SNOW DEPTH MAPPING FROM AERIAL PHOTOGRAPHS FOR USE IN PERMAFROST PREDICTION

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ABSTRACT

Detailed maps of snow depth distribution covering large areas are needed for use in permafrost prediction to aid mining operations. A method has been developed using aerial photographs taken at intervals through the snowmelt season to produce maps of the peak snow depth. The snowmelt stages recorded on the photographs are calibrated using five very large snowcourses. The maps are checked against ground peak snow measurements and show good results for a low cost, large area, method. The final area snow data obtained show good correlations with ground temperature (permafrost) data.

INTRODUCTION

This paper describes a method for the compilation of maps of peak winter snow depth by use of sequential aerial photographs taken at intervals through the snowmelt season. The studies were carried out near Schefferville, in the centre of the Nouveau-Québec/Labrador Peninsula. In areas with marked changes of relief over small distances, such as the Schefferville area, considerable variations of snowcover are common. Snow mapping techniques to deal with this problem have been developed as part of the permafrost research program at the McGill Sub-Arctic Research Laboratory. The method of snow mapping described in this paper was one of two methods first tested for the 1968/69 snowcover by Granberg (1973). Since then the method has been developed considerably, both in methodology and scale of application. It is useful to briefly examine the justification and requirements of snow mapping for permafrost work before describing the methods.

Permafrost is present in some of the open pit iron mines in the Schefferville area and causes many problems which result in higher operating costs (Garg & Stacey 1973). If the permafrost distribution can be predicted in advance, then it may be taken into account at all stages of mine planning, which makes possible a considerable increase in efficiency.

There are no reliable surface indicators reflecting the presence of permafrost in the area, (except occasional palsas, which do not occur on mine sites). The occurrence of permafrost is most closely related to snow distribution (Annersten 1966, Nicholson & Granberg 1973). The insulating effect of snow, conserving heat in the ground and hence producing higher ground temperatures, is well known. The mean annual air temperature is approximately -5°C. However, on sheltered sites where there is 1 to 1.5 m average depth of snow lying on the ground at the end of winter, this is sufficient to keep mean annual ground temperatures above freezing. Thus permafrost is absent from all sites with average or deeper snow depth - eg. most wooded sites and most of the lower lying ground of the area. However, where wind keeps the snow considerably shallower more ground heat is lost in winter and permafrost can develop. Where the snow is very shallow, permafrost may extend to 100 m or more (Nicholson & Thom 1973, Seguin 1974). Snow depth is much more useful than snow density as a single measure of insulation by the snowpack.

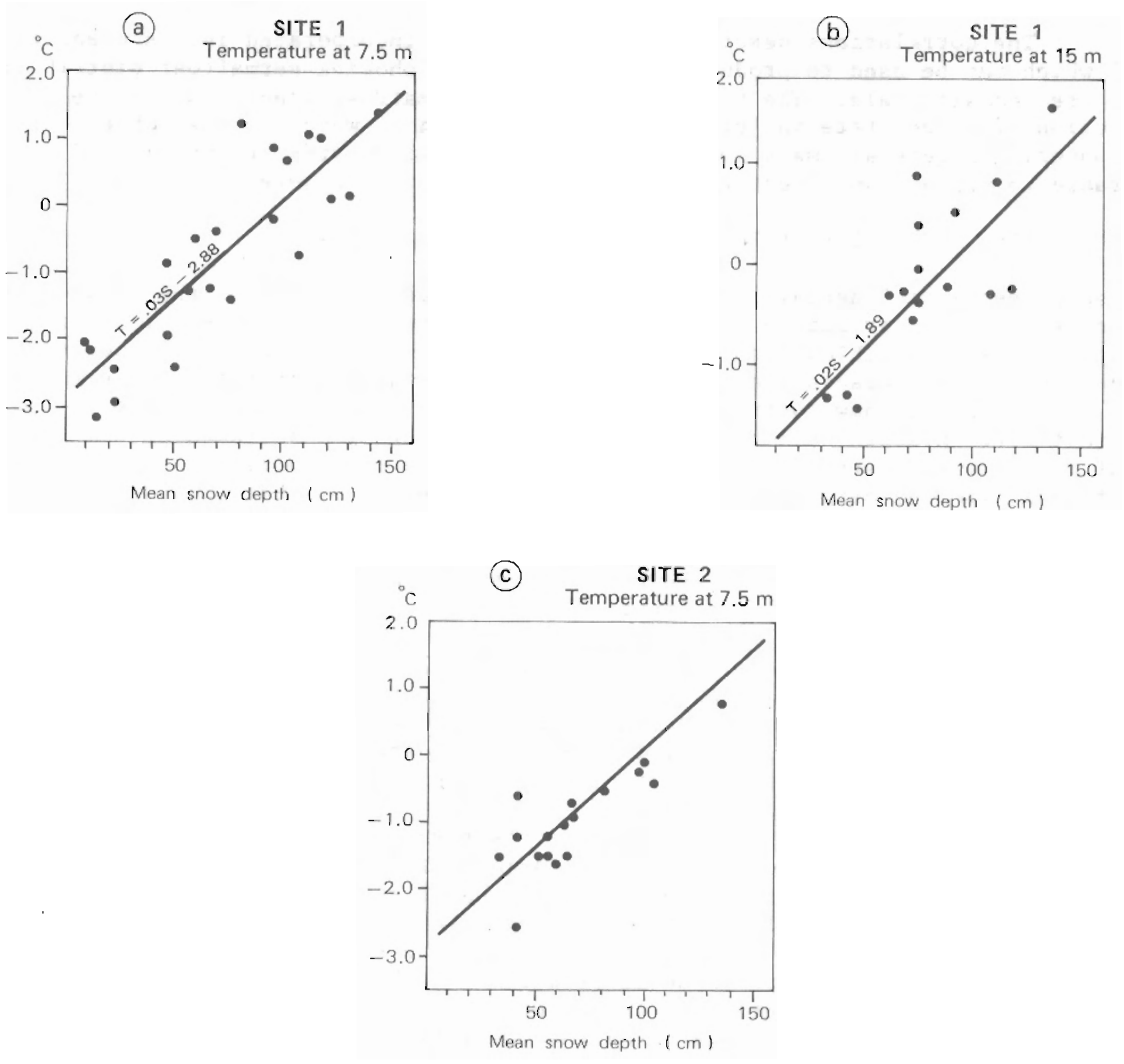

FIGURE 1. Temperature-snow relationships for 40 drill hole installations on 2 sites. Regression of mean annual temperatures at different depths against the mean snow cover over circular areas with radius twice the depth.

CORRELATIONS BETWEEN SNOW AND PERMAFROST

A first successful attempt to quantitatively relate permafrost (ground temperatures) with snow depth was described by Nicholson & Granberg (1973). A linear relationship between peak snow depth and mean ground temperature was found and has been confirmed by later work (see figure 1). As might be expected, ground temperatures are affected by the snowcover over a considerable area so that a measure of only the snow immediately above the temperature measurement point is insufficient. In practice, the snow value giving the highest correlations is the average snow depth over circular areas with a radius twice as great as the depth of the temperature measurement. This means that for increasing depth of temperature prediction, larger areas of snow need to be taken into account. A new site, established in 1973, shows very similar snow-temperature relationships to those demonstrated at the first test site (see figure 1c). Close relationships between snow and ground temperature on a small scale have been reported recently by Mackay and Mackay (1974) from the western Canadian arctic.

The correlations described above have been incorporated into a prediction model which can be used to produce maps and sections showing permafrost distribution on an ore deposit scale. The first step of this permafrost prediction is the production of an accurate map of peak snow distribution, which is the subject of this paper. In general, maps covering a few square kilometres are needed and it is desirable to map all snow features greater than 10 metres square.

OUTLINE OF THE PRINCIPLES OF THE METHOD OF SNOW DEPTH MAPPING

The use of sequential aerial photographs taken at intervals through the snowmelt season is simple in principle but it involves the assumption that certain microclimatic variations are negligible. The method assumes that on a particular date during the snowmelt period all places that originally had a snowpack greater than a certain depth will still be snow covered, whilst all places that originally had less snow than that certain depth will be bare. If aerial photography is taken on that date, a map of the snow boundary can be produced. Ground data from specimen sites can be used to evaluate the original peak snow depth represented by that boundary. A series of boundaries for different dates through the snowmelt period can be combined to produce a contour map of snow depths at the time of peak snow accumulation. A typical series of photographs is shown in figures 2-7 and a part of the map compiled from this photography is shown in figure 9.

A variety of problems complicate this simple concept. These problems can be divided into three classes - physical factors affecting the uniform snowmelt assumption: practical problems affecting accuracy and efficiency; and problems specific to the use of this particular type of snow data for this particular problem. Only the first class of problem will be discussed here.

There are a number of microclimatic factors which cause a non uniform decrease in snow depth during the snowmelt period. The most important of these is the variation of solar radiation due to variations of aspect. However there are several reasons why this is less important than might be expected. Most of the sites of importance have relatively small slope angles. The snowmelt occurs late in the year (mainly May) when the sun angle is relatively high and hence aspect differences are reduced. The snowmelt period is characterised by a high percentage of cloud cover, and hence a high percentage of diffuse radiation. Another factor producing a non uniform rate of depth decrease during snowmelt is the lack of any allowance for density variations. This effect is considerably reduced because density is usually related to depth and the range of density values is smaller in late winter, but undoubtedly some inaccuracy results from this cause. Another problem arises because the snow does not reach a peak and then decline steadily in depth. There are snowfalls after the peak and heavy falls are possible even late in the snowmelt season. It is necessary to wait until all fresh snow has melted before making a photographic flight. Meltwater in ponds and channels produces additional problems as discussed below. Woodland has been largely omitted from this study but when present, it is an additional complicating factor.

OBTAINING THE AERIAL PHOTOGRAPHY

A simple system was perfectly adequate for this part of the work. The vertical photographs were taken through a hole in the floor of the aircraft using a standard hand-held camera, and the photograph intervals were timed with a stopwatch.

The selection of the time of each flight is the biggest problem, the main limiting factor being suitability of the weather for photography. The number and ideal spacing of the flights, in terms of snow depths to be mapped, are determined in advance by the needs of the work and practical considerations, including cost and manpower and aircraft availability. Snowmelt, like all climatic events, is notoriously variable and it is essential that a close watch is kept on the progress

FIGURE 2. Sequence snowmelt aerial photography, Flight 1, 7 may 1974. The area shown is half of a very large snowcourse with 6 years operational data.

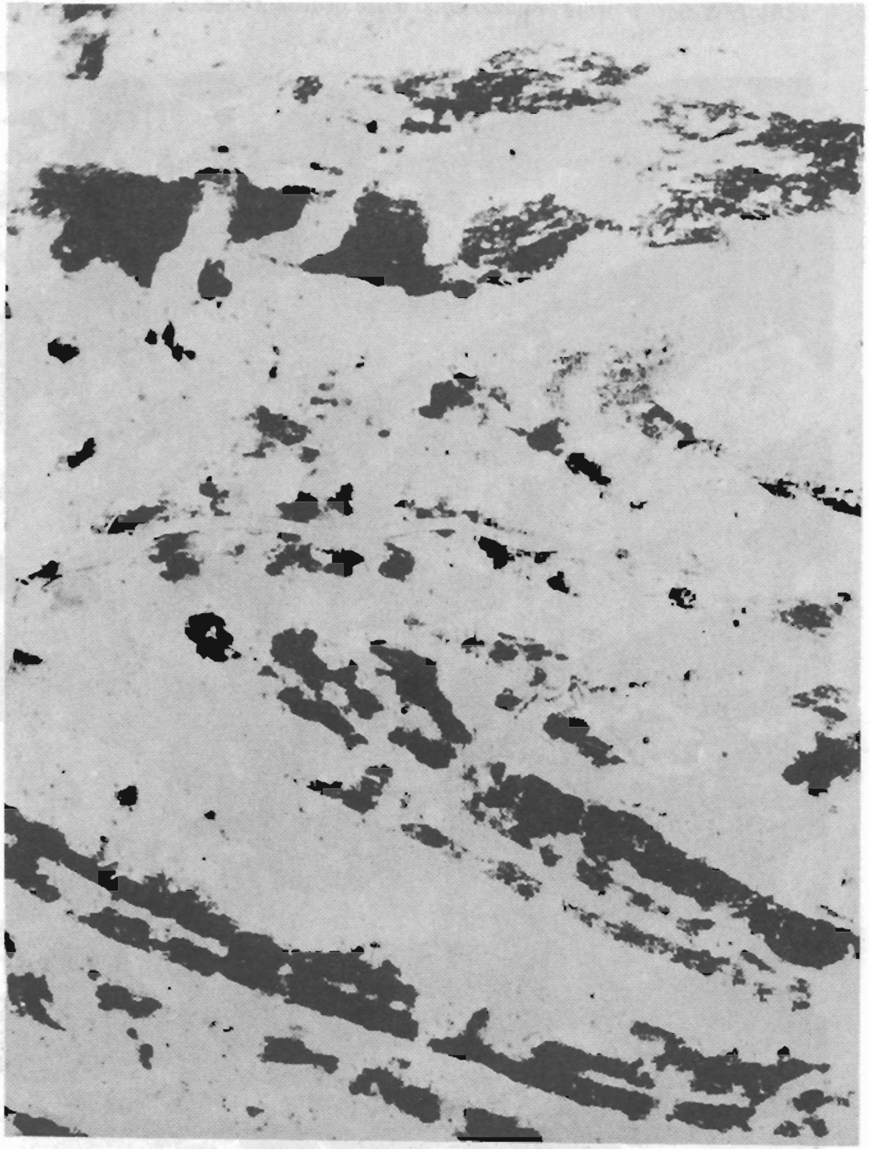

FIGURE 3. Sequence snowmelt aerial photography, Flight 2, 21 May 1974. The stages of snowmelt depicted are calibrated using the ground data. (see Figure 10).

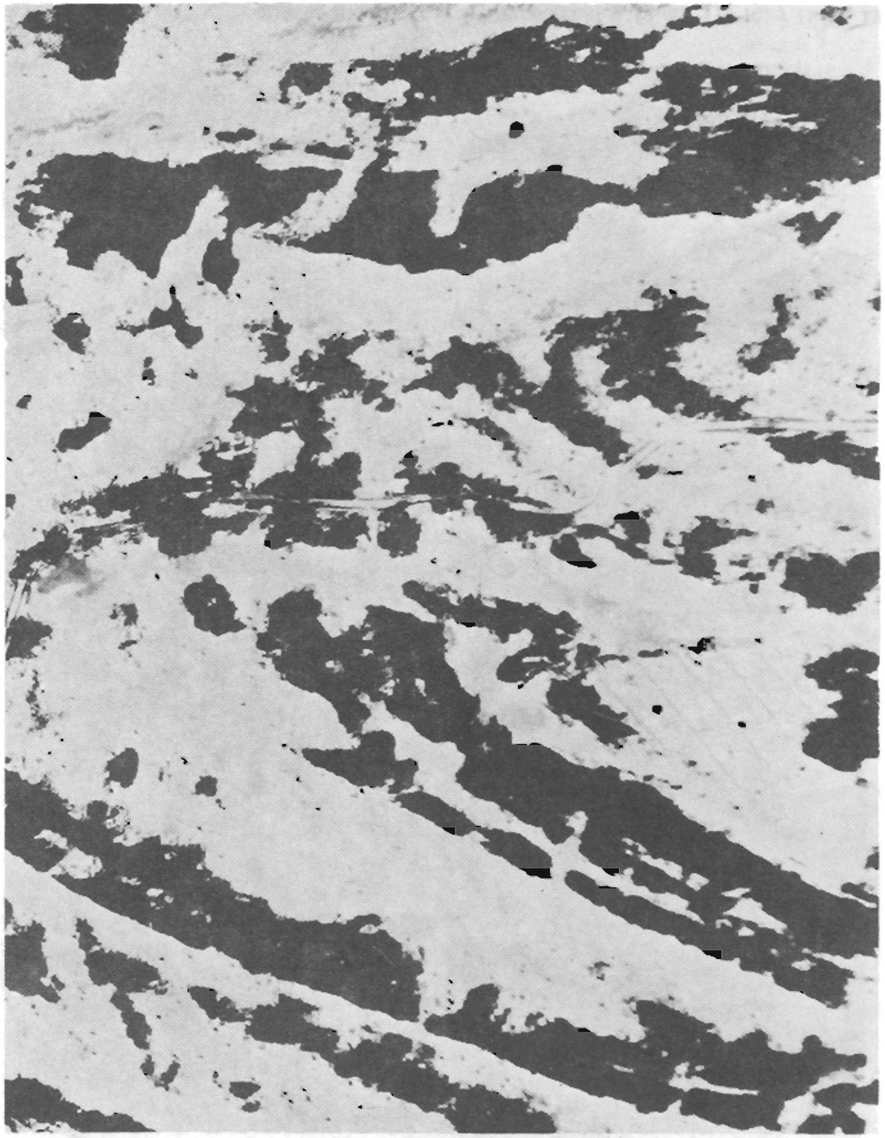

FIGURE 4. Sequence snowmelt aerial photography, Flight 3, 25 May 1974. The snowfences (right centre) are part of a permafrost amelioration experiment .

FIGURE 5. Sequence snowmelt aerial photography , Flight 4 , 29 May 1974 .

FIGURE 6. Sequence snowmelt aerial photography, Flight 5, 4 June 1974.

FIGURE 7. Sequence snowmelt aerial photography, Flight 6, 8 June 1974. (final flight for this site 1974)

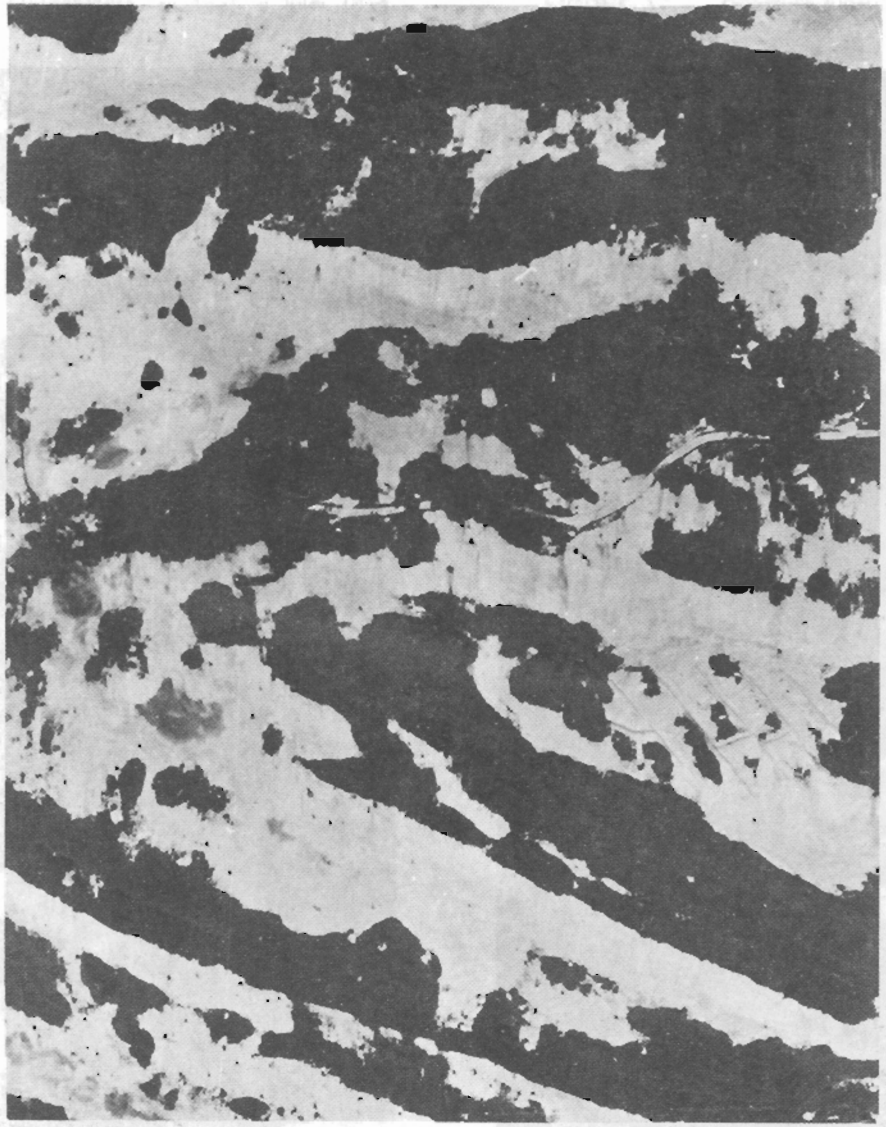

FIGURE 8. Specimen photograph from a series taken in 1972. A comparison of this photo with Figure 5, 1974, demonstrates the similarity of snow-melt patterns observed in most years.

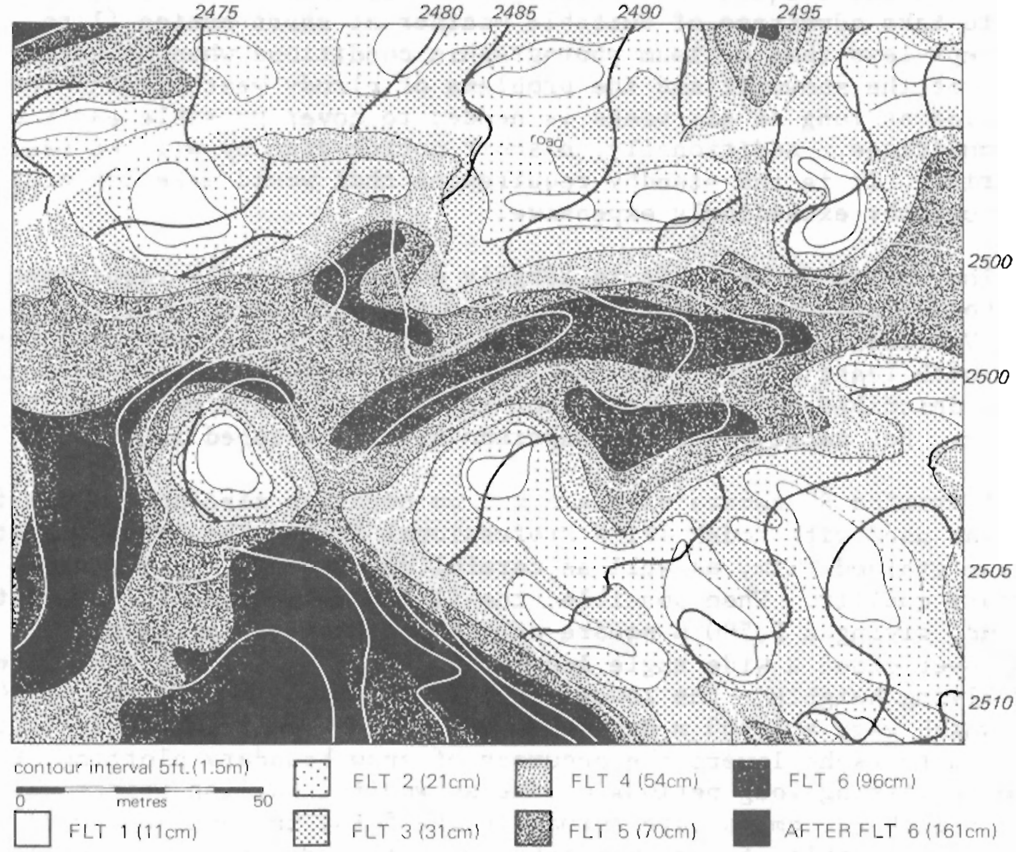

FIGURE 9. Specimen section of snow map produced from sequence aerial photography taken during the snowmelt 1974. The flight numbers correspond to Figures 2--7. The figures in brackets after each flight no. are the estimated mean peak snow depths calculated from ground data (see Figure 10).

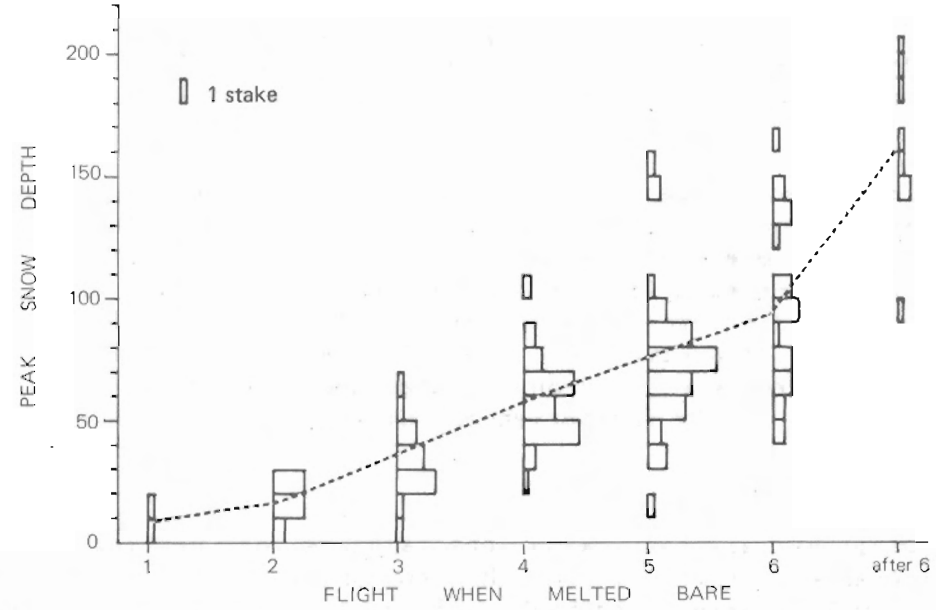

FIGURE 10. Composite histograms showing original peak snow values at each snow stake compiled by flight number when the stake was first observed to be melt bare. This shows the range of peak snow depth included in each flight. The flight means are the values used for the snow maps.

of snowmelt on the ground, in order to know approximately when to fly. In the Schefferville area, frequent and prolonged cloudy weather conditions make it essential to take advantage of suitable weather at short notice (1 to 2 hours) and also to accept less than optimum photographic conditions when necessary. The variability of the snowmelt and the problems of cloudy weather mean that a general standby period as long as six weeks is needed to cover possible early or late snowmelt conditions. Additionally, a short notice standby will be needed for part of that period. It is the standby requirement that would make commercial contract aerial photography exceedingly expensive.

The choice of aircraft is largely dominated by the requirements for vertical photography, and therefore the need for a suitable hole in the floor of the aircraft. Vertical (or very near vertical) photography is essential for accurate map making with least effort. Several different Beaver aircraft were used for most of the work described in this paper, but an Otter aircraft was found to be equally satisfactory. For safety, the cameraperson should be roped in.

A Bronica S2 camera with a 6 x 6 cm negative size and two 24 frame magazines was used with Kodak Tri-X Professional film. The large format negative and the fine grained film, as well as careful developing, are essential to obtain the necessary quality. When possible, the flying height was 10,000 feet (3,000 m) above ground, giving a 2,500 m square of ground coverage per negative. However, on days with lower cloud a wide angle lens was used to increase ground coverage from the lower flying heights - the lowest acceptable flying height was 5,000 feet (1,500 m) which gave a 1,800 m square of coverage. The greater distortion of the wide angle photographs lowers the accuracy of snow boundary plotting, but this is preferable to missing long periods of the snowmelt. Working prints were usually made on an 8 inch (20 cm) square format in the first instance but very considerable enlargement is possible if care was taken with the original film development.

Local navigation is a major problem since it is very easy to become displaced from the desired flight course and hence photograph the wrong area. Strong cross winds increase this problem. The problem arises primarily as a result of the limited downwards view from the aircraft, especially the view forward where the engine obscures almost all downward vision. The problem was solved partly by practice (allowing double time for the first flight of the season), and partly by having the navigator suitably dressed so that he could frequently open the window and put his head out to see both forward and vertically down. The time interval required to give the desirable 60% overlap between photographs is determined by timing ground distance covered whilst flying the direction(s) of the flight lines. The only equipment needed is a map, a stopwatch and a simple graph relating flying height to camera ground coverage.

During the snowmelt period 1974, some 60 to 80 line km of photography were repeated seven times (about 3 hours each time), plus three additional short flights. Approximately 100 films were used for this work. With these quantities, it is essential to contact print each film as soon as possible for film quality control, to check that the planned coverage was actually obtained and for long term use to facilitate easy location of desired coverage. By these methods, all the above photography was flown, processed, contact printed and indexed for a cost of $3,000 (excluding labour) using mainly inexperienced summer student assistants.

COMPILATION OF THE SNOW MAP

The sequence snowmelt aerial photographs were taken as near vertical as possible but still have considerable distortion. For this reason, the procedure followed has been to transfer the snow boundaries onto high quality, commercially produced, aerial photography (normally at scales of 1:4,800 or 1:2,400) and then to transfer all the snow boundaries in one step onto a 1:1,200 final map (see figure 9). Boundaries were transferred from the snowmelt photographs to the commercial photographs using visible identifiable features (bushes, rocks, exploration scars, etc.), rather than general shapes or minor relief features as control. The transfer from good quality photographs to the final map was preferably by Bausch and Lomb Zoom Transferscope, though a Ryker Vertical Sketchmaster has also been successfully used. The main problem at this stage is finding sufficient control points. If necessary, additional control points can be surveyed in the field and added to the map (which would require little extra effort during the development of a normal mine site). Production of a snow map for a typical mine site, covering 2-3 square km, requires one to two weeks work by a diligent worker.

COLLECTION OF GROUND TRUTH

The ground truth was collected from 5 large snowcourses which consist of 70 to 200 points, normally on a 60 m square grid. The snowcourse sites were selected to represent the range of conditions for which the snow maps are needed. Depth observations have been made twice each winter on all snowcourses - once for early winter accumulation and once for peak snow accumulation. In addition, density readings were taken on two of the courses at the time of peak snow. The most easily accessible snowcourse was read more frequently and has also been monitored several times through the snowmelt period. One snowcourse has been operating for 6 full seasons, which gives a reasonable measure of year to year variations. Results from the 1974 snowmelt period were especially valuable because there was an approximately average snowcover and, as far as can be judged, a normal snowmelt pattern (compare figures 5 and 8).

ASSIGNMENT OF SNOW DEPTHS TO THE MAP CLASSES

The snow depths are assigned to the map classes by dividing the ground data (peak snow depths) according to the date on which stakes were first observed to be melted bare on the air photographs, and using the average values as the assigned snow depths of the classes. For example the value assigned to flight 4 is the mean of the peak snow depth at every stake melted bare after flight 3 and before flight 4. This is shown graphically for one snowcourse in figure 10.

EVALUATION OF THE ACCURACY OF THE SNOW MAP CLASSES

A visual impression of the accuracy of the snow map classes is given in figure 10. When the same type of composite histograms were compiled for the other snowcourses very similar results were obtained. It is difficult to evaluate precisely the accuracy of data of this type. Only one attempt is presented here, using the data given in figure 10 (which are from the area shown on the specimen photos and map). When snow stake data ranging from 0 to 200 cm are assigned to only 7 classes some degradation of data automatically results. Mean deviation and standard deviation were calculated for three different situations: (a) if the snow melted perfectly according to the model assumed in the snow mapping method (b) the observed snowmelt results (c) if the snowmelt was completely random. These results are shown in table 1:

TABLE 1

	Perfect Snowmelt	Observed Snowmelt	Random Snowmelt
Mean Deviation	7 cm	16	50
Standard Deviation	10	27	63

The mean deviation is more meaningful than the standard deviation since neither peak snow data nor snowmelt data are normally distributed.

For the snowcourse with data available for 6 years, the 6-year mean peak snow depths were substituted for the 1974 peak snow depths and a very similar result to that shown in figure 10 was obtained. This is especially significant for permafrost work since the development of permafrost will be related to long term mean snowcover, and not to the snowcover of a single year. This result also suggests similar patterns of both snow accumulation and snowmelt from year to year. This is borne out by the close similarity of comparable snow stages in 1972 and 1974 (figures 5 and 8), though it should be noted that 1972 and 1974 were approximately average years and more deviation must be expected in some years.

Three factors considerably increase the scatter of snow stake depths included in each snowmelt flight class (eg. see the anomalies in figure 10). Firstly, snowmelt ponds and moving snowmelt water, which characteristically affect deep snow sites, cause much faster melting of the snow. Secondly, problems occur with very late winter snowfalls, producing occasional drifts that do not accord to the main winter pattern, especially when this occurs at stakes already recorded as shallow at the time of peak snow. A third factor is human error, both in ground data collection and in map construction.

EVALUATION OF VARIATIONS OF SNOWMELT BETWEEN DIFFERENT SITES

It is an observed fact that the timing of the snowmelt is not the same throughout the Schefferville area. Within the area there is considerable variation of altitude (range 350 m), terrain shape, vegetation and influence of human activity. The sites of the five large snowcourses were specially chosen to give a representative range of future mine site conditions.

The current permafrost problems occur mainly in ridge areas, and two sites (Timmins and Sawmill) were chosen as representative of such sites. Table 2 shows that the data from these two sites are closely similar, which indicates that the method does produce consistent results. Another ridge site (Fleming) is affected by dirt particles from nearby mines (1-2 km distant). This dirt, as expected, produced a faster snowmelt and similar melt amounts occur approximately one flight earlier on this site (table 2).

The effect of trees on snow accumulation and snowmelt has been largely ignored in this study because in areas where trees notably affect snow accumulation there is usually sufficient snowcover to prevent permafrost. However, wooded valleys occur within the areas of interest and one large snowcourse was sited with the grid running across a ridge crest and a wooded valley (see table 2, Barney). Whilst there is some general similarity, the trees have altered the mean snow values determined for this site. More work will be needed before this method can be applied to wooded areas.

The fifth site selected (Goodwood) is situated in a future mining area some 50 km north of the working mines. This is an extensive upland plateau area, not much higher than the sites described above, but the vegetation indicates a more severe climate. This difference in climate is demonstrated in the snowmelt data from this site (table 2). There is a delay of approximately two flights (normally a week) in reaching each of the snowmelt stages.

Thus the expected variation of snowmelt timing for sites of different types has been quantified and shown to follow a logical pattern. It seems that the large snowcourses provide a good basis for assigning values to snow class boundaries for most of the area of the air photo coverage, with the exception of wooded sites.

TABLE 2

MEAN SNOW DEPTHS (cm) FOR EACH FLIGHT CLASS AT THE FIVE MAIN GROUND SITES, 1974

Site Name	Timmins	Sawmill	Fleming	Barney	Goodwood
Site Type *1	A	A	B	C	D
No. of Points	147	70	170	128	100
Flight 1- 7 May	11	19	-	20	20
Flight 2-21 May	17	25	35	35	
Flight 3-25 May	35	36	58	44	10
Flight 4-29 May	58	40	71	48	23
Flight 5- 4 June	83	81	103	66	52
Flight 6- 8 June	110	103	(130)*2	115	73
Flight 7-10 June	(137)*2	(161)*2		(163)*2	
Flight 8-16 June					129
Flight 9- 5 July					165
Remaining Flight 9					?(200)*2

*1. A - Ridge top site
B - Ridge top site affected by dirt from the mines
C - Mixed site including ridge and wooded valley
D - Extensive plateau site

*2. Figures in brackets are mean snow depths for the snow remaining on the final flight useful for that site.

APPLICATION OF THE MAPS FOR PERMAFROST PREDICTION

The snow maps described here have been used very successfully in the prediction of ground temperature distribution on a major test site. The relationships shown in figure 1 were derived using the snow data obtained by the method described in this paper. No attempt will be made here to describe the permafrost prediction fully, but certain aspects of this use are of particular interest when evaluating the method of snow mapping. The consistency of snow patterns from year to year is of special importance for the permafrost prediction since it is long-term snowcover that is important.

For permafrost prediction, data from the snow maps are transferred to the computer as snow class values on a 50 feet (15 m) grid. Approximately 10,000 data points are used for each site. It would be completely impractical to attempt to approach this level of information with any form of hand sampling on the ground. For each temperature prediction point the snow data are used to compile average snow depths over circles of radii varying from 50 feet (15 m) to over 1,000 feet (300 m). Thus for the prediction process the snow data values actually used are averages of several values, or even hundreds of values, which reduces the importance of occasional badly estimated snow depths.

The equations for the permafrost prediction model are derived by relating snow data to measured ground temperature data (other parameters are applied after snow). Since the same type of snow data are used in the predictions, any errors of absolute snow depth are built into the predictive equations and therefore, only relative errors are important. This is another reason why this method of snow mapping is so successful in this application.

The method is time-consuming if detailed maps are to be compiled. However, once a set of photography has been calibrated, maps can be produced for any area covered by the photo file, within one or two weeks. This suits the timing of mine planning, which does not demand answers within hours or days of obtaining photography, but which often will not be able to wait a year or more for new field snow studies.

CONCLUSION

This paper has described a method of snow mapping that has proved successful for permafrost prediction. The method enables collection of extremely large quantities of data with relatively small effort. The current use of the method necessitates very detailed processing of areas of a few square kilometres but for different applications much faster processing methods are feasible. It has proved possible to quantify the variations of timing of snowmelt across the area and the method is potentially very useful for snowmelt studies per se. Continuing research at the McGill Sub-Arctic Research Laboratory includes a variety of snow studies, especially concerning the influence of snow on permafrost.

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