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Image Comparisons of Snow and Ice Crystals Photographed by Light (Video) Microscopy and Low-Temperature Scanning Electron Microscopy

WILLIAM P. WERGIN, ALBERT RANGO,* ERIC F. ERBE

Nematology Laboratory and *Hydrology Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland, USA

Summary: Light (video) microscopy and low-temperature scanning electron microscopy (SEM) were used to examine and record images of identical precipitated and metamorphosed snow crystals as well as glacial ice grains. Collection procedures enabled numerous samples from distant locations to be shipped to a laboratory for storage and/or observation. The frozen samples could be imaged with a video microscope in the laboratory at ambient temperatures or with the low-temperature SEM. Stereo images obtained by video microscopy or low-temperature SEM greatly increased the ease of structural interpretations. The preparation procedures that were used for low-temperature SEM did not result in sublimation or melting. However, this technique did provide far greater resolution and depth of focus over that of the video microscope. The advantage of resolution was especially evident when examining the small particles associated with rime and graupel (snow crystals encumbered with frozen water droplets), whereas the greater depth of focus provided clearer photographs of large crystals such as depth hoar, and ice. Because the SEM images contained only surface information while the video images were frequently confounded by surface and internal information, the SEM images also clarified the structural features of depth hoar crystals and ice grains. Low-temperature SEM appears to have considerable promise for future investigations of snow and ice.

Key words: low-temperature scanning electron microscopy, snow crystals, ice, video microscopy

Introduction

During the past one hundred years, the light microscope and photomacrography have been used to record numerous

Address for reprints:

William P. Wergin
Nematology Laboratory
Plant Sciences Institute
Agricultural Research Service
U.S. Department of Agriculture
Beltsville, MD 20705, USA

images of fresh and metamorphosed snow crystals, as well as to observe and photograph corings from glacial ice. One of the earliest efforts in this area was that of Wilson A. Bentley who, over the course of 30 years, photographed nearly 5,000 snow crystals (Bentley and Humphreys 1931). Bentley's pursuits appear to have been influenced mostly by esthetics. He concentrated on the flat, hexagonal dendrites and plates that he illuminated with transmitted light and photographed with a light microscope. A more scientific study of snow crystals, both natural and artificial, was pursued by Nakaya (1954) who observed numerous types of snow crystals including needles, columns, rime, and graupel (snow crystals encumbered with frozen water droplets), which he photographed by using transmitted and reflected light. Although these photographs provided a fairly complete record of the types of precipitated snow crystals that occurred in nature, those crystals which exhibited considerable depth or topography, such as graupel and multiple assemblages, were poorly resolved due to the limited depth of field that was possible with a light microscope.

Important structural features of metamorphosed snow crystals have likewise been studied and photographed using a variety of light microscopic or photomacroscopic techniques (Akitaya 1974, Armstrong 1992, Colbeck *et al*. 1990, LaChapelle 1992, Sturm 1991). Many of the metamorphosed crystals, which are relatively thick and structurally complex, attain sizes of several mm^3. Consequently, when they are illuminated with either transmitted or reflected light and photographed, the resulting image generally contains information about the internal as well as the external features of the crystals. As a result, determining the surface structure of a metamorphosed crystal, such as depth hoar, may be confounded by the internal faceting that would also be a component of the photographic image (Wergin *et al.* 1997).

Ice crystals and firn granules have also been imprinted and photographed by several methods (Ahlmann and Droessler 1949, Eckerbom and Palosuo 1963, Seligman 1949). In a procedure developed by Ahlmann and Droessler (1949), individual crystals were photographed by spreading dyes, which were nonsoluble in water, on the smooth surface of ice. Next, paper was gently pressed onto the surface of the crystals to create an imprint that could be photographed. The use of imprints was limited to relatively smooth surfaces and prevented observations of magnified

crystals. However, this technique did provide structural information about the external surface as opposed to direct observations of crystals by light microscopy in which the internal and external structural features were combined in a single image.

Recently, our laboratory successfully developed techniques to photograph precipitated and metamorphosed snow crystals in a scanning electron microscope (SEM) that was equipped with a cold stage (Rango *et al.* 1996a, b; Wergin and Erbe 1994a–c; Wergin *et al.* 1995 a, b, 1996a). This technique was also used to image ice crystals (Wergin *et al.* 1996b, 1997). However, SEM images of certain crystals, particularly those of depth hoar, frequently appeared quite different from published photographs that had been obtained with the light microscope and raised questions about the extent to which the low-temperature SEM images provided structural data beyond those attainable with the light microscope. To address these concerns, identical snow and ice crystals were observed and photographed with a video (light) microscope and a low temperature SEM. The results of this study illustrate and discuss the differences in the two techniques.

Materials and Methods

Snow

Snow crystals were collected and stored as previously described (Wergin *et al.* 1995a, 1996a). Briefly, the snow crystals that were used in this study were collected during 1994–1997 from sites near the following locations: Beltsville, Maryland; Davis, West Virginia; and Fairbanks, Alaska. The samples, which were obtained when the air temperatures ranged from –11°C to +18°C, consisted of freshly fallen snowflakes as well as metamorphosed snow collected from snowpits that were excavated in winter snowpacks measuring up to 2 m in depth. The collection procedure consisted of placing a thin layer of either clear (unmodified) or modified (blackened with India ink) Tissue Tek on a flat, roughened copper plate ($15 \times 27 \times 2$ mm) that was precooled to below 0°C. Newly fallen snowflakes were either allowed to settle on the surface of the Tissue Tek solution or were lightly brushed onto its surface and then rapidly plunge-frozen in liquid nitrogen (LN_2) at –196°C. When samples were obtained from snowpits, a precooled scalpel was used to gently dislodge a sample from the pit wall onto the plate that was either rapidly plunged into a small styrofoam box containing LN_2 or placed on a brass block that had been precooled with LN_2. Next, the plates were inserted diagonally into 20 cm long segments of square brass channeling and lowered into a dry shipping dewar that had been previously cooled with LN_2. The dewar was either sent by ground transportation or shipped by air to the laboratory in Beltsville, Maryland. Upon reaching the laboratory, the samples were transferred under LN_2 to an LN_2 storage dewar where they remained for several days to as long as a year before being further processed for observation with light microscopy and low-temperature SEM.

Glacial Ice

Ice corings were obtained from the South Cascade Glacier, Washington, by using a Sipre ice corer to extract a 30 cm long core of the upper firn/glacier ice interface. A modified cork borer (8 mm in diameter), that had teeth filed into its cutting edge, was precooled with LN_2 and used to obtain secondary cores perpendicular to the main axis of the primary core. These corings were plunge frozen in LN_2 and placed into 8 mm cryotubes that were attached to cryowands. The wands were placed in a precooled LN_2 dewar and shipped to Beltsville, Maryland, where they were transferred and stored in the manner previously described for snow samples.

To prepare the corings for video microscopy and low-temperature SEM observations, the samples were removed from the cryotubes under LN_2 and were freshly fractured. Next, segments of the core were mounted on a specimen holder, which contained Tissue Tek, and plunged into LN_2. The holders were then either transferred to a styrofoam box for video imaging or attached to the rod of an Oxford cryotansfer device so that the specimens could be inserted into the prechamber of an Oxford CT 1500 HF Cryotrans System, sputter coated with platinum (Pt) metal, and admitted into a Hitachi S-4100 SEM that was equipped with a cold stage for low-temperature observations.

Video Images at Atmospheric Pressures

Light microscopic (digitized video) images were obtained either at atmospheric pressure or under high-vacuum conditions. At atmospheric pressure, light microscopy (video imaging) of previously stored snow crystals was done through a 1.5 cm thick transparent, lexan plastic cover that was placed on an open styrofoam box measuring $12 \times 20 \times 4$ cm (depth) and with 4 cm thick walls (Fig. 1). Before the samples were placed in the box, the following measures were taken to prevent melting or sublimation of the crystals. A metal block of aluminum, $3.5 \times 12 \times 1$ cm (mass = 137 g) was placed in the bottom of the box and covered with liquid nitrogen. A styrofoam cover was placed on the box until the block had cooled to LN_2 temperatures. After the temperature had equilibrated, a previously stored sample of snow was attached under LN_2 onto a modified Oxford specimen holder and transferred to the surface of the aluminum block in the styrofoam box. The level of the LN_2 was then adjusted so that the sample on the holder was exposed above the liquid and the lexan cover was placed over the box. At this time, the aluminum block remained submerged in the LN_2, while the sample was surrounded by cooled N_2 gas and remained near –196°C due to thermal conduction through the metal holder.

To photograph the sample, a HIROX Hi-Scope KH-2200 Video Microscope System was interfaced to a video moni-

tor and computer to acquire, display, and store digitized images of the sample. The scope was equipped with an MX-250Z lens and extension tube that resulted in a working distance of about 20 cm and a magnification of 50×. The Hi-Scope was mounted vertically above the box with a bracket on a ring stand. The sample, which could be illuminated either by the fiber optic system that was built into the lens or by fiber optic or incandescent side lighting, was focused and displayed on the video monitor. Additional flexibility in magnifications and working distances could be obtained by substituting other Hi-Scope lenses or by inserting the Hi-Scope into the camera tube of a Wild Makroskop M420.

To obtain stereo pairs of photomicrographs, the entire styrofoam box was gently tilted 6 to 10° after the first image had been recorded, and an image of the tilted sample was re-recorded. These two images contained the parallax information that was necessary for stereopsis [three-dimensional (3-D) observation].

After images of the snow crystals were obtained with the HIROX system, the styrofoam box was filled with LN_2, and the specimen holder was attached to the cryotransfer device
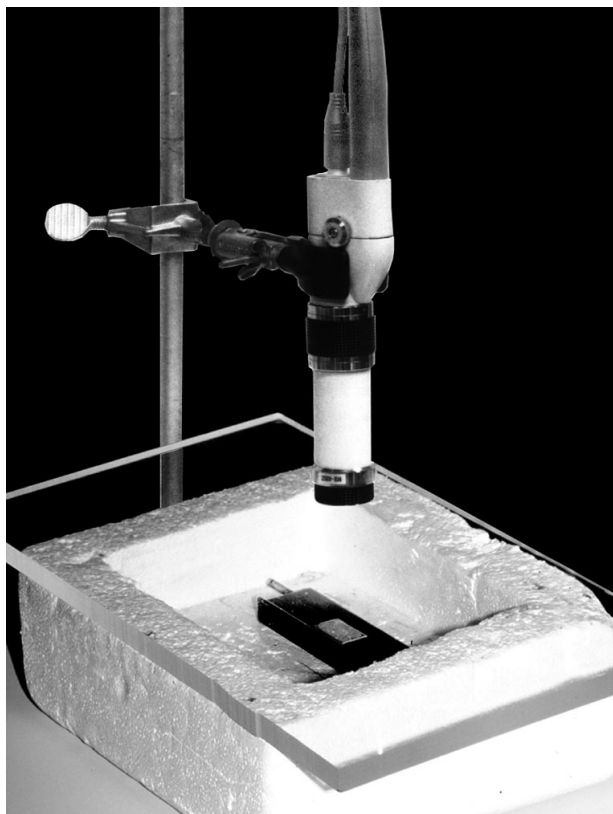

FIG. 1   HIROX Hi-Scope KH-2200 Video Microscope System equipped with an MX-250Z lens and extension tube mounted on a ring stand above a styrofoam box that is covered with a thick, transparent lexan plastic sheet. The video microscope is interfaced to a monitor and a computer that is used to acquire and display or store digitized images of the sample. This system, which can be easily and cheaply constructed, maintains the samples at –196°C and is usable at atmospheric pressures.

of an Oxford CT-1500 HF Cryotransfer System and transferred to the prechamber of the Oxford system where it was lightly etched and platinum (Pt) coated using a magnetron sputter coater. After sputter coating, the sample was inserted onto the cold stage of a Hitachi S-4100 low-voltage SEM. Crystals, which were identical to those that were photographed with the video microscope, were located, observed, and photographed in the low-temperature SEM.

Following observation in the low-temperature SEM for about 4 h, the samples were removed from the instrument and transferred back to the LN_2-cooled aluminum block in the styrofoam box so that the same crystals could be further observed and photographed with the video light microscope. This procedure provided images that could be compared with the SEM micrographs as well as to the original video images. Finally, the crystals were either discarded or returned to an LN_2 dewar for storage and future observations.

Video Images at High Vacuum Conditions

Video images that were observed at atmospheric pressure before and after SEM imaging indicated that no significant changes resulted from observation in the SEM. Consequently, an alternative method for recording video images was developed for specimens that had been previously observed in the low-temperature SEM.

After observation in the low-temperature SEM, the frozen samples were withdrawn under vacuum from the instrument with the Oxford specimen transfer device and inserted through a modified airlock onto a precooled (–190° C) cryostage in a modified Denton vacuum evaporator equipped with a DFE-3 freeze-etch unit (Fig. 2). The modified stage allowed up to a 180° tilt and could be temperature controlled from +30°to –196°C.

The HIROX Hi-Scope KH-2200 Video Microscope System was mounted above the glass cover plate of the freeze-etch unit so that images of the stage could be viewed and recorded. This instrument enabled us to locate the identical snow crystals that had been observed in the low-temperature SEM and to record images of these same crystals with the video light microscope. In addition, the tilt stage in the freeze-etch unit enabled specimen tilting so that stereo images of the crystals could be recorded. Overall, a 180° tilt was possible with this stage, which allowed recording of stereo images over a wide range of angles. Following observation and recording of the video images, the samples were either discarded or transferred back to an LN_2 dewar for storage and future observations.

Scanning Electron Microscopy Images

To prepare the samples for low-temperature SEM observation, the copper plates were attached to the transfer rod of the Oxford cryosystem and then moved under vacuum into the prechamber for etching and/or sputter coating with Pt

and then inserted into a Hitachi S-4100 field emission SEM equipped with a cold stage that was maintained at –185°C (Fig. 3). Accelerating voltages of 500 V to 10 kV were used to observe and record images onto Polaroid Type 55 P/N film. To obtain stereo pairs, the first image was recorded, the stage was tilted 6°, the specimen was recentered and refocused, and a second image was recorded.

Results

Images viewed with the video (light) microscope were illuminated with reflected light; however, light that was refracted and transmitted back through the sample undoubtedly contributed to the final image. Some snow samples were mounted in a modified (blackened) Tissue Tek to provide better contrast between the crystals and the mounting medium. To obtain a representative sampling of all types of crystals that were present in the snow pack, no attempts were initially made to separate and mount single, unique crystals from the snowpack; the crystals illustrated in the following figures constituted part of the bulk sample that was obtained from the collection site.

Video microscopy enabled one to isolate and record images of a single crystal in the bulk sample (Fig. 4). With the video system, the arms of a dendritic crystal could be distinguished and a smaller central hexagonal disc could be discerned. At similar magnifications, the low-temperature SEM images greatly clarified the surface structure of the crystal (Fig. 5). The hexagonal plate in the center of the dendrite was quite distinct, ridges and grooves in the arms were discrete, and small hexagonal secondary depositions in the form of columns were easily discerned (Fig. 5 arrows).

In the video images, rimed dendrites frequently exhibited small white spots that probably resulted from direct reflection of light by uniquely oriented rime particles (Fig. 6). Although the presence of rime could be ascertained in the video images, the structure of the material could not be deter-

Fig. 2   Video microscope system that is interfaced to a monitor and computer as described above. The microscope is mounted above the clear glass cover on a modified Denton DFE-3 freeze-etch module. With this system, the sample is maintained under vacuum at –196°C. The stage in the freeze etch-module allows the sample to be tilted through 180° so that multiple views, including stereo pairs, can be obtained at different angles.
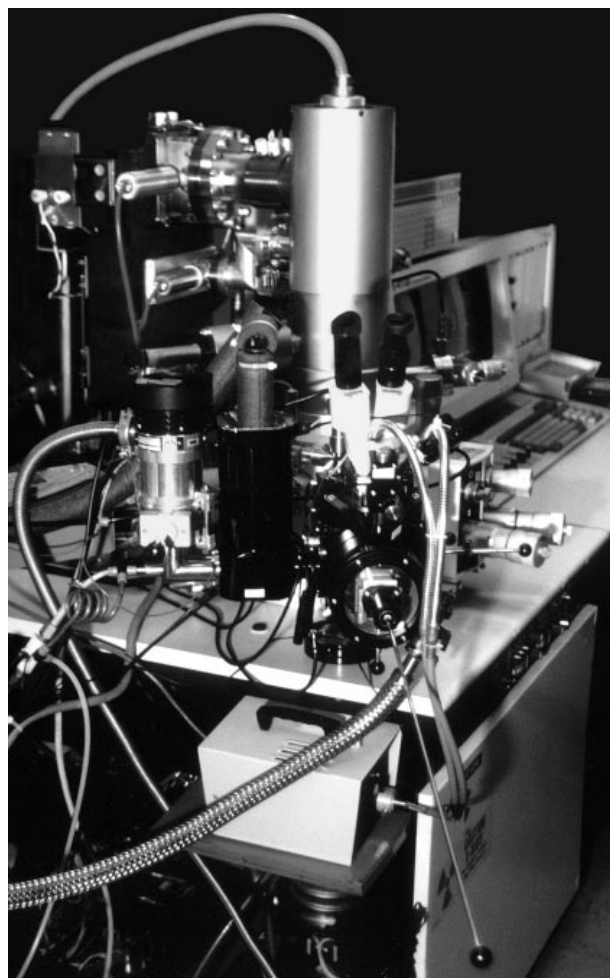

Fig. 3   Oxford CT-1500 HF Cryotrans System mounted on a Hitachi S-4100 field emission SEM. The transfer rod with the attached specimen is inserted under vacuum into the prechamber (black attachment) for etching and/or sputter coating with platinum and then inserted into the microscope that has a cold stage maintained at –185°C.

mined and the depth of focus was limited. Alternatively, accretion and distribution of rime deposition was much more distinct in the low-temperature SEM images (Fig. 7). Riming was more prevalent at the ends of the arms as opposed to the center of the crystals. The rime near the center of the crystal tended to be discrete particles, whereas the riming at the ends of the arms occurred as interconnected masses of the droplets (Fig. 7).

Extensive riming increased the size and thickness of snow crystals and resulted in graupel. The graupel, which was observed with the video microscope (Fig. 8), commonly exhibited the bright reflected light spots similar to those observed in the rimed snow crystals, such as those illustrated in Figure 6. The material that comprised the rime appeared to be particulate, but other structural features remained obscure. Alternatively, the graupel observed in the low-temperature SEM was much more clearly defined. It consisted of massive accumulations of droplets, fairly uniform in size. The droplets did not occur as distinct particles but were interconnected in sinuous or amorphous accretions that covered the surface of the crystal (Fig. 9). This accumulation was more pronounced at the margins of the graupel crystal.

Apart from the improved resolution associated with low-temperature SEM, the most dramatic differences between the video photographs and the SEM micrographs were observed when samples having complex internal structures, such as depth hoar, were recorded and compared. To insure that sputter coating and beam irradiation in the low-temperature SEM had not altered the structure of an individual crystal, a depth hoar grain was initially photographed with video

microscopy (Fig. 10), then transferred to the prechamber where the sample was sputter coated, inserted onto the cold stage of the low-temperature SEM for observation and photography (Fig. 11), and finally removed from the low-temperature SEM and rephotographed using video microscopy (Fig. 12). Initial observations of depth hoar with video microscopy generally revealed the faceted structures that characterize this type of crystal. However, the video images did not clearly indicate whether the faceting was internal or external, that is, on the surface or within the crystal (Fig. 10). Alternatively, the low-temperature SEM provided an image that clearly portrayed the external surface of the crystal, which was frequently flat (Fig. 11). External faceting was not always present, suggesting that the structural features in the video images resulted from internal facets of the crystals. In fact, the video and SEM images could be so distinctly different that initial observations failed to convince the viewer that both images represented the same crystal. However, close examination of peripheral features of the crystal revealed distinct structures that were common to both images (see arrows, Figs. 10 and 11).

After Figure 11 was recorded, the sample was removed from the low-temperature SEM and rephotographed with the video microscope (Fig. 12). Although the general structure of the image in Figure 12 was a little more sharply delineated than that shown in Figure 10, the two figures did not show any distinct differences, suggesting that coating and observation in the low-temperature SEM did not alter the original structure of the depth hoar crystal. The coating that was applied for SEM observation of the crystal shown in
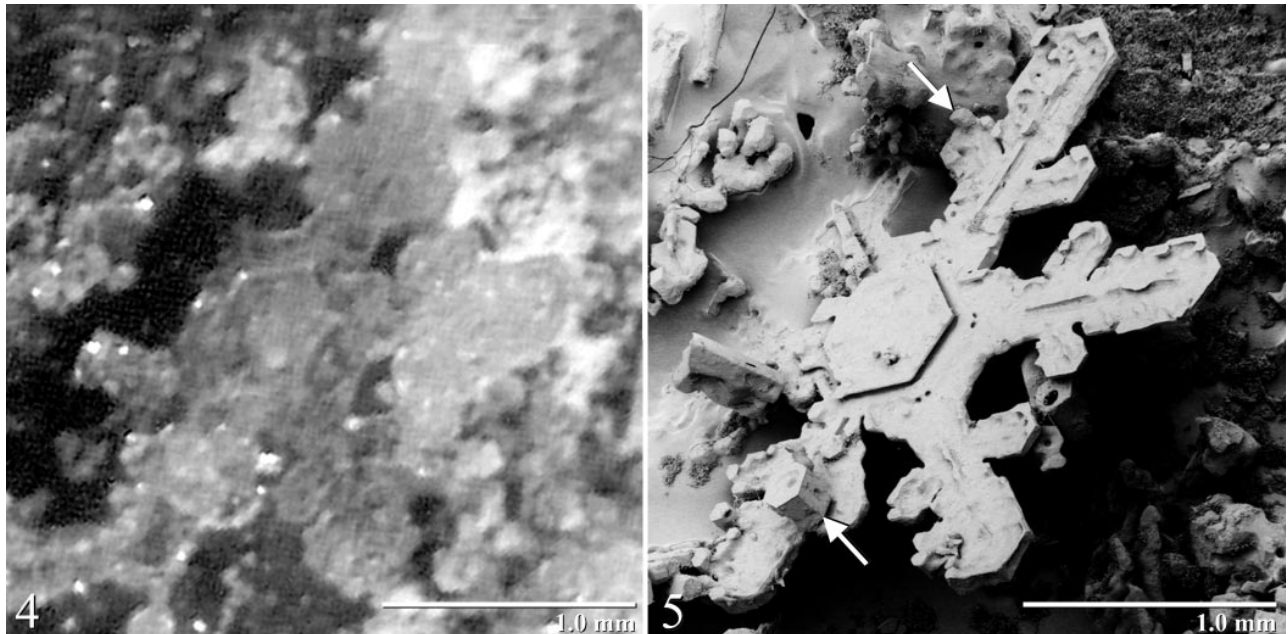
FIGS. 4 AND 5   Snow sample collected outside the Electron Microscopy Unit at Beltsville, Maryland, mounted in modified Tissue Tek, cooled in LN_2, and transferred to the laboratory for observation. Fig. 4: Light micrograph recorded with the video microscope system mounted above the styrofoam box illustrated in Figure 1. This figure illustrates a portion of a dendritic snow crystal. Fig. 5: After images were acquired with the video microscope system, the frozen sample was transferred to the Oxford preparation chamber, platinum coated, and inserted into the low-temperature scanning electron microscope to observe and record images of the same crystal shown in Figure 4.

Figure 11 actually improved the contrast of the subsequent video image shown in Figure 12. Video and low-temperature SEM images of large depth hoar crystals that did contain extensive external faceting resembled one another much more closely. When the faceting was external, the video images of the depth hoar crystals were much sharper than those of crystals having flat surfaces and internal facets (compare Figs. 10 and 13). However, the degree of faceting and the individual steps, which tended to "run together" in the video image (Fig. 13), were quite distinct and more clearly discerned in the SEM image (Fig. 14).

Video micrographs of the corings of glacial ice illustrated the general shapes and sizes of crystals (Fig. 15). Although the sample was illuminated with reflected light, transmitted and refracted light also contributed to the final image. Consequently, the structural features of the fractured surface of the core were frequently confused by information that came from below the surface. Alternatively, the low-temperature SEM images of the identical core illustrated only the surface and clearly delineated the boundaries of the individual fractured crystals and the adjacent pore spaces (Fig. 16). Three-dimensional video images of the cores helped to clarify the topography of the surface and to delineate some of the surface grains (Fig. 17); however, this information was much more evident in the stereo, low-temperature SEM images (Fig. 18).

The additional magnification that was possible with the SEM enabled observations of single crystals, their association with adjacent crystals (Fig. 19), and the grain boundaries between adjacent crystals (Fig. 20). Neither of these features was resolved with the video microscope.

Discussion

This study indicates that snow crystals of different ages and morphologies, and crystals of glacial ice can be collected from remote locations, transported or shipped to a laboratory, and stored for an indeterminate amount of time without undergoing structural changes. Specific or unique crystals can then be prepared for observation with light (video) and/or low-temperature SEM. The light microscopic examination, using video microscopy, can be performed in a simple inexpensive styrofoam box that is used to maintain the snow crystals at LN_2 temperatures, whereas the investigator can observe and photograph these samples while working at ambient temperatures rather than at the subzero temperatures that would be required in a cold laboratory. More sophisticated equipment, which employs a high vacuum evaporator, provides a cleaner environment for the sample, enables more flexibility for specimen tilt during the video microscopic observations, and permits longer time periods
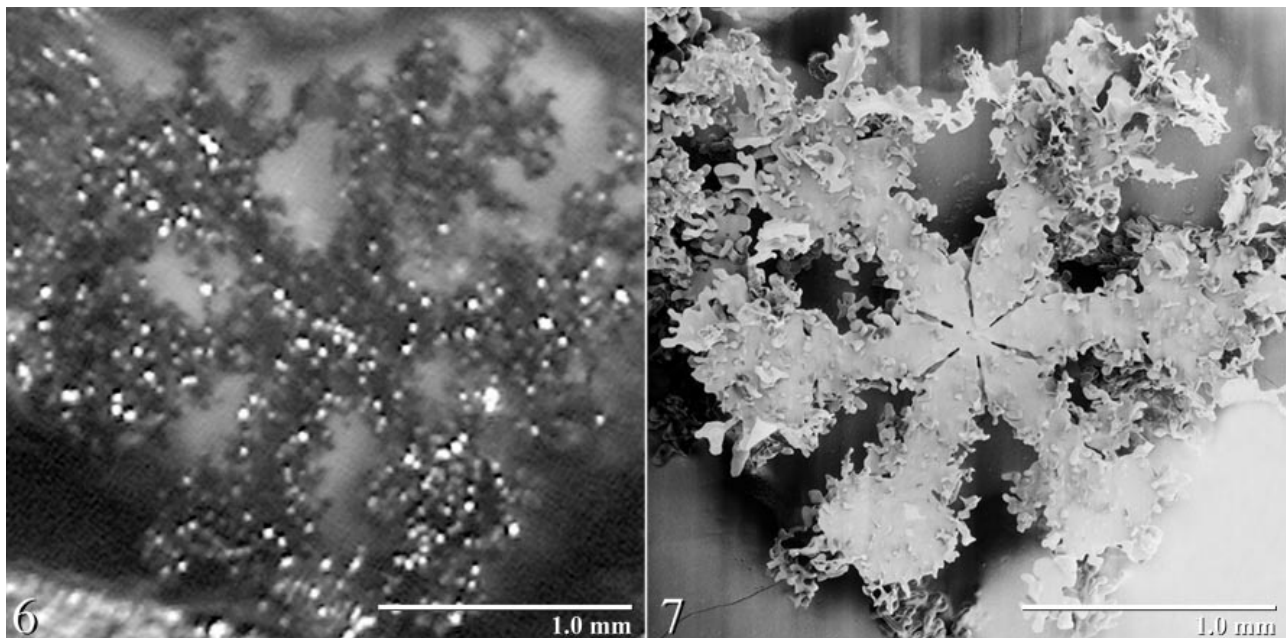
FIGS. 6 AND 7   Sample collected on Bearden Mountain, West Virginia, air temperature at 0°C, mounted in modified Tissue Tek, frozen in LN_2, and transported to the laboratory. Fig. 6: Video micrograph illustrating a rimed dendritic snow crystal. Surface of the crystal appears granular due to the presence of small super-cooled, frozen droplets (rime). The white specks on the video micrograph of the crystal apparently result from light that is reflected by the rime particles. This image, which was obtained after the sample had been observed and photographed in the low-temperature scanning electron microscope, was acquired with the video microscopy system that was mounted above the precooled (–190°C) cold stage in the Denton DFE-3 freeze-etch module where the sample was observed for 2 h without any apparent degradation or contamination. Fig. 7: The low-temperature scanning electron microscope image illustrates that riming was more prevalent at the ends of the arms than at the center of the crystals. The rime particles near the center of the crystal tended to be discrete particles, whereas the riming at the ends of the arms occurred as interconnected masses of the droplets (Fig. 7).

for observation. Both the simple box and the high-vacuum evaporator can be used to observe and record images of the snow crystals prior to and/or after their observation in the low-temperature SEM.

Comparisons of images of a specific crystal with the video microscope, then with the SEM, and finally reexamination with video microscopy indicates that sputter coating with Pt and beam irradiation in the SEM do not result in any changes, that is, sublimation or melting, that can be documented with the video microscope. Multiple photographs of the same sample can be obtained over several hours without causing structural changes in the crystals. These conclusions are also supported by the vast literature on low-temperature SEM investigations of biological materials, which must be coated with a heavy metal such as gold or platinum to make them conductive and to prevent charging during examination and photographic recording in an SEM. In our laboratory, this procedure has been used to image intramembrane particles on frozen, fractured yeast membranes (Wergin and Erbe 1991). These particles measure < 10 nm and must be magnified about 50,000 times to be resolved. Successful preparation and imaging of these small macromolecular particles

in biological tissue suggest that sputter coating and beam irradiation would not affect the integrity of structural features in snow or ice at similar magnifications and resolutions. The only observed effect of sputter coating with Pt was to improve slightly the contrast of the sample in images that were subsequently captured with the video microscope (compare Figs. 10 and 12).

No indication of sublimation or evaporation is associated with the collection, preparation and observation of samples in the low-temperature SEM. Fresh snow that was collected from remote sites, shipped and stored in the laboratory before observation, exhibited the same structural features as fresh snow that was collected at the laboratory site and immediately observed in the low-temperature SEM. From the time of collection through observing and photographing, the samples are either stored in LN_2 or are being maintained at near LN_2 temperatures ($-180°C$ to $-196°C$) on cold stages. At these temperatures and storage times, sublimation would be $< 1.49 \times 10^{-5}$ nm/s (Umrath 1983), a rate that would not be detectable under our working conditions.

Whether the resolution and depth of focus in the low-temperature SEM exceeds that of a light microscopic system for
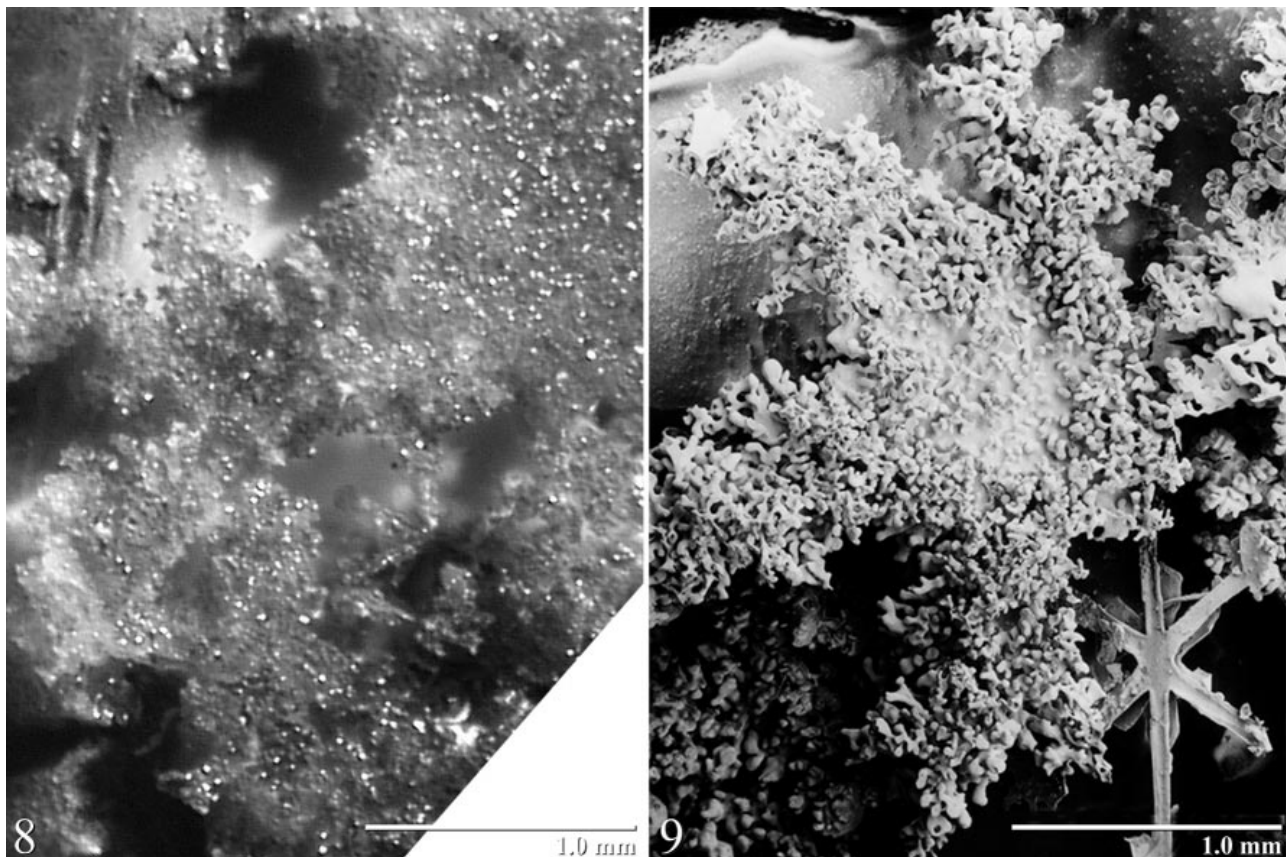

FIGS. 8 AND 9   Sample collection and preparation similar to those described for Figures 6 and 7. Fig. 8: Video micrograph illustrating graupel. The general shape of the grain indicates that the original crystal may have been a dendritic form; however, extensive accretion of small particles have covered its surface. Fig. 9: Low-temperature scanning electron microscope (SEM) micrograph of the same crystal shown in Figure 8. Low-temperature SEM illustrates that the accretion is heaviest at the periphery of the particle and appears to accumulate preferentially on one face, possibly due to a unidirectional descent through the atmosphere. The particle has the appearance of "coral" resulting from the massive accretion of fused droplets.

the purposes of investigating snow crystals has been questioned. Under ideal conditions, the light microscope has useful magnification to about $1,200\times$ and theoretical resolution to about 0.2 µm; however, as a result of the technical difficulties of working with snow, most of the published photomicrographs that have been successfully taken with a light microscope or macrophotography are published at magnifications of $<200\times$ (Ahlmann and Droessler 1949, Akitaya 1974, Armstrong 1992, Bentley and Humphreys 1931, Colbeck *et al*. 1990, Eckerbom and Palosuo 1963, LaChapelle 1992, Nakaya 1954, Seligman 1949, Sturm 1991). Alternatively, the SEM has useful magnification to at least $40,000\times$ and resolutions of 5 nm. We have published several figures of snow crystals at magnifications above $10,000\times$ to illustrate structural features such as microcrystalline extensions, which are minute structures well beyond the limitations of a light microscope (Wergin *et al*. 1996a). Likewise, the depth of focus for the SEM is considerably superior to that of the light microscope. Depth of focus (D_{fo}) for any microscope is dependent upon the magnification (M), resolving power (R) of the instrument, and aperture angle (a) of the objective lens ($D_{fo} = M^2 \times R/a$). Simple calculations indicate that the low-temperature SEM has a depth of focus approximately $1,000\times$ greater than that of the light microscope. This feature accounts for the well-focused micrographs of snow and ice crystals that contain considerable vertical relief such as that which is present in multiple aggregations, graupel, and depth hoar.

The application of low-temperature SEM for observation of snow crystals has been previously demonstrated by our laboratory (Wergin and Erbe 1994a– c; Wergin *et al*. 1995a, b, 1996a; Rango *et al*. 1996a, b). This current study indicates that the same procedure has application to the study of ice cores. Unfortunately, regardless of how an ice specimen is illuminated for observation and photography with a video or light microscope, the final image contains at least some information that results from reflected, refracted, and transmitted light. As a result, interpreting the surface features of the specimen is frequently confounded by subsurface structure which also contributes to the final image. Tilting the specimen and stereo photography aid in the interpretation of the images; however, the boundaries of individual ice grains and the adjacent pore spaces as they exist on the surface of ice cores are frequently difficult to discern. Alternatively, an SEM image results from the secondary and backscattered electrons that emanate from the surface of the specimen. Consequently, in these images the boundaries of the individual ice grains are distinctly discerned and could be easily used to distinguish and characterize glacial ice and firn.
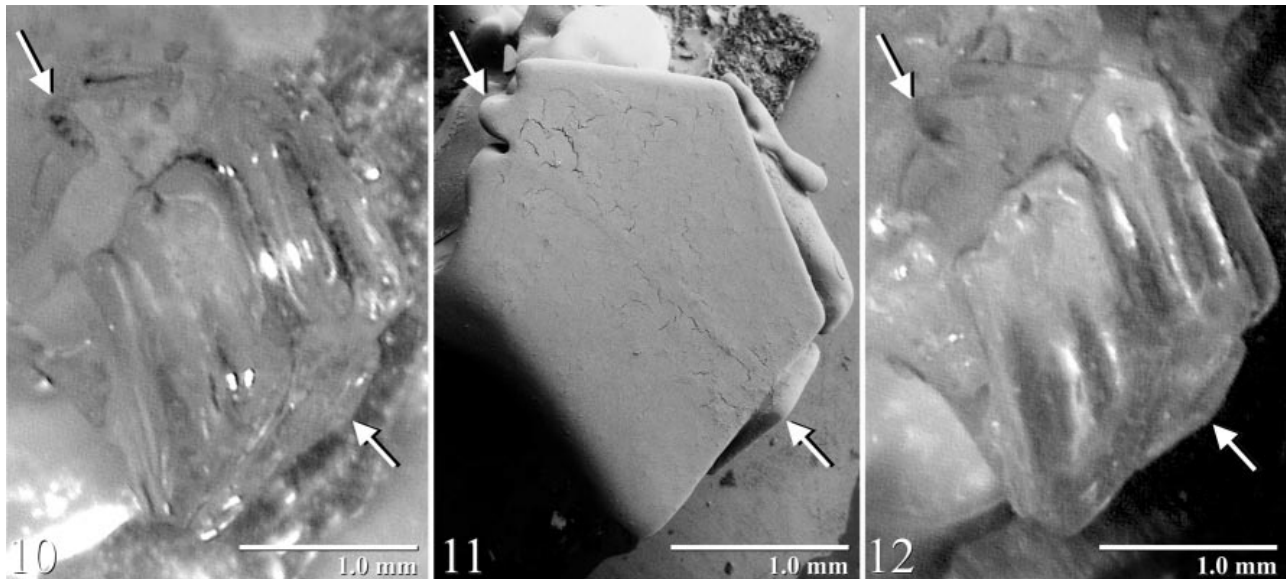

FIGS. 10–12   Sample collected near Fairbanks, Alaska, mounted in Tissue Tek, frozen in LN_2, shipped to the laboratory. Fig. 10: Video light micrograph recorded with the video microscope system mounted above the styrofoam box illustrated in Figure 1. The figure illustrates a single depth hoar crystal with characteristic "facets." Fig. 11: After images were acquired with the video microscope system, the frozen sample was transferred to the Oxford preparation chamber, platinum coated, and inserted into the low-temperature scanning electron microscope (SEM) for further observation. Figure 11 is a low-temperature SEM micrograph of the same crystal shown in Figure 10. Because the low-temperature SEM only provides surface information, the faceting, which is internal, is not evident. Alternatively, the surface of the depth hoar crystal appears relatively flat. Fig. 12: After the sample had been observed and photographed in the low-temperature SEM (Fig. 11), the sample was removed and transferred back to the styrofoam box and reexamined with the video microscopy system. The depth hoar crystal appears faceted and similar to that shown in Figure 10. This indicates that sputter coating and low-temperature SEM examination did not alter the general structure of the crystal. The coating, which had been applied for low-temperature SEM examination, appeared to enhance the general contrast of the image. Because the "facets" associated with this crystal are actually internal structural features, they do not appear as sharp or distinct as the external facets that are present on the crystal shown in Figure 13.
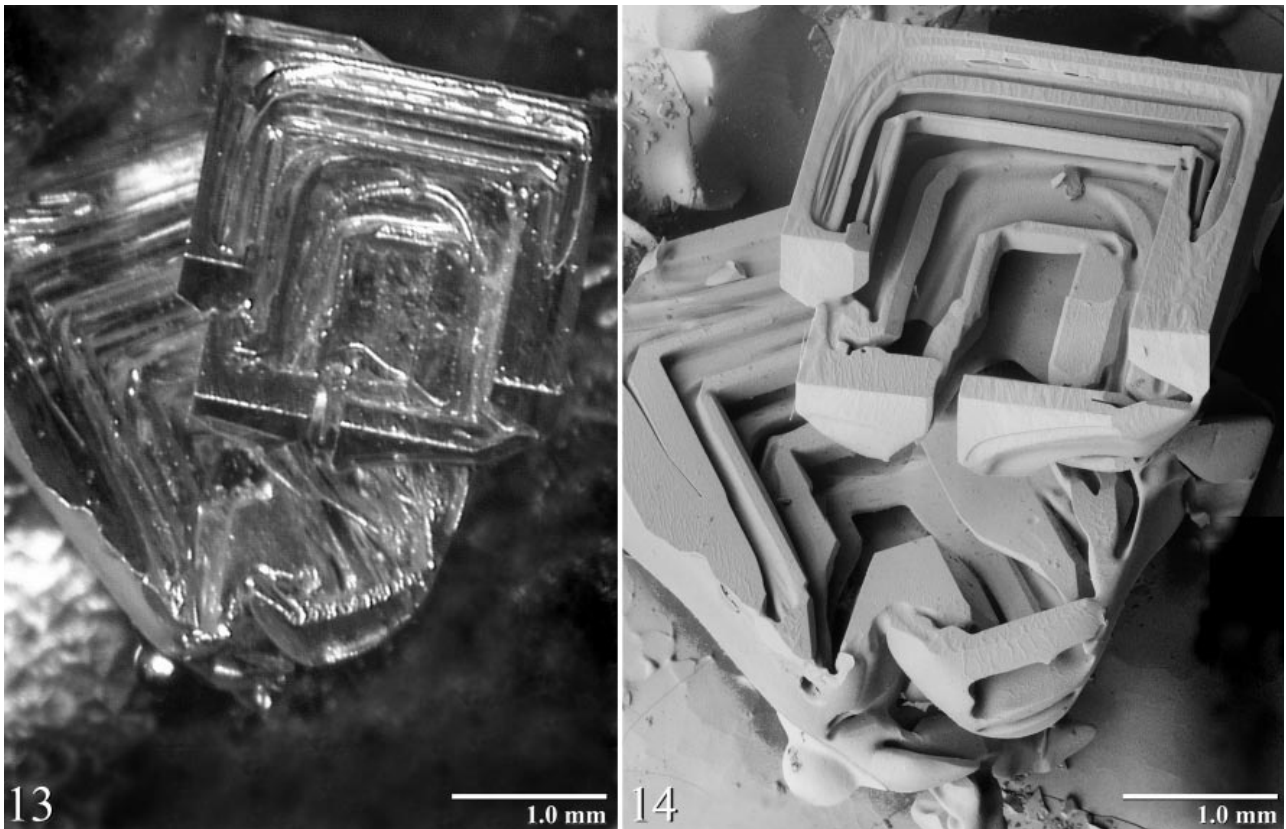
FIGS. 13 AND 14   Sample of depth hoar crystal collected at the base of a snow pit, 21 cm deep, near Marbleton, Wyoming. Video and low-temperature scanning electron microscopy (SEM) images of large depth hoar crystal that exhibits pronounced external faceting. The degree of faceting and the individual steps tend to "run together" in the video image (Fig. 13); however, these features are quite distinct in the SEM image (Fig. 14).
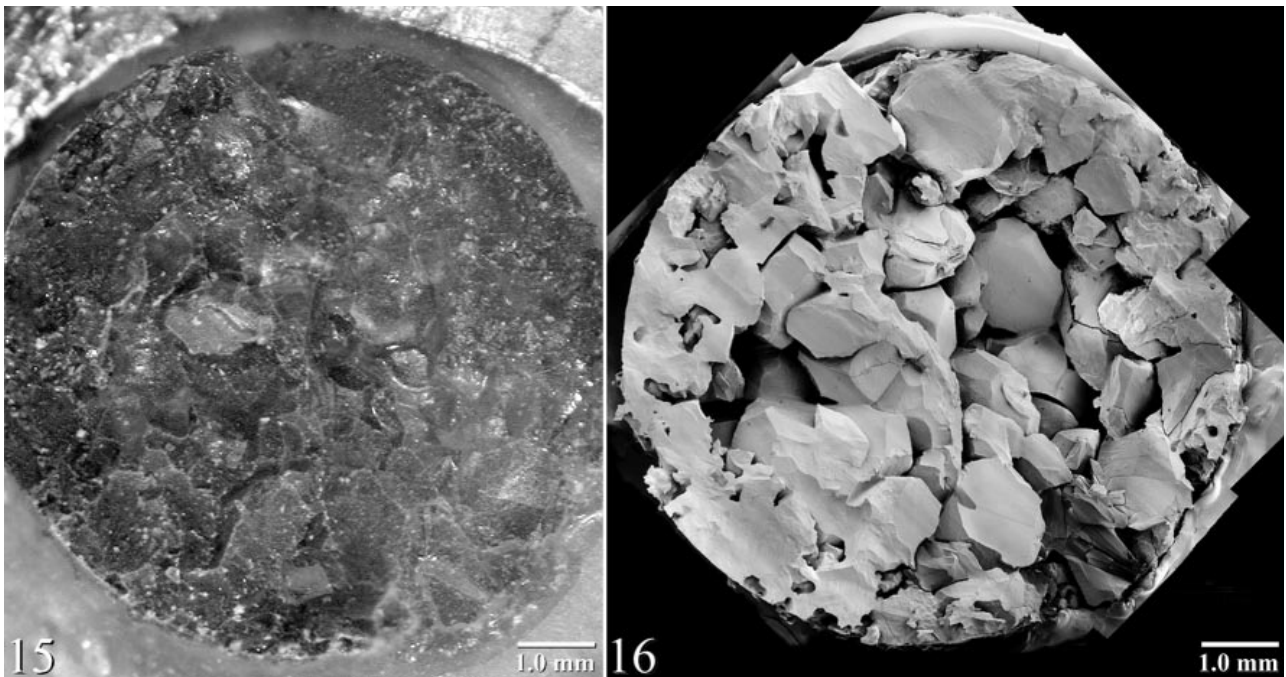
FIGS. 15 AND 16   Sample of an ice core collected at South Cascade Glacier, Washington. The ice core was fractured under LN₂ just before observation to reveal a freshly fractured internal surface in the core. Fig. 15: In the video microscope image, reflected and refracted light from within the sample results in an image in which the individual ice grains and the pore spaces are not easily distinguished. Fig. 16: In the low-temperature scanning electron microscope micrograph of the identical sample, the image is formed only from the secondary electrons that are emitted by the surface. Consequently, individual grains and pore spaces that exist at the fractured surface are sharply delineated.
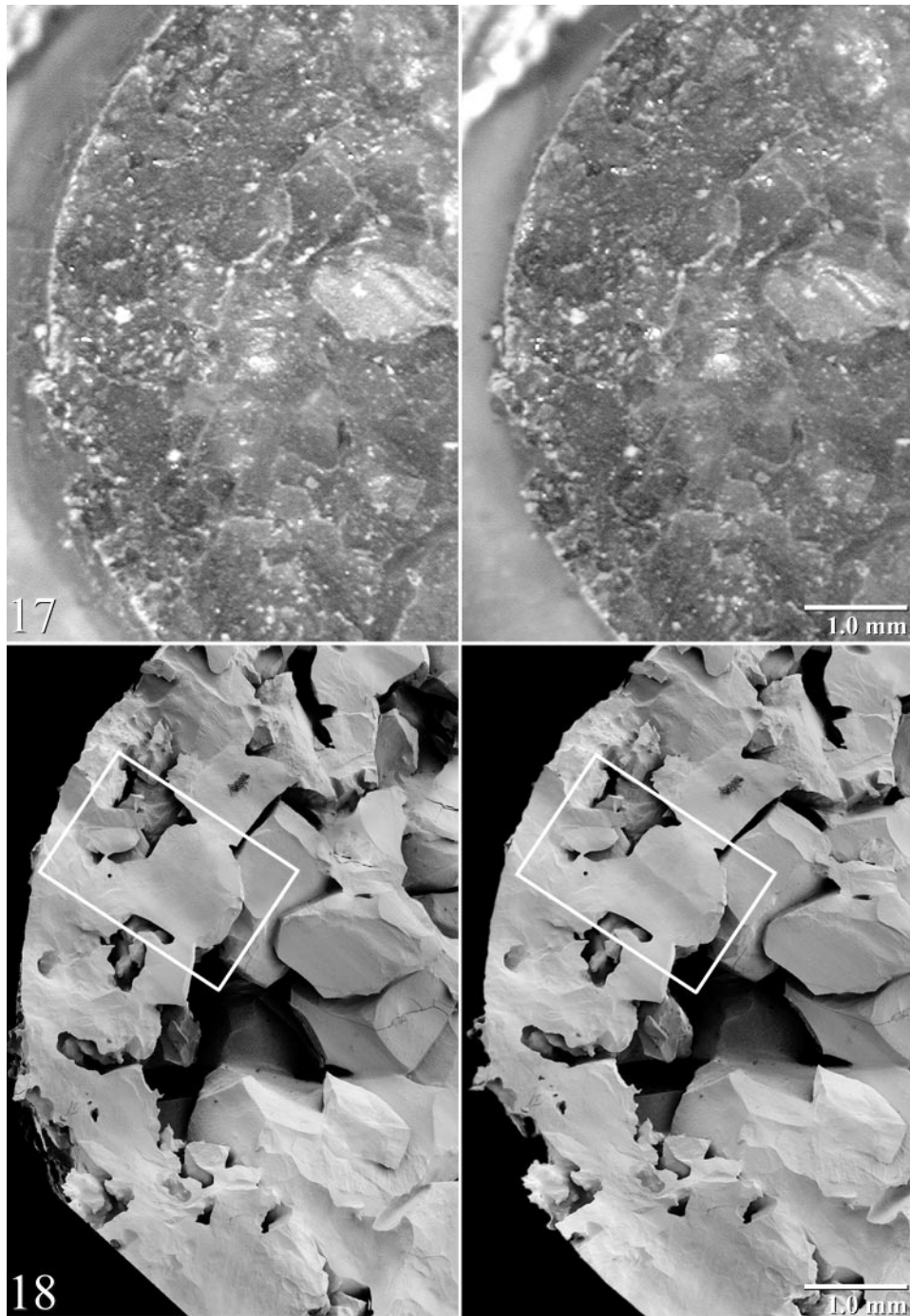
FIGS. 17 AND 18   Same sample as described for Figures 15 and 16. Stereo micrographs of a portion of the core illustrated in Figures 15 and 16. Fig. 17: This light micrograph was recorded with the video microscope system mounted above the styrofoam box illustrated in Figure 1. The topography of the surface is more clearly evident in the stereo pair. Fig. 18: Low-temperature scanning electron microscope stereo image illustrates fusing ice grains and the air spaces that exist between them. Boundaries of individual ice grains can be easily resolved. A three-dimensional (3-D) image of this stereo pair can be obtained either by the unaided eyes or with the help of a simple lens viewer by entraining the left and right eyes on the left and right micrographs, respectively. When the stereo pair is viewed in this manner, three images will be seen; the center image will be the 3-D view that results from cortical fusion.
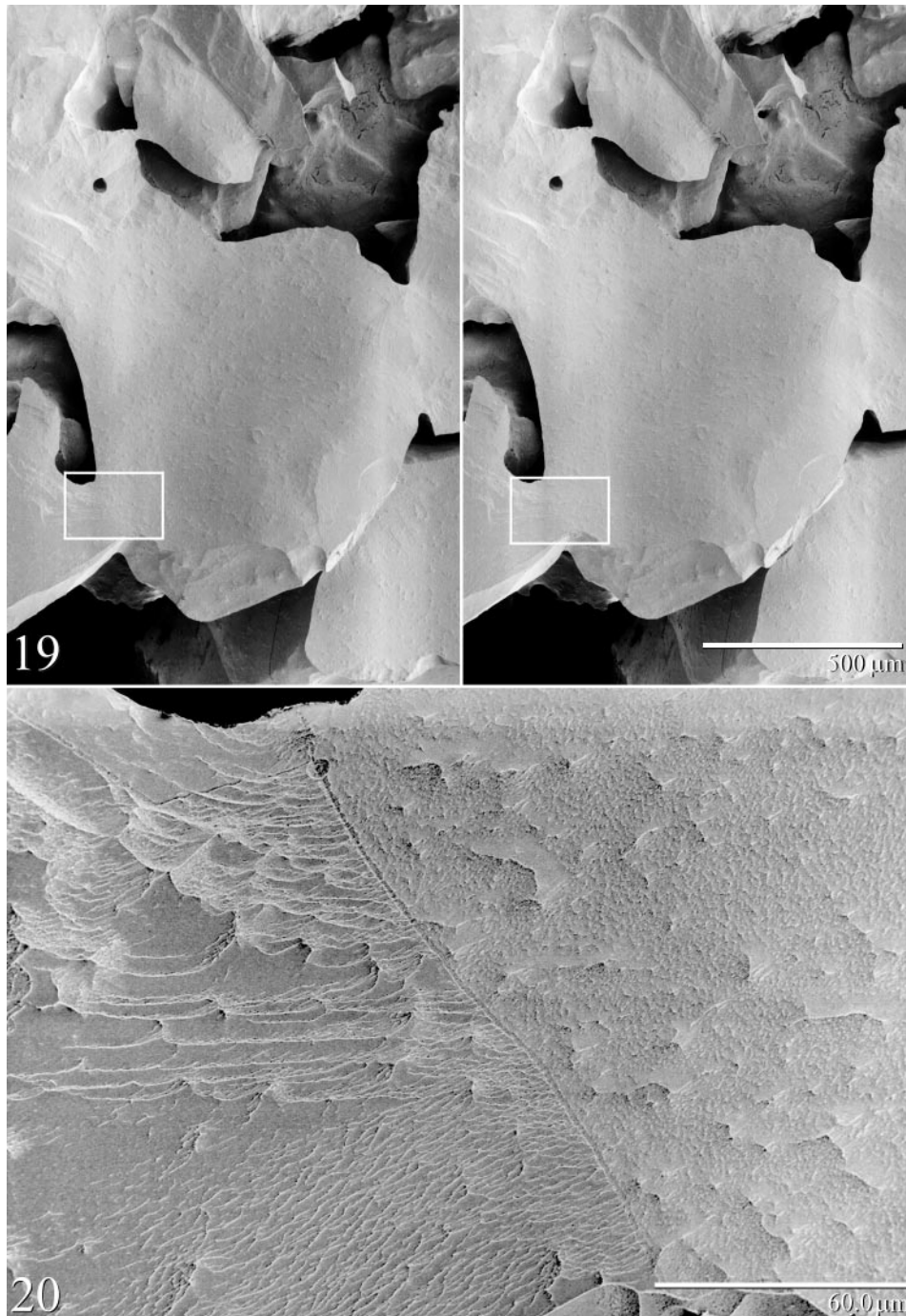
FIGS. 19 AND 20   Same sample as described for Figures 15 and 16, recorded at successively higher magnifications to reveal further details of the ice grains that are shown in Figures 17 and 18. Fig. 19: Stereo low-temperature scanning electron microscope image illustrating an ice grain that is fusing with adjacent particles. Abundant air space would apparently allow for the passage of water at this stage. Fig. 20: Grain boundary between adjacent ice grains that are illustrated in Figure 19.

Conclusion

This study attempts to illustrate that an identical snow crystal or ice grain can be easily imaged by video (light) microscopy and low-temperature SEM. The collection procedures enable samples from distant locations to be frozen and shipped to a laboratory for storage and/or observation. Imaging of the samples, which are maintained in their frozen state, can be performed with a video microscope in any laboratory at ambient temperatures. Neither the expense nor the discomfort of a cold laboratory are necessary. Stereopsis (3-D viewing) used in association with low-temperature SEM greatly increases the ease of structural interpretations. The preparation procedures that are used for SEM do not result in sublimation or melting. Furthermore, the low-temperature SEM provides far greater resolution and depth of focus than that of a light microscope so that detailed surface structure not previously attainable can be imaged and recorded.

Acknowledgments

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