The Structure and Metamorphism of Snow Crystals as Revealed by Low Temperature Scanning Electron Microscopy

W.P. WERGIN[1], A. RANGO[2] AND E.F. ERBE[1]

ABSTRACT

A scanning electron microscopy equipped with a low temperature stage was used to observe precipitated and metamorphosed snow crystals. Snow samples were collected during 1994-96 from sites in West Virginia, Colorado and Alaska. The samples consisted of precipitating snow and snow collected from pits that were excavated in winter snow fields. The samples were collected on copper plates, frozen in liquid nitrogen and then transferred to a dewar that was shipped to Beltsville, MD. Examination of the samples with this technique, which is referred to as low temperature scanning electron microscopy (LTSEM) revealed that the snowflakes consisted of aggregations of needles, columns, hexagonal plates and dendrites. Metamorphosed snow sampled from the snowpits contained rounded, sintered, faceted, and clustered forms of crystals. The development of these crystalline forms were associated with temperature and vapor pressure gradients or with melt-freeze cycles that occurred within the snowpack. The melt-freeze cycles were also associated with the appearance of "red snow" resulting from cells that were believed to be green algae. This study indicates that LTSEM is a new and feasible technique for observing snow that can be sampled at remote locations and shipped to a laboratory for examination. LTSEM can be used at high magnifications to illustrate the shapes and features of precipitated snow crystals as well as their metamorphosed states.

Key words: snow crystal, metamorphosis, depth hoar, algae, microscopy

INTRODUCTION

Much of the current knowledge on the structure of precipitated snow crystals is based on observations with the light microscope. One of the first individuals in North America to observe and photograph this information was the amateur microscopist, Wilson A. Bentley, who collected, observed and photographed snow crystals over a 30 year period in Vermont. He amassed over 6,000 photomicrographs of snow crystals, principally consisting of variations in hexagonal plates and stellar dendrites, that were recorded during this time (Blanchard, 1970). Although reproductions of Bentley's photomicrographs have been published in numerous popular articles, he only made a limited attempt at publishing scientific documentations of his work. (see Blanchard, 1970). He is best known for his publication, *Snow Crystals* (Bentley and Humphreys, 1931), which contains over 2,000 photomicrographs of snow crystals that were photographed with a light microscope using transmitted light. This study provides one of the most complete and aesthetic documentations on variations that exist in the hexagonal plates and stellar dendrites. Unfortunately, neither the atmospheric conditions under which the snow was collected nor the magnifications at which the crystals were photographed are included in his book. Furthermore, because the book concentrated on symmetrical crystals rather than on the full range of shapes that Bentley surely must have encountered, the book is somewhat compromised in its scientific value. In 1932, Nakaya began an attempt to remedy these shortcomings by observing natural and artificial snow crystals under closely controlled

[1] Nematology Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland 20705 USA
[2] Hydrology Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland 20705 USA

laboratory conditions. Nakaya observed crystals with a light microscope using oblique illumination to reveal the full range of shapes and surface features of snow crystals. He succeeded not only in illustrating the structural variations that occurred in natural snows, which he collected under carefully recorded environmental conditions, but in the laboratory he was able to simulate those conditions to artificially produce snow crystals of the same type. Nakaya documented information concerning the growth rates of snow crystals as well as how their shapes and sizes were influenced by different temperatures and moisture levels (Nakaya, 1954).

Compared to precipitated snow, the structure and development of metamorphosed snow has not been documented as completely with the light microscope. This deficiency results in part from the fact that metamorphosed snow crystals must frequently be obtained from snowpits at high elevations in remote locations. Consequently, these types of snow crystals are generally examined with a hand lens and photographed via macrophotography (with a camera) rather than microphotography (with a microscope).

In studies of both precipitated and metamorphosed snow crystals, examination with the light microscope or hand lens and micro- and macrophotgraphy are hampered by numerous adverse conditions: 1) the snow crystals must be collected, transferred and observed at temperature below 0^0 C; 2) the crystals are highly subject to sublimation and melting during these events; 3) magnification is limited to only a few 100 times with a light microscope or even less with a hand lens; 4) transmitted light, which is generally used for illumination, does not allow one to differentiate internal structures from external surface features and; 5) the depth of field that is attainable with a light microscope or close up camera is relatively shallow, therefore large snow crystals that exhibit considerable topography or size such as graupel or depth hoar are difficult to observe and photograph in focus.

Recently, preliminary reports indicate that an alternative technique can be used to observe and photograph precipitating snow crystals (Wergin and Erbe, 1994a; 1994b; 1994c; Wolff and Reid, 1994). This technique, which is known as low temperature scanning electron microscopy (LTSEM) consists of a scanning electron microscope (SEM) which is equipped with a cold stage. This combination of equipment enables observation of frozen samples that are maintained at near liquid nitrogen temperatures (-196C) where sublimation does not occur at detectable rates. As a result, a frozen, bulk specimen remains stable and can be observed and photographed (Wergin and Erbe, 1991). Use of LTSEM has enabled investigators to image and photograph newly precipitated snow crystals. Wergin and coworkers (Wergin and Erbe, 1994a; 1994b; 1994c; Wergin et al., 1995a; 1995b; Rango et al., 1996a; 1996b) used this technique to record images of newly precipitated snow crystals consisting of hexagonal plates, stellar dendrites, needles and columns that were collected at their laboratory site. Wolff and Reid (1994) attempted to use this technique to record images of snow crystals that were collected in Greenland and transported to England for observation. Unfortunately, as a result of difficulties associated with collecting, mounting and transporting their samples, most of the snow crystals were either lost or broken and the authors were only successful in recording fragments of the crystals that had been collected at the remote site.

Results in our laboratory indicate that snow crystals can now be successfully collected and transported for observation with the LTSEM (Wergin et al., 1996; Rango et al. 1996a; 1996b). The procedure not only allowed us to observe newly precipitated snow crystals collected in West Virginia but also to observe crystals that were collected from snowpits at several locations in the western US and Alaska. Examples of the results of these studies are presented in this paper.

MATERIALS AND METHODS

Snow was collected during 1994-96 from sites near the following locations: Davis, West Virginia; Jones Pass and Loveland Pass, Colorado; and Prudhoe Bay and Fairbanks, Alaska. The samples, which were obtained when the air temperatures ranged from -1^0 C to -14^0 C, consisted of freshly fallen snowflakes as well as snow that was collected from the walls of snowpits that were excavated in winter snowpacks measuring up to 1.5 m in depth.

The collection procedure consisted of placing a thin layer of methyl cellulose solution (Tissue Tek) on a flat copper plate (15 mm x 27 mm) that was precooled to the ambient outdoor temperature. Newly fallen snowflakes were either allowed to settle on the surface of the methyl cellulose solution or were lightly brushed onto its surface and then rapidly plunge frozen in liquid nitrogen (LN_2) at -196^0C. 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 styrofoam container containing LN_2 or placed on a brass block that had been precooled with LN_2. After a few minutes in LN_2 the plates were inserted diagonally into 20 cm segments of square brass channelling and lowered into a dry shipping dewar that had been previously cooled with LN_2. The dewar was either transported by van (from West Virginia) or shipped by air (from Colorado and Alaska) to the laboratory in Beltsville, Maryland. Upon reaching the laboratory, the samples were transferred to a LN_2 storage dewar where they remained for as long as nine months before being further prepared for observation with LTSEM.

Preparation for LTSEM examination

To prepare the samples for LTSEM observation, the plates were removed from the brass channelling in the storage dewar, attached to a precooled Oxford specimen holder that had been modified to accept the plate and placed in the slush chamber of an Oxford CT 1500 HF Cryotrans system that had been filled with LN_2. The holder was then attached to the transfer rod of the Oxford cryosystem, moved under vacuum into the prechamber for etching and/or sputter coating with Pt or Au/Pd and then inserted into a Hitachi S-4100 field emission SEM equipped with a cold stage that was maintained at -185^0 C. Accelerating voltages of 500 V to 10 kV were used to observe and record images onto Polaroid Type 55 P/N film.

RESULTS

Precipitated Snow

Precipitating samples of snowflakes that were collected, frozen, stored and transported from West Virginia were compared to earlier observations of samples that were collected and immediately examined at Beltsville (Wergin et al., 1995a). The results indicated that neither storage nor transport seemed to result in any significant "breakage", damage or loss of the sample. Although an occasional snow crystal could be observed with a broken arm, this type of damage could also result from collisions with other crystals as they descended through the atmosphere.

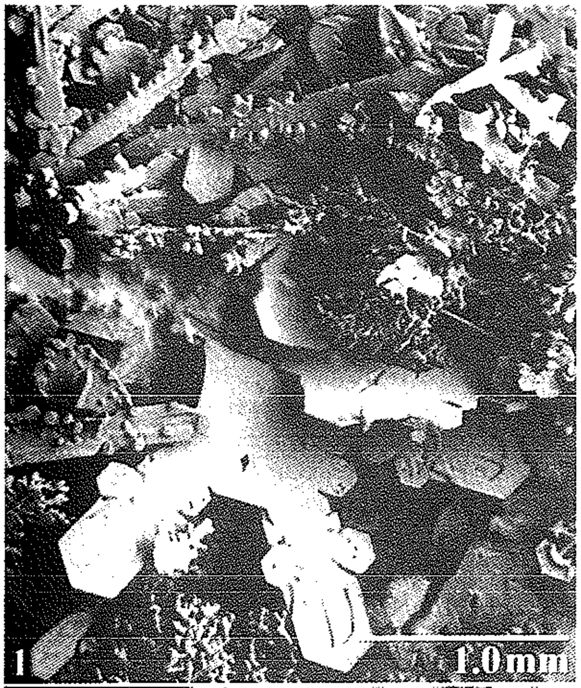
The precipitating snowflakes generally consisted of a mixture of several different types of snow crystals; however aggregations in which a single shape predominated could also be found (Figures 1 to 3). The snow crystals that aggregated to form snowflakes occurred as variations and/or combinations of needles, columns, plates and dendrites. The needles, which generally occurred as an accumulation of several cylindrical subunits, were 0.1 to 0.2 mm in diameter and commonly attained lengths of 1 to 4 mm (Figure 2). The subunits, which were less than a 0.1 mm in diameter, began and ended randomly along the length of the aggregation; consequently the aggregate tended to be somewhat irregular along its length.

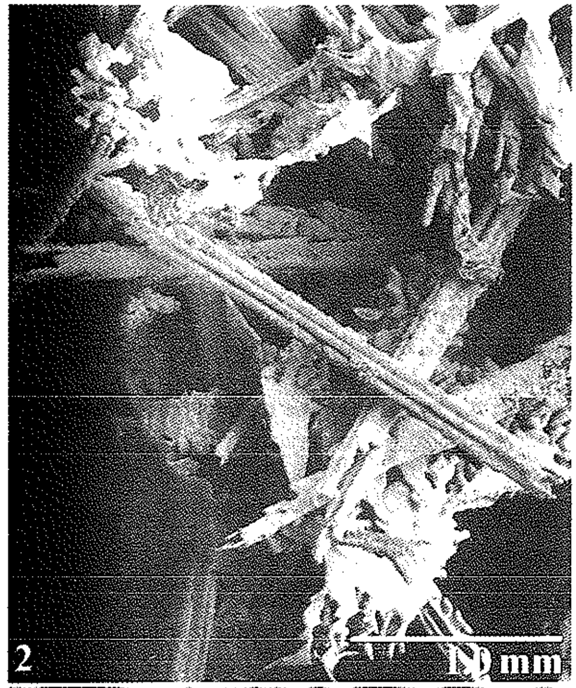
Columns did not have obvious subunits but rather occurred as single units that were usually shorter than the needles, frequently only 1 mm in length, but greater in diameter, about 0.5 mm. The ends of a column frequently appeared to be joined either with another column or capped with a flat hexagonal plate (Figure 3). The columns would seem to exhibit hexagonal symmetry in cross sections; however, the section would not appear as a regular hexagon because the six faces of the column were generally not flat. Instead each face was uniformly "stepped" into two or more levels that receded towards the center.

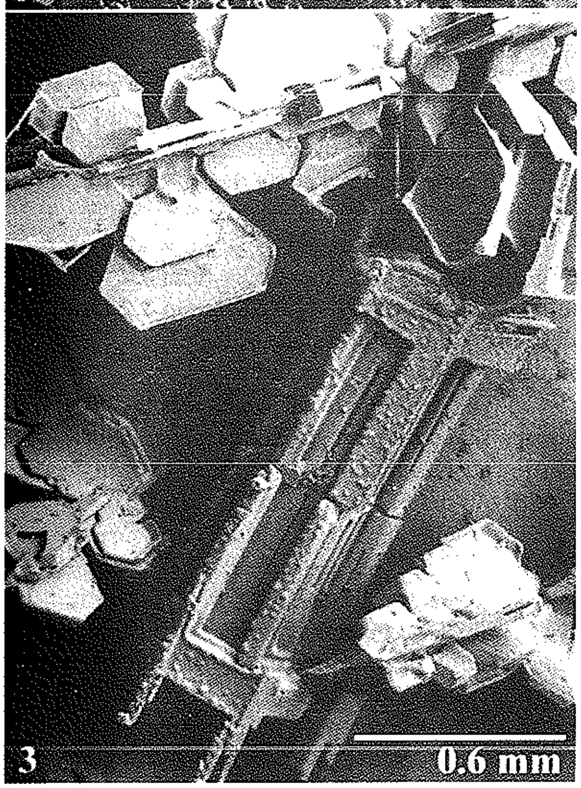
Hexagonal plates occurred as interconnected aggregations (Figure 3) but more often were observed as single crystals (Figure 4). Unlike the needles and the columns, growth of the hexagonal plate occurred along the "a" axes of the basal plane, rather than the vertical or "c" axis. Therefore, the plates tended to have a relatively large, flat surface area, measuring from 0.2 to 1.0 mm in width but were only 0.02 mm to 0.2 mm thick. In addition, the surface of the plates frequently had a slightly raised edge.

The dendritic form, which was the other common shape of snow crystal, occurred in numerous configurations. Like plates, growth was primarily in the basal plane; consequently, the crystal was relatively flat but had a large surface area (Figure 5). Dendrites normally had six arms that were often branched. Each arm of a dendritic crystal exhibited bilateral symmetry, which is accentuated by the presence of one or more pairs of branches that emanate from the main axis of the arm. A slightly raised and continuous midrib often extended along the center of the arm and continued into the branches.

In addition to the raised midribs, the surfaces of the arms and branches of the dendritic forms frequently exhibited shallow depressions (Figure 6). The depressions, which occurred as straight elongate channels, small hexagonal depressions as well as amorphic cavities, also exhibited bilateral distribution along the axis of the arms and branches. Because the presence and







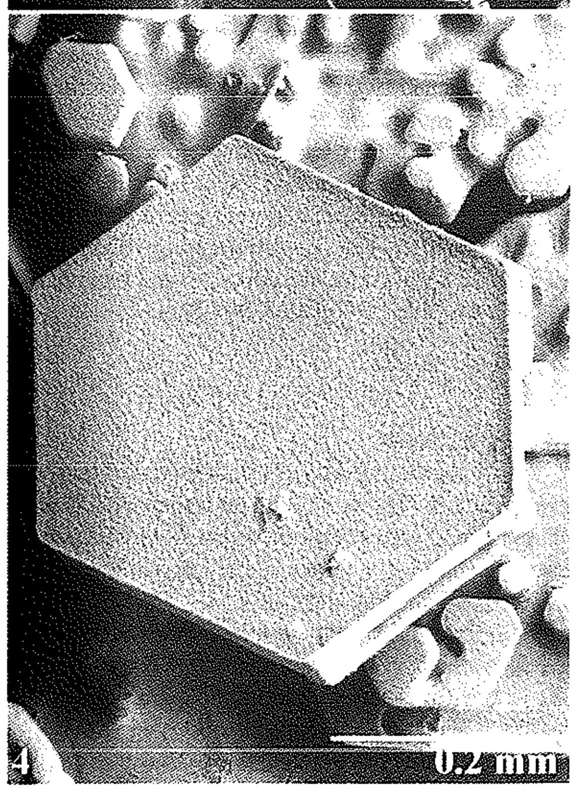
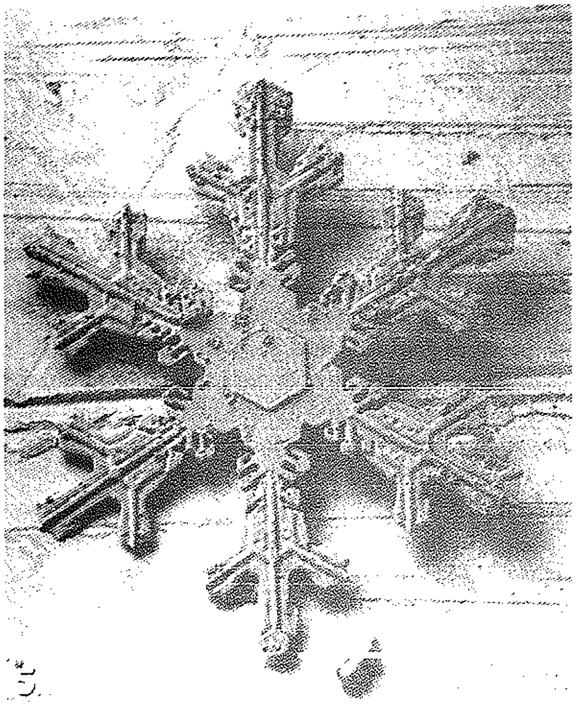


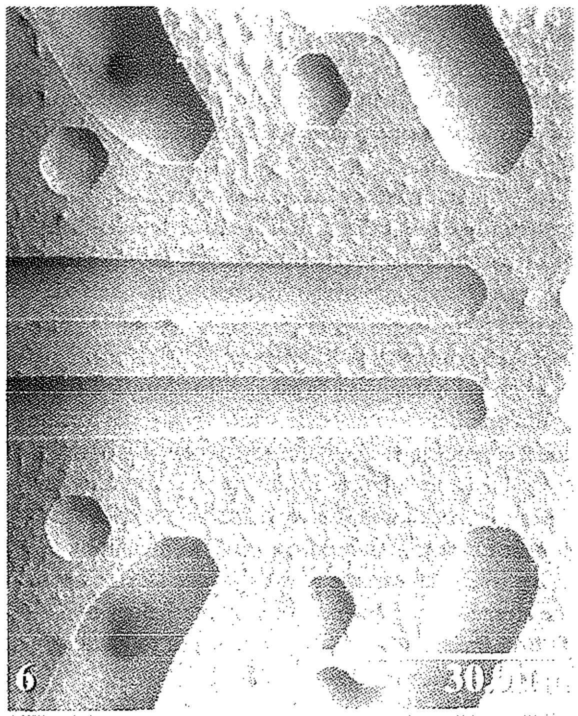
***Figure 1**. Snowflake composed of numerous snow crystals some of which are rimed. At time of collection air temperature was -1° C. Samples illustrated in Figures 1 through 9 were collected on Bearden Mountain near Davis, West Virginia, elevation 1150m ASL, transported by van in a low temperature shipping dewar to the laboratory and stored in LN_2 prior to imaging.*

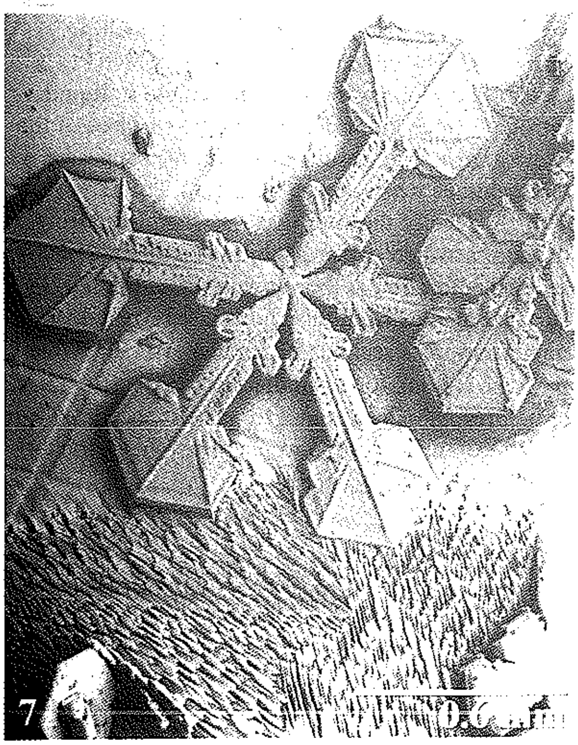
***Figure 2**. Snowflake having crystalline needles as the predominant shape. Sample collected at -2° C.*

***Figure 3**. Aggregation of hexagonal plates (upper portion of micrograph) and capped column (lower portion). Slight riming is apparent on surface of column. Collected at -3° C.*

***Figure 4**. Single hexagonal plate with slightly raised edge. Collected at -1° C.*







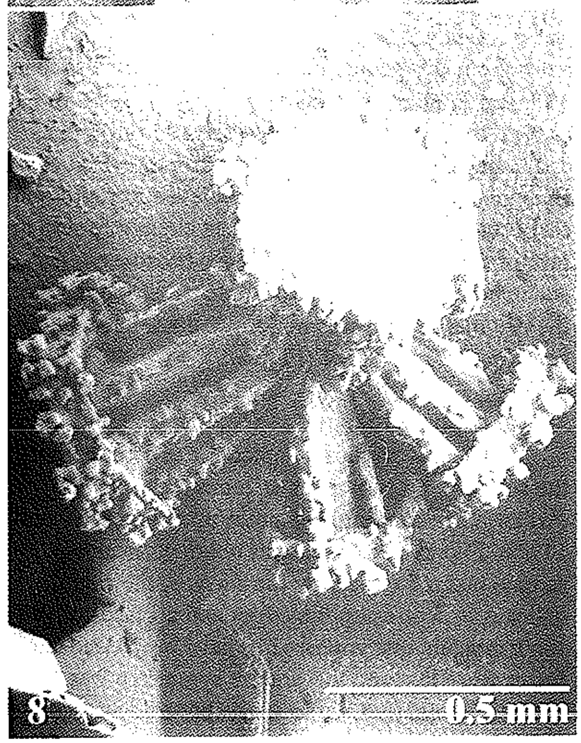


***Figure 5**. A hexagonal dendritic snow crystal with a simple hexagonal plate in the center. The dendritic arms, which are branched, contain pronounced ridges and small depressions. Sample was collected at -11° C.*

***Figure 6**. Portion of an arm of the stellar dendrite that contains cavities or negative crystals consisting of long grooves and small hexagonal depressions. Sample was collected at -8° C.*

***Figure 7**. Stellar dendritic crystal with plates at the ends of the branches. One branch appears to have been lost during descent; a small "stunted" arm has begun to form in its place (inset). Sample was collected at -8° C.*

***Figure 8**. Snow crystal consisting of capped bullets (modified columns) that exhibit surface riming. Collected at -12° C.*

distribution of ribs and cavities were fairly consistent in each of the six arms and their branches, these structural features reinforced the impression of hexagonal symmetry that was characteristic of this type of crystal.

Asymmetrical dendrites were also commonly encountered. In Figure 7, the dendrite has five arms that appeared identical having attained the same length, degree of branching and surface features; however, the sixth arm is "stunted". This type of asymmetry was believed to result from mechanical damage or breakage that resulted from collisions between crystals while they were forming and descending to the earth. Alternatively damage to a crystal could also result during the mounting and freezing procedures; however, in these cases the point of breakage would appear "fresh" and have a sharp irregular surface at the damage site. Because the stunted arm illustrated in Figure 7 does not exhibit these features, it was believed to have occurred under natural conditions.

Rime has been observed on all forms of snow crystals. The rime appeared as small amorphous crystalline deposits, measuring less than 50.0 µm in diameter, that apparently froze on the surface of the snow crystal as it passed through a dense field of supercooled water droplets (Figure 8). Examples of riming that were believed to represent early stages exhibited the droplets along one side or face of the crystal; the later stages became so encumbered with the microdroplets that the form of the original crystal was no longer distinguishable and resulted in graupel (Figure 9).

Metamorphosed Snow

Snow crystals sampled 5 to 10 cm below the surface of a snowpack at Jones Pass showed evidence of rounding and sintering (Figures 10 and 11). In Figure 10, which was obtained from a sample taken 5 cm below the surface, the fine delicate structures on the edges and surfaces of the snow crystals that appeared to have been dendritic forms were lost and the precise symmetry was absent. Alternatively, the arms appeared as sinuous extensions still radiating from a central plate. Samples taken 10 cm below the surface, exhibited further rounding as well as bonding or sintering between the adjacent crystals (Figure 11).

A second type of metamorphism occurred at even deeper levels. Figure 12 illustrates a snow crystal that was present in a sample taken from 80 cm below the surface. This large crystal appeared rounded along the lower half but sharply faceted on the opposite side. This mixed form (rounded and faceted) was believed to be an example of a crystal that resulted from rapid growth in which water vapor was evaporating from the rounded side and recondensing on the faceted side, a process that has been previously described by Seligman (1936).

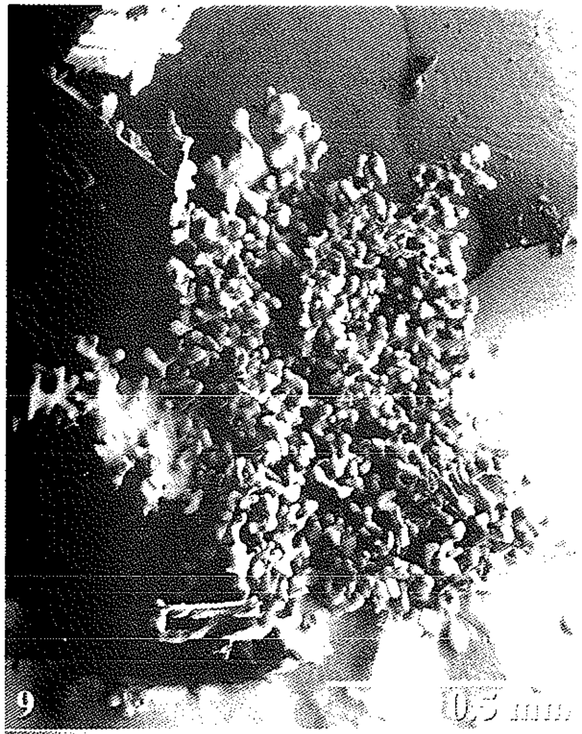
Samples taken from Ester Dome (Fairbanks) (Figure 13) and Prudhoe Bay (Figure 14), Alaska exhibited more advanced stages of crystal growth and faceting due to the high temperature gradients that were present at these sites. These crystals, which are commonly referred to as depth hoar, frequently measured 3 to 5 mm, tended to exhibit more pronounced faceting along a forming face and did not exhibit any pronounced sintering.

In June, the snowpack in Colorado was frequently subjected to successive melting and freezing cycles. This process resulted in the formation of clusters of snow grains that were well rounded, i.e., nearly spherical (Figure 15). The crystals were believed to be surrounded by a film of water that was percolating through the melting snowpack. The collection procedure, which consisted of plunge freezing the sample in liquid nitrogen, froze the water film to the surfaces of the snow grains. As a result, these samples appeared as large clumps when observed in the LTSEM.

One of the sites that was sampled during the summer melt season, exhibited a distinct pink to reddish coloration at the snow surface. Fracturing surface samples from this snowpack revealed numerous cross sections of circular structures that measured about 20 µm in diameter (Fig. 16). These structures, which appeared to be cells, occurred just below the surface of the water film. They probably corresponded to alga cells.

DISCUSSION

Our data suggest that LTSEM is a viable new technique for observing snow crystals in newly precipitated snow as well as for examining older snow grains that are obtained from excavated snowpits. Snow samples can be collected and frozen at remote locations and shipped to a laboratory for observation with this technique. Our study indicates that the LTSEM provides: 1) structural details of snow crystals that exceed those provided by the light microscope; 2) clear images of surface features, such as ridges and cavities, that are commonly present on dendrites and; 3) *in situ* observations of



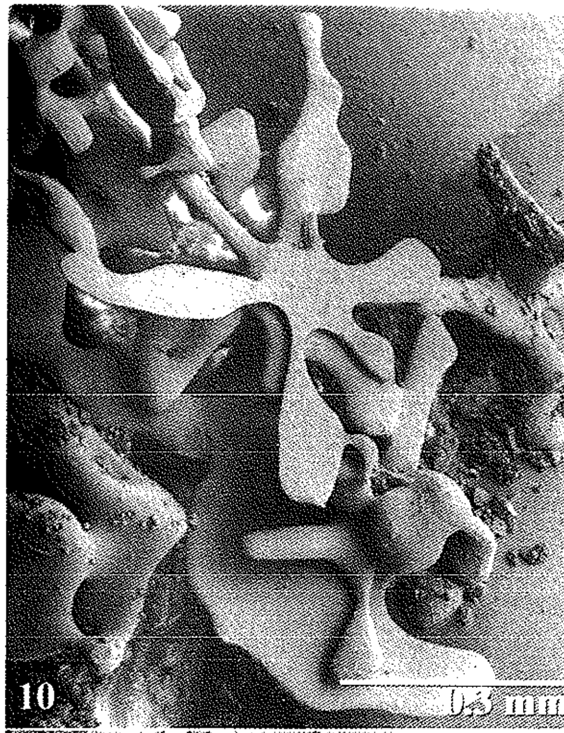
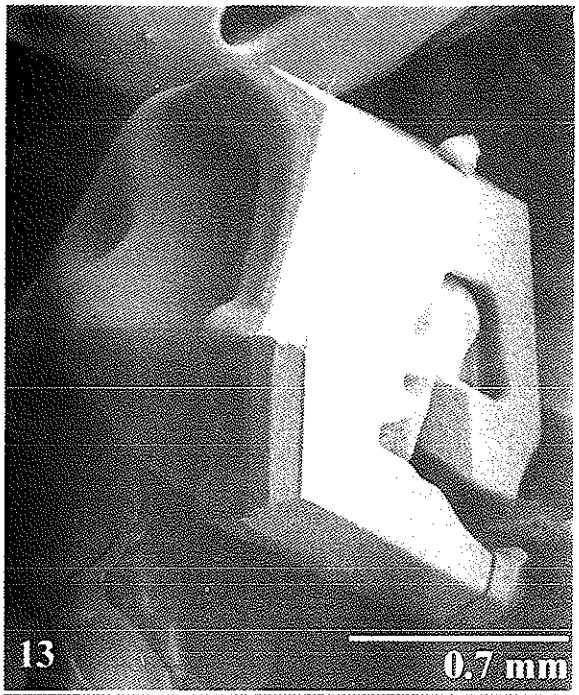
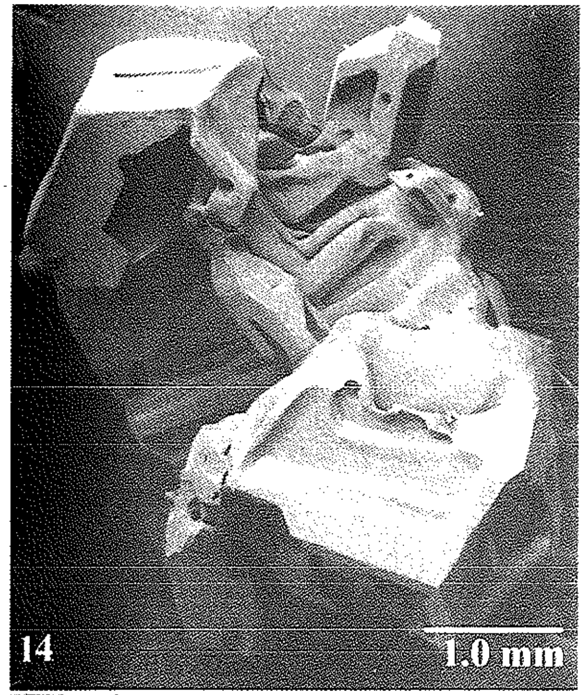
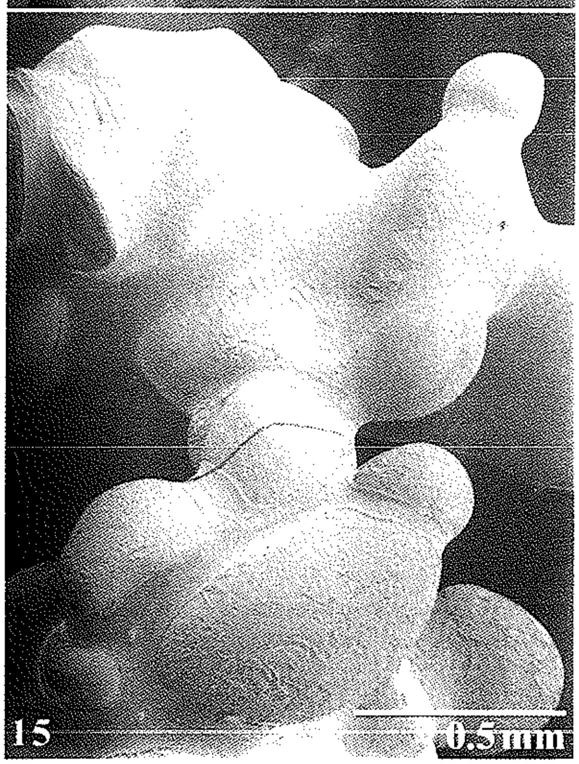


Figure 9*. Snow crystal (graupel) encumbered with supercooled water droplets. Sampled at -1°C.*
Figure 10*. Stellar dendrites, subjected to a low temperature-gradient. Samples collected 5 cm below the surface. Snowpit samples for Figs. 10 through 12 were obtained near Jones Pass, Colorado, elevation 3150m ASL, air temperature -6°C and shipped by air to the laboratory.*

Figure 11*. Snow crystals that appear to exhibit more advanced changes associated with low temperature-gradient metamorphism. The snow crystals show greater degree of rounding and bonding. Collected 10 cm below the surface.*
Figure 12*. Large crystal that exhibits rounding and faceting and is believed to result from rapid growth. Collected at 84 cm below the surface.*







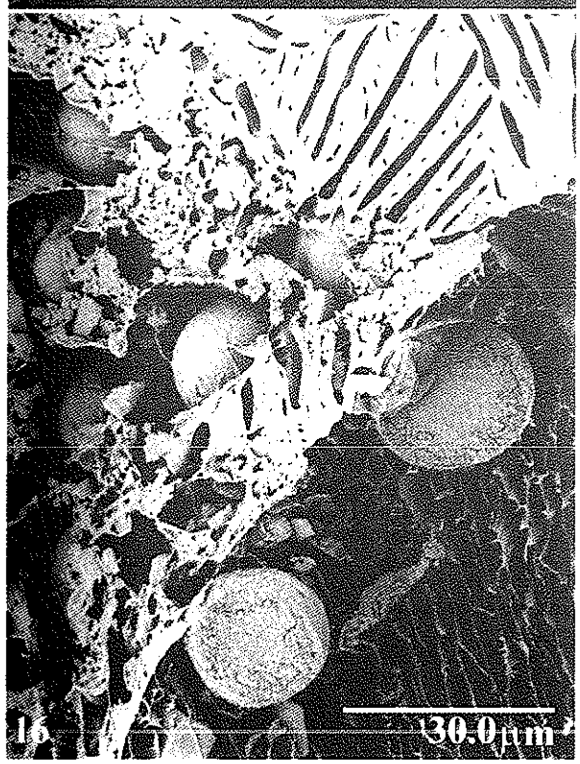


Figure 13. *Depth hoar collected 90 - 100cm below the surface of a 1m snowpit at Ester Dome, near Fairbanks, Alaska, elevation 700 m, air temperature* 2^{0} *C, shipped to the laboratory and stored in* LN_2.
Figure 14. *Large faceted depth hoar crystal collected from a glassy hard slab 25 cm above the ground surface at Prudhoe Bay Alaska.*

Figure 15. *Snow grains surrounded by a film of surface water. Samples in Figs. 15 and 16 were taken from Loveland Pass, Colorado, elevation 3600m ASL, air temperature* $+18^{0}C$.
Figure 16. *Melting snow that was fractured and etched to reveal small spherical bodies believed to be a green alga.*

microorganisms, such as algae, that can be found near the surface of melting snows.

Comparisons from Different Collection Sites

Our previous studies of snow illustrated the structural features of precipitated snow crystals that were collected at Beltsville and transferred directly to the laboratory for LTSEM (Wergin and Erbe, 1994a: 1994b; 1994c; Wergin et al., 1995a; 1995b). The results from these studies compared favorably with those of snow crystals that were collected and frozen in West Virginia, transported by vehicle over 200 miles to the laboratory and subsequently stored for several months in liquid nitrogen. In both instances, the integrity of the snow crystals was well preserved; sharp crystalline features of crystals collected in West Virginia did not appear to be affected by transport or storage.

Alternatively, the shapes of snow crystals that were collected from the two locations did vary because of differences in the cloud temperatures that occurred during crystal formation. Samples collected in Maryland were composed principally of needles and hexagonal plates while those from West Virginia exhibited dendritic forms and graupel. These observation would be consistent with those of other investigators who concluded that the shapes of newly formed snow crystals were predominantly influenced by the temperatures at which they developed (Nakaya, 1954; Hobbs, 1974; Mason, 1992).

Metamorphism of snow crystals can result from temperature gradients and melt-freeze cycles. Low temperature-gradient metamorphism, which occurs when snowpacks are subjected to temperature gradients of less than 10^0 C/m, leads to snow crystals that are sinuous or rounded and highly sintered (Armstrong, 1992). These features were well illustrated in the samples that were obtained from the upper layers of snowpack in Colorado (Figs. 10 and 11).

Samples that were collected from deeper layers of the snowpacks in Colorado and Alaska contained crystals known as depth hoar. These crystals, whose development is associated with high temperature gradients, i. e. temperatures greater than 10^0 C/m, are characterized by their large sizes (several mm or more), highly developed facets, and lack of sintering or bonding to adjacent crystals (Armstrong, 1992). The greater depth of field and resolution of the LTSEM provide images of these crystals having focus and clarity that far exceed that which can be achieved using photomacrography.

Under spring conditions, spherical snow crystals are bonded in clusters; the strength of the bonds is affected by the amount and status of water that percolates through the snow pack (McClung and Schaerer, 1993). These types of formations were evident in samples from the surface of the snowpack that was collected from Colorado in July 1995. The sample illustrated in Figure 15 was obtained under melt conditions; however, plunging the snow into liquid nitrogen froze the percolating surface water and probably simulated the refreezing that often occurs at night when temperatures fall below freezing.

Studies on the structure and metamorphism of snow crystals have several important economic and safety considerations. Snow may cover up to 53% of the land surface in the Northern Hemisphere (Foster and Rango, 1982) and up to 44% of the world's land areas at any one time. The winter snowpack supplies at least one-third of the water that is used for irrigation and the growth of crops worldwide (Gray and Male, 1981). In the western U. S., at least 80% of the water that is used for irrigation comes from snowmelt (Brown, 1949). Therefore, calculations on the quantity of water that is stored in the snowpack are extremely important for predicting the amount of water that ultimately will reach reservoirs and will be available for agricultural purposes during the following growing season. Castruccio et al. (1980) estimated that improving predictions by 1% could result in a $38 million benefit for states in the western U.S.A. Today this figure has probably doubled as a result of inflation.

To predict areal water in the snowpack, Rango et al. (1989) and Goodison et al. (1990) have tested passive microwave data for estimating snow water equivalent. Unfortunately the sizes, shapes and packing of the snow crystals or grains that make up the snowpack greatly affect these estimates. In the future, more accurate information on the sizes, shapes and arrangement of snow crystals will be used in developing new radiative transfer models to better explain microwave scattering in the snowpack and thereby assess the water equivalent that is stored.

ACKNOWLEDGEMENTS

The authors thank Christopher Pooley for converting the SEM negatives to the digital images that were used to illustrate this study. We thank Richard Armstrong and Rod Newcomb for assistance in selecting appropriate snowpits in

Colorado and Anne Nolin and Beth Boyer for assisting in data collection at Loveland Pass. We were also assisted by Dorothy Hall, Jim Foster and Carl Benson in the snowpits near Fairbanks, Alaska. This investigation was partially funded by the NASA Goddard Space Flight Center.

REFERENCES

Armstrong, R.L. (1992) The mountain snowpack: pp. 47-83 in: *The Avalanche Book*, ed. by B.R. Armstrong and K. Williams. Colorado Geological Survey, Denver.

Bentley, W.A. and Humphreys, W.J. (1931) *Snow crystals*. McGraw-Hill Book Co. Inc., New York, 227 pp.

Blanchard, D.C. (1970) Wilson Bentley, the snowflake man, *Weatherwise*, 23, 260-69.

Brown, A.H. (1949) Sno-cats mechanize Oregon snow survey, *National Geographic*, 96, 691-710.

Castruccio, P.A., Loats, H.L., Lloyd, D. and Newman, P.A.B. (1980) Cost/benefit analysis for the operational applications of satellite snowcover observations (OASSO): pp. 239-254 in: *NASA Conf Publication 2116*, ed. by R. Rango and R. Peterson. Sci. Tech. Info. Off.

Foster, J.L. and Rango, A. (1982) Snow cover conditions in the northern hemisphere during the winter of 1981, *J. Climatology*, 20, 171-183.

Goodison, B., Walker, A.E. and Thirkettle, F. (1990) Determination of snow water equivalent on the Canadian prairies using near real-time passive microwave data: pp. 297-316 in *Proc. Workshop on Application of Remote Sensing in Hydrology*. National Hydrology Research Institute, Saskatoon, Canada.

Gray, D.M. and Male D.H. (1981) *Handbook of Snow: Principles, processes, management and use*. Pergamon Press, Ontario, 776 pp.

Hobbs, P.V. (1974) *Ice physics*. Clarendon Press, Oxford, 837 pp.

Mason, B.J. (1992) Snow crystals, natural and man made, *Contemporary physics*, 33, 227-243.

McClung, D. and Schaerer, P. (1993) *The avalanche handbook*. The Mountaineers, Seattle, 271 pp.

Nakaya, U. (1954) *Snow Crystals*. Harvard University Press, Cambridge, 510 pp.

Rango, A., Martinec, J., Chang, A.T.C. and Foster, J.L. (1989) Average areal water equivalent of snow in a mountain basin using microwave and visible satellite data, *I.E.E.E. Trans. Geoscience and Remote Sensing*, 27, 740-745.

Rango, A., Wergin, W.P. and Erbe, E.F. (1996a) Snow crystal imaging using scanning electron microscopy: I. Precipitated snow, *Hydrological Sciences* 41, 219-233.

Rango, A., Wergin, W.P. and Erbe, E.F. (1996b) Snow crystal imaging using scanning electron microscopy: II. Metamorphosed snow, *Hydrological Sciences* 41, 235-250.

Seligman, G. (1936) *Snow structure and ski fields*. 555, Macmillian, London.

Wergin W.P. and Erbe, E.F. (1991) Increasing resolution and versatility in low temperature conventional and field emission scanning electron microscopy. *Scanning Microscopy*, 5, 927-936.

Wergin, W.P. and Erbe, E.F. (1994a) Can you image a snowflake with an SEM? Certainly! *Proc. Royal Microsc. Soc.*, 29, 138-140.

Wergin, W.P. and Erbe, E.F. (1994b) Snow crystals: Capturing snowflakes for observation with the low temperature scanning electron microscope, *Scanning*, 16, IV88-IV89.

Wergin, W.P. and Erbe, E.F. (1994c) Use of low temperature scanning electron microscopy to examine snow crystals. *Proc. 14th Int. Cong. Electron Microsc.*, 3B, 993-994.

Wergin, W.P., Rango, A. and Erbe, E.F. (1995a) Observations of snow crystals using low-temperature scanning electron microscopy, *Scanning*, 17, 41-49.

Wergin, W.P., Rango, A. and Erbe, E.F. (1995b) Three dimensional characterization of snow crystals using low temperature scanning electron microscopy, *Scanning*, 17, V29-V30.

Wergin, W.P., Rango, A. and Erbe, E.F. (1996) Metamorphism of snowflakes as observed with low-temperature scanning electron microscopy. *Scanning*, 18, 199-200.

Wolff, E.W. and Reid, A.P. (1994) Capture and scanning electron microscopy of individual snow crystals, *J. Glaciology*, 40, 195-197.