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Instruments and Methods

Measurement of snow density and microstructure using computed tomography

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ABSTRACT. In the past, two-dimensional images of internal snow structure have been obtained through plane surface sections or thin sections. These techniques are time-consuming and necessarily destroy the snow specimen. Computed tomography (CT) allows similar images to be obtained, but in a more efficient and non-destructive manner. To demonstrate the methodology, a CT scanner was used to obtain cross-sectional images over time of a snow sample undergoing kinetic-growth metamorphism. Densities calculated from the CT images correlated well to density measured using a traditional method. A procedure was developed that allows the CT image to be converted to binary in an objective manner. Employing innovative stereological software, the microstructural properties (grain diameter, bond diameter, neck length and intercept length) of the snow were then measured from the two-dimensional CT images. The presented methodology provides significant improvements over previous techniques, requiring less time and labor to obtain high-quality microstructural data.

INTRODUCTION

Plane surface sectioning and thin-sectioning techniques have been used for many years to obtain two-dimensional digital images of internal snow structure (Perla, 1982; Perla and Ommanney, 1985; Good, 1987). A typical procedure for preparing plane sections is outlined by Perla (1982). The process entails first filling the pore space of the snow sample with a dyed pore-filling substance (typically dimethyl or diethyl phthalate); once the filler is frozen in the pore space the sample can be shaved using a microtome. Next, the surface of the specimen is lightly polished and allowed to sublimate briefly to further define the ice-filler boundary. Finally, the section is imaged using traditional or digital photography. Recently, Schneebeli (2001) developed an automated process for performing surface sections that is able to collect and image up to 300 slices within 2 hours, vastly improving what has traditionally been a very tedious and time-intensive procedure.

While present sectioning techniques can yield high-quality images of internal snow structure, current techniques by necessity alter the specimen irreversibly. Up to this point, it has not been possible to continually analyze the properties of the *same* sample of snow during metamorphic processes. Many scientists have attempted to observe changes in snow properties over time by removing specimens of snow from a larger sample at regular intervals (i.e. Akitaya, 1967, 1974; Marbouty, 1980; Perla, 1985; Perla and Ommanney, 1985; Fierz and Baunach, 2000), but this introduces error due to spatial variation since each specimen is taken from a different location. Regarding recent metamorphism experiments, Brown (unpublished information, 1999) reported significant scatter in their data because of this variability. The advent of computed tomography (CT) as a research tool provides a new opportunity to investigate snow microstructure in a manner that is both more efficient and non-destructive, while at the same time providing a means to measure the density of the snow specimen.

CT uses an X-ray beam and digital camera to examine a cross-sectional slice of an object. The primary components of a CT scanner include an X-ray source, a sample stage and a detection system. As the X-ray leaves its source, it travels through a collimator — two parallel lead plates — that narrows the beam into a flat, horizontal plane. This "plane" of X-ray transects the sample mounted to the stage and passes through another collimator before reaching the detector. The detection system consists of a phosphor screen that converts the X-ray into visible light, and a high-resolution digital camera. The result is a digital radiograph of a very thin slice of the sample material. This process is repeated, typically in 1° steps, as the sample is rotated through a full revolution.

The variation in X-ray attenuation as it passes through the object is largely dependent on its density, and it is represented by different intensities of light reaching the camera. By recording the plane of an object at many different angles through a full revolution, it is possible to mathematically extract the density of each point within the plane. This two-dimensional density map constitutes a CT image and provides accurate information about the internal structure of an object.

The application of X-ray CT to the field of snow and ice has been relatively recent. Kawamura (1988, 1990) used CT to examine the internal structure of sea ice, and eventually to measure the three-dimensional density of ice cores. Montana State University researchers demonstrated the utility of CT technology to collect non-destructive, two-dimensional images of natural snow specimens (Lundy and Adams, 1998), and scientists at the Centre d'Études de la Neige, Grenoble, France, have achieved three-dimensional reconstruction of small

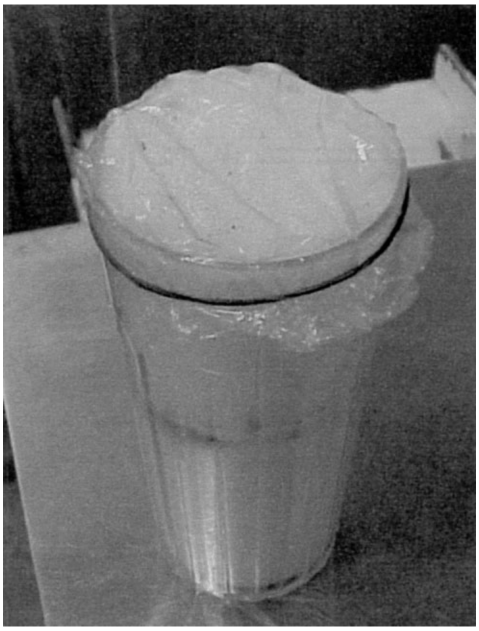

Fig. 1. Snow sample contained in tapered cup and covered with plastic wrap to prevent mass loss.

(9 mm × 9 mm) snow samples (Coléou and others, 2001). As CT is becoming increasingly prevalent in snow and ice research, the development of methodologies such as that presented here will advance the utility of this powerful technology.

Several researchers have used computers to analyze digital snow-section images in order to reduce the tedium and subjectivity inherent in hand measurements (Perla, 1985; Good, 1987; Coléou and others, 2001). One such technique developed by Edens (1997) utilizes a unique skeletonization process to describe the geometry of the interconnected snow grains, identify grain-to-grain bonds and facilitate the measurement of the two-dimensional snow microstructure. The average three-dimensional properties of the sample are then determined using quantitative stereology. These algorithms are contained in a computer program, making the process completely automated and repeatable.

DESCRIPTION OF METHOD

To illustrate the methodology, the microstructural changes of snow undergoing kinetic-growth metamorphism were investigated, but the procedure is equally applicable to studies of equilibrium metamorphism. Using a hot plate in a cold-room laboratory, natural, newly fallen snow was subjected to a large temperature gradient (50–65°C m^{-1}) for a period of approximately 1 month. The duration and magnitude of the temperature gradient was sufficient to cause significant metamorphism of the original snow crystals. To allow for the transfer of the snow sample from the experiment apparatus to the CT scanner, the specimen was contained in a plastic cup (Fig. 1). The cup is 15 cm in height, and is filled to the top with snow at the start of the experiment. A vertical taper ensures that as the snow settles, contact is maintained with the sides of the cup. Plastic wrap on top of the sample eliminated any loss of mass through sublimation.

CT imaging procedure

The snow sample was CT-scanned prior to the experiment to obtain initial images of the snow. Once the experiment was begun, successive scans were performed approximately once per week. The CT scanning was performed with a Synergistic Detector Designs system and took approximately 2–3 hours per weekly session. During the scanning process, samples were kept cold in an insulated cylindrical chamber with crushed dry ice placed above and below the specimen. The CT scanning produces a horizontal, two-dimensional cross-sectional image of the specimen, and scans were taken at 3.5, 5.5 and 7.5 cm above the bottom of the sample during each scanning session. Subsequent analysis of the CT image is performed on a 1200 mm^2 square region that lies within the sample cup. Resolution of the CT images is 100 μm per pixel.

Measurement of snow density from CT images

One of the most important aspects of using CT to examine a snow sample is the ability to measure the density of the specimen from the CT image. Since the attenuation of the X-ray is dependent primarily on material density, the intensity of each pixel forming the CT image is essentially a measure of point density within the sample. From the grayscale of each pixel, a ratio can be formed relative to the pixel values for pure ice and air. Multiplying this ratio by the density of pure ice gives the density of the sample at a particular point (Kawamura, 1990):

$$\rho_{\text{sample}} = \left(\frac{N_{\text{air}} - N_{\text{sample}}}{N_{\text{air}} - N_{\text{ice}}} \right) \rho_{\text{ice}} \,, \tag{1}$$

where N_{air} is the pixel value for air, N_{ice} is the pixel value for pure, bubble-free ice, N_{sample} is the pixel value for the snow sample, ρ_{ice} is the density of pure ice (917 kg m^{-3}) and ρ_{sample} is the point density of the snow sample.

Since the average density over the entire two-dimensional slice is generally desired, mean values over the CT image were used for N_{air}, N_{ice} and N_{sample}. The pixel values for the pure, bubble-free ice and air were determined by scanning samples of these constituents. Since the cooling chamber and specimen cup also attenuate the X-rays, the configuration used to scan the ice or air was identical to that used while scanning the snow samples. Bubble-free ice contained in the same tapered cup used for the snow specimens was placed in the cooling chamber and CT-scanned at 3.5, 5.5 and 7.5 cm above the bottom of the cup. This process was repeated with an empty cup to determine the pixel value for air.

The procedure was tested on samples of sieved snow of various densities. In each case, the average density was found by weighing the snow specimen and dividing by the volume of the sample cup. This measured value was compared to densities found from the CT images using Equation (1) (Fig. 2). The densities obtained using both methods show strong agreement, and verify the accuracy of measuring snow density using CT.

Converting CT images to binary

A CT image must first be converted to a binary image prior to analysis with the microstructural measurement software. Thus, a threshold value must be carefully selected; any pixel with a value less than the threshold becomes black (representing ice), and pixels with a greater value are turned white (representing air). Near the ice/air interface, the variation in pixel intensity is gradual and therefore it can be unclear whether a pixel represents ice or the pore space. Consequently, the choice of threshold value is extremely critical because it has a tremendous impact on the apparent density and structure of the snow, and will greatly affect any meas-

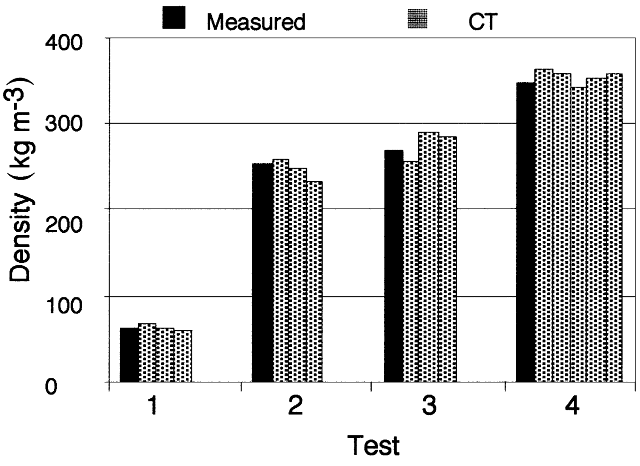

Fig. 2. Comparison of snow density measured by weighing and calculated from two-dimensional CT image.

urements of the snow microstructure. Perla and others (1986) encountered difficulty in choosing a threshold value during the image analysis of serial sections, and were constrained to choosing a threshold based on a subjective comparison to the original surface section.

The determination of snow density from a CT image using Equation (1) yields the key to objectively choosing a threshold value and obtaining an accurate binary representation of the snow microstructure. The procedure is iterative and begins by selecting an arbitrary threshold and converting the image to binary. The apparent density is then calculated based on the area fraction of black pixels which represent the ice grains, and is compared to the actual density found from Equation (1). These steps are repeated, varying the threshold until the area-fraction density is equal to that found using Equation (1). This procedure is repeated for each CT image, as the appropriate threshold was found to vary significantly from section to section. The process was automated with a short program, making it an efficient and consistent procedure.

Measurement of the snow microstructure

Once converted to binary, the images were analyzed using an automated stereology software created by Edens (1997). The program calculates a multitude of parameters describing the grains, bonds and pore space, but of particular interest to studies of snow microstructure are grain diameter, volume-weighted-volume (VWV), bond diameter, intercept length and neck length.

The grain diameter computed by the software is based on the diameter of the largest circle that can be inscribed into the snow grain. In nearly all cases, this significantly underestimates the grain diameter as measured by standard observational procedures. The stereology program also calculates the VWV, which is the grain volume mean weighted by the particle volume. In other words, larger grains are given more weight in the volume average than smaller grains. By determining the diameter of a sphere occupying a volume equivalent to the calculated VWV, an improved representation of grain diameter is found:

$$d_{\mathrm{g}} = 2\left(\frac{3\mathrm{VWV}}{4\pi}\right)^{\frac{1}{3}}. \qquad (2)$$

The calculation of bond diameter, neck length and intercept length is described in detail in Edens (1997).

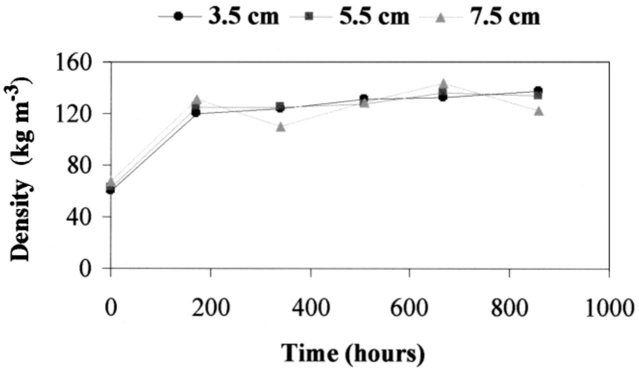

Fig. 3. Variation in density with time during the metamorphism experiment. Heights are measured above the bottom of the sample.

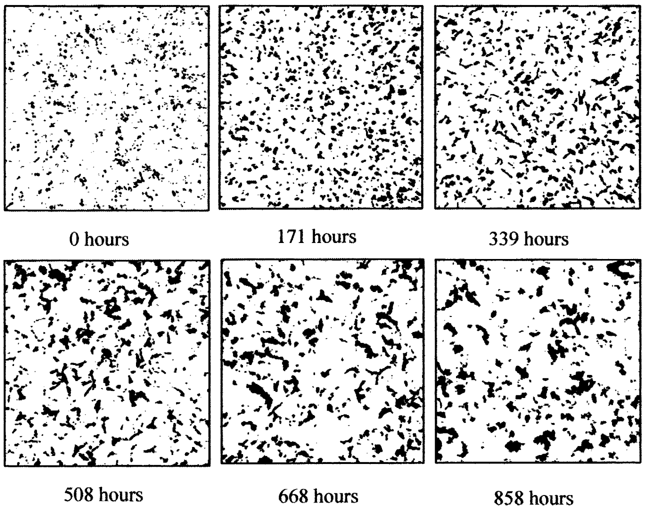
0 hours
171 hours
339 hours
508 hours
668 hours
858 hours

Fig. 4. Time series of binary CT images scanned 3.5 cm above the bottom of the sample cup. The ice grains are represented as black and the pore space is white.

ANALYSIS AND DISCUSSION

Results

A snow sample consisting of new and decomposing precipitation forms was subjected to a temperature gradient sufficient to drive kinetic-growth metamorphism. Initial densities near 60 kg m^{-3} were measured from the CT images, and a density of 63 kg m^{-3} was found by weighing the sample cup. A week later, the density at all scan levels had doubled and then experienced little change for the remainder of the experiment (Fig. 3). The original snow depth was 15 cm, but within the first week the snow settled to an average height of 9 cm.

The CT images performed during the experiment were converted to binary (Fig. 4) and analyzed using the stereological software. The changes in selected microstructural parameters are illustrated in Figure 5. The initial grain diameter as calculated from the VWV is similar to hand-lens measurements made prior to the experiment. The small decrease in grain diameter during the first week is likely due to the breakdown of the initial precipitation forms. While both grain and bond diameter steadily increase with time at all scan heights, the grain growth rate consistently outpaces the rate of bond growth, exhibiting behavior that is typical of kinetic-growth metamorphism. The change in neck length is somewhat erratic but has an increasing ten-

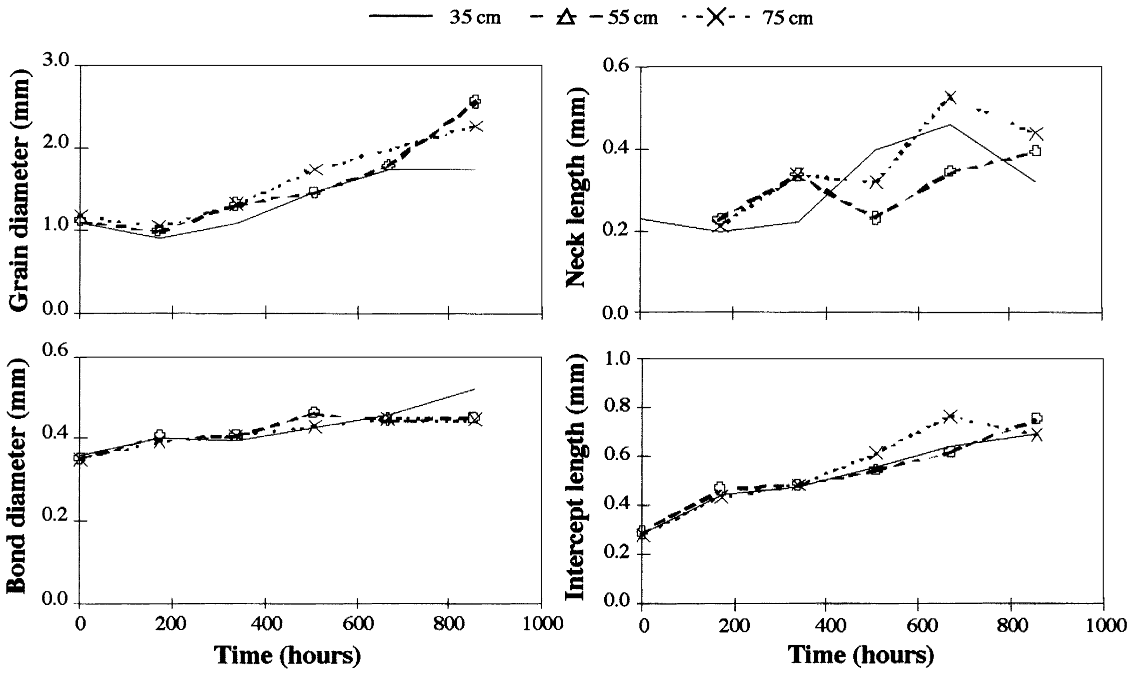

Fig. 5. Changes in the snow microstructure during the metamorphism experiment. Heights are measured above the bottom of the sample. The grain diameter is derived from the VWV as described in the text.

dency. The mean intercept length, which is related to grain diameter, also increases during the experiment. It should be noted that since the CT images are horizontal cross-sections of the snow sample, the bonds and necks identified by the software lie predominantly in this plane. Vertical scans could be performed to ascertain the variation of the microstructural properties in this direction.

Advantages

The described method provides a significant step forward in the study of snow microstructure in that it does not alter the sample under examination. Consequently, the same specimen can be repeatedly imaged over time, eliminating sample variability and associated errors. Although recent advances in serial sectioning (Schneebeli, 2001) have substantially reduced the tedium involved in collecting multiple cross-sectional images of snow specimens, CT imaging offers considerable increases in efficiency and automation when compared to traditional surface section techniques and does not require a pore filler.

While three-dimensional renderings of snow microstructure were not obtained in this study, Coléou and others (2001) demonstrated the feasibility of obtaining such reconstructions through CT technology.

Limitations

Implementing a CT imaging system represents a substantial expenditure of capital, time and energy. The learning curve for a new system can be rather steep, and the application of CT technology to the study of snow is still in the developmental phase and is not yet as proven as surface and thin-sectioning.

At the present time, a rather elementary cooling chamber that relies on dry ice to keep the sample frozen limits the CT system used in this investigation. A more advanced cold chamber able to maintain a sub-freezing temperature for long periods of time would allow many more images to be obtained during each scanning session. This would be necessary to acquire enough cross-sections to perform a three-dimensional reconstruction of the snow specimen.

This methodology may be applicable to snow samples containing a pore-filling substance; however, the similarity in densities of ice and common pore-filling substance may present some difficulty. It is also likely that imaging wet snow would be problematic due to the presence of free water which has density near that of ice.

CONCLUSIONS

A methodology is presented that combines CT with a stereology program, allowing repeated, non-destructive sampling of a snow sample and subsequent analysis of the snow microstructure. The technique allows objective measurement of the change in snow properties over time during metamorphism experiments, but requires significantly less time and labor than surface or thin sections. While the implementation of a CT imaging system requires a substantial initial investment, CT technology provides an improved tool for examining the internal structure of snow.

The results from a metamorphism experiment demonstrate the capabilities of the technique. The change in density, grain diameter, bond diameter, neck length and intercept length were measured over the course of the experiment for different heights within the sample. The results agree with our understanding of the effects of kinetic-growth metamorphism, and the minimal scatter present in the data provides additional confidence in the measurement process.

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