American Alpine Club Research Fund

15. GLACIERS OF THE GANNETT-FREMONT PEAK AREA, WYOMING

MARK F. MEIER

IT was the author's privilege to spend the summer of 1950 studying the glaciers of the higher regions of the Wind River Mountains. This study was made possible largely by the aid of the American Alpine Club Research Fund. The author wishes to take this opportunity also to thank a number of persons who very generously assisted him on the project. Among them are Professor F. M. Fryxell, Dr. David M. Delo and, most particularly, Professor A. C. Trowbridge, who directed the study. Mr. Charles F. Darling acted as field assistant and proved to be a most able collaborator.

I. General Description

Glaciers of the Wind River Mountains occur generally at high elevations along the Continental Divide. The greatest concentration is along the east slope of the Divide from Gannett Peak (13,785 ft.) to Knife Point Mountain. Most of the area is accessible only on foot, and only two brief descriptions of the glaciers have been published.[1]

The largest known glacier in the range is Gannett Glacier. As measured by maps constructed by the author from aerial photographs, it has an area of 1.77 square miles or 1130 acres. In the area studied (from Bastion Peak south to Knife Point Mountain) were found seven ice masses larger than Sperry Glacier (Glacier National Park), now the largest body of ice in other ranges of the Rocky Mountains of this country.

Morphologically, four of the ice masses in the Gannett Peak-Fremont Peak area are valley glaciers; two are large, palmate cirque glaciers; and ten are small cirque glaciers. Many vestigial glaciers or glacierettes occur throughout the range.

[1] C. K. Wentworth and D. M. Delo, "Dinwoody Glaciers, Wind River Mountains, Wyo.," *Geol. Soc. Amer. Bull.,* XLII (1930), 605-20; D. M. Delo, "Recent Recession of Dinwoody Glaciers" (abstract), *Geol. Soc. Amer. Bull.,* LI (1940), 1924.

FIG. 1. UPPER PORTION OF MAMMOTH GLACIER
Taken from point on sharp ridge which encircles southeast margin of Minor Glacier, looking south-southeast. Twin Peaks in center of background, and Mount Woodrow Wilson on extreme left

FIG. 2. POSITIONS OF TERMINUS OF GOOSENECK GLACIER
Gannett Peak (13,785 ft.) in background

Photos, M. F. Meier

II. Typical Glaciers

Mammoth Glacier is the only large glacier west of the Divide. It is a valley glacier nearly two miles long, and has an area of about 1.55 square miles. The terminus now extends about 0.3 miles farther than is shown on the U. S. Geological Survey Fremont Peak quadrangle (1909), but this discrepancy may be due to generalized mapping. This glacier carries more flour and silt in relation to its total load than do other glaciers in the area, probably owing to comparative vigor of bedrock erosion and to absence of high cliffs bordering the ice which might supply coarse debris by avalanching. No medial moraines or dirt bands were observed.

Dinwoody Glacier is the most accessible of the Wind River glaciers, and was studied in most detail. It is a palmate glacier lying in a large, compound cirque. Excluding one small, separate ice mass (Gooseneck Glacier), which was connected to the main glacier in 1930, the area of Dinwoody Glacier is 1.34 square miles, and thus is the fifth largest of the glaciers studied. The central portion of the glacier is nearly flat and rather poorly drained, and "snow swamps" are frequent. The surface of the glacier is covered with much coarse debris from avalanching and from the coalescence of medial moraines.

Upper Fremont Glacier (one of the Bull Lake Glaciers) consists of two parts. A higher ice mass, resting on the gently-sloping east flank of Fremont Peak, tapers to a narrow throat; this constriction feeds a lower cirque-type glacier. That there is an actual transfer of ice through the steep, narrow throat is indicated by evidence of crevassing beneath the snow and by the pattern of dirt bands on the glacier below. This glacier has a low average gradient, and is eroding only slightly.

III. Regime

Inferences on the regime of a typical Wind River glacier during the 1950 season are based on a series of measurements on Dinwoody Glacier. The surface ablation[2] on a water-equivalent basis was

[2] This was measured from late July until the beginning of winter snow in September. The values given here include ablation extrapolated to the beginning of the season. Because of the abnormally late spring in 1950, this early ablation was probably a minor portion of the total.

found to vary from 112 inches to 17 inches; the average over the glacier was about 52 inches. The maximum rate of ablation recorded was 3.4 inches per day over a three-day period. Recent work[3] has shown that the sum of total accumulation and total ablation at the firn limit is a close approximation to the regime of the glacier as a whole. Based on this observation, the sum of accumulation and ablation over the entire glacier has been computed to be about 44 million cubic feet (3.6 mill. $m.^3$ per $km.^2$), and the excess of accumulation over ablation to be about 11.6 million cubic feet (0.94 mill. $m.^3$ per $km.^2$). The average accumulation over the glacier must have amounted to more than 80 inches. This large figure is explained partly by wind-drifting of snow into the protected cirque.

Since nearly all glaciers are retreating at the present time, these regime figures must be regarded as unusual. In 1950 a heavy winter snowfall in the mountains was followed by an exceedingly late spring, causing an increase in total accumulation and a marked decrease both in length and vigor of the ablation season. At the end of the summer only 34% of the area of Dinwoody Glacier was below the firn limit, and on many glaciers this figure was even lower.

The fact that this positive regime is not typical is indicated by many evidences of present-day retreat of Wind River glaciers. All the glaciers visited had receded considerably since the construction (probably in the late 19th century) of large terminal moraines. The terminus of Dinwoody Glacier is now located over 900 feet from the crest of its moraine, suggesting a thinning of 250 to 300 feet. Photographs taken in the period from 1930 to 1940 show very rapid recession. During this time Gooseneck Glacier separated from Dinwoody Glacier proper and retreated nearly 2000 feet up the lower slopes of Gannett Peak (Fig. 2). Since 1940 the general recession has slowed appreciably, and since 1945 the terminal retreat of some glaciers has become practically negligible. There is abundant evidence of thickening of snow fields at high elevations in recent years, but probably the general retreat and thinning at moderate and low elevations are continuing.

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[3] H. W. Ahlmann, "Glaciological Research on the North Atlantic Coasts," *Roy. Geog. Soc. Res. Ser.* 1 (1948), 55-56; C. C. Wallén, "Glacial-Meteorological Investigations on the Karsa Glacier," *Geog. Annalen,* XXX (1948), pts. 3 and 4.

IV. Surface Features

Prominent on Dinwoody Glacier are medial moraines, consisting of a surface concentration of angular debris arranged in lines parallel to the flow of the glacier, and originating below the confluence of tributary glaciers. Apparently these do not result from the junction of two lateral moraines, but are formed from material which has been deposited in randklefts (moats) at the sides of tributary glaciers, and brought to the surface well down on the main glacier by rotational motion of the central body of ice.

Dirt bands, either parabolic or irregular, are noted on many of the Wind River glaciers. These are believed to represent annual banding of the type described by Fisher[4] as Alaskan-type bands. Below icefalls these bands are highly contorted by folding and thrust faulting (Fig. 3).

Some curious detrital ridges emerge from beneath the terminal ice of several glaciers. These are flat-topped, up to 15 feet high and 15 feet wide on top, sinuous and sometimes branching; they seem in all cases to be parallel to subglacial drainage. The ridges are composed mainly of sand and gravel, with some larger blocks. No foreset bedding could be observed, but one ridge showed traces of crude topset bedding. It is thought that these are esker-like features deposited in choked subglacial stream channels.

Numerous grasshopper remains, poorly preserved and often flattened, were found only on Minor Glacier. In times past, grasshoppers have been reported from other Wind River glaciers. Why they are now confined only to Minor Glacier is not clear.

A low rock nunatak on Gannett Glacier was visited several times. On the upstream side the ice had separated from the rock, and it was possible to travel back under the glacier for over 100 feet. Far back under the glacier several roles or tubes of ice, like toothpaste squeezed from a tube, emerged from a point where ice was tightly pressed against an obstruction of rock. It is believed that the pressure of ice perpendicular to the obstruction was here sufficient to exceed the yield stress of ice, and to cause this ice to be extruded plastically. When the pressure is released, the ice becomes hard and brittle, preserving the extruded shape. Many crystal rubbings of ice crystals were taken at this interesting location.

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[4] J. E. Fisher, "Dirt Bands," *A. A. J.*, VII (1949), 309-317.

This brief study probably serves to introduce and suggest more problems than were solved. Some of the more important areas for further study might include investigation of the glaciers farther north of Gannett Peak; determination of velocity of flow at different points on Dinwoody Glacier (this would require use of a precise transit or theodolite); and a meteorological study of regime. Future measurements of the retreat or advance of these glaciers may be facilitated by my set of photographs taken from marked locations, which show the snouts of the 12 glaciers visited.

16. THE JUNEAU ICE FIELD, ALASKA, 1948-51

MAYNARD M. MILLER

The success of advanced techniques employed by glaciologists in Europe in the past several decades and an ever-increasing interest in the northern frontiers of our own continent, because of recent world events, have added considerable impetus to planning for the Juneau Ice Field Research Project. Initiated in 1948 and continued through the summer seasons of 1949 and 1950, with the enthusiastic support of the Office of Naval Research, the American Geographical Society and a number of other Government and civilian agencies, this project has had for its primary objective achievement of a full-scaled systematic study of one of the largest remaining centers of highland ice on the North American Continent.

The Juneau Ice Field, chosen as the locus of our project, is uniquely situated to serve as a field laboratory for a long-term integrated research program. Lying at the crest of the Alaskan Coast Range, at approximately latitude 58° 40′ N., the region of activity encompasses approximately 750 square miles of interconnected glaciers and highland névé. It offers an opportunity for the thorough study of various phases of glacier science both at low altitudes and at the upper levels. The accessibility of this ice field is a particular advantage—coupled, of course, with its unique scientific interest.

The main base camp, located near the center of the ice field, is less than 40 air miles north of Juneau, the capital of Alaska. Civilian air service is available from that city for charter flights. In addition,

FIG. 3. CONTORTED DIRT BANDS
Exposed in a randkleft below a heavily crevassed area on Dinwoody Glacier. Note folding and thrust faulting

FIG. 4. BENEATH GANNETT GLACIER
Chuck Darling, who assisted the author in the field, is sitting on bedrock, with the glacier passing over his head. The peculiar gray mass behind him is extruded ice which is entirely separate from the ice above

Photos, M. F. Meier

excellent air fields in the area provide bases for the Government aircraft cooperating in the project. Besides aiding immeasurably in the transport of equipment and supplies, the use of aircraft has enabled a number of scientific advisors and specialists, who could not otherwise have visited the area, to work on the project for short periods of time. Besides its accessibility by air, several usable routes permit one to reach the locale on foot, since the western fringes of the ice field lie only about a dozen miles from the city limits. The nearness of river boat facilities and the availability of a major center of expeditionary supply at Juneau, together with the previously mentioned factors, make the Juneau Ice Field a much more practical area for such research than almost any other in the Western Hemisphere.

Six men took part in the five-week reconnaissance expedition in 1948.[1] Valuable information was gathered, not only on the nature of the terrain and on weather conditions, but on equipment, food and expedition techniques for living and conducting research on a sub-arctic ice field. A series of glaciological, botanical and meteorological observations was begun to pave the way for a more extended research program the following year.

During the winter and spring of 1949, a full program of geological, meteorological and ecological investigations, as well as the strictly glacial study, was organized. A total of 25 civilians participated in the summer season's work. A 12-man nucleus was maintained at the high-level camps through most of the 105 days the project was in the field.

A main meteorological and research station was constructed during this second field season on a rock island on the upper Taku Glacier, 16 miles above its tidal terminus. This is a well-insulated, wooden-framed and aluminum-sheathed building, equipped with living facilities, provisions and scientific instruments both for summer and winter investigations. This central station serves as the logistic and communications hub for field work extending to the 18 outlying camps. Established for the use of field parties, these camps have been supplied with equipment and provisions, and caches are being maintained for future use.

Much of the delivery of this equipment has been accomplished

[1] M. M. Miller, "1948 Season of the Juneau Ice Field Research Project," *A. A. J.*, VII (Jan. 1949), 185-91.

ALUMINUM-SHEATHED CABIN AT CAMP 10, UPPER TAKU GLACIER

CAMP 10 B, UPPER TAKU GLACIER

Photos, W. O. Field

through the cooperation of the Air Force's Tenth Rescue Squadron. On the flat névé of the Taku Glacier one mile west of the main base, a ski-wheeled C-47 effected 22 landings during 1949 and 1950. With jet-assisted take-offs, this large airplane was successful in bringing in many tons of equipment and supplies as well as in transferring personnel to and from the ice field. In addition to this Air Force support and that of the Office of Naval Research and the American Geographical Society, considerable material support for our work has been given by the Department of the Army, the United States Forest Service, the United States Geological Survey, the Weather Bureau and a number of civilian agencies.

The Arctic Institute of North America also contributed to the project. Its efforts in connection with a cooperative and correlated project on the Seward Glacier in Canada's Yukon Territory during the summers of 1948 and 1949 should also be mentioned here because of the pioneer work it has accomplished in helping to initiate this type of field research in America.

The results of our 1949 season were so gratifying that it was decided to send a party in for another season. So, in 1950, we began our third field season on the Juneau Ice Field, during which 110 days of field work were accomplished. A total of 29 men participated in this phase of the project, with a nucleus of 14 men being maintained on the ice field during most of the season.

A number of interrelated studies pertaining directly to the physical nature of snow and glacier ice have been carried out on the Juneau Ice Field during the past three years. Only some of them can be mentioned here. They included studies of the firn to determine its water content; of the manner and rate of meltwater circulation, density and structure; of the annual accumulation of snow during as many previous years as could be detected; of surface movement of ice in different areas and of ablation of the surface at different points on the névé; and of the maximum height of the summer snow line at the end of the melting season in September. Several of the techniques employed have been experimental and previously untested.

GLACIAL STUDIES

Top, left: Toothed ice corers, used for obtaining samples of known volume from pit walls for analyses of density and liquid water content

Top, right: Stanford seismologists (left, S. W. Miller; right, C. F. Allen) adjust their geophysical equipment for depth determinations on Upper Taku Glacier

Bottom, left: Dr. Henri Bader studies samples of ice from drill hole on Upper Taku Glacier

Photos, M. M. Miller

Bottom, right: Sprinkling insoluble lead oxide dye on the névé at Camp III (September 1948), to record level of late summer ablation surface. Wooden stake implanted to record surface movement by instrumental means

Photo, W. R. Latady

In the summer of 1950 a Rotary Pioneer Straitline Drill Rig on loan from the E. J. Longyear Company, of Minneapolis, was used to obtain samples of névé and undisturbed ice cores at a depth of nearly 300 feet. This is the first successful core drilling of a temperate glacier in the Western Hemisphere, and the results will serve as a valuable adjunct to the results of drilling in polar ice being undertaken by the joint British-Scandinavian Expedition to the Antarctic during 1949-1952. Petrofabric studies of ice cores were conducted in a cold laboratory dug into the névé near the site of this drilling. There, under polarized light, mineralogic and petrofabric analyses were made on ice cores brought up from drilling to depths of 150 to 292 feet.

Meteorological records were begun at six high-level stations. We were particularly fortunate in this work in having available to us, for comparison with our records, data from a number of near-by meteorological stations, one with weather records as far back as the 1880's. This represents a longer period of standard observations in proximity to an ice field than at any other glacier locality in America. A staff of at least three meteorologists was maintained continuously on the ice field during both the 1949 and 1950 seasons. Observations were obtained not only at the main central research station, but also at various intermediate stations. Studies were made of variable wind, humidity and temperature conditions, from the névé up to 40 feet above its surface. An accurate record was obtained of duration of sunshine and the actual caloric amount of insolation received at this latitude. The relation of ablation and meltwater rates was investigated for correlation with the amounts of solar radiation, and the temperature of rainwater, wind effects and other factors controlling surficial changes in the névé and the drainage of melt water. Such data will aid in evaluating the radiation heat budget of the ice field as a key to understanding what quantitative effect meteorological and climatological conditions have on the regimen and the post-maximum glacial fluctuations in this area and at this latitude.

Other members of the field party were engaged in mapping the region and in carrying on geological and botanical observations. During the past two seasons, several members of the field party have been mapping and studying bedrock outcrops and transferring geological data on vertical aerial photographs taken by the United States Navy in 1948. An extensive collection of geological specimens has been made for petrologic analysis. A three-man low-level team and a high-level plant ecologist were made a part of the general program of study. Their detailed studies revealed much of interest both to glaciologists and to plant ecologists.

The geomorphic history of the ice field and its related glaciomorphological features is being interpreted in order to correlate with studies of snow and ice as well as with the botanical investigations made in the peripheral portions of the area. The bulk of this phase of the field work, however, is yet to be done in the 1951 summer season.

Meanwhile, the geophysical team in 1949, under the direction of Dr. T. C. Poulter, accomplished its studies of ice thickness on the Taku Glacier. This ice stream was selected because of a unique situation existing there. The Taku Glacier has been advancing since about 1900. In 1890, the United States Coast and Geodetic Survey mapped the inlet and made soundings nearly to its tidewater terminus. By a computation of the elevation above sea level of the present ice surface, the total thickness of the glacier can be determined. Such a combination of factors, probably not found anywhere else in the world, provides unusually favorable circumstances in which to test the equipment and methods for measuring the thickness of ice. The method used, in which light charges are set off above the surface and the travel time for the resulting seismic waves measured, was devised by Dr. Poulter while he was acting as senior scientist on the Second Byrd Antarctic Expedition, 1933-35. Our program permitted the first successful test and refinement of the Poulter seismic method on temperate glacier ice since its development on polar ice.

Another significant program of research was begun in 1949 by the plant ecology team under the direction of Dr. D. B. Lawrence, of the University of Minnesota. He has assembled sufficient data from tree-ring studies on recessional moraines of five outflowing glaciers to formulate a rather convincing theory of synchroneity of six centuries of glacier variations to dated sunspot minima, and hence to what may be a causal relationship with extraterrestrial variations in solar radiation. The unique opportunity afforded by such botanical methods was extended in 1950 to a detailed pollen analysis of selected horizons of ice, snow and even muskeg in order to determine their age and structural relationships.

In addition to the basic scientific observations, a program of food and equipment testing and logistic experimentation has been carried out each year. A minor medical research program has been initiated, and information pertinent to emergency and practical expeditionary techniques has been gathered. Perhaps most important of all, a number of scientists have been trained in the techniques of field work on glacier, mountain and arctic terrain, and a number of young scientists have become vitally interested in the work of this project and other field studies in northern areas.

Our research station on the Juneau Ice Field is only a beginning. A small research party went in to the ice field by ski-plane during January and February 1951 to continue some special observations under severe midwinter conditions. This six-man party found much of interest in the understanding of the ice field's year-round regimen. Sub-zero temperatures were encountered during most of this period, and up to February 1st approximately 20 feet of new snow had fallen at the main base. Instruments left on the ice field the previous summer were read, and a special winter program of snow, ice, and weather study was commenced.

It is our hope that we may extend these detailed investigations in the years to come, on a periodic, and perhaps occasionally on a year-round, basis. We also hope that institutions and individuals will continue to show the same high interest and give the same fine support which has enabled us successfully to carry on this program of basic field exploration and research in these past four years.

17. DIRT BAND PROJECT

JOEL E. FISHER

In August 1946 an experiment was started on the Glacier du-Géant-Mer de Glace above Chamonix.[1] The object was to gain

[1] *A.A.J.*, VI (1947), 328-32.

further insight into the method of formation of Forbes dirt bands. Small piles of glass beads were deposited on the surface of the ice in a row 150 meters long, immediately above the icefall on the plateau of the Glacier du Géant, in a longitudinal direction. The piles of beads were five meters apart, and each pile contained about one tablespoonful of very small, brilliantly colored glass beads—scarlet, purple, navy blue, yellow, etc.—which could not be confused with duller-colored native minerals. Referring to the profile of the Mer de Glace icefall (Fig. 2), this line of beads ran, in 1946, down-glacier from the point marked *"Elev.2700 M.,"* off to the left. The idea is to check the spacing of these piles after some 20 years, when the entire line will have moved on down below the icefall, and should begin to reappear on top of finger 13 in Figure 2. (Finger 13 may be identified in Fig. 1 as the first vague indication of a true Forbes dirt band.) It seemed nevertheless to be worth reexamining the bands and the icefall of the Mer de Glace in the summer of 1950 in the light of other observations made under the auspices of the American Alpine Club Research Fund in the summer of 1948.

These 1948 observations were made on a lane of uniquely white bubbly ice among several lanes of normal clear ice on the Gornergletscher, above Zermatt.[2] (See Fig. 3.) In brief, the ice of that white lane was found to be permeated with air bubbles to such a degree that its density measured only 0.82 in contrast to that of the clear ice on either side, which was 0.91. The remarkable whiteness of the bubbly ice is due to two factors: first, the snow-like optical qualities; second, the lack of dirt on the surface, because the rock and dust particles melt themselves about ten centimeters into the ice, concealing themselves from any line of sight not in the axis of the tiny holes above them. In the light of this finding, there was particular interest in reexamining the Mer de Glace to find out whether the ice in the white bands was similar to that in the white lane of the Gornergletscher.

This was found to be the case. Facilities for measuring the relative densities of clear normal ice and white bubbly ice were not at hand last summer; but Figure 4 shows specimens of normal and

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[2] Joel E. Fisher, "Ice Pyramids on Glaciers," *Journal of Glaciology,* I (1950), 373-7.

bubbly ice from a typical pair of bands side by side—normal darker ice at the right and white bubbly ice at the left. As the density of clear glacier ice is 0.91 and as that of the extremely bubbly ice of the white lane on the Gornergletscher was 0.82, it is the writer's opinion that this bubbly ice of the Mer de Glace has an intermediate density of about 0.85. Figures 5 and 6 show close-ups of the surface of the same pair of bands on the Mer de Glace from which the specimens of Figure 4 were cut. Figure 5 shows clearly how surface dirt bores its little dust wells into the surface of bubbly ice. Bottoms of these holes, with dirt visible, can be seen only when they are directly under the observer's eye; at any angle, even slight, the eye sees only clean ice. Figure 6, on the other hand, shows how dirt remains on the surface of normal ice. Figures 5 and 6 were taken within three minutes of each other, so that there is no need to allow for the surface of ice having changed by ablation between the two photographs. The observations recorded in Figures 4, 5 and 6 were made at fingers 34 and 35 in the profile (Fig. 2).

The writer had previously concluded that bubbly ice névé develops only where firnification takes place with a minimum of melt water present, characteristically, under conditions of exceptional cold. For example, the white lane of the Gornergletscher was traced by the writer, in July 1950, back to its origin. Its area of accumulation was found to be a full square kilometer of snow fields high up against the Silbersattel of Monte Rosa, at an elevation of 4200 to 4500 meters with a northern exposure. Monte Rosa is well-known as a cold mountain; and this area of accumulation—the only area of such size, at such an altitude, in the Alps—more closely simulates true high arctic conditions than any other in the Alps, and therefore is likely to be conducive to such bubbly ice formation.[3] Bubbly ice is reported as common, sometimes omnipresent, in high arctic glaciers.[4]

It remains to deduce what peculiar mechanism could introduce into this Mer de Glace, every year, a vertical cross-glacier dike of ice, firnified under dry cold conditions, without melt water—conditions directly opposite to those controlling the firnification of its

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[3] Henri Bader, "The Significance of Air Bubbles in Glacier Ice," *Journal of Glaciology,* I (1950), 443-51.

[4] E. V. Drygalski and Fritz Machatschek, *Enzyklopädie der Erdkunde und Gletscherkunde* (Vienna, 1942), p. 74.

adjoining side walls of normal clear ice. It is clear that these broad bubbly ice bands must extend down below the surface at least as far as the amount of surface ice to be removed later by surface ablation during the years of flow to the snout. This period is counted by the number of white bands, each representing a year's flow, between the foot of the icefall (finger 13) and the snout of the glacier, some 50 bands beyond the left edge of Figure 2—75 bands in all. Additional evidence that these bands provide an accurate count of a year's flow is supplied by the movement of an enormous erratic boulder which the writer observed and photographed in 1912, located then at finger 9 in Figure 2. In 1950 this boulder had moved down to what would be finger 47—38 bands in 38 years. Its size so far exceeds that of any other on this glacier as to require no identification beyond a comparison of photographs taken in 1912 and 1950.

The basic mechanism leading to the formation of these white ice dikes was described in 1949 as the origin of Forbes dirt bands.[5] It was described how a glacier, on riding out over the rim of a step in its bed, cascading down that step as an icefall, will be broken off by *regular annual glacier-wide* crevasses at the top of the fall, if the edge of the step is straight, if the volume of the glacier is sufficient and if its velocity is within prescribed limits. Each winter's cold wave, penetrating the upper part of the ice, appears to strengthen the cantilever-like behavior of that ice as it is projected over the step. Cold thus defers the formation of the crevasses to the summer season. The yearly formation of a crevasse stretching right across the glacier results in the formation of glacier-wide strips or islands of unbroken ice across the icefall. (See Fig. 1.) If there is a sufficient cushion of flowable ice which does not fracture under the islands, they will ride more or less intact down the icefall. (See Fig. 2.) Otherwise, they will be completely broken up.

Consider now the great annual crevasse at the top of the icefall. Hardly has one season's annual crevasse opened before ice debris breaks off from its brittle side walls to begin to fill it up. Drifting winter snow will complete the back-filling of any such crevasse. As the glacier moves down the icefall, within two or three years,

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[5] Joel E. Fisher, "American Alpine Club Research Fund: 13. Dirt Bands," *A.A.J.*, VII (Sept. 1949), 309-17.

ice debris from above begins to smother the surface of the whole slope, covering ice islands and crevasses alike under one great smooth blanket. This shows well in the photograph (Fig. 1) and is marked in the profile (Fig. 2) as the tinted area at the surface between fingers 4 and 11. For several years this blanket of debris hides the structure of alternate crevasses and ice islands, developed at the start of the icefall.

Is it possible to deduce what will become of the snow and debris filling the annual crevasses as they flow down the glacier? First, we must remember that, before the crevasses formed, the ice was everywhere at the *pressure melting point.* But as soon as the ice opens in a crevasse, the ice in the wall of the crevasse, having no pressure on one side, is no longer at but *below* pressure melting point; so that the snow filling the crevasse must firnify in a sort of "deep freeze." The snow itself, accumulating in winter, will be well below its melting point, and free of melt water. These are just the conditions which have been found to lead to the formation of bubbly ice. The excessive friability of ice would lead to a far wider zone of brecciated, pulverized ice on each side of each wide crevasse than would be expected in rock faulting, so accounting for the breadth of resulting bubbly ice.

In each crevasse firnification of the back-fill proceeds with no water present, except for a thin superficial top layer into which summer melt water may percolate. As soon as the density of the ice reaches about 0.8, interconnecting passages between entrapped air will be sealed off.[6] By then, probably about the fourth year, this inlay is proof against all surface water seepage. After about 12 years, when the previously mentioned surface scruff of accumulation has been carried away by ablation, and, even further, when ablation has etched deeper to remove all the upper part of each back-filling that did experience some melt water during firnification (at about the position of finger 13), the true bubbly ice will begin to be exposed at the surface, to appear as dikes of white ice between intervening walls of darker normal ice.

In Figure 2 the profile has been drawn to show diagrammatically that crevasses extend down to a depth of some 200 meters.

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[6] G. Seligman and M. F. Perutz, *Proceedings of the Royal Society,* A, CLXXII (1939), 335-60; Bader, *op. cit.,* p. 445.

By this it is not necessarily meant that great gaping crevasses will remain open indefinitely at that depth. It is generally considered that crevasses will not stay open at depths greater than 50 meters; but cracks may extend down to 200 meters. Soft powder snow, pressing down into any such incipient downward extension of a crack, will fill it faster than it could close by slow sideways flow of ice. At depths greater than 200 meters, it is assumed that the hydrostatic pressure is enough to prevent any fracture whatever from forming: this is the region of true flow of ice (Fig. 2: dotted line). It is a layer of sufficient depth to produce, by reason of its depth and its flowability, a soft cushion on which the glacier-wide islands of ice may float down the icefall more or less intact. Such a cushion is undoubtedly one of the several prerequisites for the formation of Forbes bands.

It may be added that 200 meters is estimated to be the thickness of material removed by surface ablation over the entire life of the bands of the Mer de Glace, and it must therefore be that this bubbly ice finds opportunity to form at least that far below the surface in the icefall. If less than 200 meters of surface ice is removed by later surface ablation on the lower glacier, then a lesser depth through which bubbly ice might form would be sufficient. There appears to be no glacier of sufficient length, possessing Forbes bands, on which this can be tested.

These Forbes bands may then be considered to develop where there is a prescribed balance between volume, velocity of flow down an icefall, sufficient thickness of ice, and a sufficient seasonal variation in temperature across the freezing point. Such factors, interplaying with the principles of pressure melting points of ice or snow, produce, as described above, a sequence of dikes of bubbly ice, sandwiched, cross-glacier, between walls of normal ice.

The studies in 1950 did not deal explicitly with the origin of so-called Alaskan-type bands. They provided evidence, however, that a similar mechanism is at work: a seasonal stratification of snow, firnified under seasonally different amounts of melt water, results in horizontal laminations of alternately bubbly and normal ice. During extrusion flow these laminations are rotated and eventually appear as near-vertical dikes of white and dark ice lower down, resembling true Forbes bands so nearly as to be almost indistinguishable.