STUDIES OF CRYSTAL FABRICS AND STRUCTURES IN GLACIERS

Thesis by

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ABSTRACT

Optical orientation of approximately 5000 ice crystals was determined on the Emmons Glacier in 1950, the Malaspina Glacier in 1951, and the Saskatchewan Glacier in 1952, by means of a 6-inch universal stage mounted between crossed polaroid sheets. The crystals measured were 0.2-6 inches across, and from three to eighty were included in each $4\frac{1}{2}$ x 6-inch thin-section. The optic axes when plotted on a Schmidt equal-area projection, form consistent patterns which appear to be related to the foliation in the ice. The patterns usually feature four strong maxima at the corners of diamond shaped quadrangles. Concentrations of axes as high as 26 per cent in 1 per cent of the area were recorded.

Two possible mechanisms for producing common orientation of the crystals in glacier ice seem plausible. One is "instantaneous recrystallization" by means of which the atoms in a lattice become energized under stress and rearrange themselves into more comfortable positions. The second is the growth of crystals favorable to deformation on glide planes at the expense of those which are unfavorably oriented for gliding and consequently become strained and develop higher free energy.

From the study of fabric patterns in glaciers it seems likely that the crystals are oriented in such a way as to allow gliding either on two glide planes other than the well-known basal plane, or on the basal glide plane with the pattern later being changed by recrystallization, possibly by an ordered response within the crystals to the relaxation of stresses. This might be compared to annealing behavior in metals.

It is postulated that "solid flow" occurs in ice by deformation on glide planes and continuous recrystallization with migration of grain boundaries as local stresses on each crystal slowly change. The preferred orientation of crystals is probably developed by growth of crystals favorably oriented for gliding at the expense of the others.

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INTRODUCTION

General Statement

Crystal fabric studies offer a promising method of attack on the still troublesome problem of ice flowage. Glacier ice has recrystallized and flowed under stress and is truly a metamorphic rock. Therefore, application of the techniques of structural petrology to glaciers may eventually contribute to the problem of solid flowage in the more durable rocks. Because glaciers are monomineralic and flow in an observable environment on the surface of the earth, they should provide ideally simple subjects of study in comparison with the more complex metamorphic rocks. Surprisingly little crystal fabric work has been done on glaciers, that of Perutz (1940) in the Alps and of Bader (1951) in Alaska being the best known. The extensive studies of the late Max Demorest regrettably are largely unpublished. The studies reported here demonstrate impressive fabrics within glacier ice and raise a number of intriguing questions as to the mechanics of orientation and solid flow.

Ice, at the pressures and temperatures attained in glaciers, is in the hexagonal system, probably in the ditrigonal-pyramidal class C_{3v} (Palache, Berman, and Frondel, 1944, p. 494), although some recent work suggests that it may belong to the dihexagonal-pyramidal class C_{6v} and that it is hemimorphous with a polar hexagonal main axis (Rossmann, 1950). Ice, being optically uniaxial like quartz, lends itself readily to universal stage techniques in which the orientation of the optic axis can be easily measured in thin-sections and plotted for statistical analysis.

Glaciers Studied

Studies were made in the ablation zone of three widely separated temperate glaciers. The research was commenced on Emmons Glacier, Mount Rainier, Washington, during the summer of 1950 and was continued during the month of August, 1951, on Malaspina Glacier, St. Elias Range, Alaska. These investigations were completed in July and August, 1952, on Saskatchewan Glacier of the Columbia Icefield, Banff National Park, Alberta, Canada. The Emmons and Saskatchewan glaciers are typical valley glaciers and the Malaspina is the type specimen of a piedmont ice sheet.

Structural and Crystal Relations in Glaciers

Glacier ice commonly shows a regular planar structure usually consisting of alternate layers of relatively clear and bubbly ice, approximately 0.5-1 inch wide. On Saskatchewan Glacier the planar structure in many places consisted of layers of fine-grained, possibly granulated, ice, alternating with coarser-grained bubbly ice. Chamberlin and Salisbury (1909, p. 247) called this planar structure foliation, and most glaciologists since that time have followed this terminology. Orientation of the foliation was measured as accurately as possible with a Brunton compass on the three glaciers studied. It appears that the fabric of the glaciers is related to the foliation, but this will be treated in more detail later. The fabric investigations were supplemented by and integrated with studies of the megastructures and rates of movement where it was possible to do so.

Methods and Equipment Used

Universal stage.- A universal stage (fig. 1) with four axes of rotation, therefore comparable to a three-axis stage mounted on a rotating microscope stage, was designed and built by Rudolph von Huene, of the

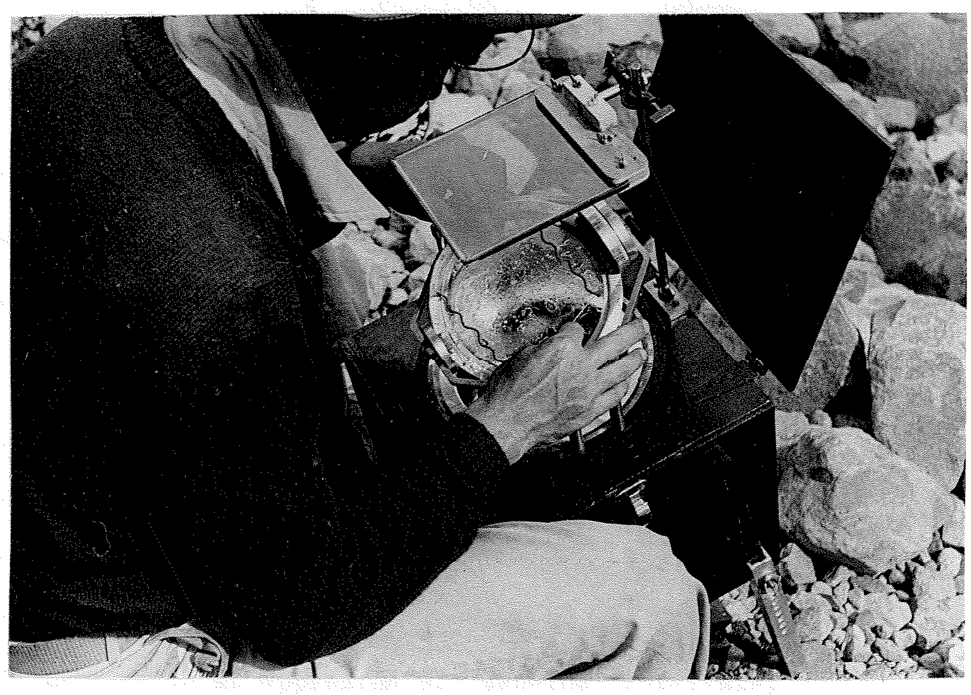

Fig. 1.- Top view of universal stage in use on glacier. Photograph by B. H. Bieler.

Fig. 3.- Method of cutting out ice blocks previous to making thin-sections. Photograph by B. H. Bieler.

California Institute of Technology, according to the author's specifications. This stage, mounted between two 6-inch squares of polaroid, accommodates a $4\frac{1}{2}$ x 6-inch thin-section of ice. It was machined out of brass and aluminum to prevent rusting by meltwater. The support for the stage also serves as a carrying case, making a compact and portable field unit.

Thin-sections.- Thin-sections of known orientation were prepared from slabs of firm, clean glacier ice (fig. 3). After debris and loose surface grains had been removed, the surrounding ice was chopped away, leaving a projecting block, from which several thin-sections were cut. Sections were taken at approximately two-inch intervals, so that the same ice crystals were generally not included in different thin-sections. Each section was cut about $\frac{1}{2}$ inch thick and "ground" to proper thinness by melting under a cooking pan filled with warm water. The bottom of this pan had been turned on a lathe to complete flatness and was applied to the ice slab with rotary motion. When the section was about 1/8 inch thick, it was placed on the stage, as thinner sections broke too easily. The final melting took place in 1 or 2 minutes by contact with the air or with the glass cover plate and stage. When the ice had melted to a thickness of about 1/16 inch, extinctions could be measured without appreciable error, although the interference colors were still high. By working rapidly and with the aid of a recording assistant, almost every grain could be measured before the section broke up or melted away.

Plotting of data.- Fabric diagrams were made by plotting the optic axes on the lower hemisphere of a Schmidt equal-area projection in the conventional manner. In studies of metamorphic rock fabrics, the optic axes of 400-500 quartz grains are frequently plotted on one diagram. Experience indicates that the fabrics in glaciers are so strong that 100 grains will easily reveal the pattern at any one location, and it is possible that too many grains confuse or disperse the pattern because of the increased size of the area from which they must be taken. This was demonstrated at several locations on Emmons Glacier where sections taken on successive days were separated by several inches because over night melting loosened the grains and necessitated a new source of ice slabs.

One hundred or more grains were measured at each location on the Emmons except where extremely large crystals required numerous sections. Later, on the Malaspina and Saskatchewan glaciers a minimum of 200 crystals per location was possible because the sections were cut vertically, the diagrams were later rotated, allowing more sections to be taken from an area of comparable size.

Sources of error.- No hemispheres were used with the universal stage, and inclinations of the stage of nearly 68° were required to measure axes inclined 45° to the thin-section. At such high angles, errors may have crept in. Inclinations of the axes of many grains which were oriented between 40° and 50° to the thin-section were measured, first, by orienting the optic axis parallel to the line of sight and, second, by bringing it parallel to one of the horizontal axes of the universal stage, which should give the complement of the angle measured by the first procedure. The sum of these angles totaled about 80° instead of 90°, even though corrected for index difference between ice and air. These errors may have been caused by various factors or combination of factors, such as the difficulty in locating the exact extinction at high angles, or because no means was available for keeping the line of sight exactly perpendicular to the plane of the stage. Thick sections of a crystal appear dark over angles of 20°-30° as one attempts to orient the optic axis parallel to one of the horizontal axes of the universal stage, but this factor should not have been important because the sections were allowed to melt until they showed sharp extinction positions. Professor F. J. Turner (personal communication) suggested that errors in measurements of axis orientation might arise from ice that had been strained enough to be biaxial, with an optic angle of several degrees. The behavior of ice in this regard is not known but the ice crystals did not appear to be biaxial on the universal stage.

Since the exact error is not known for each measurement and as it very probably decreases with decreasing angles, no correction has been made in plotting the data. It is believed that this error is no greater than 5° in any instance, and this will not affect the fabric patterns appreciably. The effect of the error for axes of high inclination is seen in the shape of contours for certain maxima located about 45° from the center of the fabric diagrams. At this angle the maxima tend to split. This is exemplified by the right-hand maximum at locations 3A and 4 on the Emmons Glacier (fig. 2). Because the critical angle for ice is between 49° and 50°, measurement of the inclination of optic axes making angles between 90° and 45° with the plane of the thin-section was always approached by the method of orienting the axis parallel to the line of sight. For axes inclined from 0° to 45° to the thin-section the method of orientation was always to bring the optic axis parallel to one of the horizontal axes of the stage. Since the measured angle apparently is always less than the true angle, a deficiency of points on the fabric diagram results at about the 45° position.

No doubt some grains appearing as separate units in a two dimensional thin-section were actually parts of the same crystal, and some errors of this type cannot be avoided. However, in an attempt to minimize this influence, recordings were made only once of duplicate orientations in the same

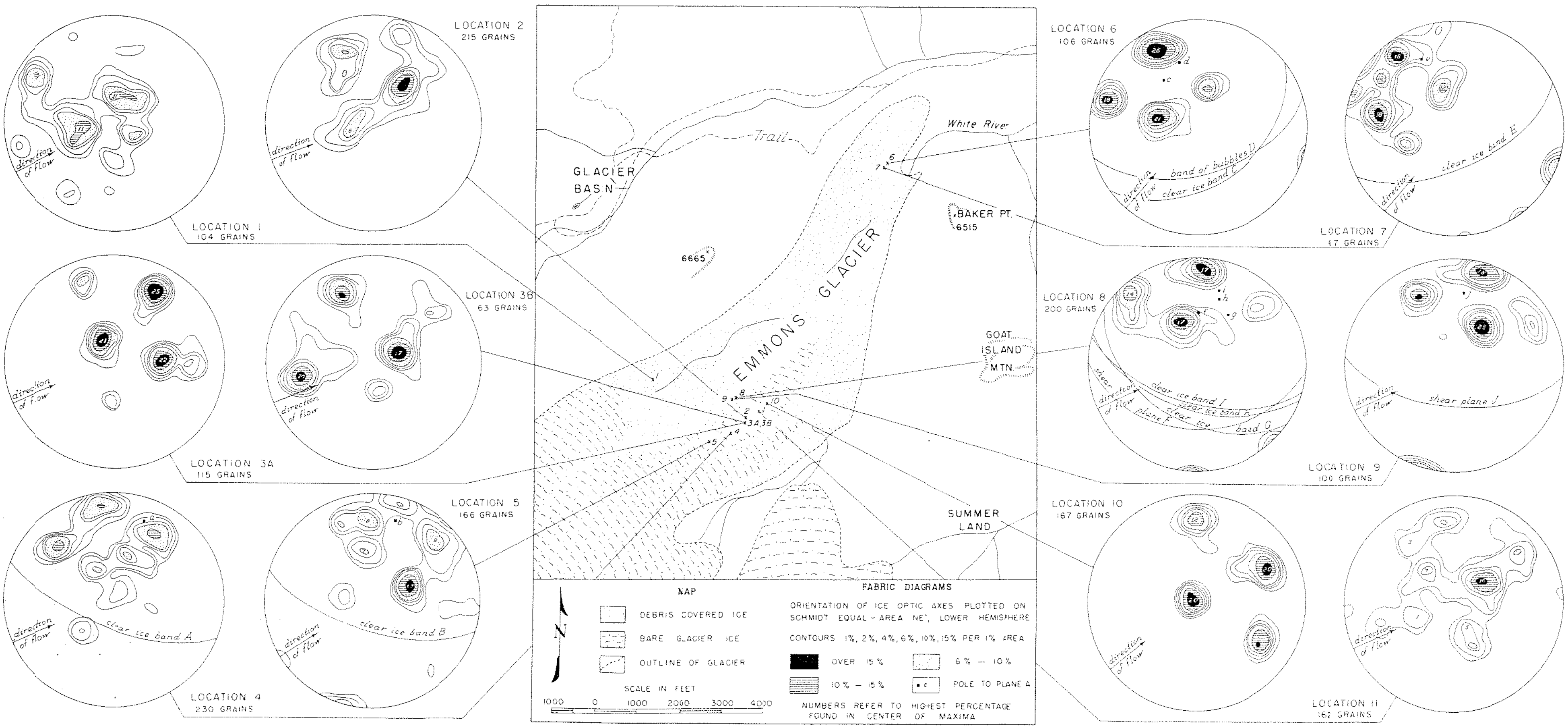

Fig. 2.—Fabric diagrams and outline map of Emmons Glacier, showing locations where thin-sections were taken

area of the thin-section. In coarse-grained ice only one recording was made for duplicate readings over the entire slide. Whenever several grains extinguished together on all axes of rotation, it was assumed that they were all parts of the same crystal following Bader (1951, fig. 2).

EMMONS GLACIER

Location and Physical Setting

Emmons Glacier on the northeastern side of Mount Rainier, Washington (map, fig. 2), is the largest of the twenty-six glaciers flowing radially down the flanks of this large volcanic cone. It is nearly 6 miles long and flows in a northeasterly direction, being confined at lower elevations by steep canyon walls and moraines. Most of the lower 2 miles of the glacier is covered with ablation debris consisting of rock detritus from the finest grains to blocks more than 10 feet in diameter. Two tongues of faster-moving bare ice extend down into the debris-covered area along the southeast side (fig. 4). The terminal and the northwest marginal parts of the glacier have an exceptionally thick cover of ablation debris and are believed to be essentially stagnant. Geological and historical evidence (Matthes, 1944, p. 681) indicates that Emmons Glacier has been retreating and thinning for at least 50 years. At the climax of the last advance, the ice was 150-200 feet thicker over the lower 2 miles than at present.

Emmons Glacier was chosen for fabric studies chiefly because of simple geometric relations in the tongue and easy accessibility afforded by an automobile road ending only 1.5 miles from the glacier snout. Camps were established along the northwest margin of the glacier. Field work extended from mid-July to the end of August, 1950.

Rate of Movement in the Emmons Glacier

Instruments and procedures.- Surface velocities were measured at four locations on this glacier during the field period. At each location a stadia rod was set in horizontal position on the glacier, and readings were taken from fixed sighting stations on the northwest lateral moraine by observing the movement of the rod past the vertical cross-hair of a

Fig. 4.- Lower part of Emmons Glacier viewed from the northeast. Photograph by B. H. Bieler.

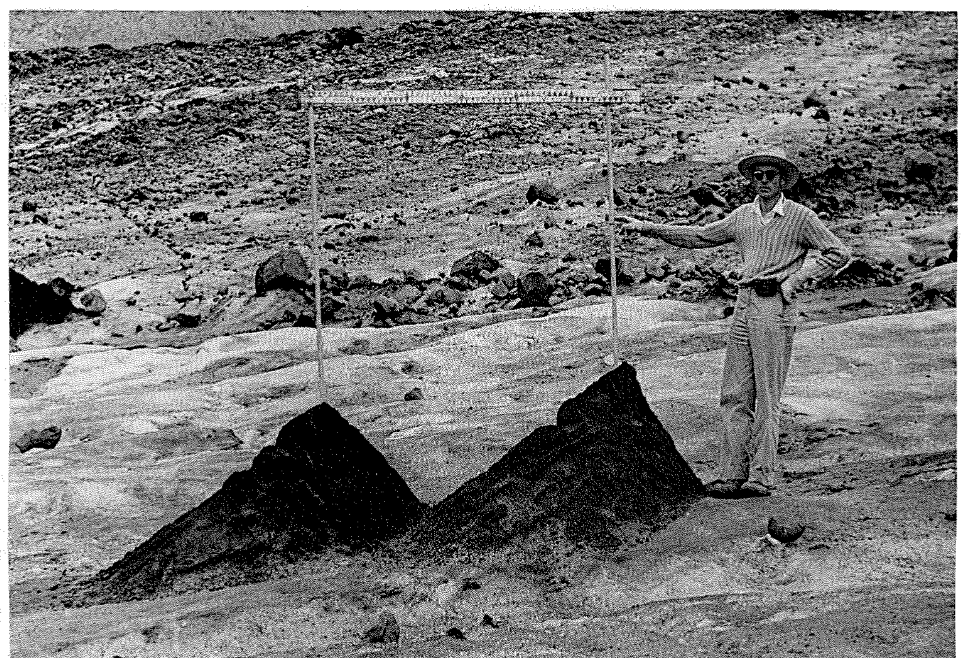

Fig. 5.- Stadia rod for movement studies as set up on glacier. Debris-covered cones at base of pipes show method of stabilizing pipe. Distance from surface to man's finger on pipe demonstrates ablation in 12 days.

twenty-power Ainsworth transit. In order to minimize temperature effects on the instrument and because it had to be moved from one location to another twice each day, the following sighting procedure was arranged. At each instrument site on the lateral moraine, pipes with brass heads threaded to fit the transit were firmly set in concrete. At a distance of 30-50 feet toward the glacier from each transit position, depending on the space available, another pipe, topped with a sharp-pointed cone, was set in concrete. The cross-hair of the transit was centered on the tip of this cone before a reading was made on the horizontal rod on the glacier, thus assuring return of the instrument to the initial position.

The stadia rod was clamped to two aluminum pipes set 6 feet into the ice (fig. 5). The holes for these pipes were made with drills based on a design used by Ahlmann (1935, p. 31) in Spitsbergen. Initially, differential ablation around the pipes caused them to tilt, throwing the rods out of position, but this was overcome by piling a cone of sand around the base of each pipe. The sand not only prevented most of the melting but also sifted into any opening which developed between the pipe and the ice, thus keeping the pipe rigid at all times.

Results.- Movement readings were recorded daily at locations 2, 5, 8, and 10 (fig. 2) for periods of 20-30 days. Stations 2, 5, and 10 were on the longest active ice tongue and in a line parallel to the direction of movement, 2 being 900 feet down-glacier from 5, and 10 being 660 feet below 2, or 1,560 feet from 5. The average movements recorded for each of these stations were 9.2 inches per day at location 5, 7.1 inches per day at 2, and 3.4 inches per day at 10. Similar down-valley decreases in movement have been recorded on other glaciers (Reid, 1896, p. 912; Hess, 1904, pp. 128-148; 1933, pp. 38-41; Finsterwalder, 1937, pp. 92-93; Drygalski and Machatschek, 1942, pp. 108-109; Matthes, 1946, p. 223;

Renaud, 1952, p. 54). The rapid reduction in rate over such a short distance on Emmons Glacier suggests that the ice is practically stagnant closer to the snout of the glacier. It also implies surfaceward movement of the ice (Demorest, 1942, p. 45), for gradual conversion of the horizontal component of flow into an upward direction appears the best mechanism for explaining the down-valley decrease in horizontal movement as well as the maintenance of the glacier's surface profile in the face of rapid ablation. A possible structural indication that this actually happens is afforded by the clear ice laminae or folia, 0.5-1 inch wide, dipping up-glacier at a steep angle in this part of the glacier. This structural feature was not always as regular or as well developed on the Emmons as the foliation on the other two glaciers.

The down-valley movement at location 8 on a medial moraine northwest of station 2 averaged 3.5 inches per day, confirming the impression previously gained from the ablation mantle that this ice was less active than the clear ice streams at the same elevation on the glacier.

Ablation on Emmons Glacier

Whenever pipes were sunk into the glacier to support stadia rods, marks were made on them level with the ice surface in order to record ablation. Figure 5 shows the amount of ablation after 12 days at location 10. The average ablation measured at the three movement stations (locations 2, 5, and 10) on active ice was 3.1 inches of ice per day from mid-July through mid-August.

Glacier Fabric

Introductory statement.- Thin-sections were made, and orientations of optic axes were measured at eleven locations on Emmons Glacier by means of the standard universal-stage procedures. Six of these, locations

2, 3, 4, 5, 10, and 11, are on the longer of two tongues of clean active ice in the central part of the glacier (fig. 2). Two, locations 8 and 9, are about 100 feet apart on a medial moraine north of location 2. The ice at locations 6 and 7 near the snout and at location 1, high on the northwest side of the glacier, appears to be essentially stagnant and consists of exceptionally large grains, up to 6 inches or larger in diameter and with more regular boundaries than in the active ice. Grains in active ice averaged 1-2 inches in diameter and had apophyses extending irregularly between other grains. Most of the seemingly smaller grains observed in thin-sections proved to be the corners or tapering ends of larger crystals when examined in successive parallel thin-sections made at 1-inch intervals. No zones of small grains, possibly indicative of clastic deformation or mechanical grinding, were noted, except for one area less than 1 inch square, which did have numerous small grains.

The average number of grains per section was 18, but as many as 40 were found in a few sections. Near the glacier's snout, some sections had as few as 3 grains. Fortunately, these were rare, and the average number in areas of coarse-grained ice was 6 per section.

Pattern of fabric diagrams.- The fabric diagrams obtained at eleven locations on Emmons Glacier are shown in figure 2. Each diagram is in the horizontal plane, and all are oriented in accordance with the map, north at the top. Many of the diagrams have four strong maxima arranged at the corners of a diamond-shaped quadrangle. Some concentrations are as high as 26 per cent in 1 per cent of the area. A few diagrams have other weaker maxima superimposed on the diamond pattern. The data for diagram 3A (fig. 2) were obtained from sections taken within an area about 14 x 18 inches on the glacier. The axes plotted in 3B (fig. 2) were obtained from a 9 x 6-inch area located 6-8 inches down the glacier from the 3A area. The initial expectation was that the grains in the sections from both areas would all have about the same general orientation, but upon plotting, they proved to be different and have, therefore, been separated. It is surprising that orientations of such distinct differences occur in areas only a few inches apart. Following this discovery, other diagrams, showing optic axes scattered away from the four principal maxima, were replotted by grouping the data from sections closely associated in location. Stronger diamond-shaped patterns resulted, even though the number of axes per diagram dropped below the desired minimum. A re-examination of field notes showed that the thin-sections for location 11 had been taken from two areas about 8 inches apart. Figure 6 shows the change in pattern obtained by plotting the data from these two areas independently. The thin-sections for location 1 were taken on successive days from three locations a few feet apart. When these were plotted separately, the four-point pattern appeared more strongly at two of the three spots, but the number of points in each was too small to make a reliable diagram.

The significance and possible interpretation of these diagrams will be considered after data from the other two glaciers studied have been described.

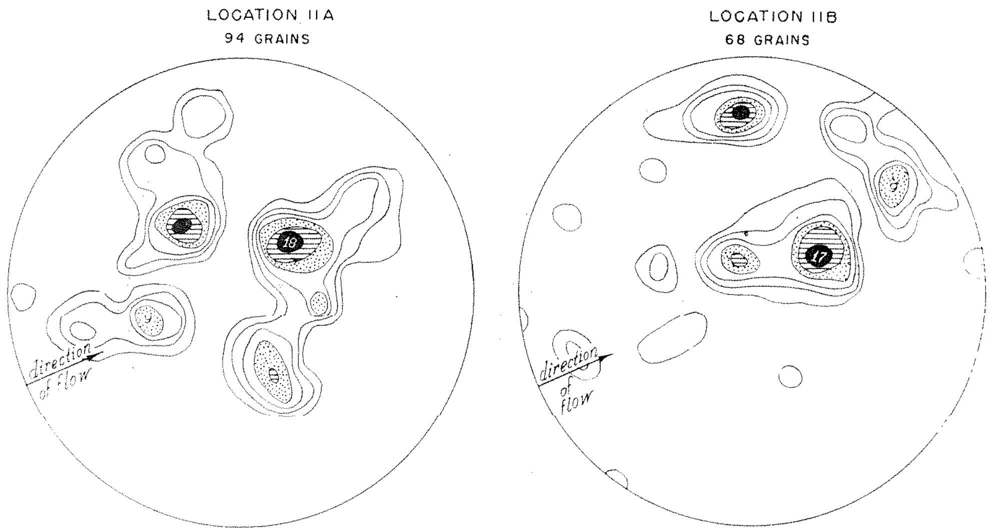

Fig. 6.- The thin-sections at location 11 (fig. 2) came from two areas about 8 inches apart. When the data from these two areas are plotted independently, as above, stronger patterns result; compare diagram for location 11 on figure 2.

Fig. 8.- A fold near center of Malaspina Glacier as viewed from the air looking east-northeast. Expression of the foliation can be seen in the linear features parallel to the fold axis. Photograph taken from about 400 feet above the surface.

MALASPINA GLACIER

Introductory Statement

The fan-shaped Malaspina Glacier lies on the southern Alaskan coastal plain at the base of the St. Elias Range and is one of the largest piedmont glaciers in North America. It is a sheet of ice, about 25 miles across in its narrowest direction, which covers about 1000 square miles (fig. 7). It is fed primarily by the Seward Glacier draining from a great intermontane basin in the heart of the St. Elias Range which is enclosed by a series of lofty peaks and ridges including Mounts Vancouver, Cook, Augusta, St. Elias and Logan. The surface of the Malaspina ranges in elevation from about 2500 feet at the Seward outlet, the point where the Seward Glacier empties into the Malaspina ice sheet, to almost sea level near the southern edge where, at the turn of the century, waves broke against the ice at Sitkagi Bluffs (Russell, 1892, p. 57).

In July, 1951, a camp was established a little south of the mid-point of the Malaspina under the supervision of R. P. Sharp of the California Institute of Technology as part of "Project Snow Cornice" directed by W. A. Wood. The Arctic Institute provided a helicopter and pilot to establish and supply the camp, which enabled the group to function with relatively greater efficiency, and made possible the use of considerable heavy equipment. A conventional aircraft was also used during the first half of the summer to bring equipment and supplies from Yakutat to the helicopter base on the beach, near the glacier margin. After tragic disappearance of this airplane in the latter part of July, supplies were brought to the beach camp by boat through the courtesy of Bellingham Canning Company and R. Gildersleeve and Earl Stober.

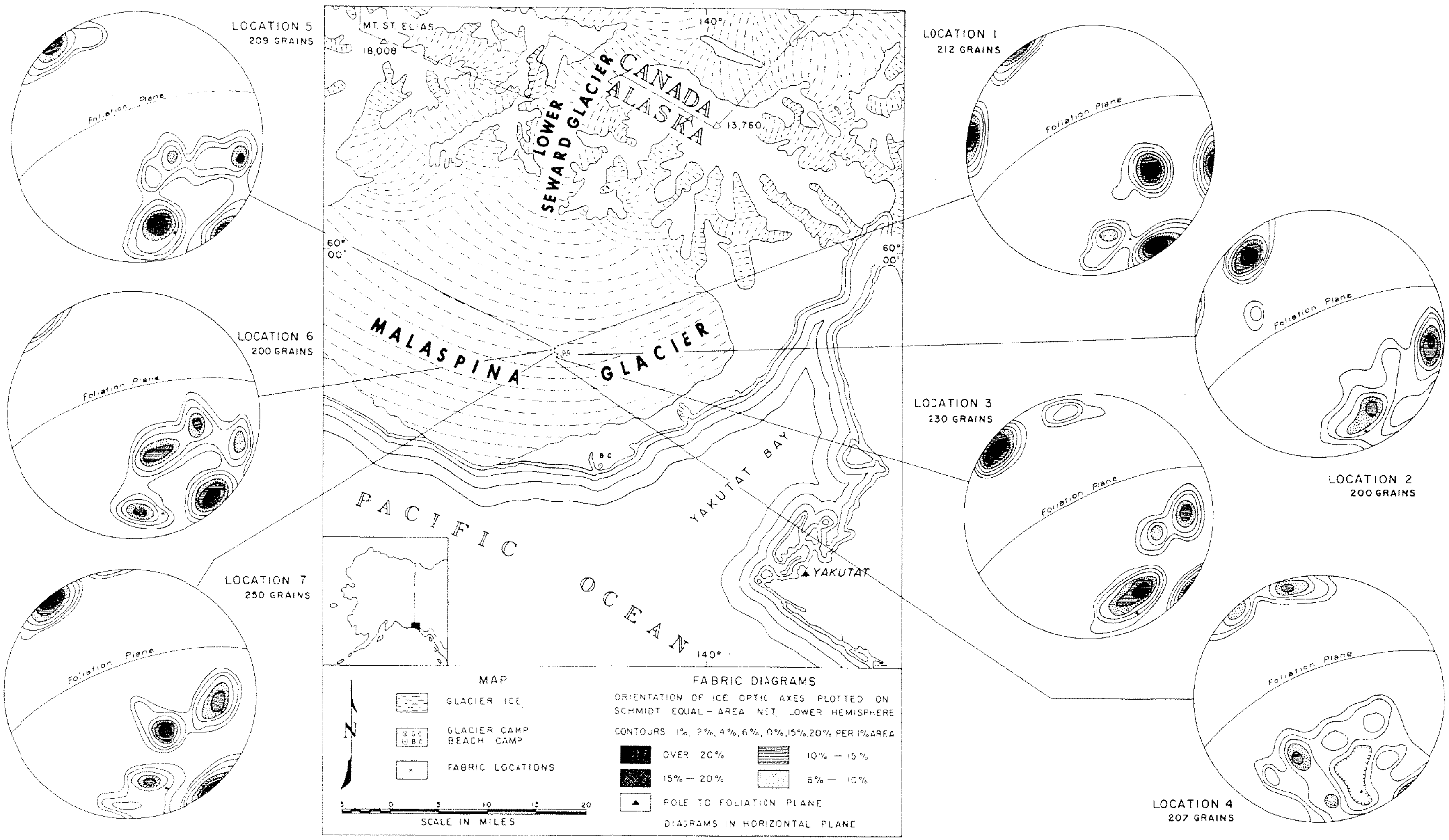

Fig 7 — Fabric diagrams and outline map of Malaspina Glacier, showing locations where thin-sections were taken

The weather on the Malaspina was foggy, rainy or overcast much of the time, and wind was rarely absent. Most of the time, except during storms this wind blew from north-northwest, the direction of the Seward Glacier. It was probably a gravity current of chilled air moving downhill along the surface.

Seismic and gravity exploration was carried out by C. R. Allen and G. I. Smith, while structural studies of the ice and other glaciological observations were conducted by Sharp and D. R. Baker, all from Caltech. The author undertook to work out relations of the crystal fabric to the larger structure of the glacier by means of the thin-section and universal-stage techniques used on the Emmons Glacier in 1950 (Rigsby, 1951).

Seismic and Structural Observations

The ice was found to be approximately 2000 feet thick at glacier camp. Southward toward the margin for about 4 miles, seismic reflections showed nearly constant thickness with only minor irregularities, but farther south the ice became thinner (Allen and Smith, in press). Northward the thickness decreased to about 1700 feet 5 miles from camp where the seismic profile had to be discontinued because of transportation difficulties and poor reflections in heavily crevassed regions. Since the subglacial floor is 600 feet below sea level at the glacier camp, the glacier must ascend a gentle slope in rising to some tens of feet above at its outer edge.

The foliation in Malaspina Glacier is extremely regular and well developed. Near the glacier camp it had an average strike of about N. 70° E. and dipped 68°-78° NNW. The dip became somewhat less toward the outer margin of the glacier. For example, about 6 miles south of camp the foliation dipped about 53° N., and Sharp (personal communication) reports a dip of 40° N. about 9 miles southeast of the glacier camp. Although only a small amount of detailed structural mapping was accomplished, the over-all structural picture seems reasonably clear and simple from aerial observations and the study of air photographs. In the areas visited by the author, the foliation strikes approximately at right angles to a line drawn from any point on the margin of the Malaspina to the Seward outlet. This probably holds only for that part of the Malaspina fed by the Seward Glacier. This line is presumably a flow direction, and the lines perpendicular to the foliation have a fan shaped arrangement. The more gentle dip of the foliation outward toward the margin probably is an expression of the fact that the dip becomes shallower with depth, possibly becoming almost parallel to the floor near the bottom of the glacier. Tensional cracks (crevasses) observed fanning outward from the ice outlet and striking at about 90° to the foliation, are probably caused by spreading of the ice sheet.

The axis of a fold in the ice striking between 65° and 70° lies about 2000 feet north of camp (fig. 9). This fold showed on the surface as dirty bands, usually several tens of feet wide, alternating with bands of clean, somewhat hummocky ice. This relation was best seen from the air (fig. 8). Because the folded structure is expressed only by a surficial accumulation of a thin layer of silt and dirt, no information as to plunge or dips on the flanks could be obtained. It must plunge, however, as the surface of the glacier is essentially flat, and the outcrops of the dirty layers still curve around the nose of the fold. It cannot be discerned whether the fold represents a plunging syncline or anticline. This surficial accumulation is probably a residual concentration resulting from hundreds of feet of ablation. Ice below the surface

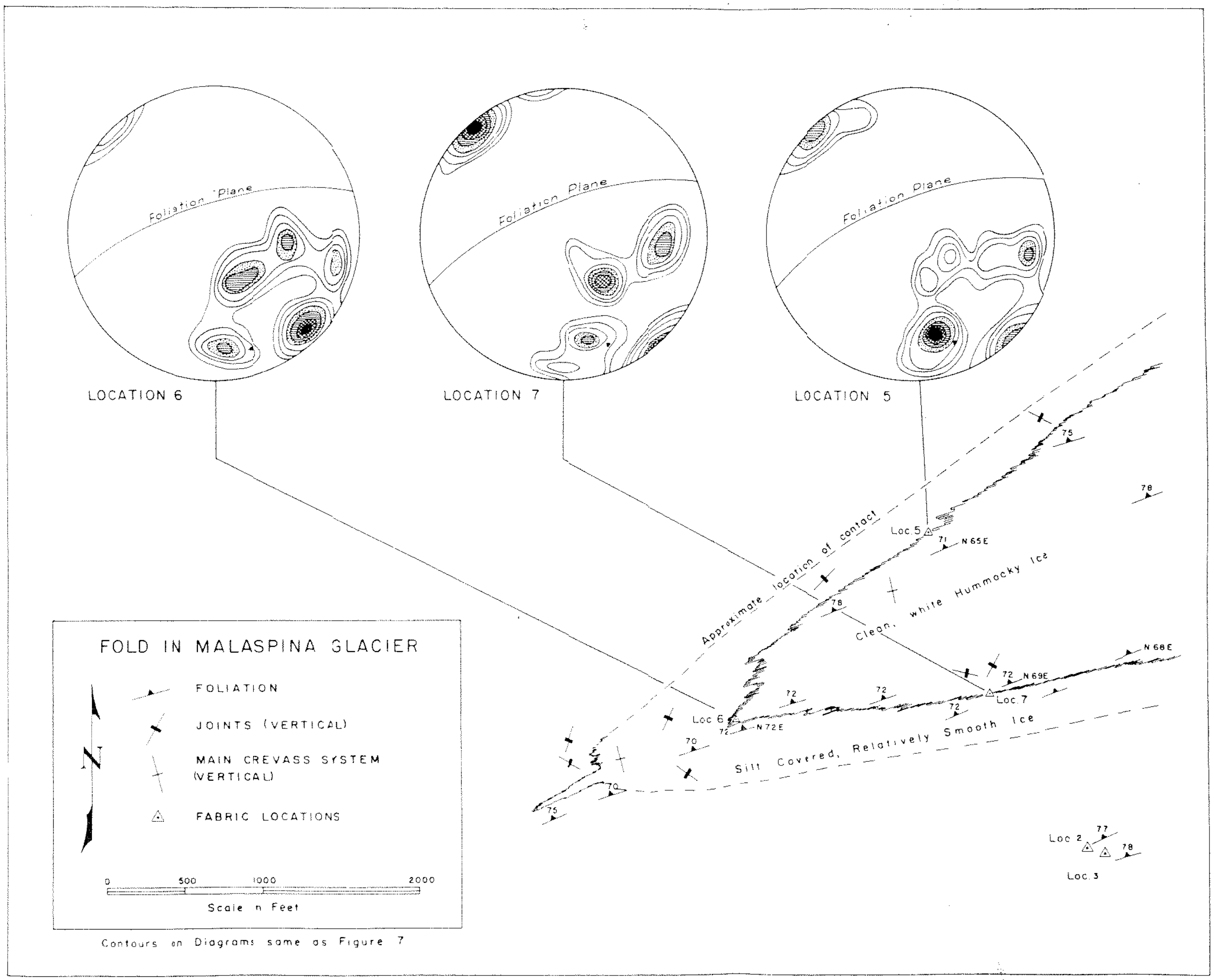

Fig 9 — Relation of diagrams to fold in Malaspina Glacier of the dirty bands appeared to be just as clean and free from debris as the ice beneath the dirt-free bands. Foliation in the ice does not change direction with the bands around the nose of the fold but passes through parallel to its axial plane and the glacier surface. The contact between the dirty ice and the clean ice around the nose of the fold is disturbed by many small offsets, all of which are parallel to the foliation, and in this sense the structure resembles shear folding (Billings, 1947, p. 90).

Near the margin, the folding is more visible because of the much greater amounts of debris in the dirty layers of ice. Here too the foliation in the ice appears to parallel the axial planes of the folds. It is difficult to ascertain whether these folds are formed by slip along the foliation planes, or by the phenomena of flowage folding. Perhaps detailed mapping can solve this enigma, and fabric studies may help throw some light on this and other structural relations in glaciers.

Fabric Diagrams

Fabric diagrams from seven locations on the Malaspina Glacier are shown in figure 7. Orientation of the c-axis in 200 to 250 crystals was measured at each location. Sections of ice were taken in a vertical plane parallel to the strike of the foliation, because vertical sections are much easier to cut. The fabric diagrams have been rotated to a horizontal position, corresponding to the Emmons Glacier diagrams. Most Malaspina diagrams show four strong maxima arranged at the corners of a diamond-shaped quadrangle, thus resembling the Emmons Glacier diagrams. However, one difference should be noted. The pole to the foliation plane is not near the center of the pattern as on the Emmons, but it is consistently closer to one of the maxima.

Two of the Malaspina locations were on opposite flanks and one on the nose of the fold near the glacier camp as described in the preceding paragraphs. It is clear that these diagrams, which are plotted in figure 9 with the map of the fold, are more closely related to orientation of the foliation plane than to the location of the ice sample on the fold. It will be noted that there is almost no difference in these three fabric patterns. It can be seen in figure 7 that there is a close similarity of all the Malaspina diagrams.

The conclusion drawn is that the foliation in Malaspina Glacier is caused by shearing movements along closely spaced planes in response to stresses developed in the ice moving outward from the source at the Seward outlet, and the relative movement between adjacent planes might be responsible for the folded appearance of the debris layering in the glacier.

SASKATCHEWAN GLACIER

Introductory Statement

During the summer of 1952 fabric studies were undertaken on the Saskatchewan Glacier in Banff National Park, Alberta (fig. 10). This glacier, draining from the Columbia Icefield, was chosen because of accessibility and simple geometric relations, at least as suggested by aerial photographs. A passable road extends to within about 0.5 mile of the Saskatchewan terminus, and the Alpine Club of Canada has a cabin about 1.5 miles below the ice, which was extremely useful for equipment storage. The glacier has no ice falls in the main channel, and it was hoped that the structure would be less complicated than in the Athabaska Glacier a few miles farther north.

The Banff Park Service moved two loads of equipment and supplies 4 miles up the glacier with a short-coupled four-wheel drive truck. This vehicle crossed the coarse outwash and the swift Saskatchewan River with little difficulty, and under the skillful handling of Park Warden William Black it traversed the hummocky surface and superglacial streams of the glacier.

In general the weather was good. Early July and late August were cloudy with some rain, but the middle of the summer produced a long stretch of almost cloudless skies.

Seismic and Movement Observations

C. R. Allen made several seismic soundings of the glacier during the early part of August and found the ice to be approximately 1400 feet thick about five miles up the glacier, with a gradual thinning toward the snout. The maximum thickness was somewhat greater than expected.

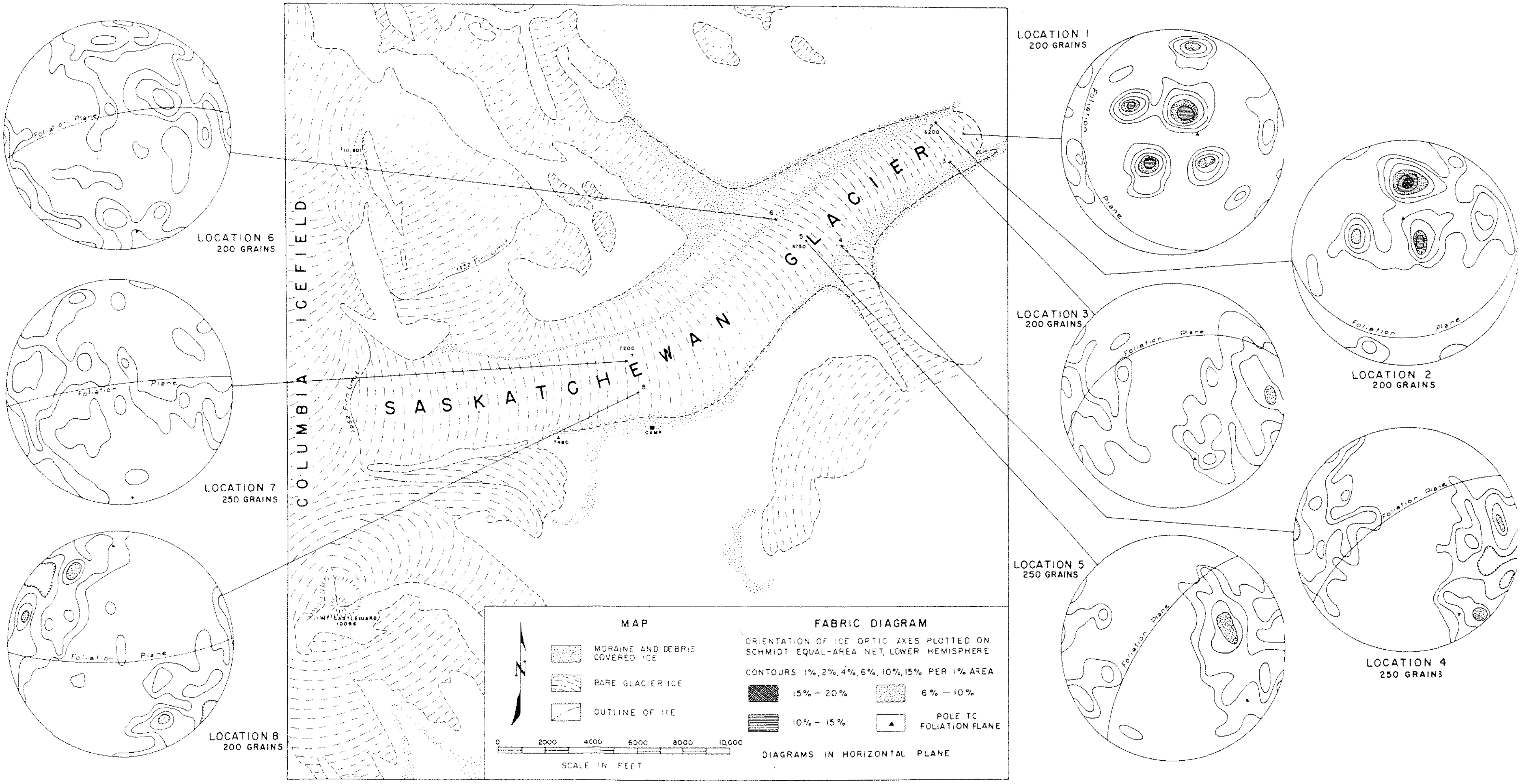

Fig 10 — Fabric diagrams and outline map of Saskatchewan Glacier, showing location where thin-sections were taken.

Mark F. Meier made velocity measurements at a number of points on the glacier's surface and found the ice to be moving about one foot a day near the center about five miles above the snout. The daily movement was progressively less near the sides and toward the terminus.

The author also undertook a micromovement study on the Saskatchewan Glacier about 4.5 miles above the snout. A 16 mm. movie camera, altered to take one frame about every 45 seconds and equipped with an extremely long focal length lens, equivalent to about three meters, photographed a horizontal stadia rod on the ice against a reference line on bed rock across the glacier. The camera was rigidly mounted on a base cemented to bed rock on the south side of the glacier, and the horizontal stadia rod in the center of the glacier was attached to pipes set in holes drilled 6 feet into the ice. A white background with a vertical marker line was painted on a cliff on the north side of the glacier. A clock with large dial was placed at the stadia rod, so that it appeared in each photograph.

It was hoped that something could be learned about the nature and variations of surface movement on a glacier by noting short-time fluctuations of velocity, but air density waves or "heat waves" caused so much undulation of the reference line image that small variations in movement were difficult to detect.

Fabric and Structure

Fabric studies were made at eight locations on the Saskatchewan Glacier. The first three stations were on the lower one-half mile of ice. The next three were made on a transverse profile about 1.5 miles up the glacier, and the remaining two were about 4 miles above the snout.

Orientation of optic axis in 200 to 250 ice crystals was determined at each of the eight stations. The sections were cut in a vertical plane parallel to the strike of the foliation, and the diagrams were rotated to the horizontal for easy visualization and comparison with the previous diagrams. The Saskatchewan diagrams are shown in figure 10.

Reid (1896, p. 919) postulates flow lines in glaciers which indicate that the deepest ice in the glacier originates nearest the head and that the ice at the surface just below the firn limit accumulated immediately above the firn limit and has always been near the surface. The ice at location 7 (fig. 10) in the center of the Saskatchewan Glacier about 1.5-2 miles below the firn line showed practically no foliation and also revealed very little preferred crystal orientation. According to Reid's flow lines this ice is not very old and was never buried deeply within the glacier. Furthermore, being in the center it was never subjected to strong shearing stresses, and this may account for its lack of preferred optical orientation.

Two of the diagrams made near the snout, locations 1 and 2, show the usual four maxima clustered about the pole of the foliation plane, as on the Emmons Glacier. This part of the glacier moves much more slowly than the upper reaches, and it may be significant that only the less active part of the Saskatchewan Glacier shows the same patterns as the Emmons and Malaspina which are also slow moving.

The larger structures of the Saskatchewan Glacier such as foliation, faults, crevasses and other cracks, were recorded in some detail, especially in the vicinity of the fabric-study localities. In general the foliation is parallel to the sides of the glacier and dips toward the center, but locally it is folded, sheared and offset along small faults.

Near the snout it loops around from one side to the other, dipping gently up glacier. Evidence of an unusual amount of surface shearing and faulting was the fact that drill holes were often sheared off over night, and in two attempts at deep drilling by thermal means, the pipe was seized at about 100 feet and the holes had to be abandoned. The foliation in the more active parts of the Saskatchewan displays much more granulation than was found in either the Emmons or Malaspina glaciers, where single crystals often extended across two or more folia. Many of the granulated layers on the Saskatchewan Glacier were so fine grained that the thickness of the thin-section was greater than the diameter of the grains, making a measure of their orientation impossible. In one thin-section a phenomenon was observed which is interpreted as indicating recrystallization of the granulated material. In one distinct fine-grained folium, the matrix between groups of small grains extinguished simultaneously on rotating the stage between crossed polaroids, giving the impression of a single large crystal almost completely filled with tiny grains of different orientations. On closer study the boundaries of the larger crystals were traced and were found to be approximately the same size as the crystals outside the granulated area. Other crystals were found with fewer included grains. This observation may indicate that foliation is caused by shearing and granulation of a layer of ice which later recrystallizes into larger crystals. After recrystallization, the folia appear as alternating clear and bubbly layers which display no difference in size or shape of the individual crystals. The fact that single crystals are not confined to a single layer on other glaciers indicates considerable recrystallization after the foliation was developed.

GLACIER FLOW AND ORIENTATION OF ICE CRYSTALS

Introductory Statement

In the early days of glacier studies De Saussure thought that glacier movement occurred wholly by sliding on the bed. The evidence now available shows that sliding at the subglacial floor does occur, but it does not account for all of the movement; some of it occurs by solid flowage within the glacier. A complete review of views on glacier motion is not attempted, but mention of a few of the more important developments as an introduction to the problem of flow and the crystallographic orientation of ice in glaciers seems in order. The following ideas have some similarity to or bearing upon a mechanism of grain-boundary migration which is discussed in a closely following section of this paper.

McConnel (1891, p. 329) demonstrated a basal glide plane in ice which is now believed to be a significant factor in glacier movement. Fabric study on the Emmons Glacier (Rigsby, 1951) suggests that glide planes other than the basal plane may be operating in glacier movement. Gliding has long been accepted as a mechanism of deformation in metals.

T. C. Chamberlin's (1904, pp. 193-206) concept of idiomolecular transfer, essentially sublimation and intergranular transfer of ice molecules from points of lesser to points of greater molecular stability, is similar to the mechanism which is discussed later in connection with migration of grain boundaries. R. T. Chamberlin (1928, p. 29) carried the idea still farther by postulating that flow in glaciers occurred by idiomolecular exchange between granules with yielding and accommodation to stress by changes of position and rotation of individual granules.

Quincke (1905, p. 545) stressed foam-cell melting, which is intergranular melting caused by the presence of weak concentrations of salt between grains, as a factor in glacier flow. More recently Renaud (1949, p. 320-324) has verified the presence of a "saline skin" between grains. He found that the salinity of the "skin" is greater in the ice of the névé than in the glacier proper, and that the purity of the ice constituting the nucleus of the crystal is greater in the terminal region of a glacier than in the névé. It seems likely that ice is continually recrystallizing by migration of grain boundaries, and the saline ions must be migrating with the boundaries. This is a possible mechanism for purifying the centers of the grains as the ice is moved toward the terminus.

Hawkes (1930, p. 122-123) summarized the mechanisms contributing to internal flow in ice by relative slip displacement as occurring: (1) along the basal planes of the crystals, (2) along intergranular surfaces, and (3) along fracture surfaces within the individual crystals. Processes (2) and (3) are supposedly facilitated by the presence of liquid at the surfaces of slip, and the cohesion of the deformed masses of ice is attributed to the refreezing of this liquid as soon as the stresses are relieved.

Mechanisms for Producing Orientation of Ice Crystals

It is apparent from figures 2, 7 and 10 that the crystals in at least some glacier ice have a strong preferred orientation of the optic axes. Before attempting to explain the patterns obtained from plotting the orientations of these axes, it is important to discuss the way in which grains may become oriented. The basic reason why crystals under stress assume a preferred orientation is so they can yield most easily to that stress. Since ice has a basal glide plane, it would seem logical to expect the stressed crystals to eventually attain an orientation favorable to basal gliding. Possible mechanisms of orientation will be considered as follows: (1) grain rotation, (2) lattice reorganization (wholly intracrystalline), (3) growth of crystals which can relieve their internal stresses by gliding at the expense of surrounding stressed crystals, (4) migration of boundaries as an aid to mechanisms (2) and (3).

One mechanism for possibly obtaining a position favorable to gliding is the rotation of crystals to the favored position as the surrounding grains yield. This assumes that once a crystal is favorably oriented it yields by gliding and no longer has a strong tendency to rotate. One of the weaknesses in this hypothesis is the extreme irregularity and intergrowth of the ice crystals in a glacier. Most grains would require a large amount of modification before they could rotate relative to neighboring crystals.

The late Max Demorest described a concept of crystallographic reorientation which he called "instantaneous recrystallization" (1941, p. 525). This was explained more fully in a paper presented before the Annual Meeting of the Geological Society of America in December 1941 and now in press in the Journal of Glaciology for 1953. As he explained it, instantaneous recrystallization is a phenomenon similar to mechanical twinning and the polymorphic changes that occur within many substances, in which "the lattice becomes energized to an unstable condition, and there immediately occurs an instantaneous reorganization of the lattice". In the case of ice, a crystal is strained, distorting the lattice, and its "potential energy is increased". At some critical point, however, the strain is too much, and as a result there is "instantaneous reorganization of the atoms -- a reorganization that simply duplicates the original lattice structure in a more comfortable position but without twinning or polymorphic change". Demorest believed that the process of instantaneous recrystallization favors reorientation of grains into a position such that the basal plane lies in the plane of flow or shear, where further deformation occurs by basal slip alone. This relieves the strain on the lattice and there is no further necessity for instantaneous recrystallization unless the direction of shear is altered. Such a process would be of considerable importance where ice grains are so irregular and interlocked that there is no freedom for intergranular rotation.

Some metallurgical work on recrystallization fabrics indicates that atoms may spontaneously rearrange themselves to give a change in crystal orientation. Kronberg and Wilson (1949, p. 501) in discussing grain growth have plotted the positions of atoms in grains that meet at some favored boundary. They find that a portion of the atoms do not have to shift position at all as the boundary moves past them; the rest have merely to shift slightly in coordinated ring movements. The magnitude of the shifts is in the order of one-third interatomic distance, and the coordination is such that there would be cooperation rather than interference between individual atoms that shift.

Through the courtesy of Dr. Eleanora B. Knopf of Stanford University, California, who has Dr. Demorest's research materials that were placed in her care by his widow, the author viewed a film taken through a microscope by Demorest. This film demonstrated the migration of the grain boundaries in a thin-section of ice subjected to stress over a period of several hours. The change was slow, but it resulted in an increase in crystal size.

It seems possible that at some point in a strained lattice a few atoms may shift to a more comfortable position almost instantaneously, and then the boundary between this new lattice orientation and the remainder of the grain may migrate rather slowly until the whole grain is reoriented.

On the other hand, the migrating boundary may start at some grain which by accident had approximately the right orientation, and because of its lower free energy, grew at the expense of the surrounding grains. This view is held by Perutz and Seligman (1939, p. 356) who state that crystals which can relieve the stress by gliding along a plane would probably possess less free energy than those which cannot glide and therefore would have a "tendency to grow at the latter's expense by the transfer of molecules across the crystal boundaries". Perhaps both mechanisms occur; growth of favorably oriented grains, the reorientation of crystal lattices by instantaneous recrystallization and twinning with subsequent growth at the expense of other grains.

Boundary migration is a slow process, but it is accelerated by higher temperatures, and the occurrence of larger grains at the end of a glacier may be the result of the longer time available for growth and the higher temperatures (Hawkes, 1930, p. 118). The effect of temperature on crystal growth is well illustrated at the Jungfraujoch (Seligman, 1949, p. 263) where long corridors, excavated in the Sphinx ice apron, were lit by electric lights close to the walls. The bulk of the ice apron was at about $-4^{o}C.$, and the normal crystal size throughout the excavations was of the order of 0.29 cm., but near the lights where the temperature was probably raised almost to the melting temperature, crystal measurements showed a mean size of 1.07 cm. Seligman states that there was no sign of melt water close to the lights. This shows that temperature alone promotes recrystallization without the aid of shearing stresses, and, in this case, it seems impossible to call upon instantaneous recrystallization. It is suspected, therefore, that boundary migration in ice is accelerated both by temperature and stress, and, because of energy relations, one grain will grow at the expense of another.

Most petrologists agree that intergrain openings in rocks are of the order of 5 to 10 Angstrom units wide, and it is probably reasonable to assume that the openings between ice grains are of this same order of magnitude. This space may be more or less filled with water molecules held on the surface but in disordered arrangement even though no visible liquid is present. Hawkes (1930, p. 117) prefers to speak of this film between grains as amorphous because the molecules in these films do not possess the freedom of movement normally attained in their liquid condition. Weyl (1951, p. 396) assumes an ice surface to be coated by a mobile, noncrystalline film having a thickness of several hundred molecules even at temperatures below 0°C., but believes this film freezes between crystals thereby accounting for regelation. In order for the crystal boundary to migrate under these conditions, disordered molecules would have to become ordered and attached to one crystal while those across the boundary left their ordered positions, thus keeping the energy level constant. This requires very little shifting of molecules in space, but it may require rotation of the molecules in order to fit the structure as the two OH bonds in a molecule make an angle of 104°31'. It appears that any opening between grains would require more movement of atoms than that calculated by Kronberg and Wilson unless such a mechanism as just described can operate. The existence of these openings is demonstrated by the fact that ions diffuse faster along crystal boundaries than through the lattice and larger ions can pass between crystals than through the lattices. The author is trying to point out that migration of boundaries in ice can occur, and that it is a common occurrence; in fact it must be almost a continual process extending from the snow crystal in the névé until the ice is melted in the terminal region. Boundary migration cannot in itself be a direct cause of ice flow, as it is the boundaries which migrate and not the substance, but it would be a means of orienting the ice crystals to a position favorable for gliding, or any other method of displacement requiring an oriented crystal.

ORIGIN OF FABRIC PATTERNS

Introductory Statement

Glacier ice is usually foliated and in many glaciers the foliation is strongly developed. Chamberlin and Salisbury (1909, p. 247) attributed foliation to shearing in moving ice. Perutz and Seligman (1939, pp. 347, 356-357) among many others have also related it to differential movement. Ice on Saskatchewan Glacier which showed little or no foliation was high on the glacier not far below the firn limit, and, as suggested in a previous section, this ice has not been deeply buried nor moved far from its point of origin. The conclusion is drawn that the folia are developed by flow in the glacier and that in general the farther the movement the better developed is the foliation. Besides foliation, all visible structures such as crevasses, cracks, fault planes, and isolated blue bands were plotted on the original fabric diagrams. The fabric patterns in many instances show a definite relation to the foliation while no other structure seemed to have any consistent relation to the patterns. Therefore, the task here is to discover what properties or mechanisms cause the ice crystals to assume this orientation with respect to the foliation.

Thin-sections show that crystal boundaries are independent of the folia in Emmons and Malaspina glaciers, for a single crystal commonly crosses two or more ice laminae. Debris layers in the Emmons also passed through individual grains without regard to crystal boundaries. This suggests the possibility of recrystallization after shearing, which might destroy any relation between the fabric patterns produced by shearing and the s-surfaces. However, ice may behave in an analogous manner to the annealing of deformed metals where hexagonal metals seem to retain their rolling textures after recrystallization (Barrett, 1952, p. 503). If so, the patterns in the ice as found at the surface should be the same after recrystallization as when last subjected to enough stress to orient the crystals.

Summary of Relations between Megascopic Structures and Fabric Patterns

On the Emmons and Malaspina glaciers the relation between foliation and fabric patterns is consistent although there is some difference between glaciers (figs. 2 and 7). When the poles to the foliation and debris layers were plotted on the fabric diagrams made from the Emmons data, they fell, for the most part, near the centers of the diamonds formed by the four maxima. The fabric diagrams from the Malaspina Glacier vary in the angular relation between maxima more than those of the Emmons, although some of them are closely comparable. In many of the Malaspina diagrams the pole to the foliation falls in the edge or near one of the maxima. Assuming differential motion in the foliation plane one might expect to find drag effects which would rotate the crystal axes different ways on opposite sides of the plane. Such rotation of patterns may be present in quartz diagrams which show some pattern variance with distance from a thrust plane (Balk, 1952, pp. 424-426). As the ice sections often included two or more folia it seems possible that two maxima with a small angle between them may actually be a single maximum which has been split by these drag effects, and the whole pattern may be rotated from its centered position with reference to the foliation plane. If this consideration is valid, it is surprising that the angular relations between maxima are so constant.

Foliation in the Emmons and Malaspina glaciers showed little distortion by folding or faulting. In contrast the foliation on the surface of the Saskatchewan Glacier is badly contorted by small-scale folding and faulting, and six of the eight diagrams on this glacier (locations 3 to 8, fig. 10) fail to show the conformity with foliation found on the other two glaciers. It seems likely that this is due to distortion of originally strong patterns by the folding and faulting observed. No doubt new shear forces were imposed on many of the grains which could cause a shift in orientation if they acted long enough and with sufficient intensity. This assumes, of course, that shearing can cause orientation of ice grains. It is also possible that the folding on Saskatchewan Glacier has changed orientation of the grains with little change in relations between them. This would be true only in small scale distortion where a single thin-section might cut both flanks of a fold. Some rolling of grains might also be expected to occur along a fault plane. For these reasons it is believed that the distortion of the foliation is responsible for the weak patterns on the Saskatchewan Glacier. The diagrams at location 1 and 2 on this glacier (fig. 10) are similar to those on the Emmons Glacier. These were taken near the snout, and according to Reid's flow lines (1896, p. 919), this ice was deepest in the glacier during its movement from the névé field and was probably subjected to the most shear.

Mechanics of Fabric Pattern Development

The means by which fabric patterns in glaciers are formed is a troubling and unsolved problem. The following mechanisms will be considered:

(1) Gliding on the basal plane.

(2) Gliding on planes other than the basal plane.

(3) Gliding on the basal plane in four different but consistently oriented shear planes within the glacier.

(4) Twinning.

(5) Ordered relaxation from a pattern developed by basal gliding parallel to one foliation plane.

The existence of a basal glide plane in ice and the origin of foliation in glaciers through shearing would lead to the expectation that the ice crystals should be oriented with their optic axes perpendicular to the foliation plane. The fabric diagrams (figs. 2, 7 and 10) show that this simple relationship does not hold in the instances studied; therefore, other possible explanations of the patterns are sought.

The possible significance of the four-maxima patterns found on the Emmons Glacier is speculated upon as follows. Let it be postulated that the center of each diamond-shaped pattern is the pole to a shear plane in the ice. On this basis, all the diagrams have been rotated to bring the shear plane into a horizontal position, making the pole to the plane the center of the diagram. The individual diamond patterns have then been rotated about this pole until their long and short diagonals coincide. The results of these manipulations are plotted in figure 11, where the maxima of the six strongest patterns are represented by dots. The weaker patterns, requiring a more subjective analysis, are represented by crosses. All maxima plotted in figure 11 are numbered according to location. A striking uniformity in the angular distance between maxima is immediately apparent.

The angular separation of opposite corners of the diamonds in the six strongest patterns average 84° and 52° respectively. If the weaker patterns are included, the angles are 80° and 53° respectively. If

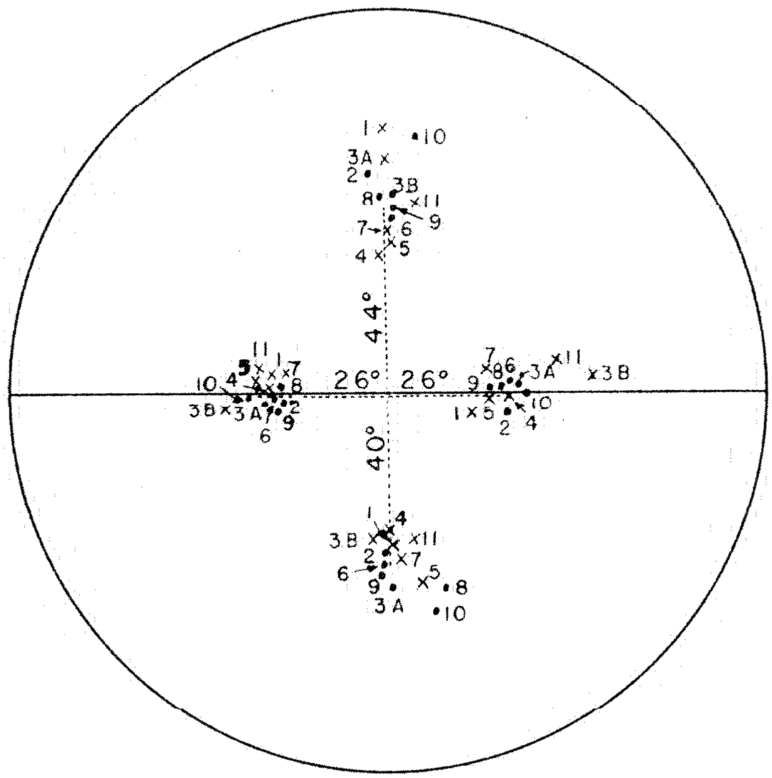

Fig. 11.- Plot of centers of maxima after postulated shear planes have been rotated parallel to horizontal plane, and then all diamond-shaped patterns have been rotated about center until long and short diagonals are parallel. Angular distances between pole to shear plane and maxima shown in degrees.

these patterns are caused by gliding on planes within the crystal and if only one shear direction in the glacier at each location is responsible for these maxima, then the patterns cannot be attributed to movement on the basal glide plane. Under these assumptions the diamond patterns require two planes with a glide line or direction in each.

The angles between the c-axis and the poles of three crystal forms commonly found in the hexagonal system are calculated to be approximately 43° for a $\{11\bar{2}2\}$ face; 28°.5 for a $\{10\bar{1}2\}$ face; and 25° for a $\{11\bar{2}4\}$ face, using the unit cell given by Bernal and Fowler (1933, pp. 523-524) with 12 water molecules. These appear to be possible faces in the structure of ice but not necessarily the most favorable faces for gliding. Usually glide planes are parallel to actual crystal faces, but no pyramidal or other faces inclined to the c-axis in ice have been found. Barnes (1929, p. 682), however, obtained strong and medium-strong X-ray reflections from planes parallel to $\{11\bar{2}2\}$ and $\{10\bar{1}2\}$ but lists the reflection from a plane parallel to $\{11\bar{2}4\}$ as exceedingly weak. The Miller-Bravais indices for his planes, based on a 4-molecule unit cell, have been converted into the 12-molecule cell.

Using the $(11\bar{2}2)$ and $(10\bar{1}2)$ faces, two glide lines satisfying the conditions indicated by the fabric patterns are (1) the edge between $(11\bar{2}2)$ and the prism $(11\bar{2}0)$ and (2) a line perpendicular to the edge between $(10\bar{1}2)$ and the prism $(10\bar{1}0)$ or the trace of the c-axis projected onto the $(10\bar{1}2)$ face. These two lines coincide with the one drawn in figure 11. By interchanging these lines, one could obtain the same pattern, but the glide line on figure 11 would be rotated through 90° in the glide plane to a north-south position. Perhaps an edge between two faces making the proper angles with the c-axis can be found to fit the data by rotating the possible glide line 40°-50° on the same figure.

As pointed out, the pole to the foliation in the Malaspina Glacier falls very near one of the maxima in almost every fabric diagram. This may indicate that the basal glide plane is more operative here than on the Emmons. If there are glide planes in addition to the basal plane in ice, the speed of deformation or some other factor may dictate which plane or planes can operate. Such a factor might account for differences in patterns from glacier to glacier.

As an alternative hypothesis, the possibility that the four-maxima fabric patterns were formed by gliding on the basal plane along four different shear directions within the glacier may be considered. This concept would be supported by a diagram such as the one at location 8, on Emmons Glacier (fig. 2), if the poles of each of the four planes plotted lay in the center of each of the maxima. The fact that they do not may possibly be due to errors in measuring the orientation of the planes, a difficult procedure in the field. Shearing on these four foliation planes would presumably have to occur at different times, and the maxima would be of different ages. Support for this might be drawn from the fact that some of the maxima are weaker than others, possibly being partly destroyed by later shearing. The great weakness of this explanation is the improbability that such consistent angular relations between the shear planes or s-surfaces could persist over such widely separated locations as are represented by the diagrams on Emmons and Malaspina glaciers. It also seems extremely unlikely that four planes with consistent angles to one another would form synchronously throughout the glacier. With the exception of location 8 on Emmons Glacier, no indication of four shear planes was seen.

It has been suggested by Linus Pauling (personal communication) that the patterns obtained might be explained by a twinning mechanism similar to the artificial twinning in calcite. It would appear that the twinning would have to progress on uneven planes until the entire crystal was changed, as no evidence of mechanical twinning has been observed by the author or by other workers (Perutz and Seligman, 1939, p. 354). If this mechanism were to function the crystals would have to be oriented in a position favorable for twinning before the optic axis could change to the new position. After the twinned position most favorable to the stress environment was attained, no further movement could take place without a change in the stress conditions. By assuming a twinning angle of 52° between the two optic axes of a possible twin, corresponding to the angles observed between maxima in the fabric patterns, the author worked out possible optic axis positions and obtained a very different pattern from that observed. It appears that this method does not have the possibilities that are afforded by directional gliding along certain planes, or at least it cannot be the sole mechanism.

At the present time all ice studied in thin-section has been at or very near the surface of a glacier. The possibility that ice at the surface does not have the same orientation pattern as at depth must be considered. As yet, there is no means of obtaining an oriented sample from the stressed interior of a glacier. That an ice crystal may twin by relaxing the forces as it is brought to the surface of the glacier by ablation may be feasible, but the four-maxima pattern does not seem compatible with the symmetry of the hexagonal system. If the optic axes were all perpendicular to the foliation plane under stress and if twinning could occur on relaxing the forces, it appears that the pattern obtained should consist of one central maximum surrounded by three maxima at equal distances and 120° apart or six maxima also at equal distances from the center and 60° apart.

The effect of relaxation of stresses and pressure on ice as it is slowly brought to the surface by flow and ablation is a matter of speculation in which some crude comparisons with recrystallization of metals may be useful. The recrystallization of metals is brought about after cold working by elevating the temperature to relieve the internal stresses. In the annealing of cold rolled metals some recrystallization textures resemble the deformation textures from which they grew, some are entirely different in orientation and some are random. As has been already stated, hexagonal metals seem to retain their rolling texture upon recrystallization (Barrett, 1952, pp. 503, 508). Whether this can be extrapolated to hexagonal ice is doubtful, especially since the recrystallization of ice near the surface takes place at approximately the same temperature as that at which the original texture developed for temperate glaciers are always at the pressure melting temperature except near the surface in winter time. Burgers and Louwerse (Barrett, 1952, p. 503) suggested that recrystallization textures were determined by nuclei in the deformed material, but Barrett stated that such oriented-nucleation theories encounter the objection that there are likely to be sufficient nuclei in any orientation whatever to provide the number that are needed to determine a texture. He proposed that a theory of recrystallization textures might better be based on the principle that certain orientations grow into the deformed material more rapidly than others, the shifting of atoms from the strained matrix to the new grain proceeding slowly when the new grain has about the orientation of the matrix, and fastest when it differs from the matrix in a certain, but often unknown, way. Some experimental evidence in support of this has been found (Beck and Hu, 1950, p. 1058). Barrett concludes that one important principle governing recrystallization textures is orientation-dependent growth velocity, but that there can be no doubt that supplementary principles must also be effective.

It may not be possible to make comparisons between metals and ice, but it can probably be said that if ice does not have the same orientation pattern at the surface as it did at depth, the present pattern is probably related to the old one in a definite way. The need is to discover that relation if a change in pattern has occurred.

AN HYPOTHESIS FOR GLACIAL FLOW

It is necessary to recognize at least two significant processes promoting glacier movement other than "solid flow". One of these, sliding on the base, leaves its evidence on the bedrock beneath in the form of grooves, striations and glacial polish. The second, and probably the less important, is the actual break and slipping of one mass of ice over another or faulting. Faulting may be important only in the upper 100-150 feet of the glacier. Probably the most important type of fault displacement which promotes downhill movement is thrusting. This is especially obvious near the terminus of most glaciers. However, faulting in the crust is merely an expression of a more fundamental type of "flow" at depth, and the subject of "solid flow" is the principal concern here.

A proposed hypothesis for glacier "flow" should not conflict with the following observations:

1. Crystal size varies directly with time (age and distance traveled) and temperature of the ice, but it varies indirectly with velocity and steepness of profile.

2. Actual granulation of larger grains may occur in very active glaciers especially near the surface thereby reducing the grain size.

3. Crystals in active ice below the firn area are usually irregular in shape, but in stagnant or dead ice they are largest and appear in thin-section to have somewhat smoother boundary surfaces between grains, though not necessarily a more equidimensional shape.

4. Lattice orientations in glacier ice usually show strong preferred directions.

5. There is usually a well-marked foliation which appears to

be related to the crystal fabric.

6. Grains do not tend to be longer in one crystallographic direction than another, and when long grains are seen there seems to be no preferred orientation of the long axes.

7. No evidence of mechanical twinning is seen in the thin-sections of ice crystals.

8. Strain shadows are rarely seen in thin-sections from glacier ice, although Demorest (in press, Jour. Glaciology) reports a high degree of irregular extinction in grains deformed in the laboratory.

9. In a temperate glacier, ice is deformed and recrystallized at melting temperature, which gives the maximum rate of ionic or molecular diffusion.

Compaction, regelation, sublimation and condensation, idiomolecular transfer, intergranular shifting and the freezing of melt water from the surface by contact with firn at temperatures below freezing during the spring all help to transfer the firn into glacier ice. Under the influence of gravity many of these processes will promote downhill movement during the early stages, but sometime after becoming glacier ice the grains have grown and become so interlocked that it appears that some sort of deformation of the individual crystals must occur in order to explain glacier movement.

Probably the greatest shearing forces are applied to the ice near the bottom and sides of a glacier. As stress is applied, foliation develops parallel to the direction of greatest shear possibly by granulation along discreet planes with later recrystallization. If the stresses are not applied too rapidly, foliation may develop by gliding and recrystallization, allowing the most active zones to rid themselves of more air bubbles than adjacent layers or folia. At the same time recrystallization is accelerated, and either because of lattice reorientation or growth of favorably oriented crystals at the expense of less favorably orientated ones, the ice takes on a fabric.

It is postulated that the crystals must become adjusted to the local stress environment, if long enough maintained, because of energy relations. A crystal whose lattice is in favorable orientation for gliding would never become stressed enough to raise its free energy to the point of being absorbed by another crystal, nor would it have a tendency to reorient the lattice as the atoms would initially be in the most comfortable position. Every grain within the glacier is surrounded by other grains and a local stress condition is set up along grain boundaries which may be concentrated at a corner or some other point depending on the surrounding grains and their orientations. The resulting migration of the boundary is such that the grain of lower free energy grows at the expense of the crystal of higher free energy. This may continue until the stressed portion of the grain has been absorbed or until a shift of stress causes migration of some other portion of the boundary in another direction. The disappearance of grains of unfavorable orientation will probably be the final result, but the surrounding grains will have had their boundaries considerably altered. The fact that perfect orientation is never attained indicates that stress conditions on each crystal must be shifting slowly but continuously. Hence, boundary migration is a continuing process in all flowing glacier ice. Recrystallization continues after cessation of movement as is shown by the large crystal sizes in stagnant ice.

It might be reasoned that the grains must become elongated or "strung out" if gliding on the basal plane occurs. In view of the fact that the temperature conditions favor maximum diffusion of molecules, the ice grain always has a tendency to keep the ratio of the surface area to the volume at a minimum. Whatever the nature of the forces, an atom located inside the body of a solid is subjected to equal forces in all directions, whereas an atom in the plane of the surface is subjected to unbalanced forces, the inward pull being greater than the outward forces. This results in a tendency to decrease the surface. Solids not only have surface tensions like liquids, but these forces are greater than those of liquids (Brunauer, 1945, pp. 4-5). Any process that tends to decrease the free surface energy, the product of the surface tension and the surface area, occurs spontaneously. This tends to keep grains equidimensional as well as to make crystals grow in size, as in both cases the surface to volume ratio is becoming smaller. However, with the continually changing local stress conditions on the crystals in moving ice, they never get as large as in nearly stagnant or dead ice. Thus, recrystallization must occur continuously in flowing ice even if all grains are favorably oriented. Hence, the mechanism of flow is one of gliding and continuous recrystallization from the time the firn has been changed into ice until movement ceases and the ice disappears by melting.

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