Ice Fabrics and the Universal Stage

by Chester C. Langway, Jr.

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PREFACE

This report was prepared by Mr. Chester C. Langway, Jr., crystallographer, Snow Ice and Basic Research Branch, as a part of USA SIPRE Project 22.1-11, Structure of snow and ice. Work was under the general direction of Mr. James A. Bender, branch chief.

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SUMMARY

Techniques for using a specially constructed universal stage for study of ice fabrics are outlined, methods of preparing ice-thin sections are discussed, and the construction of fabric diagrams is described. A table of angular corrections is given for the differences in refraction indexes between air and ice relative to the orientation of the optic axis. Applications of the data are indicated and discussed.
ICE FABRICS AND THE UNIVERSAL STAGE

by

C. C. Langway, Jr.

INTRODUCTION

This report outlines and explains the procedures used and the mechanics involved in the fabric study of ice samples and the use of a special type of universal stage to accomplish this study. Field and laboratory techniques are discussed and various methods of preparing the ice sections for analysis are suggested. The construction of a fabric diagram, which permits a statistical analysis of the data obtained from universal stage measurements, is described. Essentially, most of the information given in this report is a compilation of existing data from the field of structural petrology, with emphasis placed on its application to ice fabrics. By no means can this report be considered a complete summarization of the subject, but it should provide the necessary background for the organization and investigation of a research study in the field of snow and ice.

No attempt has been made to show the optical reasoning behind each step in orienting a crystal, except when illustrating a particular point, as a number of textbooks are readily available on the subject of optical crystallography.

THE UNIVERSAL STAGE

The universal stage described in this report was developed by Dr. George Rigsby while at the California Institute of Technology and was designed specifically for ice fabrics (Rigsby, 1951). Further improvements and modifications were made during the period that he worked at the U. S. Army Snow Ice and Permafrost Research Establishment.

A universal stage is an instrument used for orienting crystals or crystal sections so that the position of the optic axes may be measured. To fully understand the manipulation of the universal stage, it is desirable to be familiar with the optical symmetry of crystals. However, ice, being a uniaxial substance, is relatively simple to orient and it is possible to master the mechanics involved without a thorough knowledge of crystal optics. In general, crystals are oriented on the basis of extinction and to recognize the extinction position accurately is critical.

This universal stage utilizes essentially the same principles as the type first introduced by Fedorow, which is used on a polarizing petrographic microscope, in that it permits the angular rotation of the axes of the stage to optically orient a crystal. This stage (Fig. 1) has four axes of rotation, comparable to the three axes of a rotating microscope stage. The stage is mounted between two 6-in. disks of polaroid and can accommodate a thin section up to 5 in. in diameter. The frame of the stage is cast of anodized

Figure 1. Four-axis universal stage complete with camera mount and camera.
aluminum and has three of its axes of rotation graduated; one axis serves as an azimuth control; the other two permit the angle of inclination to be recorded. The fourth axis allows the entire stage to be rotated on a vertical axis without disturbing the oriented specimen and serves as a check. The circular rotating disk that supports the thin section is made of glass (a spare of clear plastic is advisable in the field). Two knurled knobs serve to facilitate the azimuth rotation of the section and also to clamp the cover plate over the thin section. The cover plate, made of clear plastic, is etched with a centimeter grid for direct grain-size measurements. The grid-plate is also helpful in making a systematic coverage of the thin section, similar to a mechanical stage. A small copper indicator is attached to the cover plate for an index in obtaining azimuth positions.

The stage is mounted on a wooden base that doubles as a carrying case. The base has a hinged opening which permits storage of the component parts of the stage. A polished stainless steel sheet is attached to the bottom hinged door of the base. When properly positioned, this sheet is used to reflect light and transmit it through the instrument during field use. If a power source is available, an ordinary extension cord and bulb (150 w) is recommended as a light source. Ordinarily a heat absorption plate is inserted in a slot provided under the polarizer, and also serves to diffuse the transmitted light and reduce glare.

PREPARATION OF THIN SECTIONS

The preparation of thin sections of ice involves no great difficulties if a sufficiently cold working area is available (about -10C). Preparing thin sections of snow is considerably more difficult. The snow sample must be treated in such a way that it will withstand the mechanical abrasion necessary to reduce the snow section to the proper thickness. Care must also be taken not to alter the natural form or position of the individual grains. In most cases, it is impossible to work with snow sections on this type of universal stage because of the difficulty in distinguishing extinction on the usually small diameter grains, without a magnification system. When working with small-grained aggregates, the conventional type Fedorow universal stage and a polarizing microscope are used. The preparation of snow samples for fabric work is discussed by Schaefer (1941) and Fuchs (1956).

Several methods exist for the satisfactory preparation of thin sections of ice. The one used is primarily dependent upon the availability of equipment, the conditions (field or laboratory), and the purpose of the study.

All techniques require reducing the section to an optimum thickness for study under crossed polaroids. Because of the low birefringence (0.0014) of ice, there is usually considerable latitude in the thickness of sections used. However, when the grains are so fine that the thickness of the thin section is greater than the diameter of the grains being measured, orientation is not possible. A section cut parallel to the optic axis of an ice crystal exhibits maximum birefringence. In this position, an ice crystal that is 0.4 mm thick will exhibit first-order red and one 0.8 mm thick will exhibit second-order red: in other words, a thickness of 0.4 mm per order of interference colors.

With grains of average polar glacier ice (diam. 0.2 to 1.5 mm), the usual thickness of the thin section is 0.4 mm. Direct measurement or casual inspection under crossed polaroids for a maximum color of first-order red in a randomly oriented section will reveal this.

The ice sample from which a thin section is to be made should be oriented to some known azimuth position or to a stationary geographical position. This will permit the spatial orientation of the thin section by referring it to the ice sample. The ice sample or ice core can be marked for orientation purposes with ordinary finger nail polish or by grooving or indenting the sample or core with a saw blade. The following steps are suggested in preparing a thin section:

1. Make one surface of the ice sample flat by sawing (preferably with a saw having widely spaced and offset teeth or, if available, a band saw) and then-sanding with progressively finer sandpaper (a carborundum mesh-screen appears to be best suited for this process as the cold does not curl the edges or cause it to crack).
2. Warm a clean glass slide, large enough to support the entire sample, on the palm of the hand or some other heat source — hot plate, sterno can, etc. The amount of heat applied to the glass is very important. Melting more of the sample than is necessary is particularly troublesome if the ice sample contains bubbles under pressure. These entrapped bubbles, when melted free, form large voids at the glass-ice interface. Conversely, too little heat applied to the glass slide will cause a weak bond between the glass and ice and the thin section may be damaged or lost later while reducing the thickness of the section. It is advisable to use a glass slide with a thickness no greater than 1.5 mm as it is difficult to apply the proper amount of heat to thicker glass.

3. Hold the warmed glass plate over the flat ice surface — inclined to it, then lower gently and, with one quick movement, press it firmly to the ice. The heat dissipates rapidly from the glass and a smooth bubble-free bond should be observed by reflecting light from the glass-ice interface. The water film that forms at the glass-ice interface, from the heat of the glass plate, refreezes without altering the grain size or the grain orientation. This application of glass to ice is something of an art, but with a little practice a satisfactory bond can be obtained.

4. Cut the sample parallel to the glass plate, leaving approximately a 1-mm thick section of ice adhering to the glass. This is accomplished with a handsaw or, preferably, a motor-driven band saw using a fence as a guide.

5. Reduce the section to the desired 0.4-mm thickness. Sanding with wire mesh is the simplest technique, requiring only the sandpaper, but it is a crude method that rarely produces a plane parallel section. Furthermore, the mechanical abrasion often loosens the poorly bonded finer-grained specimens. Another field method uses a heated copper plate or any heated plane surface (e.g., a teapot filled with hot water), holding the section inclined in a special holder to drain the melt water. (This method is not strongly recommended as the heating process may cause annealing and subsequent alteration of the grains.) For laboratory preparation of a thin section, more elaborate techniques and equipment may be used, such as a modified standard milling machine with a vacuum plate to grip the plate during the reduction.

The recommended instrument to reduce the thickness of the section is the standard biological microtome (Fig. 2), also modified with a vacuum plate. This instrument produces an extremely smooth and plane parallel surface. With a microtome, one to 20 microns of the ice section may be removed with each passing of the carriage under the blade. With care, it can be used to reduce a section to less than 0.1 mm (rendering it adaptable for snow sections). An added feature of the microtome is that its weight (60 lb or 27 kg) does not prevent its use in the field.

If the thin section is to be studied in a sufficiently cool environment, no additional precaution is necessary to preserve the section. If, however, the ambient temperature is greater than -5°C, or the section is extremely thin, or if it is to be saved for further investigation, a protective cover glass should be used to prevent evaporation. It is also advisable to place the thin section in an airtight bag, such as polyethylene, with fragments of scrap ice.

Figure 2. Microtome showing attached vacuum plate and hose leading to vacuum line (or portable vacuum pump for field use).
PROCEDURE FOR ORIENTING A CRYSTAL WITH THE UNIVERSAL STAGE

Many explicit descriptions of the proper way to orient a crystal by using the universal stage exist in the literature. No standard procedure is used, nor should there be, for each investigation involves different considerations. The following procedure is an attempt to establish the simplest and most efficient technique to orient an ice crystal, using some of the methods outlined in the literature (Fairbain, 1954; Wahlstrom, 1935; Knopf and Ingerson, 1938; Emmons, 1942; Bader, 1951; and others).

First, introduce the analyzer and make sure the two polaroids are crossed. The polarizer is oriented to transmit light that is vibrating in a north-south direction and the analyzer to transmit light vibrating in an east-west direction.

The four axes of rotation of the universal stage are designated as follows:

- $A_1$ = Inner vertical axis
- $A_2$ = North-south axis
- $A_4$ = East-west axis
- $A_5$ = Outer vertical axis (axis of the stage).

Initially, in what is referred to as the rest position, $A_1$ and $A_5$ are parallel to the line of sight (normal to the thin section) and $A_2$ and $A_4$ are mutually perpendicular and lie in a horizontal plane. Figure 3 shows the position of the rotation axes at the starting rest position.

Figure 3. Plan view of the rotation axes of universal stage at the rest position.
With ice crystals, either the optic axis is oriented parallel to the line of sight and referred to as the polar position, or the plane normal to the optic axis is oriented in a vertical position parallel to the $A_2$ axis, referred to as the equatorial position.

In the following manipulations, (following Fairbain, 1954) no effort has been made to expand on the optical reasoning behind each step.

1. Set the horizontal axes ($A_2$, $A_4$) at zero readings.
2. Select a grain for measurement and rotate on the $A_1$ axis to extinction.
3. Test the extinction by rotation on $A_2$. If the grain departs from extinction, return $A_2$ to zero; rotate $90^\circ$ on $A_1$ to the alternate extinction position and test again to see if the grain remains dark upon rotation of $A_2$. In this position, it will remain dark, indicating that the east-west plane contains the optic axis (principle section).
4. Depress $A_4$ 15° to 20° (or as much as necessary to illuminate the grain) and then rotate $A_2$ to an extinction position.
5. Return $A_4$ to the zero position, then rotate approximately 45° on $A_5$. If the grain remains dark, the optic axis coincides with the line of sight (polar position). If the grain becomes illuminated, the optic axis is normal to the line of sight and $A_2$ (equatorial position).

Two special orientation cases that commonly occur are:

1. When in its initial position, the crystal remains dark for all positions of $A_1$. This indicates that the optic axis is parallel, or nearly so, to the line of sight. However, because of the difficulty of estimating the completeness of the extinction, it should not be assumed that the axis is exactly parallel to the line of sight. The following additional steps are recommended:
   a. Rotate on $A_2$ until grain is illuminated.
   b. Rotate on $A_1$ to restore extinction.
   c. Return $A_2$ to zero, retaining the $A_1$ position.
   d. Proceed with steps 4 and 5.

2. When step 3 gives extinction in both $A_1$ positions. This indicates that the optic axis is normal to the line of sight. The following additional steps are recommended:
   a. With the grain at one of the two extinction positions, rotate $A_4$ an arbitrary amount to illuminate the grain.
   b. Depress $A_2$. If the grain remains dark, the horizontal optic axis lies in the north-south plane; if extinction is lost, the horizontal axis lies in the east-west plane.
   c. Either extinction position may be recorded, but, to be consistent in the readings, when the horizontal axis does not lie in the east-west plane (parallel to $A_4$), rotate grain 90° on $A_1$. This procedure simplifies the plotting of each reading on the Schmidt net.

Keeping the line of sight normal to the plane of the stage and vertically over the crystal being measured is difficult without some type of a collimating apparatus. Since no device is provided to align your eye, it is helpful to place your eye directly over the grain being measured and collimate your line of sight with your eye image, which is reflected from the top of the analyzing polaroid. Care should be taken to pursue this technique because of the possible error in locating the exact extinction position, especially at the higher angles of inclination.

After the individual grain or crystal has been measured on the universal stage, the data should be tabulated so that the angular corrections can be made and the information can be transferred readily to the Schmidt net. A suggested form for tabulation is shown in Figure 4.
Ice Fabric Data Sheet

Parent crystal or core

Thin section

Remarks

<table>
<thead>
<tr>
<th>Grain No.</th>
<th>A₁ Stage reading</th>
<th>A₂ Stage reading</th>
<th>A₂ Corrected</th>
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</table>

Figure 4. Suggested form for tabulating measurements obtained from universal-stage readings.
ICE FABRICS AND THE UNIVERSAL STAGE

OPTICAL MEASUREMENT OF ICE CRYSTALS

Ice is optically uniaxial and positive (\(\varepsilon > \omega\)) with \(\varepsilon = 1.3120\), \(\omega = 1.3106\) for sodium light (daylight mean), and the birefringence \(\varepsilon - \omega = 0.0014\) is very low. The critical angle of ice for index of refraction \(n = 1.31\) is 49°45'. When the true polar angle in reference to the plane of the thin section exceeds this, it is not possible to "stand up" the optic axis (polar position) to obtain a measurement. In this event, it is customary to "lay down" the optic axis parallel to the east-west axis of the stage (equatorial position).

The only optical direction which can be determined in ice is the optic axis, which coincides with the \(c\)-axis in hexagonal minerals such as ice. Crystal faces, cleavage planes, or observable twinning are absent; therefore, the true spatial orientation of an ice crystal is not completely defined. Nevertheless, the determination of the arrangement of the optic axes yields significant information.

The main disadvantage of the universal stage arises from the large differences between the refractive indexes of air and ice. With the Fedorow type stage, glass hemispheres are used to increase the angle through which a section may be rotated before total reflection results, and to reduce or remove the necessity for making angular corrections. No hemispheres exist for this type of stage. This limits the permissible measuring range of the instrument and necessitates an angular correction. Inclinations of the stage to 68° are required to measure optic axes inclined 45° to the thin section. An angular correction curve for ice has been constructed (Fig. 5) based on Snell’s law

\[
n = \frac{\sin i}{\sin r}
\]

where \(i\) is the angle of incidence, \(r\) is the angle of refraction, and the constant

\[
n = 1.31.
\]

Rigsby (personal communication) found that the theoretical values based on Snell's law held when the optic axis was "stood up," but did not hold when the optic axis was "laid down." He found that, when the optic axis was inclined 40° to 45° to the thin section, it was possible to orient the optic axis by standing it up (parallel to the line of sight) and also by laying it down and bringing it parallel to one of the horizontal stage axes. With this procedure, the two measurements should produce complementary angles. However, the sum of these angles does not total 90°, even when corrected for index differences between ice and air. To investigate this, he made a series of thin sections from a pure single crystal of ice cut with known inclinations in reference to the optic axis. These sections were measured on the stage, without hemispheres, and the measured angles compared with the true angles. It was found that the maximum inclination of the stage, when standing the optic axis up, is 70° to 80°, which corresponds to a true polar angle of 45° to 48°. These values confirm the theoretical values based on Snell’s law. Therefore, when the optic axis is inclined more than 45° to the thin section, it must be "laid down," and the theoretical correction cannot be used. The empirical correction curve to be used when the optic axis is laid down is also shown in Figure 5.
SOURCES OF ERROR

Sources of error involved in obtaining a measurement from the universal stage are: (1) The error in measuring the exact extinction position at high angles, and (2) the possible parallax effect when the eye is not quite normal to the plane of the thin section and in line with the grain being measured. There is also (3) the measuring error in reading the values from the $A_1$ and $A_2$ axes of the stage, and (4) the inherent mechanical error of the universal stage itself (reproducibility of readings from the same grain is usually between $1^\circ$ and $2^\circ$).

When all the above sources of error are considered, it is believed that the total error is no more than $5^\circ$. This is not as grave as one would suspect at first because, if the same individual measures the entire thin section, he will probably be consistent in his orientation technique and, therefore, the $5^\circ$ total error is a maximum value. Furthermore, since the final evaluation of the fabric analysis is based upon the statistical interpretation of the fabric diagram, a $5^\circ$ shift in the pattern is not critical, in most cases. This does not imply that it is not necessary to make accurate measurements. On the contrary, this means that, if the utmost care is taken in performing the mechanical steps and making the physical corrections, not more than a $5^\circ$ total error exists in the results.

FABRIC DIAGRAMS

Fabric diagrams are graphical representations of the spatial arrangement (or orientation) of the optic axes of the individual ice crystals. When a sufficient number of optic axes assume a certain non-random orientation (a clustering of points on the diagram), it is said to have a preferred orientation. This statistical preference is revealed by counting the number of points that fall within areas corresponding to a given percentage of the whole projection — commonly $1\%$. From many such values, contours may be drawn to show orientation density.

At least 200 axes should be plotted if a reliable statistical analysis is to be made. If the section shows a very strong pattern, as revealed by inspection, it is possible to use fewer points. However, it is usually advisable to plot at least 200 axes; then, if an axis is not correctly read or plotted, little statistical significance will be attached to this point.

The construction of fabric diagrams is a standard procedure and well documented in the literature. The following discussion is essentially a digest of outlines by Haff (1938), Fairbain (1954), and Billings (1942).

The most useful and convenient type of an equatorial-net to use for plotting data is the Schmidt equal-area net (Fig. 11) which is so constructed that a unit area in any position on the net corresponds to a unit area on the spherical projection from which the net was derived. A stereographic equatorial net may be used, but the areal distortion is excessive beyond $50^\circ$ from the center and misrepresents the fabric pattern. Because it is desirable to show the relative spatial concentration of the data measured, the Schmidt net, which eliminates nearly all areal distortion, is usually employed. Data are plotted on the net as points corresponding to the optic or $c$-axis of the ice crystal. The standard procedure in fabric studies is to use the lower hemisphere of the spherical projection as the basis for plotting points. Before plotting the data, the universal stage measurements are tabulated and the angular corrections are made (Table I).

Plotting data

A sheet of tracing paper is placed over the equal-area net (a turntable device manufactured by Leitz is an excellent aid and expedites the plotting). This paper has a base circle inscribed on it with the same diameter as the net (20 cm). A zero index arrow is arbitrarily placed somewhere on the perimeter of the circle. The $A_1$ position is placed on the net by rotating the tracing paper until the index arrow on the net corresponds to the azimuth that was read on the universal stage. Next, still assuming the lower hemisphere as the basis for the projection, the $A_2$ angle is plotted on the east-west diameter of the net. The location of the point depends upon whether a polar or
Table I. Correction table.

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<th>Measured angle (deg)</th>
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Critical angles
Standing axis up: 49°45' 85
Laying axis down: ≈ 65° 90
Equatorial orientation is to be plotted (Fig. 6). For polar orientations, measure the $A_2$ reading, from the center out, along the E-W axis of the net in a direction opposite to that given in the stage reading; i.e., for an E reading, read west from the center. For equatorial orientations, measure the $A_2$ reading from the perimeter of the net inward toward the center in the same direction as given by the stage reading; i.e., for an E reading, read in from the east perimeter of the net. (E means the thin section was inclined while on the universal stage with the east arm up.) Suppose a polar reading gives the values: $A_1 = 92^\circ$; $A_2 = 40^\circ$E. The projection of this polar axis $P$ is found by bringing the index arrow opposite $92^\circ$ ($A_1$) and then measuring $40^\circ$ from the center toward the west on the east-west diameter of the net (see Fig. 6, la-c).

With an equatorial reading of $A_1 = 60^\circ$; $A_2 = 30^\circ$W, the azimuth is found by rotating the index, as before, until it is opposite $60^\circ$ on the net and $30^\circ$ is counted in on the east-west diameter from the west perimeter (see Fig. 6, 2a-c).

After all of the points have been plotted on the tracing paper, the points are counted, using a 1% counter and a centimeter grid. The counters are made of clear plastic, with specifications as indicated in Figure 7. The centimeter grid is placed under the tracing paper with an intersecting node on the grid coinciding with the center of the diagram.
Figure 7. Specifications for 1% counters for use with a standard 20-cm diam net. Counters may be made of 2 mm thick plastic.

A - Periphery counter
B - Interior counter

Next, the 1% interior counter is centered over each node of the grid and the number of points falling inside the circle is counted. Later this number is divided by the total number of plotted points, to obtain the percentage of grains in that area. This value is placed in the center of the circle. To record areas on or near the perimeter of the net, the peripheral counter is rotated through a centimeter interval along the perimeter of the net. The total number of points in the circles at both ends of the peripheral counter is counted and then divided by the total number to obtain the percentage. This percentage value is noted at the center of both circles (Fig. 8).

After all the numbers have been converted to percentage values, the diagram is contoured. The contour interval depends upon the density of the pattern, but any convenient interval may be used. In a study consisting of several diagrams, the same contour interval should be used for each diagram. More accurate contours may be located by shifting the counters without regard to the grid; however, unless an extremely large number (over 200) of grains are counted, this additional detail is usually not significant.

Figure 8. Method of using peripheral and interior 1% counters.

Contours are drawn from values plotted in the center of the small circles. Interpolate where values do not exist.
Rotation of the diagrams

To compare fabric diagrams of different orientations, it is sometimes desirable to rotate one or more of the diagrams so that all fabric axes coincide. A 90° rotation is commonly all that is necessary, for often core samples are taken from a horizontal or a vertical position, but the procedure holds for any angular rotation. Each point may be rotated, but rotation of the contour line is usually sufficient in the case of fabric diagrams. Three or four widely separated points along the contour lines are rotated and then connected in the same configuration that the line originally had. The arcs of latitude on the net which intersect the great circles are the trajectories by which rotation is carried out.

![Diagram of rotation of points using lower hemisphere of Schmidt net.](image)

**Figure 9. Rotation of points using lower hemisphere of Schmidt net.**

RA = axis rotation
P = original plot
P₁ = 90° rotation clockwise
P₂ = 90° rotation counter-clockwise
X = intermediate position in counter-clockwise rotation.

First, the rotation axis (RA) must be decided upon; then, rotate the diagram so that this axis is on the north-south diameter of the net. With a lower hemisphere projection, a 90° clockwise rotation of a point P gives P₁, and a 90° counter-clockwise rotation gives P₂ (Fig. 9). At an intermediate point X in the counter-clockwise rotation, P projects as a line across the net and connects with a parallel of latitude on the north side of the equator. The remainder of the rotation follows the new arc. In other words, if the perimeter of the net is reached before rotation is completed, the remainder of the rotation follows the arc 180° removed from the initial one.

When publishing data in a diagram, certain fundamental information should accompany the data in the form of a legend. This should include: (1) the number of grains measured; (2) the orientation of the thin section relative to the diagram; and (3) the contour interval. Other information such as features of primary origin (e.g., sedimentary layering) and secondary origin (e.g., foliation planes) may be of value in interpreting the diagrams and also should be included in the legend or directly upon the diagram as traces of the planes.

PHOTOMICROGRAPHS

Thin sections may be studied in transmitted or reflected light or between crossed polaroids depending upon the nature of the study. However, to orient a crystal optically, crossed polaroids are necessary.

Prior to a detailed study of a thin section, it should be photographed between crossed polaroids for a permanent record (Fig. 10). A cover plate scored with a 1-cm grid will provide a linear scale on the negative.

The photograph should be used to number each grain during the measurement of the section. This permits a further analysis of the section in respect to size, shape, and orientation of any grain relative to its neighbors.
Any reflex type camera is satisfactory for photographing thin sections, but the larger film sizes produce a better negative for enlarging. A special press-type camera attachment has been adapted for this universal stage (Fig. 1). A polaroid land camera back may be attached to the press camera for field studies. With crossed polaroids, a good photographic print can be made of a thin section under the following suggested conditions:

- **Light source** — A 150-w ordinary light bulb transmitted through a frosted glass plate to diffuse the light
- **Film** — Kodak Panatomic X (ASA Daylight 32, Tungsten 25)
- **Shutter speed** — 1 or 2 sec
- **f stop** — f/5.6 or f/8.

Focusing is an important consideration and, if good results are to be expected, some care should be exercised in trying to obtain a sharp image on the negative.

Figure 10: Photograph of an ice-section between crossed polaroids, with an overlying 1-cm grid. This section is from the 300-m level of a core from Site 2 on the Greenland Ice Cap. Small intergranular and intragranular spheres are entrapped air bubbles. The narrow band of fine-grained ice crystals at the perimeter of the section is the melt that refroze during the bonding.
COMMENTS ON INTERPRETATION OF FABRIC DATA

The following brief discussion is not intended to be conclusive and is included in this report to give the reader some indication of the interpretive value of fabric studies. It is important to understand what is involved in producing a preferred orientation that may be revealed in a fabric study of a polycrystalline aggregate. Fairbain (1954, p. 2) refers to Bruno Sanders's classification of fabric data as vectorial or scalar. Here, scalar data are those physical features defined by measurement of length, width, etc., where no directional properties are included; vectorial data are spatial measurements which indicate directional properties produced by solid or fluid flow. Generally speaking the directional properties may originate by deformation, growth, or deposition.

A deformation fabric is created by stresses acting upon the mass and is the fabric type that most concerns investigators of glacial ice. A growth fabric originates through growth of the individual grains, in situ, by crystallization or recrystallization; such as the annealing process that produces "basket-ball" sized single ice crystals at the snout of the Mendenhall Glacier in Alaska (personal communication, Dr. H. Bader), and the selective growth of individual crystals in lake and sea ice (personal communication, Dr. W. Weeks). A deposition fabric arises when the grains become oriented by means of mechanical processes, such as in newly fallen snow or in wind blown snow drifts or dunes.

Most glaciers are constantly in motion, and their flow mechanism is understood in part. Since glaciers undergo differential movement in their various parts, most glacial ice has undergone some form of deformation and exhibits a deformation fabric related to the magnitude and direction of the strain, with possible influence from the initial deposition fabric and secondary growth fabric. These influences are difficult to ascertain, but it is the responsibility of the investigator to be fully aware of all the considerations in an ice fabric study.

According to E. B. Knopf (1957), "A fundamental tenet of structural petrology is that the preference of certain constituents for one or more positions in preference to others was determined by the movement that brought them into the position they now occupy," but she warns that reasoning from the movement that is recorded in the fabric diagram to the dynamics of the movement is a matter that requires the utmost caution.

The movement can take the form of shear strain, as manifested in foliation planes and observed in valley glaciers and at the terminus of continental glaciers. Rigsby observed a direct relationship between crystal orientation and the foliation plane in his studies of glacial ice from the Saskatchewan glacier, Alberta, Canada, (1954) and the Moltke Glacier, Thule, Greenland (1955). He reported the strength of the pattern to be more or less proportional to the strength of the shearing stresses imposed on the ice.

The stresses can also be compactive, as in the upper layers of the dry-snow zone of a high-polar glacier. This compactive stress has a shear component of a much lower magnitude that the shear stresses acting at the terminus of a glacier. Therefore, a weaker fabric pattern would be expected, and this is exactly what has been found. At 6 to 7% preferred orientation was the strongest pattern found in studies of high-polar snows to a 50-70 depth on the Greenland Ice Cap (Fuchs, 1958). A preliminary investigation by the author of the ice between 50 and 300 m from the same area revealed that the pattern does not get much stronger than 8%, even at 300 m. The conclusion is that the shear stresses are not sufficient to noticeably alter an orientation pattern initiated in the snows near the surface. This would appear strange in light of the fact that recrystallization contemporaneous with metamorphism has brought about a gradual increase in grain size; with depth. It is not strange however if one considers the concept as reported by Steinemann (1954) that a shear strain is necessary to produce a reorientation and that a shear stress, although capable of producing a recrystallization, as evidenced by the grain size increase with depth, cannot in itself alter the general fabric pattern that has been initially established.

The recognition of the stress-strain relationship to ice crystal orientation is not a new concept (M. Demorest, 1941; H. Bader, 1951; and, Perutz and Seligman, 1939) have all mentioned it in some of the early work on snow and ice fabrics.
Dr. Bader concludes that this relationship between stress-strain and orientation pattern is a valuable key to the stress distributions in glaciers and to a fuller understanding of glacial motion.

Basically, then, the interpretation of the fabric diagrams of glacial ice is essentially a matter of relating the pattern revealed to the forces that caused the ice to move, or alter, in the first place.

REFERENCES


Billings, M. F. (1942) Structural geology, Prentice-Hall, Inc.


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Figure 11. Schmidt equal area net. Standard 20-cm diam.