NONDESTRUCTIVE COLLECTION OF NATURAL SNOW SPECIMENS FOR USE WITH CT SCAN ANALYSIS

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ABSTRACT: Recently, CT (CAT) scanning technology has been utilized to analyze snow and ice samples. To facilitate applying this technology to natural snow, a procedure has been developed that allows snow specimens to be transported from an outdoor location to the laboratory for the purpose of CT imaging. A snow sample is first obtained in a tubular container. A screen is placed beneath the container, and dimethyl phthalate cooled to a temperature just below 0°C is slowly poured in the top of the snow. The wetting front moves downward, filling the pore space and expelling air out the base of the specimen. Packing the sample in dry ice freezes the substance in the pore space, protecting the snow microstructure and prohibiting metamorphism during transportation. The methodology presented is intended for CT imaging, which offers a nondestructive means to investigate grain structure and intergranular bonding, but is also applicable to surface sectioning. CT scans demonstrate that this technique provides adequate penetration of the dimethyl phthalate into the interstitial pores to prevent structural damage or metamorphism of the snow. Differences in X-ray absorption provide distinction between the ice grains and the dimethyl phthalate filled pore space.

KEYWORDS: snow and ice, methods of sampling; snow cover structure; computed tomography

1. INTRODUCTION

Recently, CT (CAT) imaging technology has been utilized to analyze snow and ice samples. Comparable in application to surface or thin sectioning, CT imaging provides much improved resolution and a nondestructive means to collect numerous images of the snow microstructure. Application of CT scanning techniques to snow obtained from the field may yield valuable information on grain structure, providing insight into processes such as kinetic growth metamorphism and near-surface faceting. To facilitate applying this technology to natural snow, a procedure is used which preserves the snow microstructure and prohibits metamorphism, allowing snow specimens to be safely transported from an outdoor location to the laboratory for the purpose of CT imaging.

2. BACKGROUND

2.1 Preservation of Snow Samples

Snow has been obtained in the field and transferred to the lab for purposes such as crystal characterization and scanning electron microscopy (SEM). Brun and Pahaut (1991) collected individual snow crystals in small flasks filled with iso-octane at a sub-freezing temperature. As soon as the snow grain surface is wetted by the iso-octane, all metamorphism is halted as long as the crystal remains immersed and the temperature of the liquid is less than 0°C. In a refrigerated laboratory, the iso-octane is poured through a filter and the snow grain is retrieved and identified with a microscope. Individual crystals were also obtained by Wolff and Reid (1994) for examination by an SEM. Their complex and expensive technique utilized liquid nitrogen to preserve the snow grain during transportation from Greenland to England.

Both of these procedures are applicable to the collection of individual snow crystals, but are not readily adaptable to obtaining a larger snow sample for the purpose of analyzing grain structure. However, Perla (1982) presented a method that preserves a snow specimen by saturating the snow pore space with a cooled filler liquid and subsequently freezing the sample solid. This technique was intended for use with surface sectioning. The sample is placed in a small metal tray and when the pore filler is poured into the tray, capillary action pulls the liquid into the pore space of the snow specimen. According to Perla, the pore filler will climb at least 20-30 mm above the level of the liquid in the tray, and will not be as effective on dense snow (> 600 kg m^{-3}) or on large-grained snow with large pores. The tray

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containing the snow specimen and the filler material is finally placed in a cold chamber (< -20°C) until it solidifies. Once the sample is frozen, all metamorphism is inhibited and the sample can be handled or analyzed without risk of damaging the snow microstructure.

Listed below are certain parameters that characterize an effective filler liquid:

- High degree of water insolubility.
- A freezing point 5-10 degrees below that of water.
- Have sufficiently low viscosity at about -5°C to effectively infiltrate the snow pore space.

Additionally, the liquid should be safe to use in confined and poorly ventilated refrigerated laboratories, low in cost, and possess a reasonable shelf life. Aniline has been used successfully (Kinosita and Wakahama, 1960) but is toxic and water soluble. Bader and others (1939) employed Tetrabromoethane, a toxic and mutagenic compound. Perla states that dimethyl phthalate, a relatively benign chemical, gave consistently favorable results. A brief summary of dimethyl phthalate's physical properties of are presented below:

Molecular Formula	$C_{10}H_{10}O_4$
Molecular Weight	194.19
Freezing Point	approx. -10°C
Density	1.194 g cm^{-3} @ 20°C
Solubility	less than 1 in 100

Another important property not mentioned by Perla is that dimethyl phthalate experiences little density change during the freezing process so that dilatation of the pore space or formation of air gaps is prevented.

2.2 *Computed Tomography*

Computed tomography (CT) uses a columnated X-ray beam and digital camera to examine a cross-sectional slice of an object. The variation in X-ray absorption within the object is represented by different intensities of light reaching the camera. By recording the plane of an object at many different angles, 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 use of CT technology in the medical field is well known and its prevalence among other branches of science is on the increase.

Naturally, CT imaging can be a powerful instrument to explore the internal structure of snow and ice. To date, its use in this regard is not well documented; however, Kawamura (1990) recently scanned ice cores to determine their three-dimensional density, and scientists at Montana State University have begun to investigate deformation of snow under axial loads using this technology. Although CT imaging has not been extensively applied to snow samples collected from the field, this technology offers a nondestructive means to investigate grain structure, intergranular bonding, and metamorphism within natural snow.

3. METHODOLOGY

This project was undertaken to adapt the basis of Perla's method for use with CT imaging. Based on existing information, the procedural outline is as follows: a snow sample is collected, the snow pore space is saturated with cooled dimethyl phthalate, and the chemical is frozen in the sample. Each step of this procedure was developed so that it could be executed in the remote and unpredictable conditions of a field location. Additionally, the modified method is effective on large-grained snow crystals, such as depth hoar, and is more suitable for larger snow specimens than Perla's original technique. The effectiveness of the following field procedure was evaluated both in a refrigerated laboratory (T = -14°C) and a remote outdoor setting.

3.1 *Collection of Snow Specimen*

First, a method was devised to obtain an undisturbed snow sample from a snow pit in a manner suitable for addition of dimethyl phthalate, transportation from the field site, and subsequent CT scanning. For the purposes of this procedure, a length of acrylic tubing with a diameter of 38.0 mm, a length of 60.0 mm, and a 1.8 mm wall thickness was used. Because the tube is clear, the snow sample can be easily inspected for cracks or voids and the percolation of dimethyl phthalate can be observed. PVC caps are placed on the ends of the tube in order to prevent leakage. While PVC tubing was also tested, the larger wall thickness of 4.0 mm caused unacceptable disturbance of the snow during collection.

The desired tube diameter varies depending on the grain size of the snow under consideration. Since each CT image has a fixed number of pixels (1024 × 1024), scanning a decreased sample diameter distributes these pixels over a smaller area and results in greater pixel density and higher resolution. Thus, if small grains are to be examined, a smaller sample diameter will be required to achieve the necessary resolution. However, larger diameter samples are easier to collect and may be suitable for large-grained snow type such as depth hoar.

At the field site, the collection tubes are first inserted into the snow to equilibrate their temperature with that of the snow. Next, the acrylic tube is reinserted into the snow pit wall, the snow is cleared from around it using a spatula, and the snow-filled tube is carefully removed (see Figures 1-3). For snow with a density of less than 100 kg m^{-3}, it was found that the tube could not be

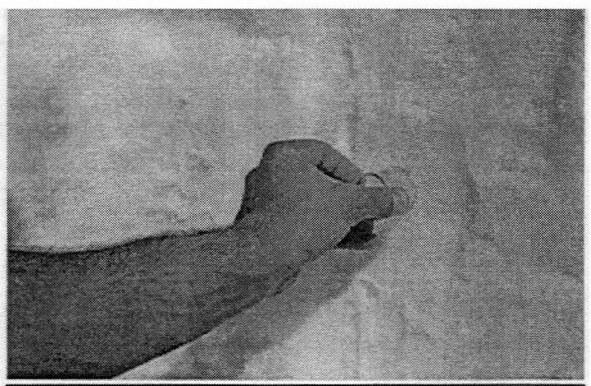

Figure 1. Tube is inserted into snowpit wall to obtain snow sample.

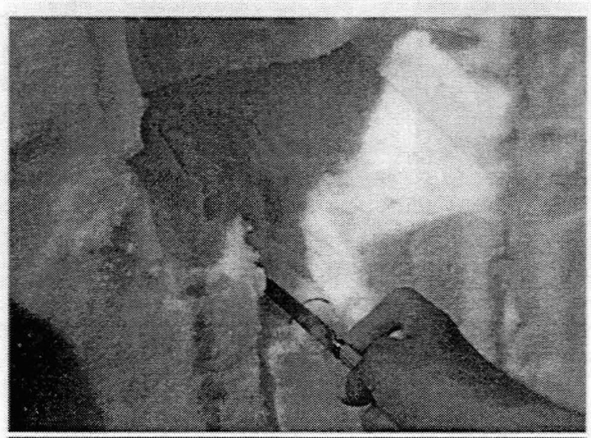

Figure 2. Snow is cleared from around sample prior to removal.

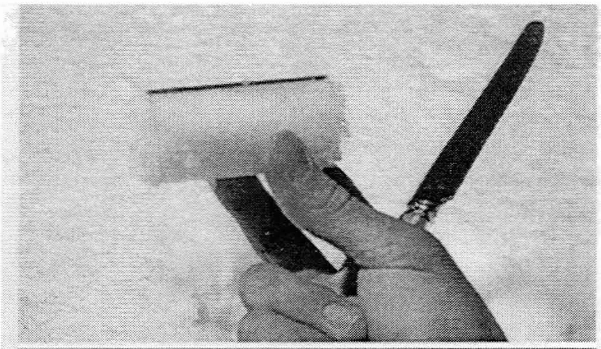

Figure 3. The removed snow specimen.

inserted without disturbing the surrounding snow. As a final step, the ends of the snow sample are cut flush with the tube using the spatula. The depth and snow density, temperature, grain diameter, and classification is recorded for each sample. At this point, the specimen is ready for the addition of dimethyl phthalate.

3.2 _Addition of Dimethyl Phthalate to Snow Sample_

The addition of dimethyl phthalate into the sample is the most critical element of the technique. Perla's method relied on capillary action to carry the filler liquid into the snow pore space, but this placed limitations on the dimensions of the specimen and grain size of the snow. A technique was devised that allows dimethyl phthalate to be quickly and easily added to a natural snow specimen and provides a means to monitor and control the temperature of the filler chemical in a field scenario.

The dimethyl phthalate is contained in a 125 ml laboratory squeeze bottle that has a thermocouple inserted into the wall of the bottle for precisely monitoring the temperature of the liquid (see Figure 4). The chemical must be added at a temperature below the freezing point of water; however, the working temperature range is actually very small because if it is added too cold, it becomes more viscous and may not adequately infiltrate the snow pore space. A temperature between -2 and -5°C was found optimum. During the field procedure, the appropriate temperature can be maintained by cooling the chemical bottle in a small cooler with dry ice or warming through hand contact. This technique proved to be effective, and keeping the pore filling liquid at the appropriate temperature was not as difficult as anticipated.

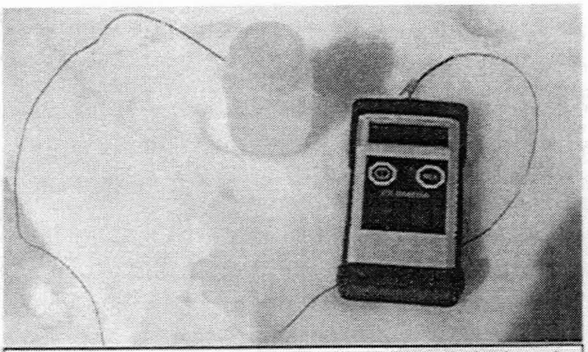

Figure 4. Temperature of dimethyl phthalate is monitored using a thermocouple.

Once a snow sample is obtained, it is placed upright on a small tray covered with a section of permeable screen. This screen keeps the snow from falling out the tube bottom during the addition of dimethyl phthalate. The filler chemical is slowly poured on the top surface of the sample and allowed to infiltrate downward (see Figure 5). Once the wetting front reaches the screen, the sample is removed and both ends of the tube are capped. By allowing the dimethyl phthalate to infiltrate downward and expel the air out the bottom of the sample, air trapped in the snow specimen is minimized.

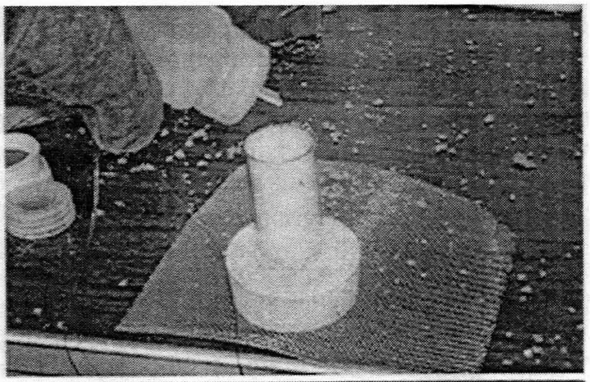

Figure 5. Dimethyl phthalate is added to the snow specimen.

Other techniques of adding dimethyl phthalate to the snow were tested with inferior results. One method used a syringe to inject the chemical at the base of the specimen, filling the interstitial pores from the bottom up and expelling air out the top of the tube. Inconvenience and constant freezing of the syringe needle made this technique problematic. In another method, the dimethyl phthalate is dripped down the side of the tube, also filling the snow from the bottom up. This technique was very time consuming and trapped significant amounts of air in the snow specimen.

3.3 _Freezing of Snow Specimen_

After a snow sample is collected and pore filler is added, the sample is cooled so that the chemical freezes in the interstitial pore space of the snow. Once the dimethyl phthalate reaches a frozen state, the original microstructure of the snow is preserved and the sample can be transported without damaging the structure or allowing metamorphism to take place.

After the dimethyl phthalate is added to the snow and the tube is adequately capped to prevent leakage, the sample is placed in a small, portable cooler and packed with dry ice. This cooler has foam cutouts to keep the containers from shifting. In the field, the temperature in the cooler was found to be at least -30°C after 30 minutes, and the specimens were frozen solid. During a lab test, 462 g of dry ice was placed in a cooler with a volume of 4500 L. Ambient temperature during the experiment was -4°C, a temperature similar to what might be experienced in the field. A snow specimen saturated with liquid dimethyl phthalate was placed inside. After 35 minutes, the sample was frozen solid; this time reflects results obtained during the field test. Under these test conditions, it was found that the dry ice lasted at least 12 hours. If necessary, the time required to freeze the dimethyl phthalate in the snow can be decreased by adding a small seed of dry ice to the sample immediately after it is filled.

3.4 _Cross-sectional Images of Snow Samples Using CT Scanning_

An important aspect of this project was verifying that this field procedure, in conjunction with CT imaging, could be a powerful tool for analyzing the microstructure of natural snow. Whether or not the dimethyl phthalate could be differentiated from the snow grains was thus an important consideration. A CT scan of two identical snow samples, one containing dimethyl phthalate and the other without, displays a distinguishable boundary between the dimethyl phthalate and the individual snow grains (see Figure 6-7).

CT technology was utilized to check for air trapped within the snow sample in order to evaluate the penetration of the filler liquid into the interstitial pores. The images revealed very few air gaps within the sample, demonstrating that the pore space is adequately penetrated by the filler chemical and that metamorphism will be prohibited

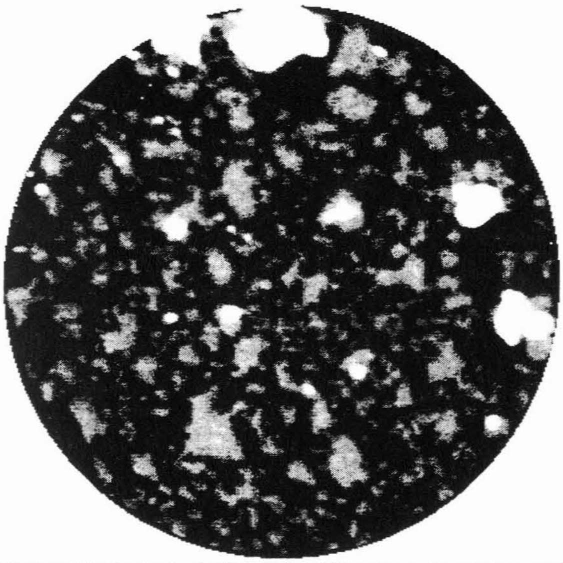

Figure 6. CT image of snow sample containing dimethyl phthalate. Light gray color is snow, dark gray is the filler liquid. Grains are approximately 1-4 mm in diameter. Field-of-view is 115 mm.

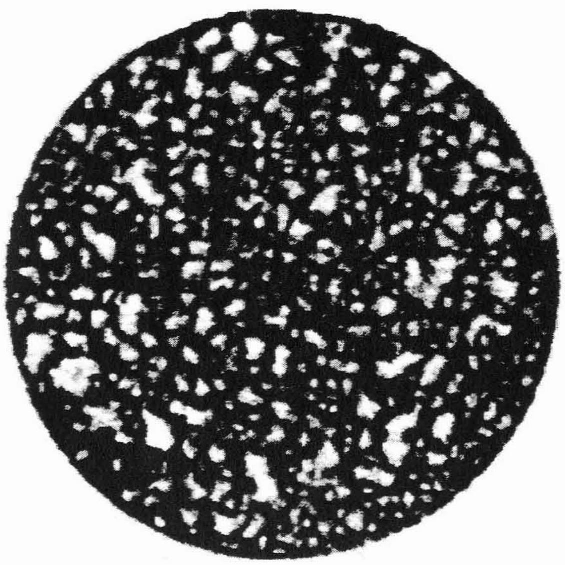

Figure 7. CT image of snow sample containing no dimethyl phthalate. Grains are approximately 1-4 mm in diameter. Field-of-view is 115 mm.

during transportation from the field to the lab.

CT images were produced from snow samples contained in the 38 mm diameter acrylic tubing with a field-of-view of 115 mm (see Figure 6). This resolution seemed appropriate for larger-grained snow with grain diameters greater than about 3-4 mm. At a field-of-view equal to 75 mm, snow grains greater than 2 mm could be satisfactorily resolved (see Figure 8). For grain sizes of less 1-mm, a smaller sample diameter is required and higher resolution becomes necessary for acceptable results.

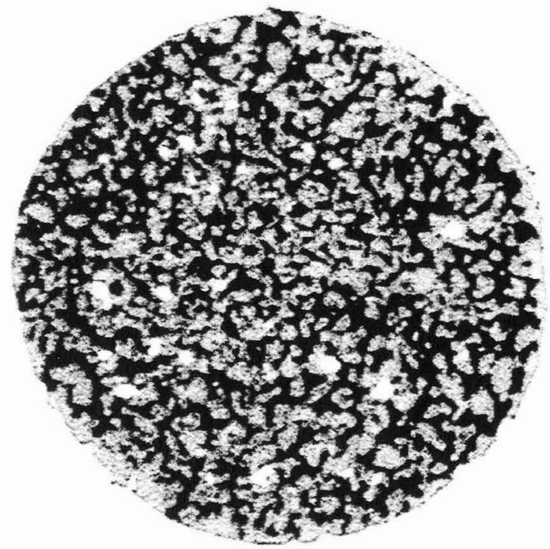

Figure 8. CT image of snow sample consisting of grains approximately 1-2 mm in diameter. Light gray color is snow, dark gray is dimethyl phthalate, and small white spots are air gaps. Field-of-view is 75 mm.

While the field procedure presented is appropriate only for dry snow, a sample of melt-freeze snow grains obtained in the field was CT scanned with limited success. Due to the saturated nature of this type of snow, the dimethyl phthalate and the snow grains blended together in a mottled image.

All imaging was performed with a Synergistic Detector Designs CT scanner. Snow specimens are kept frozen during the scanning process by packing them in a container along with dry ice. This canister attaches rigidly to the stage platform of the CT machine, eliminating motion of the sample as it is scanned.

4. LIMITATIONS OF PROCEDURE

This technique is suitable only for unsaturated snow. Using the acrylic tubes described above, snow with a density less than about 100 kg m^{-3}

could not be satisfactorily collected. A thinner walled tube may be more effective under these conditions. The maximum sample size that can be preserved with this procedure was not established. Very cold snow temperatures may cause the dimethyl phthalate to freeze in the snow pore space before it fully penetrates the sample, effectively forming a solid barrier and preventing complete infiltration of the filler liquid. Conversely, if it is above freezing it will be difficult to keep the dimethyl phthalate cold and prevent the snow specimens from melting during the process. Additional experimenting and field-testing may yield other limitations or solutions to those described above.

5. CONCLUSIONS

In order to formulate a procedure that preserves the microstructure of a natural snow specimen for subsequent CT scanning, the basis of Perla's procedure was modified for use with this new technology. First, natural snow is collected from a snow pit using a clear collection tube. Cooled dimethyl phthalate is poured in the top of the sample and allowed to percolate down through the snow specimen until it reaches the bottom, which is covered by a screen. Finally, the ends of the collection tube are capped and the sample is placed in a cooler with dry ice. Once the dimethyl phthalate freezes in the snow pore space, metamorphism is prohibited and the snow specimen can be transported back to the laboratory for analysis by CT scanning or surface sectioning. This procedure was tested successfully in both a cold room laboratory and a remote field location.

CT images displayed good distinction of the boundary between the dimethyl phthalate and the individual snow grains, and revealed very few air gaps within the sample. A 38 mm diameter sample scanned with a field-of-view of 115 mm provided adequate resolution for 3-4 mm grains. With a similarly sized specimen and a field-of-view equal to 75 mm, snow grains greater than 2 mm could be resolved. For grain sizes of less 1 mm, a smaller sample diameter and higher resolution is required.

The field method presented provides a simple and inexpensive means of obtaining and transporting dry snow specimens from the field while inhibiting structural damage or metamorphism of the snow. Used in conjunction with CT imaging, this procedure may be a beneficial tool for analyzing the microstructure of snow found in a natural snowpack.

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6. REFERENCES

Bader, H. and others. 1939. Der schnee and seine Metamorphose. *Beitrage zur Geologic der Schweiz. Geotechnische Serie. Hydrologie,* Lief. 3.

Brun, E. and E. Pahaut. 1991. An efficient method for a delayed and accurate characterization of snow grains from natural snowpacks. *J. Glaciol.,* **7**(127), 420-422.

Kawamura, T. 1990. Nondestructive, three-dimensional density measurements of ice core samples by x ray computed tomography. *J. Geophys. Res.,* **95**(B8), 12,407-12,412.

Kinosita, S. and G. Wakahama. 1960. Thin sections of deposited snow made by the use of aniline. *Contributions from the Institute of Low Temperature Science*, Hokkaido University, No. 15, 35-45.

Perla, R. 1982. Preparation of section planes in snow specimens. *J. Glaciol.*, **28**(98), 199-204.

Wolff, E. M. and A. P. Reid. 1994. Capture and scanning electron microscopy of individual snow crystals. *J. Glaciol.,* **40**(134), 195-197.