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## On the Optical Axes of Snow Crystals of the Side Plane Types

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### Abstract

The optical axes of snow crystals of the side plane types were determined by various methods, e.g. under a polarization microscope, from the shapes of etch pits produced on the plane, and from the apparent hexagonal shapes of the planes.

As a result of the determination, it was found that there are two kinds of snow crystals in the so-called side plane type; one is a mere spatial assemblage of plates (crossed plates) whose optical axes are vertical to their planes, another is a snow crystal with true side planes which are an extension of one of the prism planes (side planes) of a columnar portion.

Generally two side planes extend from two columnar portions respectively, then they form a polycrystal because the columnar portions stretch radially from a single original point.

If two columnar portions are in parallel, the resulting snow crystal appears as a single crystal form.

### 1. Introduction

The physical property of snow crystals has been studied in detail by many researchers hitherto in temperature regions warmer than  $-20^{\circ}\text{C}$ , however snow crystals of the colder region were not compared with those in the warmer region. This may be because most of the researchers live in fairly warm countries.

Recently Kikuchi<sup>1)</sup> brought from the Antarctica microscopic photographs of snow crystals of singular types which are considered to be formed in the colder temperature region. Several examples of them are shown in the photographs in Plate I.

The snow crystal in Photo. 1 is composed of four bullets and a thin flat branch. The flat branch has two thin columns at both ends and has two fine parallel structures between the thin columns. The snow crystals shown in Photos. 2 and 3 have flat portions like the side planes.

Photo. 4 illustrates a snow crystal of typical side plane type. Nakaya<sup>2)</sup>

showed snow crystals of this type as examples of the side plane type. It is seen in Photo. 4 that the snow crystal is composed of two systems of plates whose directions are uniform in each system. Plates in one system are in parallel with each other and are parallel also to the surface of the paper, while plates in another system are nearly vertical to the surface of the paper, therefore they are seen darkened in the photograph. This type is referred to as the crossed plate type, in this paper.

As a first step, the determination of the optical axis ( $c$ -axis) of snow crystals of the side plane types was undertaken by various methods. This paper will describe the result of the measurements and considerations about their formation mechanisms.

## 2. Methods

Snow crystals of the side plane types were formed in a snow-making cold box of Nakaya's convection type<sup>3)</sup> in temperature regions which mostly ranged between  $-22$  to  $-27^{\circ}\text{C}$ . The  $c$ -axes of the snow crystals were determined by the following methods.

### 2.1 *Under a polarization microscope*

According to the usual method, a snow crystal of the side plane type was set in such a way as to keep one of its plane vertical to the optical axis of a polarization microscope, utilizing a universal stage, then it was rotated around the axis of the microscope by  $90^{\circ}$  under the microscope. If the plane is not colored by the rotation, the  $c$ -axis of the plane is in parallel with the axis of the microscope.

However the method was not always useful in the case of side planes of snow crystals, because the thickness of the planes was sometimes insufficient to make a detectable difference in the optical path between normal and abnormal rays. Therefore another method as reported by Magono and Suzuki<sup>4)</sup> was also used, as follows.

In order to determine the  $c$ -axis of a plane of the side planes, a snow crystal of this type was set in such a way as to keep one of the side planes in parallel with the optical axis of a polarization microscope (vertical to the surface of paper). In this case, a horizontal cross section of the plane is observed. If the  $c$ -axis of the plane is vertical to the optical axis of the microscope, the cross section shows a specific color. After photographing the cross section by a color film, the snow crystal was rotated around the axis of the microscope by  $90^{\circ}$ . The color of the cross section may change to other colors

by this rotation.

If a snow crystal with a known axis, for example a columnar crystal is contained in the same photograph as that of the side plane, the  $c$ -axis of the plane is determined by comparing the color change by the rotation of  $90^\circ$ , with that of the columnar crystal.

### 2.2 *By the shape of etch pits*

The  $c$ -axis of plates of snow crystals of the side plane type was determined by observing the shape of etch pits produced on the plates thermally, as demonstrated by Higuchi<sup>5)</sup>.

### 2.3 *By the apparent shape of side planes*

If a side plane has a regular hexagonal plate shape, it is assumed intuitively that the  $c$ -axis of the plate is vertical to the plane of the plate. It is also probably possible to determine the  $c$ -axis of a plane by the use of the shape of a secondary branch which develops from the end of the plane, for example a usual sector-like branch.

However it is difficult to determine the  $c$ -axis of snow crystals of complicated shapes only by their apparent shapes.

## 3. Results

Because it was noted from the preliminary observation that snow crystals of the side plane types were classified into two groups; 'extended side planes' (Photos. 1 and 2) and 'crossed plates' (Photo. 4), the result of measurements will be described in the respective groups below.

### 3.1 *Crossed plates*

Photo. 5a in Plate II shows the color distributions of snow crystals of crossed plates and a bullet. Several crossed plates whose planes are in parallel with the surface of paper are seen. They are colored in brown the same as that of the background. One also sees a yellowish portions of the cross sections of a short bullet and a crossed plate near the center. It is a matter of course that the  $c$ -axis of the bullet coincides with the longitudinal direction of the bullet, although the bullet is fairly short, in other words the  $c$ -axis is pointed from the left bottom to the right top in the photograph. It is noted that the color of the cross section of the crossed plate is yellowish in approximately the same manner as that of the bullet. A black line at the upper right is the outline of a rabbit hair which was used to suspend the snow crystals in the snow-making cold box,

When the snow crystals were rotated by  $90^\circ$ , the color of both the bullet and the plate changed to green, as seen in Photo. 5b. This common change in color shows that the *c*-axis of the plate was in parallel with that of the bullet whose axis was pointed from the left bottom to the right top, in other words the *c*-axis of the plate was vertical to the plane of the plate. Hereafter, the color photographs will be arranged so that the *c*-axes point from the left bottom to the right top, if the color distribution is composed from yellow or red.

The colors of crossed plates whose planes were in parallel with the surface of the paper was the same as that of the background, as seen in Photo. 5a and they were not changed by the right angle rotation, as seen in Photo. 5b. This suggests that the *c*-axes of the plates were all in parallel with the optical axis of the microscope, namely they were vertical to their planes, because their colors should be changed slightly if their *c*-axes were oblique to the optical axis of the microscope, considering the depth of the plates. Incidentally, the background of photographs was colored reddishly, because a light sensitive color plate was inserted in the optical system of the microscope in order to increase the sensitivity in the color change.

A snow crystal of the crossed plate type is seen near the center of Photo. 6a. One of the crossed plates is in parallel with the surface of paper and is colored in the same manner as that of the background, and another is vertical to the surface of paper and its cross section is colored pink. Several long columns are also seen on the right hand in the photograph. Two of them are colored in yellow or pink and point to the right top. This color distribution suggests that the *c*-axis of the pink colored cross section of the crossed plates points approximately to the left top, the same as the two pink colored columns.

When the snow crystals were rotated by  $90^\circ$  as seen in Photo. 6b, the color of the cross section of the plate became blue in the same manner as that of the two columns. This color distribution shows that the *c*-axes of the vertical crossed plate and of the two columns were nearly in parallel, in other words the *c*-axis of the plate was vertical to its plane. The color of the plate in parallel with the surface of paper was the same as that of background and it was not changed by the rotation. This also shows that the *c*-axis of the plate was in parallel with the optical axis of the microscope, namely vertical to its plane.

In Photo. 7a, one sees greenly colored parallel cross sections of two crossed plates and non-colored (the same color as the background) plates whose outer

portions are partially sublimated. A line of air bubbles are overlapped on one of the greenly colored cross sections.

When the snow crystals were rotated around an axis in parallel with the green lines of the sections by about  $90^\circ$  (not around the axis of the microscope) until the surface of the two greenly colored crossed plates became in parallel with the surface of paper and the non-colored plates became nearly vertical to the surface of paper, as seen in Photo. 7b, the color of the cross section of new vertical plates became green. The air bubbles which overlapped the green portion are now seen on the plane of a plate which was made newly in parallel with the surface of paper. These green colors in the cross sections of plates in Photos. 7a and 7b show that their *c*-axes point from the right bottom to the left top, in other words their *c*-axes are always vertical to the plane of the plates.

In order to verify this, the determination of *c*-axes of crossed plates was further made by the etch pit method, as follows. A snow crystal of the crossed plate type was coated with ethylene dichloride solution of polyvinyl formal, then the shape of etch pits which were produced on a plate in parallel with the surface of paper, was observed. Because the etch pits were all regular hexagonal, as shown in Photo. 8 in Plate III, it was considered that the direction of the optical axis of the plate was vertical to the surface of paper, namely vertical to the plane of the plate.

According to the result of measurements by various methods, it was confirmed that the *c*-axes were always vertical to the plane of plates, as far as the snow crystals of the crossed plate type were concerned.

### 3.2 *Extended side planes*

The chance of forming snow crystals of the extended side plane type was few in the laboratory experiment, however it was found that the direction of *c*-axes of the extended side planes was quite different from that of the crossed plate type.

It may be seen in Photo. 1 that branches developed from an original point, and in case of the flat branch, the thin and flat portion seemed to be held between two fine bullet-like arms which intersected at nearly a right angle with each other. In the present paper we do not note the magnitude of the angle, because various angles were observed in other snow crystals. In an extreme case, the two fine bullet-like arms were parallel. Rather it was noted in the flat branch that there are two kinds of fine parallel patterns which extended perpendicularly from each fine bullet-like arm, and the parallel

patterns are connected by an irregularly curved double line as seen in Photo. 1. The authors noted the *c*-axis of the flat portion with parallel fine patterns.

Photo. 9a shows a color distribution of a snow crystal of the extended side planes whose outline is of a sector form and the angle between two bullet-like arms (columnar structures) are considerably narrower than the right angle. One sees two domains in the sector form region in the photograph. One is the upper domain where a bullet is colored in grey and a grey flat plane extends perpendicularly from the bullet (downwards in the photograph). The grey portion is shown by the dotted area in the right hand picture. Another is the lower domain where a yellow bullet is seen under the grey domain and a red flat plane extends perpendicularly from the yellow bullet (obliquely upwards in the photograph). Those color distributions suggest that the snow crystal are composed from two domains whose *c*-axes are different from each other.

When the snow crystal was rotated by 90°, as shown in Photo. 9b, the grey domain became red, while the yellow and red domains changed to bluish color. The change in the color distribution shows that in each domain the bullet and the flat portion extending from the bullet form one single crystal respectively, in other words the snow crystal of extended side planes is composed of two single crystals whose axes are different from each other, and their boundary is connected by a curved line. In each single crystal, the flat portion extended perpendicularly from the respective column, considering the direction of the fine parallel pattern in that portion. The *c*-axis is common to both the bullet and the flat portion, although their colors are slightly different from each other due to the difference in thickness.

#### 4. Considerations

As a result of determining the *c*-axis of snow crystal of the crossed plate type, it was confirmed that the snow crystal of this type was composed of plates whose axes were vertical to their respective planes, as shown schematically in Fig. 1, in other words the snow crystal was only a spatial assemblage of hexagonal plates, although their six corners were not perfectly formed.

Accordingly it may be not correct to classify snow crystals of this type as the side plane type, although Nakaya showed photographs of snow crystals of this type as examples for the side plane type. Rather the present authors wish to call this type the 'crossed plate type'. However the mechanism for the growth of the crossed plates is not yet clarified in detail,

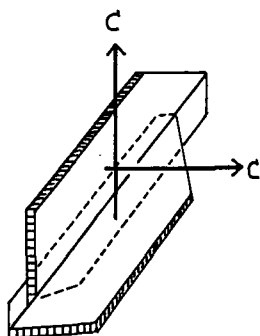


Fig. 1 C-axes of crossed plates.

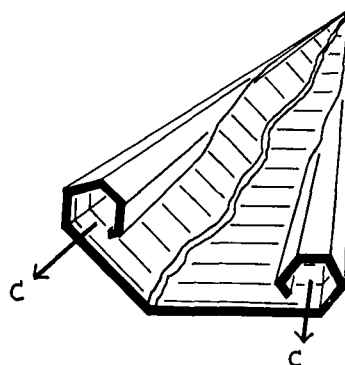


Fig. 2 C-axes of extended side planes of polycrystals.

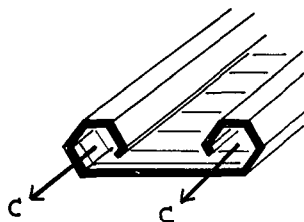


Fig. 3 C-axis of extended side plane with parallel columnar structures at both ends.

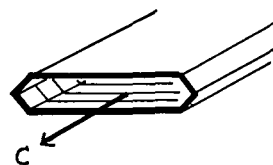


Fig. 4 Flattened hollow column.

Concerning the formation mechanism of the extended side planes, some problems remain, however it is considered at present that the thin columnar structures at both ends are not perfect bullets but are a type of scrolls and one of planes of the scroll extended perpendicularly from the bullet-like scroll, as shown schematically in Fig. 2, because it is difficult to consider that one of side planes of a completed bullet extends perpendicularly from the bullet.

It is noted in Photo. 1 that the scroll structure is not perfect near the original point. The structure is gradually completed as it extends. This thin extended portion was called an 'extended side plane' in this paper. This mechanism proposed here is nearly the same as that given by Nakaya<sup>2)</sup>, however he considered that the side planes extended from a column, and the examples given by him were inadequate, as described above.

If side planes extend from two scrolls which develop radially from a point, two single crystals are formed and their boundary is connected by a curve, thus a snow crystal of poly crystal type is produced as schematically shown in Fig. 2, and if the two scrolls are parallel, a snow crystal as shown in Fig. 3 will be formed. Snow crystals with the extended side planes of the latter type are sometimes observed as a portion in nature, as shown in a circle of Photo. 2, Plate I. The portion in the circle forms a single crystal. The extended side plane of this type is apparently similar to a flattened hollow bullet as shown in Photo. 3 and in Fig. 4, at the point that they have parallel structures at both ends. However the former is distinguished by the existence of the scroll-like structure from the latter.

As seen in Photo. 1, four bullets and one extended side plane developed from an original point. It is not explained why only one branch developed to the extended side plane. It is a matter of course that the side plane did not develop after the growth of the scrolls at both ends but rather it developed outwards from the original point together with the growth of the scrolls, making fine parallel structures which were vertical to the longitudinal direction of the scrolls.

## 5. Conclusion

As a result of determining the  $c$ -axes of snow crystals of the so-called side plane type, it was found that there are two kinds of snow crystals in the "side plane type". One is the crossed plate type in which the  $c$ -axes of the plates are always vertical to the plane of the plate. Snow crystals of this type may be considered as spatial assemblage of plates. Accordingly it may be not reasonable to include snow crystals of this type into the side plane type.

Another is the extended side plane type in which thin flat portions are seen between two columnar portions, and the  $c$ -axes of the flat portions are in parallel with the longitudinal direction of the columnar portions, in other words each flat portion and the respective columnar portion form a single crystal. Because the two columnar portions extend radially from an original point, they are combined to form a polycrystal. If the columnar portions are in parallel with each other, the snow crystal forms a single crystal.

It was considered that the columnar portion has a scroll structure, because it is difficult to consider that one of the side planes (prism planes) of a column extends outwards.

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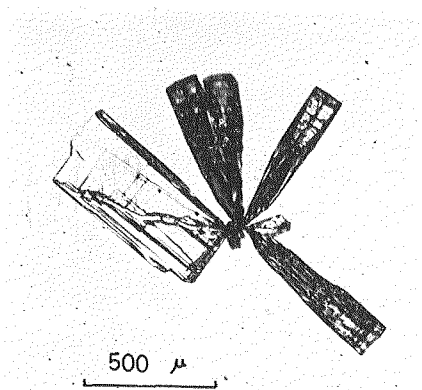
Kikuchi who noted the existence of snow crystals of singular side plane types in the Antarctica and offered the use of his photographs of the snow crystals.

The expense of this work was defrayed by the Special Fund for Scientific Research of the Educational Ministry of Japan.

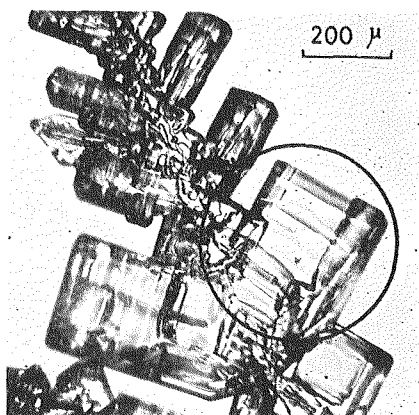
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- 3) NAKAYA, U.: Ibid, 151.
- 4) MAGONO, C. and S. SUZUKI,: A study on crystal axes of snow crystals with complicated shapes, utilizing a polarization microscope. Jour. Fac. Sci., Hokkaido Univ., Ser. VII, **3** (1967), 27-55.
- 5) HIGUCHI, K.: Etching of ice crystals by the use of plastic replica films. Jour. Fac. Sci., Hokkaido Univ., Ser. VII, **1**, (1958), 81-91.

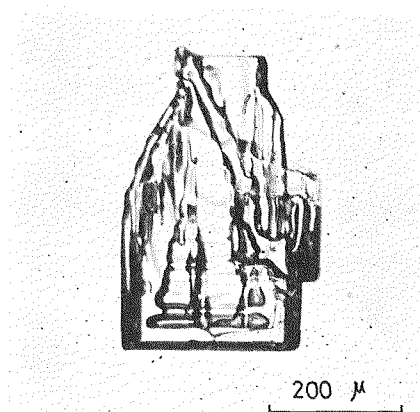
Plate I Snow crystals of the side plane types



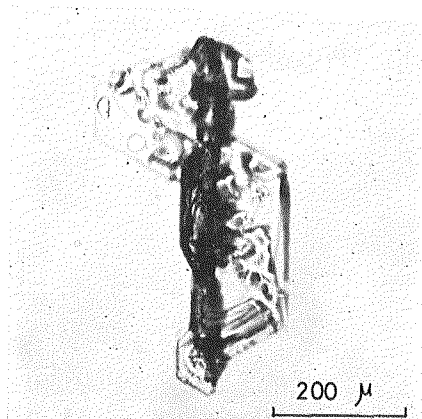
Photo, 1 Combination of an extended side plane and bullets,



Photo, 2 Extended side plane with parallel scrolls, indicated in a circle,



Photo, 3 Flattened hollow bullet.



Photo, 4 Snow crystal of crossed plate type, Plates vertical to the surface of paper are seen dark,

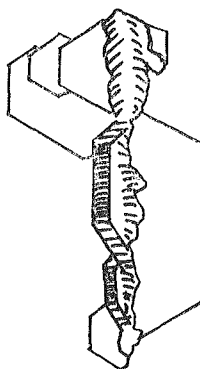


Plate II Snow crystals of the crossed plate type under a polarization microscope.



Photo. 5a Crosssections of a short bullet and a crossed plate, coloured in yellow.



Photo. 5b Rotated by  $90^\circ$  from angle in Photo. 5a, crosssection coloured in blue.

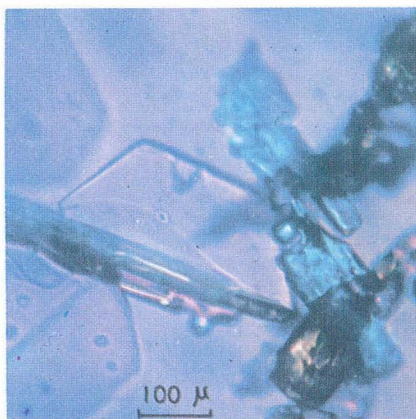


Photo. 6a Crosssection of a crossed plate, coloured in pink.

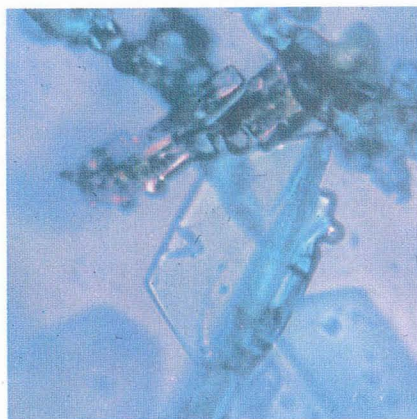


Photo. 6b Rotated by  $90^\circ$  from angle in Photo. 6a, crosssection coloured in blue.

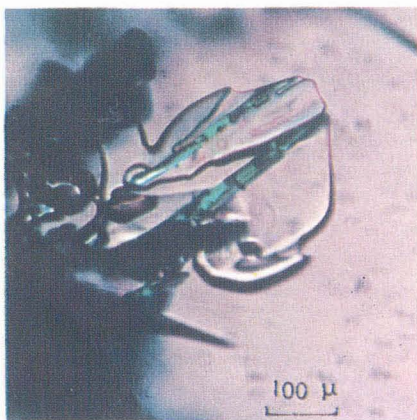


Photo. 7a Crosssections of two crossed plates coloured in green.



Photo. 7b Rotated by  $90^\circ$  from angle in Photo. 7a, crosssection coloured in green.

Plate III Snow crystals of the side plane types under a polarization microscope.

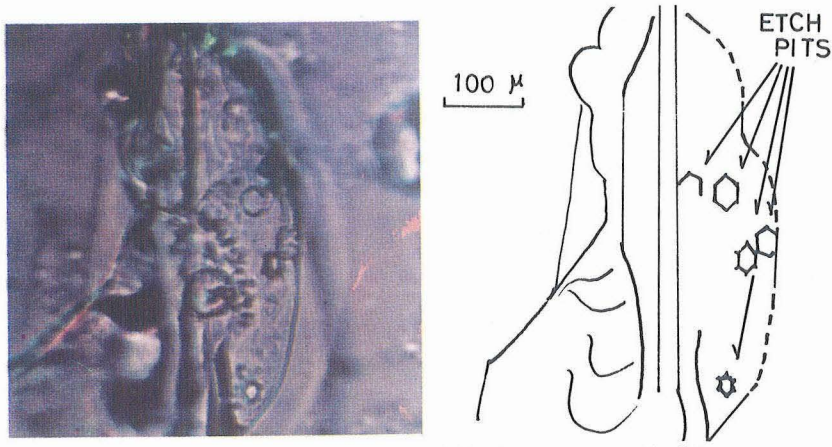


Photo. 8 Hexagonal etch pits on a crossed plate.

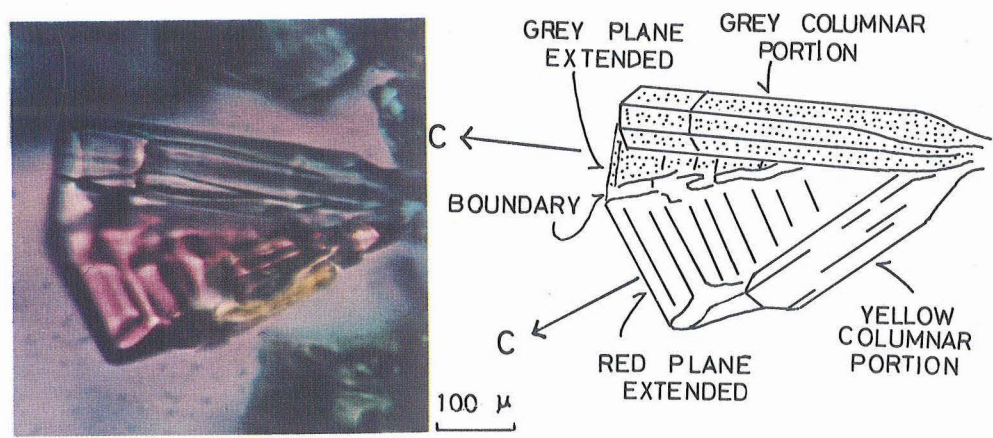


Photo. 9a Extended side planes.

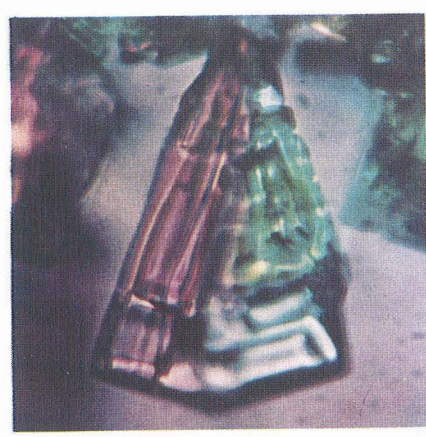


Photo. 9b Rotated by 90° from angle in Photo. 9a.