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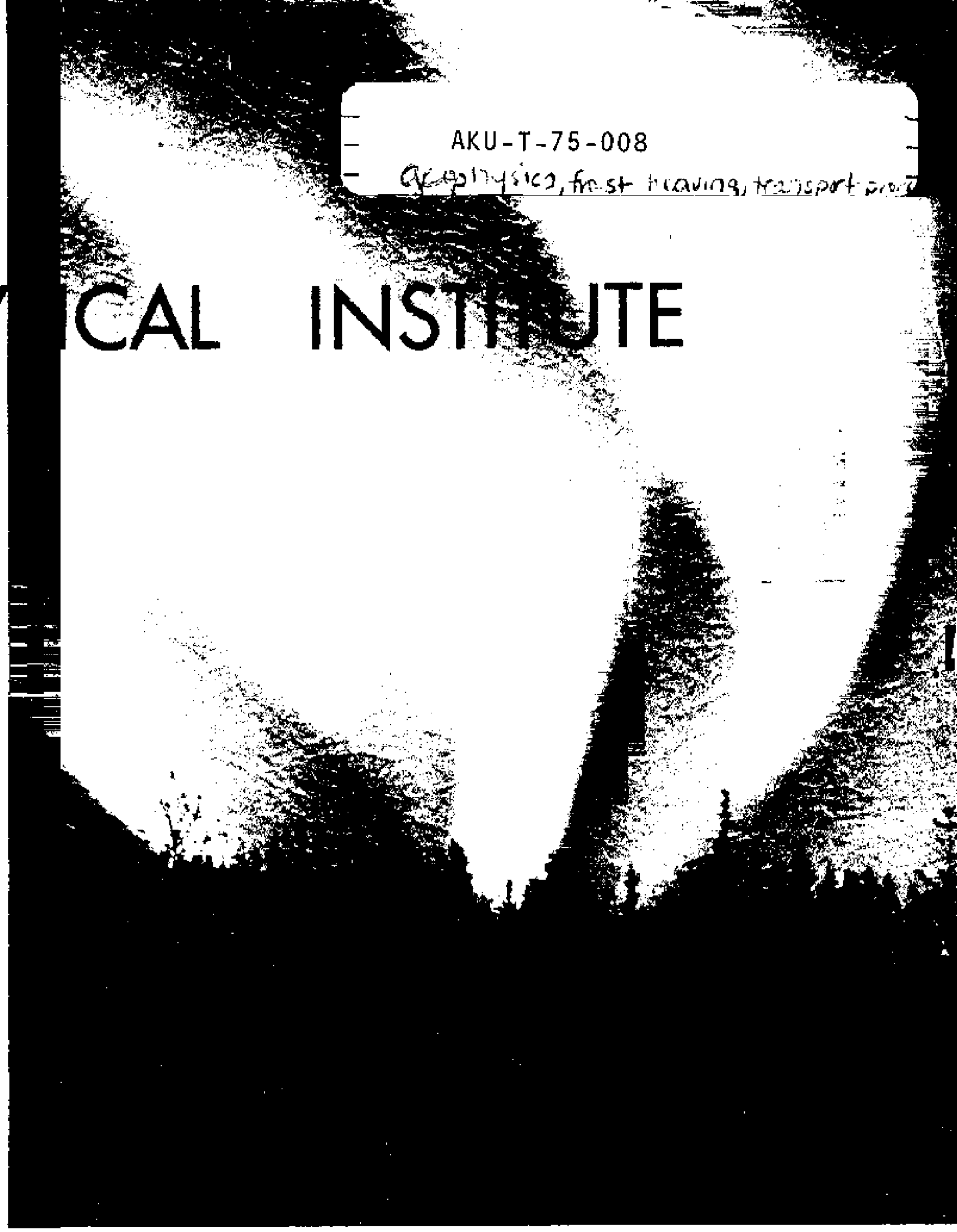

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STRUCTURE AND PROPERTIES OF ICE LENSES IN FROZEN GROUND

by

T. E. Osterkamp

SCIENTIFIC REPORT

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Sea Grant Report No. 75-2

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SUMMARY

A diamond wire saw was modified for cutting thin sections of frozen soil and suitable operating conditions were determined experimentally. It was found that a lubricated wire, 0.34 mm in diameter, operated at cutting speeds < 30 cm s^{-1} and cutting forces < 100 g produced smooth cut surfaces on thin sections 0.4-0.5 mm in thickness. The temperature and wire size were not critical operating parameters and the wire tensions recommended by the manufacturer were satisfactory. A technique for mounting, photographing and storing the thin sections is described.

More than 50 thin sections were cut from several frozen ground cores. Ice lenses in a well-drained silt were few in number and formed as filaments or small platelets. Ice lenses in a sandy clayish loam were numerous and formed as thin platelets (0.01-5 mm in thickness and up to several cm^2 in area). The ice crystals in these ice lenses were elongated in the vertical direction with nearly vertical crystal boundaries extending from one side of the lenses to the other. Crystal sizes in horizontal cross-section were $\sim$ 1 mm^2 and the number of 3-grain boundaries intercepting a horizontal plane was $\sim 1.2 \times 10^2$ cm^{-2} of ice lens.

The possible flux of water through ice lenses in frozen soil near the melting point was estimated to be $\sim$ 1 cm day^{-1}. The equilibrium

temperature of ice lenses in the soil was found to be dominated by pressure and impurity effects. The apparent specific heat capacity of the ice lenses increases near the melting point of the ice, but may not have a significant effect on the apparent specific heat capacity of the frozen soil due to the relatively small unfrozen water content ($W_u' \sim 4 \times 10^{-3}$) of the ice lenses.

INTRODUCTION

Frozen ground often contains ice lenses which form when the soil freezes. These ice lenses cause frost heaving and also have a marked effect on the physical and mechanical properties of frozen soil. In addition, ice lenses modify transport processes (e.g., infiltration of water into frozen soils, moisture migration during freezing and heat transfer) in frozen soils. While some effort has been directed toward determining the structure and properties of ice lenses (Penner, 1961; Kinosita, 1966; Miller, 1973; see also the review by Anderson and Morgenstern, 1973) it has been hampered by the lack of a method for cutting frozen soils into thin sections which are necessary to study the structure of the ice. This paper describes methods for cutting frozen soils into thin sections and for preparing and photographing these thin sections. Results obtained on the structure of ice lenses are presented and the observations and implications of liquid 3-grain boundaries in ice lenses at temperatures near the melting point of the ice lenses are discussed.

EXPERIMENTAL

A diamond wire saw (Lastec Model 2006A) used for cutting semiconductor elements for micro-electronic applications was modified to cut thin sections of frozen soil. The modifications consisted of using low temperature lubricants in all moving parts and redesigning the sample support table to accommodate cylindrical frozen soil cores. Thin sections as thin as 0.2 mm were cut with the saw but these proved to be too fragile to handle conveniently and thicknesses of 0.4-0.5 mm or more were used for these studies. The thin sections were cut with the saw mounted in a deep freeze unit as in Figure 1 or in a cold room. Operating temperatures ranging from -3°C to -25°C were used but the temperature did not appear to affect the quality of the thin sections.

At high wire speeds (wire velocities > 40 cm s^{-1}) excessive wire vibration caused rough surfaces on the thin sections. Wire speeds in the range 10-30 cm s^{-1} produced smooth cut surfaces in a reasonable period of time. Cutting forces > 100 g left ridges on the thin sections and forces of 20-100 g were found to produce a smooth cut surface. The wire tension recommended by the manufacturer was satisfactory and wire sizes 0.076-0.38 mm diameter were used, however, the fine wires had a tendency to break and the thickest wire was stiff and difficult to handle. A wire diameter of 0.34 mm was found to be a convenient compromise. It was necessary to use a lubricant (Dow Corning 200 fluid) applied at a rate of several drops per minute to the wire to obtain smooth cuts and to prevent deposition of soil particles on the surface of the thin sections. The guide pulleys for the wire had to be cleaned regularly to prevent soil particles from depositing on them which caused the wire to wander and produce a ragged cut surface.

When a thin section was cut from a core it was placed on an absorbent tissue and the lubricant wiped from it with another tissue. The thin section was then mounted between two projector slide cover glasses, the edges sealed with tape, and then placed in a plastic bag which was also tightly sealed. Thin sections prepared and mounted in this manner were kept for several months in a deep freeze at -25°C with no apparent deterioration. The thin sections were photographed with ordinary light and with polarized light using a 35 mm SLR camera with a macro lens. Details of the ice crystal structure and the 3-grain boundaries were determined by placing the thin sections on the cold stage of a low power binocular microscope which was also fitted with a camera attachment for photographing the thin sections.

RESULTS AND DISCUSSION

Several frozen ground cores were obtained from a well-drained site (Footprint Creek) near Barrow, Alaska. These cores were silt overlain by organic material a few cm thick. A frozen ground core was also obtained from a wet, silty area (Goldstream Creek) near Fairbanks, Alaska. One frozen ground core was obtained from the Tomakomai field station of the Institute of Low Temperature Science, Sapporo, Japan. This core was a sandy clayish loam (28% sand, 31% silt and 41% clay) with an average specific surface area of 57 m^2 g^{-1} (Kinosita, 1973). More than 50 thin sections were cut from these cores and the structure of the ice lenses examined by the above methods. The thin sections were cut with their planes either vertical or horizontal with respect to the ground surface.

The soil at the Footprint Creek site was relatively dry and not typical of the wet tundra nearby. An example of a vertical thin section illustrating the size and distribution of the ice lenses is given in

Figure 2. The ice in this soil formed in isolated lenses often separated by several cm with scattered ice masses up to ~ 1 mm in size. Many of these ice masses were single crystals of ice. The ice mass in Figure 3 is ~ 0.2 mm x 2 mm and consists of several individual crystals or grains. Figures 4 and 5 are horizontal thin sections. Comparison of Figures 2-5 suggests that the ice lenses in this soil exist as filaments or small platelets.

A root (~ 0.5 mm thick) is shown in Figure 6 in a vertical thin section. An ice layer can be seen at the edge of the root and an ice layer also appears to exist under the surface layer of the root. Since this method of cutting frozen soil preserves the relationship of the ice, roots and soil it may be possible to use it to study the effects of root damage by freezing.

The soil at the Goldstream Creek site was overlain by several cm of ice. Figure 7 shows a vertical thin section with the ice on top and Figure 8 is a horizontal thin section. A root with an associated ice layer can also be seen in the lower part of Figure 7. The ice lenses shown in Figures 7 and 8 are up to ~ 0.2 mm thick and ~ 1 cm^2 in area. The largest ice lens in Figure 8 contains several mm size crystals.

Figure 9 shows a vertical thin section cut from the 11-14 cm depth from the core obtained at the Tomakomai field station. Numerous ice lenses exist in this thin section with thicknesses in the range 0.01-5 mm with lenses < 1 mm thick predominant. The number of ice lenses intercepted along a randomly placed vertical line was 1-12 cm^{-1}. Figure 10 shows the details of the crystal structure of several small ice lenses. The ice crystals within the lenses were elongated in the direction of heat flow (vertically) which made the grain boundaries nearly vertical and the horizontal soil-ice boundaries were uneven, implying that the freezing plane was also uneven as it penetrated the soil. These observations are similar to those of Penner (1961).

Figure 11 is a horizontal thin section through a thick ice lens ($\sim$ 5 mm). The grain size was $\sim$ 0.8 mm and the number of 3-grain boundaries intercepting the horizontal plane was $\sim 1.2 \times 10^{2}$ cm^{-2}. The grain size of the small ice lenses was nearly the same ($\sim$ 0.7 mm). Very few air bubbles were in the ice lenses but the ice always contained small soil particles (0.01 mm and smaller) interior to the crystals and occasional soil particles could be found at the 2- and 3-grain boundaries.

Nye and Frank (1973) have proposed that temperate glacier ice (ice near its melting point) should be permeable to water along a 3-dimensional network of veins lying in 3-grain intersections. Raymond and Harrison (1975) have recently observed these veins in temperate glacier ice and Langham (1974) observed similar veins in ice layers in a wet snow cover. Browman (1973) observed veins in lake ice near its melting point and Osterkamp (unpublished research) has observed these veins in lake ice and river ice at temperatures near their melting points. Due to the general nature of the physical mechanisms that produce the veins (Nye and Frank, 1973) it was believed that they should also occur at 3-grain boundaries in ice lenses in the soil and a search was initiated for them. Figure 12 shows a sequence of photographs of a horizontal thin section of ice ($\sim$ 2 mm thick) taken from an ice lens which was allowed to warm and slowly melt on the cold stage of a microscope. It can be clearly seen that liquid filled 3-grain boundaries developed at an early stage in the melting process. The dimensions of the 3-grain boundaries in Figure 12C were ~ 0.1 mm (vertex to vertex distance) with an area $\sim 3 \times 10^{-3}$ mm^2.

The importance of the liquid filled 3-grain boundaries for ice in lenses derives from their ability to act as channels for water flow during freezing and melting and from their possible modifications of the thermal properties of the ice lenses in the soil. The water flux through the ice near its melting point is (Raymond and Harrison, 1975)

$$J \sim 2.8 \times 10^{13}\ n\ A^2\ F \qquad 1)$$

where n is the number of veins (3-grain boundaries) per unit area, A is the area of a vein, F is the pressure gradient and the units are m-bar-year. As a sample calculation, consider a freezing or melting ice lens assuming $F \sim 10^{-2}$ bar m^{-1} and using the values for n and A above, the water flux through the ice lens is ~ 1 cm day^{-1}. This is a substantial water flux and implies that during freezing or melting it may not be necessary to assume that the ice lenses in the soil are impermeable to water.

Since impurities in the soil water are rejected by the ice phase during growth of the lenses, it may be expected that they will concentrate at the 2- and 3-grain boundaries in the ice lenses. This impurity concentration will cause a freezing point depression of the water in the veins. The equilibrium temperature of a vein in °C is

$$T_o = 0.0100 - T_p - T_c - T_s \qquad 2)$$

where the first term is the triple point temperature of water, T_p is the pressure correction, T_c is the curvature correction and T_s is the correction due to impurities in the water in the vein. The pressure correction is

$$T_p = B\ P \qquad 3)$$

where B is the Clausius Clapeyron slope (0.00751°C $atmos^{-1}$) and P is the pressure on the water in the veins. Since it may be expected that the water in the veins is connected to the soil water films then P on the water in the veins may differ substantially from atmospheric pressure (particularly during freezing). In any event, $T_p \sim 0.0075\ P$ (°C) and P must be known to evaluate T_p. The curvature correction may be written (Raymond and Harrison, 1975)

$$T_c = \frac{0.82x10^{-8}}{\sqrt{A}} \qquad 4)$$

For the veins shown in Figure 12c, $T_c \sim 0.0002$°C. The correction due to impurities is

$$T_s = 0.0024 + 1.858S \qquad 5)$$

where the first term on the right is due to air saturation of the water and S is the impurity concentration in the water in units of molality. Equation 5 can also be written (Beattie et al., 1937)

$$T_s \sim 0.0024 + 55K \qquad 6)$$

where K is the electrical conductivity of the water in the veins measured at 0°C in $(ohm\text{-}cm)^{-1}$ units. Equation 6 assumes that all impurities have the equivalent conductance of NaCl and neglects the electrical conductivity of air saturated, pure water [0.7×10^{-6} $(ohm\text{-}cm)^{-1}$]. It is difficult to obtain a value for K of the water in the veins because of the salt rejection process during the formation of the ice lens and during freezing at the vein walls, however, for calculational pruposes a value of $K \sim 10^{-3}$ $(ohm\text{-}cm)^{-1}$ will be chosen which makes $T_s \sim 0.0574$°C.

Combining Equations 1-6, it is seen that the value of T of the vein in the ice (at P=1 atmos) is T $\sim$ -0.0551°C and that pressure and impurity effects are dominant.

The liquid phase (veins) in the ice lenses at temperatures near the melting point of the lenses may lead to complications in the heat capacity of a soil containing ice lenses. Anderson (1966) has shown that the apparent specific heat capacity

$$C_a = C_s + C_i\ (W_w - W_u) + C_u\ W_u + \frac{1}{\Delta T} \int_{T_1}^{T_2} L\ (\frac{\partial W_u}{\partial T})\ dT \qquad 7)$$

where the units of C_a are cal/°C/unit weight of soil; C_s is the specific heat capacity of the soil matrix; C_i is the specific heat capacity of ice; C_u is the specific heat capacity of unfrozen water; $W_w = W_i + W_u$ is the total water content; W_i is the ice content; W_u is the unfrozen water content; T is the temperature in °C; $\Delta T = T_2 - T_1$ and L is the latent heat of fusion of ice. Equation 7 assumes that W_u is associated with all interfaces in the soil-water-air-ice system (except for the ice-ice interface) but does not include the unfrozen water at 3-grain boundaries. In principle, the total unfrozen water content could be written as the sum of two terms; the unfrozen water associated with the veins in the ice lenses plus all other unfrozen water. However, the relative magnitude of these two terms is unknown as is the functional dependence of the unfrozen water in the veins on T which is necessary to evaluate the integral in Equation 7.

An alternative procedure for evaluating the effect of unfrozen water on the heat capacity of ice was devised by Schwerdtfeger (1963) for sea ice and applied by Harrison (1972) to glacier ice. These procedures should be applicable to ice lenses in soil and therefore the apparent specific heat capacity of the ice lenses may be written as (Harrison, 1972)

$$C = C_i \left(1 + \frac{\theta_t^2}{\theta^2}\right) \qquad 8)$$

where the temperature

$$\theta = T_o - 0.0100 + T_p + T_c + 0.0024 \qquad 9)$$

and

$$\theta_t = -\left(\frac{-L\theta_m}{C_i}\right)^{1/2} \qquad 10)$$

and

$$\theta_m = -\alpha\sigma \qquad 11)$$

or

$$\theta_m = \theta W_u' \qquad 12)$$

where α is a positive constant characteristic of the impurity composition of the unfrozen water in the veins, σ is the fractional salt content of the ice lens and W_u' is the fractional unfrozen water content of the ice lens. Equation 12 is of the same form as that proposed by Anderson et al. (1973) for the unfrozen water content of a frozen soil,

$$W_m = mT^q \qquad 13)$$

where T is the temperature in °C below zero and m and q are parameters characteristic of each soil.

To apply Equations 8-12 to ice lenses in the soil σ and either θ or W_u' must be known. The unfrozen water content W_u' of the ice lenses in the thin sections can be estimated from the measurements on the 3-grain boundaries which yield $W_u' \sim 4 \times 10^{-3}$g of water per g of ice lens. At this point, it is somewhat academic to carry out further calculations since σ, the effects of pressure that enter through the T_p term in Equation 9, and the in situ characteristics of the veins in the ice lenses are unknown. However, it is clear from Equation 8 that $C > C_i$ and may even be much greater than C_i but the overall effect on C_a may not be noticeable since $W_u' << W_u$ (see Figure 6, Anderson and Morgenstern, 1973).

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