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**PREDICTING THE LOCATION OF PERMAFROST
IN CENTRAL YUKON TERRITORY**

by

Deborah J. Williams, B.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Arts

Department of Geography
Carleton University
Ottawa, Ontario
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ABSTRACT

An empirical model to predict the location of discontinuous permafrost is developed for central Yukon Territory. Nineteen variables from soil, vegetation, and landform characteristics were documented at 60 sites in a 2500 km² area, and analyzed to establish a ranking of the variables in order of their association with the presence or absence of permafrost. The ranking forms the basis of the model. The strongest predictors of permafrost are soil moisture, thickness of organic layer, and the presence or absence of hummocks. A second data set was collected independently in the same area to validate the model. The model correctly predicted the presence/absence of permafrost at 92% of sites in the first data set, and 95% of sites in the second. A method of mapping the probability of permafrost, based on the model and related empirical evidence, was developed. The technique requires only three field measurements.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The objective of this thesis is to develop a model to predict the location of frozen ground in the discontinuous permafrost of central Yukon Territory. The study analyzes a data set derived from field observations to develop an empirical model correlating various terrain and soil variables with the presence or absence of frozen ground during the latter part of the thaw season. To determine the physical significance of the empirical model, it is tested against a numerical microclimate simulation model (Outcalt 1972; Smith and Riseborough 1983). To assess the validity of the empirical model for central Yukon, its predictions are compared with a second data set from the same region collected independently.

Prediction of frozen ground in the discontinuous permafrost zone is of interest for land use planning decisions, as construction on permafrost presents costly engineering challenges. The most economical and efficient land use decisions in the discontinuous permafrost zone may follow a principle of minimizing the use of areas with frozen ground.

The presence of frozen ground in the discontinuous permafrost zone cannot be directly observed; to avoid the expense of on-site drilling, frozen ground may be inferred from other characteristics of the terrain.

1.2 Distribution of Permafrost

1.2.1 Permafrost

Permafrost is defined as ground that remains at or below 0°C for at least two years (Harris et al., 1988). It is defined on the basis of temperature alone, so as to include all components of the ground: mineral and organic material, water and ice. This definition accomodates soil water freezing over a range of sub-zero temperatures in fine-grained soil.

The most important factor determining the existence of permafrost is climate. Permafrost can occur wherever the annual mean ground temperature (AMGT) is below 0°C. The annual mean air temperature (AMAT) approximates ground temperature, which is usually a few degrees warmer at any site due to the effects of winter snow cover and vegetation. The distribution of permafrost varies in time and space with variations in climate and ground conditions. The influence of past climates may be preserved in permafrost by ground temperatures which are not yet in equilibrium with the current climate.

The permafrost region has been divided into two

zones - the continuous zone, where permafrost exists more or less everywhere below the ground surface except beneath rivers and lakes, and the discontinuous zone, where areas of frozen and unfrozen ground coexist in response to variations in microclimate, terrain and soil conditions (See Figure 1.1). From the southern fringe where perennially frozen ground occurs only in isolated islands in certain types of terrain, to the High Arctic, the extent and thickness of permafrost in Canada increases gradually.

1.2.2 Climate of northern Canada

The spatial distribution of permafrost in Canada reflects the spatial variation of climate. In general, a decrease in annual mean temperature accompanies an increase in latitude, and higher precipitation totals occur in the coastal regions (Figure 1.2). These basic patterns are modified by a number of factors, including the large continental land mass with its western mountain barrier to Pacific maritime influences, the pattern of the prevailing westerlies, the seasonal changes of ice cover in the Arctic Ocean and Hudson Bay, and the incursion of maritime air from the North Atlantic.

Two broad climate zones for the Canadian north - the Arctic and Subarctic - are defined in terms of temperature, with the average temperature of 10°C for the warmest month as the division (Bone 1992). The southern limit of

Figure 1.1

Permafrost in Canada

(after Brown 1978b; and Harris et al., 1988)

Figure 1.2
Annual mean precipitation in Canada (mm)
(after Findlay 1978a)

the Subarctic occurs where annual mean temperature is near or below 0°C (Rouse 1993). Vegetation zones correlate with the climate zones; arctic vegetation is typically tundra, which grades southwards into the boreal forest of the Subarctic zone over the treeline.

Precipitation and snowfall are higher in the East with proximity to Atlantic air masses, and lower in central Canada, inland from the orographic barrier of the Cordillera (Figures 1.2 and 1.3). The cold temperatures and long-lived ice pack of the Arctic archipelago result in low precipitation in the far north.

Treeline and the isotherms deviate from the parallels of latitude for a number of reasons. Rouse (1993) cites as an example the -25°C mean daily January isotherm, which crosses the Beaufort Sea coast at 71°N, the west coast of Hudson Bay at 55°N, and the Ungava coast at 63°N, reflecting penetration of cold air into central and eastern Canada with the trough in the flow of the westerlies. In summer, the trend of isotherms running from the western Arctic coast to Hudson Bay is due to long-lived sea ice on Hudson Bay.

For most of the Canadian North, the treeline correlates well with the southern limit of continuous permafrost as the position of the treeline integrates many of the variables that are involved in the distribution of permafrost (Bird 1972).

Figure 1.3
Annual mean snowfall in Canada (cm)
(after Findlay 1978b)

1.2.3 Macro- and meso-scale climatic influences on permafrost conditions

The thickness of equilibrium permafrost varies with latitude, approximately following the air temperature isotherms. At its southern limit, permafrost may occur in scattered islands a few decimetres thick, usually in association with peat bogs (Vitt and Halsey 1994). In the northernmost regions, permafrost is everywhere beneath the land surface and reaches a thickness of over 700 metres in arctic islands north of the Parry Channel (Judge et al., 1981).

In mountainous regions of middle and low latitudes where the climate in the adjacent lowlands would not support permafrost, alpine permafrost may be found at high elevations (Harris et al., 1988). Permafrost occurs in mountains in temperate regions because of the decrease in air temperature with elevation (Williams and Smith 1989). The lower limit of global permafrost distribution roughly corresponds to sea level at 60° N and rises at about 100 metres per degree of latitude to 5000 metres a.s.l. in the subtropics (Haeberli et al., 1993). Using this criterion for the lower limit of permafrost, alpine permafrost in Canada is any permafrost occurring south of the discontinuous zone (Figure 1.1). In the widespread discontinuous permafrost zone in central Yukon, continuous

permafrost is found in the mountains (Slaymaker 1993).

1.2.4 Regional influences

Regional conditions also control the distribution of permafrost. Advection brings air masses of different temperature and humidity into a region. Maritime air masses entering northeastern Canada from the Atlantic Ocean in winter produce a deep snowcover which insulates the ground against winter cooling and restricts permafrost to windswept locations in central Quebec (Granberg 1989). By contrast, the St. Elias Mountains prevent the advection of maritime air from the Gulf of Alaska into central Yukon, limiting winter snow cover and allowing permafrost to develop to a greater extent (Burn 1994). In the Hudson Bay lowlands, cool onshore winds from the ice remaining in summer produce cooler air temperatures, slowing thawing. This causes a southward extension to the southern boundary of continuous permafrost (Rouse 1993).

The lower altitudinal limit of permafrost occurrence in mountain areas is also influenced by regional climate. In the western Cordillera in Canada, the lower limit of permafrost is higher with a maritime climate, than with a continental climate (Slaymaker 1993). This is due to thicker snowcover in the maritime regions.

A regionally-important topographic effect occurs in the Cordillera where winter thermal inversions in valleys

within mountainous areas are maintained by low shortwave radiation, continuing longwave loss, and prolonged atmospheric stability. Cold air drainage into the valleys and exclusion of maritime air masses by surrounding high mountains contribute to the intensity and duration of the inversions (Burn 1993), and to the maintenance of permafrost in valley-bottom locations.

1.2.5 Microclimatic influences

In addition to air temperature and large-scale climatic factors, there are several microclimatic factors influencing the site-specific distribution and nature of permafrost. These include proximity to large water bodies, snow depth, topography, surficial geology, geomorphology, drainage, and vegetation conditions. These factors influence the depth of the seasonally thawed active layer in the continuous zone. In the discontinuous zone, their impact can be more significant because the permafrost is thinner and closer to its thawing temperature, and so one or more of these factors may determine the presence or absence of permafrost (Smith 1975).

1.3 Development of the Model

Between 1960 and about 1985 when imminent development of Canada's northern petroleum reserves was expected, much research attempted to understand and predict the location

and distribution of frozen ground in the discontinuous permafrost zone (Brown 1967; Judge 1973; Granberg 1973; Ferrians and Hobson 1973; Dingman and Koutz 1974; Harris 1981 and 1983; Nelson and Outcalt 1983; Morrissey and Strong 1986; Jorgenson and Krieg 1988).

Traditional methods of predicting the nature and distribution of permafrost include interpretation of information from geological maps, aerial photography, remotely-sensed images, temperatures from boreholes and wells, extrapolation based on climate, properties of surficial materials and bedrock, drainage, topographic setting, vegetative cover, proximity to large bodies of water, and permafrost-related landforms (Ferrians and Hobson 1973). Previous studies using traditional methods to predict the location of permafrost have identified a number of factors which seem to vary in significance from one region to another, particularly with changing latitude (Brown 1974, 1975, 1978a). Permafrost often appears to correlate with groups of factors rather than with any outstanding individual factor. The correlations reported have been qualitative, in the sense that the predictive strength of the various factors has not been quantified or ranked. Thus only general guidelines have been produced.

By quantifying the influence of several factors, the present work seeks to design a more rigorous predictive method, which should allow assessment of the likelihood of

permafrost on a scale suitable for land use planning decisions at the site level.

The factors included in this model were derived from studies of permafrost in the past three decades in Canada, Alaska and continental United States, the former Soviet Union, Scandinavia, Japan, and China (e.g. Brown 1967; Péwé 1983; Van Cleve and Yarie 1986; Kolchugina & Vinson 1993; King 1983; Fujii & Higuchi 1978; Lanzhou Institute 1975).

Data on several factors were collected at 60 sites in a 2500 km² area in central Yukon. Statistical analyses were used to isolate and rank factors significantly associated with the presence or absence of permafrost. A ranking of these factors forms the empirical model. The success of the empirical model depends on its ability to predict permafrost conditions at the site level in central Yukon. To validate the model, a second data set was collected from sites within the same region. Results show the reliability of the model is from 92 to 95 percent. A sensitivity analysis was performed using a modified version of Outcalt's (1972) microclimate simulation program to assess the physical significance of the two most important factors in the model. The results of the sensitivity analysis give some indication of the extent to which individual factors in the empirical model may make meaningful predictions for other regions.

1.4 Organization

This thesis is presented in six chapters. The next chapter reviews the theoretical background of the predictive model which is developed. Chapter three describes the study area and the methodology used in collecting the data. Chapter four discusses results of field work, the empirical model, a sensitivity analysis of main factors, and tests the model against further data from the study area. In chapter five, a method of mapping the probability of permafrost, based on the empirical model, is presented with examples of its application. Chapter six summarizes and concludes the thesis.

A note on terminology

The word "frost" has been used throughout the text to signify frozen ground occurring towards the end of the thaw season. This may be understood to be permafrost on the strength of the evidence cited at the end of section 3.4.5.

CHAPTER 2
LOCATING FROZEN GROUND IN THE
DISCONTINUOUS PERMAFROST ZONE

2.1 Introduction

Since ground temperatures may vary over small distances, many sites with and without permafrost may be found in close proximity in southern portions of the discontinuous permafrost zone (Ferrians and Hobson 1973; Smith 1975). Therefore to establish the presence or absence of permafrost at a proposed building site, it has often been necessary to drill for subsurface information.

A more efficient method for locating permafrost at the site level may be the use of techniques based on more readily obtained local surficial information. This thesis develops such a model, focussing on the interaction of environmental factors determining the presence or absence of permafrost at the site level.

2.2 Predicting the location of permafrost with climate and geophysical information

Climate is a primary determinant of ground temperature. Figure 2.1 shows how permafrost varies in response to colder

Figure 2.1
Variation in permafrost with latitude in Yukon
(after Washburn 1979)

Location	Latitude	Annual Mean Air Temp. °C
Old Crow	67°35'N	-10.1
Mayo	63°37'N	-4.0
Whitehorse	60°43'N	-1.2
Source: Atmospheric Environment Service (1982)		

climate with increasing latitude in Yukon. Where other factors affecting ground temperature are relatively uniform, and the density of weather stations is high enough to permit accurate interpolation between stations, climate-based methods may be used to obtain estimates of ground temperature conditions on a regional scale. In the discontinuous permafrost zone, where the annual mean ground temperature is close to 0° C, climatic methods are not sufficient for precise delineation of permafrost occurrence, because small differences in other factors may influence the presence or absence of frost. Annual mean ground temperature in permafrost regions, below the depth of zero annual amplitude, is a few degrees (°C) warmer than the annual mean air temperature (Judge 1973). The annual mean ground temperature at several sites near Mayo is -1.3 °C, while the annual mean air temperature is -4.0 °C (Burn 1992). The figure -1.3 °C represents average near-surface ground temperature at sites in glaciolacustrine sediments in the area, including ground a few degrees warmer or colder.

Climatic methods provide regional-scale information, with ground temperatures calculated from air temperature. For site level information, geophysical methods are more informative. Geophysical methods use temperature measurements, information on ground thermal properties and heat flow, and instruments that detect changes in physical properties of the ground with changes in ground temperature

and change of phase of soil water. The latter group includes acoustic and seismic wave propagation, microwave radiometry (radar) and electrical resistivity.

2.2.1 Climatic methods

Climatic methods which have been used for predicting permafrost include freezing and thawing indices, frost number, and snow depth. The freezing index is a measure of the duration and intensity of a cold period, calculated as the sum of days times their negative temperature ($^{\circ}\text{C}$) and expressed as $-^{\circ}\text{C}$ days, or freezing degree-days (Williams and Smith 1989). The thawing index is determined in the same way for a period with positive temperatures ($^{\circ}\text{C}$).

Freezing and thawing indices (Harris 1981, 1983) may be used to predict permafrost occurrence on a regional scale where other frost-related factors are fairly uniform and local relief is subdued. In areas with large local relief, such as the Yukon, the freezing and thawing indices respond differently to changes in altitude and must be interpreted with caution (Harris 1981). This climatic method of predicting permafrost occurrence tends to underestimate its distribution in montane settings, possibly as a result of the effect of cold-air drainage on the annual mean temperature at such sites (Harris 1983).

The regional distribution of permafrost can be predicted using Nelson and Outcalt's (1983) Frost Number,

which combines monthly mean maximum and mean minimum temperatures with the Stefan solution for annual frost and thaw depths. A Frost Number of 1.0 indicates annual ground freezing equals annual ground thawing and represents the southern limit of permafrost. A frost number of 2.25 correlates with the southern limit of continuous permafrost. Frost Numbers for sites in Yukon and adjacent Northwest Territories are given in Table 2.1.

2.2.2 Geophysical methods

Temperature data from boreholes and wells are useful for estimating presence or absence of permafrost and its thickness (Judge 1973), but the accuracy of maps based on these data depends on the spatial density of the field measurements. In the discontinuous permafrost zone, small areas with and without frost occur in close proximity, so that a network of ground temperature measurements dense enough to reflect the spatial variability would not be practical.

Temperature data represent the most fundamental geophysical approach to obtaining information about permafrost (Scott et al. 1978). There are several more sophisticated methods. Some of the most successful ones used in North America include ground-penetrating radar, seismic methods, and inductive electromagnetic methods.

Ground-penetrating radar is a relatively new technique

Table 2.1
Frost Numbers in Yukon and adjacent Northwest Territories

Station	Elevation (m)	Latitude	Frost Number
Inuvik, NWT	68	68°18'N	2.03
Old Crow, YT	253	67°35'N	1.99
Fort McPherson, NWT	30	67°26'N	1.85
Keno Hill, YT	1472	63°56'N	1.74
Fort Good Hope, NWT	53	66°16'N	1.66
Norman Wells, NWT	73	65°17'N	1.53
Elsa, YT	814	63°55'N	1.44
Dawson, YT	320	64°03'N	1.43
Mayo, YT	504	63°37'N	1.36
Whitehorse, YT	703	60°43'N	1.12

$$F = (-DDF/DDT)^{\frac{1}{2}}$$

F = frost number

DDF = freezing degree days

DDT = thawing degree days

climate data source: A.E.S. 1982

which has been used to collect subsurface information since the late 1970s. Ground-penetrating radar has a number of capabilities including the detection of boundaries between frozen and unfrozen soil in discontinuous permafrost (Pilon et al., 1979). The data obtained by this method consist of cross-sectional images with patterns indicating differences in electrical properties in the ground. Interpretation of the data requires specialized training and knowledge of site conditions because the electrical properties of frozen ground are affected by several factors: changes in material type, phase of soil water, and amount of unfrozen water (Dallimore and Davis 1987). In central Yukon, coarse-grained surficial materials are commonly found in unglaciated areas, while fine-grained materials are common in glaciated areas such as valley bottoms. A limitation to the use of ground-penetrating radar in central Yukon is that, although it is useful for investigating coarse-grained frozen materials (sand and gravel) because they are electrically resistive, depth of signal penetration is limited in clay and silt, which are electrically conductive (Dallimore and Davis 1987).

Seismic refraction methods can provide estimates of active layer thickness, ice-content, ground temperature and material type. This technique is used in construction of roads, railways and pipelines in permafrost areas (Scott et al. 1978).

Inductive electromagnetic methods (EM) have been successful in mapping the distribution of shallow permafrost in the discontinuous zone. This technique became popular in North America in the 1970s for locating the base of permafrost during petroleum exploration and production in permafrost regions (Scott et al. 1978)

2.3 Surface characteristics associated with permafrost

Surface characteristics known to relate to ground temperature in a particular region can be used to predict the presence or absence of permafrost. Some surface characteristics contribute to low ground temperatures while others are a result of the presence of frost. Interaction between factors is common: for instance, vegetation type at a given site can be a response to drainage which in turn depends on soil texture. Surface characteristics which correlate with ground temperature may be grouped into four general classes: soil properties, geomorphology, hydrology, and vegetation. Soil properties associated with ground temperature include: soil texture and composition, drainage, soil moisture, and organic surface cover. Geomorphic factors include: altitude, topography (slope angle and aspect), and geomorphic features. Vegetation factors include: vegetation type, density, and patterns of vegetation succession after disturbance.

At the southern fringe of the discontinuous permafrost

zone, for example at 60°N (Figure 2.1), permafrost is confined to particular types of terrain, mostly peat bogs (Brown 1969). Further north, permafrost is found in north-facing slopes as well as peat bogs. With increasing latitude, permafrost is found in a gradually increasing variety of terrain types.

2.3.1 Soil Properties

Soil thermal properties

The presence or absence of permafrost in the discontinuous zone ultimately depends on local-scale differences in heat transfer between the atmosphere and the ground. (The distribution of permafrost in this zone is not significantly affected by variations in geothermal heat flow, although locally groundwater circulation may be important). Seasonal changes in soil temperature depend not only on changes in air temperature but also on thermal properties of the soil.

The rate of heat transfer into or out of the soil depends on its thermal conductivity. This property is affected by soil texture, mineral composition, bulk density and water content. At the same water content, sandy soil with a density of 1600 kg m^{-3} has a thermal conductivity of $0.30 \text{ W m}^{-1}\text{K}^{-1}$, while peat soil with a density of 300 kg m^{-3} has a thermal conductivity of $0.06 \text{ W m}^{-1}\text{K}^{-1}$ (Williams and Smith 1989, Table 4.1). Because of the low bulk density,

high porosity, and high gravimetric water content of organic soils, the primary influence on the thermal conductivity of organic soils is water content (Farouki 1981). Figure 2.2 compares how thermal conductivity of three soils varies with water content. Conductivity increases with water content for each soil, with that of peat soil almost a linear function of water content.

The amount of heat energy required to raise the temperature of a unit volume of soil by 1°C , the soil's heat capacity, is also influenced by soil texture, mineral composition, bulk density, and water content, but in a different way. Figure 2.3 shows the volumetric heat capacity of three soils all increasing in a linear manner with water content. Although the mass heat capacity of organic material ($1920\text{ J kg}^{-1}\text{K}^{-1}$) is over twice that of quartz sand ($800\text{ J kg}^{-1}\text{K}^{-1}$), the volumetric heat capacity of a dry organic soil (80% porosity) is less than half that of a dry sandy soil (40% porosity), as it has a much lower bulk density (Williams and Smith 1989).

The thermal diffusivity, which is the ratio of thermal conductivity to heat capacity, determines the rate at which a temperature wave is propagated through the ground. Figure 2.4 compares the change in diffusivity with water content for three soils, and illustrates the very low diffusivity of peat soil at all water contents below 80%. Thermal diffusivity follows different trends at high and low water

Figure 2.2
Thermal conductivity vs water content
(Farouki 1981, Fig. 53)

Figure 2.3
Heat capacity vs water content
(data from Williams and Smith 1989)

Figure 2.4
Thermal diffusivity vs water content
(Farouki 1981, Fig. 77)

contents. At low water contents, an increase in moisture causes conductivity to increase faster than heat capacity, so diffusivity rises. At high water contents, an increase in moisture causes heat capacity to continue rising at the same rate, while conductivity increases more slowly, so diffusivity decreases. Thus at low water contents, diffusivity is low due to low thermal conductivity, while at high water contents, it is low as a result of the large heat capacity of water (Williams and Smith 1989).

Of the three thermal properties, Riseborough (1986) points out that it is the low thermal diffusivity of organic soil which most contributes to the presence of permafrost at sites in the boreal forest where a thick organic layer is present. This low diffusivity slows the transmission of rising summer air temperatures into the ground beneath a thick organic mat.

Soil thermal properties are temperature-dependent, largely due to the influence of soil water. Soils have higher thermal conductivities when frozen than unfrozen, because the thermal conductivity of ice is four times that of water (2.24 and $0.56 \text{ W m}^{-1}\text{K}^{-1}$ respectively, at 0°C). With soil freezing or thawing, the soil water gradually undergoes a change in phase, with a large exchange of latent heat energy. This latent heat value may be added to soil heat capacity to produce an "apparent heat capacity". Thus, to thaw ice requires much more heat energy

($3.34 \times 10^5 \text{ J kg}^{-1}$) than is needed to raise the temperature of water through one degree ($4.2 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$) (Williams and Smith 1989).

The extent of response of a frozen soil to summer air temperatures in central Yukon, and whether it remains frozen, depends not only on the duration and intensity of the warm and cold periods, but also on soil moisture (both frozen and unfrozen), soil texture and composition, presence or thickness of the peat layer, and thickness of the frozen soil layer.

Soil Texture and drainage

Coarse-textured soils (sands and gravels) in relatively elevated locations, are typically well-drained, while fine-textured soils (silt and clay) tend to be poorly-drained. Permafrost investigations in northern Quebec and Labrador showed that the active layer is thicker in well-drained sandy and gravelly soils than in poorly-drained fine-grained materials (Brown 1974). Poorly-drained soils tend to have lower temperatures than well-drained soils at nearby sites with the same exposure because much of the incoming solar radiation is used for evaporation of water from the soil at the poorly-drained site, while at the well-drained site more of the solar energy is available for warming the soil (Brown and Williams 1972).

Where permafrost is found in the discontinuous zone,

its low permeability generally results in a poorly-drained soil environment (Luthin and Guymon 1974). Poor drainage can be a cause or an effect of permafrost. There can be a positive feedback where a high frost table impedes drainage, and in the resulting moist soil, the development of moss and peat is encouraged, which further contributes to the preservation of permafrost (Luthin and Guymon 1974).

However, a nearby large body of water tends to prevent permafrost formation, as discussed below in section 2.3.2.

Surface organic layer

In the boreal forest of central Yukon, the ground surface in many places is covered with a layer of moss and peat, from a few centimetres to two metres thick. This material tends to promote lower ground temperatures and to maintain permafrost (Luthin and Guymon 1974). Moisture-related changes in the thermal properties of the peat and moss result in a rapid heat loss from the ground in winter, and a very slow warming in summer (Brown 1978a). The low thermal conductivity of dry peat slows heat transfer into the ground in summer. The higher thermal conductivity of frozen wet peat allows rapid heat loss from the ground in winter. Thus a lower annual mean ground temperature exists beneath a thick organic layer (Brown and Williams 1972). The organic layer affects ground temperature on a short time scale as well (Riseborough and Burn 1988). Rapid

heat loss occurs in cool, wet weather, while slow warming occurs in warm, dry weather. Removal of the organic layer results in higher ground temperatures and a lowering of the frost table (Mackay 1970).

2.3.2 Hydrology

The ground in permafrost zones remains unfrozen (talik) beneath large bodies of water which do not completely freeze in winter (Tyrtikov 1964). Permafrost is absent beneath present river channels and in freshly-deposited alluvium (Viereck 1973). Recently-flooded riverbanks and lowlands along shores may be free of permafrost due to convective heat transfer during flooding and the presence of a residual talik in the former river channel. Along the banks of meandering rivers, slip-off slopes recently occupied by a migrating river channel remain free of permafrost for some time until the thermal influence of the river water has receded (e.g., Smith 1975). Effects of recent flooding include a thawing of permafrost by the relatively warmer river water, warming of the soil by the high water table associated with the river, and destruction and compaction of the moss cover by sedimentation. These effects lead to warmer ground temperatures (Viereck 1973). The distribution of permafrost in the discontinuous zone is also modified by groundwater (Burn 1992).

Small lakes in the discontinuous permafrost zone can

provide information about the location of permafrost. Actively-developing thermokarst lakes are an indication of the presence of permafrost with a localized disturbance to the surface resulting in thawing of massive ground ice (Burn 1992).

2.3.3 Geomorphic factors

Frost-related geomorphic features

There are a few frost-related geomorphic features which have been used to assist interpretation of permafrost from aerial photographs (e.g., ice-wedge polygons, pingos). A problem with this method is the existence of relict features, and those which indicate degradation of permafrost (e.g. thermokarst) which may or may not be still present. Use of frost-related geomorphic features is inadequate for predicting the presence or absence of permafrost in southern Yukon because of the relative scarcity of such features as pingos and patterned ground in the discontinuous permafrost zone (Harris 1983).

On a local scale, certain landforms may be indicative of permafrost due to the landform's characteristic soil texture or relationship to the surrounding topography. Soil texture and topographic position influence soil temperature through drainage. For example, a well-drained hillslope or elevated former alluvial delta may be frost-free while a valley at the base of the slope has permafrost.

Where the glacial history of a landform is known, the related soil texture, drainage and thermal character may be inferred. Thus on a local scale, particular landforms may be classed according to relative likelihood of permafrost.

Altitude

In general, there is a predictable decrease in annual mean air temperature with increase in elevation, and this is reflected in a decrease in annual mean ground temperature. In central Yukon this pattern is modified by the effects of winter thermal inversions (Harris 1983; Burn 1993).

During a winter inversion in late January 1975, the daily minimum temperature was 20° C higher on Keno Hill, than in Mayo, 968 m below (Burn 1993). Prolonged inversions in the valleys produce lower than average winter temperatures and contribute to a higher than expected incidence of permafrost at low elevations (Harris 1983).

In the western Cordillera, thick snow cover inhibits the development of permafrost at altitudes where lapse rates in the atmosphere would otherwise predict frozen ground (Slaymaker 1993).

Topography

At a given latitude, variation in slope aspect and angle results in variation in the amount of solar energy received. Thus sites in close proximity may show

topographically-caused strong differences in ground temperature. South-facing slopes are known to be warmer than north-facing slopes due to more direct exposure to incident solar radiation. Evidence for permafrost being preferentially located on north-facing slopes and absent from south-facing slopes in the discontinuous permafrost zone has been cited from various locations: the Mackenzie Valley, N.W.T. (Heginbottom 1978); the Kebnekaise Massif, northern Sweden (max. elev. 2100 m a.s.l.), Jotunheimen, southern Norway (max. elev. 2470 m a.s.l.) (King 1983); and the Ruby Range in the St. Elias Mountains, Y.T. (Price 1974). At the southern fringe of the discontinuous permafrost zone, even at very small slope angles of 1° or 2°, permafrost was found on north-facing slopes and absent from south-facing slopes at Thompson, Manitoba (Brown 1969).

The concept of equivalent latitude has been used to predict permafrost occurrence through calculation of potential insolation based on latitude, slope angle and slope aspect (Dingman and Koutz 1974). Potential insolation can give good estimates of permafrost occurrence in areas where factors modifying potential insolation are limited.

There are three significant factors modifying potential insolation, which reduce the effectiveness of using slope angle and aspect as predictors of frozen ground. These factors are: shading by vegetation cover, topographic shading, and topographically-caused variation in snow depth.

Where vegetation cover varies from dense forest to shrub tundra, as in central Yukon, variations in vegetation cover may have a stronger impact on ground temperature than variations in slope aspect and angle. The effect of topographic shading may be seen for example where a south-facing slope is shaded by a high ridge. Topography is largely responsible for snow distribution in the mountains, and thus influences the distribution of mountain permafrost (King 1992).

2.3.4 Vegetation factors

Vegetation type

Vegetation cover on the landscape reflects several factors, including atmospheric climate, soil climate, soil chemistry, rooting depth, and disturbance (e.g., flooding, fire).

Some plants are adapted to survive in conditions resulting from long-term presence of a high frost table (e.g. *Picea mariana*, *Ledum decumbens*, *Arctostaphylos rubra*, *Hylocomium* spp. and *Sphagnum* spp.: Chernov 1985). Where permafrost is present near the surface, the soil tends to be shallow, cold, poorly drained, and low in plant nutrients. The high heat capacity of wet soils causes them to warm more slowly in spring (Van Cleve and Yarie 1986), contributing to a lower annual mean temperature. In the discontinuous permafrost zone, landscapes dominated by frost-tolerant

plants are most likely underlain by permafrost.

Tree species are a good indicator of relative soil temperature in the discontinuous permafrost zone because of the different thermal and moisture requirements of various species. Coniferous forests can thrive in cooler soil than deciduous forests, and black spruce tolerates cooler soil than white spruce (Slaughter and Viereck 1986). In the discontinuous permafrost zone, black spruce is a good indicator of permafrost because as well as enduring cooler soil temperatures than other species, black spruce is most tolerant of the higher soil moisture levels commonly associated with the presence of permafrost (Luthin and Guymon 1974).

Floodplains of subarctic rivers where sedimentation occurs frequently, are permafrost-free due to loss of the organic surface layer through frequent burial and the high water table with warm temperatures associated with the river. These permafrost-free areas can be recognized in central Yukon by identification of their dominant vegetation species: *Salix alaxensis*, *Alnus* spp., and *Equisetum* spp. (Gill 1973).

Vegetation density

In general, an increase in vegetation is accompanied by a decrease in ground temperature due to the role of vegetation in shielding the ground from solar heating in the

summer (Brown and Péwé 1973). For example, in the Mackenzie Delta, the annual mean ground temperature in a mature spruce forest was -4.2°C , while the temperature in a willow-alder association was -3.0°C (Smith 1975; see Table 2.2).

Although the reduction in incoming solar radiation due to increasing density of tree cover tends to produce lower soil temperatures, the ground temperature in a forest may be warmer than that of the surroundings due to reduced wind speed and accumulation of snow in low vegetation (Smith 1975; Rouse 1984).

Patterns of vegetation succession

Variations in vegetation patterns on the landscape in the boreal forest result from a number of factors - slope angle and aspect, soil moisture, elevation, soil temperature, and natural disturbances. In the boreal forest the main natural disturbances to large areas of vegetation are forest fires and river channel migration. Both result in removal of existing vegetation species and re-establishment of vegetation through patterns of succession. The ground thermal regime is affected by these disturbances and gradually changes as the vegetation pattern evolves. It has been observed in vegetation succession studies that the ground temperature cools as the revegetation of disturbed areas in the boreal forest approaches the mature spruce forest stage, where permafrost is re-established (Smith

Table 2.2
Influence of cover type on ground temperature
near Inuvik, Northwest Territories
(data from Smith, 1975)

Surface cover	Annual mean ground* temp. (surface)	Active layer (cm) (July)
spruce forest	-4.2	30.8
shrub (willow/alder)	-3.0	62.6
bare ground	-1.0 to -1.5	110.6
snow drift area	0.0	103.3
lake, unfrozen portion	3.2	talik
river, unfrozen portion	4.0	talik

* Annual mean air temperature: -9.0 to -10.0

1975; Zoltai 1993).

After a fire, changes in the surface albedo and the removal of surface vegetation and some of the organic mat result in warmer soils and a deeper active layer (Viereck 1973). A forest fire usually does not entirely destroy the insulating moss and peat layer, so its impact on the active layer is not as marked or as rapid as the disturbance resulting from bulldozing (Heginbottom 1973). Where the permafrost has a high ice content, subsidence accompanies deepening of the active layer (Mackay 1970). When a new vegetation cover is established in a burned area, the active layer may differ from that of the surroundings owing to the different thermal influence of the new vegetation (Mackay 1970).

As forest succession proceeds on new alluvial deposits resulting from river migration, permafrost develops concurrently with the vegetation, and in later stages of succession, the active layer gradually thins (Viereck 1973). In the early stages of succession, after a sufficiently long flood-free period, a new surface layer of moss and peat develops on a new alluvial deposit.

Peat bogs and fens

Peatlands are those wetlands which have a peat layer of 40 cm or more in thickness (National Wetlands Working Group 1988). In the Canadian wetland classification system, bogs

and fens are two separate classes of peatland. They are distinguished by closed drainage and low plant nutrient status in peat bogs, and open drainage with nutrient enrichment entering the system from upslope in fens. The throughflow of relatively warm water in fens contributes to permafrost-free conditions of the ground in a manner comparable to the influence of streamflow (see 2.3.2)

In central Yukon there are no extensive peatlands but small peat bogs are common (Vitt et al., 1988). Peat bogs are an environment of significance to permafrost because the thermal regime of peat bogs differs from that of mineral soil terrain owing to vegetation, micro-relief, water content and thermal properties. The thermal regime of a peat bog gives it a lower annual mean ground temperature than mineral soil, a significant factor in the distribution of permafrost (Brown and Williams 1972). In the continuous permafrost zone, the active layer is thinner in peat bogs, while at the southern fringe of the discontinuous zone, permafrost is found almost exclusively in peat bogs (Brown and Williams 1972). Peat bogs develop in areas with poor drainage. The cool temperatures and waterlogged conditions slow the rate of decomposition and allow the buildup of an organic layer of moss and peat. This material contributes in turn to lower temperatures.

2.3.5 Regional and local mapping of permafrost from surface characteristics

Regional mapping of permafrost from surface characteristics has used (i) identification of frost-related landforms, (ii) the interpretation of topographic effects through equivalent latitude, and (iii) analysis of vegetation cover and topography, usually from remotely-sensed images and aerial photographs. The limitations of using frost-related landforms and equivalent latitude for mapping discontinuous permafrost were discussed in section 2.3.2.

Regional mapping of permafrost has been generalized and small-scale (large region covered, coarse resolution of detail), for example, maps at a scale of 1 to 2.5 million (Ferrians and Hobson 1973). Local scale mapping is necessary for site-level planning in the discontinuous permafrost zone because sites with and without permafrost can occur in proximity. Surface characteristics have been a traditional part of local scale mapping of discontinuous permafrost (e.g. Johnston et al., 1963; Brown 1967, 1974). Surface characteristics which have been mapped at local scale for permafrost prediction include patterns of vegetation, relief and drainage (Johnston et al., 1963). Surface characteristics are better predictors of permafrost at the local scale than climate methods, since the spatial variation of vegetation, relief, and drainage occurs over

smaller distances than the spatial variation of atmospheric climate. The use of surface characteristics to predict and map permafrost at the local scale can be simpler and more economical than geophysical methods, which may require sophisticated equipment and expertise, or drilling, installation and long-term monitoring of temperature cables.

2.4 Conclusion

The factors described in this chapter work together to produce the ground thermal conditions leading to the presence or absence of permafrost. Table 2.3 summarizes the general associations between environmental variables and permafrost in central Yukon.

Table 2.3

**General Associations between Environmental Variables
and Permafrost in central Yukon**

<u>Variable</u>	<u>Conditions</u>	<u>Permafrost status</u>
1. Air Temperature, annual mean	-8.3°C	northern limit of discontinuous zone
	-3.9°C	southern limit of widespread discontinuous zone
2. Soil	coarse texture (sand and gravel)	permafrost usually absent
	fine texture (silt loam to clay)	permafrost often present
3. Drainage	well-drained	permafrost usually absent
	poorly drained	permafrost often present
	flooded every 1 - 5 years	permafrost absent
4. Topography	north aspect	permafrost often present
	south aspect	" usually absent
5. Forest Vegetation	deciduous	permafrost absent
	coniferous	" often present
	black spruce bog	" often present
6. Moss and Peat	none	permafrost absent
	thick	" often present

Sources: 1. Brown (1978a); 2. Brown (1974); 3. Luthin & Guymon (1974), Tyrtikov (1964); 4. Brown (1974); 5. Luthin & Guymon (1974), Slaughter & Viereck (1986), Van Cleve & Yarie (1986); 6. Luthin & Guymon (1974), Tyrtikov (1964), Viereck (1970).

CHAPTER 3

STUDY AREA AND FIELD METHODS

3.1 Introduction

This chapter describes principal physical characteristics of the study area and their relation to permafrost conditions. Topography and drainage, geomorphology and glacial history, climate, soils, and vegetation are considered. Previous work on permafrost in the area is identified to provide background information on location, thickness, and temperature of permafrost and development of the active layer. Field methods are presented in detail.

3.2 Physical characteristics of the study area

3.2.1 Introduction

The study area is located in central Yukon Territory, in the quadrangle defined by 63°56'N, 63°23'N, 135°10'W, and 136°40'W (Fig. 3.1 and 3.2). It includes the settlements of Elsa, Keno, Mayo, and Stewart Crossing. The topographic region is the Yukon Plateau, a rough highland sub-region of the Canadian Cordillera (Wahl et al., 1987). Drainage is westward towards Yukon River by Stewart River and its tributaries. Much of the surficial material in the

Figure 3.1

Yukon and adjacent portion of Northwest Territories.
The study area includes the settlements of Mayo, Elsa, Keno and Stewart Crossing.

Figure 3.2
The study area

region originated during the advance and retreat of the McConnell glaciation at the end of the Wisconsin period, between 30,000 and 14,000 years B.P. (Tarnocai et al., 1985). The extent of this glaciation is shown in Figure 3.3.

The study area is in the Cordilleran climate region, which includes British Columbia north of 58°N, Yukon Territory, and western District of Mackenzie. The climate is high-latitude continental (Kendrew and Kerr 1955). Winters are long (October to April) and are dominated by cold, dry, continental arctic air. Annual precipitation is low (300 - 400 mm) on plateaux and in valleys and lowlands because the St. Elias and Coast Mountains block the entry of Pacific maritime air masses into the region, and because the Arctic air masses of the interior are dry (Kendrew and Kerr 1955; AES 1982). There is no pronounced wet or dry season, although spring is relatively dry and maximum precipitation occurs in summer (Kendrew and Kerr 1955).

There are two principal soil types in the study area -- Eutric Brunisol and Turbic Cryosol (White et al., 1994). The cold climate results in low soil temperatures which restrict chemical weathering, organic matter mineralization, and soil profile development (Van Cleve and Yarie 1986). Soil development is more advanced in moderately well-drained forests, and less so in poorly-drained lowlands and on mountains. Thick organic soils are found in poorly-drained

Figure 3.3
Limit of McConnell glacial advance
(after Hughes 1983)

depressions, which usually contain permafrost. Soil development is inhibited on mountains by steepness of slope, solifluction, and frost action.

The study area is within the Eastern Yukon subregion of the Boreal Forest vegetation region, with tundra above treeline (Oswald and Senyk 1977). The area is predominantly forested, with white and black spruce (*Picea glauca* and *Picea mariana*) as the climax species on moderate to well-drained slopes. Forest patterns are modified by frequent fires. The forest in poorly-drained areas consists of open woodland of stunted black spruce with a thick moss ground-cover. Shrub communities are restricted to recently flooded riverbanks, disturbed areas, wetlands and near treeline. Willow and alder (*Salix* spp. and *Alnus* spp.) are found on better-drained sites, and ericaceous shrubs on poorly-drained sites. Grassland is restricted to steep, dry, south-facing slopes on coarse-textured soils. Alpine tundra is above treeline, with shrubs, grass, sedge, forbs, lichens and mosses.

3.2.2 Topography and drainage

Within the study area, elevations range from 480 m in the valley of the Stewart River, to 1850 m on top of Keno Hill (Fig. 3.2).

Stewart River is strongly meandering, with cut banks,

slip-off slopes, and former channels in the floodplain clearly visible on aerial photographs (Fig. 3.4a). Many of the tributary streams are steeply incised into glacial drift in the uplands (Brown 1967).

Drainage varies from excessive on steep slopes to poor in valley bottoms and depressions. Peat bogs occur in some depressions. Thermokarst lakes are found in places along the valleys of the Stewart and Mayo Rivers.

The principal topographic units of the study area are the valley of Stewart River, gently sloping hills on either side of it, and steep mountains to the north and northeast.

3.2.3 Geomorphology and glacial history

In Stewart River valley, hills were smoothed and rounded and valleys widened by glacial erosion prior to the end of the last glaciation, around 13,600 years B.P. (Hughes 1987). There were at least four glacial advances in central Yukon during the Pleistocene: Nansen (oldest), Klaza, Reid, and McConnell (youngest) (Bostock 1966).

The limit of the McConnell advance (Fig. 3.3) is evident in a prominent moraine, about 20 kilometres west of Mayo, which is the type location for this advance. Soils on the moraine are typically coarse-textured and frost-free in mid to late summer (Hughes et al., 1972). During the McConnell advance, terrain above 780 m in the Mayo area was unglaciated (Hughes 1983).

Figure 3.4a Aerial photograph of Stewart River showing migration pattern parallel to shoreline. These patterns are accentuated by vegetation succession. (A27482-84, National Air Photo Library)

Figure 3.4b Forest cover. Deciduous and mixed forests occupy recent alluvial sites.

Lakes formed where moraines or ice obstructed drainage, and glacial streams carried debris into these lakes, the coarser material being deposited near the point of discharge, and the finer materials being carried further before deposition (Keele 1957). The levels of the glacial lakes are marked by deltaic deposits of sand and gravel formed where streams entered the lakes (Vernon and Hughes 1966). Fine-grained sediments accumulated within the glacial lakes, producing areas of glaciolacustrine sediments. In these areas, permafrost is common. An example of the alluvial delta and glacial lake environment is found north of the village of Mayo where an alluvial delta forms a high dry south-facing cliff of sand and gravel. In the lowlands of Stewart River valley at the foot of the cliff is fine-textured soil with permafrost. This valley was once occupied by a pro-glacial lake (Hughes 1983).

Typical of the major valleys of the region, the Stewart River Valley near Mayo is filled with thick sequences of glacial deposits. Here, outwash deposits are mixed with glaciolacustrine sediments (Hughes 1983). East of Mayo, some glacial deposits have been reworked by Stewart River and replaced with sandy material. After deglaciation, drainage of pro-glacial lakes occurred during a period of cold climate conducive to the formation of permafrost and segregated ice in the glaciolacustrine sediments (Burn et

al., 1986). At present, thermokarst lakes and thaw slumps are found in these sediments (Burn 1986).

3.2.4 Climate

The study area straddles two climatic regions of the Yukon classification: the Central Yukon Basin (southern part of study area) and the Ogilvie-Mackenzie Mountains (northern part of study area) (Wahl et al., 1987).

The climate of Yukon in the broadest sense is sub-arctic continental. Criteria for a continental climate are large annual, day-to-day, and daily ranges in temperature, low to moderate atmospheric moisture content, and moderate or light and irregular precipitation (Wahl et al., 1987). The climate of the study area is more strongly continental than that of Whitehorse, as it is further inland. There are three settlements in the study area with weather records: Mayo, Elsa, and Keno (Table 3.2). The data from these stations show a decrease of annual mean temperature and increase of annual mean precipitation and snowfall with increasing elevation. The weather records in the valleys show a greater degree of continentality than those at higher elevations (Table 3.2). The lower winter temperatures in the valleys are due to inversions which are common from December to February, in the absence of diurnal heating.

The data given for Elsa are considered by Green (1972) to be more representative of the area than the Mayo data

Table 3.2

Climate Statistics from Mayo, Elsa, & Keno Hill, 1951-1980

Station	Elevation (m)	Annual Mean		
		Air Temp (°C)	Precip. (mm)	Snowfall (cm)
Mayo	504	-4.0	306.3	130.5
Elsa	814	-4.4	413.0	202.9
Keno Hill	1472	-5.0	590.2	365.7

(Atmospheric Environment Service, 1982)

Monthly Mean Air Temperature (°C)											
Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov. Dec.
Mayo	-29.0	-19.9	-11.7	-0.4	7.5	13.4	15.2	12.6	6.5	-2.3	-15.2 -24.2
Elsa	-25.1	-18.1	-12.3	-2.9	5.7	12.5	14.1	11.0	4.6	-4.9	-15.3 -21.5
Keno Hill	-19.6	-13.9	-13.7	-6.6	1.4	7.8	10.0	7.9	2.0	-6.3	-12.3 -16.9

(Atmospheric Environment Service, 1982)

because the local climate of Mayo is modified by its valley situation, giving it lower precipitation, warmer summers, and colder winters. Average snow depth in central Yukon is 50 cm (Wahl et al., 1987). Snow is deeper and remains longer in the uplands than in the valleys (Kendrew and Kerr 1955). The relatively shallow snow and the abundant forest cover at low elevation result in a fairly uniform distribution of snowcover. This provides a uniform spatial influence of snowcover on ground temperature, so that snowcover variation between valley sites is not currently a factor in permafrost distribution.

3.2.5 Soils

As mentioned in section 3.2.1, Eutric Brunisol and Turbic Cryosol are the principal soils in the study area.

Brunisols develop in forests in a range of environments including the boreal forest, the arctic, and southern Canada. This soil has the beginnings of a soil profile, with a distinct Bm horizon indicating definite changes in chemistry, composition, or structure (Agriculture Canada 1987). Within the study area, Eutric Brunisols are found in Stewart River Valley, in the hills west of Wareham Lake between Minto Lake and Stewart River valley, and in the hills south of Stewart River valley (Fig. 3.5). Eutric Brunisol develops under forest or alpine vegetation where the parent material is basic or calcareous. Brunisols are

Figure 3.5
Soils of the study area
(White et al., 1994; field data collected in thesis)

Zone	Soil	Parent Material
1	Turbic Cryosol	colluvial
2	T. Cryosol	glacial moraine
3	T. Cryosol	colluvial
4	Eutric Brunisol	colluvial
5	E. Brunisol	moraine
6	T. Cryosol	alluvial
7	E. Brunisol	moraine

most frequently developed on coarse to medium textured glacial till, outwash, and aeolian deposits (Clayton et al., 1977). Eutric Brunisol is found in the lowlands and hills in the study area, and these are well covered with glacial drift and outwash deposits (see section 3.2.3).

The other principal soil type in the region, Turbic Cryosol, reflects a different environment. The northern portion of the study area, where Turbic Cryosols occur, is mountainous with a high proportion of land over 600 metres above the river valley (Fig. 3.2 and 3.5). Thus the north has more rock outcrop and colluvial materials and less glacial drift (on which Brunisols often form) than the southern portion. Cryosols are common in sub-arctic forests where the soil is fine textured and permafrost is present. Turbic Cryosol is characterized by permafrost within 2 metres of the surface, and a disturbed and broken soil profile resulting from frost action. Patterned ground is commonly found on the surface in the form of stone polygons or earth hummocks.

3.2.6 Vegetation

The study area includes portions of two ecoregions of Yukon: Pelly River in the south, and Mayo Lake - Ross River in the north (Oswald and Senyk 1977). Treeline is at 1350 - 1500 m in the entire study area, but vegetation varies from north to south, reflecting the cooler temperatures and

higher precipitation in the northern portion.

Tree species found in the study area include: white spruce (*Picea glauca*), black spruce (*Picea mariana*), alpine fir (*Abies lasiocarpa*), balsam poplar (*Populus balsamifera*), white birch (*Betula papyrifera*), and a few trembling aspen (*Populus tremuloides*).

Forests of white and black spruce with shrub and moss are common in the south. Open forests of black spruce with moss and lichen are common in the north. In the north, white spruce is confined to warmer drier sites. Aspen and white birch are more common in the south than in the north. In both areas, black spruce bogs, with scattered small trees and thick moss cover, occur in poorly-drained lowlands.

Shrubs and forbs in central Yukon are associated with soil moisture so a particular group of species is found in dry forests, another group in wet forests and heath (Oswald and Senyk 1977). In the study area, shrubs and forbs of dry forests include kinnikinnick (*Arctostaphylos uva-ursi*), wild rose (*Rosa acicularis*), lupin (*Lupinus arcticus*), and bunchberry (*Cornus canadensis*). Shrubs of wet forests include Labrador tea (*Ledum palustre*), lowbush cranberry (*Vaccinium vitis-idaea*), arctic blueberry (*Vaccinium uliginosum*), red bearberry (*Arctostaphylos rubra*), and alpine bearberry (*Arctostaphylos alpina*).

Vegetation species distribution in the area is associated with slope aspect, drainage, soil temperature,

forest fire history and river channel migration.

Aspen and white spruce favour warmer, drier locations than black spruce, and this is reflected in tree species colonizing slopes of different aspects and drainage conditions. Aspen is restricted to well-drained, steep, south-facing slopes, and black spruce is the only tree growing in poorly-drained peat bogs with permafrost.

Willow and alder are the first woody plants to colonize new alluvial flats, followed by balsam poplar, and eventually white and black spruce. The moss layer increases with this forest succession, promoting cooler soil temperatures and eventually permafrost (Smith 1975). Forest-succession patterns along the shifting channel of Stewart River are clearly visible in aerial photographs (Fig. 3.4b). Older undisturbed landscapes on the outside of meanders have large black spruce trees, thick moss, and permafrost, while recently-flooded areas have willow and alder shrubs with an equisetum understory.

Four landscape types for the region between Stewart Crossing and Mayo have been identified by Rostad et al. (1977) in terms of distinctive associations of species of trees, shrubs, and mosses. These landscape types are high river terraces, low river terraces and floodplains, lowlands, and fluvial sands. The factors responsible for these landscape-related vegetation associations appear to comprise slope aspect, soil moisture, and soil temperature.

It is evident throughout the study area that the close association between landform and soil microclimate (temperature and moisture) is expressed on the landscape in vegetation species patterns. An example of this association is shown in Figure 3.6.

3.3 Local permafrost

According to the permafrost map of Canada (Brown 1978) the study area lies within the Widespread Discontinuous Permafrost zone. The boundaries of the Widespread Discontinuous Permafrost zone are formed by the annual mean air temperature isotherms of -8.3°C and -3.9°C (Brown 1978).

Data on permafrost in the study area are found in the mining records of United Keno Hill Mines, in a report by Wernecke (1932); and in reports by Brown (1967); Riseborough (1986); Burn et al. (1986); Burn and Smith (1988); Burn and Friele (1989); and Burn (1991, 1992).

According to an account from United Keno Hill Mines (Brown 1967), above an elevation of 1371 m a.s.l., maximum thickness of permafrost in the mine is 137 m, while in the valley below at 700 m a.s.l., maximum thickness of permafrost is 43 m. Across the valley at an elevation of 777 m, no permafrost was found in mine exploration investigations on a south-facing slope.

Near Mayo, permafrost in alluvial sediments is 20 to 30 m thick, and in glaciolacustrine sediments it is 30 to 40 m

Figure 3.6

Soil-landform-vegetation associations in a
subarctic environment (after van Cleve and Varie, 1986)

thick (Burn 1992).

The ground temperature at 10 m has been measured at three sites in glaciolacustrine sediments near Mayo at -1.3°C (Burn 1992), but at seven other sites, a range of annual mean ground temperature between -2.1°C and 3.5°C has been recorded nearer the surface (Burn and Smith 1988).

3.4 Field methods

3.4.1 Introduction

In the summer of 1993, sixty sites were investigated in a 2500 km² region. The resulting data were used to develop an empirical model of factors associated with the location of frost in central Yukon. In 1994, fifty-nine sites were investigated in a 4687 km² region (extending the study area 25 km westwards and 12.5 km southwards). The resulting data were used to validate the model.

3.4.2 Site Selection

Sites for field investigation were chosen to represent as fully as possible the variety of environments found in the study area, accessible by road or river. This was achieved by selecting sites which bring into the data base the widest possible range of each variable measured.

3.4.3 Variables measured

Variables for measurement or identification were selected on the basis of factors affecting ground temperature suggested in the literature on discontinuous permafrost (Luthin and Guymon 1974; Brown 1969, 1978a; Viereck 1973; Smith 1975; Dingman and Koutz 1974; Tyrtikov 1964; Chernov 1985; Brown and Péwé 1973). Nineteen variables were used, which can be grouped into four classes: soil properties, vegetation, solar energy, and landscape (Table 3.3). Soil temperature measurements were collected to provide information about the position of the frost table.

3.4.4 Instrumentation and method of data collection

i) Soil properties and temperature

Soil samples were taken from the centre of each visible horizon in a shallow pit under 1.5 m in depth, excavated manually. Simple portable tools were used: shovel, trowel, and moisture-proof soil bags. Depth of samples and thickness of soil horizons, moss and organic layer were determined (± 1.0 cm) using a tape-measure. Depth was measured from the top of the living moss cover. Organic layer thickness was measured as the total thickness of moss, peat, humus and leaf litter. Gravimetric water content was determined for each soil horizon at each site in 1993 field work, and at approximately 50 cm in 1994 field work. Water

Table 3.3

Variables Measured

<u>Class</u>	<u>Variable</u>
I. Soil properties	1. gravimetric water content at 0.5 m 2. bulk density of mineral soil 3. bulk density of organic soil 4. thickness of moss + organic soil 5. soil texture 6. soil pH 7. sediment origins 8. organic content of mineral soil
II. Vegetation	9. small vegetation species 10. tree species 11. vegetation groups (deciduous/ coniferous/mixed forest; willow/alder; sphagnum bog; equisetum meadow)
III. Solar energy	12. canopy closure 13. slope angle 14. slope aspect
IV. Landscape	15. landscape unit type 16. landform 17. microtopography (hummocks) 18. elevation 19. glacial history

content ($\pm 0.1\%$) was determined by drying in a soil oven.

Peat and mineral soil samples for bulk-density measurement were collected using non-standard methods. Bulk density was determined using volume of sample and weight of soil after removal of water by drying in a soil oven for at least 12 hours.

Peat soil samples for bulk-density measurement were collected with a sampler consisting of a square metal plate with a perpendicular sharpened rod at each corner. The rods were inserted horizontally into the centre of the peat soil horizon, and a 216 cm^3 ($\pm < 2.0\%$) cube of peat was cut from the ground by trimming around the sampler with a knife.

Mineral soil samples for bulk density measurement were collected using a large soil tin with a hole drilled through the bottom to allow air to escape. The open top of the tin was pushed horizontally into the soil in the centre of the horizon to be sampled. A 229 cm^3 ($\pm < 2.0\%$) sample of mineral soil was collected.

Soil temperature ($\pm 0.6^\circ\text{C}$) was measured at three depths using a probe consisting of a string of three YSI thermistors encased in a moisture-proof 150 cm long, 2.6 cm diameter aluminum pipe full of dry sand. The thermistors were accurate to $\pm 0.25^\circ\text{C}$. The probe was accurate to $\pm 0.6^\circ\text{C}$. The depths at which ground temperature was measured varied from 15 to 120 cm according to site conditions. Thermistors were located at 1 cm from the lower

end of the probe, and at 6 cm and 11 cm. The purpose of this probe was to collect temperatures at three depths for a thermal profile to estimate depth to the 0° C isotherm (frost table). Residence time before temperature reading was approximately 20 minutes. The thermistors were connected to a portable digital multimeter in the field for resistance readings, which were converted to temperatures using tables and a computer program. The thermal probe was inserted into a hole in the ground made by a soil probe.

In addition to the probe described, a second instrument was used in the second field season, to locate the frost table and distinguish between frost table and gravel. Both instruments were used in the second field season. The first one was retained for comparability of data between field seasons and in case of damage to the new instrument. The second instrument was a combination soil probe and thermal probe, consisting of a steel pipe 100 cm long and 1.8 cm in diameter, containing one thermistor. The thermistor was located in the 4 cm metal (non-steel) point of the lower end of the probe, thermally insulated from the steel pipe by a 2.3 cm polyvinyl-chloride (plastic) connecting sleeve. This probe was used to determine ground temperature at a depth of up to 1 m. A portable digital multimeter was used for the resistance readings. Residence time before temperature reading was the same for both probes.

Soil texture was estimated in the field in terms of

dominantly sand, silt, clay, or organic. For greater accuracy and objectivity, soil texture was also determined in the laboratory using mechanical analysis (sedimentation method) and classified according to the Soil Texture Triangle (U.S.D.A. 1951).

Soil pH was measured (± 0.2) with the colorimetric method in the laboratory.

Organic content of the mineral soil at a depth of approximately 15 cm (measured from top of mineral horizon) was determined using a non-standard method. Oven-dry soil samples were heated to 350° C for 8 hours in a muffle furnace, igniting the organic material. The organic content is measured as loss of weight of the sample through this process.

An approximation of sediment origin and glacial history was obtained from a surficial geology map (Hughes 1983).

ii) Vegetation

An inventory of vegetation below the canopy was taken in an area of approximately 10 m² for each site, recording percent cover of each species. Percent cover was taken at the first few sites using a vegetation quadrat, and subsequently estimated by eye and verified by independent estimation by a field assistant.

Inventory of tree species was taken in the same manner as vegetation below the canopy, but a note was also made of

species adjacent to the site.

Vegetation groups (e.g., coniferous forest) were identified in the field or from site inventory of species.

iii) Solar energy

Canopy closure should be determined for the 180° arc above a site. Two methods were used to approximate this, to insure data collection in the event of malfunction of one method. One method involved taking photographs with black and white film and a wide-angle lens (60°) from approximately 50 cm above the ground, looking directly upward into the canopy. The other method involved placing a convex mirror with an 84° angle field of view, 50 cm above the ground. The mirror had a gridded surface for determining relative areas of canopy and open sky.

Canopy closure was determined from percentage of photograph or surface of mirror filled by vegetation, and processing of this data to represent a 180° angle view by assuming increasing density of the same vegetation type toward the horizon.

Slope angle and aspect were determined for a 10 m² area for each site, irrespective of slope of surroundings. Slope angle was measured using a clinometer. Slope aspect was measured with a compass.

iv) Landscape

Location and elevation of each site were determined from topographical maps with the assistance of a global positioning system and landmarks.

Landscape types were classified according to visible expression of environmental variables in terms of landform, vegetation, soil moisture, and permafrost conditions. Relief and drainage were major components of the landscape types. Landscape types comprised: thermokarst area; sphagnum bog; outside river meander/just outside of flood zone of river; inside river meander/recent slip-off slope; lowland at foot of slope; wet slope with moss; dry cliff; flood-prone alluvial flat; equisetum marsh/fen; and well-drained hillside. These landscape types were mutually exclusive, so that no site was classed as more than one type.

Landscape and landform were recorded photographically and descriptively for each site, and verified using topographic and surficial geology maps. One element of microtopography was recorded: the presence or absence of hummocks. These were of a nearly constant size in the study area - approximately 60 cm wide by 15 to 20 cm high.

3.4.5 Field definition of permafrost

Field work was carried out in July and August, near the end of the rapid thaw season, at different dates. To

standardize the depths to frost table, a typical rate of thaw for the area was assumed, calculated from existing data on the local ground thermal regime. The thaw rate used was 0.46 cm/day, which was the average rate of thaw from early June to mid August, 1982 (Burn 1986), and frost table depth was calculated for July 31st at each site.

Permafrost was assumed to exist at a site if the frost table was within 1 m of the surface on July 31st. According to the permafrost record for the area, an active layer less than 1 m thick at end of July indicates permafrost. The observed rate of thaw in the area and the air temperature record show that after July 31st, little further thawing occurs. For example, at sites with active layer depths reaching 75 to 110 cm by the end of the thaw season, approximately 10 centimetres of thaw occurs between July 31 and mid to late September when the frost table reaches its maximum depth (Burn 1986).

CHAPTER 4

FIELD RESULTS AND EMPIRICAL MODEL

4.1 Introduction

Chapter four has three parts. First the results of field work are presented in detail to show the range and pattern within the data for each variable for the various environments found in the study area. An aim of this project has been to characterize the spatially diverse environment of the study area in terms of each variable influencing the occurrence of frozen ground. As associations appeared between values of variables and particular types of environment, the spatial applicability of the results became evident.

The second part describes the empirical model that was developed to summarize the associations found between the factors measured and the presence or absence of frozen ground. The empirical model predicts accurately the presence or absence of frozen ground at 92% of the sites in the data base. The model consists of two sets of factors. One set is associated with the absence of frost, and the other set is associated with the presence of frost. The findings suggest that the most reliable predictors of the presence or absence of frozen ground in the study area are soil moisture and thickness of the surface organic layer.

Part three (4.4) presents results of testing the empirical model. The model was tested in two ways: with an independent set of data collected in the second summer of field work in the same study area, and with a microclimate simulation program. The empirical model predicted the presence or absence of frozen ground for 95% of the sites in the new data set. This result compares favourably with the 92% prediction of the model for the data base from which it was calibrated. Thus the second data set validates the model. The microclimate simulation program (modified from Outcalt 1972) was used to perform a sensitivity analysis of the physical significance of the strongest factors in the model - soil moisture and organic layer thickness. If varying these factors produced results which agreed with the empirical model, it would indicate that these factors have a physical basis independent of the boundaries of the study area. Thus the model could be used throughout central Yukon, and in other places where the climate is similar to that of the region.

4.2 Results of field work

4.2.1 Introduction

This section gives a detailed picture of the study area according to the data collected on soil properties, vegetation, solar energy, and landscape. Soil properties were the factors most strongly associated with the

presence or absence of frost. Of these, soil water content, organic layer thickness, and soil texture were the most important. Forest type was associated with the presence or absence of frozen ground, deciduous forests being frost-free, and coniferous forests having the highest likelihood of frost. Two small vegetation species tolerant of the soil conditions associated with a shallow frost table were found in greater numbers on sites with permafrost. All slope aspects had sites with and without permafrost, but north-facing slopes had the highest percentage of sites with permafrost, and south-facing slopes had the lowest. Canopy closure only showed an association with presence or absence of frost on south-facing slopes. On these slopes, the canopy was more open over frost-free sites. Altitude was not clearly associated with the presence or absence of frost, but the data set focuses on elevations from 400 to 1000 metres, and does not fully represent mountain areas with elevations from 1200 to 1840 metres. Landscape types were identified, for example sphagnum bog, dry cliff, thermokarst area, based on visible differences between distinct homogeneous units of the landscape. Landscape types are associated with the presence or absence of perennially frozen ground through combinations of factors, with soil moisture playing a leading role.

4.2.2 Soil properties

Gravimetric water content

In the study area, gravimetric soil moisture content varied from 0% on a steep, dry, south-facing cliff of gravel and coarse sand, to 600% in frozen peat near a thermokarst lake. Soil moisture was higher in coniferous forests, with values from 25% to over 100%, and lower in deciduous forests, with values from 3% to 24%.

Water content at 0.5 m was associated with the presence or absence of frost. Sites with frost had soil moisture contents over 25%. Frost was absent from all sites with less than 25% soil moisture. The only frost-free sites with soil moisture over 25% included flood-prone areas beside the river and marshy areas with standing water. With the exception of frequently-flooded sites, all sites with sandy soil and thin organic layer had soil moisture under 25% (Fig. 4.1).

Organic layer thickness

Organic layer thickness ranged from 0 cm to over 25 cm. The thickest organic layer found in the study area was over 48 cm (in the 1994 data set). A thin organic layer of 1 cm or less was associated with two types of sites: very dry sites with soil moisture less than 7%, and flood-prone sites on riverbanks, where frequent sedimentation prevented growth of a moss layer. A thick organic layer (20 cm or more)

Figure 4.1

Distribution of frost-free sites according to primary factors associated with absence of frost

was associated with coniferous forests, lowlands, thermokarst and sphagnum bogs.

Sites with frost had an organic layer over 8 cm thick. Frost was absent from all sites with an organic layer less than 8 cm thick. The only frost-free sites with an organic layer over 8 cm thick were dry sites - with less than 25% soil moisture content.

Organic content of mineral soil

Organic content of mineral soil at a depth of approximately 15 cm, ranged from 0.36% to 18% and was directly related to thickness of organic layer. Where organic content of mineral soil was less than 2%, all sites were frost-free, but many frost-free sites had a higher organic content.

Soil texture

Soil texture in the study area ranged from silty clay (one site in 60) to sand (4 sites). Stoney soils were found on moraine between Mayo and Stewart Crossing, in glacial outwash on Hansen-McQuesten Road, and on an alluvial delta about 2 km north of Mayo. The most common textural class in the database was silt loam, which comprised 43% of sites (Fig. 4.2). The second largest class, sandy loam, was represented by 20% of the sites.

All soils with over 45% sand, including sand, loamy sand, and sandy loam, were frost-free. All sites with over 45% sand were entirely subsumed within two other

Figure 4.2
Particle size distribution range for the study area

classes of factors associated with frost-free conditions: low soil moisture or thin organic layer (Fig. 4.1).

Soil pH

Soil pH ranged from 3.9 to 8.0. There was no clear association between pH and frost, although higher pH values were found at sites with a thin organic layer. At sites with moss and peat, pH ranged from 3.9 to 7.8. At sites with negligible organic layer, pH ranged from 4.5 to 8.0.

Soil bulk density

Bulk density of the mineral soil and organic soil appeared to be within expected ranges: mineral soils 1.0 to 1.6 g cm⁻³; organic soils 0.2 to 0.3 g cm⁻³ (Brady 1984). Soil bulk density showed no clear association with frost conditions.

Active-layer thickness

Permafrost was assumed to exist at a site if the frost table was within one metre of the surface (measured from top of moss and peat layer) on July 31. Among the sites with frost, the depth to frost table ranged from 15 cm to 92 cm, with an average of 57 cm. The frost table was defined as the depth at which the ground temperature was 0° C.

Frost action in soil profile

Frost action is evident in soil profiles where Turbic Cryosol is shown on the soil map (Fig. 3.6). The most common soil profile types in the study area were those of Turbic Cryosol and Eutric Brunisol, e.g., sites 35 and 33,

Figure 4.3a. Turbic Cryosol has permafrost within 2 m of the surface, and frost-churned horizons (Fig. 4.3a, site 35). Eutric Brunisol profiles show an early stage of development achieved through a period without permafrost. Warm sites with the longest permafrost-free history showed the most developed profiles (Fig. 4.3a, site 38). Alluvial soils experiencing frequent flooding and sedimentation are free of permafrost due to the thermal influence of the river. In these soils (Fig. 4.3a, site 56), a history of sedimentation is evident in alternating layers of silt and sand, and the absence of organic layers.

4.2.3 Vegetation

Forest type

In selecting sites, an effort was made to accurately represent the environment of the study area. According to the database, approximately 85% of the study area is forested. Coniferous forest is the dominant forest type, followed by mixed forest, with deciduous forest in the minority (Table 4.1a).

Forest type was associated with the presence or absence of frost (Table 4.1b). The association between forest type and frost seems to be mediated to some extent by organic layer thickness. The organic layer was less than 5 cm thick at all deciduous forest sites. Sites with mixed forest and coniferous forest showed the same range of organic layer

Figure 4.3a

Soil profiles of the study area

Soil texture
silt
sand
organic

Soil colour	
B	black
BR	brown
G	grey
PR	pale red
R	red
Y	yellow

Figure 4.3b

Contrast between soil
profiles of adjacent
landscape units.

Table 4.1a

Forest Cover Distribution

<u>Cover type</u>	<u>Percent of sites</u>
Coniferous forest	40.0
Mixed Forest	30.0
Open space	16.7
Deciduous forest	13.3

Table 4.1b

Probability of frost with forest type

<u>Forest type</u>	<u>Probability of frost (%)*</u>
Coniferous	73.0
Mixed	17.6
Deciduous	0.0

* percent of sites in this forest type
with frost

thickness (1 to 25 cm), with the average for coniferous forest at 13.6 cm and mixed forest at 9.6 cm.

Small vegetation species

All sites with over 50% cover of Labrador tea (*Ledum palustre*) and all sites with at least 1% Bearberry (*Arctostaphylos rubra* and *A. alpina*) had frost. Both of these plants are associated with higher soil moisture content, thick moss and organic soil. Labrador tea in particular is associated with the wet, cool, acidic soil found in peat bogs and lowlands with stunted black spruce trees and permafrost.

4.2.4 Solar Energy

Slope aspect

Slope aspect was weakly associated with frost conditions, but the expected pattern emerged from the data - colder north-facing slopes, warmer south-facing slopes (Table 4.2). Fifty percent of sites with northerly aspect (northeast through northwest) had frost, while 31% of sites with southerly aspect had frost. East and west-facing slopes showed an equal propensity for frost at 45% of sites with either aspect.

Slope angle

A statistical analysis was conducted to determine the significance of the association of slope angle with frost, for slopes at each of four aspects - north, south, east and

Table 4.2

Probability of frost with slope aspect

<u>Slope aspect</u>	<u>No. of sites</u>	<u>Probability of frost (%) *</u>
North	6/12	50
East	5/11	45
West	5/11	45
South	4/13	31

* percent of sites on this slope aspect with frost

west. (e.g., north aspect includes northeast to northwest, as above). The Mann-Whitney U test was used because, as a non-parametric test, it is suitable for data which are not normally distributed, and because it allows testing of small samples (less than 20 items in each of two classes). A significance level of 0.05 was chosen (Ebdon 1977). The results showed that for all aspects, slope angle was not a significant factor (Table 4.3).

Canopy closure

In each forest type, canopy closure showed a large range, the low end for all forest types being equivalent to open shrub landscape. The maximum canopy closure at the deciduous forest sites was 88%. Mixed and coniferous forests showed maxima of 94% and 95% respectively. A lower incidence of frost might be expected at more open sites, but sphagnum bogs, where the trees are small (less than 3 m high) and scattered, almost always have permafrost. No association between canopy closure and frost appeared in analysis of the data, except in combination with slope aspect. All south-facing slopes with less than 70% canopy closure were frost free.

4.2.5 Landscape

Microtopography: hummocks

Hummocks, a form of patterned ground, are common in areas with permafrost. They may be found in relict form at former permafrost sites (Washburn 1979). In the study area,

Table 4.3

Results of Mann-Whitney U-test of significance of slope angle within each of four slope aspects, in distinguishing the two classes of sites.

Slope aspect	Class of site	Sample size	U sample	U* critical	Samples ** different
South	Frost-free Frost	9	8	6	no
		4	28		
North	Frost-free Frost	6	15	7	no
		6	21		
East	Frost-free Frost	5	22	4	no
		5	22		
West	Frost-free Frost	6	15	5	no
		5	15		

* If U critical is greater than smallest U sample, then samples are different.

** at 0.05 level of significance

2 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

hummocks were found at all sites with frost, and at 13% of sites without frost. The frost-free sites with hummocks resembled frost sites on the surface, having coniferous forest and/or thick moss, but all had dry sandy soil, which is associated with absence of frost in the empirical model. This suggests these hummocks may be relict from a wetter climate in the past.

Altitude

The database includes a range of altitude for the study area from 400 metres in the Stewart River valley to 1840 metres at the top of Keno Hill (Fig. 4.4). 83% of the sites were below 1000 metres. Sites between 1200 and 1840 metres were on a southwest-facing mountain slope (Keno Hill), which may have resulted in under-representation of frost conditions above 1200 metres, as southerly aspects in this area tend to be warmer than others. No association between altitude and frost condition was found.

Landscape types

Landscape types were identified for the sites in terms of visible differences between homogeneous units of terrain. These differences correspond to singular combinations of environmental factors, such as location with respect to a landform, soil moisture, vegetation, and permafrost conditions. Landform determines slope aspect, drainage, and soil texture of a site. These factors are often reflected in vegetation (see 3.2.6). An association was found between

Figure 4.4
Altitude transect from Mayo to Keno Hill

landscape type and frost, which appears to operate through soil moisture. Landscape types, ranked according to soil moisture, ranged from sphagnum bog to southwest-facing cliff (Table 4.4). Except for alluvial lowlands with a high water table, frost-free landscape types had lower soil moisture than landscape types with frost. Apart from the alluvial lowland sites, the 25% soil moisture value distinguishes between the two classes of landscape types (i.e., landscape types with and without frost).

Each landscape type has a characteristic combination of soil moisture, organic layer thickness, and soil texture, which together contribute to a site's tendency toward frost. These factors often trend in the same direction, as they are to some degree interacting. For example, consider a site with silty soil at the foot of a slope. Its location with respect to the slope gives it poor drainage, the silty texture enhances the soil's moisture-holding capacity, the higher moisture content promotes moss growth, resulting in a thicker organic layer, and the thick organic layer and high moisture content in different ways contribute to lower soil temperature (see 2.3).

Contrasting landscape types are often found in close proximity, with distinct boundaries. They can thus be mapped at local and regional scales to show the spatial distribution of probability of permafrost (see chapter 5). Figure 4.3b shows the soil profiles for adjacent contrasting

Table 4.4

Landscape types based on soil moisture - frost relation

Site class	Landscape type	Average gravimetric soil moisture content (%)
Sites with frost	1. sphagnum bog	512
	2. outside meander (with moss)	68
	3. lowland at foot of slope	57
	4. thermokarst	41
	5. wet cliff top (with moss)	28
Wet sites without frost	6. flood-prone lowland beside river	45
Dry sites without frost	7. dry cliff top (no moss)	24
	8. inside meander (no moss)	22
	9. upper equisetum marsh	18
	10. dry steep hillside	13
	11. S.W. cliff face	3

landscape types. The sites were 80 metres apart. One was in a sphagnum bog with mossy hummocks, scattered stunted black spruce trees, thick organic soil over silt, a soil moisture content of 512%, and frozen ground at 15 cm. The other site was on an adjacent steep hillside on glacial outwash, densely forested with white and black spruce and alpine fir, with a thin organic layer, soil moisture content 10%, and a frost-free soil profile showing a predominance of coarse sand and gravel.

4.3 The empirical model

The empirical model summarizes the associations between the various factors measured and the presence or absence of frozen ground. Nineteen variables were measured, which can be grouped into four classes: soil properties, vegetation, solar energy, and landscape (Table 3.3). Data were collected at 60 sites in the summer of 1993 to generate empirical relations of factors associated with frozen ground. Analysis of the data showed which factors were most strongly associated with the presence or absence of frost. A factor was considered physically significant if it was found at 5 or more sites and a diagnostic pattern was evident in the data. For example, all sites with soil moisture less than 25% were free of frost.

Data analysis

The diagnostic pattern for selection of factors consisted of a clear separation of frost-free sites from frost sites when the values of a variable were ranked. The separation seldom exactly divided the two classes, but one class was always more uniform. For example, although all sites with frost had hummocks, there was a small minority of frost-free sites with hummocks. Factors associated with more than 50% of the sites in either class were defined as primary factors (Table 4.5). Ones associated with less than 50% of the sites of either class were defined as secondary factors. Some factors are subsumed within others. For example, sand content over 45%, as a frost-free factor, is subsumed within the two factors: organic layer less than 8 cm, and soil moisture less than 25% (see Figure 4.1). All secondary factors are subsumed within primary factors, so the secondary factors can be omitted without changing the model's predictive ability.

Primary and secondary factors for absence of frost

Six factors are associated with the absence of frost (Table 4.5). The primary factors are: (1) a thin organic layer: moss and peat less than 8 cm thick; (2) low soil moisture content: gravimetric water content less than 25%; (3) sandy soil texture: mineral soil more than 45% sand. Secondary factors associated with the absence of frost

Table 4.5

**Factors associated with presence or absence
of frost in the study area**

Factors associated with absence of frost		Percent of Frost-free sites
Primary	1. organic layer < 8cm	78
	2. soil moisture < 25%	76
	3. sandy soil texture (> 45% sand)	57
Secondary	4. organic content of mineral soil < 2%	30
	5. deciduous forest	22
	6. south aspect and canopy closure < 70%	14

Factors associated with presence of frost		Percent of Frost sites
Primary	1. hummocks present, soil moisture > 25%, & organic layer > 8 cm	100
	2. fine soil texture (<45% sand)	100
Secondary	3. >= 1% cover of bearberry	39
	4. > 50% cover of Labrador tea	22

include (1) a less than 2% organic content of the upper mineral horizon, (2) deciduous forest cover, and (3) a combination of south aspect and less than 70% canopy closure.

Primary and secondary factors for presence of frost

Four factors are associated with the presence of frost (Table 4.5). Of the primary factors, the most strongly predictive one is a combination of three variables: the presence of hummocks, soil moisture content over 25%, and organic layer over 8 cm thick. The other primary factor is fine-textured soil (sand content less than 45%). The two secondary factors associated with the presence of frost include the presence of Bearberry (*Arctostaphylos rubra* and *A. alpina*) (plants requiring high soil moisture, as distinct from *Arctostaphylos uva-ursi* which requires low soil moisture) covering at least 1% of the site, and Labrador tea (*Ledum palustre*) covering over 50% of the site.

Statistical significance

The sites were divided into two classes: frost-free sites and frost sites. Primary factors shared by both classes include organic layer thickness, soil moisture content, and soil texture (sand content). These variables were subjected to a statistical test to determine the significance of the difference between the two classes. The Mann-Whitney U Test for each of the variables, organic layer thickness, soil moisture content, and sand content, showed

Table 4.6

Results of Mann-Whitney U-test of significance of organic layer thickness, soil moisture content, and soil texture (sand content) in distinguishing the two classes of sites

Variable	Class of site	Sample size	U sample	U* critical	Samples ** different
organic layer thickness	Frost-free Frost	37 23	760 69	202	yes
soil moisture content	Frost-free Frost	37 23	766 85	209	yes
soil texture (sand content)	Frost-free Frost	37 23	-59 628	209	yes

* If U critical is greater than smallest U sample, then samples are different.

** at 0.05 level of significance.

that the two classes were different at a significance level of 0.05 (Table 4.6).

Most efficient factor

A goal of the project was to find the simplest method, derived from the data, to predict the presence or absence of frozen ground at any site in the study area. Table 4.7 presents the complete distribution of factors for both classes of sites. The combined factor consisting of hummocks, high soil moisture, and thick organic layer, for frost sites, is the only factor which applies to all the frost sites and none of the frost-free sites. Thus this factor can be used alone to predict the presence or absence of frozen ground at a site. Examination of Table 4.7 might suggest that a combined factor for frost sites could be made from low sand content, high soil moisture, and thick organic layer. However, three frost-free sites were found in this category, all in low-lying riverside locations with a high water table. Therefore the simplest or most efficient method to predict the presence or absence of frost in the study area is the combined factor of hummocks, high soil moisture and thick organic layer. In practical terms, this requires the collection of three pieces of data in the field: (1) presence or absence of hummocks; (2) thickness of moss and organic soil; (3) soil moisture content.

Table 4.7

Distribution of factors

<u>Primary factors</u>			
<u>Factor</u>	<u>Category</u>	<u>Class</u>	<u>% of class</u>
Soil moisture	< 25%	frost-free	76
	> 25%	frost-free	24
	> 25%	frost	100
Organic layer thickness	< 8 cm	frost-free	78
	> 8 cm	frost-free	22
	> 8 cm	frost	100
Sand content	> 45%	frost-free	57
	< 45%	frost-free	43
	< 45%	frost	100
Hummocks	absent	frost-free	87
	present	frost-free	13
	present	frost	100
Hummocks & high moisture & thick organic layer	absent	frost-free	100
	present	frost	100
<u>Secondary factors</u>			
Deciduous forest	present	frost-free	22
	absent	frost-free	78
	absent	frost	100
Organic content of mineral soil	< 2%	frost-free	30
	> 2%	frost-free	70
	> 2%	frost	100
South aspect & canopy < 70%	present	frost-free	14
	absent	frost-free	86
	absent	frost	100
Labrador tea percent cover	< 50%	frost-free	100
	< 50%	frost	78
	> 50%	frost	22
Bearberry	absent	frost-free	100
	absent	frost	61
	present	frost	39

4.4 Results of testing the empirical model

4.4.1 Independent data set

In the second season of field work, an independent data set of similar size to the initial set (59 sites and 60 sites respectively) was collected in the study area (see 3.4.1 and Figure 3.1). This data set was analysed to determine whether the presence or absence of frost could be predicted accurately with the empirical model at the new sites. A refined model (see section 4.3) including only the primary factors, was used to compare the two data sets. Figures 4.1 and 4.5 show the distribution of primary factors for the two data sets. Table 4.5 shows results of analysis of the initial data set from which the empirical model was developed. Table 4.8 compares results of analysis of primary factors for both data sets. The empirical model is considered validated by the second data set if the model predicts the presence or absence of frost for the second data set at least as well as it did for the initial data set. The model predicted presence and absence of frost for 92% of sites in the first data set and 95% of sites in the second data set. Thus the second data set validates the model.

4.4.2 Microclimate simulation

The two factors found to be the most reliable predictors of the presence or absence of frost in the

Figure 4.5

Distribution of frost-free sites according to
primary factors associated with absence of frost
(second data set)

The second set of data fits the empirical model
in a manner comparable to the first set of data
(see figure 4.1).

Table 4.8

Comparison of data sets 1 and 2, percentage of sites
in either class associated with primary factors

Class	Primary factors	Data set	
		1	2
frost	hummocks & high soil moisture & thick organic layer	100	100
frost	low sand (sand content < 45%)	100	100
frost-free	thin organic layer*	78	71
frost-free	low water content**	76	89
frost-free	high sand (sand content >45%)	57	66

* set 1: <8 cm
set 2: <11 cm

** set 1: <25%
set 2: <24%

empirical model were tested with a modified version of Outcalt's (1972) microclimate simulation model. This is an analytical model which can be used to simulate the ground thermal response to changes in climate or in microclimatic factors. Inputs include climate data, and ground thermal and physical properties. The factors tested were soil moisture content and organic layer thickness. These were systematically varied, and resulting changes in active-layer thickness were observed. A thinner active-layer was interpreted as a greater tendency toward permafrost. Trends rather than actual values of active-layer were noted, as climate data input into the model were for Whitehorse. These data are not representative of conditions in the study area, but are from the nearest station with complete climate data required by the model, including global solar radiation. Results of simulations showed that as organic layer thickness was increased, active-layer thickness decreased (Figure 4.6). This agreed with expectations that a thicker organic layer would tend to promote lower ground temperatures and permafrost (see 2.3.1). The result shows that this component of the model has a physical basis independent of the boundaries of the study area so it may be applied throughout central Yukon and in places with a similar climate.

Results of simulations of soil moisture content were inconclusive. Further modifications of the program may be

Figure 4.6

Results of microclimate simulation of
varying organic layer thickness

required to make simulations of this variable meaningful. High soil moisture content was found in the field in two different kinds of circumstances - one where permafrost was present, the other in association with a high water table beside a river. In the first instance, high soil moisture content may be a result of the presence of the frost table. In the second instance, a nearby large water body is maintaining the soil at above-freezing temperatures.

CHAPTER 5

MAPPING THE PROBABILITY OF PERMAFROST

5.1 Introduction

Two sections of the study area with a high density of field sites were chosen to demonstrate how permafrost probability can be mapped using the empirical model and other information from the data base (see Figure 5.1). The mapped areas are centred on MacIntyre Park and Wareham Lake. These areas represent two of the local landscapes - river floodplain and hilly terrain.

The purpose of the mapping exercise was to identify the permafrost probability at a site of size 20 x 20 m to 50 x 50 m where a building could be located. The resolution of information on the resulting maps is such that the smallest polygon is larger than one building site. It is assumed that a uniform site is selected.

Information contributing to the maps included aerial photographs, topographical maps, surficial geology maps, site information, the empirical model, and related information derived from analyzing the data base. Data from field investigations were used to assist in identification of landscape types, soil texture, and tree species.

Figure 5.1
Location of Wareham Lake and MacIntyre Park
within the study area

5.2 Mapping permafrost probability with four variables

The empirical model shows that permafrost can be predicted accurately at a site using three pieces of information - the presence or absence of hummocks, soil moisture content, and thickness of the organic layer. However, maps of this information are not readily available, so surrogates in the form of related variables which can be readily read or interpreted from maps are helpful. Surrogate variables were found for soil moisture and organic layer thickness in the form of landscape type and forest type respectively. Two other variables were chosen for this mapping method - soil texture and slope aspect, as both were found to be relevant to the presence or absence of permafrost in this study and because mapped information on both is readily available.

Soil moisture and landscape type

Landscape type was used as a surrogate variable to map soil moisture. Table 4.4 shows associations between soil moisture and landscape type in the data. The empirical model indicated that sites with soil moisture contents over 24% had permafrost, with the exception of flood-prone lowlands beside the river. Sites with lower soil moisture contents were free of permafrost. Table 5.1 lists the landscape types found in the data according to presence or

Table 5.1

Landscape types indicating permafrost status**(A) With permafrost**

1. thermokarst area
2. above treeline
3. lowland at foot of slope/ sphagnum bog
4. outside meander/ just outside river flood zone
with moss
5. wet steep slope/ wet cliff top with moss

(B) Without permafrost

5. open water, river channel and islands
6. flood zone beside river
7. equisetum marsh/ fen
8. inside river meander (recent slip-off slope)
9. dry steep hillside
10. dry cliff face/ top of dry cliff

absence of permafrost. Landscape type is determined from interpretation of topographical maps, aerial photographs, and surficial geology maps. Assuming that the data in this study accurately represent the study area, permafrost in the study area may be predicted from landscape type alone.

Organic-layer thickness and forest type

An association between organic-layer thickness and forest type was noted in section 4.2.3. Deciduous forests in the study area have an organic layer less than 5 cm thick. In mixed and coniferous forests, organic layer ranges from 1 to 25 cm, with an average of 9.6 cm for mixed forest and 13.6 cm for coniferous forest. Forest type was associated with permafrost (Table 4.1b), with a higher percentage of coniferous forest sites having permafrost than mixed forest sites, and deciduous forest sites being permafrost-free. With the exception of deciduous forest, which is clearly associated with the absence of permafrost, forest type may be used as a surrogate for permafrost status through organic-layer thickness in an approximate or qualitative sense. Forest type may be interpreted from aerial photographs at a scale of 1:50,000.

Soil texture

Soil texture is an important component of the empirical model, where it was shown that all sites with coarse-

textured soil (over 45% sand - or with the term 'sand' or 'sandy' in the nominal classification) were free of permafrost (Table 4.7). Thus soil texture mapping can identify coarse-textured sites as free of permafrost. An approximation of soil texture for a site, based on surficial geological maps, may be determined using information shown in Table 5.2.

Slope aspect

Analysis of the data showed that 50% of north-facing slopes had permafrost, 31% of south-facing slopes did, and 45% of east- and west-facing slopes had permafrost (see 4.2.4). Thus slope aspect mapping can provide information on the relative likelihood of permafrost. Slope aspect can be read from topographical maps and stereo pairs of aerial photographs.

5.2.1 Determining the probability of permafrost

It was assumed that the data were representative of the study area. Landscape type alone was sufficient to identify any site in the data set accurately as a permafrost site or a permafrost-free site. A method of mapping was designed which would allow identification of probability of permafrost also at sites where landscape type is uncertain. It is not always possible to identify the landscape of a site without field verification.

Table 5.2

Approximating soil texture from surficial geology map:

Genetic category and textural modifier were read from a surficial geology map. This information was translated into soil texture using Table 5.2c (following page).

(a) Genetic categories¹

Organic deposits
Alluvial deposits
Colluvial deposits
Glaciofluvial deposits
Morainic deposits
Bedrock

(b) Textural modifiers¹

fen
peat bog
clay
silt
sand
gravel

1. Hughes 1983

Table 5.2c

Mode of deposition and resulting texture⁻²

<u>Mode of deposition</u>	<u>Texture</u>
1) Morainal material deposited by ice.	Mixture of boulders, stones, sand, silt, & clay.
2) Fluvioglacial material deposited by flowing glacial meltwater.	Mostly sand and/or gravel.
3) Lacustrine material deposited by glacial lake water.	Mostly silt and clay.
4) Alluvial material deposited by rivers and streams.	Mostly sand, silt & gravel.
5) Colluvial material deposited under influence of gravity on steep slopes.	Mostly sand, silt, & angular bedrock fragments.
6) Colluvial material deposited under influence of gravity on gentle slopes in unglaciated landscapes.	Mostly silt & clay.

2. Agriculture Canada 1993, Soil Landscapes of Canada
Publication 5281/B.

If landscape type is not known, the flow chart in figure 5.2 can be used to determine the probability of permafrost. Figure 5.2 summarizes the probabilities of permafrost in the study area for all possible combinations of soil texture, forest type and slope aspect. The probabilities of permafrost are based on the frequencies of occurrence and absence of permafrost for each particular combination of variables. For example, 67% of sites with fine to medium (non-coarse) soil texture, mixed forest, and Northeast- or Northwest-facing slopes had permafrost. Figure 5.2 may be used for mapping permafrost probability, or in the field to estimate permafrost probability at a site.

5.2.2 Combining the input maps

Four maps were used as inputs to the permafrost probability maps. The input maps show landscape type, soil texture, forest cover, and slope aspect. These maps were combined manually as transparencies to produce a map showing all combinations of the four variables in the area. The technique is similar to that used by McHarg (1969). Where landscape type was known, permafrost status was identified according to Table 5.1. Elsewhere, the flow chart (Figure 5.2) was used, facilitated by a computer spreadsheet of the variables with logical statements representing steps in the flow chart. For example: If soil texture = fine and forest

Figure 5.2

Method for determining probability of permafrost using only soil texture, forest type and slope aspect, based on the data set from this study

type = coniferous and slope aspect = NE or NW, then permafrost probability = 67%. A computerized Geographical Information System was not used because the small area of land covered in this exercise made the manual technique more efficient.

5.3 Case study - MacIntyre Park area

This mapping project examined a two by three kilometre area of land centred on MacIntyre Park, approximately 2 kilometres north of the village of Mayo (Fig. 5.3). The landscape consists of the floodplain of the Mayo River sloping gently southwards toward the Stewart River, slightly higher land to the east of the floodplain, and a level area at the top of a high (over 70 metres) steep cliff which forms the southern end of a former alluvial delta in the northwest portion of the map.

Input maps

The input maps are shown in Figure 5.4. The information and its origin are as follows:

- 1) Landscape types from field data, aerial photograph interpretation, topographic map interpretation, and surficial geology map.
- 2) Forest cover from field data and aerial photograph interpretation.
- 3) Soil texture approximation from surficial geology map.
- 4) Slope aspect from topographic map and stereo aerial

Figure 5.3

**The MacIntyre Park area with
the north end of the village of Mayo
(A19604-25, National Air Photo Library)**

Landscape types (soil moisture)

C: dry cliff face & top of dry cliff
 I: inside river meander (recent slip-off slope)
 L: lowland at foot of slope
 T: thermokarst
 R: open water, river channel & islands
 U: unclassified

Soil texture

C: coarse
 F: fine & medium
 W: water

Forest cover (& organic layer)

C: coniferous
 D: deciduous
 M: mixed
 U: open (unforested)
 W: water

Slope aspect

N: north-facing
 NE: northeast
 S: south-facing
 SE: southeast
 W: water & river channel
 All other areas are level
 to gently sloping.

Figure 5.4
 Inputs to the permafrost probability map
 for the MacIntyre Park area

photograph interpretation.

Permafrost probability map

Figure 5.5 shows the resulting permafrost probability map for the MacIntyre Park area.

5.4 Case study - Wareham Lake area

This mapping project examined a 5 by 6 kilometre area of land centred on Wareham Lake, a reservoir on the Mayo River, approximately 10 kilometres north of the village of Mayo (Fig. 5.6). The landscape consists of lowlands to the southeast and north of the lake, and steep hills to the east, west, and south. The Mayo River flows into the lake from the north, where thermokarst is common in the river valley. Thermokarst is also present in the lowland to the southeast of the lake where the lake water has been thawing deposits of ground ice.

Input maps

The input maps are shown in figure 5.7. The information and its origin are as follows:

- 1) Landscape type from field data, aerial photograph interpretation, topographic map interpretation, and surficial geology map.
- 2) Soil texture approximation from surficial geology map.
- 3) Forest cover from field data and aerial photograph interpretation.
- 4) Slope aspect from topographic map and stereo aerial

Figure 5.5

Permafrost probability, MacIntyre Park area

Figure 5.6

**Wareham Lake area
(A27483-197, National Air Photo Library)**

Landscape types (soil moisture)

C: cliff face
 H: steep hillside
 I: inside river meander
 L: lowland at foot of slope
 T: thermokarst
 W: open water, river channel & islands
 U: unclassified

Soil texture

C: coarse
 F: fine & medium
 W: water

Forest cover (& organic layer)

C: coniferous
 M: mixed
 W: open water & river channel
 & islands

Slope aspect

N: north-facing S: south
 NE: northeast SE: southeast
 NW: northwest W: water
 Other areas are east or west
 facing, or level to gently sloping.

Figure 5.7
 Inputs to the permafrost probability map
 for the Wareham Lake area

photograph interpretation.

Permafrost probability map

Figure 5.8 shows the resulting permafrost probability map for the Wareham Lake area.

5.5 Interpretation of results

The permafrost probability maps for the MacIntyre Park area and the Wareham Lake area are based on the assumption that the data set for all sites in the study area is representative of the study area. A small portion of each of the two maps consisted of combinations of variables not found in the data set. A field check of areas on either map where field sites did not occur in the study could reveal how accurately the data set represents the study area.

The permafrost probability maps have a resolution of information from 20 m (MacIntyre Park) to 50 m (Wareham Lake) which corresponds to the site of a small building project. The resolution was determined by inspection of the aerial photographs (1:50,000) used for mapping forest type. On these aerial photographs, the smallest area of identifiable vegetation type was 20 m for MacIntyre Park and 50 m for Wareham Lake.

The maps are simple enough to provide quick information on permafrost probability at a given location. The information in the maps is based on data directly or indirectly related to soil moisture, organic layer

Figure 5.8

Permafrost probability, Wareham Lake area

thickness, and soil texture. The empirical model for the study area (see chapter 4) emphasizes these soil characteristics as the variables most strongly associated with the presence or absence of permafrost at a site.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Objectives and background

The objective was to develop a model to predict the occurrence of perennially frozen ground in the discontinuous permafrost zone of central Yukon. The literature from the 1960's to 1980's identified a number of environmental variables associated with the occurrence of permafrost in the discontinuous zone. These variables include (1) soil properties; (2) vegetation cover; (3) thickness of moss and peat; (4) topography - solar energy interactions. However, no quantitative analysis of these variables had been conducted to determine their relative importance. This thesis assesses the relative importance of each variable within the study area, and develops a simple model to predict the occurrence of permafrost at a scale of resolution suitable for a small engineering project of 20 x 20 m to 50 x 50 m.

Field work

Field work was carried out in July and August of 1993 in a 2500 km² area around Mayo, Y.T. Nineteen variables were measured at each of 60 sites. Sites were selected to represent the extent of natural variability of the

environment within the study area. The variables measured can be summarized into four classes: soil properties, vegetation, solar energy, and landscape. Soil temperature measurements were collected to locate the frost table. The resulting data base was used to develop an empirical model to predict permafrost occurrence. In the summer of 1994, a second set of data was collected in the same area to test the empirical model.

Field methods

Soil samples from shallow pits less than 1.5 metres deep were collected and analyzed for texture, moisture content, pH, bulk density, and organic content. Soil profiles were sketched to identify sites with turbic cryosol, the soil type characteristic of permafrost sites. Organic layer thickness was measured. Ground temperatures were recorded using a thermal soil probe and digital multimeter. Soil moisture analysis was conducted within 24 hours of sampling, using a portable soil oven and electronic scale. Depth to frost table was measured where possible, and in other cases estimated from three temperature measurements at different depths.

Vegetation inventories were carried out at each site.

Solar energy differences were assessed by measuring slope angle and aspect, and estimating canopy closure by two methods: (i) from photographs taken with a wide-angle lens, and (ii) calculating the shaded area on a gridded

convex mirror positioned within 50 cm of the ground surface in the centre of the site.

Landscape types were classified according to visible expression of environmental variables in terms of landform, vegetation, soil moisture, and permafrost conditions.

Since the field work was conducted during the thaw season, it was important to distinguish between seasonal frost and permafrost. A field definition of permafrost was chosen according to the existing permafrost data base for the area which has established that by the end of July, an active layer less than one metre thick indicates permafrost.

6.2 Results

Soil

Soil properties were the factors most strongly associated with the presence or absence of permafrost. Of these, soil moisture content, organic layer thickness, and soil texture, were the most important.

Other variables

The presence or absence of hummocks was another factor showing a strong association with permafrost status of a site. Apart from soil properties and hummocks, all other variables were of secondary importance to the empirical model, and could be ignored without detriment to its predictive ability.

Forest type and slope aspect are examples of variables

analyzed and found to be of lesser strength than soil properties as predictors of permafrost. However, associations between these variables and permafrost probability were found. These associations were useful in mapping the probability of permafrost.

The empirical model

In its simplest form, the empirical model consists of three primary factors for frost-free sites and two primary factors for sites with permafrost.

Frost-free sites

- (1) thin organic layer: moss and peat less than 8 cm.
- (2) low soil moisture content: gravimetric water content less than 25%.
- (3) sandy soil texture: mineral soil more than 45% sand.

Sites with permafrost

- (1) a combination of three variables:
 - (i) the presence of hummocks.
 - (ii) high soil moisture: gravimetric water content over 25%.
 - (iii) thick organic layer: moss and peat over 8 cm.
- (2) fine-textured soil: less than 45% sand.

Most efficient factor

The combined factor for sites with permafrost (hummocks, high soil moisture, and thick organic layer) can be used alone to predict the presence or absence of

permafrost at a site, as it is the only factor which is present at all sites with permafrost, and absent from all frost-free sites. To determine in the field whether a site has permafrost or not, only three measurements are required: (1) presence or absence of hummocks, (2) thickness of moss and organic soil, (3) soil moisture content.

Testing the empirical model

The empirical model was developed from the first data set, and it predicted the presence or absence of frost at 92% of the sites in this data set. It predicted the presence or absence of frost at 95% of the sites in the second data set. The second data set thus validates the model.

A modified version of Outcalt's (1972) microclimate simulation program was used to perform a sensitivity analysis of the two factors which were the most reliable predictors of the presence or absence of permafrost. These factors were soil moisture content and organic layer thickness. Soil texture, although itself a primary factor, was subsumed within these factors. Results of organic layer tests showed that this factor has a physical basis independent of the study area boundaries, so the model could be applied throughout central Yukon. However, results of testing soil moisture were inconclusive. This appears to be partly due to limitations of the microclimate model for conducting tests of this factor, and partly due to the dual

nature of the relation between soil moisture and permafrost in the field.

Mapping the probability of permafrost

A method for mapping the probability of permafrost was developed, based on the empirical model and related information derived from the data base. The maps combine four variables, two of which are surrogates for variables in the empirical model. The variables are: landscape type (surrogate for soil moisture), soil texture, forest cover (surrogate for organic layer thickness), and slope aspect. The mapping method was intended to identify permafrost probability at sites of 20 x 20 m to 50 x 50 m.

6.3 Conclusions

The empirical model predicts the presence or absence of permafrost at a site the size of a small engineering project with an accuracy of 92 to 95%.

The key factors are:

- 1) The model is simple. Only three measurements are required in the field to determine the permafrost status of a site.
- 2) There are indications that the model may be applicable beyond the study area throughout central Yukon.
- 3) The method for mapping probability of permafrost based on the empirical model allows the model to be applied away from the site, given adequate information.

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