3-D CHARACTERIZATION OF SNOW CRYSTALS UTILIZING LOW TEMPERATURE SCANNING ELECTRON MICROSCOPY

By

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ABSTRACT

The two dimensional shapes of snow crystals have been previously studied and photographed with light microscopes and cameras. Past investigators have been hampered by sublimation and melting of the snow crystal sample and by the limited resolution of the instruments. Better methods for measuring snow crystals are needed for understanding snowpack processes and improving microwave remote sensing of snow. Snow samples from Maryland, West Virginia, Colorado, Wyoming, and Alaska have been examined with low temperature scanning electron microscopy (SEM) to produce startling new images of snow crystals. Low temperature SEM avoids problems with sublimation and melting, provides extreme magnification capability, and allows quantitative measurement of snow crystal size and shape with the assistance of 3-D or stereo imaging. The 3-D representations show in stereo several different types of newly fallen or precipitated snow crystals, numerous examples of crystals in different stages of metamorphism from natural snowpacks, and algae and bacterial forms present in a melting snowpack. The techniques for sampling, storing, and transporting snow crystals to the SEM facility are simple and easy to use.

INTRODUCTION

Precipitated or falling snow crystals may take on a wide variety of shapes and forms depending on the temperature and moisture conditions that prevail during formation and descent of the snow crystal. According to the International Classification system (ICSI, 1954; Colbeck et al., 1990), there are six major types of precipitated snow crystals -- namely, columns, needles, plates, stellar dendrites, irregular crystals, and graupel. The more detailed classification system of Magono and Lee (1966) for natural precipitated snow crystals list 80 different categories. When two or more snow crystals adhere to one another, a snowflake is born.

After falling snow reaches the snowpack surface, changes in the fine structure of the snow crystals begin, and a second category of snow results - metamorphosed snow. Vapor and temperature gradients in the snowpack cause both a breakdown of crystal structure and a reformation of crystals. Classification systems of snow on the ground have been widely accepted and used (ICSI, 1954; Sommerfeld and LaChapelle, 1970; and Colbeck et al., 1990).

BACKGROUND

Observation and permanent recording of the various types of snow crystals or grains in precipitated and metamorphosed snow has been difficult. The most frequestly used approaches employ microscopes (photomicrography) and cameras (photomacrography) (LaChapelle, 1969). Most of the famous precipitated snow crystal photographs (micrographs) made by Bentley in the early 1900s (Bentley and Humphries, 1931) were made with an outdoor microscope and transmitted illumination. Nakaya's (1954) snow crystal micrographs were done with a microscope in a cold room and used low oblique transmitted illumination. The photographs (macrographs) of LaChapelle (1969) were all taken with 35 mm cameras using reflected, transmitted, and low oblique transmitted illumination.

The problems with either the light microscope or 35 mm camera approaches are numerous. The snow crystals must be protected from body heat, heat from slide mounts, warmer ambient air, and heat from strong illumination or they will melt. Low cold room temperatures and high humidities sometimes result in condensation on the crystals and in frost on the optics. The snow crystal samples are also susceptible to metamorphism and evaporation. When using transmitted light, it is also difficult to distinguish between internal and external snow crystal surfaces. We have attempted to solve some of these problems through the use of low temperature scanning electron microscopy (SEM).

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Recent attempts to use SEM equipped with cold stages have successfully avoided the problems of preserving the snow samples and focused mostly on external snow crystal surface structure (Wergin and Erbe, 1994a; 1994b; and Wergin et al., 1995). Use of the low temperature SEM allowed snow crystals that were sampled in the field and frozen in liquid nitrogen at -196°C to be observed in their frozen state on the cold stage of the SEM at about -185°C. Operation at such very low temperatures prevents any metamorphism of the snow samples. Recrystallization or sublimation effects at temperatures of -186°C to -196°C are minimal or nonexistent. Because no illumination of the snow sample is required in the SEM approach, this further reduces the chances that the snow crystals will change during observation.

In the SEM, a stream of electrons in an intense beam (5-10 nm in diameter) is focused on the surface of the snow sample in the vacuum of the instrument column. The snow sample has been previously sputter coated with a thin layer (100Å) of platinum (Pt) metal to promote conduction of the electrons over the surface of the snow crystals. The focused beam is deflected (scanned) across the sample in a manner similar to an electron gun producing an image on the screen of a TV picture tube. The primary electron beam excites the surface electrons of the snow sample. These so-called secondary electrons escape from the surface of the snow sample and are collected by a detector. In the detector, the escaped electrons hit a scintillator producing photons that are photoamplified and converted to an electrical signal used to generate a snow crystal image on the viewing screen. A photograph of the snow crystal is taken by transferring the image to a photo CRT and projecting the image onto Polaroid Type 55 positive/negative film. Both a print and a negative are produced. The print is used primarily for viewing, and the negative is digitized and used for CD-rom storage and digital image processing.

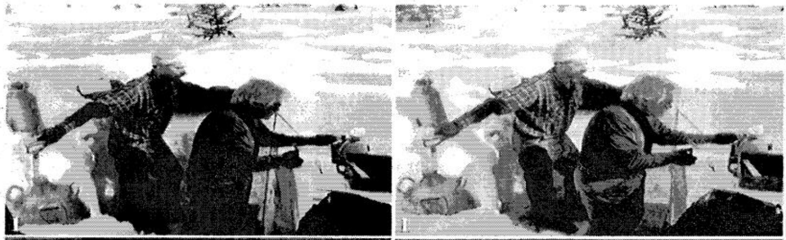
METHODS

Acquisition of snow samples in the field is relatively simple. For precipitated snow, a thin layer of methyl cellulose solution (Tissue Tek) is placed onto a precooled copper plate placed in a Petri dish at ambient outdoor temperatures. Snowflakes are allowed to fall or are lightly brushed onto the Tissue Tek-coated plate. After a visible sample of snowflakes has accumulated and adhered to the Tissue Tek in this manner, the copper plate and snow sample is plunged into a styrofoam container of liquid nitrogen at -196°C and frozen.

For metamorphosed crystals in a snowpack, the method is slightly different. A snowpit similar to those used for assessment of avalanche danger is dug in the seasonal snowpack. Snow crystal samples from selected distinct layers of the snowpack are gently dislodged from the snowpit wall onto the Tissue Tek-coated copper plate. The snow sample is again frozen by plunging the plate into a reservoir of liquid nitrogen. Figure 1 shows our snowpit for sampling snow crystals at the Elkhart Park station in the headwaters of the Green River in Wyoming. All figures in this paper are arranged for 3-dimensional viewing with a pocket stereoscope. For unassisted viewing, you can merge the two pictures by relaxing your gaze (as if staring into the distance) so you avoid the tendency to cross your eyes. Then hold the pictures close to your eyes, center on the picture pair and look closely at the pictures, and slowly move them away (about 25 cm) until a third central image forms in focus.

With both the precipitated and metamorphosed snow crystal samples, the copper plate, after freezing, was transferred to a square profile brass tube for low temperature storage and shipping. Once filled with sample holders, the brass tubes were placed in dry shipping dewars at liquid nitrogen temperatures and shipped by ground and air to our Beltsville, Maryland laboratory for analysis. The samples were in transit to Beltsville for 1-7 days, but the dewars maintained a temperature of -196°C and the samples were undisturbed upon observation. It is estimated that the samples in the dewars would be preserved for up to one month before additional LN_2 would have to be added to maintain the temperature level.

Figure 1.	Snowpit at Elkhart Park, WY used for sampling snow crystals from different layers of the snowpack.
Figure 2.	Agricultural Research Service low temperature scanning electron microscope located at Beltsville, MD.
Figure 3.	Scanning electron microscope image of a radiating assemblage of hexagonal plates (collected at -5°C).
Figure 4.	Hexagonal plate covered with rime (collected at -12°C).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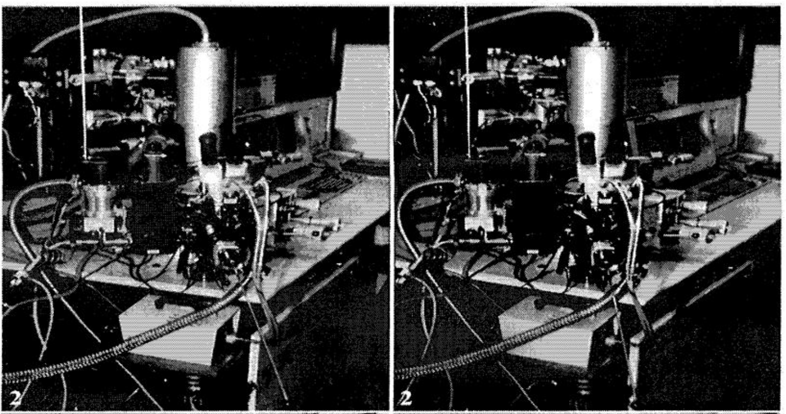
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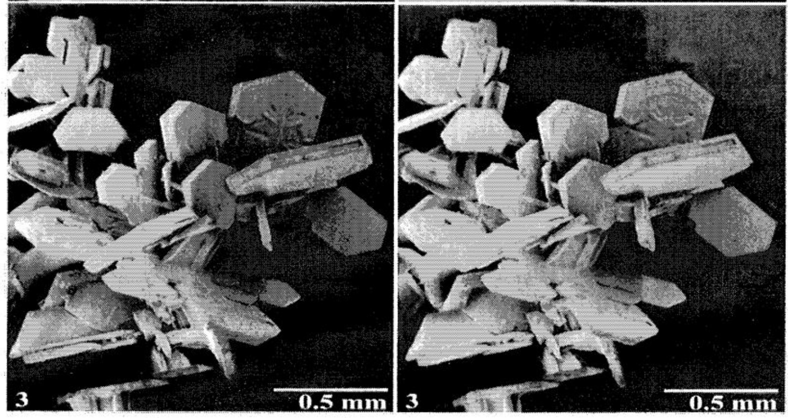
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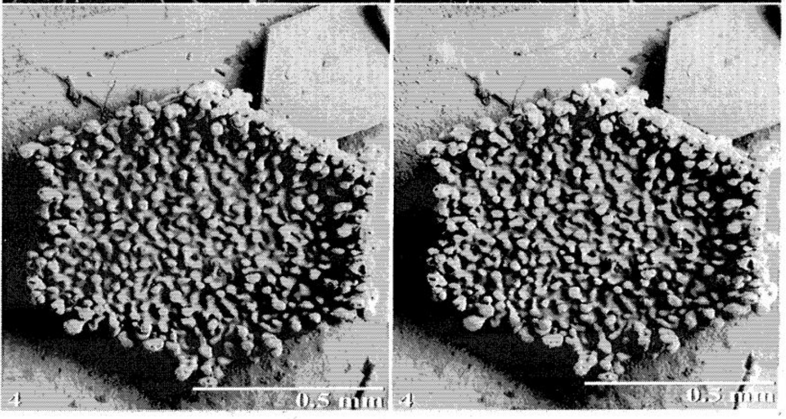
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For snow crystal sampling in the field, not much additional equipment over and above that required for normal snowpit characterizations is needed. A moderate supply of liquid nitrogen is primarily needed along with sampling plates, Tissue Tek foreceps, storage tubes, and a shipping dewar. This equipment has been easily transported to snowpits throughout the western U.S. by snowshoes, skis, sleds, snowmobiles, snowcats, or 4-wheel drive vehicles depending on the local situation.

The imaging of the snow crystal sample requires considerable investment in instrumentation, however. Our laboratory has been equipped with a new generation of SEMs, namely, a Hitachi S-4100 field emission SEM with an Oxford CT 1500 HF Cryosystem (see Figure 2). This combination of instrumentation, known as a low temperature scanning electron miscroscope, allows us to use a SEM at low accelerating voltages, normally 1-10kV, to observe and record images of delicate, frozen samples that are maintained at a temperature of about -185°C. The instrumentation described here costs about $350,000.00. However, it may be possible for other interested users to arrange a working relationship with owners of other such systems. We estimate that there are about 20 similar systems in the United States.

The SEM also has the capability to produce 3-dimensional views of snow crystals through stereo viewing. To obtain the stereo pairs necessary, a first image of a snow crystal is recorded, the SEM stage is tilted 5-10°, the snow crystal is recentered, and a second image is taken. The capability to view the snow crystals in stereo allows more information to be obtained about surface structure, snow crystal growth mechanisms, bonds and spatial relationships between crystals, and quantitative measurements of crystal size (stereometry).

RESULTS

Precipitated Snow Crystals

The classification system of Magono and Lee (1966) lists 80 distinct types of falling snow crystals. Thus far, in three winter seasons we have observed 68 of the 80 types with the SEM method. Additionally, we have observed at least 20 types of crystals not covered by the Magono and Lee (1966) system. Figure 3 is a radiating assemblage of hexagonal plates which show a characteristic double-sheet structure with the largest individual plates up to 0.75 mm in diameter. Figure 4 presents another hexagonal plate a little over 1 mm in diameter covered with rime deposits probably acquired upon falling through a supercooled water cloud. Figure 5 is an example of needle snow crystals which are more common in the eastern U.S. where warmer snow storms occur. Needles form between -3°C and -5°C and and grow rapidly making for the possibility of heavy snowfalls. The needles in Figure 5 are about 1.8 mm long.

More common snow crystals are shown in Figures 6 and 7. Figure 6 is a stellar dendrite a little over 1 mm in diameter with a distinct hexagonal plate at the center. Figure 7 is a snow crystal with broad branches, about 1.5 mm in diameter, and possessing a hole in the middle where the freezing nucleus may have been. Figure 8 is a variation of column or a bullet crystal. With the hexagonal plates or caps at the end and the thin neck, this crystal is an excellent example of the tsuzumi (Japanese tomtom). The crystal in Figure 8 is a little over 1 mm in length.

Metamorphosed Snow Crystals

Once falling snow is deposited on the snowpack, the individual crystals start to lose their sharp corners and points because vapor pressure is very high over sharply pointed surfaces, and the crystals are unstable in the lower supersaturations of the snowpack. As a result, the sharp edges sublime away, and the general trend is toward the formation of stable spherical grains in a snowpack that has relatively small temperature gradients (generally <10°C/m). Figure 9, taken from the near surface layer of the snowpack, shows a

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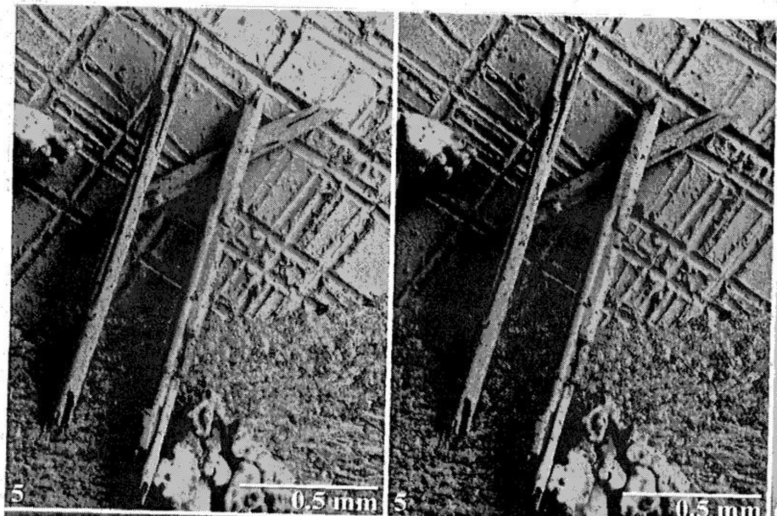
Figure 5. Needle snow crystals resting on the boundary between the Tissue Tek and the copper plate that has been scored with a scalpel (collected at -2°C).

Figure 6. SEM example of a plate with dendritic extensions (collected at -10°C).

Figure 7. A snow crystal with broad branches which is a variation of a hexagonal plate (collected at -5°C).

Figure 8. Japanese tsuzumi or tomtom which is a variation of a column capped with plates (collected at -12°C).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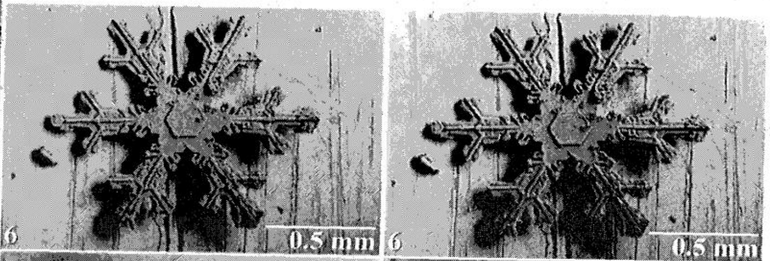
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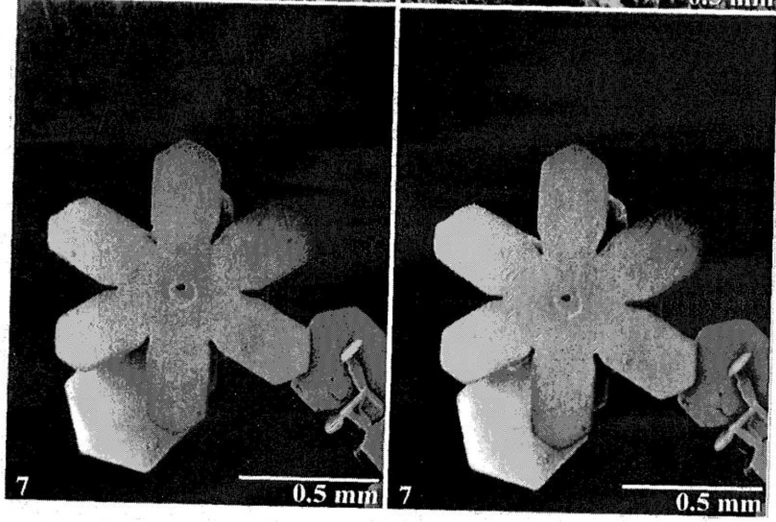
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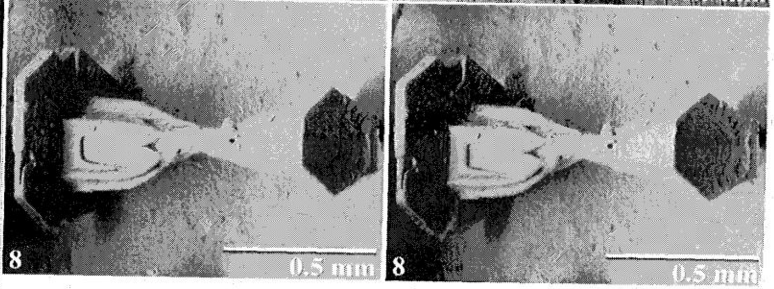
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remnant stellar crystal that has experienced considerable rounding. At this stage, the crystal is only a little larger than 0.5 mm in diameter, and some of the surface patterns on the original crystal are still apparent. Figure 10 is later in this transition to equilibrium conditions, and the remnant crystals are still somewhat visible but are much more rounded. Bonds between some of the grains have formed through sintering. The grain sizes are now between 0.2-0.4 mm.

When cold weather sets up over a snowpack for extended periods, the temperature gradient can exceed 10°C/m. Under low temperature gradients, the rounded grain is the dominant shape. When the temperature gradient approaches or exceeds 10°C/m, faceting of the snow grains is possible. Because of differing temperature history, some grains such as shown in Figure 11 can be rounded and faceted at the same time (mixed forms). This bonded snow crystal, which is about 1-1.5 mm across, comes from the lower half of a snowpack in Colorado.

When the temperature gradient exceeds 10°C/m for extended periods and high growth rates prevail, faceted crystals are dominant. They tend to be layered, hollow, and have weak bonds with other crystals. At the base of the snowpack, the growth rates tend to be highest resulting in layers of depth hoar. Figures 12, 13, and 14 show three examples of depth hoar that possess layered surfaces, hollow cavities, and an intricate interior structure. These crystals range in size from 2.0-3.0 mm.

When energy input to the snowpack is sufficient in the Spring, the snowpack becomes isothermal and rounded grains once again become the dominant form, this time associated with melt metamorphism. These rounded grains usually are found bonded to each other in a cluster. The bonding can be fairly strong in the early stages of melting when liquid water content is low and loosely bonded when liquid water content increases later in the melt season. Additionally, Colbeck (1979) points out that snow at low liquid water contents will not have spherical grains like saturated snow. Figure 15 shows a cluster of melting snow grains taken from the surface layer of a melting snowpack in Colorado. In this figure, the grains range between 0.2-0.7 mm in size. We have observed clusters of grains as big as 7 by 14 mm.

Algal and Microbial Forms

During the sampling of the melting snowpack in Colorado, we had the opportunity to sample some "red" snow also. So-called green algae (chlamydomonas nivalis) is responsible for the red snow. We were able to image the suspected green algal cells which were from 15-20 µm in diameter. Fortuitously, some of the algal cells were fractured in the freezing process which permitted observation of the subcellular structure. Figure 16 shows a portion of the fractured algal cell showing the cell wall, plasma membrane, and organelles. Associated with the algal cell in Figure 16 are other microbial forms which we speculate to be fungal hyphae and possibly bacterial cells. These kind of images have not been possible with the light microscope in the past because of a limitation in magnification. Figure 16 was made with a SEM magnification of 3500x. Magnifications up to 40,000x have been applied to many snow and ice samples. Photos presented in this paper represent only a few of the more than 7,500 photos taken to this point.

DISCUSSION AND CONCLUSIONS

The advantages of using SEM methodology for snow crystal imaging are numerous. Snow samples obtained in the field can be immediately frozen in liquid nitrogen and preserved at

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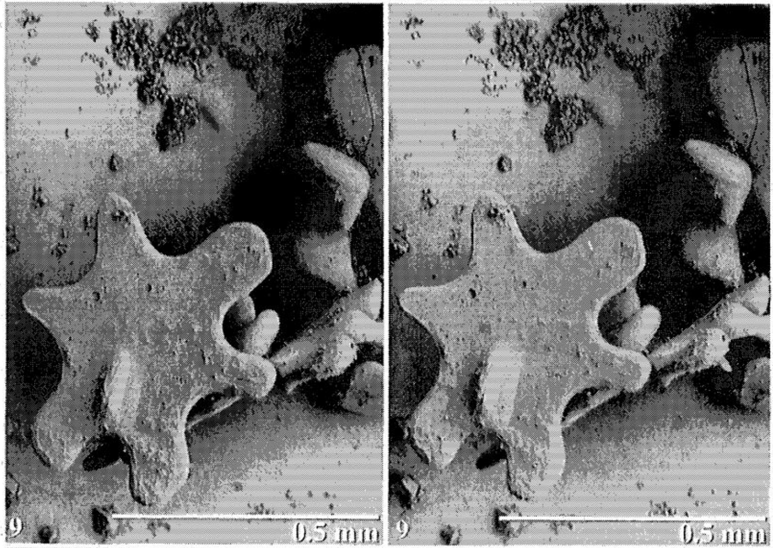
Figure 9.	A remnant stellar crystal showing considerable rounding taken from the upper layer of the seasonal snowpack (collected at a snowpack temperature of -4°C; stored for 188 days in a dewar).
Figure 10.	Well-rounded crystals with sintering and a faint resemblance to the original snow crystals, from the upper layers of the seasonal snowpack (collected at a snowpack temperature of -6°C; stored for 10 days in a dewar).
Figure 11.	Snow crystal with both rounding and faceting (mixed forms) taken from a lower intermediate layer of the seasonal snowpack (collected at a snowpack temperature of -6°C; stored for 10 days in a dewar).
Figure 12.	Depth hoar crystal from a lower layer of the seasonal snowpack (collected at a snowpack temperature of -2°C; stored for 15 days in a dewar).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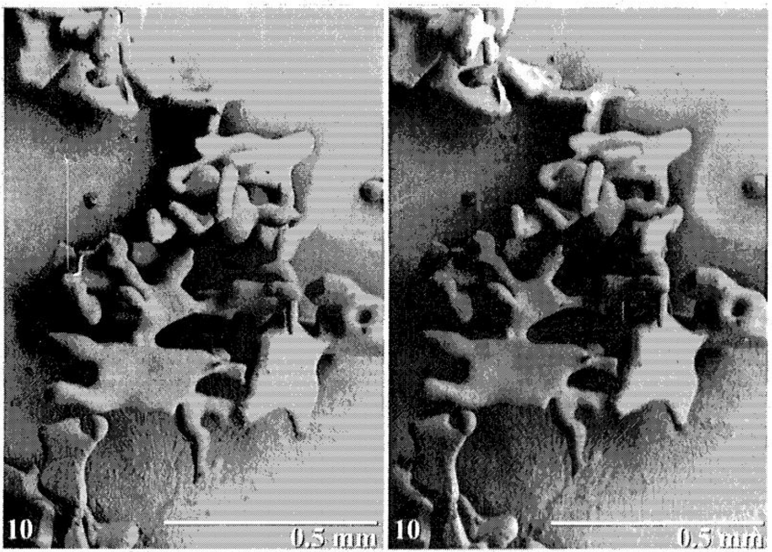
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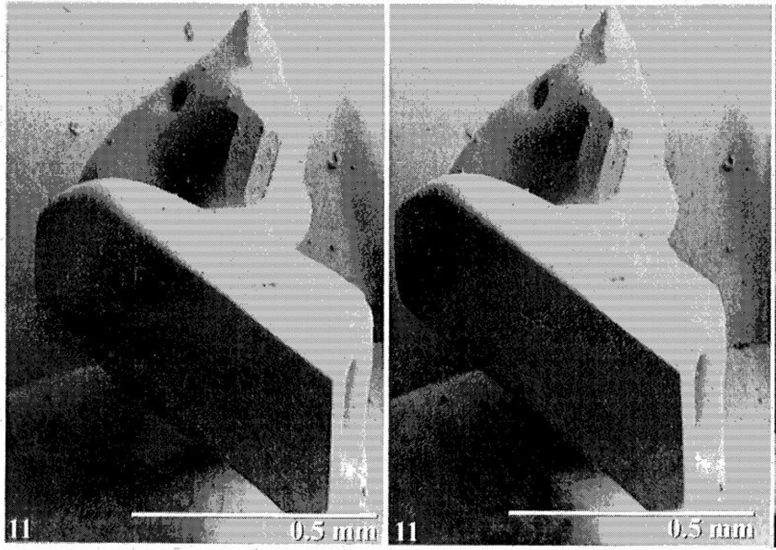
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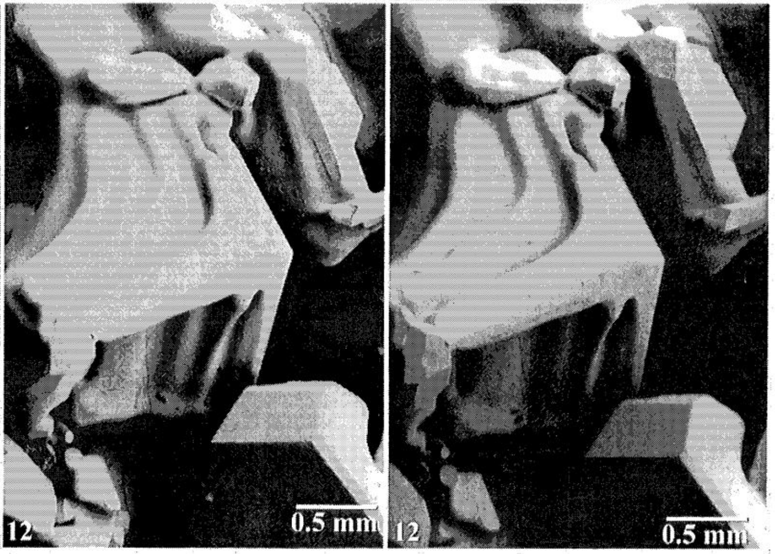
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liquid nitrogen temperatures for shipping and future analysis. The field methods are simple and easy to use. The SEM allows enormous magnification of the frozen samples much in excess of light microscopy. There is very little worry that the snow sample will experience melting or any other metamorphic change of the low temperatures used. The SEM approach images only the surface features of the snow crystal and no internal characteristics are transmitted. Internal ice structure can be observed by fracturing samples identified on the cold stage.

By using SEM, 3-dimensional views of the snow crystals are possible. This capability allows more information to be obtained about crystal surface structure, snow crystal growth mechanisms, bonds and spatial relationships between crystals, and quantitative measurements of crystal size. In addition, the stereo viewing provides a very dramatic and new way to visualize snow.

Several future applications of SEM are anticipated. The shape and size information may allow improvement of radiative transfer modeling for satellite microwave estimates of snow water equivalent. It is possible that the SEM data will be useful in helping us to further understand snow metamorphism conditions leading to avalanches, relationships between snow algae and other microbial forms, pollutants carried in snow, and visualization of other forms of ice, e.g., sea ice, glacier ice, and ice cores.

The images produced so far will also have importance for educational tools for teachers. Development of slide sets of the crystal images are a possibility. In all the images we have studied so far, no two snow crystals have been alike and, by close inspection afforded by the large magnification capability, no one snow crystal has been truly symmetrical. We continue the search.

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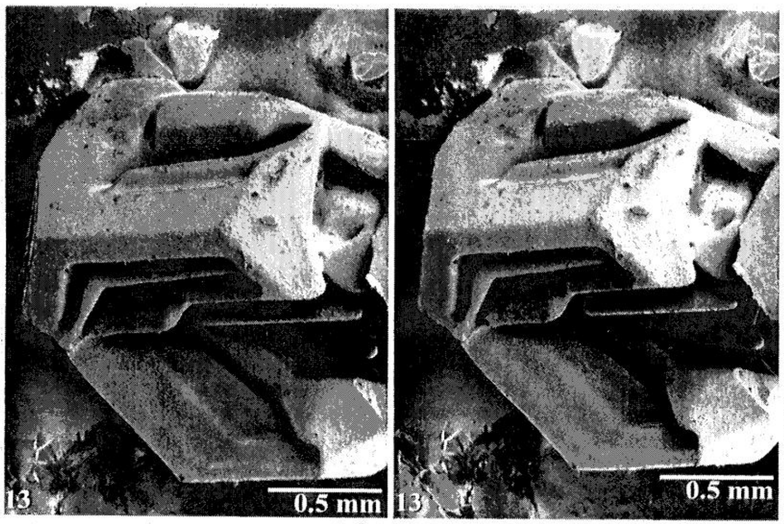
Figure 13.	Depth hoar crystal from the bottom of a shallow snowpack (collected at a snowpack temperature of -16°C; stored for 103 days in a dewar).
Figure 14.	Intricate angular and stepped crystal from the middle layer of a snowpack illustrating the hollow nature of depth hoar (collected at a snowpack temperature of -3°C; stored for 15 days in a dewar).
Figure 15.	Cluster of nearly spherical snow grains present in the surface layer of the melting snowpack (collected at a snowpack temperature of 0°C; stored for 7 days in a dewar).
Figure 16.	Sample from a "red snow" melting snowpack showing a portion of a fractured algal cell and other associated microbial forms (collected at a snowpack temperature of 0°C; stored for 3 days in a dewar).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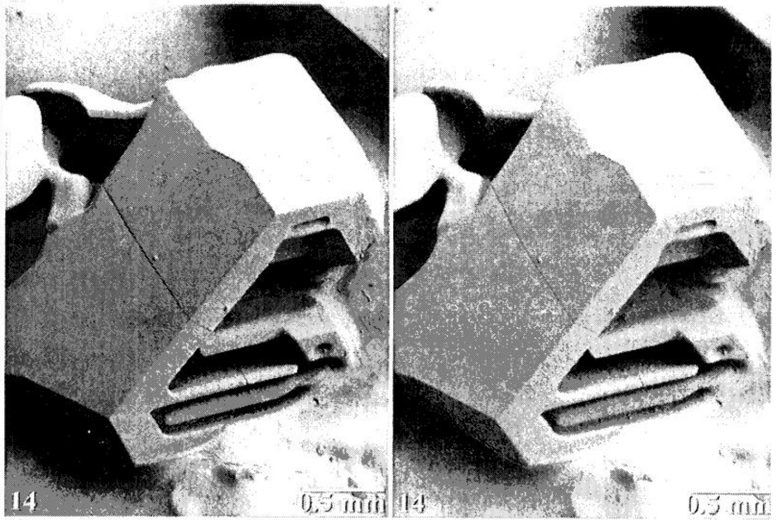
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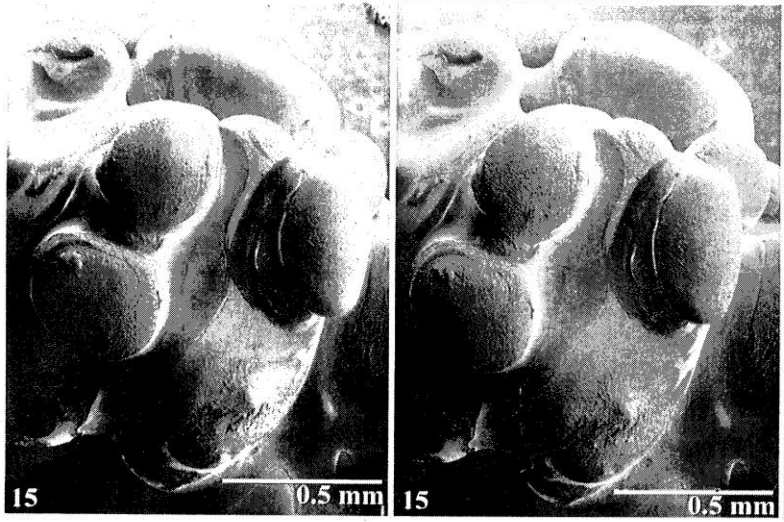
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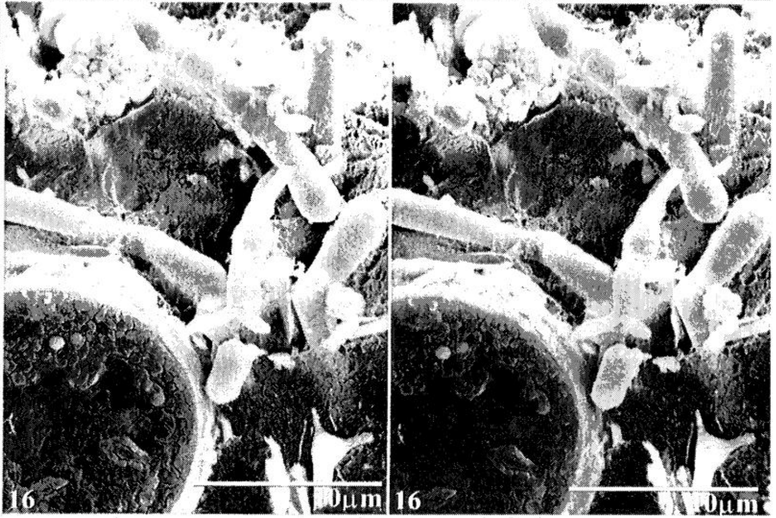
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