# FLOW FINGERS AND ICE COLUMNS IN A COLD SNOWCOVER

By

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## INTRODUCTION

Melt water does not move uniformly into a snow cover, but instead a large proportion of the water follows distinct flow paths. These flow paths are commonly referred to as flow fingers. Colbeck (1979) postulated that flow fingers are established with the initial movement of water into the snow cover, and that they become preferential paths for future water flow. Because of the higher melt water fluxes in these flow fingers, the water travelling in them may move more rapidly through the snow cover. This is responsible for the field observations that water can move rapidly to the base of the snow cover before the entire pack is wet and isothermal (Gerdel, 1948, 1954; U.S. Army, 1956; Wakahama, 1968), and for the discrepancy between observations and predictions of water movement in homogeneous snow (Colbeck, 1979). Although most models assume that the snow cover is homogeneous, three recent models (Colbeck, 1979; Marsh and Woo, 1984a, 1985) used multiple flow paths to account for the presence of flow fingers. Unfortunately, the required data on the physical properties of the flow fingers were limited and these models have therefore not been tested under different snow pack conditions.

The processes controlling the development of flow fingers are not well known. Wankiewicz (1979) postulated the pressure conditions surrounding a stratigraphic layer under different meltwater fluxes and classified the resulting movement of water over and through the layer. He suggested that under certain conditions a stratigraphic layer would accelerate the flow of water with flow fingers developing below the layer. These flow fingers are similar to those described in other porous media (Parlange, 1974; Wooding and Morel-Seytoux, 1976).

Although flow fingers are an important feature of water movement in snow covers there is little information concerning the development of flow fingers or measurements of their physical properties such as size, volume of water carried compared to non-finger areas, or their relationship to stratigraphic layers. Marsh and Woo (1984b), found that the fingers only developed below stratigraphic boundaries and that the fingers were relatively consistent in size and spacing. Colbeck (1979), using modelling results, suggested that most of the water moves down the flow fingers. Using field measurements, Marsh and Woo (1985) also found that the flow fingers carried the majority of the melt water, with 48% of the flow occurring in only 22% of the area covered by the flow fingers. Unfortunately, these measurements were limited in the range of snow properties and melt rates sampled. As a result, it is not clear whether they are applicable to other snow covers. Certainly, measurements of flow finger properties under different snow cover conditions are required in order to apply the multiple flow path models to a variety of melt run-off conditions.

The primary reason for this lack of data is that flow fingers are very difficult to study in the field. Dye injection test have been used previously, but in situ measurements are preferred. The problem with in situ measurements is that the flow fingers are short lived, they are difficult to observe in a snow pit, and they are not easily studied with remote instrumentation since the instruments themselves disrupt the movement of water. If

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the snow is sufficiently cold, however, water flowing in the fingers will freeze, blocking all the snow pores. The resulting vertical ice bodies, are easy to locate and provide an excellent method to study the movement of water through natural, stratified snow covers.

The purpose of this paper is to report on field observations of flow-finger and ice column growth in a low density Arctic snow cover, and to compare measurements of their size, spacing and aerial coverage to those from a denser snow cover in the High Arctic. Finally, the implications of these features to water movement in snow covers will be discussed.

## STUDY AREA AND METHODOLOGY

Field work was carried out in the Mackenzie Delta in May of 1986 and 1987 at a field site located approximately 5 km south west of Inuvik (Marsh, 1987a). At this site, changes in snow cover properties were monitored at two snow pits. Prior to sampling each day, half the snow pit face was cleared back for approximately 0.2 m. Alternate sides of the pit were used on consecutive days to provide undisturbed snow for sampling and to allow the continuity of the layers to be determined. Measurements were made of density, temperature, grain size, location of the wetting front, ice layer thickness, and the occurrence of flow fingers and ice columns. After daily measurements were completed, the snow pit was refilled with snow to protect the pit face from melting.

## PRE-MELT SNOW COVER CHARACTERISTICS

Due to the low winter snowfall, which averages only 159 cm between October and May at the Inuvik Atmospheric Environment Service weather station, snow depth at the research site is typically between 30 and 80 cm at the start of melt, with a mean of 37 cm in 1986 and 60 cm in 1987. Low winter wind speeds and the sheltering effect of the trees resulted in a snow cover with a mean density of 140 kg/m$^3$ and 230 kg/m$^3$ in 1986 and 1987 respectively. This is typical for treed locations in the sub-Arctic. At the study sites, the snow cover was composed of two to four well defined layers (Figure 1), with the bottom layer consisting of depth hoar. Within each layer the snow is relatively uniform, with few marked variations in properties. The boundary separating the layers represents a sudden sharp change in snow properties. There were no ice layers or wind blown crusts at these boundaries.

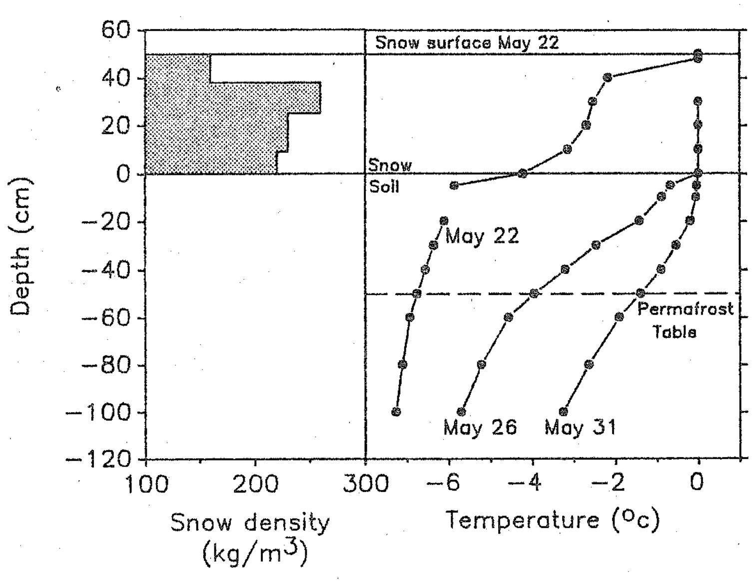


Figure 1. Snow density of May 22, 1987, and snow and soil temperatures on the first day of melt (May 22), the first day that the pack was entirely wetted (May 26), and the last day of melt (May 31) at the Mackezie Delta study site.

The snow cover is relatively warm, ranging from 0 to -5°C immediately prior to the beginning of melt in mid- to late May (Figure 1). The underlying soil is considerably colder with a temperature of approximately -7°C at a depth of 1 m, resulting in a heat flux from the snow cover into the soil of 17 W/m$^2$ during the melt period (Marsh, 1988).

## DEVELOPMENT OF FLOW FINGERS AND ICE COLUMNS

Field observations have shown that during the first day of melt in the spring, thin wet layers form at major pre-melt stratigraphic boundaries in the upper layer of the pack, and that flow fingers extend below these wet layers. Typically, individual fingers extend vertically from one stratigraphic boundary to the next, but in some cases they may extend throughout the 30 to 40 cm thickness of the snow cover. These flow fingers are surrounded by dry snow. During the next few days of the melt period, liquid water moves down through the pack and similar wet layers and flow fingers develop in progressively deeper portions of the pack.

Since the snow surrounding these flow fingers initially has a temperature below 0°C, the water within them begins to freeze. In this early stage of development, the ice column is composed of large ice grains (up to 3 to 5 mm in diameter) which are frozen together into a honeycomb structure. It is hypothesized that these large ice grains are due to rapid grain growth under the high liquid water saturation (Colbeck, 1986; Marsh, 1987b) that occurs within the flow fingers. However, as freezing continues, due to heat conduction into the dry, cold snow surrounding the ice columns, the honeycomb structure is transformed into a solid column of ice. Observations have shown that these ice columns have densities of approximately 800 kg/m$^3$.

During this progression from a flow finger to an ice column, the liquid permeability of the initial flow path undergoes large changes. Initially, it increases as the snow grains grow in size, but then, as the snow pores are gradually blocked by ice the permeability decreases to a very low value. As this occurs, the water moving in the flow finger is forced out of the original flow path and follows a path down the outside of the ice column. This progression is very different from the situation in warm snow covers, where the permeabilty of the flow finger increases throughout the life span of the finger. This is due to the growth of the snow grains under high liquid saturations. As a result, the flow fingers are able to carry a larger and larger percentage of the total flow.

When a flow finger first reaches an impervious ground surface, the meltwater will flow laterally away from the flow finger. If the snow and ground are sufficiently cold, this water will freeze, forming a basal ice layer. At this stage in their development, the ice columns are solidly attached to the basal ice.

Once the pack is wet and warmed to near 0°C, the ice columns slowly decay due to the melting of the intergranular boundaries at temperatures close to 0°C, and the penetration of solar radiation into the upper layers of the snow cover (Langham, 1974). Since these processes occur at a faster rate in the upper layers of the pack, few residual ice columns are found in these upper layers. Under certain conditions however, the ice columns remain intact, and have been observed protruding 3 to 5 cm above the snow surface. This probably occurs during periods of rapid snow melt, where the snow surface lowers rapidly, not giving the ice columns within the snow sufficient time to decay. This processes is enhanced in shady forest locations where the solar radiation receipt is low.

Near the end of the snow-melt period, when basal ice is often found around the outer edges of the snow cover, the last vestiges of the ice columns are seen as small bumps protruding from the basal ice surface. These bumps often provide an excellent way to determine the spatial distribution of flow fingers and ice columns.

## SIZE, SPACING AND SPATIAL COVERAGE OF ICE COLUMNS

Field observations have shown that the ice columns are very regular in both their width and spacing (Figure 2). They are roughly circular, two to nine cm in diameter, with a mean of 5.0 cm, and a standard deviation of 2.1 cm. The spacing between columns varied from 10 to 15 cm, with a mean of 13.3 cm and a standard deviation of 3.4 cm.

Figure 2. Ice columns in the snow pack near Inuvik. Note the regular size and spacing.

On May 23, 1987, small areas of the snow cover were carefully removed, revealing a number of ice columns firmly attached to the underlying basal ice. This provided an excellent opportunity to observe the spatial distribution of ice columns. Figure 3 illustrates the dense packing of the ice columns which is typical of the study sites near Inuvik. Given the mean diameter of 6 cm, for the ice columns shown in Figure 3, and the total area of 600 $cm^2$, these ice columns covered approximately 27% of the total area.

These observations allow a comparison of flow fingers which developed in the low density snow found near Inuvik, with those occurring in the dense snow cover near Resolute Bay as reported by Marsh and Woo (1984b). They presented two estimates of flow finger size. First, using dye injections, they found a mean size and spacing of 3.3 cm and 12.1 cm respectively while the ice columns averaged 4.6 cm and 14.8 cm. Based on these measurements, they estimated that the flow fingers covered 22% of the cross sectional area. These data show that flow fingers in the high Arctic snow are generally small and closely spaced (Figure 4), with similar values for the size, spacing, and area covered as the present study found near Inuvik. This similarity is quite surprising given the differences in the snow cover characteristics at the two sites. However, the melt rates and the resulting fluxes of water reaching the stratigraphic boundaries within the snow cover may be more important in controlling the development of flow fingers. During the study periods, the surface melt rates at both Resolute and Inuvik were very similar, with values of between 5 and 20 mm/day (Marsh and Woo, 1984b; Marsh, 1987a). Certainly more work is required to determine the effect of melt flux on the development of flow fingers.

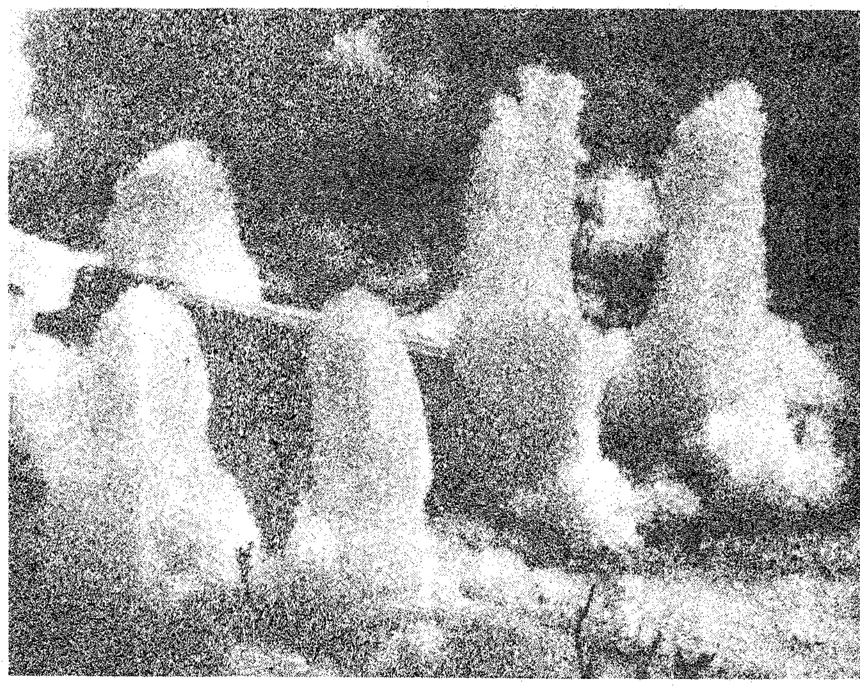

Figure 3. Exposed grouping of ice columns, May 23, 1987.

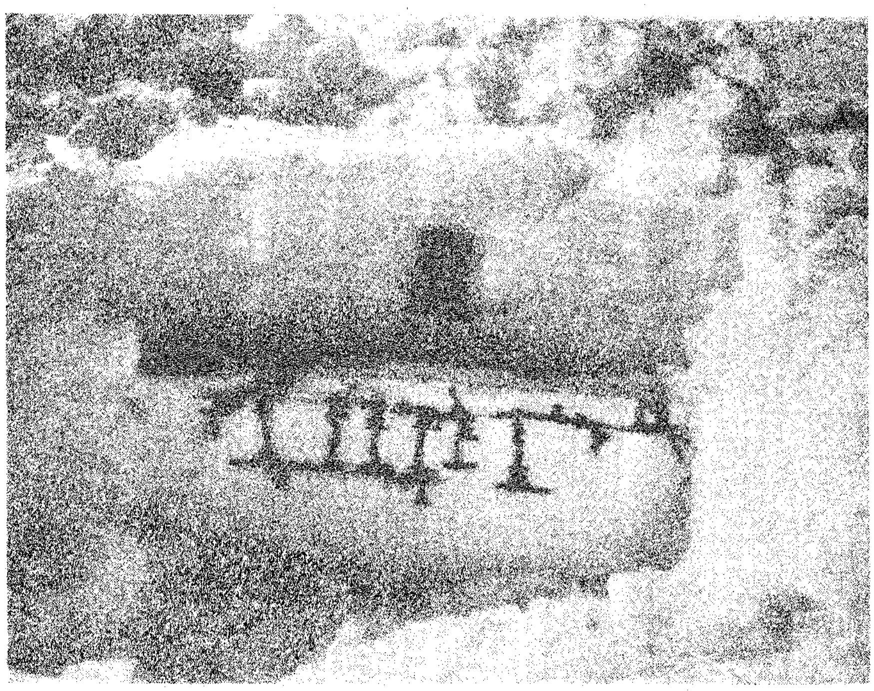

Figure 4. Dye injection test carried out near Resolute Bay. Note the similarity of the flow fingers in the dye test and the ice comumns shown in Figure 2.

## DISCUSSION

The occurrence of ice columns provides excellent evidence of the initial pathways that melt water follows as it enters into a dry snow pack. The first important point is that flow fingers and ice columns are normally associated with stratigraphic boundaries. They always start below a major structural boundary, and usually end at the next lower stratum. It is very rare to see a column which begins in the middle of a major stratigraphic unit. In addition, it appears that flow fingers occur below most stratigraphic boundaries. Using the definitions given by Wankiewicz (1979), it appears that most boundaries at the study sites are accelerating.

The second point is that during the early melt period, when ice columns are forming, they are not found in the upper stratigraphic unit of the snow pack. This may be because the flow is homogeneous in this upper part of the snow cover, and as discussed above, flow fingers do not form until the melt water intersects the first stratigraphic layer in the pack. Another possibility is that the snow cover is not sufficiently cold to form ice columns.

These flow fingers play an important role in the movement of water in the snow pack. At the Inuvik study sites, they resulted in water reaching the base of the snow cover within one day of the start of melt, while it took 3 days for the entire pack to be wetted. This can be compared to a similar depth snow pack at the Resolute study site reported by Marsh and Woo (1984a) where it took approximately 3 days for the flow fingers to reach the pack base, and only slightly longer for the entire pack to be wetted. The difference in the propogation of the flow fingers at these two sites illustrates an important difference between warm and cold snow covers. In cold snow, the advancement of the flow fingers is slowed by the rapid growth of ice layers and the ice columns themselves. While in warm snow covers the flow fingers move rapidly through the snow. This is illustrated by Figure 5, for two snow covers identical except for their initial temperature profile.

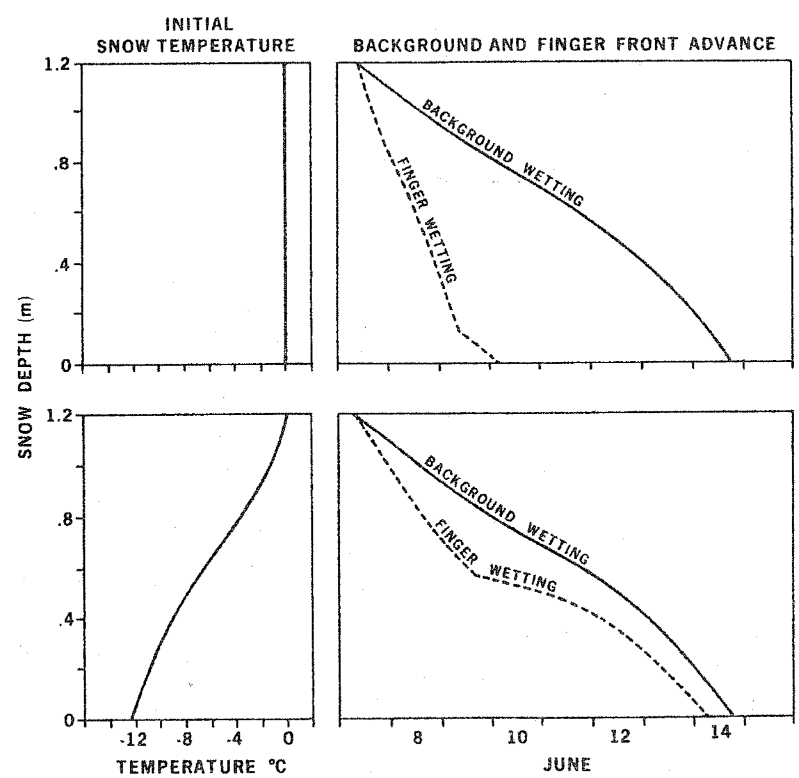


Figure 5. Simulation of background and finger fronts in warm and cold snow covers. All other snow properties and melt rates are the same. From Marsh and Woo (1984a).

Although this simulation used the snow properties and melt rates for the Resolute example, it provides a general comparison of the effect of snow temperature on flow finger propagation. For the cold case, the flow fingers required approximately 2 days to reach 0.4 m below the snow surface, while it took 3 days for this entire depth to be wetted. In the warm snow however, the flow fingers reached 0.4 m in only 1 day, while the entire 0.4 m thickness was wetted in 3 days. The results of this simulation are very similar to the observations from Inuvik and Resolute. Note that at both sites the snow pack was wetted in approximately the same length of time, but that the flow fingers were able to propagate to the base of the snow cover much more quickly in the warm case (Inuvik). This difference becomes even more significant in deeper snow covers, where the flow finger arrives at the snow base many days before the entire pack is wetted in a warm snow pack, but within a day in cold snow (Figure 5). This difference is very important when modelling the initiation of snow-melt run-off.

## CONCLUSIONS

Field observations of flow fingers and ice columns in a melting snow cover provided excellent examples of the pathways followed as melt water initially moves into dry snow. These observations showed that the ice columns always begin at a pre-melt stratigraphic layer and that the flow fingers/ice columns are surprisingly uniform in both their size and spacing, with values similar to those reported previously for a snow cover in the high Arctic. This may be related to the similar melt rates experienced at both sites.

Flow fingers are important in moving water very quickly into the snow cover. In warm snow the flow fingers allow water to reach the snow base long before the entire pack is wet. While in cold snow, the fingers move water into the colder parts of the pack, where it freezes to form ice layers and columns. The resulting release of latent heat is important in warming the snow and underlying soil.

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