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A Study on Crystal Axes of Snow Crystals with Complicated Shapes, Utilizing a Polarization Microscope

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Abstract

Various kinds of snow crystals were observed under a polarization microscope with colour films, in order to determine the c-axis of snow crystals of complicated shapes.

As a result of the observation it was considered that the colouring of the snow crystals was influenced by many factors other than the orientation of the c-axis. However it was found that the determination of c-axis was possible by the use of colouring patterns which were characteristic to the orientation of the c-axis, even if the shape of the snow crystals was extraordinarily complicated.

As a result of applying the method to various kinds of snow crystals, it was confirmed that in the case of branches of plate or plane type, their c-axis was always vertical to the surface of their plate or plane.

It was also found that the method was useful to study the crystal axis of cloud particles which were frozen to a snow crystal.

1. Introduction

It is difficult to determine the crystal axis of snow crystals with complicated shapes[1),2)] such as side planes, irregular assemblage of planes and columns, spatial dendrites, and rimed crystals, although the crystal habit of these snow crystals are important in the field of ice physics and precipitation physics. It is therefore desired at least to determine the c-axis of components of the snow crystals. This paper will describe the result of an approach along this line, utilizing a polarization microscope with colour films.

2. Observation method

2.1 *Expected factors colouring the image of snow crystals*

As well known, the polarization microscope is a good tool to observe the habits of a crystal, however in the case of snow crystals additional cautions are required, because the thickness of solid ice portion of the snow crystals is very small and is not always uniform. In addition, they include surfaces oblique to the optical axis of the polarization microscope. Because of these factors, the following colouring factors are expected when a snow crystal is set under a polarization microscope with a colour film.

1. Interference of polarized lights due to the crystal habit of the snow crystal.
2. Interference due to partial polarization by the reflection and refraction at an oblique ice surface of the snow crystal.
3. Interference of lights due to the small difference in the optical path.
4. Colouring characteristic to a sensitive colour plate, if it is used.
5. Characteristic colour of a colour film, used.
6. Colouring by inadequate exposure and developing process.

2.2 *Considerations on the colouring factors*

As described above, because many colouring factors of snow crystals were expected, further considerations were made on the effect of the colouring factors prior to the actual observation and analysis.

Factor 1: Colouring due to the crystal habit. Under a polarization microscope, a snow crystal is coloured by interference due to the difference in optical paths between ordinary and extraordinary lights: $d(n_2-n_1)$ namely the retardation, where d is the thickness of solid ice portion of the snow crystal, and n_1 and n_2 are the refraction coefficient of the ordinary and extraordinary lights respectively. The difference: n_2-n_1 changes according to the inclination angle between the c-axis of the snow crystals and the optical axis of the microscope. Utilizing these properties, the observation of the c-axis is made.

However in the case of snow crystals, colouring due to this factor is usually insufficient, because the retardation $d(n_2-n_1)$ is too small, therefore a sensitive colour plate was added in order to increase the retardation in the present observation. In this case with the sensitive colour plate, the colour changes, distinctly according to the angle between the c-axis of the snow crystal and the c-axis of the sensitive colour plate. Utilizing this distinct change in colour due to the rotation of the c-axis, the c-axis of the snow crystals was determined. This was the main purpose of the present observation.

As described above, the colouring is influenced by the retardation: $d(n_2-n_1)$. Therefore if the thickness: d is not uniform, change in colour occurs not only by the rotation of c-axis but by the difference in the thickness. This fact should be remembered in the observation of snow crystals without uniform thickness.

Factor 2: *Colouring due to partial polarization.* When a light beam hits an ice surface at an angle near the polarization (53°) angle (Brewster's law), partial polarization occurs in the reflection and refraction lights, independing on the crystal habit. In the case of snow crystals of hexagonal column type, the incidence angle of 60° occurs frequently. This effect is not ignored. Even if in a case of a glass cylinder of non-crystalline, it was observed that colouring was detected. No method was found to remove this effect, however this effect was not an essential disturbance for the observation of the crystal habit of snow crystals, as will be described later.

Factor 3: *Interference due to the difference in optical path.* The colouring due to this factor occurs only when the thickness is in the order of a light wave length. In the present case, the thickness of snow crystals is two orders greater than the light wave length. Therefore this effect is negligible.

Factor 4: *Colouring due to a sensitive colour plate.* As described in the consideration about *Factor 1*, a sensitive colour plate with retardation of 530 $m\mu$ was inserted between a snow crystal and the polarizer of the microscope, as shown schematically in Fig. 1, in order to increase the retardation. The angle between the axis of the sensitive plate and the axis of the polarizer

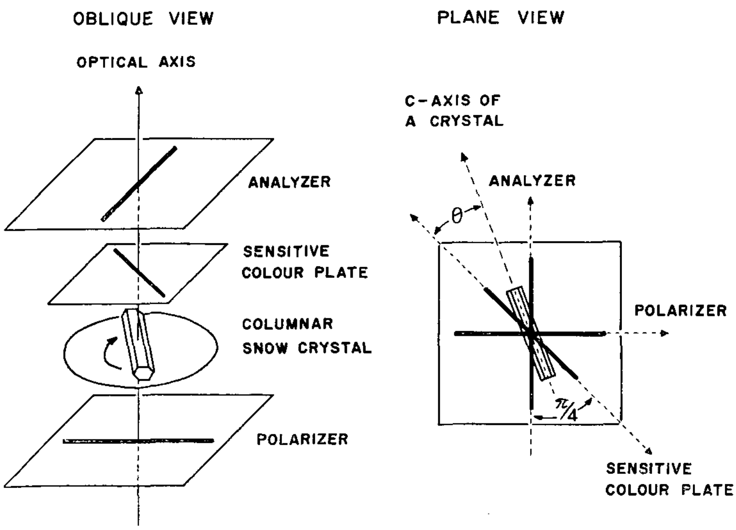

Fig. 1 Relative directions of polarizer, analizer, sensitive colour plate and a columnar snow crystal.

was set as $\pi/4$. Because this plate was added, the background of the microscope was always coloured in red which is the characteristic colour of the sensitive colour plate itself.

If the colour of the background is not red, some inadequate treatment is expected in the exposure or the developing process or the original colour film.

As assumed from Fig. 1, when the orientation of the c-axis of an snow crystal is parallel to that of the sensitive colour plate, the retardation is added to each other, namely it becomes 530 $(m\mu)+d(n_2-n_1)$, while when they cross at right angles, the retardation decreases to 530 $(m\mu)-d(n_2-n_1)$. Owing to this relation, the colour of the snow crystal changes according to the relative angle: θ between the c-axis and the axis of the sensitive colour plate. The determination of c-axis of a snow crystal in the present observation was made by the use of this property.

Factor 5: *Characteristic colour of a colour film.* If the colour film used is perfect, the non-exposed portion of the film should be dark, but in the usual colour film the non-exposed portion is coloured in dark blue. Because the thickness of solid ice portion of snow crystals was small, the loss due to absorption by the ice portion was negligible, however, the loss due to total reflection was considerable. Such portions were coloured in dark blue. This colouring was easily checked by rotating the snow crystal around the optical axis of the microscope, because the colouring is independent of the angle.

Factor 6: *Colouring due to inadequate treatment.* Colouring due to inadequate exposure or developing process of the colour film was checked by the basic red colour in the background, because if the treatment is inadequate, the colour of the background is shifted a little from true red.

After the above considerations, it was confimed that in the observation of the c-axis of snow crystals under a polarization microscope, the colouring effects due to the factor of non-crystalline are checked easily except the partial polarization and the non-uniform thickness. Therefore the latter two factors should be remembered always in the analysis of the polarized colour photographs of snow crystals.

3. Results of observation of crystal axis of snow crystals under a polarization microscope with a colour film

As described above, colouring of snow crystals under a polarization microscope is influenced by many factors. Therefore, the observation was begun from the examination of snow crystals with known axes.

3.1 *Snow crystals of hexagonal columnar type*

It is well known that the c-axis of snow crystals of hexagonal columnar type is parallel to the axis of the column which is easily determined from the external shape. Therefore a snow crystal of hexagonal columnar type was examined at first under a polarization microscope with a sensitive colour plate. Examples of the colour photographs obtained are shown in Photos. 1 and 2 in Plate I. In the case of Photo. 1, the orientation of c-axis of the snow crystal agrees with that of the sensitive colour plate, namely the retardations are added to each other. It is seen in the photograph that the colour of the columnar crystal is not uniform but it has a pattern in which a yellow band area is sandwiched by two green band areas. Photo. 2 shows the colour pattern, in the case of which the axis of the snow crystal was rotated by a right angle around the optical axis of the microscope. It is seen that the yellow band area is sandwiched by two red band areas. In this case, the effective retardation is the difference between that of the sensitive colour plate and that of the snow crystal.

If a snow crystal is a single crystal, it usually should be coloured uniformly. Therefore the colour pattern of the columnar snow crystal described above seems strange. About the colour pattern, it was considered that the difference at both sides of the column was caused by the difference in the thickness between the center and sides and partially by the partial polarization

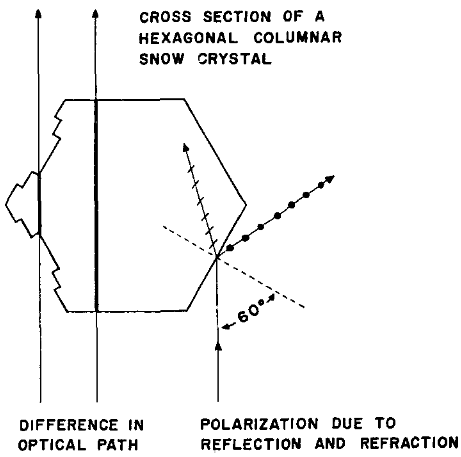

Fig. 2 Difference in the optical path due to different thicknesses, and polarization due to the reflection and refraction at an oblique surface.

due to the reflection and refraction at an oblique ice surface as shown in Fig. 2. In addition to that, the snow crystals of columnar type are not always perfectly solid but most of them are partially hollow. Such complicated shape makes it confusing to analyze the result of colouring under a polarization microscope.

Although the thickness of a columnar snow crystals is not uniform, the pattern of colour distribution was nearly common to almost all columnar snow crystals. Perhaps this was caused by the tendency that almost all columnar snow crystals have nearly the same thickness. Therefore, as far as such columnar snow crystals are concerned, it was considered that it was possible to determine their c-axis by the pattern of colour distribution, independing on their external shape. Namely when a columnar snow crystal has a colour distribution with a yellow band area which is sandwiched by two green band areas under a polarization microscope with the sensitive colour plate, the c-axis of the crystal is oriented from the upper left to the lower right. This may be confirmed by rotating the snow crystal at a right angle around the optical axis of the microscope where the snow crystal may have a yellow band sandwiched by red bands.

This method is useful when the external shape of the columnar crystal is imperfect.

3.2. *Snow crystals of bullet type*

Photo. 3 shows a colouring distribution of a snow crystal of combination of bullets. Fortunately the bullets point in various directions, it is easily understood that the colouring pattern in each bullet changes according to the angle around the optical axis of the microscope. It is seen that the relation of c-axis (axis of bullet) to the colouring pattern is the same as in the case of the columnar crystals. It is noted here that the bullets of the snow crystal do not always have a hexagonal cross-section but a nearly circular one, however the method to determine the c-axis of the bullets by the colouring pattern is the same as the hexagonal cross-section.

Photo. 4 shows colouring patterns of columns, bullets, a skeleton and a plane crystal. It is seen that the colouring patterns of the columns and the bullets are the same as in Photos. 1, 2 and 3. The snow crystal of skeleton form is seen at the right bottom. Its colour is the same as the background, although fairly dark due to the total reflection loss. The colour is considered to be caused by the agreement of its c-axis with the optical axis of the microscope.

A snow crystal of hexagonal plane type is seen at the upper left under a green column. Its colour is also the same as the background. The reason is the same as in the case of the skeleton snow crystal, and is partially the small thickness of the plane crystal.

3.3. *Snow crystals with side planes and bullets*

As a result of the observation of snow crystals with known c-axis, a method to observe the c-axis of snow crystals was obtained. Thereafter this method was tried to apply for snow crystals of other complicated forms. Photo. 5 shows the colouring pattern of a snow crystal with side planes and bullets. The direction of c-axis of side planes were never observed exactly. The upper left branches of the snow crystals are composed of side planes which cross each other at a right angle, namely one plane is parallel and other plane is perpendicular to the surface of the photograph. It is seen here that the former plane has the same colour as the background, while the latter plane is coloured in brown, although fairly dark. After the determination method for the c-axis, it is considered that the former plane parallel to the surface of the photograph has its c-axis vertical to the surface (namely parallel to the optical axis), and the latter brown plane perpendicular to the surface has its c-axis parallel to the surface (namely perpendicular to the optical axis). These relations may be described simply as follows. The c-axis of side planes is always vertical to the plane.

The small bullets at the lower right of the snow crystal is coloured in blue. The yellowish portion is lacking compared with the pattern in columns and usual bullets. This lack of the yellowish part may be caused by the small thickness of the bullets, considering the blue band at both side portions of the columns. Therefore, it is assumed that the c-axis of the small bullets is oriented from the upper left to the lower right in the photograph.

3.4 *Irregular assemblage of columns, plates and side planes*

The determination of c-axis of snow crystals with irregular assemblage of columns, plates, bullets and side planes was difficult because their external shape was very complicated.

In Photo. 6, two examples of colouring pattern of snow crystals of irregular assemblage of columns, plates, bullets and side planes are given. At the right hand snow crystal, colour patterns of a yellow band sandwiched by blue bands are seen. As far as these portions are concerned, it is certain that their c-axis are oriented from the upper left to the lower right in spite of their external shapes. The c-axis of the horizontal plate portions which have the same colour as the background, are assumed to be parallel to the optical axis.

The snow crystal at the left hand of Photo. 6 is of radiating assemblage of side planes. All side planes are coloured in dark red or in dark violet. This colouring pattern suggests that the c-axes are oriented roughly from the upper right to the lower left, in other words, their c-axes are not parallel to the apparent longitudinal dimension but to the lateral dimension. This means that the c-axes of the side planes are vertical to their planes. The lack of the yellow portion may be caused by the inclination of the c-axes to the optical axis.

3.5 *Snow crystals with radiating assemblage of plane branches*

Photo. 7 shows a colouring pattern of a snow crystal of radiating assemblage type. All branches are oblique to the optical axis, but it is seen clearly that the upper branches are reddish in colour, while the lower three branches are coloured nearly green. These colouring patterns show that the c-axis of the former orients roughly from the upper right to the lower left, while the c-axis of the latter orients roughly from the upper left to the lower right. This suggests that their c-axis is always oriented vertically to their plane.

Photo. 8 gives another example of colouring pattern of a snow crystals of radiating type. The colour of their cross-section is fairly well observed in this case. It is seen that the cross-section of two branches which faced the upper left has nearly the same colouring pattern as the yellow portion sandwiched by blue or green portions. These colouring patterns show that the c-axis of the branches are oriented vertically to their plane. On the other hand, the cross-section of the branch which faces the upper right is coloured in brown. This shows that the c-axis of the branch orients vertically to its plane.

3.6 *Snow crystals with spatial assemblage of dendritic branches*

Photo. 9 shows a colouring pattern of a plane snow crystal with spatial assemblage of dendritic branches. It is seen in the photograph that several branches extend spatially from the basal plane of a dendritic crystal. Although the basic colour of the background shifts a little from red to violet, it is seen that the spatial branches facing the upper right are coloured in brown, while the spatial branches facing the upper left are bluish in colour. This colouring pattern shows that their c-axes are oriented vertically to their planes.

3.7 *Rimed snow crystals*

Photo. 10 is a close-up photograph of a rimed snow crystal. Although the basic colour shifts a little from red to brown, a cloud particle at the center is clearly coloured in blue, while other cloud particles have the same colour as the background. This shows an interesting fact that the c-axis of the blue cloud particle is quite different from the c-axis of the basal dendritic crystal, although almost all other cloud particles were frozen to the same axis as the basal crystal.

4. Conclusions

A method to determine the c-axis of snow crystals under a polarization microscope was studied by the use of snow crystals with known axis. The method was extended to the determination of c-axis of snow crystals of complicated shapes. As a result, it was found that the determination of c-axis of snow crystals of very complicated shape was possible, although rough. This roughness is avoidable by the help of the external shape of the snow crystal. It was also confirmed that in the snow crystals of plane or plate type, their c-axis is always vertical to their plate or plane.

The method described above is also useful to determine the crystal axis of cloud particles which are frozen to a snow crystal.

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Plate I Colouring patterns of snow crystals of column. bullet and of side plane type under a polarization microscope.

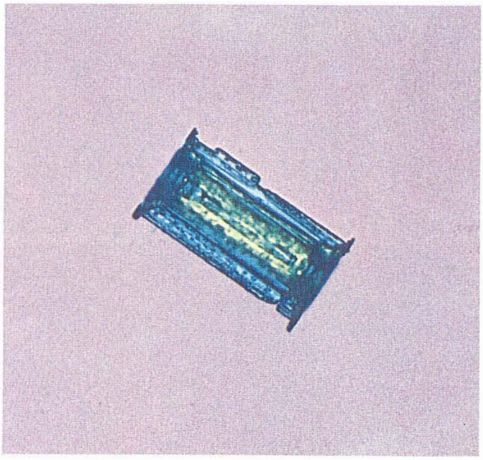

Photo. 1 A columnar crystal with a yellowish band sandwitched by blue bands.

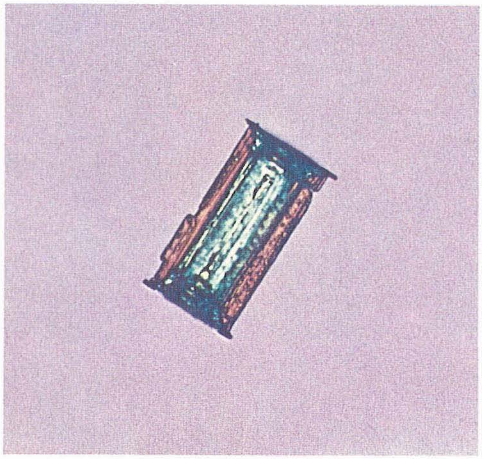

Photo. 2 Rotated at right angles from the position of Photo. 1. A yellowish band sandwitched by red bands.

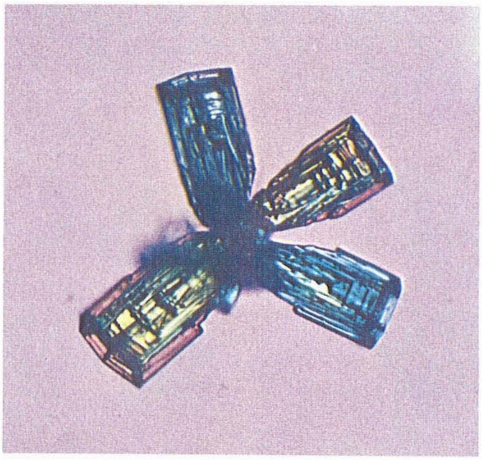

Photo. 3 Combination of bullets. Colouring patterns are different according to the angles.

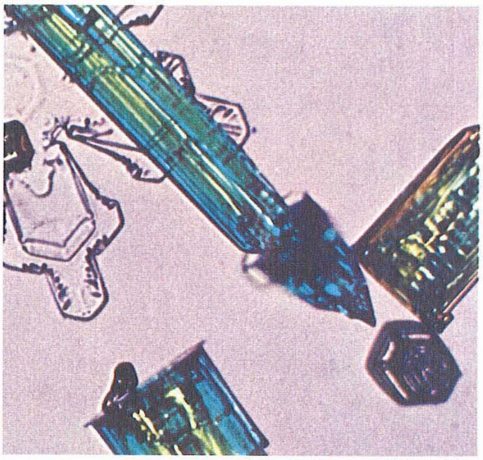

Photo. 4 Columns, a skeleton, a bullet and a hexagonal plane crystal.

Photo. 5 Radiating assemblage of side planes and bullets.

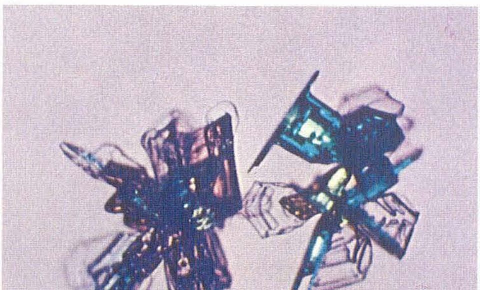

Photo. 6 Irregular assemblages of columns, plates, bullets and side planes.

Plate II Colouring patterns of snow crystals of radiating assemblage type, and of rimed type under a polarization microscope.

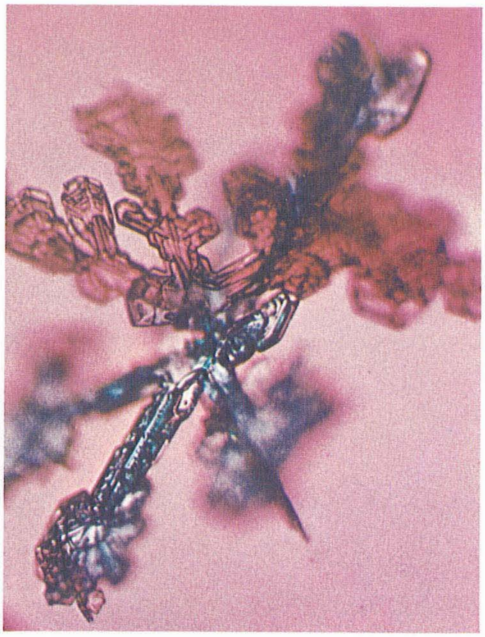

Photo. 7 Radiating assemblage of dendrites.

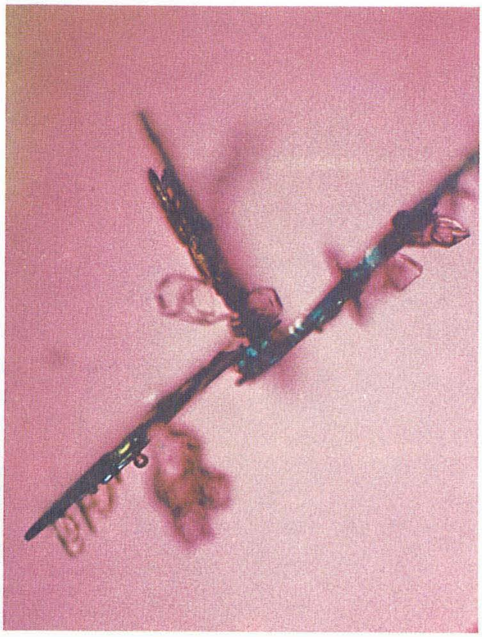

Photo. 8 Radiating assemblage of dendrites whose crosssections are coloured according to their directions.

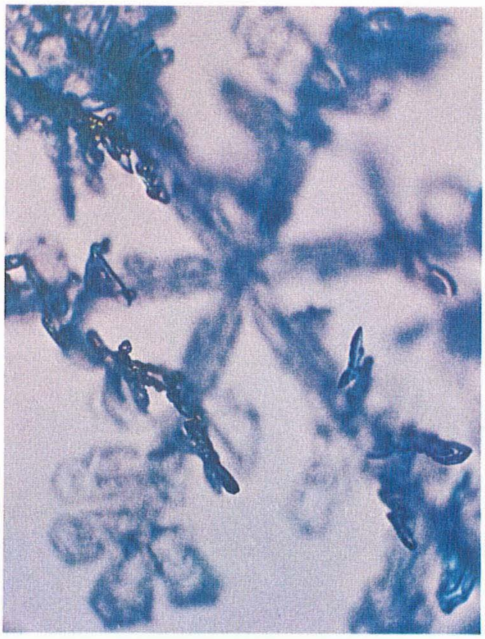

Photo. 9 Spatial assemblage of dendrites whose crosssections are coloured according to their directions.

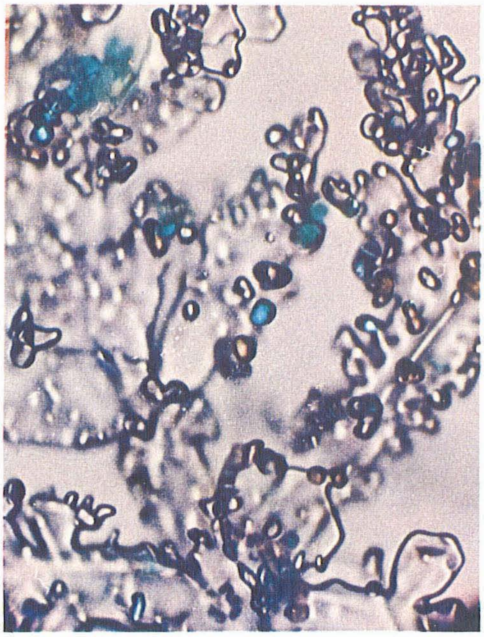

Photo. 10 Rimed dendritic crystal. A cloud particle near the center is coloured in blue.