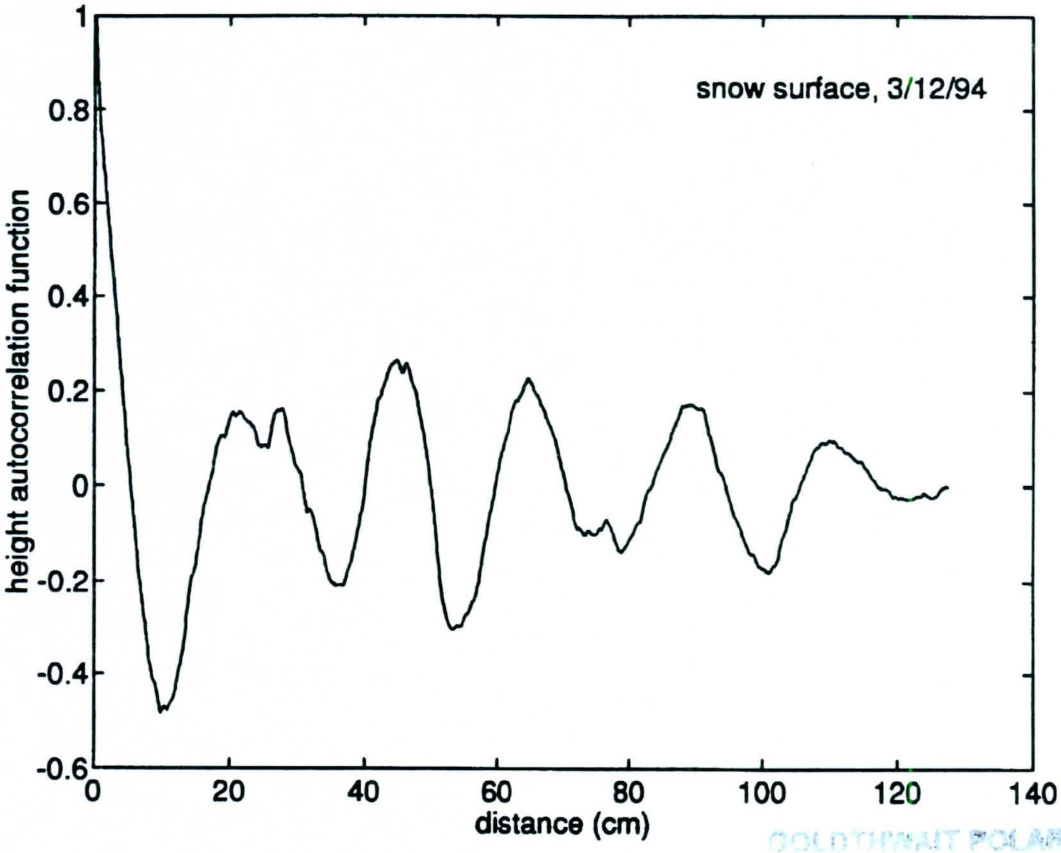
CRRELEX 1994: Surface Roughness and Physical Properties Measurements from Two Experiments



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CRRELEX 1994: Surface Roughness and Physical Properties Measurements from Two Experiments

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1 Introduction

This note summarizes physical properties measurements made by an Ohio State group on two ice sheets grown at CRREL during January and March 1994. The measurements were made in conjunction with radar measurements made by an Ohio State/University of Kansas team. The physical property focused on was ice surface roughness, although other properties were measured as well. More extensive measurements of additional snow and ice properties (temperature and salinity profiles within the ice, brine pocket geometry, etc.) were made by several other investigators [*Jezek*, 1994].

This note is divided in sections as follows. In section 2 we describe the roughness measurements from the first ice sheet. In section 3 we discuss additional physical properties we measured on this ice sheet. Sections 4 and 5 contain information about roughness measurements and other physical properties measurements, respectively, on the second ice sheet.

2 Surface Roughness; First Ice Sheet

The first ice sheet began growing in a covered, outdoor tank in December 1993. By early January 1994 it had reached a thickness of 30 cm, and had grown under dark conditions. Coolers were used to sustain the growth during warm periods; air blown from these coolers created several slightly bumpy patches on otherwise smooth ice.

In the first phase of the experiments we allowed several centimeters of snow to fall on one third of the ice sheet. In the second phase, we roughened the surface of another third of the ice sheet by sprinkling crushed ice cubes on the surface (Figure 1). This created a surface with localized bumps rather than one with smoothly varying undulations. A final third of the ice sheet remained bare throughout the experiment. Figure 2 shows sections of the bare ice, the roughened ice, and the snow-covered ice. The bumpy regions on the bare ice in the foreground of the photo were created partially from disturbing the ice to insert instruments; the bumpy region in the left, upper corner of the photo, however, was due to air blown from the cooling system during inital growth.

We measured surface roughness with two types of comb gauges. Primarily we used five plastic gauges, each 26 cm long (Figure 3), and set them up along a line to get a complete linear profile 130 cm long. In addition, we occassionally used the comb gauge developed during the previous year [*Zabel and Jezek*, 1993] for use on thin ice. Since both ice sheets this year were quite thick, we tended to use the plastic gauges since one could easier obtain long linear profiles with them.

The profiles were traced, photographed, and then digitized. The digitized profiles were detrended to get rid of linear trends in the data due to uneven application of the comb gauge to the surface. We calculated the standard deviation of surface heights about the mean (rms roughness), and the correlation function and correlation length of surface heights. Table 1 shows these statistics for the bare, snow-covered, and rough ice.

To determine the noise in our measurements, we photographed and digitized a flat comb gauge. In this case we found an rms roughness $\sigma = 0.01$ cm. Comparison of this value with values of σ listed in Table 1b shows that the signal to noise ratio for the roughness of the first ice sheet ranged from 2 (for the snow-covered ice) to 19 (for the rough ice). *Beaven et al.* [1994] have shown that low signal to noise ratios can lead to underestimation of correlation lengths. For instance, with a signal to noise ratio of 2 (3 dB), they predict a percent error in the measured correlation length between about 19% and 30% (here percent error is defined as $(l_{true} - l_{measured})/l_{true}$). This result came from a simulation of a rough surface with the addition of Gaussian white noise. As the signal to noise ratio increases, the percent error in correlation length decreases. For instance, for a signal to noise ratio of 6 dB, the percent error in correlation length may be about 13% [*Beaven et al.*, 1994]. Thus we suspect that the true correlation lengths of the very smooth surfaces we measured may be substantially larger than those listed in Table 1b.

3 Other Physical Properties; First Ice Sheet

We focused mainly on the snow-covered portion of the ice sheet, in particular the snow-ice interface. At the center of the pond, the snow thickness was 4.5 cm on Jan. 8, and 8-10 cm on Jan. 15. The interaction of snow with brine near surface of the ice has been shown in previous experiments to lead to increased microwave scattering due to the creation of a rough, saline slush layer at the interface. During the January 1994 experiment, however, we found very dry snow and no slush layer at the snow-ice interface, except at the East and West edges of the tank. The southern edge of the tank had snow-covered ice, but we did not find slush layers. We suspect that this lack of interfacial slush was due in part to the extremely low air temperatures (see Table 3), inhibiting the release of brine to the surface. The slush may have formed at the East and West edges of the tank because the ice sloped downward slightly at those edges.

Figure 4 shows two profiles of snow salinity at the snow-ice interface from West-East cross-sections of the tank, from Jan. 9 and Jan. 11. Inspection shows that salinities are high only at the edges of the tank, and in the center salinities are near or at zero parts per thousand. Figure 5 shows measurements of snow salinity vs. depth from a sample at the East edge of the tank. A saline slush layer of $\sim$ 0.5 - 1 cm thickness existed here, as is apparent in the salinity and in Figure 6. Again, however, for most of the snow-covered region the snow-cover was dry and fresh, even near the snow-ice interface.

Other salinity measurements we made include surface scrapings of the bare ice after a very thin layer of snow had fallen on top of it (Table 2), additional samples of the slush at the tank edges (Table 2), and salinity scrapings in the near surface of the bare ice, down to 5 mm depth (Figure 7).

Table 3 shows several temperature measurements we made at various places on the ice and snow. Much more extensive temperature records were collected by CRREL personnel.

4 Surface Roughness; Second Ice Sheet

In late January the first ice sheet was broken up and removed from the tank, and a new ice sheet grew in its place. We made radar and physical properties measurements on this second ice sheet in March 1994, after it had reached a thickness of 33 cm. At the time of the experiments, the ice had a snow cover with more complex stratigraphy than in January. For instance, the snow cover contained regions of slush and regions of hard crusts. The details of this stratigraphy will be discussed in the next section.

During several days the snow surface warmed melted slightly, then froze at night, leaving a hard crust. This crust was strong enough that we could place comb gauges on it. We obtained one long (130 cm) measurement of the snow surface roughness statistics, and found rms roughness σ = 0.06 cm and correlation length l = 3.0 cm. This was the longest correlation length of any surface we measured, and indeed the snow surface appeared to the eye to have long-wavelength, gentle undulations (Figure 8).

As part of the March experiments we scraped away about 5 cm of snow in the center of the pond, down to a hard crust. We then made radar and roughness measurements on this snow-free but disturbed surface (Figure 9). Table 4 gives roughness statistics for this surface. It was not as rough as the ice-cube roughened ice produced on the first ice sheet, but it was rougher than undisturbed bare ice.

Finally, we attempted to measure the roughness of this buried crust in a small region along the edge of the pond, where the overlying snow could be scraped away more carefully. We found, from an average of two measurements, σ = 0.07 cm and l = 1.2 cm. These results may still not represent the true roughness of the crust, since one could not uniformly remove the overlying snow and slush which had formed along the edge. But these measurements show that the crust was probably less rough than the results from a coarser removal of snow (Table 4) suggest.

5 Other Physical Properties; Second Ice Sheet

Figure 10 shows several snow stratigraphies from the snow cover on the ice sheet. The upper portion of the snow cover consisted of about 5-10 cm of wet snow, interbedded with slushy snow layers, and covered by a hard, large-grained crust (Figure 11). Below this snow was a hard crust, followed by a wet, slushy zone of perhaps 5 to 15 cm thickness. When the hard crust was penetrated, water emerged from this slushy zone, making the total depth and character of the zone difficult to determine. The crust contained some large-scale air pockets ($\sim$ 1 cm in diameter), as well as many smaller bubbles ($\sim$ 100 - 400 per cm^2) with diameters ranging from about 0.1 to 3 mm (Figure 12).

Table 5 gives densities at various depths in the snow layer, taken by measuring the mass of snow collected in several different scoops of known volume. The table also lists salinities of the density samples. Table 6 lists temperatures in the air, at the snow surface, and at the surface of the buried, hard crust at various times. On March 12 at 07:30, temperatures of the crust (now exposed after the snow cover was scraped away), the slush beneath the crust, and the ice sheet surface; these temperatures were, respectively, -5.1°C, -0.9°C, and -1.0°C. The negative temperature of the slush suggests that it was slightly saline.

6 Acknowledgements

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7 References

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Table 1a

Surface roughness of first ice sheet (σ = rms roughness; l = correlation length).

Date	Sample length (cm)	σ (cm)	l (cm)	comment
Jan. 8	105	0.02	0.45	south end, ice under snow
Jan. 8	105	0.02	0.28	south end, ice under snow
Jan. 9	168	0.15	2.75	bare ice, bumpy patch
Jan. 9	168	0.1	2.2	bare ice, bumpy patch
Jan. 9	42	0.03	0.6	bare ice, smooth region
Jan. 9	42	0.03	0.6	bare ice, smooth region
Jan. 9	189	0.09	2.2	bare ice, bumpy patch
Jan. 9	189	0.10	2.0	bare ice, bumpy patch
Jan. 11	104	0.05	1.8	bare ice, bumpy patch
Jan. 11	130	0.11	2.0	bare ice, bumpy patch
Jan. 12	130	0.09	2.6	bare ice, bumpy patch
Jan. 14	130	0.22	0.8	rough ice
Jan. 14	130	0.20	0.8	rough ice
Jan. 14	130	0.18	0.6	rough ice
Jan. 14	104	0.19	0.8	rough ice
Jan. 14	130	0.22	0.6	rough ice
Jan. 15	130	0.13	0.6	rough ice
Jan. 15	130	0.16	0.8	rough ice
Jan. 15	130	0.05	1.4	bare ice
Jan. 15	130	0.04	1.6	bare ice
Jan. 15	130	0.03	1.4	bare ice
Jan. 15	130	0.08	2.6	bare ice
Jan. 15	130	0.17	1.0	rough ice
Jan. 15	130	0.15	1.0	rough ice
Jan. 16	130	0.25	0.8	rough ice
Jan. 16	130	0.20	0.6	rough ice
Jan. 16	130	0.17	1.0	rough ice
Jan. 16	130	0.25	0.8	rough ice

Table 1b
Mean surface roughness statistics for the first ice sheet.

	mean σ (cm)	mean l (cm)
south end, ice under snow:	0.02	0.36
bare ice, bumpy patch, Jan. 9,11,12	0.1	2.22
bare ice, smooth region, Jan. 9	0.03	0.6
rough ice, Jan. 14,15,16	0.19	0.8
bare ice, Jan. 15	0.05	1.75

Table 2
Assorted salinities

Date and time	location	comment	salinity (ppt)
Jan. 9, 20:00	pond center	surface scrape, bare ice and light snow dusting	47
Jan. 9, 20:00	east edge	surface scrape, bare ice and light snow dusting	48
Jan. 10, 16:30	east edge	surface scrape, bare ice and light snow dusting	46
Jan. 10, 16:30	east edge	slush at ice/snow interface	28
Jan. 11	east edge	snow surface	0
Jan. 11	east edge	ice/snow interface	14
Jan. 11	east edge	ice surface scrape	52
Jan. 16	-	bare ice	50-80

Table 3
Temperatures (some are averages of several readings)

Date and time	air (°C)	air/snow interface (°C)	snow/ice interface (°C)	bare ice surface (°C)
Jan. 8, 22:00	-	-10.2	-5.0	-
Jan. 8, 23:15	-11	-	-	-
Jan. 9, 20:00	-11	-14	-10	-
Jan. 11, 17:30	-	-5.9	-7.1	-
Jan. 15, 20:30	-19.9	-20.7	-3.6	-13.6

Table 4
Surface roughness of scraped ice/hard crust layer (March 12, 1994)

sample length (cm)	σ (cm)	l (cm)
130	0.12	1.0
78	0.12	1.0
52	0.24	0.8

Table 5
Snow cover densities and salinities

Date and time	density (g/cm^3)	grain diameter (mm)	salinity (ppt)	comment
Mar. 11, 16:10	0.64	0.5 - 2	<0.1	surface crust; large, round grains
Mar. 11, 16:10	0.30	0.2 - 0.5	<0.1	snow depth 1.5-4.5 cm
Mar. 11, 16:10	0.33	fine grains	0.4	snow depth 7-10 cm, some slush
Mar. 11, 16:25	0.58	0.5-2	<0.1	surface crust; large, round grains
Mar. 11, 16:25	0.33	fine grains	<0.1	snow depth 2-5 cm
Mar. 11, 16:25	0.28	fine grains	1.3	snow depth 5-8 cm, some slush.
Mar. 11, 17:30	0.24	fine grains	<0.1	snow depth 3-8 cm; wet snow
Mar. 11, 18:30	0.56	-	<0.1	surface crust
Mar. 11, 18:30	0.28	-	<0.1	snow depth 2-5 cm
Mar. 11, 18:30	0.34	-	0.4	snow depth 8-11 cm, some slush
Mar. 11, 19:15	-	-	0.8	slush directly below crust at depth
Mar. 12, 11:55	0.39	-	-	mix of surface crust and snow

Table 6
Temperature

Date and time	air (°C)	snow surface (°C)	buried crust (°C)
Mar. 11, 16:10	2.0	0.4	0.1
Mar. 11, 16:45	0.1	-1.1	-0.1
Mar. 11, 18:40	-4.0	-4.7	0
Mar. 12, 06:45	-12.7	-12.3	-4.7
Mar. 12, 11:55	-	3.8	-0.1

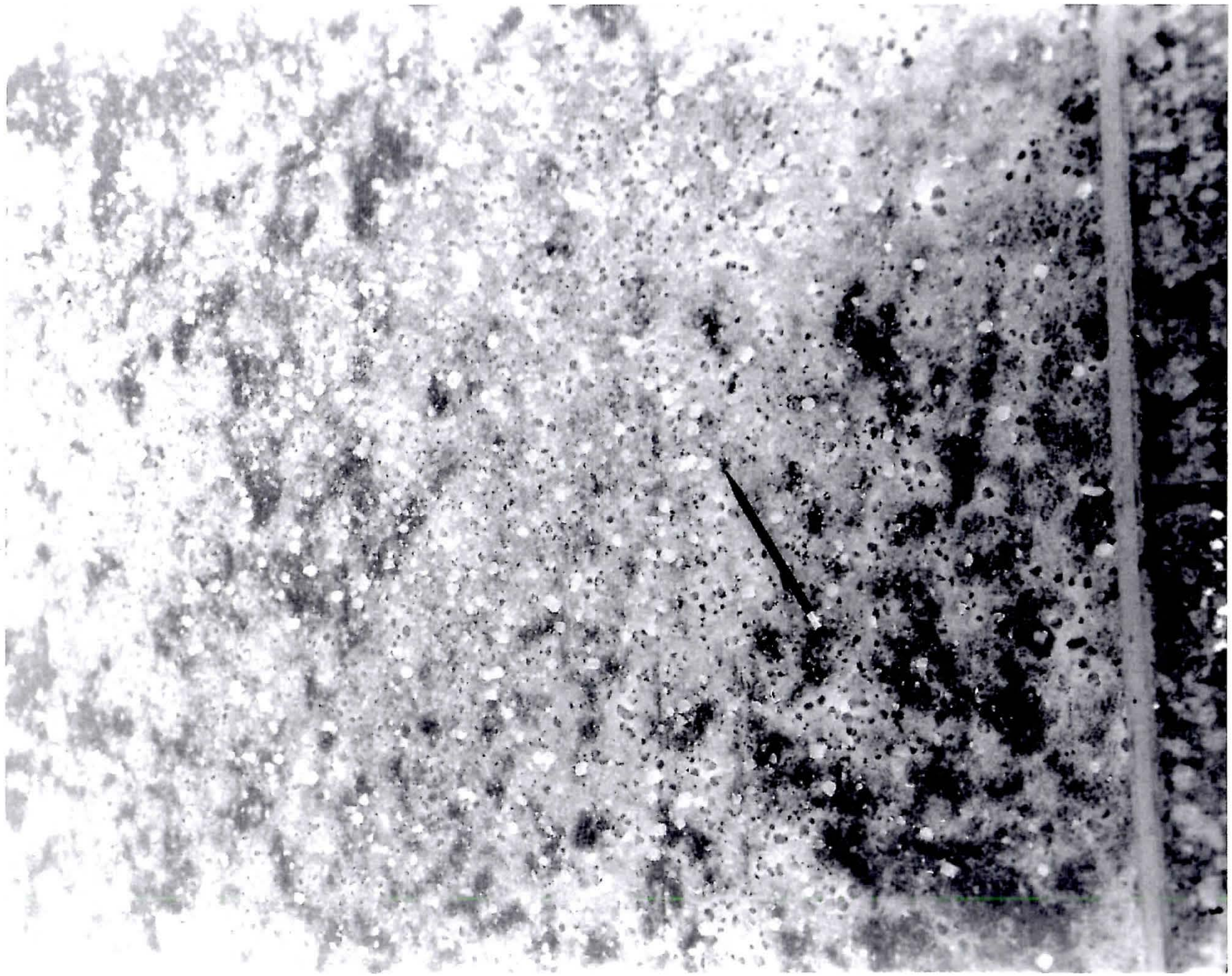

Figure 1: Detail of roughened portion of first ice sheet.

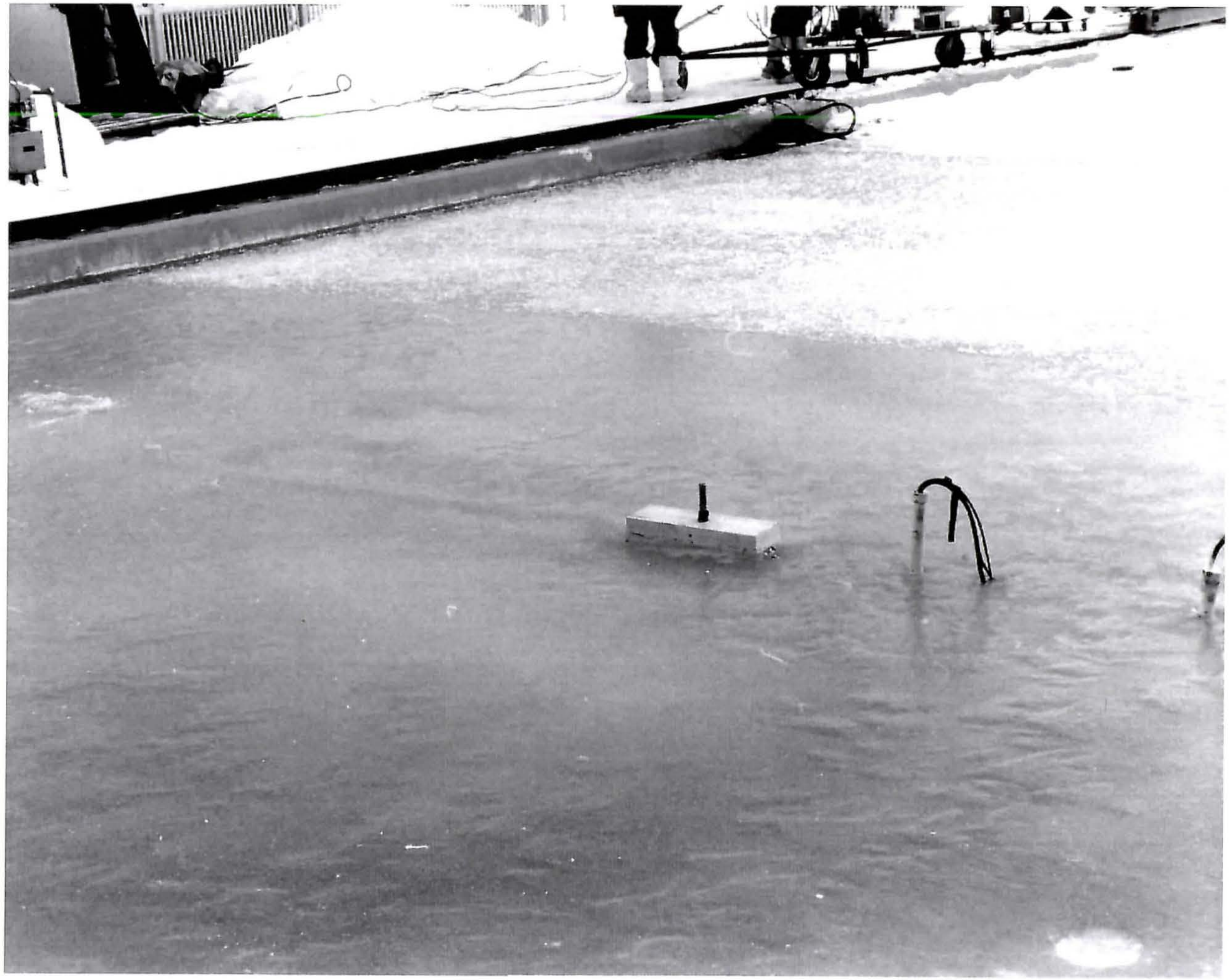

Figure 2: Bare, rough, and snow-covered portions of first ice sheet. Rough patch in upper left corner of the photo resulted from air blowing from a cooler during initial growth. Several such patches existed throughout the ice sheet.

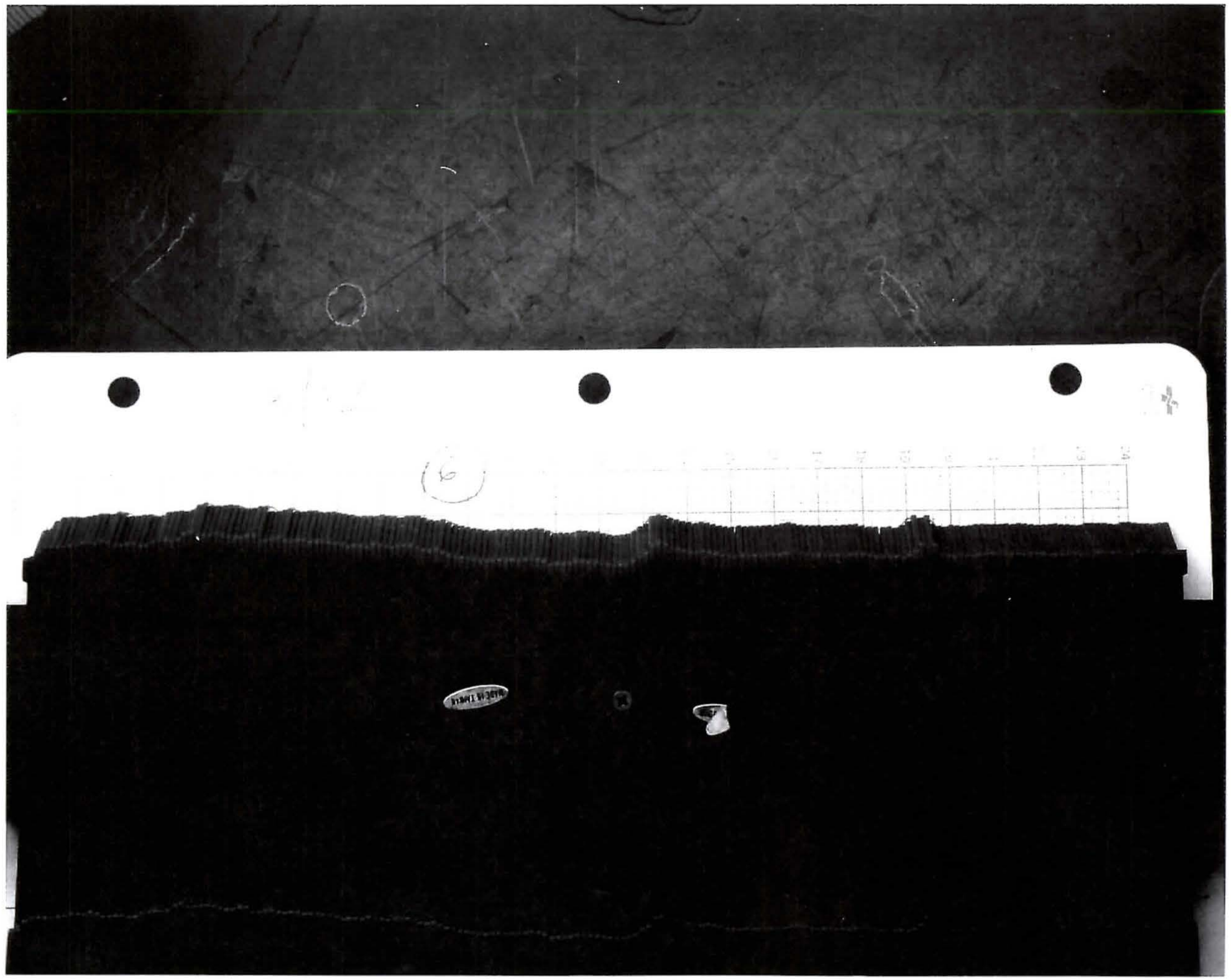

Figure 3: Plastic comb gauge used for most roughness measurements.

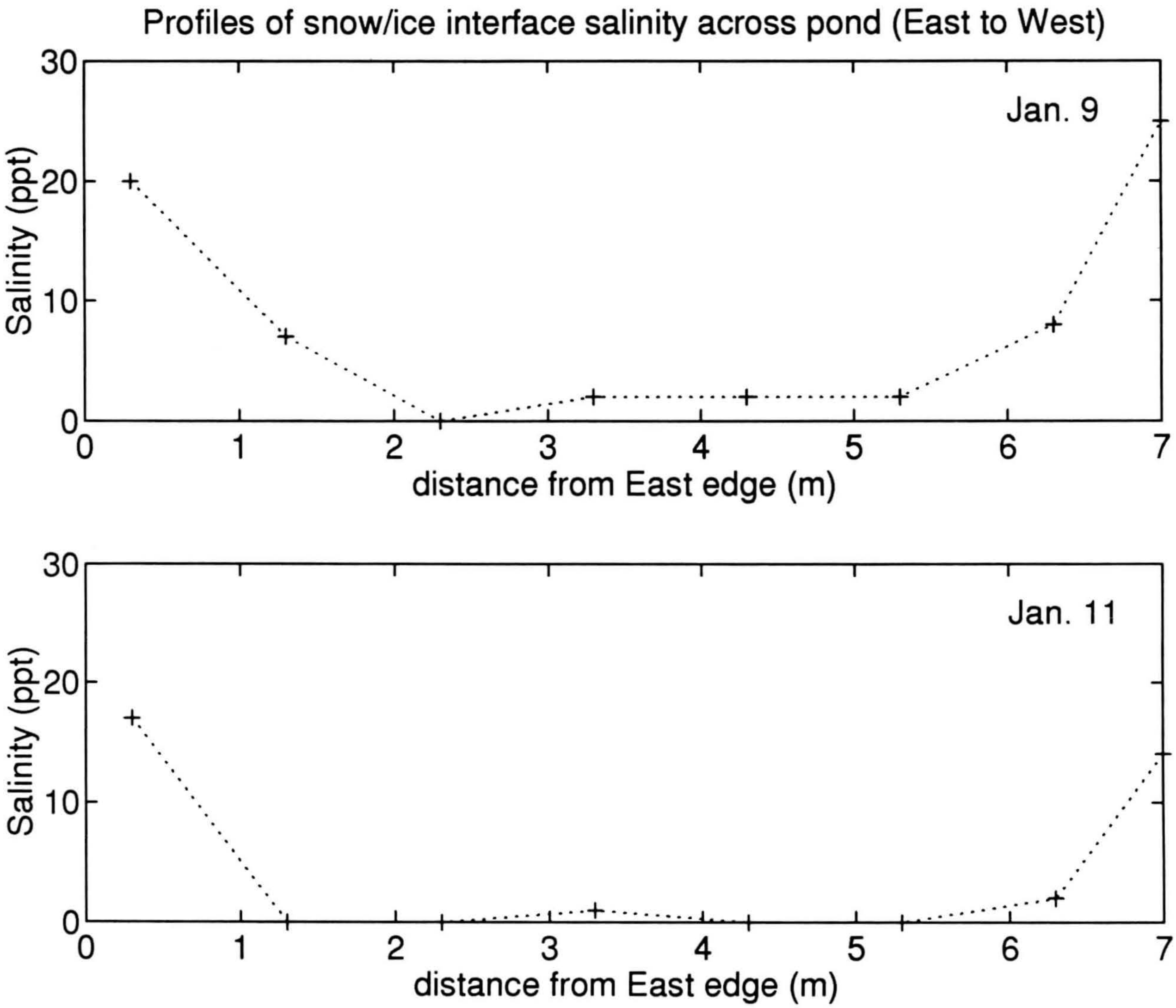

Figure 4: Transects of salinity of snow/ice interface across the first ice sheet. Salinity was measured in the snow at the interface. Distances are approximate.

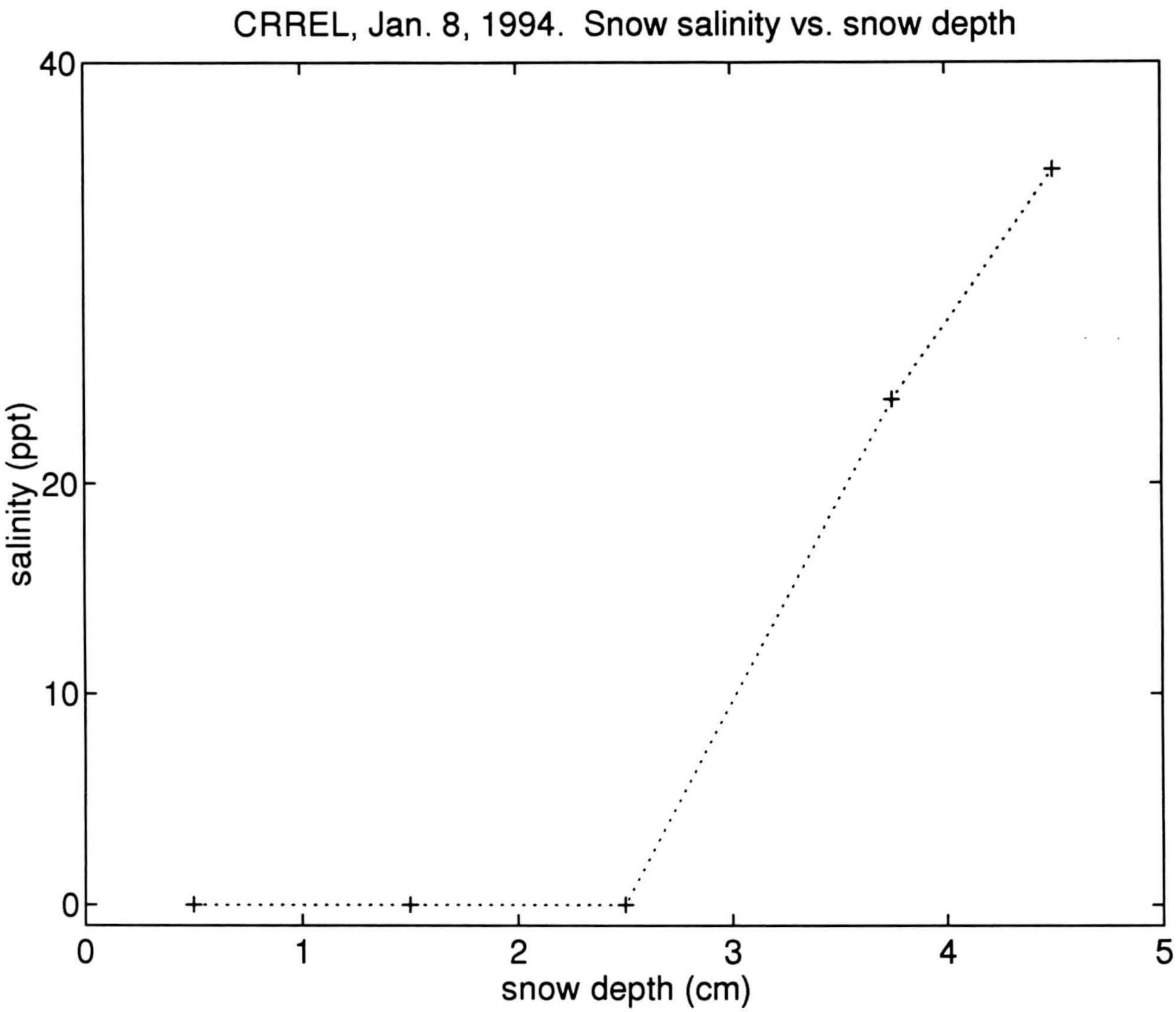

Figure 5: Salinity vs. depth in the snow covering the first ice sheet, at the East edge of the pond.

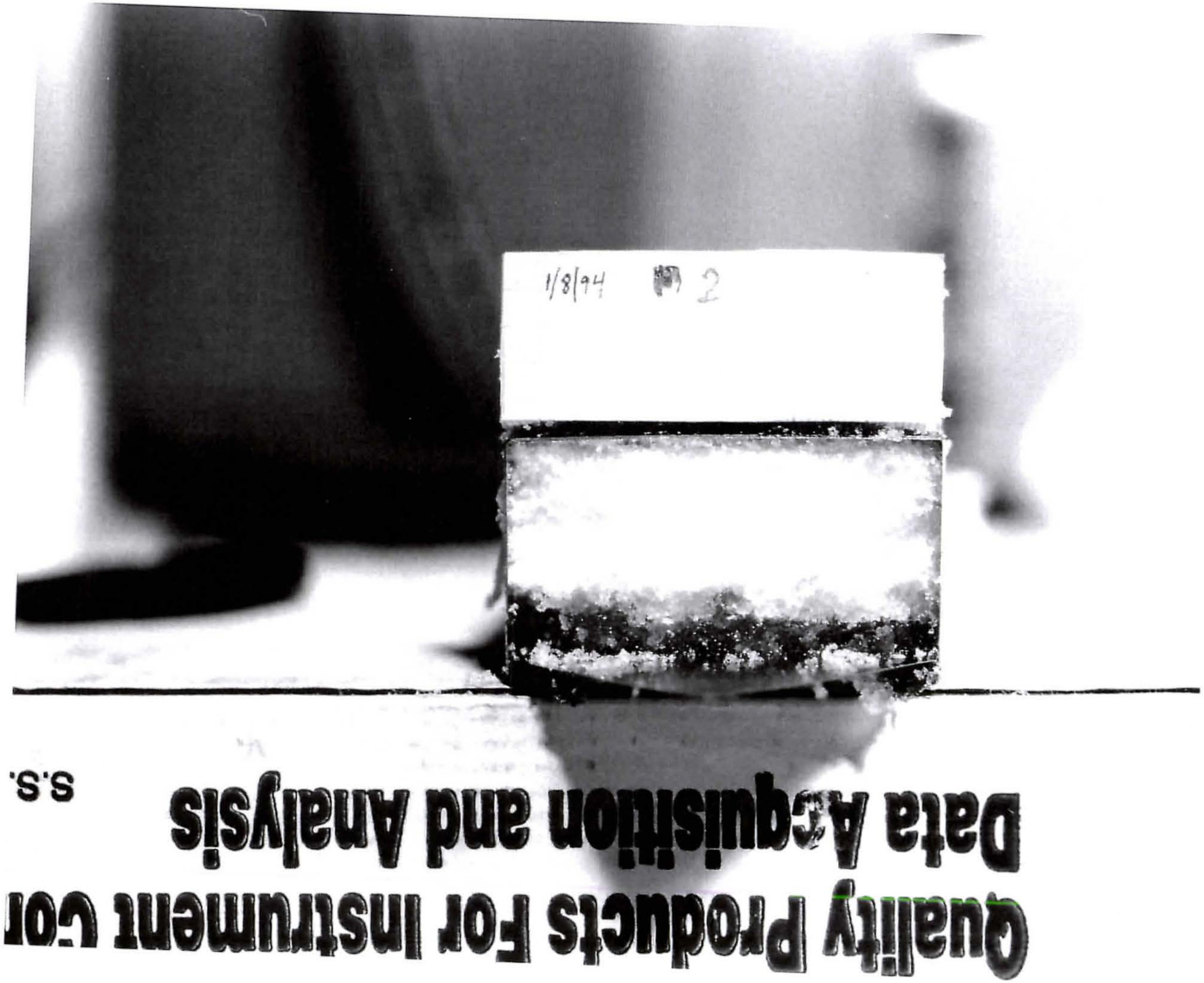

Figure 6: Sample showing snow cover and slush layer at ice interface from the first ice sheet, East edge of the pond.

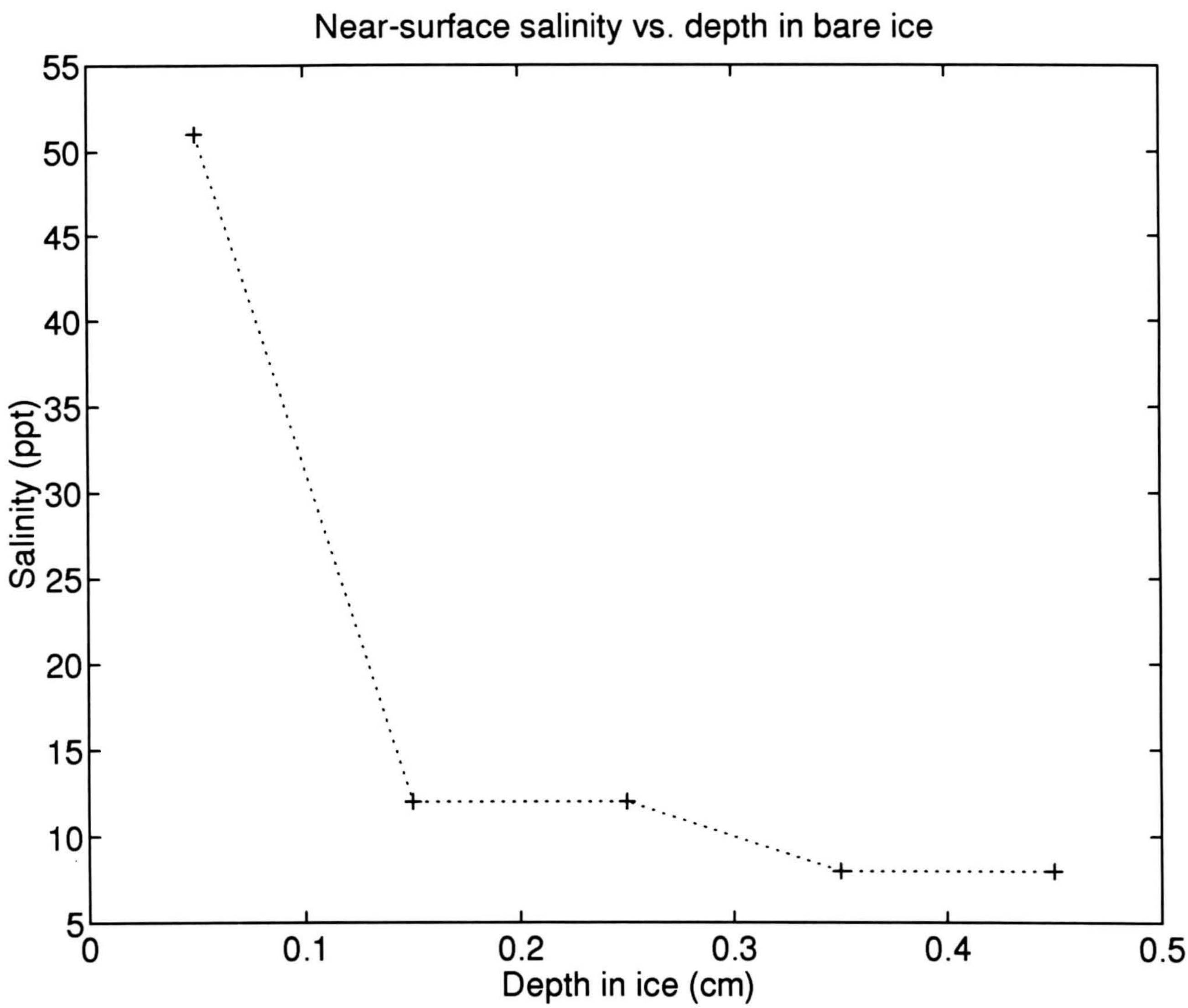

Figure 7: Salinity vs. depth in the near surface of the bare ice, acquired using T. Grenfell's instrument. First ice sheet.

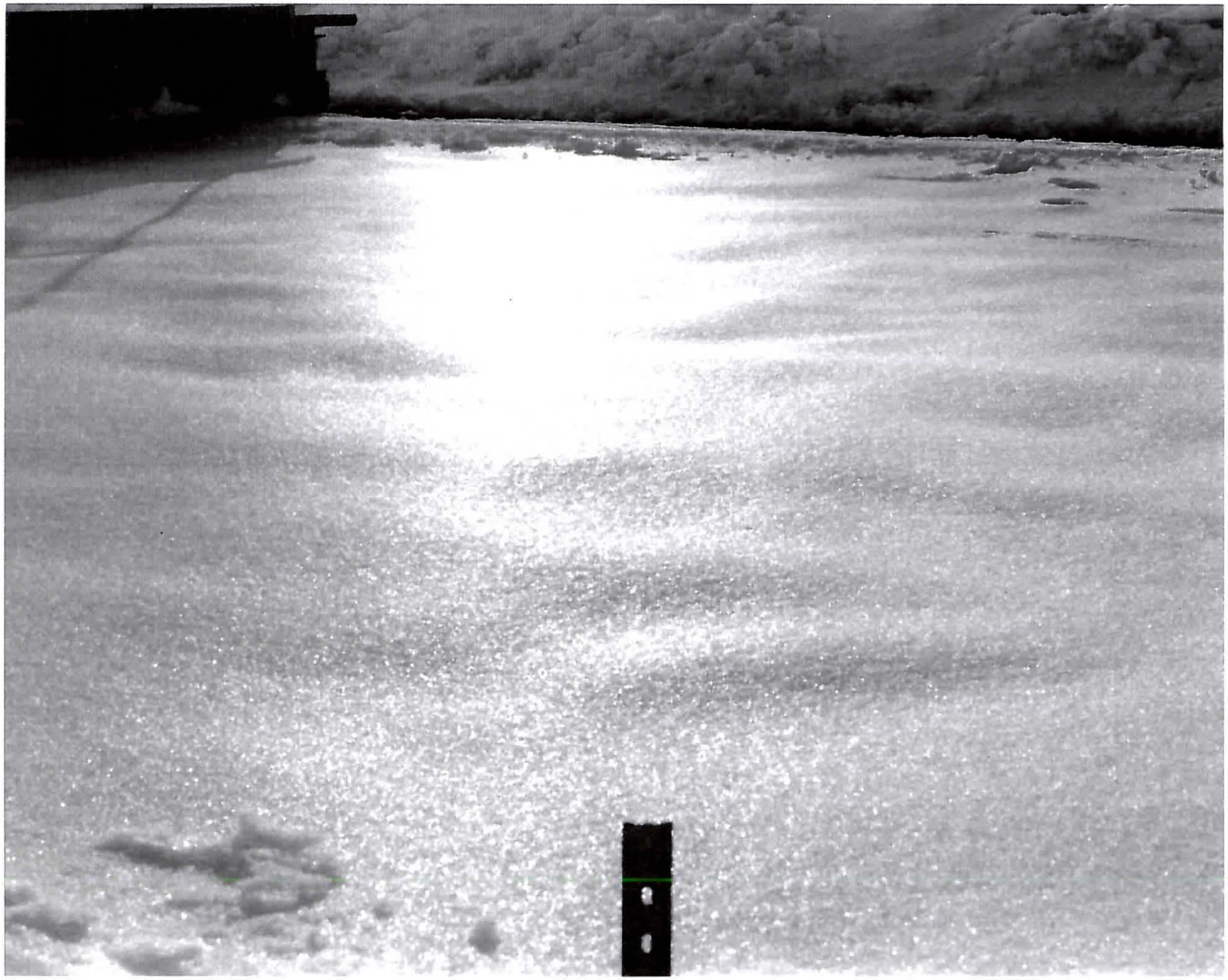

Figure 8: Long-wavelength, gentle undulations on surface of snow cover on second ice sheet.

Figure 9: Portion of second ice sheet where snow cover was scraped away down to a hard, icy crust.

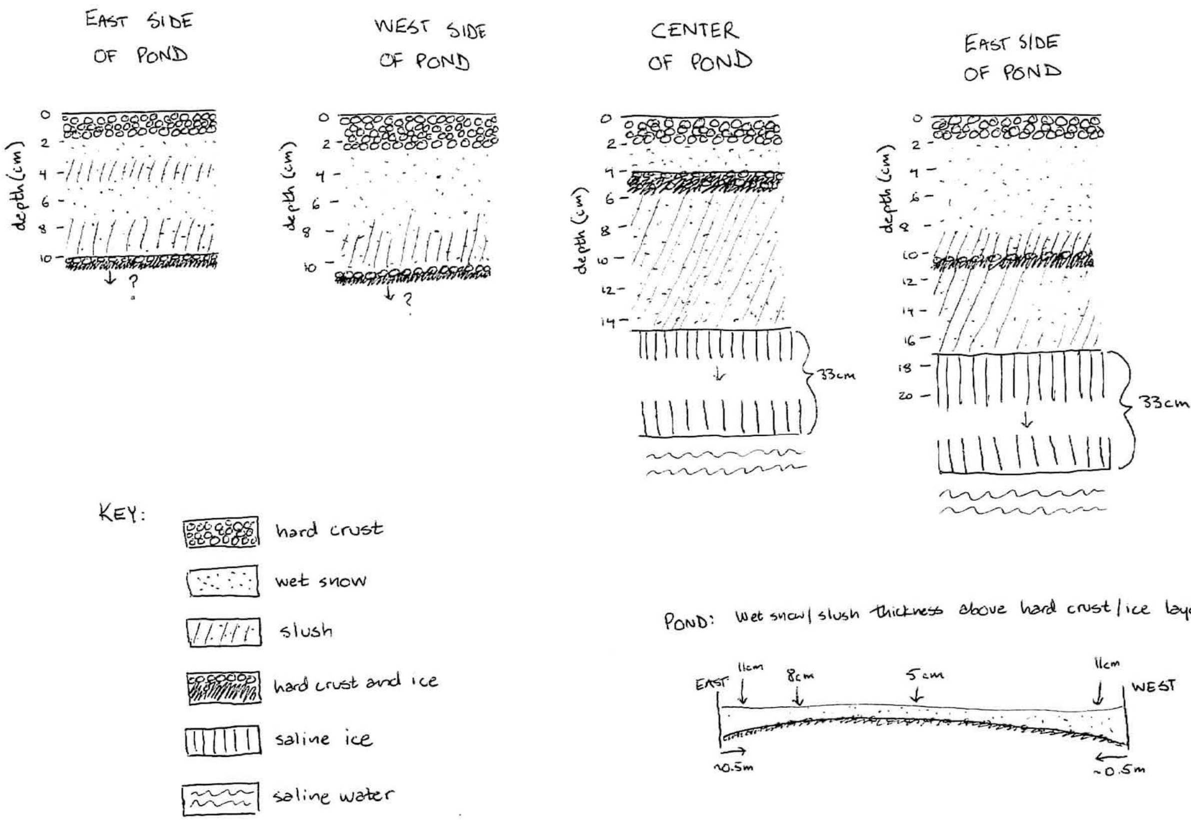

Figure 10: Snow stratigraphies from second ice sheet at various locations.
The two shallow stratigraphies only probed down to the hard, icy crust.
Also shown: linear profile of snow thickness above this crust, across the pond.

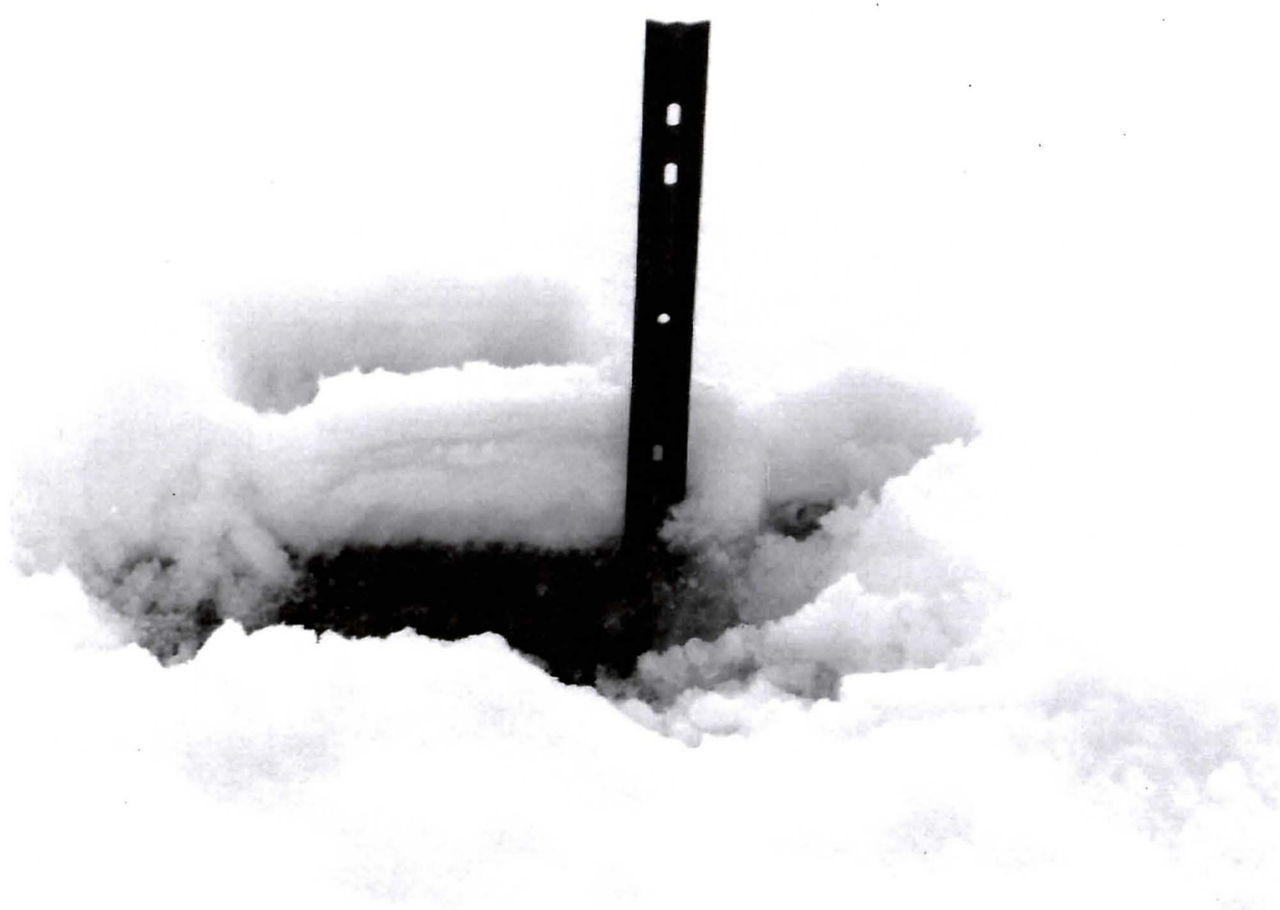

Figure 11: Snow cover on second ice sheet; note slush bands. Taken at East edge of ice sheet.

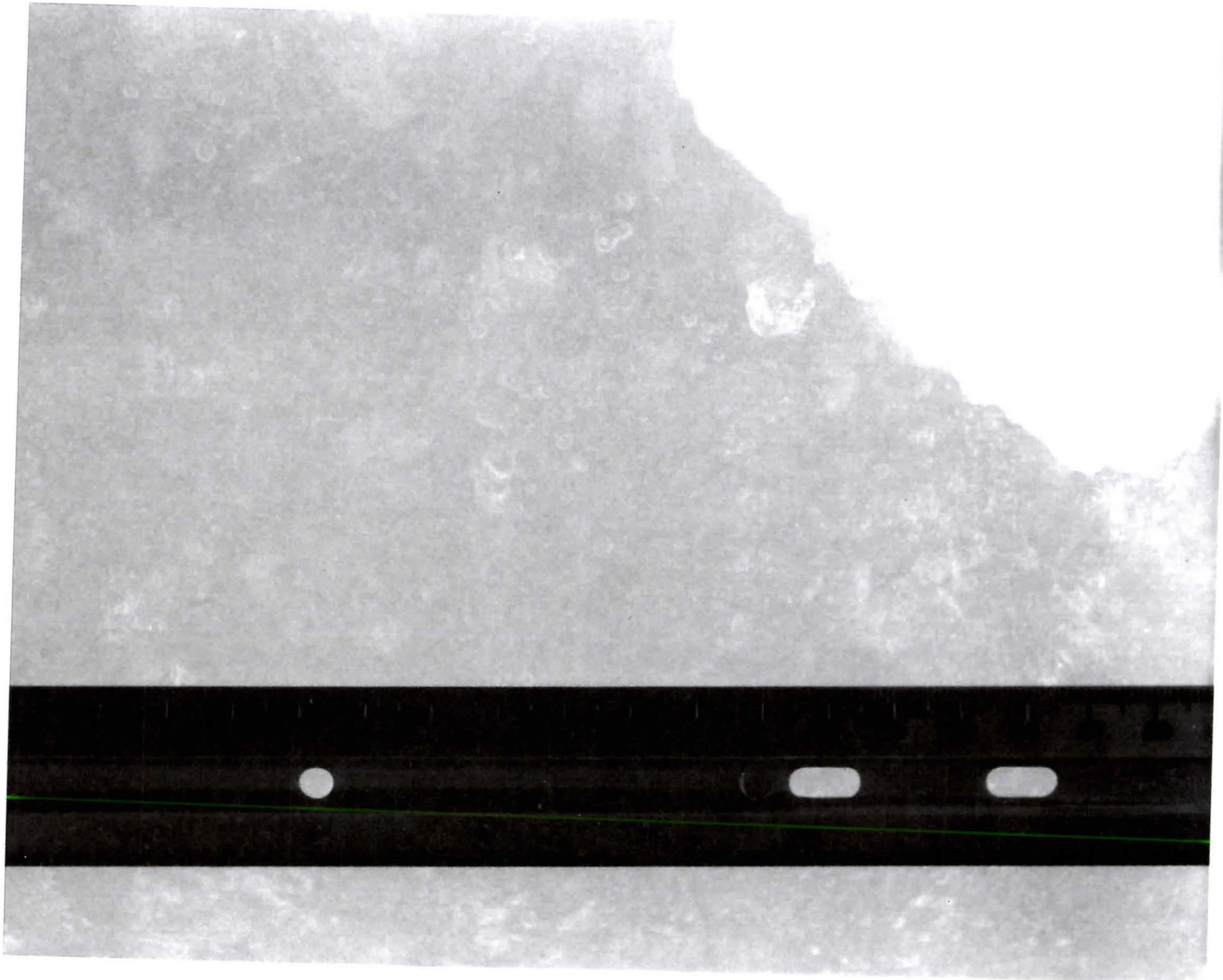

Figure 12: Top view of air bubbles in hard, icy layer revealed after scraping away snow cover (cf. Fig. 9).