

## INSTRUMENTS AND METHODS

### DETERMINATION OF *a*-AXIS ORIENTATIONS OF POLYCRYSTALLINE ICE

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**ABSTRACT.** Two new methods have been devised for measurement of crystallographic lattice orientations of individual crystals in polycrystalline ice. The first uses edge-length ratios of etch pits. The second uses a combination of optical measurement on a thin section and etch-pit technique. Although the second method does not work for crystals with their *c*-axis oriented parallel to the thin section, it is much simpler and more practical than the first method. When used on polycrystalline glacier ice, this method gave the three *a*-axes orientations as well as *c*-axis orientation for each crystal with an accuracy of 5°.

**RÉSUMÉ.** Détermination des orientations des axes-*a* dans la glace polycristalline. Deux méthodes nouvelles sont élaborées pour mesurer les orientations du réseau cristallin des cristaux individuels dans une glace polycristalline. La première méthode utilise les rapports des longueurs des arêtes dans une cavité de gravure. La seconde utilise une combinaison de mesures optiques d'une lame mince et d'une technique de gravure. Bien que la seconde méthode ne soit pas valable pour des cristaux à axes-*c* parallèle à la lame mince, elle est beaucoup plus simple et plus pratique que la première méthode. Quand elle a été appliquée à une glace polycristalline de glacier, elle a donné les orientations des trois axes-*a* comme celles des axes-*c* pour chaque cristal avec une précision de 5°.

**ZUSAMMENFASSUNG.** Messung der Orientierung von *a*-Achsen in polykristallinem Eis. Es wurden zwei neue Verfahren zur Messung der kristallographischen Gitterorientierung einzelner Kristalle in polykristallinem Eis entwickelt. Das erste benützt das Längenverhältnis von Ätzgrübchenkanten; das zweite verbindet optische Messungen an Dünnschliffen mit Ätzgrübchentechniken. Das zweite Verfahren lässt sich nicht auf Kristalle mit *c*-Achsen parallel zum Dünnschliff anwenden, es ist aber viel einfacher und leichter anwendbar als das erste. Wurde dieses Verfahren auf polykristallines Gletschereis angewandt, so gab es die Orientierung der drei *a*-Achsen als auch der *c*-Achse für jeden Kristall mit einer Genauigkeit von 5°.

#### 1. INTRODUCTION

Since the first work of Rigsby (1951), the crystal orientation fabric of glacier ice and other polycrystalline ice has been of major interest. Hitherto the determination of crystallographic axes of individual crystals in a polycrystal has been restricted to the *c*-axis. This is a consequence of using the standard optical method, which cannot distinguish *a*-axis orientation because of the optical isotropy of ice around the *c*-axis.

Thermal etching was used first to determine the orientation of surfaces relative to crystallographic axes (Schaefer, 1950; Higuchi, 1958). Then, by using the angles between edges in an etch pit, Aufdermaur and others (1963) determined the crystallographic orientations of the *a*-axes as well as the *c*-axis of a hailstone. However this method is not available for the special case when the *c*-axis is oriented parallel to the ice section.

This paper describes a new method using edge lengths in an etch pit by which both *c*- and *a*-axis orientations can be determined for the crystal in any orientation. There is another much simpler and more practical method for determining the *a*-axis using a combination of optical measurements on a universal stage and etch-pit techniques, although it also breaks down for the special case mentioned above. This method is also described in the present paper.

#### 2. RATIO OF ETCH PITS

The etch-pit figures in Figure 1 are geometrically-derived accurate configurations. Each set of edge lengths ( $\alpha_1, \alpha_2, \alpha_3$ ) and ( $\gamma, \gamma'$ ), has a simple relationship with the inclinations of the corresponding crystallographic axes,  $\omega$  and  $\phi$  respectively. For the *c*-axis,

$$\gamma - \gamma' \tan^2 \phi = 0.$$

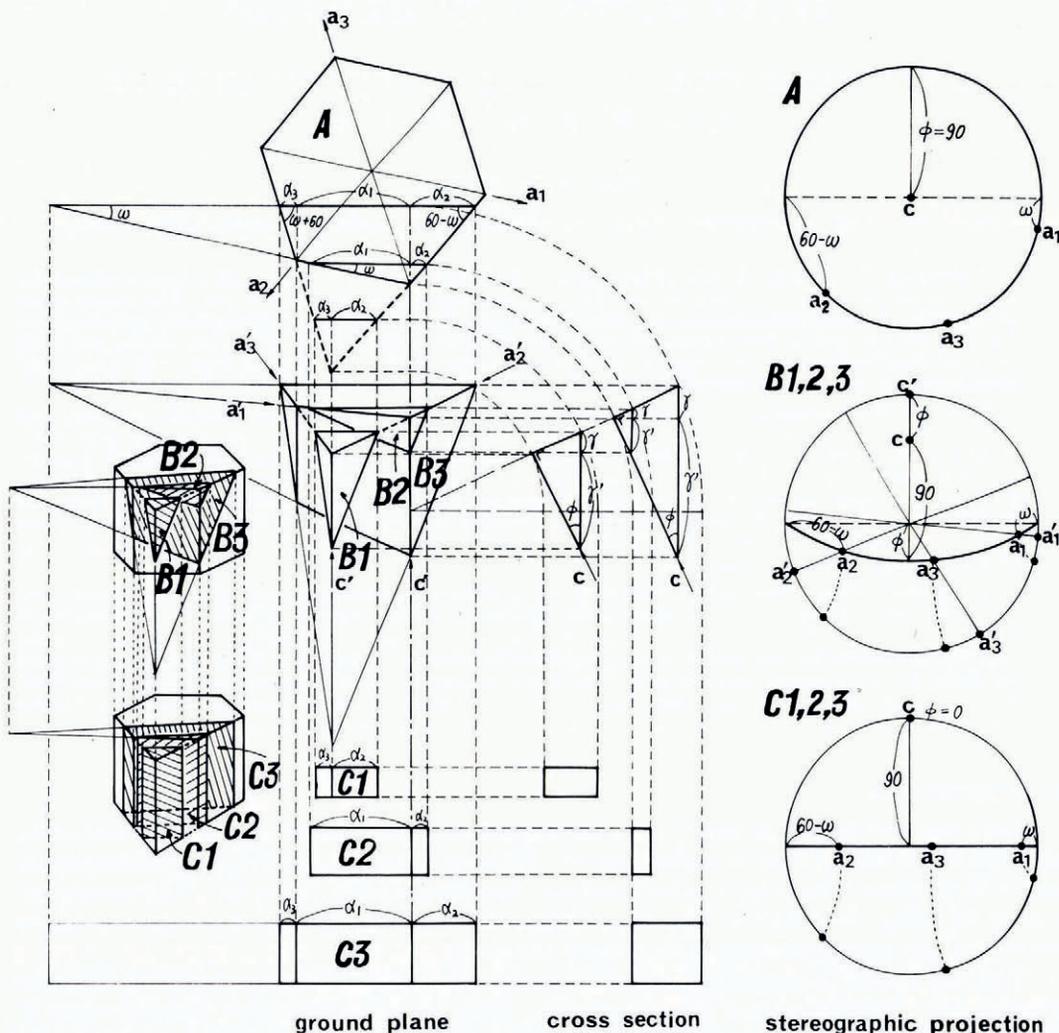


Fig. 1. Geometric configuration of etch pits with *c*-axis oriented vertical (*A*) to the thin section, slanting (*B*<sub>1</sub>, *B*<sub>2</sub>, and *B*<sub>3</sub>) and parallel (*C*<sub>1</sub>, *C*<sub>2</sub>, and *C*<sub>3</sub>).  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are the horizontal components of the edges corresponding to the  $a_1$ ,  $a_2$ , and  $a_3$ -axes respectively.  $\gamma$  and  $\gamma'$  are those for the *c*-axis. Examples of corresponding etch pits are shown in Figure 2.

$\phi = 0$  and  $90^\circ$  are the special cases *A* and *C*<sub>1</sub>, *C*<sub>2</sub>, *C*<sub>3</sub> respectively. For the *a*-axis,

$$\alpha_1 \tan \omega + \alpha_2 \tan (\omega + 120^\circ) + \alpha_3 \tan (\omega + 60^\circ) = 0.$$

For the cases *B*<sub>1</sub> and *C*<sub>1</sub>,  $\alpha_1 = 0$ , and for *B*<sub>2</sub> and *C*<sub>2</sub>,  $\alpha_3 = 0$ .

$\omega$  and  $\phi$  give the full crystallographic orientation of any ice crystal including the crystal with its *c*-axis oriented parallel to the ice section. This method is, however, rather tedious since it involves measuring the edge lengths for a large number of individual crystals. It has similar operational disadvantages as the method of Aufdermaur and others which involves measuring the angles between edges. A simpler method is needed for practical application to polycrystalline ice.

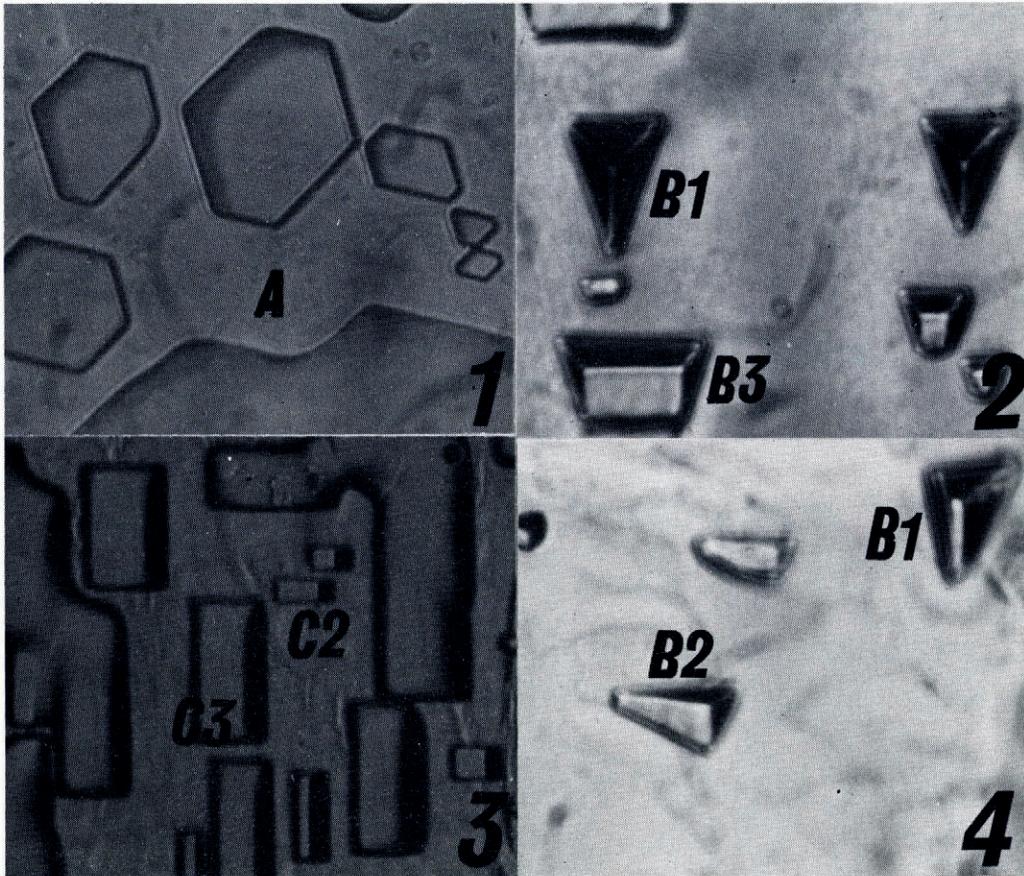


Fig. 2. Etch pits of ice crystals, each of which corresponds to the configuration in Fig. 1. 1, 2, 4:  $\times 400$ ; 3:  $\times 100$ .

### 3. COMBINED OPTICAL AND ETCH-PIT MEASUREMENT

The orientation of  $c$ -axes can be determined by the use of a universal stage (Langway, 1958). The orientation of etch pit sides gives the azimuths of both  $a$ -axes and  $c$ -axis which define vertical planes in which these axes lie. The orientation of the  $a$ -axis is represented by the intersection of the above vertical plane and the basal plane, which is perpendicular to the  $c$ -axis.

To apply this method to a polycrystalline aggregate, an ice section is prepared and fixed on a slide glass scored with 0.5 or 1 cm grid, depending on the grain size. The grids provide reference for positions of individual crystals and also for the orientation of the ice section itself. The ice section is photographed between crossed polaroids for identifying and numbering each crystal in the ice section. The  $c$ -axis measurement using a polarizing universal stage should be done very carefully and as accurately as possible, because any error also causes error in the  $a$ -axis determination.

After dropping a solution of polyvinyl formal dissolved in ethylene dichloride onto the surface of the ice section, it is set on the stage of a microscope (Fig. 3). The etch pit to be observed must always be near the centre of the field of vision of the microscope. For this

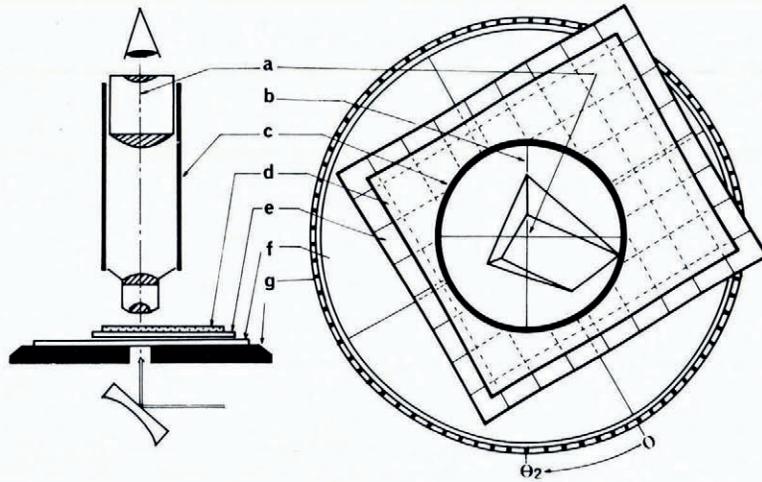


Fig. 3. Etch-pit figure seen through microscope, showing the procedure of a-axis determination. a: rotation axis of the stage; b: crossed hairs; c: tube of microscope; d: thin section of ice sample; e: slide glass scored with grids; f: glass plate scored with crossed lines; g: stage.

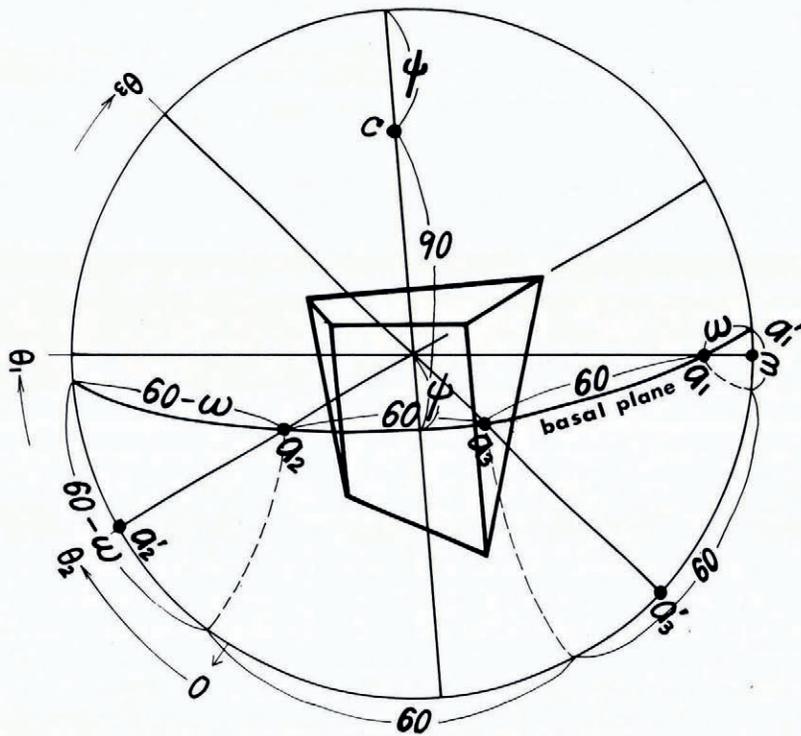


Fig. 4. a-axis orientations projected on a Wulff net, represented by the intersections of a basal plane and the vertical planes which are determined by rotation angles of the stage.

purpose another piece of glass plate on which crossed lines are scored, is prepared and fixed on the stage. Cedar oil is applied on this glass plate so that the slide glass holding the ice section can be easily slid over it. Parallelism of the scored lines on the slide glass and on the glass plate is essential in order to maintain the orientation of the ice section.

Then the stage is rotated to make the edge  $a_i'$  ( $i = 1, 2, 3$ ) in an etch pit parallel to either of the cross-hairs. The rotation angle  $\theta_i$  gives the azimuth of the corresponding crystallographic axis  $a_i$  (Fig. 4). It is important for good accuracy that several etch pits with sharp edges should be chosen in one crystal to obtain the average azimuth. This procedure is repeated for every crystal by parallel movement of the ice section on the stage.

This method breaks down for the crystals oriented with their  $c$ -axis parallel to the ice section ( $c_1, c_2$ , and  $c_3$  in Figs 1 and 2). However in practice it can be avoided by cutting an ice section so as to be on a slant to the  $c$ -axis-concentrated orientations of the ice sample.

#### 4. ERROR IN THE COMBINED OPTICAL AND ETCH-PIT MEASUREMENT

Second method was applied to a polycrystalline glacier ice. Error in  $c$ -axis measurement comes simply from the optical and mechanical limits of the universal stage. The comparison was made between the  $c$ -axis azimuth optically obtained from careful operation of the universal stage and that determined from the corresponding edge orientation in an etch pit. These two azimuths agreed to within a few degrees.

As regards the  $a$ -axis, the angles between the orientations of the three  $a$ -axes determined from the edges in one etch pit were within the range of  $60^\circ \pm 5^\circ$ . The measurement of a number of corresponding edges of different etch pits developed at the different parts of the same crystal gave the same  $a$ -axis orientations within a few degrees, except for a crystal with  $c$ -axis nearly parallel to the thin section. Thus, those results show that the second method gives reliable  $a$ -axis orientations with a similar accuracy of  $5^\circ$  to that of the  $c$ -axis measurement by the universal stage.

By using this method, a number of polycrystalline ice samples of different origin were examined. The results will be reported separately. This method could also be applied to determining the crystallographic orientations of other hexagonal minerals. Quartz would be the mineral to which it is best applicable.

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