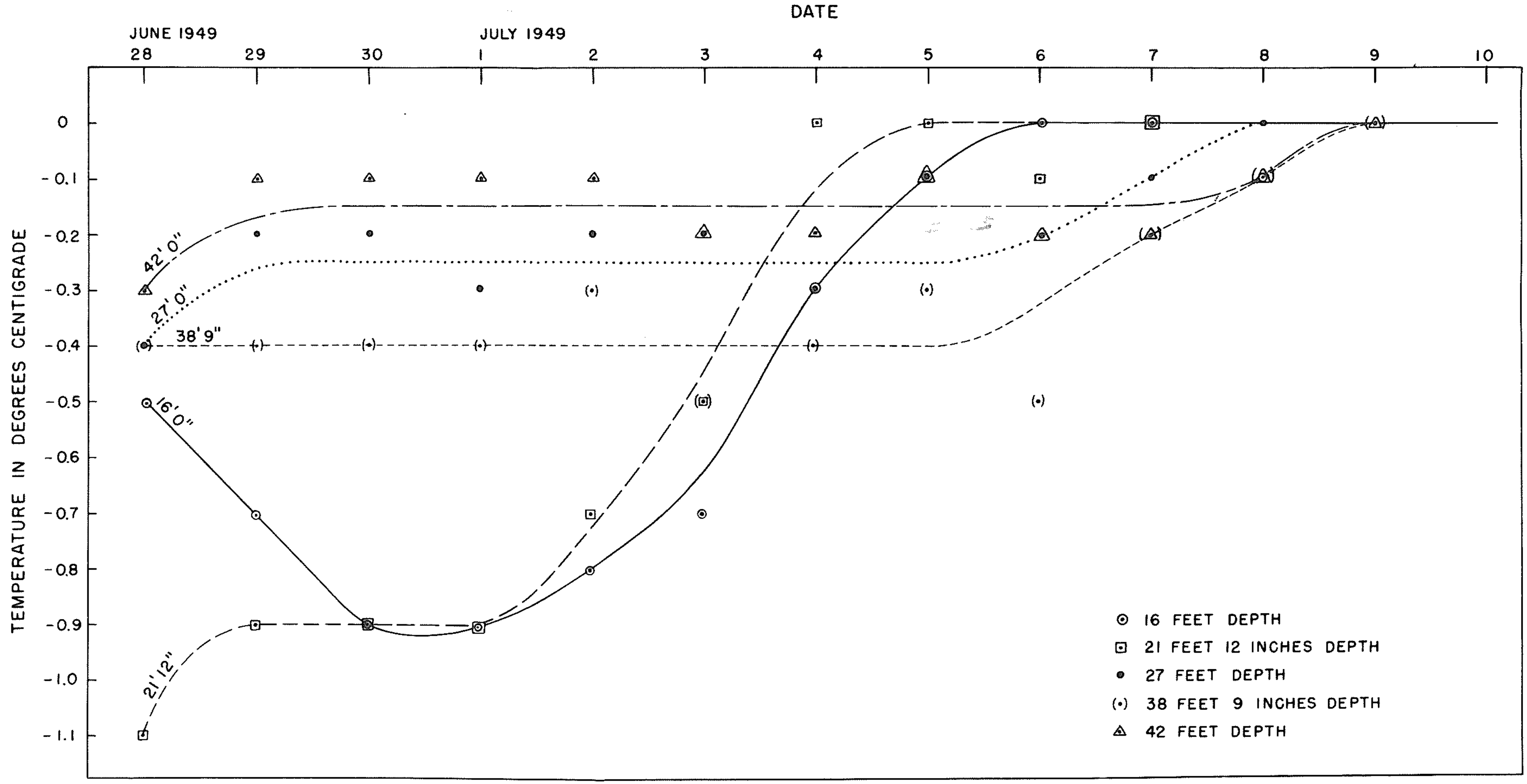


Fig. 5. Plot of daily temperatures at various levels in the firn.

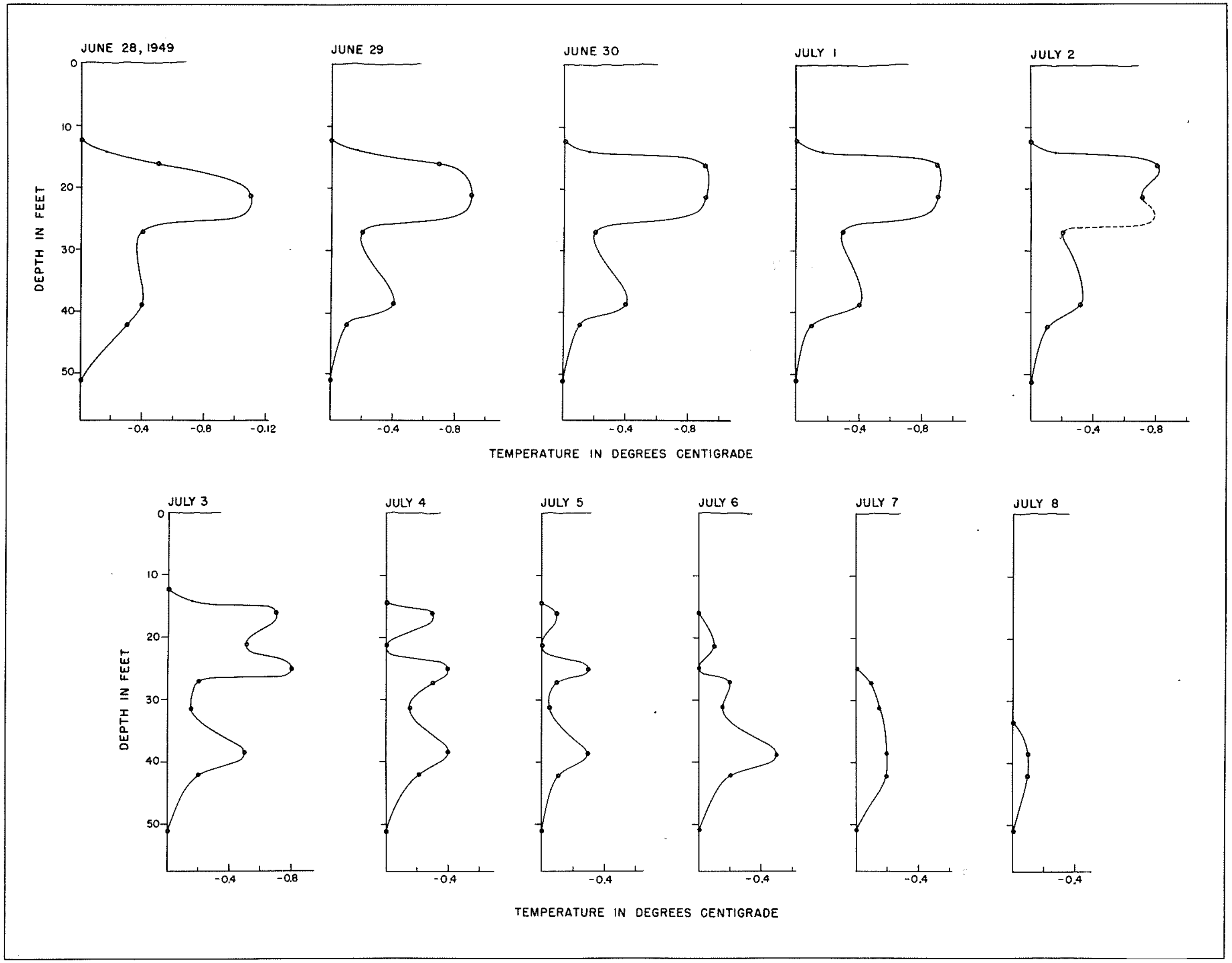


Fig. 6. Plot of daily temperature measurements during deterioration of winter's chilled layer.

upper bulge on the curve, and bringing that layer to the melting temperature. Irregularity in the circulation of meltwater is the probable cause for these variations in temperature. It is known that meltwater does not percolate uniformly down through the firn, and that the upper surface of the zone of sub-freezing temperatures is very uneven (Sverdrup, 1935 p. 87-88). No doubt this is caused by inhomogeneities in the firn, such as ice bands, and by lateral variations in density and porosity. Circulation of meltwater laterally along some particularly pervious layer, or just above an impervious band, could easily produce the temperature behaviors described above after equilibrium is reestablished. The term "equilibrium" can only be applied to a relatively small area during the time involved. The temperature change caused by the latent heat released at these lower levels must be distributed by conduction past the boundaries of the actual penetration of the water. This effect can be no greater laterally than vertically.

From the chart it can be seen that on July 4th the temperature at 16 feet was sub-zero whereas at 21 feet the melting point had already been reached. Little change takes place in the lower lobe of the curve until near the end of the period of sub-freezing temperatures, and the layer of zero degree had started to encroach upon the lower zone. This departs somewhat from Sverdrup's (1935, p. 70) generalized chart of vertical temperature distribution, in which he has indicated that the temperature of the entire zone is rising, presumably by conduction, as the thickness of the zero layer increases from above. However, since the period of observation is short, little change in temperature is to be expected in the lower portion of the zone, for the rate of heat transfer by conduction is slow compared with that of meltwater. In colder regions, where much of the summer is required to destroy the winter's chilled layer and where temperature differences are larger, the effects of conduction may be considerable.

Thermal Conditions of Firn

The temperature variation of snow and ice at the surface can be attributed chiefly to the changing temperature of the air; however, radiation may be important. Obviously, the temperature cannot rise above 0° C, as melting will absorb the heat keeping the temperature fixed until the ice has disappeared. In winter a cold wave starting at the surface penetrates the firn principally by conduction (Chamberlin and Salisbury, 1909, p. 274; Sverdrup, 1935, p. 76). The depth of penetration depends on the degree of sub-zero temperature and the length of time the low temperature prevails.

In summer when average air temperatures are above freezing, the firn temperature rises, but probably only a small proportion of this rise can be attributed to conduction. Melting occurs at the surface by means of heat exchange from the air to the firn and by radiation from the sun. As the meltwater thus formed percolates downward through the porous firn, it carries with it a great deal of heat in the form of latent heat of fusion, which can be released upon coming in contact with sub-zero ice particles, rapidly raising their temperature to zero. Since the specific heat of ice is about 0.50 and the latent heat of fusion stored in water at freezing temperatures is about 80 calories per gram, freezing of one gram of water will raise the temperature of approximately 20 grams of ice from -8° C to 0° C.

The rate at which firn can absorb heat at the surface is limited only by the rate of heat-supply since it can change its state and drain away thereby removing the heat absorbed from the surface. Melting may occur on the first warm day, regardless of the length and intensity of the previous winter. On the other hand, firn can lose heat only by conduction, outgoing radiation, and to a minor extent, by evaporation. Conductivity calculations by Sverdrup (1935, p. 76) and Hughes and Seligman (1939, p. 627) show heat transfer by conduction through firn to be slow, for snow and firn are good insulators. The low density snow, which usually covers the surface in winter, has better insulating qualities than higher density firn, because of its higher percentage of air, a substance with low conductivity, which is confined in spaces too small to permit convection.

If the proper conditions exist, even during a small portion of the day, melting will occur, regardless of how cold the rest of the day is, or what the average temperature of the day may be. Several days of cold weather may be required to offset the effects of this small amount of meltwater which has moved downward and refrozen, raising the temperature of the surrounding firn.

Effects of radiation a few inches below the surface are probably almost nil. According to Brunt (1934) and Wilson (1941), as much as 80-90 per cent of the solar radiation may be reflected upwards from the surface of fresh snow ~~at the snow surface (fresh snow)~~, leaving only a small fraction to be absorbed. Wallen (1948) uses 70-75 per cent for the Albedo on frozen old snow and 60 per cent on a wet and melting surface. Transfer of heat to or from the snow-surface by this means depends upon the net effect of incoming and outgoing radiation. Wilson (1941, p. 188) states, "Paradoxically as it may seem, the outgoing radiation may more than compensate for the net radiation-income with a cold dry snow-surface on a clear sunny day". Experiments by Gerdel (1944, 1948) at Soda Springs, California, show that most of the radiation is absorbed in the upper 10 inches of snow or firn and almost none penetrates to 20 inches. In higher latitudes the ratio of the outgoing to the incoming radiation is also much greater (Brunt, 1934, p. 152). However, the author found that some brass plates embedded in the wall of a pit at different depths below the surface of the firn, which was already at the melting temperature, melted out within 6 to 8 hours on a sunny day, and he believes this was caused principally by radiation penetrating the firn. The principal sources of heat for melting snow are usually considered to be conduction from turbulent air, condensation from moist air which releases the heat of vaporization, and radiation. Warm rain may be a minor source in some areas.

After warm weather sets in and melting starts at the top, a surface layer at 0° C exists, and the thickness of this layer increases during the summer until the bottom of the winter's chilled layer has been reached (Sverdrup, 1935, p. 71-72). The conclusion is reached that heat, in the form of heat of fusion in meltwater, is transported into the glacier at a far greater rate than is possible by thermal conduction. In fact, no conduction from the chilled layer to the surface can take place after an isothermal layer at zero degrees is established near the surface, as this zone is of uniform temperature and no conduction can take place across the region without a temperature gradient (Sverdrup, 1935, p. 71). This suggests that regardless of the mean annual temperature any glacier producing a reasonable amount of meltwater in the névé area will be at pressure melting temperature. This, of course, requires a permeable firn to the depth penetrated by the cold wave. In other words, the mean annual temperature can be below freezing, and the winter's chilled layer can be destroyed every summer. This appears to be contrary to Chamberlin's (1909, p. 278) conclusion that the zone below the penetration of the winter wave should be at the mean annual temperature of a region, if below freezing. He states, "we may deduce the generalization that in the zone of constant temperature" (below the zone affected by seasonal temperature variations) "within the area of glacial growth, the temperature of the ice is generally below the melting-point." Thwaites

(1946, p. 16) also says, "the temperature at 50 feet is close to the mean annual temperature." These statements may be true for areas where little, if any, meltwater is produced, as in the Antarctic, but no such distinction was made by these men. Wade's (1945, p. 170) experiments on the Ross Shelf ice indicate that the temperatures below the zone of annual temperature fluctuation on high polar-glaciers may correspond to the mean annual temperature. Here the temperature rise in the upper layers in summer as well as the cooling in winter must be due chiefly to conduction, since no meltwater is produced.

Warming by meltwater may not be as effective in solid glaicer ice under the firn layer or below the firn line, because of its relative impermeability. However, if the thickness of the firn is greater than the average thickness of the winter's chilled layer, the ice below would be at the pressure melting temperature in a temperate glacier, since it would not be affected by the winter cold. Ice below the firn line probably reaches the melting point throughout, owing to (1) the higher air temperatures at these levels, and (2) to some percolation of meltwater along boundaries between crystals.

FIRN DENSITY

Density measurements on the Seward firn field

A shaft about 46 feet deep was dug near the landing strip on the Seward firn field for the purpose of density and firn structure studies. Beach Leighton, a graduate student at the California Institute of Technology, also used this pit for studies of meltwater movement, which were conducted at the same time (Leighton, F. B.; Cal. Tech. Master's Thesis).

After considering several methods of measuring the density of snow, firn and ice, it was decided that the best and easiest method was to take a core of known volume and weigh it on a fairly sensitive balance. The coring apparatus was patterned after that used by Seligman, Hughes, and Perutz on the Jungfraujoch Research Expedition of 1938 (Seligman, 1941, p.302). The coring shells had saw edges to facilitate cutting and were rotated by hand (Fig. 7). These shells had slots near each end through which knife-edged plates could be inserted, thereby cutting the core to a specified length. The core was then weighed and the density calculated from the weight and volume.

In using the coring apparatus errors were introduced by grains of the loose firn being rotated and rearranged in the core by the saw teeth of the shell. This caused a lengthening of the core in the shell by as much as 5-10 per cent over the space originally occupied in the wall of the pit. This was noticed early in the use of the apparatus, and the error was practically eliminated by taking a core and measuring the volume of the hole rather than the volume of the sample. For ease of calculation the core barrell was forced into the wall of the pit a specified distance, usually chosen so as to give a hole of 400 cc volume.

Fig. 7. Apparatus for measuring firn densities.

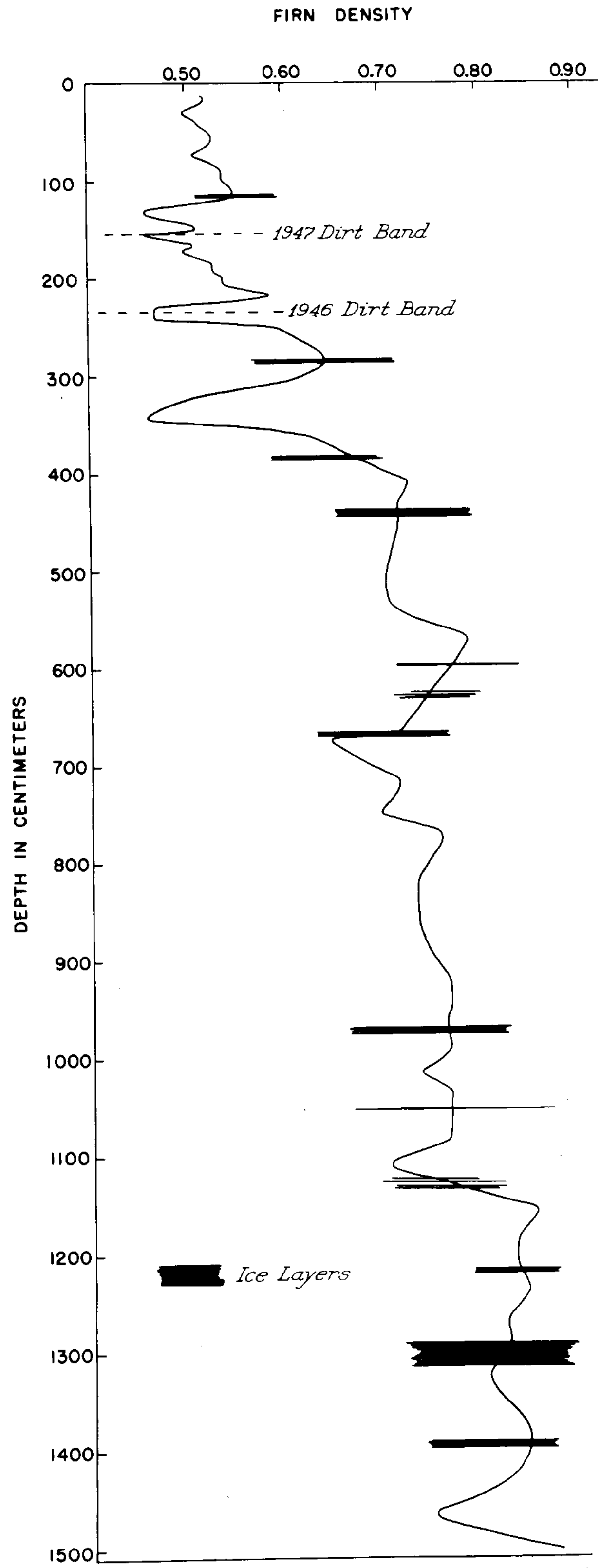
The scales used to weigh the cores were ordinary sliding weight chemical balances with an accuracy of about ± 0.1 gram (Fig. 7). Originally the capacity of this balance was 600 grams, but by using an extra detachable weight on the lever arm, the capacity was increased to 1100 grams with little loss in sensitivity. The accuracy decreased with increased weight of core to about ± 0.2 grams at full capacity.

The surface density was found to average about 0.5 and with variations increased to 0.82 at 45 feet depth. Horizontal bands of almost solid ice, were found at irregular intervals. Their density could not be measured accurately as the ice was too tough to core with light-weight coring shells. However, some approximate measurements were made by drilling with a large carpenter's bit, weighing the cuttings and measuring the hole for volume. In general the firn was more coarsely crystalline, but of lower density, just under the ice bands. Figure 8 shows the variations in density with depth found at pit number 1.

It is not known just how much free water was contained in the firn, but several tests near the surface were made. The free water content varied from 8.7 per cent at 20 cm. depth to 3.0 per cent at 270 cm. It is apparent that any free water present in the core samples would increase the weight, and if this water drained away before freezing in the winter, the density values obtained would be too high. These measurements were made after the method of Klein (1946, p. 17-18) with some modifications.

Discussion

Increase of firn density with depth can be attributed to several factors, but compaction and settling, and the freezing of water received from the surface are probably the most important. Wind packing is important only on the surface. Attempts were made to measure compaction and settling



Courtesy R. P. Sharp.

Fig. 8. Density of firn in July 1948.

on the Seward, but the brass compression plates melted out within a few hours, probably because of warm daytime air temperatures and penetration of solar radiation through the upper layers of the firn.

Hughes and Seligman (1939, p. 645) found that the initial increase in snow density following a snow storm is due very largely to slow settling and compaction. They observed a settling rate in new snow of about 0.13 cm/cm/day at sub-zero temperatures. This rate fell off gradually as the snow packed. Daytime rates exceeded nighttime rates because of higher temperatures and the presence of a lubricating layer of water around the snow crystals. From studies of crystal size with depth, they conclude that settling is the most important means of increasing the density throughout the firn, and cite Sorge (1935) who attributed density increase in Greenland almost wholly to consolidation of the firn. The argument is: if density increase had taken place by freezing of meltwater at the crystal boundaries, a considerable growth of the crystals would be entailed; whereas, if the density were increased by closer packing of the crystal grains, little or no grain growth would be expected. On the Jungfraujoch only slight grain growth occurred with density increase.

Compaction may be produced by: (1) readjustment of crystals and grains for closer packing, (2) crushing of grains under pressure, (3) melting of crystals at points of contact, and (4) molecular transfer, including vapor transfer, from one crystal to another. The mechanism of grain readjustment is obvious and is probably accelerated by the presence of liquid water around the grains as a lubricant. Crushing ice grains under pressure may be significant only in fresh snow when the light skeleton crystals crush very easily. Melting at contacts may be very important, especially when the firn mass is at the pressure-melting temperature. When stress is applied to a crystal at the melting temperature the crystal will melt at the point of greatest stress. The solid near the point of contact becomes chilled in order to furnish the latent heat of fusion for the change of state. The water immediately refreezes as it flows away from the point under stress. This allows settling of the firn and provides broader contacts of the grains. The effect of uniform pressure is to lower the melting point of ice by 0.0075° C per atmosphere of pressure and non-uniform pressure may lower the melting point up to 12 times as much (Tarr and von Engeln, 1915, p. 114). Owing to the diurnal thawing and freezing at and near the surface, some crystals may be entirely destroyed, and their substance is added to other ice crystals thereby increasing their size. (Seligman, 1941, p. 313). Molecular transfer from small to larger crystals at greater depths may occur by variations in the vapor pressure of crystals of different sizes causing the larger ones to absorb the smaller. This is explained by the fact that vapor pressure of a solid varies inversely with the radius of curvature, therefore the vapor pressure around a smaller grain is higher than around a larger grain. Perutz (1940) suggests that crystals having the right orientation for yielding to stresses by gliding along their basal planes, would have a tendency to grow at the expense of the others owing to their energy difference. He applies this to solid ice rather than to firn, however, and it may have little, if any, bearing on the increase of density in firn.

In the Antarctic where meltwater is nonexistent, Wade (1945) concludes that the density must increase by settling. The rate of settling on the Ross Shelf Ice at a depth of 1.5 meters varied from about 1.4×10^{-4} cm/cm/ day in September to over 4.25×10^{-4} cm/cm/day in January (summer). He states that it is quite probable that the settling rate is a function of the temperature, even when the temperature is continuously below the freezing point.

The increase of firn density attributable to the freezing of water may occur (1) during spring and summer, when decending water is frozen out in destroying the chilled layer, and (2) during winter by the incidence of the cold wave.

When raising the temperature of sub-zero firn by releasing latent heat of liquid water, the density is increased by the amount equivalent to the weight of water frozen in a given volume. Expressed as an equation, the density of the dry firn is increased by $\rho c \Delta t/80$ grams per c.c., where ρ is the initial density, c is the specific heat and Δt is the temperature rise of the firn in C°.

During winter any water retained in the firn penetrated by the cold wave is frozen out and thereby increases the density. Sverdrup (1935, p. 75) infers that the retention of free-water in the firn is very small, and that it is practically dry when the frost penetrates it in winter.

Conclusions

No conclusions can be drawn concerning the method of density increase on the Seward firn field from the 1948 data alone. Through the courtesy of R. P. Sharp of California Institute of Technology, the 1949 data are included in this report, and figure 9 shows the density curves for the 1946-1947 ~~and 1947-1948~~ accumulation layer~~s~~ in the summers of 1948 and 1949. Measurements suggest a decrease of about 1 inch in thickness of the 1946-1947 layer between 1948 and 1949, but this cannot be as entirely reliable as the measurements could not be taken in exactly the same place each year. It is assumed that actual thinning of a buried firn layer with time at any one place will be due to compaction, as it is difficult to account for it by any other means, but measurements of layer thickness are likely to be unreliable unless made

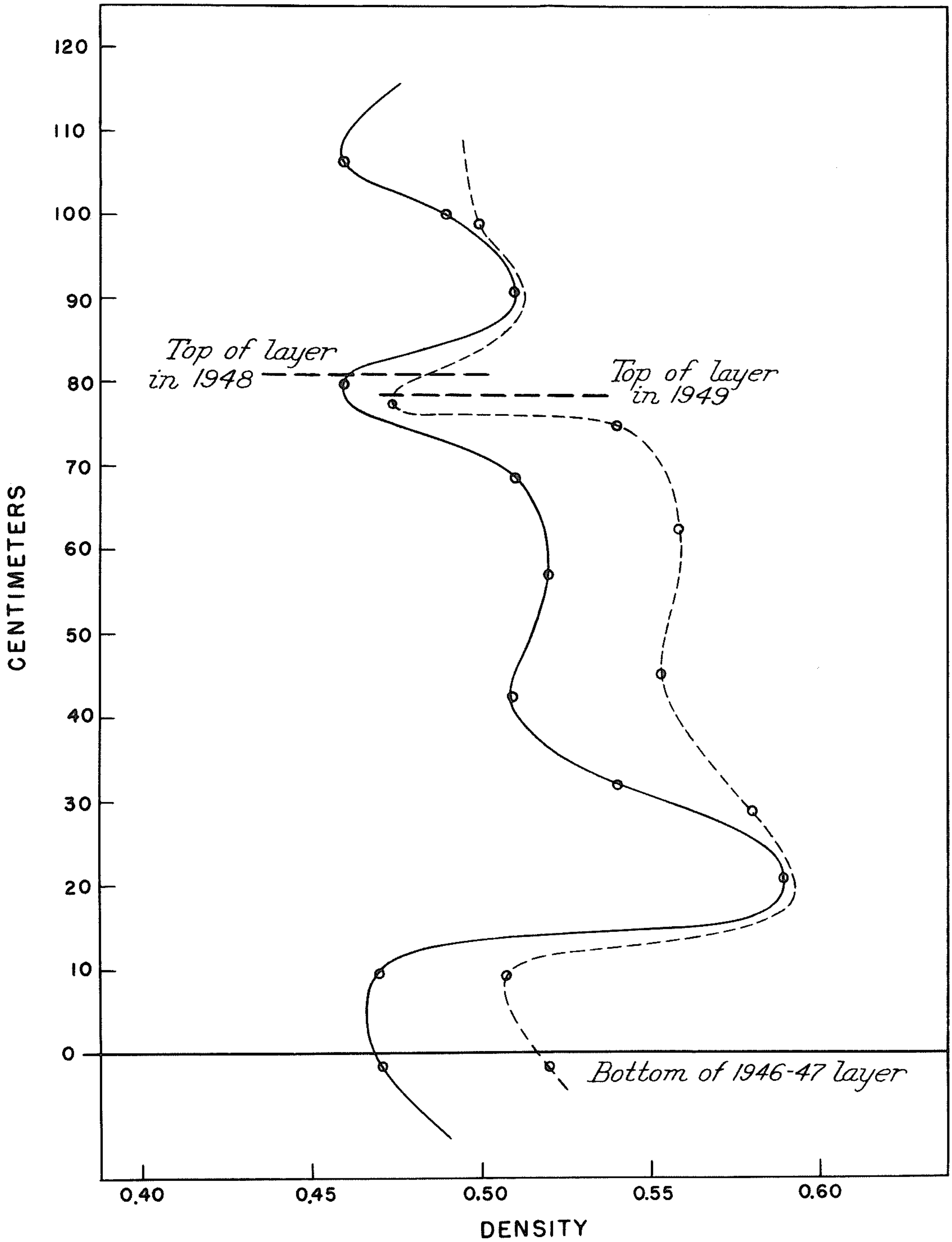
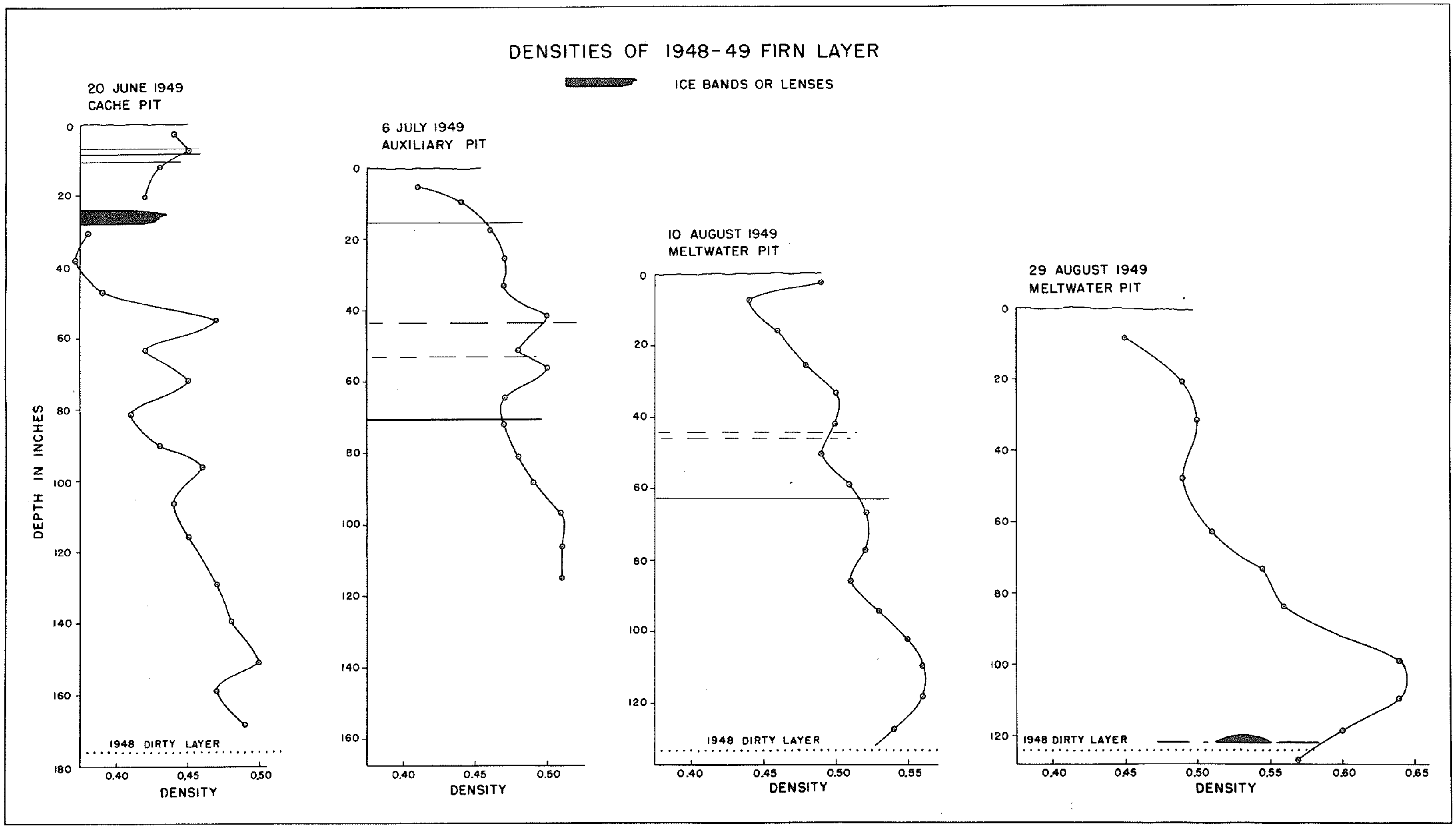


Fig. 9. Density change within the 1946-47 firn layer between 18 July 1948 and 13 August 1949 (solid line-1948, dashed line-1949).

at exactly the same place each time owing to an unevenness in the upper surface at the time the next layer of snow fell. The average density of the 1946-47 layer on 18 July 1948 was 0.514 and on 13 August 1949 it was 0.536. The thickness of the layer, where measured in 1948, was 81.3 centimeters, and since the density of any substance being compressed is inversely proportional to the thickness, assuming no change in the other two dimensions, it is easy to calculate the amount of compression or compaction necessary to increase the density from .514 to .536. This would reduce the thickness from 81.3 to 78.0 centimeters. The variation in initial thickness probably exceeded 3.3 cm, so one cannot calculate what part of the increase in density is due to compaction. Some increase must have taken place during the destruction of the winter's chilled layer if the function of meltwater postulated in the section "Temperature Regimen" is valid.

Figure 10 shows the density of the 1948-1949 accumulation layer in three pits at different times during the summer of 1949. The two curves on the right are drawn from data obtained in the same pit on 10 August and 29 August. The firn reached an isothermal condition at zero degrees centigrade by 8 July, so the increase in density during August could not be due to the freezing of meltwater. Since the last curve shows an increase in density chiefly near the bottom of the layer, the conclusion is reached that much of this increase is probably caused by compaction as explained in the following paragraphs.

Liquid water in the firn is considered to be of two kinds in this report. That amount of liquid which can be held by the ice particles either by surface tension, capillary action, or any other means of retaining liquid among ice particles, will be called fixed freewater, and that amount of liquid which is percolating through the firn by gravity will be called transitory freewater. It is believed that the fixed freewater will be reasonably constant



Courtesy R. P. Sharp

Fig. 10. Plots of density changes during summer of 1949.

throughout the summer, and, for all practical purposes, might be considered to be the minimum amount found in the firn at any time during the ablation season after isothermal conditions are reached. The true fixed freewater would be that amount of water retained in the firn after draining for an infinite amount of time. If the amount of freewater present in the firn were plotted against time, under conditions of no melting or freezing, over a period of several weeks, or perhaps less, the curve would probably approach the true fixed freewater asyptotically. This value is probably very near the amount of freewater present in the firn at the time of freezing of a given layer of firn by the winter cold wave, and as such may be considered part of the substance of the firn. In this study we are chiefly concerned with the transitory freewater which varies with the ablation at the surface. If density measurements are made in a layer at a time when the maximum amount of meltwater is percolating through that layer, the indicated density would be higher than at any other time. Therefore, comparative density determination should be made at about the same time of day and under as nearly equivalent conditions of ablation as possible. Otherwise some means of determining and correcting for the amount of free water must be devised.

Meltwater studies made by the 1949 expedition demonstrated a wave of abundant meltwater, the maximum of which started at the surface about noon on a day warm enough to allow melting, and progressed downward at about six inches per hour. Such a maximum would reach that part of the 1948-49 firn layer showing the greatest density increase between 15 and 20 hours later. Since no densities were taken at that time of the day the density increase cannot be attributed wholly to variations in meltwater. It must be pointed out, however, that the ablation and therefore the supply of meltwater was greater during the period immediately preceding August 29 than during the corresponding period before August 10. These figures are given in the following table.

Date		Amount of ablation in millimeters		
		Station 1	Station 2	Station 3
August 7, 1949		20 mm.	21 mm.	21 mm.
8	new snow	(added 9 mm)	(added 11 mm)	(added 10 mm)
9		6	6	4
10		7	5	6
4 day average		8-1/4	8	7-3/4
August 26, 1949		8	9	5
27		17	18	17
28		18	20	21
29		14	15	11
4 day average		14-1/4	15-1/2	13-1/2

These figures suggest that the amount of freewater contained in the firn even at a time of minimum meltwater flow may have been greater on August 29 than on August 10. Certainly more water must have been present during the passage of the maximum. Freewater measurements made on August 29 at various depths range from 3.5 to 10 per cent water. As the maximum change is only 6.5 per cent of the total sample and assuming that these figures represent the minimum and maximum for the two periods involved, it stands to reason that any density increase of more than 6.5 per cent cannot be attributed to differences in amount of transitory meltwater contained in the firn. Even if the firn were completely dry on August 10, any increase in density of more than 10 per cent cannot be caused by retained meltwater.

The third and fourth curves (figure 10) show that the maximum density increase occurred about 20 inches above the 1948 dirty layer. This amounted to 0.08 which is 14 per cent increase in density at that point. As the possible conditions just outlined are extreme, it is concluded that a least half of this density increase and probably more, was caused by compaction.

SURFACE MOVEMENT OF GLACIERS

Studies of glacier movement have been made by various workers including Sherzer (1907), Slater (1925), Chamberlin (1928), Washburn and Goldthwait (1937), Ahlmann (1940), Sugden (1940), and Matthes (1946). These studies indicate that the surface movement of valley glaciers is retarded near the confining walls and near the terminus where thinning occurs by wastage. The major factors which appear to influence velocity are slope of the surface over which the glacier flows, the resistance offered by this surface, and the thickness of the ice mass which is a function of the supply. The rigidity of the brittle crust and its changes with temperature variations may also influence velocity. This is probably a minor factor except on relatively thin glaciers. Another factor may be amount of meltwater within the ice since it promotes recrystallization, independent movement of grains, or transfer of material through pressure melting and refreezing or idiomolecular movement. Surface gradient differs from the slope of the floor and is so closely tied up with the supply of ice that it is considered to be an aspect of the thickness factor. The characteristics of the channel such as width and roughness influence ice velocity. Other factors being equal, velocity is greater in situations where the ratio of ice volume to contact surface is large, as is demontrated by the fact that the velocity in the center of a valley glacier is greater than near its confining walls. (Sherzer, 1907, p. 89; Ahlmann, 1940, p. 105; Matthes, 1946, p. 223).

Chamberlin (1928, p. 13) has postulated that glacier movement occurs as a series of small jumps or little elastic-accumulations and reliefs. This may well be true in the brittle upper portion which is often referred to as the zone of fracture. It seems less likely that the movement in the zone of flow would be of this nature, however, Bridgman (1936, p. 661) reports that plastic flow in 40 per cent of the substances he checked was not perfectly smooth. He states that a jump is terminated by the automatic healing of the rupture after which the phenomenon can be repeated, possibly ad infinitum. It seems likely that non-uniform movement at the surface would occur chiefly where the glacier flow meets any type of obstruction causing faulting in the ice. No doubt fracture can occur even in the zone of flow if stresses are applied rapidly enough, analogous to deep focus earthquakes which are believed to be caused by fracturing in the zone of rock flow. At times stresses are probably applied rapidly enough to cause deep fracturing when a glacier makes a sharp bend or is passing over an uneven floor, if its velocity is great enough to allow sufficient stresses to build up. The products of this fracturing may be the blue bands and shear zones seen near the terminus of glaciers. Conclusions reached by one of the more recent studies (Washburn and Goldthwait, 1937, p. 1659) that the movement, based on half hourly observations, is extremely jerky seem unjustified.

Two types of movement studies were made on the Seward firn field. One was a relative measurement made by recording through transit surveys, the movement of a long line of wooden dowels set deeply in the firn surface near the Airstrip. The other was a study of absolute surface movements made with a surveyors level set on bedrock and a level rod in horizontal position on a valley glacier.

In the relative movement study, 9-foot wooden dowels, $\frac{3}{4}$ inch in diameter were set about 6 feet deep in a straight line at intervals averaging 600-700 feet. Two lines were set starting near the airstrip camp, one 4820 feet long with a bearing of N47°44'W, the other 7184 feet long and bearing S34°45'E. The lines were established July 29 and August 1, 1948 respectively and the relative positions of their dowels were checked on August 23 and

August 24,1948 in the same order. The results are given in Figure 11 which shows that the Airstrip was moving more rapidly than the extreme ends of either line. This was expected from surface indications. The absolute southwestward velocity of neither the Airstrip nor any of the dowels is known, but the displacement in 23 days of the Airstrip relative to the ends of the surveyed lines was approximately 113 inches more to the southwest than the easternmost dowel of the southeast line and about 37 inches more to the southwest than the westernmost dowel on the northwest line. The chief reason for the difference between these relative movements is the great difference in the length of the lines.

The study of absolute movements was made on a small glacier to the east of the Base Nunatak named Institute Glacier by the expedition. Figure 12 is an aerial photograph of the area and shows the location of the instruments. The measurements were made with a Keufel and Esser level mounted on a sturdy tripod and shaded by a small tarpaulin (fig. 13). A level rod mounted in horizontal position (fig. 14), and capable of being read to the nearest 0.05 foot, was used in conjunction with the level. The level was left mounted and was not touched for the duration of the observations. Observations were made every fifteen minutes part of the time, and the results were very enlightening though of no value as to the absolute movement of the glacier. According to the readings the glacier surface moved upstream during part of the day. After checking the instrument on a bedrock reference point across the valley, the conclusion was reached that the instrument was shifting sufficiently to alter its angle as much as 0.2 of a foot in 15 minutes by temperature expansions on the adjustment screws. The instrument,even though shaded, usually went through a diurnal cycle apparently controlled by the temperature and position of the sun. If the velocity of the glacier had been several times greater, this instrumental shift might not have been

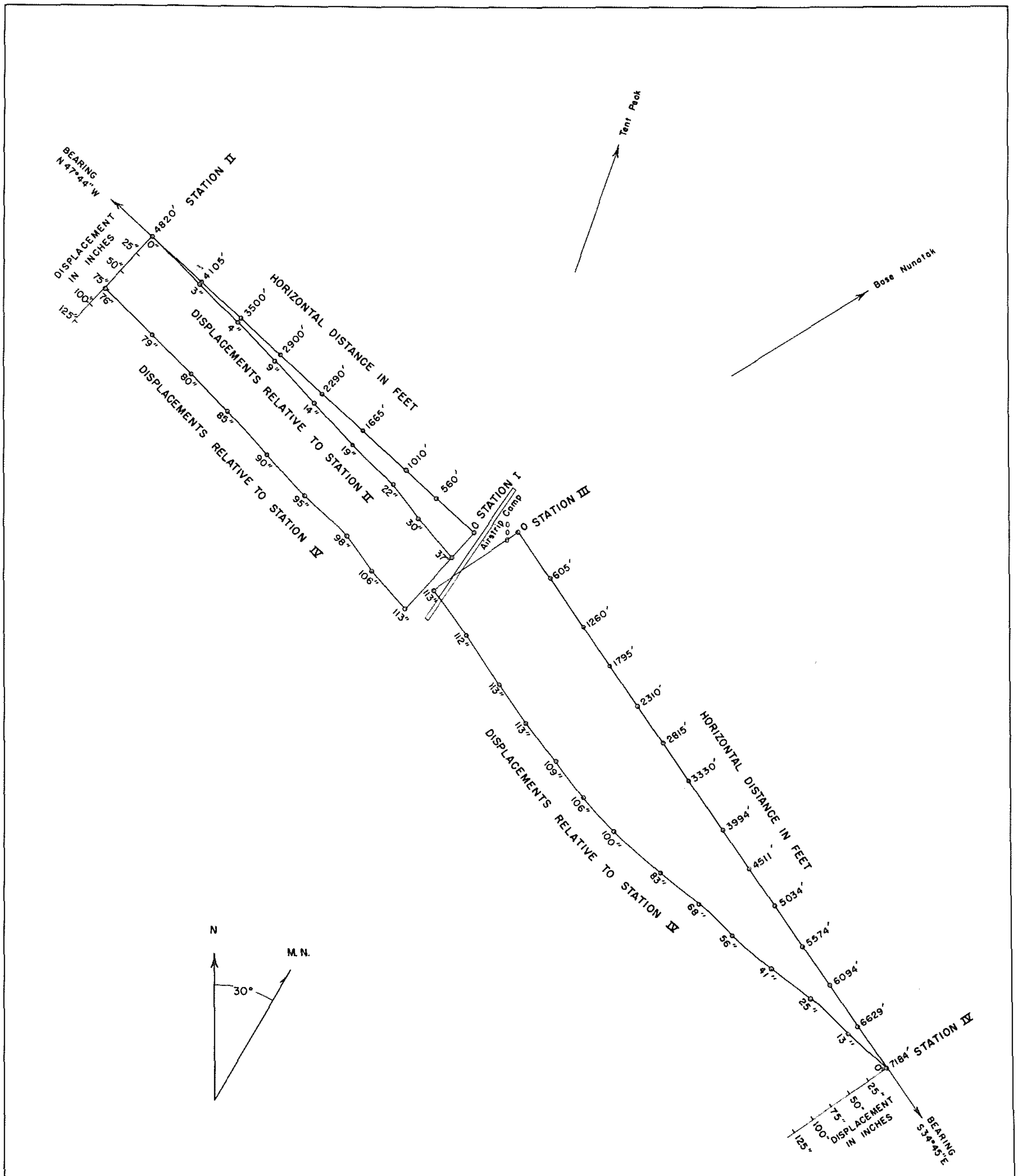


Fig. 11. Relative movement along lines of dowels. Absolute movement to southwest.

Fig. 12. Aerial photograph looking east at eastern edge of Seward Basin.

A - Airstrip Camp
B - Nunatak Base Camp
C - Location of Surveyor's level.
D - Location of rod.

Sta. I and III - Ends of relative movement lines (See Fig. 11.).

Fig. 13. Observation of glacier movement through level.

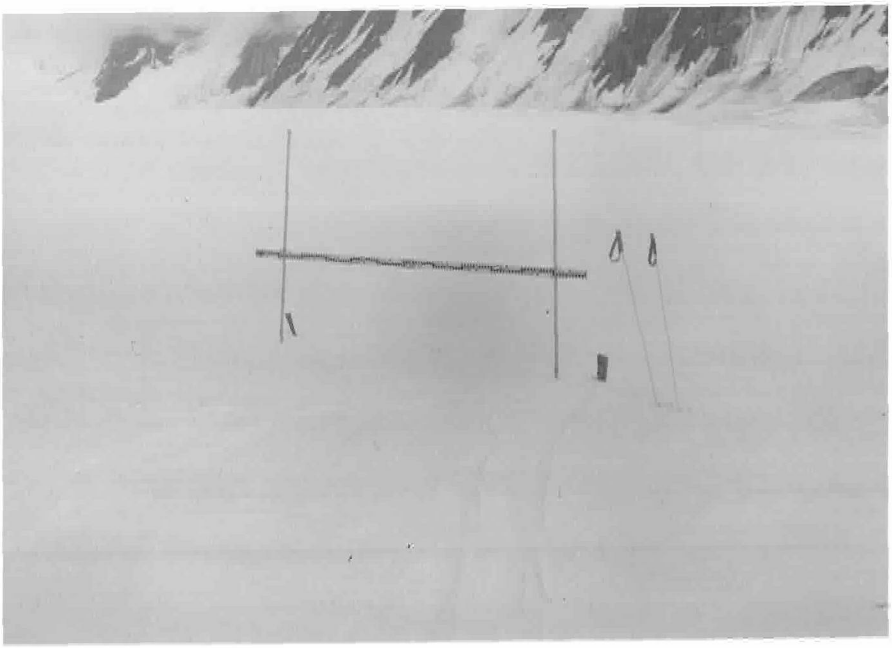


Photo by R. P. Sharp

Fig. 14. Stadia rod installed for movement studies.

discovered, and a cyclic variation in velocity for the glacier surface might have been assumed.

These results indicate that some earlier reports of the glacier movements may be in error, especially where conclusions are reached that the glacier moves most rapidly during certain hours of the day. Such temperature effects may have caused migration of the instruments producing an apparent decrease or increase in velocity.

It is believed by the author that such effects may have occurred on the South Crillon Glacier, Crillon Lake, Alaska, from the study of which Washburn and Goldthwait (1937, p. 1655) conclude that the rate of movement of a typical Alaskan valley glacier is irregular, varying from zero to a maximum of nearly 6 centimeters an hour. These authors also state that several periods of accelerated velocity occur during the course of each day. These conclusions may not be valid unless one is sure he has eliminated all possibilities of temperature effects on the instrument. Because of the experience on the Seward Glacier, the present author wonders if these periods of faster motion described by Washburn and Goldthwait may not have been the product of a cyclic instrumental variation found during the Seward work.

It is difficult to believe that a thick mass of ice can be sensitive to small diurnal changes in temperature, especially since the surface during most of the summer is at a constant temperature. Of course there is the small possibility of some effect caused by meltwater which varies with diurnal changes, but glacier ice in the zone of flow probably is not very permeable. Meltwater effects would be so greatly delayed (owing to slow percolation) as to be wholly out of phase with the observed variations in temperature. Also, as most of the flow apparently occurs at depth in a glacier, the lower ice merely carrying the surface along with it, it does not seem possible that diurnal changes can affect the glacier velocity at all. Since only the surface ice to a depth of not more than 40-50 feet appears to experience annual temperature change on the Seward firn field, it seems reasonable that a thick ice mass such as the South Crillon Glacier could be only slightly affected even by annual cycles of temperature changes. A more rigid crust caused by hard freezing would probably influence flow more on thin glaciers than on glaciers where the winter's chilled layer composes but a small proportion of the total thickness.

The accuracy of the measurements, made by Washburn and Goldthwait (1937, p. 1658), might also be questioned because of the slumping of their marker or target. They state that several observations were missed because of this fact. The author's limited experience with any object set on the surface of the ice has shown continual shifting and slumping by ablation. Only by sinking a pole or pipe deeply into the surface was a marker made sufficiently stable to be useful.

It is suggested that the temperature effects on the instrument may be almost completely eliminated by constructing a sighting system with as long a base as is practical on bedrock. The telescope of the observing instrument can be used as the rear sight, and a pipe with a knife edge for centering the cross hair as a front sight. These should be set firmly to the bedrock by cement if possible. The distance between these two sights could, in many cases, be 50 to 100 feet giving a long sighting base for greater accuracy.

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