OBSERVATIONS OF SNOW STRUCTURE[1]

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Abstract.--Two methods are used to study snow structure. The *thin-section* method produces high contrast photomicrographs and information on crystal orientation and boundaries, but it is a slow and tedious method. The *section-plane* method is much faster and can be used to prepare a large number of adjacent parallel planes (serial sections) through a sample in order to describe the three-dimensional interconnection of the phases. Photomicrographs of section-planes can be converted to video format, digitized, and analyzed on a desk computer.

INTRODUCTION

The structure of snow consists of two interconnecting phases, ice and pore space (gas), and sometimes a third phase, liquid water. This paper is mostly limited to methods for observing the structure of cold, dry snow (ice and pore). The problem of observing all three phases is taken up only briefly in the last section.

The ice phase can be idealized as a complex assembly of polyhedra, tubes, plates, spheres, needles, and shells. Figure 1 illustrates three very simplified idealizations: an assembly of polyhedra (top); an assembly of tubes (middle); and a combination of polyhedra and tubes (bottom). Figure 1 is an attempt to represent older snow that has recrystallized and sintered. Newly fallen snow is better represented by a connected system of delicate cloud forms: such as needles, plates, and dendrites.

Snow is characterized by connectivity of the pore space. Pore connectivity decreases as density increases. At some high density near 800 kg/m³ the structure consists of isolated pore bubbles, and can be called *ice* rather than snow.

All snow properties pertinent to engineering and hydrologic problems depend on snow structure. Density is an example of a simple and useful measure of structure; however, it is an incomplete measure. The thermal conductivity of snow, the strength of snow, and the response of snow to the electromagnetic spectrum are examples of properties that are crucially determined by the spatial distribution of the phases, as well as by the density.

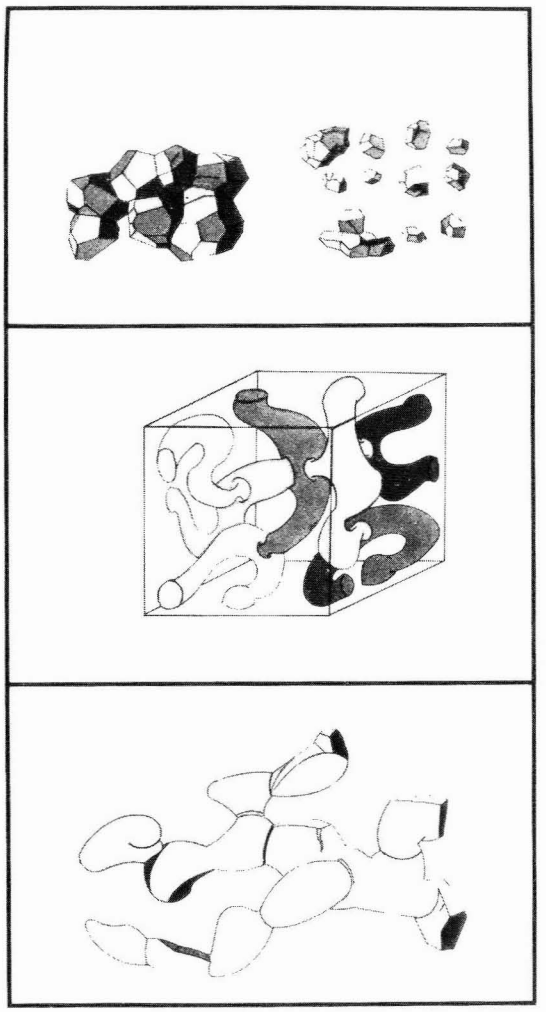

Figure 1.--Three simple idealizations of snow structure.

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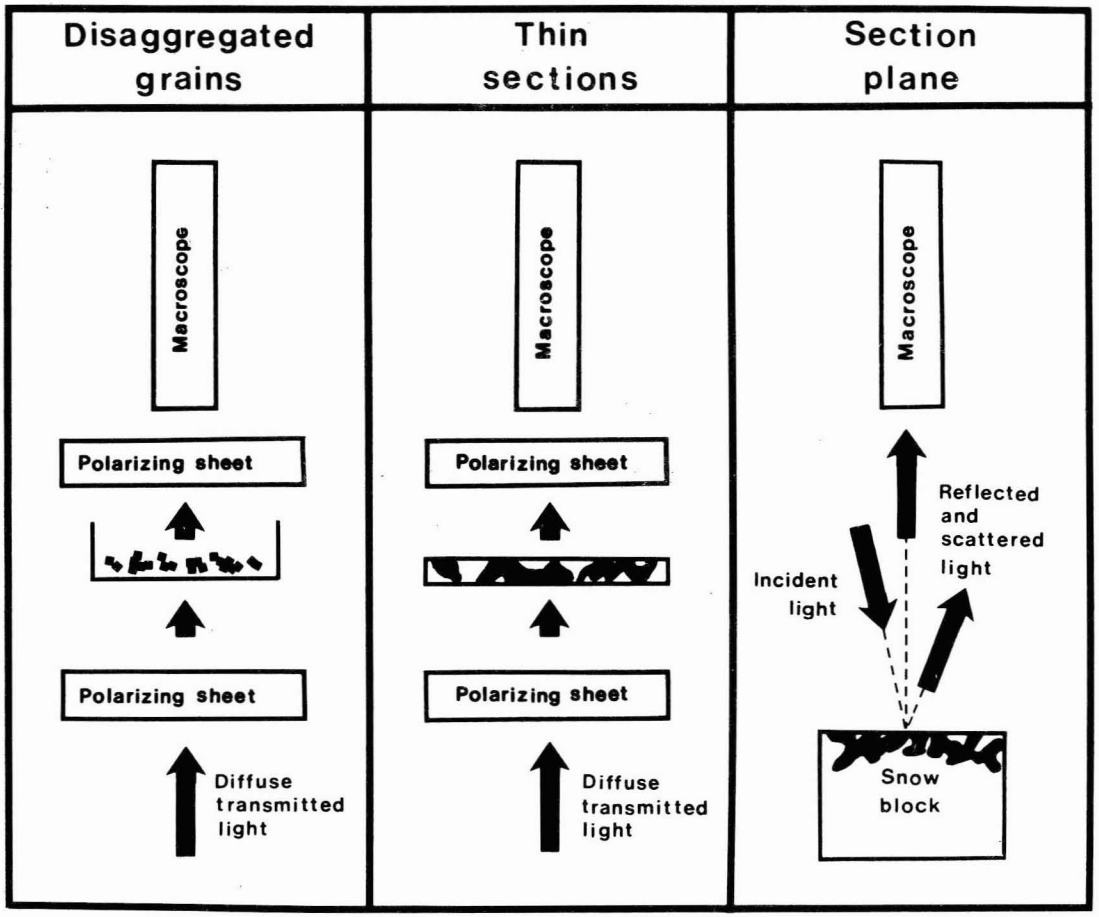

Figure 2.--Three methods for microscopic observation of snow. The image may be captured with a photomacroscope (as shown), photomicroscope, video camera, etc.

DISAGGREGATION OF STRUCTURE

Figure 2 illustrates three methods for microscopic observation of snow. The simplest method is to disaggregate the structure into individual grains which can be studied under a magnifying glass, microscope, or macroscope using incident reflected light or transmitted polarized light as shown in Figure 2 left. This yields important qualitative information on crystal morphology, and possibly some quantitative indices such as maximum crystal size. It is a quick and practical field method, and at present it is probably the only feasible method for classifying snow in operational hydrology, avalanche forecasting, ski area management, ski racing, or whenever one needs to be specific about snow crystal morphology. However, disaggregation destroys the structure and any hope for obtaining fundamental predictors of snow properties.

THIN-SECTIONS

There are two known methods for observing snow structure: the method of *thin-sections* (fig. 2 centre); and the method of *section-planes* (fig. 2 right). Both are research tools that so far have not been used operationally in snow studies. Preparation of thin-sections involves the following steps:

- The pore space of a snow sample is filled with a supercooled, water insoluble liquid.
- The liquid is frozen solid.
- A small block is sawed off from the sample and mounted in a microtome.
- A flat surface is shaved.
- This flat surface is bonded to a glass slide.
- The glass slide is fixed in the microtome (e.g. held by vacuum suction on a preshaved plane of ice or wax) such that the microtome knife can shave planes parallel to the glass slide -- alignment is critical.
- Sucessive shaves are performed until the desired thin-section thickness is obtained (10 μm to 100 μm).
- The thin-section is photographed using transmitted polarized light.
- Contrast is improved if the water insoluble filler is melted back to a liquid (or dissolved chemically).

The above steps are more fully described by Kinosita and Wakahama (1960). Transmitted, polarized diffuse light provides information on crystal boundaries and orientation, and produces high contrast photomicrographs that can be analyzed manually as described by Fuchs (1959) or converted to video format and digitized (Good, 1979, 1980, 1981, 1982).

Unfortunately, the method of thin-sections (as presently followed) has certain disadvantages:

- It is a time consuming method limited to a few sections per day per person.
- Structural parameters depend critically on the section thickness (Keeler 1969).
- The method (at least based on the above steps) does not lend itself to the preparation of adjacent parallel sections through a sample.

However, technological breakthroughs could remedy the above disadvantages.

SECTION-PLANES

A simpler and faster alternative is to prepare a single plane surface for photomicrography using incident reflected light (fig. 2 right) in accordance with techniques described by Narita (1969), Kry (1975), and Perla (1982). The preparation of the sample block for microtoming follows the initial three or four steps used to prepare a thin-section. However, it is very important to dye the pore filler to dark blue or red for a reason to be explained shortly. Figure 3 illustrates the basic steps which are performed in a refrigerated laboratory (-5 °C to -10 °C).

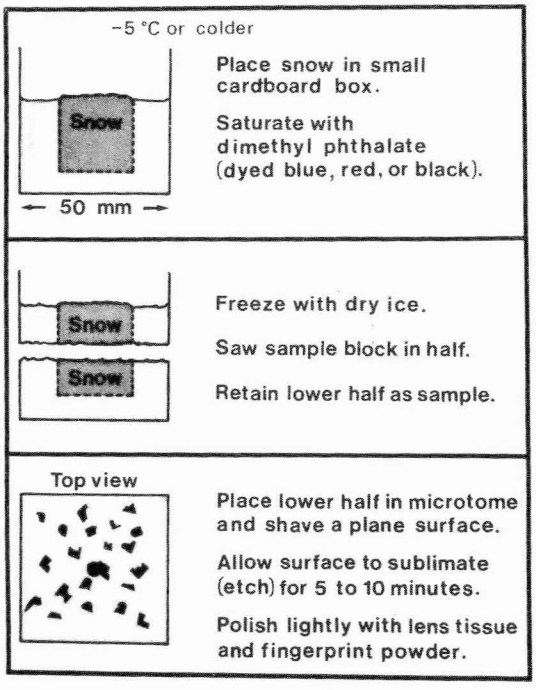

Figure 3.--Preparation of a section-plane in a snow sample.

- Place a small snow sample with approximate cubical dimensions 25 mm X 25 mm X 25 mm into a small cardboard box, which is cut and taped together to dimensions larger than the snow sample but small enough to fit into the microtome clamp.
- Slowly fill the box with the dyed pore filler until the snow cube is completely saturated. Note: If the snow sample is too large it may not be possible to completely saturate its interior.
- Use dry ice particles to initiate freezing of the filler; complete the freezing by storing the sample in a freezer (below -20 °C) for several hours.
- Saw the cardboard box in half, and mount the bottom half in a microtome.
- Make several large cuts, and then some smaller finishing cuts with a clean knife. In between cuts, the microtome knife and the sample surface are vacuum cleaned. The cutting will be smoother if (in the above step) a thin rim of cardboard is removed from around the perimeter of the section so that the knife does not scrape the cardboard edge.
- The sample is removed from the microtome, and allowed to stand for about 5 minutes at -10 °C to -5 °C during which time the ice profiles in the section-plane will sublimate (etch) back from the filler.
- The section-plane is polished very gently with lens tissue.
- A light dusting of fingerprint powder is applied to the section-plane with a cotton swab, and gently polished with lens tissue.

The Appendix provides a list of equipment and supplies needed to prepare section-planes.

PHOTOMICROGRAPHY AND ANALYSIS

The last steps are repeated one or two times until contrast appears adequate for photomicrography. To obtain optimum contrast using incident reflected light, *it is important that the light source and the objective lens of the microscope (or macroscope) be raised as high as possible above the section-plane,* that is, the "working distance" (objective to stage) should be as high as possible; this can be achieved by adding a 0.5X objective lens. The high working distance minimizes the amount of obliquely scattered light that enters the objective. It is also essential to dye the pore filler. Contrary to what may be expected, a dark filler insures that the transparent ice profiles appear much darker than the filler (the analogy is looking through a window into a room with dark walls).

Section-plane preparation is far simpler and quicker than thin-section preparation. The resulting "mathematical plane" can be analyzed using well-developed formalisms from the field of stereology (Weibel 1979, 1980). Section thickness does not enter into the problem, and thus a major disadvantage of the thin-section technique is avoided.

On the otherhand, the section-plane technique (using present technology) provides no information on orientation of crystal axes, and very little,

if any, information on crystal boundaries. Perhaps future improvements in the preparation technique could accentuate crystal boundaries.

SERIAL SECTIONS

The technique of *serial sections* (De Hoff 1983) involves cutting successive, parallel planes down through the sample at sufficiently close intervals (~10 μm to ~100 μm) so that a three-dimensional model can be constructed by correlating ice profiles as illustrated in figure 4, adapted from Steele (1972).

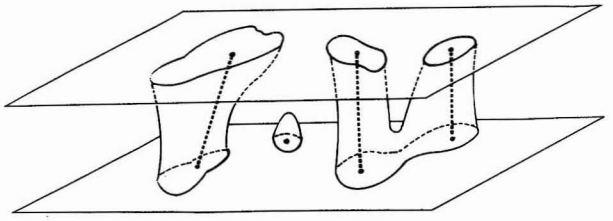

Figure 4.--Correlation of ice profiles on two parallel section-planes. Adapted from Steele (1972).

In order to cut the large number of parallel section-planes, (50 to 150) that are required to characterize the structure, it seems essential that the photomacroscope be mounted directly over the microtome because alignment with the knife will be disturbed if the sample is removed from the microtome for photomicrography and then replaced in the microtome. Alignment with the objective plane of the photomacroscope is not very critical; it is only necessary that 2 or 3 reference points be established in the section (e.g. toothpicks can be inserted in the snow cube before the filler is poured). The photomacroscope can be mounted on a frame which is brought into position over the microtome (fig. 5).

It can be understood that modeling the three-dimensional structure of snow is a challenging and perhaps tedious experimental and theoretical problem, but without some measure of snow topology and/or geometry a systematic treatment of fundamental snow properties will remain elusive.

VIDEO DIGITIZING

In order to analyze mathematically the ~100 serial sections, it is first necessary to convert the photomicrographs into digital format. Walter Good (1979, 1980, 1981, 1982) demonstrated that thin-section images (photomicrographs or real-time imagery with transmitted light) can be captured to a sufficient level of contrast and resolution with a video camera to allow digital processing. Sommerfeld (1983) used digitized data from thin-sections to study snow metamorphism.

The contrast and resolution of section-plane photomicrographs are not as good as thin-section images; however, if the recommended preparation

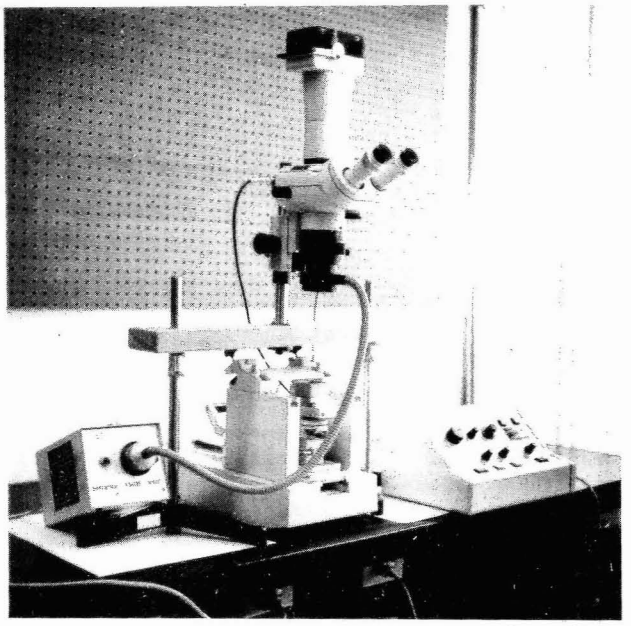

Figure 5.--Arrangement for preparing and photographing serial sections. The photomacroscope is supported on a frame over a microtome.

steps are followed the majority of section-plane photomicrographs will have high enough quality for digital processing.

Reasonable results were obtained using the relatively low-cost equipment diagrammed in figure 6. The photomicrograph in the form of a 35 mm colour slide transparency is inserted in a video adapter (Sony video photolab adapter HVT 3000), converted to a video signal using a Sony HVC-2800 video camera, and digitized in an IBM PC by a video digitizing card (Tecmar's "Video Van Gough"). The digitized image consisted of 240 X 250 = 60,000 pixels. Each pixel is characterized by an 8 bit (0 - 255) brightness level. Similar equipment was used effectively by Yanuka et al (1984) to digitize and analyze other types of porous media.

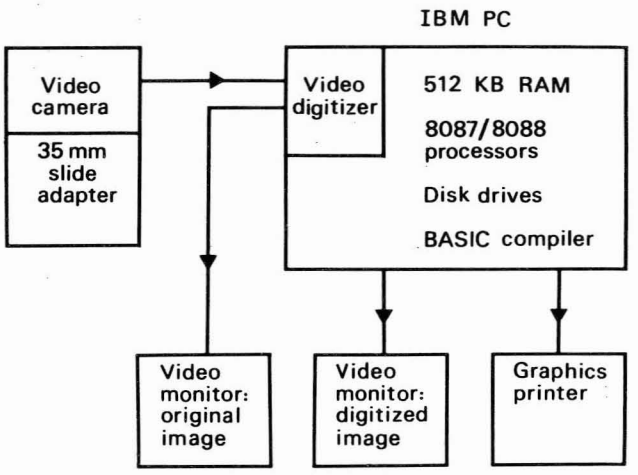

Figure 6.--Block diagram of low cost video digitizing equipment for section-plane analysis.

According to the Nyquist theorem, 60,000 pixels on a 35 mm X 25 mm image yields information to a resolution of (2)(35)(25)/60,000 or about 0.03 mm² which is a square 0.17 mm X 0.17 mm. If the photomicrograph is a 1 : 1 image of the section-plane, then this grid is too coarse for many types of seasonal snow where morphological features of interest are observed at the 0.1 mm scale, and sometimes smaller. A finer scale 512 X 512 pixels seems preferable, and, in fact, video digitizing cards at that scale are now available for the IBM PC (and equivalent micros). Perhaps even a finer scale - 1024 X 1024 pixels would be useful for some sections, although handling that quantity of information for ~100 serial sections would be outside the capability of present microcomputers.

Figure 7 provides an example of a section-plane and part of its digital image constructed with the equipment shown in figure 6.

THREE-PHASE SECTIONS

The distribution of the liquid phase in wet snow is a matter of speculation since neither thin-sections nor section-planes have been prepared for three-phase samples. Existing models based on the concept of liquid water surrounding packed spheres are crude approximations of the interconnected structure.

It is possible to prepare a section-plane from a quasi-three-phase specimen using the following steps:

1. Start with dry, metamorphosed snow with relatively large grains.
2. Bring the sample to 0 °C. Add 0 °C water dyed with acid fuchsin to simulate wet snow.
3. Freeze rapidly with dry ice (liquid nitrogen may be better).
4. Follow steps for section-plane preparation. Allow sublimation, but do not polish the microtomed surface since that would smear the acid fuchsin.

An example is shown in figure 8. In order to prepare a true three-phase section (rather than a quasi-section) it is probably necessary to avoid the freezing of the liquid phase in step 3.

CONCLUDING REMARKS

Thin-section preparation is slow and tedious. One possibility for a faster technique is to develop a compliant pore filler such that the section could peel over the microtome knife as is common practice in histological studies.

The alternative is to use section-planes. Here, the major improvement would be to devise a technique that accentuates crystal boundaries. A physical discontinuity exists at the crystal boundary by definition, and it could be possible to observe this discontinuity using incident, reflected light.

An important breakthrough would be to develop a technique for preparing three-phase sections.

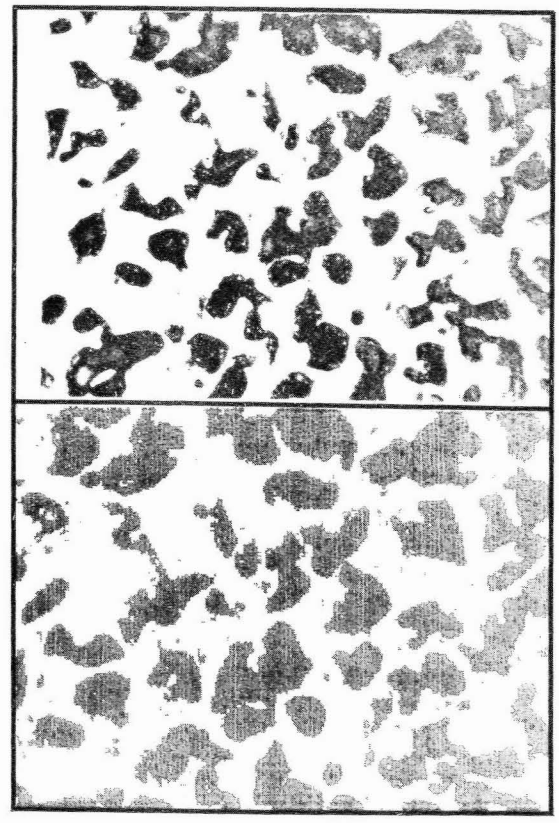

Figure 7.--Photomicrograph of section-plane (top); part of its digital image (bottom).

Figure 8.--Section-plane prepared from a quasi-three-phase sample. Left grid marks are 1 mm apart.

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APPENDIX: SUPPLIES AND EQUIPMENT FOR SECTION-PLANE PREPARATION

There are many combinations of equipment and supplies that can be used in connection with the preparation of section-planes. The list (below) is not meant to endorse any particular brands, but represents equipment and supplies used in our studies.

- Refrigerated workspace. Evaporator fans, baffled by a false ceiling so cold air sinks gently on workers and equipment. The 2.5 m X 2.5 m area is well lit, has viewing windows, and two work benches. Temperature is controllable in the range of 0 °C to -20 °C with ±1 °C fluctuation in long term operation.

- A freezer chest which operates in the refrigerated lab, and maintains storage temperature of -35 °C for long periods.

- Automatic photomacroscope and accessaries: Wild-Leitz M400 optics carrier with drive housing, built-in camera, and binocular tube. Macro-zoom objective 1 : 5. MPS 55 electronic control. Bright-field/darkfield base (needed for transmitted light photomicrography, but not section-plane work).

- Fiber optic ring illuminator (Intralux 150H) compatible with above.

  Base sledge microtome (Leitz model 1400). Cardan object clamp. Two microtome knives (profile C, wedge shape, 240 mm).

- Vacuum cleaner and accessaries (featuring quiet operation at cold temperatures 0 °C to -20 °C.

- CO_2 gas cylinders with siphon attachment.

- Pore filler: dimethyl phthalate (mp 0 °C). Good results were obtained using Matheson, Coleman, and Bell brand.

- Dye: many possibilities. Good results using oil blue N, from Aldrich Chemical Co.

- Fingerprint powder: Good results with Faurot brand "Supersensitive Black".

- Lens tissue (Kodak), cotton swabs, stainless-steel beakers (250-500 ml), shop knife, small hand-saw, bench clamps, Ektachrome film ET 160, dust masks.