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To cite this article: A. RANGO , W. P. WERGIN & E. F. ERBE (1996) Snow crystal imaging using scanning electron microscopy: II. Metamorphosed snow, Hydrological Sciences Journal, 41:2, 235-250, DOI: [10.1080/02626669609491495](https://doi.org/10.1080/02626669609491495)

To link to this article: <https://doi.org/10.1080/02626669609491495>



Published online: 24 Dec 2009.



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## **Snow crystal imaging using scanning electron microscopy: II. Metamorphosed snow**

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**Abstract** Low-temperature scanning electron microscopy (SEM) was used to observe metamorphosed snow crystals and grains obtained in the field. Metamorphosed snow was obtained from seasonal snowpacks in the Colorado Rocky Mountains and in Alaska. The snow samples obtained in snowpits were mounted on modified SEM stubs, frozen in liquid nitrogen, transported in Dewar flasks to the SEM facility, sputter coated with platinum, and imaged with an electron beam. Analysis of a representative set of snow samples revealed examples of metamorphosed stellar crystals, fine snow grains with sintering, rounded and faceted crystals, several types of depth hoar, rounded grains of melt metamorphism, and an ice lens. Some of the crystals exhibiting both rounding and facets indicated that both equitemperature and temperature gradient metamorphism influenced the snowpack. The SEM methods developed are operable in the field and can be used to quantify three-dimensionally size, shape and bonding characteristics of crystals. SEM appears to have direct application for better understanding of snow crystal metamorphism and snowpack processes, increasing knowledge of conditions leading to avalanche formation, and improving modelling of the transfer of microwave energy from the ground surface through the snowpack for eventual estimation of snow water equivalent.

### **Images de cristaux de neige obtenues par microscopie électronique à balayage: II Neige transformée**

**Résumé** La microscopie à balayage à basse-température a été utilisée pour observer des cristaux de neige en cours de transformation recueillis directement sur le terrain. La neige en cours de transformation a été prélevée dans les apports hivernaux des Montagnes Rocheuses au Colorado et en Alaska. Les échantillons de neige obtenus dans des forages réalisés dans la couche de neige ont été montés sur des supports pour microscope à balayage, plongés dans l'azote liquide, transportés dans des vases Dewar au centre de microscopie, recouverts d'un film de platine, et observés sous un faisceau d'électrons. L'observation de plusieurs cristaux de neige transformé a révélé l'existence de cristaux stellaires modifiées, de délicates structures de cristaux ayant été réchauffés sans fondre, de cristaux arrondis ou anguleux ainsi que d'une forme de givre profond. Quelques uns des cristaux présentant des facettes et des arrondis indiquent qu'existent la fois des températures stables et un gradient de température dû au métamorphisme affectant l'amas de neige accumulé. Les méthodes d'observations en

microscopie à balayage que nous avons développées sont applicables sur le terrain et permettent d'évaluer quantitativement la taille, la forme et les liaisons des cristaux de neige. Cette technique semble avoir de grandes potentialités pour mieux comprendre la transformation des cristaux de neige, pour accroître notre connaissance sur les conditions conduisant à la formation des avalanches et pour améliorer notre compréhension du transfert de l'énergie de micro-onde du sol à travers le manteau neigeux accumulée en vue d'éventuelles estimations de la quantité d'eau disponible.

## INTRODUCTION

Because the water supply of most high mountain regions is dominated by snow-melt runoff (Goodell, 1966), estimating the quantity of water that is present in the winter snowpack is an extremely important forecast activity that attempts to estimate the amount of streamflow that will be available for the subsequent growing season. Ground surveys of the snowpack provide point measurements that can be used to estimate the snowpack volume; however, in this time of constrained budgets, the number of such point measurements is being reduced. In remote regions, it is extremely difficult to obtain any ground surveys, and reliable areal estimates of the snow water equivalent are presently non-existent. In attempts to provide better data, remote sensing approaches using passive microwave data have been successfully tested in certain situations to calculate areal water equivalent of the snowpack prior to melting (Rango *et al.*, 1989; Goodison *et al.*, 1990). Unfortunately, these estimates can be easily confounded by the variability in the sizes and shapes of the snow crystals or grains in the snowpack. In a companion paper (Rango *et al.*, 1996), the capture of precipitated or falling snow crystals for electron microscope imaging was described; however, modified sampling techniques are necessary to image snow crystals or grains in the snowpack.

After falling snow reaches the surface, changes in the fine structure of the snow crystal begin and a second type of snow results. LaChapelle (1969) distinguishes between precipitated snow and metamorphosed snow. Equi-temperature (equilibrium) metamorphism will begin breaking down the fine crystal structure of new snow through vapour transfer so that small snow grains are formed in the place of crystals (Colbeck, 1983). If strong temperature differences between the ground and snow surfaces are established, temperature gradient (kinetic growth) metamorphism results and new types of crystals form in the snowpack (Colbeck, 1983). If subjected to steep temperature gradients ( $> 10^{\circ}\text{C m}^{-1}$ ) (Armstrong, 1986) for extended time periods, these new crystals can be much larger than the original precipitated snow crystals. Later in the snow season, melt-freeze metamorphism will cause major changes in snow grain texture once again (Colbeck, 1983). As a result of melt-freeze metamorphism, clusters of rounded grains form with bonds that vary from fairly strong to nearly cohesionless depending on the amount of liquid water present.

Classification systems of snow on the ground have been widely accepted and used (ICSI, 1954; Sommerfeld, 1969; LaChapelle, 1969; Sommerfeld & LaChapelle, 1970; Colbeck *et al.*, 1990). Observation and permanent recording

of the various categories of snow on the ground have been difficult. Of the approaches described by LaChapelle (1969), cameras (photomacrography) have been used more than microscopes (photomicrography) for observing snow crystals in the snowpack. The photographs of snow crystals in the snowpack by LaChapelle (1969) were taken with 35 mm cameras using reflected, transmitted and low oblique transmitted illumination (sometimes with additional transmitted light). The same problems associated with imaging precipitated snow crystals (changes in crystal form due to outside heat and humidity) are true of metamorphosed snow crystals. It was of great interest to see if the technology that was previously developed for precipitated snow (Wergin & Erbe, 1994; Wergin *et al.*, 1995; Rango *et al.*, 1996) could be adapted for imaging snow crystals in the snowpack. If successful, this method of grain size and shape characterization could ultimately be used for improved microwave modelling of the snowpack.

The same techniques of scanning electron microscopy (SEM) described by Rango *et al.* (1996) for precipitated snow crystals are applicable with modification to the analysis of snow crystals from the snowpack. The major changes involve the method of sampling the snow crystals and the subsequent transfer to the SEM facility. In order to test the methodology, snow crystals were sampled from seasonal snowpacks in the Colorado Rocky Mountains, USA, in February, March and July 1995. Snowpits were dug near Jones Pass, Eldora, Berthoud Pass and Loveland Pass, Colorado and samples from the various layers were collected for SEM analysis. Additional snow crystal samples from snowpits near Fairbanks and on the North Slope, Alaska, USA, were acquired in April 1995.

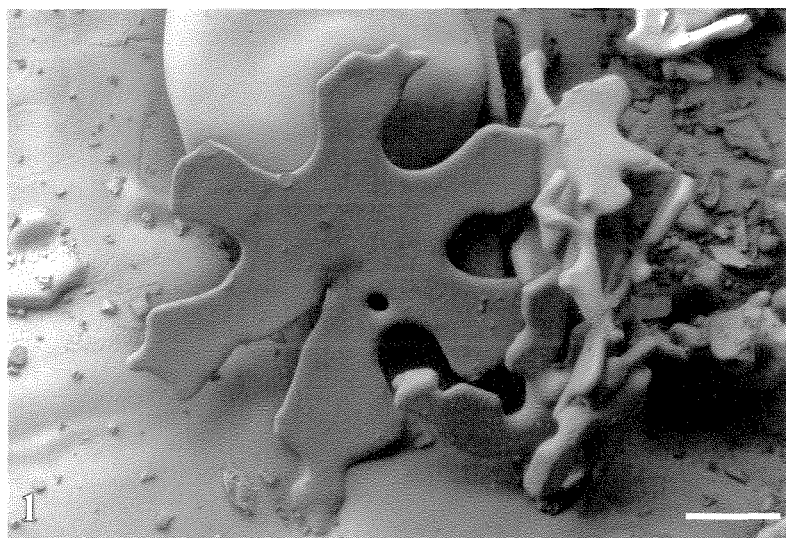
## MATERIALS AND SUPPLIES

Much of the materials and methods described by Rango *et al.* (1996) is applicable to metamorphosed snow crystals except that everything had to be done in the environment of a snowpit. The sample holder was covered with a thin layer of methyl cellulose solution (Tissue Tek) and placed near the pit wall. Snow crystal samples from selected layers of the snowpack were gently dislodged from the pit wall and collected on the surface of the sample holder. After obtaining a visible accumulation of snow crystals in this manner, the holder was plunged into a styrofoam reservoir containing liquid nitrogen (LN<sub>2</sub>) at  $-196^{\circ}\text{C}$  and transferred to a square profile brass tube for low temperature storage during transport. Once filled with sample holders, the brass tubes were placed in dry transport Dewar flasks at LN<sub>2</sub> temperatures and transferred by ground and air to the Beltsville laboratory for analysis. The samples were in transit to Beltsville from 1-7 days, but the Dewar flasks maintained a temperature of  $-196^{\circ}\text{C}$  and the samples generally appeared to be undisturbed upon observation. It is estimated that the samples would be preserved for up to one month before additional LN<sub>2</sub> would have to be added to maintain the temperature level.

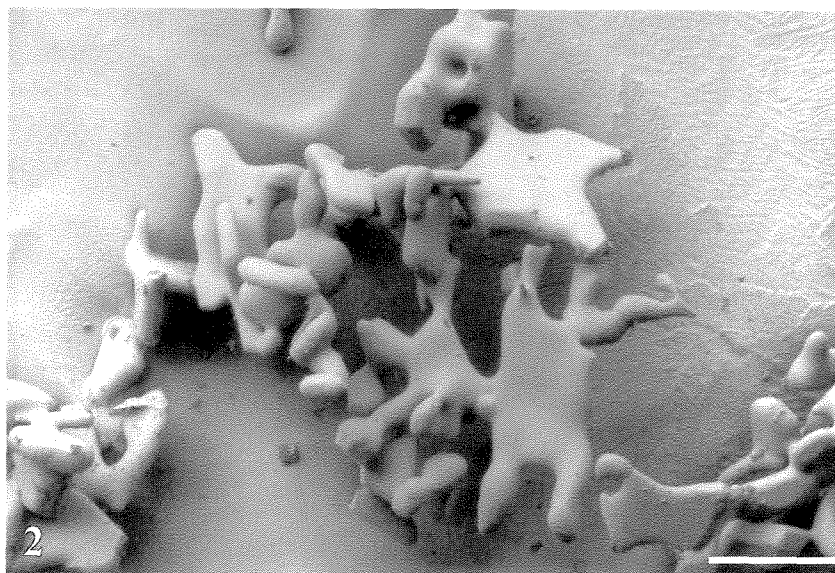
After the metamorphosed snow crystal samples arrived in Beltsville they were treated like precipitated snow crystals for analysis by SEM (Rango *et al.*, 1996). Thus, the major differences between the precipitated and metamorphosed snow crystal analyses were: (i) in collection of snow crystals falling onto a holder for the former versus snow crystals dislodged onto the holder in the snowpit; and (ii) long distance transport of the snowpit snow crystals.

## RESULTS

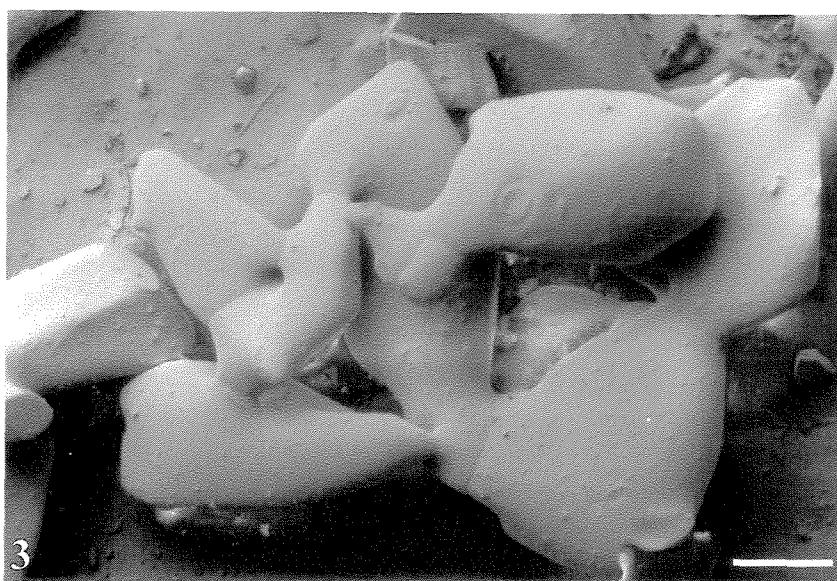
The process by which new snow crystals are transformed after they fall on a seasonal snowpack can be rapid and dramatic. Initial equitemperature metamorphism causes the fine structure of the new ice crystals to be lost in favour of rounded grains, illustrated in Figs 1-3 from Jones Pass (3170 m a.s.l.) An early stage of this metamorphism in the surface layer of the snowpack is illustrated by the distorted stellar crystal (1.2 mm in diameter) in Fig. 1 where the sharp edges of the original crystal have been rounded. The continuation of this process results in many small grains having only a vague resemblance to the original snow crystal shapes (Fig. 2). The crystal size in Fig. 2 is generally in the 0.25-0.5 mm range and is from a layer in the snowpack just beneath the surface layer. During this equitemperature process, bonding or sintering between snow grains can also take place (Fig. 2) as a result of a mass transfer from convex to concave surfaces.



**Fig. 1** Early stage of equitemperature metamorphism of a stellar snow crystal (on the way to becoming fine grained snow) obtained in the upper layer of a seasonal snowpack at Jones Pass, Colorado. (Collected at a snowpack temperature of  $-6^{\circ}\text{C}$ ; stored for 10 days in a Dewar flask; magnification  $65\times$ ; bar = 0.2 mm).



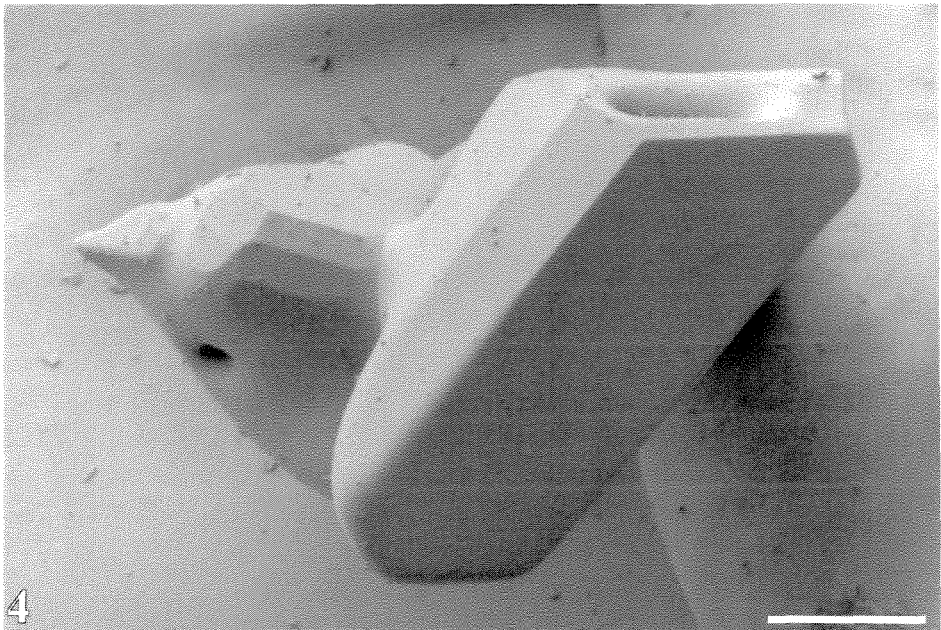
**Fig. 2** Later stage of equitemperature metamorphism where the snow grains still bear a faint resemblance to the original new snow crystals in the upper layer of the snowpack at Jones Pass, Colorado. Bonding or sintering has taken place between the grains. (Collected at a snowpack temperature of  $-6^{\circ}\text{C}$ ; stored for 10 days in a Dewar flask; magnification  $90\times$ ; bar = 0.2 mm).



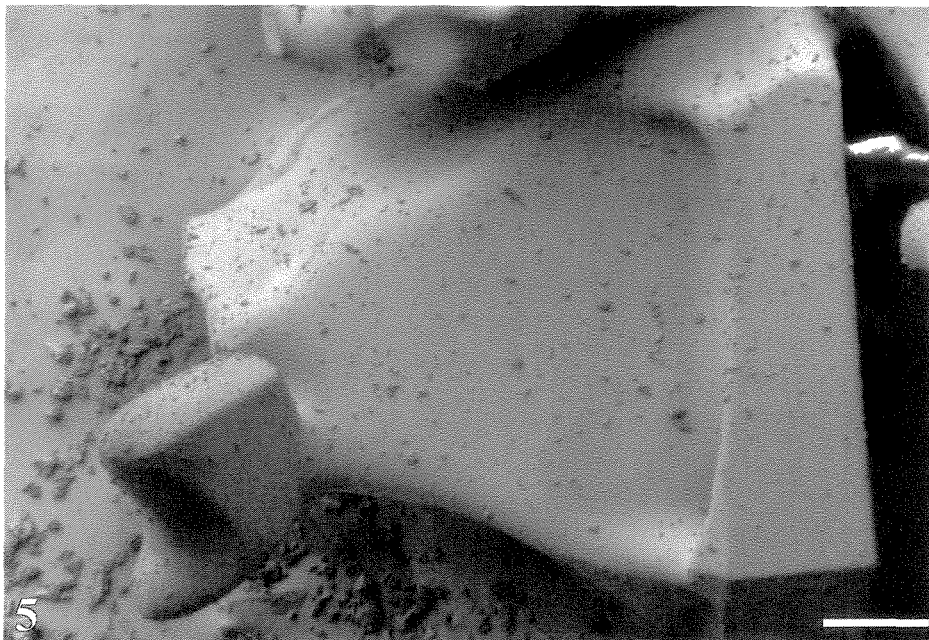
**Fig. 3** Rounded, irregular grains from intermediate layer of the seasonal snowpack at Jones Pass, Colorado, giving evidence of continuing equitemperature metamorphism. (Collected at a snowpack temperature of  $-6^{\circ}\text{C}$ ; stored for 15 days in a Dewar flask; magnification  $60\times$ ; bar = 0.2 mm).

If equitemperature metamorphism continues, a predominance of rounded grains, gradually increasing in size, will result. Figure 3 shows a sample of grains from an intermediate layer of the dry snowpack at Jones Pass where equitemperature metamorphism had been active. The crystal shape is irregular, with rounding the predominate feature, and the grain size is 0.5-0.75 mm.

When a strong temperature difference between the ground surface and the top of the snowpack exists, temperature gradient metamorphism causes a more rapid growth of faceted crystals in the snowpack. At temperature gradients of less than  $10^{\circ}\text{C m}^{-1}$ , mixed forms of rounded and faceted crystals result. Figure 4 shows a pair of rounded crystals with facets about 1 mm in length that are also bonded together. This crystal was obtained from the bottom layers of the Jones Pass snowpit. Both equitemperature (rounding) and temperature gradient (faceting) metamorphism probably influenced the crystal in Fig. 4. Under temperature gradients at or above  $10^{\circ}\text{C m}^{-1}$ , the more classic cup-shaped crystal may result. Figure 5 shows a cup-shaped crystal with some facets that is almost 2 mm in length. This crystal, which appears to be hollow, seems to be a form of depth hoar, but without the characteristic stepped pattern. It was obtained from the bottom layer of a snowpit on a north-facing slope at Eldora (2835 m a.s.l.).



**Fig. 4** Faceted and rounded snow crystals, one with a hollow central area, obtained from a lower intermediate layer of a seasonal snowpack at Jones Pass, Colorado. This crystal probably grew at an intermediate growth rate under the influence of temperature gradient metamorphism and equitemperature metamorphism at different times. (Collected at a snowpack temperature of  $-6^{\circ}\text{C}$ ; stored for 10 days in a Dewar flask; magnification  $100\times$ ; bar = 0.2 mm).



**Fig. 5** Faceted, cup-like crystal obtained from the bottom layer of a seasonal snowpack at Eldora, Colorado. This crystal probably grew at a relatively high growth rate under the influence of temperature gradient metamorphism. (Collected at a snowpack temperature of  $-2^{\circ}\text{C}$ ; stored for 10 days in a Dewar flask; magnification  $50\times$ ; bar = 0.2 mm).

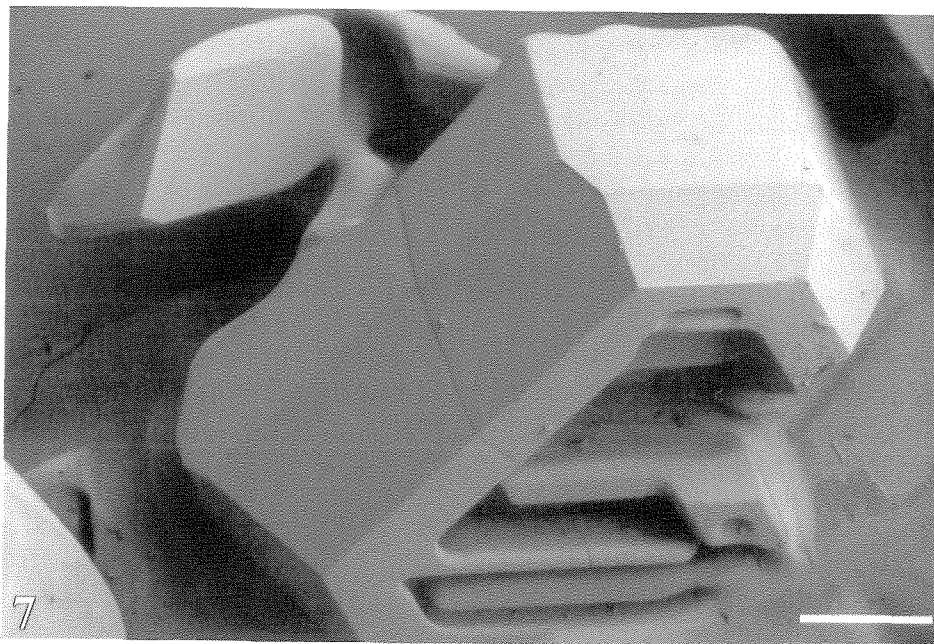
Additional depth hoar crystals, with the stepped pattern in evidence, were obtained at some of the other snowpits. Many of these crystals appear to be hollow with a complex variety of faceted forms. Figure 6 comes from the bottom layer of the snowpack at Berthoud Pass (3355 m a.s.l.) in March 1995. The layered or stepped crystal form is very evident. The horizontal dimension is about 3.25 mm. The top of the crystal appears to be fractured, possibly as a result of inserting this high-profile crystal into the square brass storage tube for transport. Figure 7, from a middle layer of the snowpack at Ester Dome (700 m a.s.l.) near Fairbanks, Alaska, shows the hollow, stepped, and intricate angular nature of depth hoar. Figure 8 is from a lower layer of the Ester Dome snowpit and also depicts the hollow and stepped nature of the depth hoar. Figure 9 shows a multi-layered crystal from the bottom of the Ester Dome snowpack which exceeds 4 mm in length. Figure 10 depicts a depth hoar crystal from the North Slope near Prudhoe Bay, Alaska (20 m a.s.l.).

During the spring melt season, the snowpack becomes isothermal and rounded grains become the dominant form 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. The

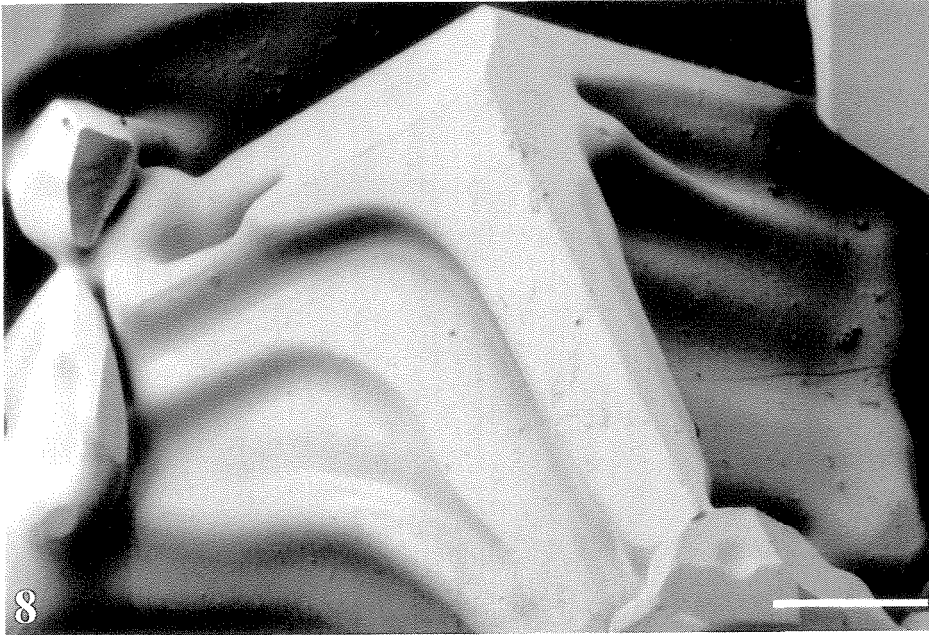




**Fig. 6** Layered crystal indicative of depth hoar from the bottom layer of the Berthoud Pass, Colorado snowpack. (Collected at a snowpack temperature of  $-3^{\circ}\text{C}$ ; stored for 5 days in a Dewar flask; magnification  $30\times$ ; bar = 0.4 mm).



**Fig. 7** Intricate angular and stepped crystal from Ester Dome, Alaska, illustrating the hollow nature of depth hoar. This sample was obtained from a middle layer of the snowpack. (Collected at a snowpack temperature of  $-3^{\circ}\text{C}$ ; stored for 15 days in a Dewar flask; magnification  $30\times$ ; bar = 0.5 mm).



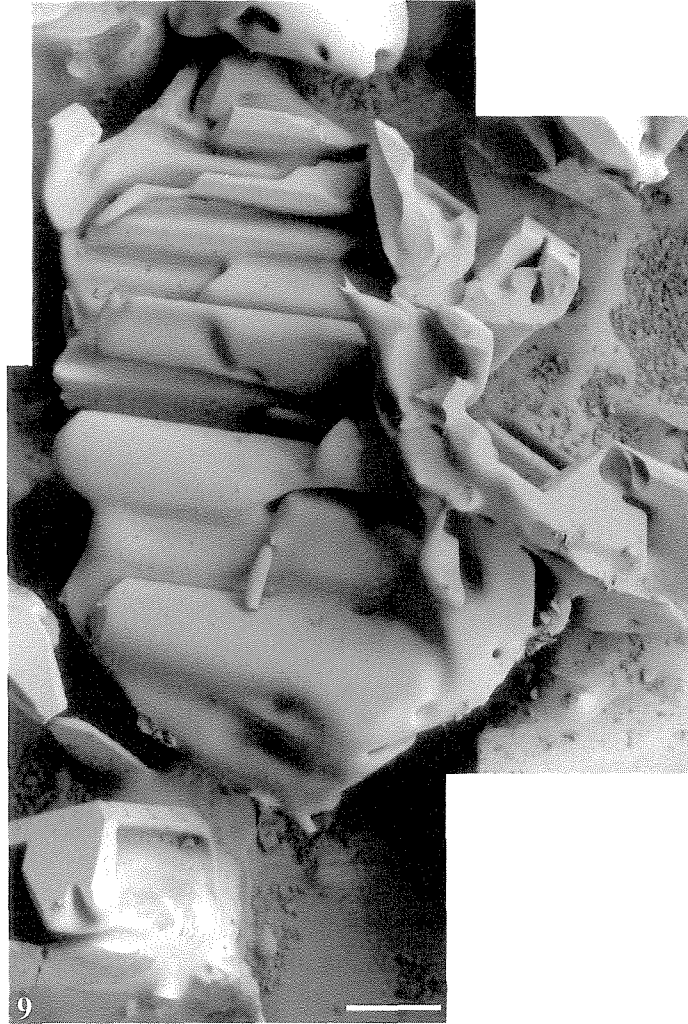
**Fig. 8** Depth hoar crystal from a lower layer of the Ester Dome, Alaska snowpack. (Collected at a snowpack temperature of  $-2^{\circ}\text{C}$ ; stored for 15 days in a Dewar flask; magnification  $45\times$ ; bar = 0.4 mm).

melting snowpack at Loveland Pass (3625 m a.s.l.) was sampled in July 1995. Figure 11 is taken from the middle part of the Loveland Pass snowpack which, upon qualitative inspection, did not appear to be as saturated with meltwater as the surface layers. As such, the reasoning of Colbeck (1979) can be used to explain why these grains in the middle of the snowpack are bonded and rounded but not spherical. The individual grains range from 0.5-1.5 mm in size. Near the surface the greater amount of liquid water holding the more spherical grains in a cluster is evident (Fig. 12). In Fig. 12 the grains range from 0.2-0.7 mm in size. Figure 13 also comes from the surface layer of the Loveland Pass snowpack. The individual grains vary from 0.2-0.8 mm in size, but the cluster is much larger than Fig. 12. In fact, the SEM revealed that this was a continuous cluster of about 7 by 14 mm.

Figure 14 shows a network of surface layer clusters with significant void space between the clusters. A comparative micrograph shown in Fig. 15 depicts similar voids filled with water and frozen as an ice lens in the bottom portion of the Loveland Pass snowpit. It appears to be a solid cross section of ice with imbedded grains of up to 0.8 mm in size.

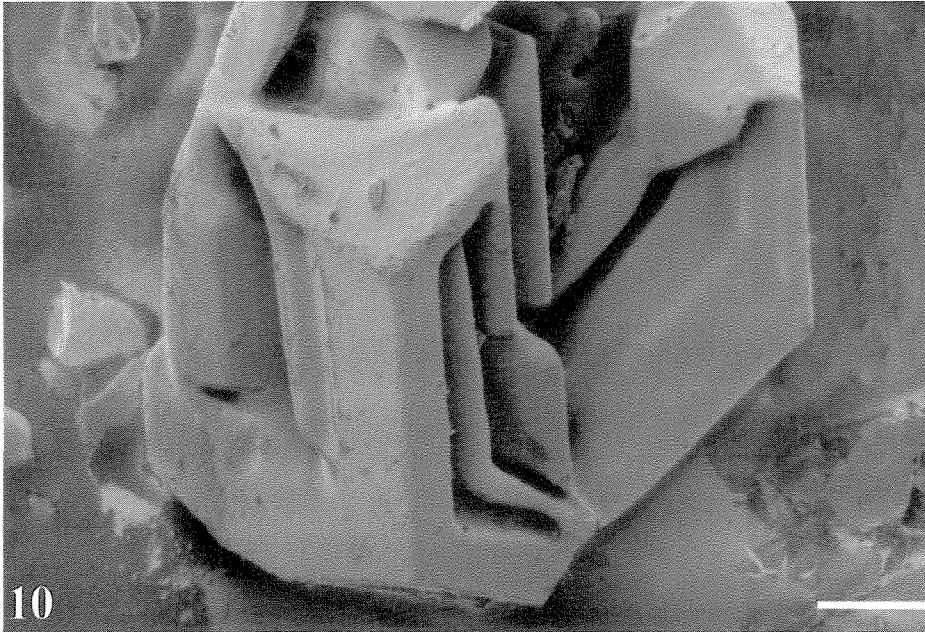
## DISCUSSION

In Rango *et al.* (1996), low temperature scanning electron microscopy was shown to solve many of the problems of photomicrography and photomacro-



**Fig. 9** Composite of three SEM images of depth hoar from the bottom layer of the Ester Dome, Alaska snowpack. (Collected at a snowpack temperature of  $-1.5^{\circ}\text{C}$ ; stored for 21 days in a Dewar flask; magnification  $30\times$ ; bar = 0.5 mm).

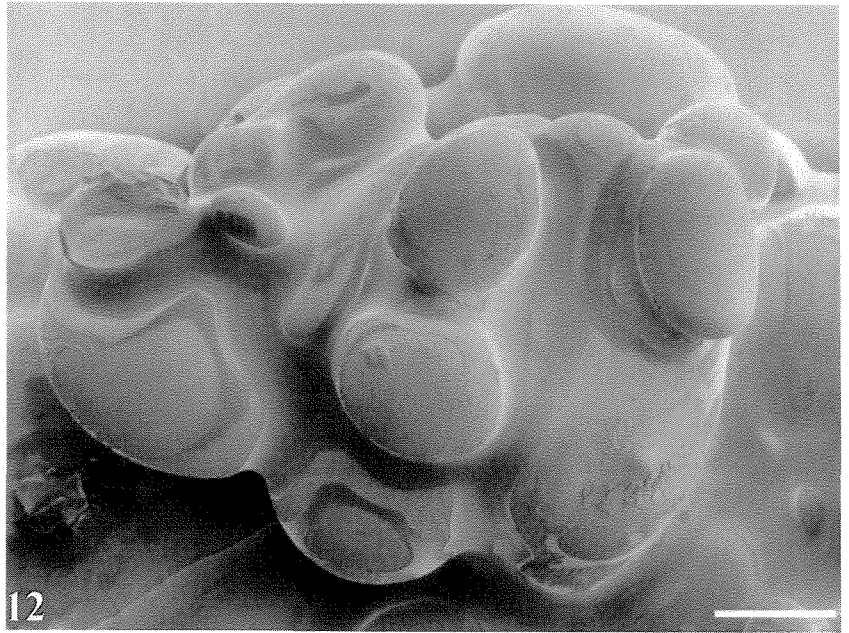
graphy for imaging precipitated snow crystals. This study shows that the technique can be used in the field to investigate a seasonal snowpack to provide similar imaging of metamorphosed snow crystals. In addition, this study shows that snow samples can be stored and transported in  $\text{LN}_2$  Dewar flasks for extended periods of time (probably a month) before additional  $\text{LN}_2$  must be added to maintain the low temperature. Both precipitated and metamorphosed snow crystal samples can be collected remotely and transported for electron microscope imaging with ease. Once the samples arrive at the SEM facility, they can be analyzed immediately or they can be placed in  $\text{LN}_2$  long term storage Dewar flasks for analysis at a later time. Although not shown in this



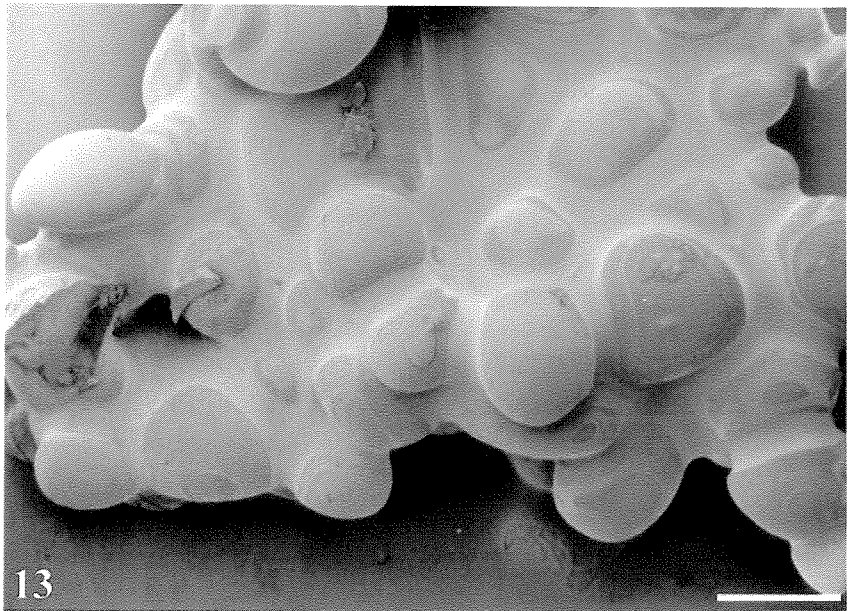
**Fig. 10** Depth hoar crystal from North Slope near Prudhoe Bay, Alaska. (Collected at a snowpack temperature of  $-16^{\circ}\text{C}$ ; stored for 103 days in a Dewar flask; magnification  $40\times$ ; bar = 0.3 mm).



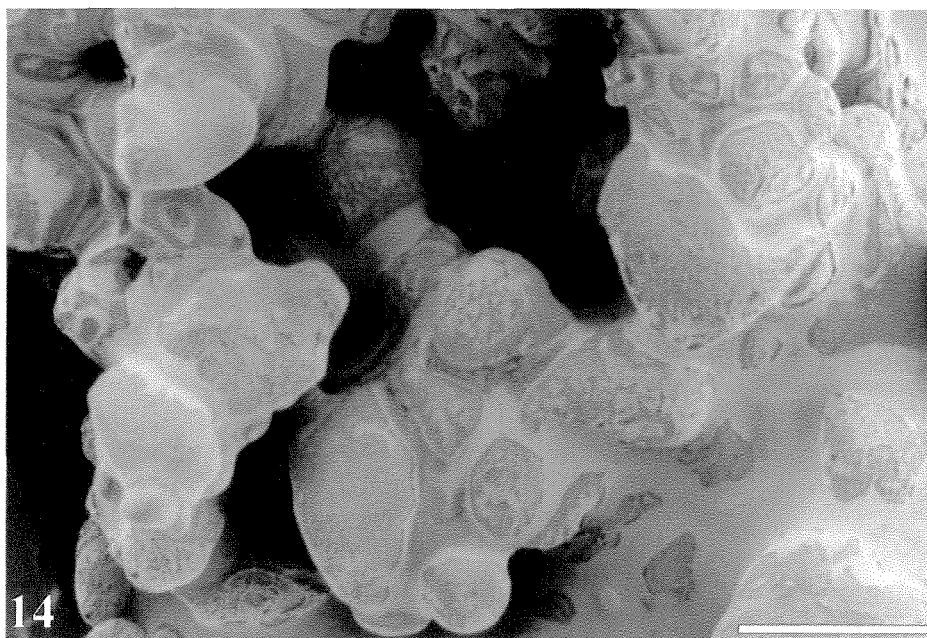
**Fig. 11** Bonded and rounded snow grains from the middle layer of the melting snowpack at Loveland Pass, Colorado. This part of the snowpack had little visible liquid water and snow grains are not spherical. (Collected at a snowpack temperature of  $0^{\circ}\text{C}$ ; stored for 7 days in a Dewar flask; magnification  $30\times$ ; bar = 0.5 mm).



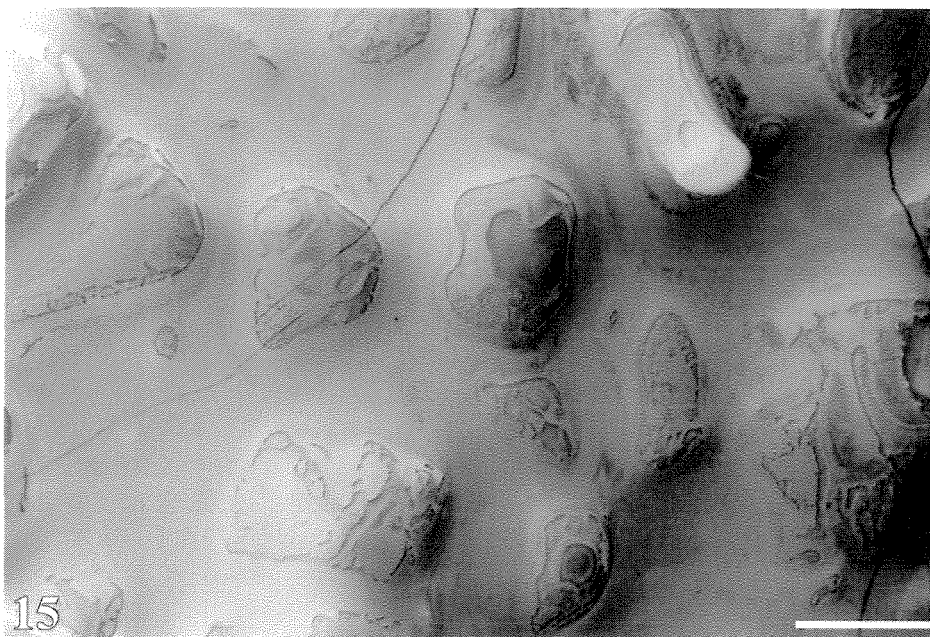
**Fig. 12** Cluster of nearly spherical snow grains present in the surface layer of the melting snowpack at Loveland Pass, Colorado. The surface layer is saturated with liquid water which loosely holds the snow grains in a cluster. (Collected at a snowpack temperature of  $0^{\circ}\text{C}$ ; stored for 7 days in a Dewar flask; magnification  $50\times$ ; bar = 0.3 mm).



**Fig. 13** Cluster of nearly spherical snow grains from the surface layer of the melting snowpack at Loveland Pass, Colorado. This scene is just part of a larger cluster measuring about  $7 \times 14$  mm. (Collected at a snowpack temperature of  $0^{\circ}\text{C}$ ; stored for 7 days in a Dewar flask; magnification  $30\times$ ; bar = 0.5 mm).



**Fig. 14** Network of grain clusters in the surface layer of the melting snowpack at Loveland Pass, Colorado. Void spaces between clusters are evident. (Collected at a snowpack temperature of  $0^{\circ}\text{C}$ ; stored for 3 days in a Dewar flask; magnification  $20\times$ ; bar = 1.0 mm).



**Fig. 15** Sample from ice lens in the bottom portion of the Loveland Pass, Colorado snowpack showing no void spaces. (Collected at a snowpack temperature of  $0^{\circ}\text{C}$ ; stored for 29 days in a Dewar flask; magnification  $30\times$ ; bar = 0.5 mm).

paper, stereo images of the snow crystals were made to allow stereo viewing of the three dimensional structure of the metamorphosed snow.

The recent snow crystal classification system of Colbeck *et al.* (1990) provides many categories of snow crystals on the ground. It was possible to observe and image many of these categories including decomposing and fragmented precipitation particles, rounded grains, faceted crystals, mixed forms, depth hoar, wet grains and ice layers. The SEM approach seems to be an excellent method for permanently recording and storing images of the various crystal forms that can be present in a snowpack.

## **APPLICATIONS OF SNOW CRYSTAL SIZE AND SHAPE OBSERVATIONS**

SEM, as well as visual, light microscopy and other camera techniques, can be used to observe important stages of development of snowpack crystals and grains. Measurements of crystal or grain form, shape, size and bonding can be applied to various types of studies.

First, although photomicrography has been used to study snow crystals in various stages of change, SEM provides an improved way of observing the crystal changes from precipitated snow to metamorphosed snow. This improved observation capability should provide a better understanding of snow crystal metamorphism and snowpack processes under varying conditions. The SEM measurements have been made in several different types of snowpacks and will be made on crystals obtained from different mountain, tundra and prairie snowpack situations where various stages of metamorphism can be observed. At a minimum, SEM will be used for future observations of new snowfall (natural and artificial), recent snow on the snowpack, wind blown snow, metamorphosed snow in the snowpack under conditions of equitemperature or temperature-gradient metamorphism or both, and melt-freeze metamorphosed snow in the snowpack. Two other situations are envisaged, namely, imaging of glacial firn and algae and bacteria in a seasonal snowpack. The latter observations could make excellent use of the extreme magnification that is possible with SEM. A time history of crystal changes in different layers of the same snowpack will also be attempted to increase understanding of seasonal snowpack processes.

Second, SEM techniques for snow crystal observations should provide a better understanding of conditions leading to snow avalanches. Both newly fallen snow and old snow crystals in the snowpack are important in avalanche formation, and both types can be observed with SEM. As mentioned by Rango *et al.* (1996), the type of falling snow crystal provides information on atmospheric conditions and also directly influences avalanches. Certain new snow types such as graupel and heavily rimed crystals do not bond well to other snow layers and set up conditions for snowpack failure. Changes in crystal type during a storm can also create conditions where one layer does not bond well to the next. For

snow in an existing snowpack, crystals that are produced under high growth rate conditions form weak, unstable snow that is often responsible for serious avalanches (McClung & Schaerer, 1993). Such crystal forms usually associated with these high growth rate conditions are surface hoar, faceted snow and depth hoar. The detection of these forms in the snowpack indicates increasing avalanche hazard. Additionally, the detection of bonds between snow crystals (or the lack thereof) is further pertinent information regarding avalanche potential because bond formation is closely related to snow strength. The SEM techniques developed here provide a new means for increasing knowledge of conditions leading to avalanche formation.

Third, SEM techniques will provide a much better understanding of the interaction between snow crystal characteristics and microwave radiation from the snowpack. Microwave emission from a layer of snow over ground consists of the contributions from the snow itself and from the underlying ground. The microwave emission is affected by the amount, size and shape of the snow grains. Presently, a number of microwave algorithms exist to extract the snowpack water equivalent (amount of snow grains) empirically (Chang *et al.*, 1982; Goodison *et al.*, 1990). Much attention has been directed to correcting the algorithms for the effects of grain size (Armstrong *et al.*, 1993), but, as yet, little is known. Furthermore, very little is known about the effects of crystal shape and bonds between crystals on the microwave emission. The use of SEM to gather information on snow grain size, shape, and bonding will be a valuable input to improved radiative transfer modelling to mimic the microwave response to crystal characteristics and a better understanding of the transfer of microwave energy from the ground surface through the snowpack.

Finally, the techniques described may find far reaching application in fields where studies of snow and ice or other frozen materials are needed. This study has shown that the worldwide shipment of frozen samples is feasible and the methodology should be transferrable to other disciplines.

## FUTURE PLANS

Studies will continue to document the various types of snow crystals that appear as precipitated or metamorphosed snow by obtaining samples in different snow regions for SEM analysis. The information gathered will be directed to improving understanding of atmospheric conditions favourable for snow, relationships between snowfall intensity and crystal type, snowpack processes, avalanches, and snow crystal effects on microwave radiation. Stereo images will be used to examine the three-dimensional structure of snow crystals and grain bonds. The biogeochemistry of snow will also be examined by observing the algae and bacterial forms that are present in a snowpack.

**Acknowledgements** This study was partially funded by the NASA Goddard Space Flight Center. The authors wish to thank R. Armstrong and



R. Newcomb for assistance in selecting appropriate snowpits in Colorado, and A. Nolin and B. Boyer for assisting in data collection at Loveland Pass. In Alaska, assistance was given by D. Hall, J. Foster, and C. Benson in the snowpits near Fairbanks. C. Benson and M. Sturm obtained samples from the North Slope snowpits. C. Pooley converted the SEM negatives to the digital images that were used to illustrate this study.

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Received 22 May 1995; accepted 19 November 1995