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NAME OF AUTHOR/*NOM DE L'AUTEUR* Thomas M. Naughten

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NAME OF SUPERVISOR/*NOM DU DIRECTEUR DE THÈSE* Colin B. Crampton

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PERMAFROST: AN EXAMINATION OF INTERACTIVE INFLUENCES ON DISTRIBUTION AND CONDITION.

by

Thomas M. Naughten

B.A. Dublin University, Ireland, 1977.

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APPROVAL

Name: Thomas M. Naughten

Degree: Master of Science

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Examining Committee:

Chairman: R. Hayter

C.B. Crampton
Senior Supervisor

W.G. Gill

R.M. Strang
External Examiner
Executive Director & Secretary
to the Council of the Secretariat
on Forestry, Research & Development
Forest Research Council of B.C.

Date Approved: June 21, 1983

Title of Thesis/Project/Extended Essay

Permafrost: An Examination of Interactive

Influences on Distribution and Condition

Author:

(signature)

Thomas M. Naughten

(name)

21 June 1983

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ABSTRACT

The purpose of this thesis is to evaluate a method for predicting the presence or absence of permafrost and its ice content. This information is required in order to select the least expensive and least damaging routes for linear development projects.

Two of the data sets were taken from the alignment sheets published for the proposed gas pipelines along the Mackenzie River valley (Northwest Territories) and the Dempster Corridor (Yukon Territory). The third set comprised logs of soil profiles obtained by the author from the Dempster Highway and Klondike Loop (Yukon Territory).

The data were analyzed in order to determine which environmental factors best described the presence of and ice content of permafrost. A variety of statistical methods, ranging from simple linear regressions to stepwise multiple regressions with dummy variables, were employed. The multiple regression identified five variables as the best predictors of ice content in the Dempster Corridor: texture, depth below surface, landform genesis, elevation and texture of the substrate above the sample. When expanded to thirty dummy variables, a maximum of 66.6% explanation of the variance was obtained. Finally, a statistically-based program, Analysis of Ecological Systems, was used to analyze the predictive capabilities of combined multi-variables. A four-variable interaction of aspect, slope, texture and vegetation explained 75.5% of the variance in ice

content of permafrost encountered in the Dempster Corridor. The results suggest that prime environmental conditions for ice formation in permafrost are best explained in synergistic terms and that analysis by combined multi-variables can facilitate the identification of such synergy in the ecosystem.

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I. INTRODUCTION

This thesis is concerned with permafrost in northwestern Canada. Historically permafrost has been a bane to northern development. Joseph Robson and James Isham, employees of the Hudson Bay Company make reference to the problems of frozen ground in their diaries of the 1750's (in Legget, 1972). The miners of the Klondike Gold Rush of 1897-99 devised many a scheme to deal with the rigidly-bonded gold-bearing gravels that hampered their fortunes. The Canol Road, airports along the Northwest Staging Route and the Alaska Highway all came into being around the time of the Second World War and each project had to contend with the permafrost terrain. An awareness of permafrost is not a new phenomenon. Canada has been active in northern research for many years. The Division of Building Research of the National Research Council formed the Permafrost section in 1950, and two years later established the Northern Research Station at Norman Wells in the Mackenzie River Valley, N.W.T. The experiences gained in such research permitted the construction of the new northern town of Inuvik in the early 1960's. Today there is another proposal, another dream, to build a gas pipeline linking the reserves of the Mackenzie Delta and Prudhoe Bay oil and gas fields to the markets in the south. The key engineering problem in developing the Northern lands, as always, is the permafrost.

Permafrost is defined as ground material with a temperature of less than 0°C for two or more consecutive winters and an intervening summer (Johnston, 1981).

Disturbing the thermal balance of the ground in areas of permafrost can lead to problems of slumping and subsidence lessening the integrity of a pipeline. The extent and magnitude of these problems depend on the amount of ice in the underlying permafrost. A predictive model of ground conditions would be useful for pipeline route selection. This thesis attempts to assess such a model for the prediction of permafrost and its ice content in northwestern Canada. It is a study of the relationships between permafrost and its environment and of the interrelationships among those environmental factors themselves.

Permafrost is of major concern to those involved in the construction of the Alaska Highway Gas Pipeline because the proposed routes traverse areas known to contain permafrost. Our ability to modify the environment increases faster than our ability to forsee the effects of such activities (Bella and Overton, 1972). This predicament results from a lack of understanding of complex organized ecosystems. A study of this nature, it is hoped, will lead to a more enlightened and responsible development of the northern ecosystems of Canada by orienting route selection procedures to a more ecological standpoint.

The Need for Research

> In a region which acts as a vast refrigerator, the natural operations of decay and regeneration are slowed to a snails pace. Soil bacteria develop slowly, resulting in an extremely thin layer of soil; and the growth of vegetation is many times slower than the south. Any altering of the physical environment can take hundreds of years to redress.
>
> (Anon, 1982a).

Northern lands recover more slowly from disturbance than those of the South. The relative impacts of disturbing events are very different. Within the first recovery period of a disturbed northern ecosystem, should another disturbing action occur the compounded effect will be far greater than the first. The first disturbance initiates a slow northern recovery rate and subsequent disturbances depress the rate beyond anything the South has to contend with, possibly beyond our perceptions. It is essential then, to provide careful pre-planning for large linear-development projects.

Permafrost varies with changes in the natural weather pattern, but more dramatic are the variations caused by modifying the ground cover or introducing a heat source. The dominant agent for these events is man and his activities. Ice content of the frozen northern soils determines the magnitude of the effects of man's engineering (Burdik et al., 1978). For example, in building a road the ground surface is modified, and if the heat balance is not maintained by providing some insulation, the permafrost will warm, excess ice will melt and subsidence will occur. If the ice crystals are dispersed throughout the soil and the volume of ice is less than that of soil then the final settlement will be small. However, if the volume of ice is large relative to that of the soil the potential settlement increases dramatically. Melting out of ice in the frozen ground beneath a roadway can lessen the bearing capacity, and applying a load to the surface will cause subsidence and possibly failure. Gravel embankments 1.2 to 1.8 m (4 to 6 ft) thick provide the necessary insulation for roads in the continuous permafrost zone. But farther south, in the discontinuous permafrost zone, the temperature of the permafrost nears 0°C and the thermal balance is more tenuous. The height of gravel embankments required to preserve the "warm" permafrost is far greater. Often such quantities of fill cannot be obtained economically so a continuous maintenance of a less than adequate depth of fill is needed until a new thermal balance is achieved. This is well demonstrated in the case of the Alaska Highway north of Beaver Creek where the road must be continually upgraded every three years to prevent it from sinking below the level of the surrounding terrain (EAP, 1979). Similarly, the first fifty miles of the Dempster Highway had to be rebuilt. Initially, cut and fill construction methods had been employed, exposing the subsurface materials and permitting heat to penetrate. The costs of such maintenance and reconstruction are extreme. In addition degradation of permafrost is often self-perpetuating, increasing the costs to governments and private industry alike. Northern construction necessitates prior knowledge of the ground ice because disturbance of the thermal balance in high ice content soils will quickly lead to undermined foundations by slumping and subsidence.

Route Selection

With the proposals to build the Alyeska Oil Pipeline and the Mackenzie Valley Gas Pipeline there evolved a public awareness of environmental concerns in the North. The Governments response has been to enact Federal legislation pertaining to northern linear development projects require, amongst other things, submission of an environmental impact assessment statement to the Minister of the Environment. Where there is potential for significant environmental effects, provision for a formal review process is made under the auspices of the Environmental Assessment Panel.

For example, the Environmental Land Use Committee responsible for the Environment and Land Use Act (1971) in British Columbia, devised a set of guidelines for the development of major linear development projects such as, roads, railways, powerlines and pipelines (ELUC, 1971). For large scale projects traversing one or more Resource Management Regions of British Columbia, or areas identified as particularly sensitive to disturbance, four stages are identified in the guidelines:

Stage 1: Route selection. To identify economic, environmental and sociological impacts for alternative routes.

Outline of the proposed development program.

Description of the existing environment.

Evaluation of alternative routes.

Identify impact-related planning actions and mitigative procedures.

Public consultation.

Presentation and review of Stage 1, report.

Stage 2: Detailed alignment assessment and planning.

Details of the preferred route.

Site specific analysis.

Detailed mitigations.

Detailed enhancement of the environment.

Cost analysis.

Public response.

Presentation and review of Stage 2, report. With Environmental Land Use Committee (ELUC) acceptance there is approval in principle.

Stage 3: Operational plans and approval procedures.

Obtain licenses and permits.

Environmental manual for contractors and developers.

Stage 4: Project implementation.

(after ELUC, 1971; ECSTF, 1981).

There is an additional step that is important, omitted in the above but introduced in the Mackenzie Valley Pipeline Inquiry.

Stage 5: Abandonment.

Abandonment program.

Detailed mitigation procedure.

Cost responsibilities defined.

(after Berger, 1977).

It can be seen that permafrost data is required at all stages of the environmental impact assessment; the detailed plans, the environmental manual, the mitigation procedures and so on. However, probably most important is to have the necessary permafrost information at the Route Selection stage so that ecologically sound and informed appraisals may be made.

A variety of methods for determining the 'best' route exist, but some of the most commonly used for northern linear development projects are;

1. Expert Committee Method: A task force of experts is assembled and each individual reports on a particular aspect of the problem. A summary or overview is written by the chairman. Much of the early work for the Mackenzie River Valley Gas Pipeline project was done in this manner. The credibility of the findings is wholly dependent on the credibiity of the task force members.

2. Checklist: Environmental conditions or factors to be reported are defined. A review team completes the checklist study in the field and summary reports are written. This was the basis for the wildlife studies for the proposed Mackenzie gas pipeline and

the now completed Alyeska oil pipeline. However, there is neither allowance for identification of possible impacts nor for an estimate of their severity.

3. Matrix: This is little more than a two-dimensional checklist, with one axis being causal factors and the other, the selected environmental elements representing conditions affected by the actions. The advantage here is that functional interrelationships may be identified (Leopold et al., 1971). But the analysis does not distinguish between long and short-term impacts. Nor is there any guarantee that all mitigative solutions have been identified.

4. Three-dimensional Matrix Analysis: is termed cause-condition-effect networks. The method is based on the premise that an action causing changes in one or more environmental conditions has one or more terminations. This two-step anaysis recognises some of the complexity of the ecosystems, but it offers no solution to the problem of exponentially increasing numbers of matrices with each step, other than to create the arbitrary cut off point after two steps. The method has been employed in a variety of settings on a variety of problems but so far as is known here, it has never been tried on the larger northern setting.

5. Descriptive Land Use Analysis: is an attempt to identify areas tolerant of development. Major landscape types are located and combined with information on biota and land use. Land units are ranked according to their ability to withstand disturbance

and the routes are calculated to avoid sensitive areas. The method is time consuming and expensive because of the amount of field work involved. However, the process is becoming more refined; an Ecological Land Survey was carried out by Lands Directorate of 35,130 km² of the Northern Yukon at a survey cost (excluding salaries) averaging $1.43 per km² (Wicken et al., 1981).

6. Cartographic Overlays: Field studies of various environmental factors are initiated and the results are mapped individually. A summary map is created by overlaying the single factor sheets. Regions having similar characteristics may then be identified and their sensitivity determined. Routes again may be outlined so as to avoid areas of sensitivity as much as possible. With computers available the data sets can be stored and manipulated easily and the maps produced quickly. However, the ecological and biophysical units comprising combined variables must be defined manually. To do this requires extensive field-experienced personnel. The Federal Government applied this method in its Ecological Land Classification Survey of Canada (Thie and Ironside, 1976). Foothills and Arctic Gas both employed this method in preparing submissions for applications to build gas pipelines in the North. In this way they were able to identify areas populated by rare species of birds and animals whose numbers would be decreased by industrial development.

7. System Analysis: This is similar to the method outlined above but with more extensive application to computers. The map areas

are broken into cells at some convenient scale and statistical or mathematical simulations of the ecosystem are developed. In this way sensitivity of the area is determined and also the success of possible mitigative measures may be studied. The amount of data required for this type of analysis is prohibitive and all too often non-existent so that only a very few projects can be analyzed in this way.

8. Mathematical Surfaces: as above, but with the models all based on mathematical surfaces representing highs and lows in costs and/or environmental sensitivities. Routes are fitted within the troughs to minimize expenditure or disturbance. The output may be made visually attractive and easily comprehensible however, the operational processes involved at the early stages are quite complicated and fully understood only by specialists.

All of the methods discussed have the same drawbacks; a large degree of subjectivity in rankings, ratings and comparison of data. In addition, they neither provide alternate choices in routings, nor do they facilitate assessment of the possible alternatives (ENB, 1980; Newkirk, mimeo).

Most often pipeline companies have used Ecological Land Surveys based on descriptive land use analysis for permafrost prediction along northern routes. But the limitations prove severe; the presence or absence of permafrost may be identified only at small scales and there are no facilities to indicate the ice content in other than qualified "high" or "low" estimates.

The companies have been forced to decide on the "best" route before adequate environmental data are available. Thus any environmental consciousness a pipeline company might have is soon frustrated because the routing decisions can be made only on short-term economic bases.

The company must drill and sample the ground to determine ice content. This is impractical, time consuming and expensive for large linear development projects at the early stages of route selection. The Trans Alaska oil pipeline route was drilled at 15 m (50 ft) intervals in ice-rich permafrost areas (EAP, 1979). Over 5,000 boreholes were drilled, 3.7/km (6/mile) along the Alaska Highway route at a cost of $10,000 per hole. Canadian Arctic Gas Pipelines Ltd. by 1977 had spent $150 million (Grey, 1979) in presenting their case to regulatory forum, much of which was spent on environmental research. Foothills Pipelines Ltd. spent more than $20 million preparing plans for the Mackenzie Project and to date, over $200 million in preparation for the Alaska Highway Gas Pipeline (Anon., 1982b). Today large sums are being spent on research in the Beaufort Sea. Geophysical costs for these large scale projects can amount to 10% of the total exploration budget (Brooks, 1980). To minimize such expenditures while, at the same time, obtaining the necessary planning information is a major concern of these companies.

In attempting to resolve the problems inherent in the above methods, researchers have begun investigating computer techniques in storing and retrieval of data (Lawrence, 1974), running statistical analyses (Law, 1970) and producing both statistical and cartographic displays. In this way latitude, soil and texture have been studied in their relationships to the ice structures of permafrost (Heginbottom et al., 1978). However, to the present time, only frequency distribution studies of three variables, taken one at a time, have been published for permafrost.

The variables were taken only one at a time because it was found an impossible task to deal with an ever expanding matrix of interrelationships when variables were used in combinations in multi-variate analyses. Crampton (1978a, 1978b, 1981) suggested a solution to the problem by re-coding the multi-variate combinations back into the same number of categories as the initial variables. Analysis of Ecological Systems (ANECSY) (Crampton, 1981) is a statistical procedure employing regression analysis of dummy variables. By pre-processing the matricies of combined variables it can identify an independent multi-variate combination that is capable of greater explanation of the variance in the dependent variable. By employing such combinations it is feasible to indicate sites of potential synergism. This study adopts the program ANECSY for use in the prediction of the presence of permafrost and its ice content to determine the most efficent multi-variate predictor combination.

From the work on environmental sensitivity within the forum of northern pipeline inquiries there emerged a call for consideration of synergistic relationships in the studies of northern ecosystems. Defining threshold conditions as an adjunct to linear relationships was not found to add understanding of the environment but only to lessen the applicability of the models in use because of the additional constraints imposed in proposing non-continuous variables. Work on curvilinear relationships within ecosystems should prove valuable but somewhere the intricacies of synergistic actions must be examined. The move to develop ANECSY is in answer to the problems of subjectivity, assessment of alternate routings, budgetary constraints and overly simplistic linear modeling of environmental relations.

In short, work on permafrost to date has been restricted primarily to site specific studies with the application of single variable analyses (Roberts-Pichette, 1972; Brown and Grave, 1978), a few workers have done multi-variate analyses (Gill, 1973), but with the possible addition of the study by Heginbottom et al. (1970), Crampton's (1981) is the only multi-variate study of a macro-scale study area.

Research Objectives

As a working hypothesis it is suggested that the use of the multi-variate analytical tool, Analysis of Ecological Systems, provides a stronger technique for predicting the distribution and ice content of permafrost on a regional basis than single or multi-variate techniques. The criteria for assessment are the power of statistical explanation and field applicability.

To assess the program, ANECSY, for multi-variate analysis of regional areas in the prediction of permafrost distributon and ice content, it is necessary to begin with a very simple analytical approach and then develop, step by step, to multiple regression with dummy variables. In this way it can be seen whether the same inter-variate relations are systematically reported throughout and whether information is added at progressively more complex levels of analysis.

There are four methods to consider:

1. to compute scattergrams and correlation coefficents within a set of environmental variables and assess the levels of interrelation,
2. to regress the variables on the ice content of permafrost in multiple linear fashion and determine which are most important,
3. to derive dummy variables and regress these on the ice content so as to identify the secondary influences on the distribution and ice content of permafrost,

4. and finally to employ Analysis of Ecological Systems (ANECSY) (Crampton, 1981), a multiple regression procedure using dummy variables with data pre-processing features, to predict the ice content of permafrost and assess its capabilities relative to the other statistical models.

This thesis, then, is a response to the inadequacies of the analytical procedures presently in use for predicting the occurrence of permafrost and its ice content and the costs involved in drilling over long distances to appraise proposed route-ways.

Research Setting

The research was conducted in northwestern Canada (Fig. 1), specifically the Mackenzie River Valley, N.W.T., from just south of Fort Simpson at around 61°N to Richards Island in the Delta at about 69°N and also the Dempster and Klondike Highways, Yukon Territory, from Whitehorse at about 61°N to near Fort MacPherson at the territorial border about 67°N. Sites were included from the Alaska Highway; from Kluane to Boundary from the Robert Campbell Highway; from Tungsten Cutoff to Carmacks and from the South and North Canol Roads from Jakes Corner to Macmillan Pass. Foothills Pipelines Ltd. and Arctic Gas Pipe Lines Ltd. submitted alignment sheets to the various northern inquiries and the core logs from these were used as data for the Mackenzie Valley and Dempster Corridor data sets. In addition, field work

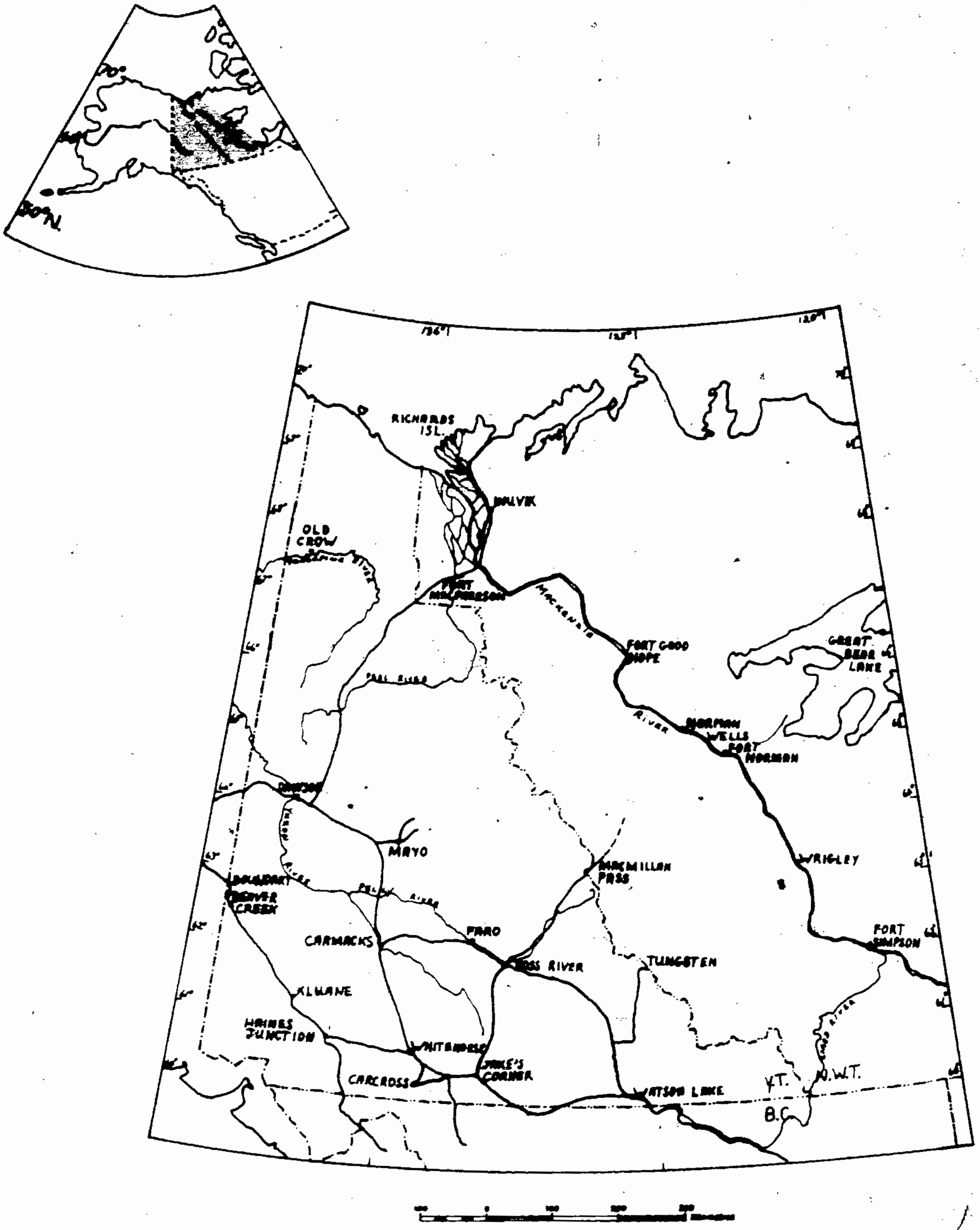


Fig. 1: The Yukon and Western Northwest Territories.

was done to obtain cores throughout the Yukon and these are presented within the Dempster-Klondike Highways data set.

Chapter Outline

This thesis comprises five chapters. The first two chapters focus on the issues of predicting the distribution of permafrost and its ice content and route selection for northern linear development projects, the third focuses on research design while the last two discuss the empirical aspects of the study.

The second chapter explores the issues introduced in chapter one and examines them in greater detail, with reference to the appropriate literature. The issues are; permafrost distribution, identification of the variables associated with permafrost, single and multi-variate studies, predicting the ice content of permafrost and synergism as a new viewpoint for environmental analysis. Chapter three outlines the research design; the data coding structures and the statistical analysis used to predict permafrost and evaluate Analysis of Ecological Systems. The analysis and findings are presented in chapter four and the conclusions are discussed in the final chapter.

II. LITERATURE REVIEW

Since this thesis is concerned with the prediction of permafrost, the distribution as perceived within the literature must be discussed, in addition, the variables employed within the predictive procedures are important to consider. In this chapter, therefore, permafrost distribution and the associated variables and methodolcgies are investigated and presented identifying the issues involved. But first the definition and dynamics must be outlined.

Permafrost: a Definition

In 1954, Dr. S. Muller coined the term permafrost, as a short form for 'permanently frozen ground'. Permafrost is defined as the condition in soil or rock where temperatures are below 0°C for at least two consecutive winters and the intervening summer. The definition is based solely on temperature, for moisture as water or ground ice may or may not be present. The formation and persistence of this condition in earth materials are controlled primarily by the climate and various terrain factors and greatly influenced by man's activities (Johnston, 1981). The definition is temperature dependent as permafrost is not a condition of a particular material but rather can exist equally in rock or unconsclidated materials. It is time dependent to distinguish it from frost penetration in the upper portions of the soil profile.

Dynamics of Permafrost

Permafrost is in accord with its surroundings and is, therefore, only as stable as its environment. It is not permanent as Muller's (1945) definition would suggest (Brown, 1970). Permafrost increases or decreases vertically and/or horizontally with changes in the thermal regime. A change of 1°C in the mean annual air temperature could produce over time a change of 1°C in the mean annual ground temperature, thereby altering permafrost thickness by about 20-160 m (Brown and Johnston, 1964). Change is a function of alteration in:

Climate: temperature, snow cover, wind and micro-climatic conditions,
Geology: the texture and thermal properties of the soil and rock materials and the geologic history,
Hydrology: drainage, soil moisture and the size of water bodies,
Topography: altitude, slope and its aspect, and latitude,
Biology: primarily vegetative cover and human activity, though large migrations of animals have their effect,
(after Ferrans and Hobson, 1973).

Obviously there is much interrelation amongst factors here and changes in one may lead to changes elsewhere, in addition to modifications to the extent of permafrost. A change in one feature of the ground might subsequently alter soil moisture, thermal conductivity of the soil, vegetation and micro-climate. Just as permafrost may be altered in extent, it can be altered in condition or ice content. Ice content is measured as a proportion of the soil moisture expressed as a percentage:

$$\frac{\text{Mass of Moisture}}{\text{Mass of Dry Soil}} \times 100$$

(Foothills, 1979).

Ice content can range from virtually zero percent, (e.g. in rock material) to many thousands of percent where permafrost contains almost pure ice. The condition or ice content of permafrost is a most important consideration for construction. Where permafrost is warmed, excess moisture is forced out by overburden pressure or gravity. If the ice content is high, then the voids left after thawing are large and soil replacement creates slumping at the surface. This process is termed subsidence.

Another consideration is frost heave (Northern Pipeline Agency, 1978). Ice expands between 0° and -4°C. Thereafter it decreases in volume with cooling as is normal for other compounds. In the expansion phase, if moisture is permitted to migrate to a freezing face the resultant ice will infill the spaces and expand, thus exaggerating them. In this way telephone poles, pilings and even pipelines have been heaved up right out of the ground. The effects of these cryogenic processes are dependent on the amount of ice formed and the moisture availible. The degree of change is a function of the ice content of the permafrost and this study being interested in predicting the presence of permafrost must therefore concern itself with the ice content of permafrost if development with minimized damage to northern environs is proposed.

Permafrost Distribution

The Canadian Federal and Provincial Governments instituted an environmental impact assessment process in 1970, to aid with decision making on the environmental effects of major construction projects (Peterson, 1974). Though this is not a statutory requirement, industry has often complied with the process (Wake, 1980) so that of impact assessments can be found for the Mackenzie River Valley, N.W.T. and the North Slope of the Yukon Territory. For pipeline companies with aspirations of developing the North it has become the accepted rule to have impact assessment studies accompany their applications to government. The sensitivity of Northern lands to disturbance and consequent environmental impact is tied to permafrost and the ice content of the soils. Thus impact assessment studies must at least outline permafrost distribution.

Found about the polar regions of the globe and at high elevaions elsewhere, permafrost underlies twenty percent of the earth's surface. Half of Canada is in permafrost. The Permafrost

Map of Canada (Brown, 1967a) shows the Arctic region to be underlain by a continuous body of permafrost, broken only where water bodies are large enough to preserve a thaw bulb beneath, and called the Continuous Permafrost Zone. The depth of frozen ground in this region varies from 457 m (1,500 ft) in the north to 61 m (200 ft) at the southern boundary, and the active layer, thawing in summer and freezing in winter, is 0.5 to 1 m (1.5 to 3 ft) deep to the permafrost table. South lies the Discontinuous Permafrost Zone, the limits of which are approximated by the Sub-Arctic region. Here the permafrost is 61 to 15 m (200 to 50 ft) thick, with an active layer of 3 to 6 m (10 to 20 ft) or more. Isolated bodies of permafrost can exist on north facing slopes at the southern fringe of the Discontinuous Permafrost Zone, otherwise known as the Sporadic Permafrost Zone. Permafrost can occur with increased elevation southward. At the 49th. parallel it may be found at the 1,829 to 2,134 m (6,000 to 7,000 ft) level.

The foundation for all discussions of permafrost distribution is Brown's Permafrost Map of Canada (1967a). It is the compilation of a series of reports (Brown, 1964, 1965a, 1967b, 1968) surveying the southern fringe of permafrost in Canada. The map is based on air temperature measurements and field observations with limited drilling and ground temperature measurements. Though it is clear that there exists a relationship between mean annual air temperature and mean annual ground temperature it is a broad relationship, for these mean temperatures differ from one another and the differences are not consistent. Brown's map, then is a generalized view of the presence of permafrost across Canada. Brown (1970) asserts that with increased field measurements, adjustments in the permafrost boundary may be made, however, these he predicts, will be slight.

The distribution of permafrost is divided into a northerly Continuous Permafrost Zone where permafrost is everywhere present, except in newly deposited unconsolidated sediments where climate has not yet fully imposed its influence on the ground thermal regime (Brown, 1970), and the southerly Discontinuous Permafrost Zone. In the Discontinuous Zone bodies of permafrost are separated by unfrozen ground, and towards the southern fringe they are very scattered and occur only under particular circumstances. Brown separates the Zones on the basis of the -5°C isotherm of mean annual ground temperature measured beneath the zone of annual variation. It is suspected that the number of such data points available across Canada are very few and so this line, representating the interface between the Continuous and Discontinuous Permafrost Zones is open to varying interpretations. The southern limit of discontinuous permafrost, itself, is not a well defined line but a belt of land several hundred kilometres wide where permafrost bodies become more sporadic southerly (Anon., 1972).

Others have attempted to delineate the the boundaries. Hughes (1969) discusses the the distribution of open system characteristic of the Continuous Permafrost Zone, inferences may be made on the placement of the southern boundary (cf. Johnston, 1982, pp.184). Harris (1981), while studying climatic methods for predicting the distribution of permafrost, suggests there is a relationship between the zones and freezing and thawing indices for areas with low mean annual winter snow cover (Fig. 2).

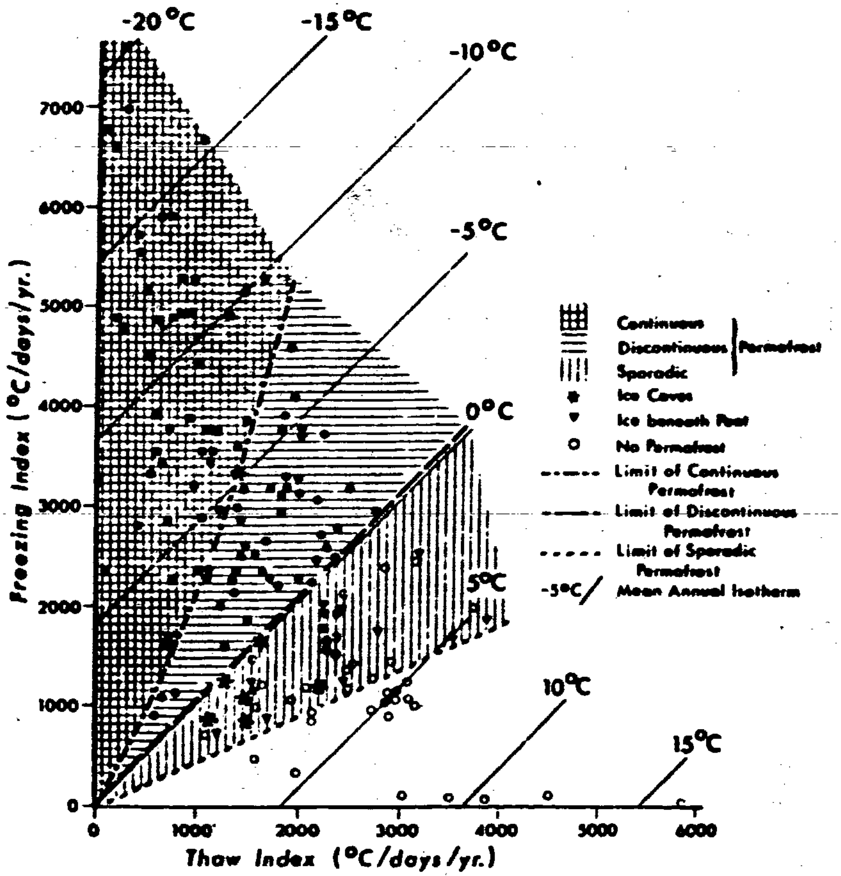


Fig. 2: Relationship between the occurrence of permafrost zones and freezing and thawing indices for stations with under 50 cms mean winter snow cover (after Harris, 1981).

Further there is a relationship between the zonal permafrost landforms and permafrost zones (Fig. 3). The boundary between continuous and discontinuous permafrost is thought to approximate the southern limit of active ice wedges by Pewe (1969), and to approximate pingos by Mackay (1972).

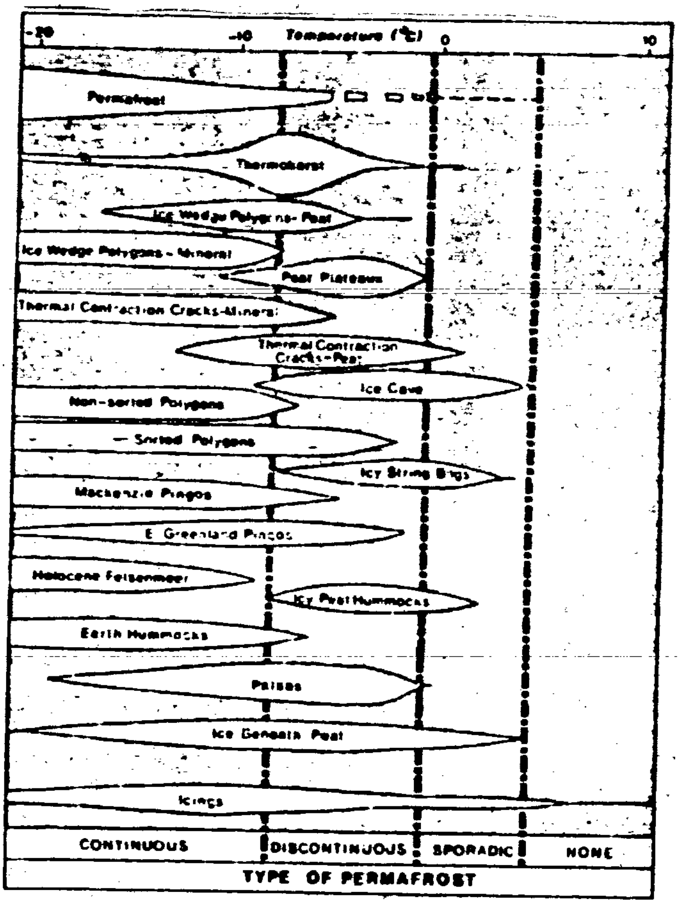


Fig. 3: Relation between zonal permafrost landforms and permafrost zones (after Harris, 1981).

Permafrost boundaries are not static; they advance and retreat in response to fluctuations in climate (French, 1967), active geomorphic processes (Gill, 1973) or locally in response to fire and disturbance. The boundaries are not well defined to fire and disturbance. The boundaries are not well defined lines but transition zones, 50 to 100 kms wide, similar to the biological limit of the continuous forest and the absolute limit of tree species (French, 1976), or the kampfzone of a timberline ecotone, i.e. the transition zone between the closed forest stands and the tree limit (Tranquilline, 1979).

Gill (1973), on the basis of a spatial correlation between plant distribution and unfrozen ground, argues that the southern limit of of the Continuous Permafrost Zone be moved 200 kms northward to include the Mackenzie River Delta within the Discontinuous Permafrost Zone. Reinne et al. (1978) observed that the southern fringe of discontinuous permafrost extended farther south than previously believed, especially along the Mackenzie Valley. McComas (1980) suggests that the real distribution of permafrost in the southern Yukon does not match with the theoretical model because of volcanic ash acting as an insulator. This ash is to be found in two plumes eminating from the St. Elias Mountains and spread over a large portion of the southern half of the Yukon. The eruptions are recent happenings (about 1220 B.P.), with the ash very evident in the upper portions of the soil profiles. In the valley bottoms the deposits may be metres thick, conceivably preserving relic permafrost bodies (Oswald and Senyk, 1977).

Brown bases the differentiation of continuous and discontinuous permafrost on the mean annual air isotherm of -8.3°C. Thus Aklavik and Inuvik in the N.W.T. are within continuous permafrost for their average annual air temperature is below this value. However, Mackay (1967) reports that the average annual ground temperature at a depth of 15.2 m is -2.4°C for Inuvik and -3.8°C for Aklavik. This, he contends, indicates that the Delta is an outlier of discontinuous permafrost. Arctic Red River is close to the boundary having an average annual ground temperature of -4°C at 15.2 m, and Fort MacPherson is within discontinuous permafrost with -3°C at 15.2 m depth (Smith, 1976). In the Beaufort Sea Production Environmental Impact Statement (Dome Petroleum Ltd. et al., 1982) it is stated that the permafrost in the Mackenzie Delta is continuous, varying in thickness from 20 to 60 m and increasing to 600 m to the east and west. Permafrost becomes discontinuous some 300 kms south of the coast or around Fort Good Hope.

Brown's map provides a generalized view of the distribution of permafrost, however there does exist some controversy over the specific details. For pipeline construction the map is of limited value because of its scale and lack of detailed information with respect to ice content of encountered permafrost.

Prediction of Permafrost

Attempts have been made to map permafrost on bases other than temperature. Surficial features of the landscape characteristic of continuous permafrost have been documented

(Brown, 1969 and 1970; Brown and Pewe, 1973; Harris, 1981; Johnston, 1981; Sterns, 1966; Washburn, 1956 and 1973). These include the various patterned ground phenomena such as polygons, circles, nets, steps and stripes as well as mounds, pingos, palsas and peat plateaus, and the results of thermokarst subsidence. Because these features are often identifiable in air photographs, remote sensing of the surface using black and white aerial photography becomes most useful in surveying the vast expanses of the northern wilderness (Ferrans and Hobson, 1973), and in the subsequent prediction of the existence of permafrost. Unfortunately this is not the case for the discontinuous permafrost zone. In this region the correspondence between surficial morphology and permafrost conditions is not as well defined. In addition, more dense southern vegetation cover obscures the landforms and hampers their identification.

The Beaufort Sea Environmental Impact Statement (Dome Petroleum Ltd. et al., 1982) indicates that the nature and occurrence of ground ice is related to surficial materials. Till plains and drumlinoid moraine have low to medium ice contents formed in thin seams, 1.5 to 3 m (3 to 9 ft) thick but comprising less than 25% ice by volume. Glaciolacustrine silts and clays contain up to 50% of ice by volume in a reticulate network of thin lenses and inclusions and as layers 1 m and greater in thickness.

Vegetation and its relation to the presence of permafrost has been researched (Bliss, 1980; Brown, 1963; Roberts-Pichette, 1972; Tyrtikov, 1959) on the premise that delineating the boundaries of vegetation associations would delimit the bodies of permafrost. Some suggested that the degree of accuracy attained in predicting soil frost conditions by ground reconnaissance or from photos is proportionate to the degree of understanding of the interactions of vegetation and soil frost (Benninghoff, 1950 and 1952; Sigafoos, 1950). In the discontinuous zone vegetation characteristics such as height of trees, species, combination of species, wetness, etc., can be used as evidence for the presence or absence of permafrost in a given locality, but criteria for one locality may not be automatically transferred to another. In areas of continuous permafrost it is neither possible to predict the presence nor amount of permafrost, nor the depth to ground ice from vegetation patterns alone (Roberts-Pichette, 1972).

Water bodies, if they are deep enough will not completely freeze in winter and will not have permafrost beneath them. This relation is a major influence on the distribution of permafrost in such areas as the Mackenzie Delta. Aspect of the land influences the amount of solar radiation available to the surface. South facing slopes are therefore warmer than northerly slopes. As one climbs higher, it becomes cooler and so some mountain tops have permafrost where the valleys below do not. Snow cover, with its low thermal conductivity, inhibits freezing in Fall and thawing in Spring. The albedo of the snow lessens the amount of solar radiation reaching the ground surface. Wind alters the distribution of snowfall, moving it from areas devoid of vegetation to hollows in terrain and areas of low level vegetation. In summer the areas of accumulated snow are wetter and thereby kept cooler than elsewhere.

Latitude is considered important for the prediction of permafrost occurrence for, as a general rule, permafrost increases from south to north.

The texture of the soil is important too. Finer materials such as clays and silts tend to have icy permafrost while coarser materials such as sand and gravels do not. The reasons are quite complex but suffice it to say here that with finer materials the moisture is more easily retained because of the greater surface area and smaller voids between the soil particles. Research in the Mackenzie Valley concludes that the degree of slope influences the depth of permafrost (Code, 1973).

In the final analysis, ground temperature is the control on the presence or absence of permafrost, but ground temperature is the culmination of a variety of environmental components comprising the ecosystem.

The focus of the present study is the prediction of the presence or absence of permafrost. Much of the permafrost encountered today has been frozen since the Pleistocene (Pewe, 1969) but to postulate Ice Ages as an explanation of the occurrence of permafrost hides the truth. Permafrost is a product of equilibrium with the present climate (Burdik et al., 1978) and is in accord with its surrounding geomorphology.

Variables and Methods in Prediction

Various studies have been implemented from a variety of viewpoints to gather information on specific aspects of the permafrost environment. Johnston et al. (1963), at Thompson, Manitoba, concludes that,

> Given a particular climatic regime that is conducive to the existence of permafrost, it is the thermal characteristics or properties if the various surface and sub-surface terrain features operating singly and in combination that control the local variation in permafrost conditions.

The variation in permafrost conditions that are a concern to engineering and development are firstly the presence of permafrost and secondly the ice content of that permafrost. These are often outlined in terms of terrain sensitivity and susceptibility to disturbance by construction techniques in development.

Kurfurst (1973) in Norman Wells and Lavkulich (1973) in Wrigley, N.W.T., prepared maps of terrain sensitivity. Susceptibility of the terrain to human-induced disturbance is considered by Kurfurst to be a function of the ice content of the soil, the type of material, the slope and relief of the terrain. McRoberts and Morgenstern (1973) studied landslides in the vicinity of the Mackenzie River. Code (1973) looked at the factors influencing the stability of natural slopes and found that fire damaged slopes had a minimum angle of 4 degrees for movement to occur. In a progress report to Arctic Land Use

Research (ALUR), Bliss and Wein ed. (1972) reported on modified habitats of the Mackenzie region. Strang (1973) discussed case histories of disturbance and appraised the changes occurring. Change was deemed damaging where its effect extended beyond the initial impact area.

The Mackenzie Valley investigations began in the 1970's and are published as government reports in Task Force on Northern Oil Development, Arctic Land Use Research and Environmental Studies Series. Much of the results were compiled to produce two 1:1,000,000 terrain sensitivity maps, in a report of the Environmental-Social Committee on Northern Pipelines (1975). These maps show surficial deposits, terrain sensitivity, disturbance level and the type of reaction expected. Terrain sensitivity is divided into classes based on the degree of reaction to disturbance. It is dependent upon; ground ice, slope, material and insulating cover. The presence or absence of permafrost and the type of ground ice are the the two most important factors. Van Eyke and Zoltai (1975) state the above for the Mackenzie and Northern Yukon but allege that applications of a regional sensitivity classification faces the problem of variability of terrain within the map units and variations in local factors, particularly ground ice and water content, mineralogy, material texture, surface morphology, exposure, local relief, aspect, vegetation and type, season of year, duration and intensity of the disturbing process.

Variables Identified by Disturbance Studies

Specific types of disturbance have been studied; summer traffic by tracked vehicles (Muskeg Research Institute, 1971; Radforth, 1973), highway cuts (Pufahl et al., 1974) and oil spills (Hutchinson and Hellibust, 1973). Hok (1979) states that the most important variable in forecasting permafrost disturbance is the season of operation, with summer the worst. In summer the degree of blading, degree of slope, and substrate moisture content are next in importance and are so interrelated that it is difficult to discuss any one in isolation. The degree of surface disturbance determines changes in the air/substrate interface heat balance, and the substrate responds according to its composition until a new equilibrium is reached, but a balance cannot be established if the slope is great enough to transport the thawed material, thus exposing more frozen material.

With regard to ground surface oil spills, it was found that the active layer increases in depth as the vegetation is destroyed. Often times the spills are burned on the surface so as to stop pollution of the water table, but as this gravely damages the vegetative cover the active layer can increase even more. Such fires have a profound effect on the permafrost for long periods of time i.e., 35 to 50 years (Kelsall et al., 1977; Roberts-Pichette, 1972).

Fires in the North constitute, on average, a healthy element in the environment as a mechanism for change, but increased incidence with the intrusion of industry makes fire an erosive force to be reckoned with (Tyrtikov, 1959). Secondary effects on the permafrost result from erosion and gully formation, particularly where such fires are fought by blading and clearing fire lines with bulldozers (Brown and Grave, 1978; Evans ed., 1976, 1977). Heginbottom (1973) reported on work done in Inuvik and concluded that fire, of itself, was not a serious disturbing force. It was the thickening of the active layer leading to increased slope failure that was the problem. Stripping of the surface vegetation had serious consequences. However, removal of the trees with little damage to the ground flora had no marked effect. Heginbottom also commented that the degree of seriousness was related to the season in which the disturbance occurred, with summer worst, and the intensity of the initial disturbance was important. Slopes complicated all disturbance since water volumes increased with melting and could lead to increased erosion. Fire has varying effects with site characteristics, being related to the presence or absence of a humus layer in the aftermath, the type of permafrost, slope and nature of the substrate (Crampton, 1973). Decomposition of the litter is slow and so fire acts to return nutrients to the soil. Causes of fire are divided half and half between lightning and human activities, but lightning fires burn 95% of the total area burned in any year (Webber and Wein, 1974). Kelsall et al.

(1977), in a review of the problem contended that the vegetation re-establishes quickly after fire, but it is unknown how long this accelerated growth lasts (Wein and Webber, 1974). However, the pioneer vegetation is a poor insulator for the permafrost and thermal subsidence occurs such that ponds form and this, in turn, leads to increased melting (Zoltai and Pettapiece, 1973).

Heginbottom (1974) found that the depth to the icy permafrost from the surface was important in predicting the effects of surface disturbance such as bulldozing and fire. If the ice is within 1 m of the surface then the excess ice disasppears, within 2 m of the surface and there is significant change and when beneath 3 m the surface conditions would be unaltered.

The factors identified in such studies are directly related to construction activities, i.e. the season of work, degree of blading, and the consequences of increased incidence of fire, however, there is information on variables for sensitivity and prediction of frozen ground.

Northern Surveys and Developing Predictive Models

Surveys of permafrost conditions were done in the North employing a variety of environmental indicators. Crampton and Rutter (1973), using air photo analysis, identified landscapes or terrain types in terms of surficial geology, micro-relief and vegetation in a survey of the discontinuous permafrost of the

Upper Mackenzie Valley. Regarding the characteristic permafrost conditions for each landform they found; high forest indicates freely drained sites of alluvial terraces and glaciofluvial deposits suitable as construction sites; relatively featureless flats indicate seasonally waterlogged lands on lacustrine or till deposits and terrazoid patterns indicate raised peat with near surface permafrost, best avoided by engineering.

Crampton (1973) when surveying the Central and Upper Mackenzie Valley used soil, parent material and landscape, a composition of landform, drainage and vegetation, to map terrain susceptibility to damage by pipeline construction. Munroe (1972, 1973) produced terrain classification and sensitivity maps for the Lower Mackenzie Valley, the Delta and westward along the coast. Hughes et al. (1973), Rampton (1974) and Rutter et al. (1973) produced terrain evaluations of the Mackenzie Transportation Corridor specifically aimed at the effects of building a gas pipeline. The maps were designed to fulfil two requirements, namely, to provide terrain data for preliminary assessment of transportation routes and to develop a terrain classification that would permit application of the apppropriate land use regulations and practices to differing terrain types (Hughes, 1972).

The Mackenzie Valley and the Dempster Corridor were surveyed by Foothills and Arctic Gas for pipeline route appraisal by air photo analysis and use was made of the above landscape surveys in the choice of route. In addition to, and as part of ground truthing and verification a series of boreholes were made at selected sites down the length of the valley, averaging six holes per mile (or about 4 per Km). Sampling by drilling was necessary because the landscape studies presented their results on permafrost prediction as qualified estimates and not in real expected volumes, as required for detailed engineering. The holes were drilled through the active layer into the permafrost beneath and the cores were logged and sampled for later analysis. The relative volumes of soil and ice were computed and the soil thereby evaluated for its suitability for construction purposes. This proceedure was time consuming and costly if only because the study area was so large. Compromises were struck in the number of field observations and drill holes taken to obtain a true picture of the underlying permafrost in an effort to keep the costs in check. But these decisions proved none too successful and the inadequacy of base-line data has been cited often by critics of the project, for the long-profile of permafrost depths along the route had to be interpolated long distances.

Remote Sensing as an Aid to Prediction

In an attempt to bring costs down, and striving for as rapid a procedure as possible, great strides were made in the field of augmenting the landscape approach to surveying the inaccessible expanse of the North by remote sensing. From black and white photography evolved the use of colour and false colour imagery for identifying such phenomena as the changing health in plant species. But their uses proved limited, as did infra-red scanning devices and side-looking radar (SLAR). Each technique and development had its specialty uses such as greater precision in defining terrain unit and land-water boundaries (infra-red), but no tool proved as versatile and thereby as useful for general purposes as the black and white air photography. Only as supplementary information used in conjunction with conventional panchromatic air photography have other methods proved useful in surveying routes.

For surveying the extent of permafrost more directly, rather than by interpolation between data points, remote sensing by acoustic methods have been employed. The basic premise is that frozen ground is more conductive than unfrozen ground, because the conductivity of ice is higher than that of water (Scott et., 1978). Moisture in soil does not freeze at one temperature. Depression in the freezing point may be caused by; disolved solids, intergranular forces and overburden pressure. The amount of ice then increases as the temperature decreases. In the presence of a temperature gradient there exists a seismic velocity gradient. So it is possible to relate seismic velocities to ice forms in permafrost. However, the seismic velocity is dependent not only on temperature, but also on the ground material and the thickness of the permafrost, and because temperature and pressure are related the seismic velocities vary with depth in the substrate. This then leads to a highly complex set of relationships that are still being actively investigated (Canadian Symposium on Remote Sensing, 1981) Companies involved in oil exploration in the Arctic are one of the prime movers of this research, since to interpret the seismic logs of offshore tests the acoustic behaviour of permafrost must be known. Permafrost may extend out from the coast, beneath the sea, for anything from 100 m (Werenskiold, 1953) to 600 m (Lachenbruch, 1957; Dome Petroleum Ltd. et al., 1982) and permafrost has been found to a depth of 610 m in Prudhoe Bay, Alaska (Howitt, 1971; Mackay, 1967).

Remote sensing using electrical methods may also hold out promise as frozen materials exhibit different electrical resistances compared with unfrozen materials (Hoekstra and McNeill, 1973). It was postulated that the soil and rock types could be characterized by resistivities in either temperature state. But at that time it was a new field and Mackay (1969) suggested that it was impossible as there was overlap in the resistivities of frozen and unfrozen unsorted sediments.

Sensitive instruments for electromagnetic resistivity mapping have become commercially available and one such, a Geonics Ltd. EM31. was tested at Churchill, Manitoba, by two members of the Geological Survey of Canada in the presence of the author during August of 1978. Essentially, the instrument consists of two coils mounted at either end of a six foot boom with metering at the centre. The whole is encased in a tough but light plastic and is fitted with shoulder straps. It is intended for use by one man. The ground survey can be carried out as quickly as the person can proceed along the transit. In this case, readings were taken at seven sites and along two traverses over discontinuous permafrost of varying active layer depth. At each site the active layer depth was probed manually with a steel probe. The results showed the relationship between thaw depth and conductivity as too complex to allow prediction. A regression analysis of the predicted versus measured thaw depth resulted in a very weak correlation (correlation coefficent = 0.18). Factors such as local drainage and topography appeared to be critical (Nixon, pers. comm.).

A geophysical survey for permafrost delineation was conducted along 200 kms of the Alaska Highway by Klohn Lenoff Consultants Ltd. for Foothills and a report completed in March of 1979. The purpose of the survey was to locate the most likely areas of unfrozen ground, and to delineate the frozen-unfrozen boundaries at stream crossings and overland. For the survey a Geonics EM31 and an EM34-3 were used. Both operate at high frequencies of 10 KHz, but have differing capabilities in the depth of signal penetration. Since the electromagnetic fields decay rapidly with distance the readings may be considered as local. The major advantage of these instruments over traditional methods of manual frost probing is that they operate in a non-contact mode with the ground thereby allowing transits to be run more speedily and efficently. The equipment measures conductivities in millimohs per metre and is presented in terms of resistivity in Ohm-metres. The electrical conductance in millimhos of a material is the inverse of its resistance in Ohms to current flow. Resistivity is a function of porosity, moisture content, electrolyte concentration, amount and composition of colloids, temperature and phase state of pore water in the ground material. The mobility of ions in the pore water decreases with temperature and the resistivity increases (Table 1). Thus it was concluded in the report that with enough drillhole information and other geological data it is possible to make a reasonable accurate estimaticn of the surface location of the frozen/unfrozen boundaries. This method shows promise in producing a continuous long-profile of the permafrost surface between drillholes.

SOIL	RESISTIVITY (Ohs/m)		CONDUCTIVITY (millimho/m)	
	Frozen	Unfrozen	Frozen	Unfrozen
Silt	500	50	2	20
Silty sand	500	50-100	2	20-10
Sand	500-1000	100-200	2-1	10-5
Sand & gravel	1000	150-200	1	6.67-5.0
Gravel	1000	150-300	1	6.67-3.33

Table 1: Resistivities and Conductivities of Soil Types (Klohn Leonoff Consultants Ltd., 1979).

Ferrians and Hobson (1973) in a review go into some detail regarding the various geophysical methods of mapping and predicting permafrost by direct means. They conclude that there are many unknowns to be overcome and, as yet, no fully competent geophysical method to determine the ice content of permafrost is available. However, they suggest, this does not detract from the urgent need for more permafrost data. Whether obtained by traditional or geophysical methods, or a combination of both, accurate determinations of the distribution of permafrost are necessary to determine the best route-ways and sites for engineering structures, their design integrity and the minimization of adverse environmental impacts for an orderly development of the Canadian North.

Prediction Based on Single Variables

To satisfy the need for a method of prediction of permafrost, studies were carried out on specific aspects of the environmental influences on permafrost; vegetation being a prime example (Roberts-Pichette, 1972). Employing black and white air photography the landscape was dissected on the basis of vegetation patterns. Then each pattern was associated with the presence or absence of permafrost. In this way a list of ecosystems was drawn up, each ecosystem having an association with permafrost. Unfortunately the presence of permafrost is not always the deciding factor in the development of one or another type of vegetation (Brown and Pewe, 1973). There are few vegetation associations developed exclusively on soils underlain by permafrost.

From intensive work on vegetation it was recognised that the success rates of single variable analysis of the distribution of permafrost would never be high. Thus it was conceeded that a variety of factors comprising the landscape must be considered.

The Multi-Variate Studies

While there are development projects continuing in the North, requiring practical tools to solve the environmental problems of construction, research in many cases is only at the level of defining the input variables for theoretical models for distribution of permafrost. On the other hand, there are a few studies accepting the complexity involved, and attempting to get beyond distribution and into the problems of predicting permafrost ice content by means of multi-variate studies. Lau and Lawrence (1976), using information from the Mackenzie Valley Geotechnical Data Bank (Lawrence, 1974), computed frequency plots of permafrost type (Pihlainen and Johnson, 1963) versus depth to permafrost for a variety of soil groups. It is interesting that the type of permafrost structure was used as a variable since, with such information, good estimates of ice content volumes could be made.

Lau and Lawrence, found the amount, form and distribution of ground ice varied considerably with soil type and location (synonymous with latitude). They conclude that most coarse grained soils in the valley are frozen in winter, with the type of ice being variable, though the quantity of visible ice increased northwards markedly. Visible ice in gravels and sands increased as the amount of fines increased. It appeared that the visible ice is the main type found in fine textured soils and, again, the amounts increase south to north. Nearly all the organic soils and peats freeze in winter, and contain large amounts of visible ice.

Heginbottom et al. (1978) continued this work. They divided the data by way of the National Topographic System map areas and considered the proportions of frozen soil with visible ice, frozen soil with no visible ice and unfrozen soil in the samples. This was done for each of the map areas, first for each genetic soil class and then for each engineering soil group. From this they found only a general increase in the amount of frozen ground and ground ice from south to north, with some parts of the Upper Mackenzie predominantly unfrozen, while in the Delta region frozen ground was ubiquitous. This last point contrasts sharply with the findings of Gill (1973). Heginbottom et al. concluded that the permafrost condition does not change uniformly nor consistently with latitude. In fact they found the greatest change occurred between San Sault Rapids (65°N) and Travaillant Lake (67°N). It is suggested here that this could be the boundary between the Discontinuous and Continuous Permafrost Zones, the high rate of change indicating a transition. The significant controls on distribution found in Heginbottom et al's. study were location (latitude), soil texture, surface drainage, surface disturbance, vegetation and slope aspect. Soils of fine texture such as clays and silts were found to contain more moisture and more ice than sandy and gravelly textured soils. A positive relationship was acknowleged between natural moisture and engineering properties of fines.

Since 1978 this work has stopped (Heginbottom, pers. comm.) and only one paper has been published using the Mackenzie Valley Geotechnical Data Bank (Pollard, 1981). It is proposed here that Crampton's "Analysis of Synergy" is not a radical departure from the literature, but an orderly advance from Heginbottom et al.'s work and forming a natural continuation. Crampton (1981), using the Mackenzie River Valley as a study area attempted to increase the number of variables in the analysis and initiate the use of intervariate relationships that would account for and identify the secondary influences on the distribution of permafrost and thus increase the explanation level. But with increased complexity there evolved a different view of the environment and this is discussed next.

The New View of the Environment

From the results of the Mackenzie Valley and other studies, the identification of the most influential factors on the presence of permafrost, and the subsequent mapping of the best routes for pipelines, it can be appreciated that there are actively operating interrelations between the various components of the ecosystem. Of late there has been a realization of the importance of incorporating these interrelationships within the analysis thereby permitting cumulative and synergistic effects to be considered for impact analysis of major development proposals (CARC, 1979). There is a need to increase investigation into long-term effects on ecosystems rather than short-term effects at species level (McComas, 1980).

Fisher and Davies (1973) observe that;

> ...once thresholds are exceeded by cumulative developments disproportionate cumulative environmental changes are induced and the environment is permanently altered.

This means that assessment methods are required which are able to detect and identify specific threshold conditions. Oswald and Senyk (1977) state that the terrain factors which influence the development of permafrost are interrelated and therefore discussion of any one factor must consider the others. In studying the world about us each component should not be considered in isolation, for then destruction of the environment by insignificant increments becomes a real possibility (AHPP, 1973). McTaggart-Cowan (1976) states of the Mackenzie Valley Gas Pipeline, that:

> It is certain that the total environmental impact of the project will be greater than the sum of the individual impacts we have just considered because the components of an ecosystem are interrelated. This is, an action that affects one component of the ecosystem can start a set of reactions in other components. Eventually one of the reactions compounds the initial action thereby

> producing a multiplier effect. An exceedingly small impact can eventually cause disproportionately large environmental change. In this manner, any project can have any overall impact greater than the sum of the immediate impacts. As a result, it is only prudent for developers to proceed with caution, and for assessors of impact to err on the side of caution...

Factors or variables make up the component parts of an ecosystem, where a variable is a factor coded or measured in numerical form. Factors interrelate with the ecosystem to characterize it. The relationships have certain forms, some of which are predictable and have predictable consequences. For example increasing the moisture content of a medium or fine textured soil makes it more malleable. This is a linear and additive relationship; the more moisture, the more malleable the soil. However, if the moisture content continues to increase, a point is reached where any additional moisture will create an instability and the soil will flow. Such changes across boundary or cut-off points are beyond the linearity of the relationship. That is to say, the original rules no longer apply. Beyond the boundary point the relationship is generally characterized by an exponential curve or it is discontinuous.

Inquiries into environmental sensitivity to development in the North have focused on cumulative effects of disturbance (Berger, 1977; EAP, 1979; Lysyk, et al., 1977). Ecologists have noted that the great complexity of an ecosystem is not accounted for in linear relationships, and have applied non-linear models with more success (Goodrich, 1978; Heginbottom et al., 1978). Ecosystems viewed as a whole, as a multi-variate entity, exhibit behaviour predictable in non-linear curves; multiplicative, exponential, trigincmetrical and others of greater complexity. One form in particular needs discussion here.

A change in one variable in a multi-dimensional or multi-faceted system such as the physical environment of an ecosystem can simultaneously affect another variable or a series of variables and alter it considerably. The system is highly interrelated and should be expected to act in this fashion. What is surprising is that ecosystems are only very rarely considered in this way by physical geographers and others involved in such studies. The concept of synergy is well known to chemists, but not to geographers.

To explain synergy let us take an illustrative example from the field of physics. The tensile strength of chrome-nickel steel is approximately 350,000 pounds per square inch (psi). This is 100,000 psi greater than the sum of the tensile strengths of each of all of its alloyed metallic elements (Fuller, 1974). This is a 50% increase over the sum of the individual parts, not predicted by the behaviour of the separate components. Such behaviour is termed synergy. Synergistic relationships are non-linear and intially non-predictable. Other non-linear relationships are often to be found within areas of instability or transition between ecosystems, so it suggested that synergistic relationships also, will be most evident where the ecosystem is in a tenuous balance.

Another point to note is that linear-additive alterations encompass a negative in that they can suppress alteration as easily as accelerating change. It follows, then, that synergy may have, or operate in, a reverse direction, inhibiting change.

Applying This Viewpoint

Crampton (1973) worked on ecological and biophysical landscape surveying and land sensitivity mapping of the Upper and Central Mackenzie Valley. Recognising the limitations of map overlays, he began work on a method of analysis for identifying primary and contributing secondary interacting influences in an ecosystem that would accurately predict the effects of imposed alterations. In 1976 a computer program entitled: Analysis of Ecological Systems (ANECSY), was produced. It was put to a variety of uses; forest productivity (1977a), bio-physical analysis (1977b), terrain evaluation (1978a) and to devise soil drainage models (1979). The analysis was evaluated and compared with normal field methods (1978b).

Crampton (1981) took sections of the Central and Upper Mackenzie Valley data and evaluated the terrain sensitivity to disturbance. From this analysis he found that the least ice in permafrost occurs at the highest elevations, over 800 ft (244 m) south of Fort Simpson (60°-63°N), over bedrock or where conifers occupy dry sandy and gravelly silts, facing southwest. Moderate amounts of ice, i.e. 1 to 3 times the weight of soil, occur at low to high elevations from Fort Good Hope to Inuvik (66°-69°N), in morainal silts and clays, supporting sedge-lands with some open stunted forest. The ice is found predominantly at shallow depths of 1.8 to 4.6 m (6-15 ft). The most ice, 3 to 11 times the weight of soil, occur in layered organic, silty or clayey sediments at mid-elevations of 122 to 213 m (400-700 ft), at mid-latitudes about Fort Norman and Norman Wells (65°-66°N), beneath open stunted spruce-lichen forest or lichen vegetation, on gently sloping northeast facing ground. The ice is close to the surface but occurs especially at 4.9-6.1 m (16-20 ft).

Crampton notes a number of points of particular interest.

1. Large accumulation of ice just below the surface, decreasing with depth. However, at about 5.5 m (18 ft) a concentration of ice may occur associated with organics and some silts and clays. Ice content increases with increased elevation to about 198 m (650 ft) and then decreases sharply to the highest elevations of 260 m (850 ft).
2. Mackay (1972) reports increasing ice with elevation except beneath the summits of ranges.
3. High ice content of organic silts and clays, and low amounts of ice in sands and gravels is a well documented relationship (Brown and Johnston, 1964).
4. Large amounts of ice beneath lichen cover, and less beneath forest cover is also documented (Crampton, 1975).
5. Sediments around Norman Wells and Fort Norman (65°-66°N) can contain more ice than those to the north and south.

Analyzing the distribution of ice in the profile (as Heginbottom et al. did), Crampton found that the least ice occurs in sandy and gravelly morainal sediments in lower latitudes (60°-63°N), at high elevations about a southwestern aspect. Moderate amounts of ice, distributed as scattered ice crystals or inclusions, occur in silty or clayey, bouldery or cobbly, water re-worked alluvial-tills or in peat plateaus at mid latitudes (63°-66°N) and mid-elevations (122-213 m) (400-700 ft). The most ice (3-7 times the weight of soil) distributed as lenticular or solid ice bodies occurs in layered, silty and clayey deltaic sediments below sandy and gravelly sediments, on northeast facing slopes of higher latitudes (66°-69°N) and low elevations (0-122 m) (0-400 ft).

Strang (1973) and Mackay (1972) also observed large accumulations of ice along interfaces of sandy over silty sediments throughout the Mackenzie Valley. Crampton's results also show that the most rapid increase in ice content with increasing latitude occurs around Fort Norman and Norman Wells (65°-66° N). This confirms his impressions from field work that there is a rapid transition from discontinuous to continuous permafrost (Crampton, 1981), and supports Heginbottom et al. (1977) in their findings that permafrost does not increase consistently with latitude.

Summary

Terrain evaluations of the proposed Mackenzie Valley Gas Pipeline, and route appraisals for the proposed Alaska Highway and Dempster Lateral Pipelines have been undertaken by employing air-photo analysis and field sampling procedures. More rapid and less expensive geophysical remote sensing procedures for terrain surveying of permafrost conditions are being actively investigated but, to date, no adequate system exists. The above surveys, however, have provided a large data base for subsequent analysis. Thus, detailed investigations into the relationships between specific aspects of the environment and permafrost have been carried out, providing insights into the distribution of permafrost and the variables associated with permafrost and its ice content.

Few multi-variate studies exist on the distribution and form of permafrost. Lau and Lawrence (1976) and Heginbottom et al. (1977) found that permafrost generally increases in extent from south to north, but does not do so in a consistent manner with latitude. Crampton (1981) found the greatest change in ice accumulation between 65° and 67°N in the Mackenzie Valley. The exact reasons for this are unknown, but it is interesting to note that this coincides with the boundary between the Continuous Permafrost and Discontinuous Permafrost Zones as proposed by Brown (1967).

III. RESEARCH DESIGN

The objective of this work is to assess a variety of methods which investigate the interactions of a complex of variables with the occurrence of permafrost and its ice content in the Canadian northwest.

To operationalize the objective a research design was devised (Fig. 4). From the question of prediction of permafrost there follows the techniques of analysis and the choice of variables to be employed. There is the data base to construct and the actual analysis to compute at its various levels. The results are then gathered, interpreted and the conclusions drawn in light of the original question and objectives. This chapter looks at the process in detail; firstly the selection of variables are discussed then the data base, the coding structures for the variables follows and lastly the analytical procedures are outlined.

Identifying the Variables for Analysis

The studies reviewed in the previous chapter reveal some of the important variables for analysis while others may be identified by a review of the energy balance. The key points of the latter approach are outlined here.

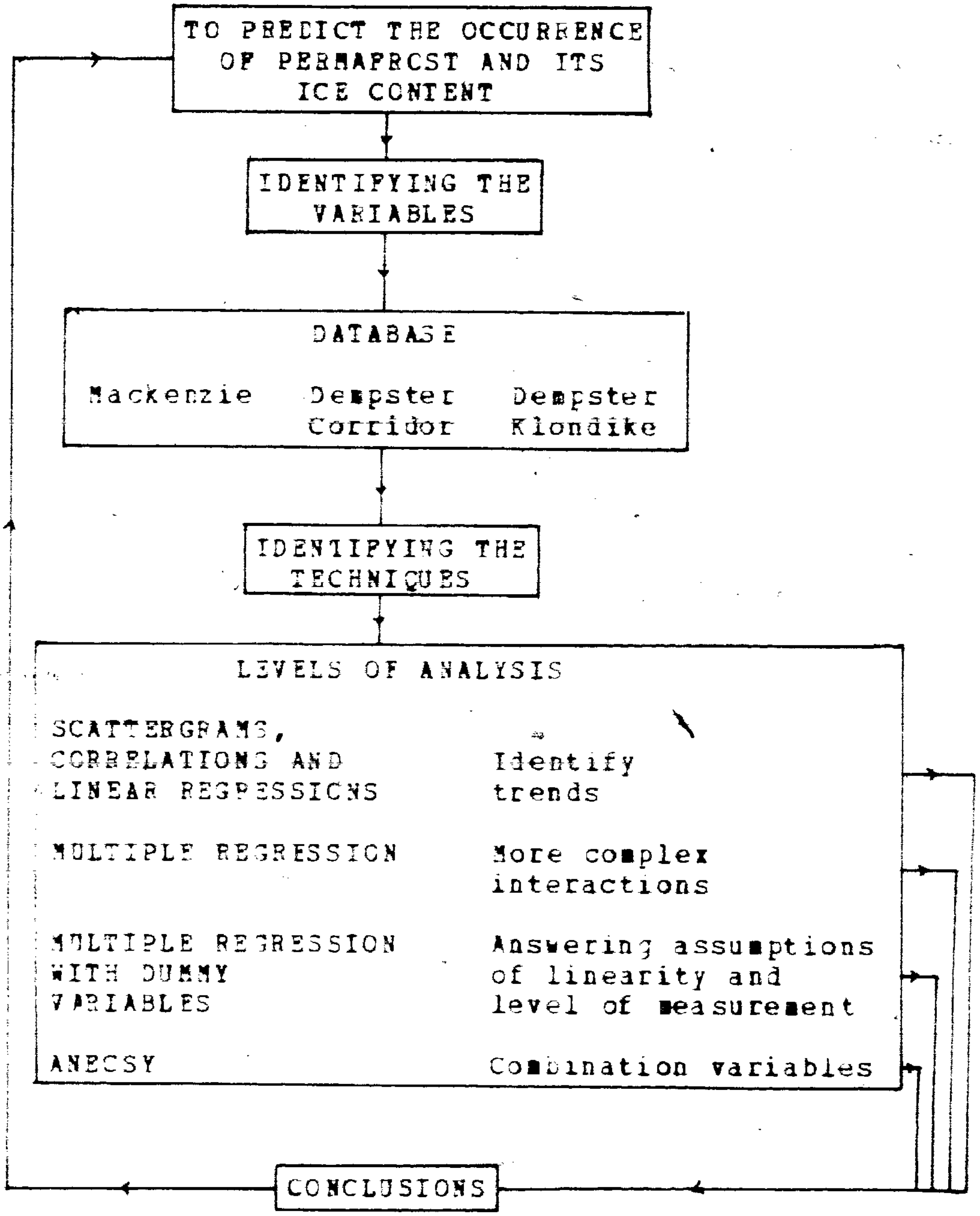


Fig. 4: Flow Diagram of the Research Design.

Net radiation at the surface is the sum of the difference between incoming and outgoing long- and shortwave radiation.

$$Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow)$$

where Q^* is net radiation,

$K\downarrow$ is incoming shortwave radiation,

$K\uparrow$ is outgoing shortwave radiation,

$L\downarrow$ is incoming longwave radiation

and $L\uparrow$ is outgoing longwave radiation.

But $(L\downarrow - L\uparrow)$ is small for northern latitudes and $K\uparrow$ is a function or albedo. Thus $Q^* = f(K\downarrow, \text{albedo})$ but

$K\downarrow = f$(latitude, declination of the sun, slope, elevation, cloud cover, time of day and year).

These then are some of the variables to consider for analysis. In energy balance terms, at the surface

$$Q^* = f(Le, H, Qg \text{ and Others})$$

where Le is latent heat of vaporization,

H is sensible heating of the air, these two are the largest terms in the equation. Also

Qg is the energy left over for soil warming,

and Others include terms amounting to less than 5% in the equation.

Thus Qg representing heat transfer in the profile is the term of interest.

Qg = f(soil moisture, soil texture, unfrozen and frozen phase changes).

For a site specific study these variables comprising Qg might be readily available but for studies such as the present one where the data base covers the length of the Mackenzie Valley and the Yukon Territory such is not the case. Information is available, however, on derived expressions in the landscape such as landforms, topography and vegetation etc., and while the broad controls over permafrost formation and distribution are climatic in nature, local variations are determined by a variety of terrain and other factors. The effects of relief and aspect are important as are the nature and physical properties of the soil, and the controls exerted by vegetation, snowcover, drainage and fire though more complex (French, 1976) are nonetheless significant. So Qg may be inferred by secondary factors and re-written;

Qg = f(geology, landform, slope, elevation, aspect, soil textures, vegetation, snowcover, drainage and fire history).

Thus with reference to the literature on site specific studies and being cognisant of Qg, it is possible to employ environmental variables to assess and predict the distribution of permafrost and its ice content. The data available from alignment sheets for the proposed pipelines in the Mackenzie Valley and Dempster Corridor are ice content and structure of the permafrost, latitude, elevation, aspect, slope, landform, surficial geology, depths to the sample textures through the profile and vegetation cover.

The Database

There are almost 4 1/2 thousand site observations in the data base, divided into three sections. The first section is the Mackenzie Valley data set, the second is data for the Dempster Corridor and the third is from the Dempster and Klondike Highways of the Yukon Territory.

1. The Mackenzie Valley Data:

The data were taken from the alignment sheets published by Foothills Pipe Lines Ltd. (1973) and by the Canadian Arctic Gas Pipelines Ltd. (1973) in their proposals to build gas pipelines over the Canadian north. The alignment sheets give logs of the drilling holes along the routes. Thus, each datum is a record of the ice content and the associated geomorphic parameters for positions in the cored profile. The routes most often follow the valley bottoms and so the core sites are biased areal estimates of the terrain. If the data set is considered as a transect from north to south, and not as an areal distribution of points, then the bias may be largely ignored.

2. The Dempster Corridor Data:

The Dempster Corridor set was also taken from Foothills alignment sheets (1977). Geomorphic bias is small here as the right-of-way followed a corridor traversing highly diversified terrain, however, the transect concept of the route is retained.

3. The Dempster-Klondike Highways Data:

The data were collected by the author in the summer of 1979. The field work covered the Dempster from the cutoff at km 0, to the Peel River crossing at km 542 (mile 337) in the N.W.T.. It could not be extended into the Delta area as the ferry did not come into operation until late August. Though concentrated along the highway, data are also included from the Klondike Highway; Dawson City to Carmacks, the Robert Campbell Highway; Carmacks to Tuchitua, and the North Canol Road; Ross River to Macmillan Pass. In affect these constitute sub-parallel transects over the northwestern Yukon. Sites were sampled along the Highway, their choice being limited by the route-way. However, the routes proposed by the pipeline companies mostly follow the Highway so this is not a limitation as much as an advantage. Each site was chosen at fairly regular intervals of about 2.5 km (4 miles) and the cores were extracted at least 15 m (50 ft) from roadside so as to avoid any mollifying influences on the permafrost table by the presence of the road. Where the road had been rebuilt and the old scar was evident, no measurements were taken. However, where differences in vegetation or landform were evident, a site in each was studied.

3.(a) Field Procedure

Having selected a site the field procedure was to record the location. This was done on a 1:2,500,000 map of the Yukon and the truck's mileage was recorded in the daily diary. The surface characteristics of vegetation, relief, landform and drainage were noted. Aspect and slope were determined by Brunton compass. The permafrost table was then probed using a 1/4 inch (0.63 cm) diameter by six foot (1.8 m) long steel probe. On encountering the permafrost table, the depth of active layer was recorded. The unfrozen active layer was augered and the soil textures determined with depth in the profile. Permafrost cores were retrieved by means of a 1 1/2 inch (3.8 cms) inside diameter corer-bit normally used for concrete, attachable to heavy steel rods. In this way 6 inch (15 cms) sections of frozen core were extracted at a time. Each section was examined and sampled immediately. The frozen permafrost structures were recorded and the sample bagged sealed and weighed. Thus it was possible to document the profile to a depth of about five feet in soils ranging from clay textures to silts and sands. However, where there were more granular materials present, cuts in the roadside were generalized and considered representative of the profile. Attempts to excavate pits proved fruitless as the bonding strength of the ice in the permafrost was generally too great.

3.(b) Laboratory Procedure

The sealed samples were analyzed in the Geomorphology Laboratory at Simon Fraser University. They were re-weighed to check on any moisture loss during transportation from the field. Only eight samples proved to have lost significant moisture. The samples were then dried at 115-110°C, re-weighed and the ratio of moisture to material calculated as a percentage of dry weight (Foothills, 1979; MacFarlane ed., 1969). Thus 100% would mean equal amounts of moisture and material. It was assumed that all moisture was initially frozen. To develop a field procedure that would account for unfrozen moisture would be difficult and it is doubtful that the information gained would be worth the extra time and effort. The volume of moisture below 0°C in the samples, in retrospect, was always very small. Finally, the dried samples were checked against the field records for their textures.

Coding Structures for the Variables

The program ANECSY requires that the input data be coded. The dependent variable may have any number of classes, but the independent variables must each have the same number of possible categories for the analysis. Crampton (1981) devised a system of codings for the Mackenzie Valley data, which were mostly modified for use with the data from the Dempster. Though these revisions were extensive in places, the basic formats were retained. The independent variables were each coded into six categories and the dependent variable spans about 25 to 30 classes.

1. Ice Content:

In the laboratory, ice content is measured in terms of moisture content as a percentage of dry weight (Foothills, 1979). Ice content is the dependent variable and the values range from zero percent, or unfrozen, to 2,500%, or 25 times the weight of ice over material in the sample. Low ice content soils are regarded as those having ice contents less than 50% while high ice content soils range generaly above 100%. It should be noted here that there is a slight difference in the measurement of ice content between Foothills' field procedure and that for the Dempster-Klondike data set. Foothills samples were larger, including a complete section of each textural stratum encountered in the profile, whereas, samples for the Dempster-Klondike were taken within each textural stratum encountered. In effect there is an averaging process in Foothills computations of ice content that is absent in laboratory analysis here and this implies a generally lower value in ice content for Foothills.

CODE	ICE CONTENT (%)	CATEGORY RANGE
1	0 (unfrozen)	0
2	1 - 5	5
3	- 15	10
4	- 30	15
5	- 50	20
6	- 75	25
7	- 105	30
8	- 140	35
9	- 180	40
10	- 225	45
11	- 275	50
12	- 330	55
13	- 390	60
14	- 455	65
15	- 525	70
16	- 600	75
17	- 680	80
18	- 765	85
19	- 855	90
20	- 950	95
21	- 1050	100 etc.

Table 2: Codes and Ranges for Ice Content.

Of concern to this thesis are the hypothetical cutoff points between large values of massive ice where surface disturbance of virtually any kind or intensity could well lead to grave erosion problems, and lesser amounts of ice where the degree of disturbance is important to the initiation of corrective or containing operations. For example, the Northern Pipeline Agency suggests avoidance of frozen soils with 20% or greater ice content. Some method of coding structures is needed that would spread the data in such a way that many categories for the lower values of ice content could exist and fewer categories for the high values. Such a spread of data categories can be devised using a power or trigonometric transformation, but a far simpler method is to use an increasing difference between the high and low values in each category (Table 2). In this case an increase in ice content of 5% per category was employed.

2. Latitude:

For the variable Latitude, a variety of coding structures were examined. However the simplest proved the most effective; one code for each degree of latitude. Inequalities may arise from working with different map projections, but the data run from 60° to 67°N and errors generated in this range are of little consequence or significance. Latitude coded by Crampton (1981) is used for the Mackenzie Valley data set (Table 3).

CODE	LATITUDE	LATITUDE (Mackenzie)
1	61° to 62°N	61°, 62°N
2	62° to 63°N	63°
3	63° to 64°N	64°
4	64° to 65°N	65°
5	65° to 66°N	66°
6	66° to 67°N	67°, 68°N.

Table 3: Codes for the Variable Latitude.

3. Elevation:

For the variable Elevation, a frequency distribution of the data was plotted and the clustering noted. A 500 foot (152 m) interval for each category was used above a baseline of 1,000 ft (305 m) as it both covered the spread of data and preserved the clusters evident in the plot.

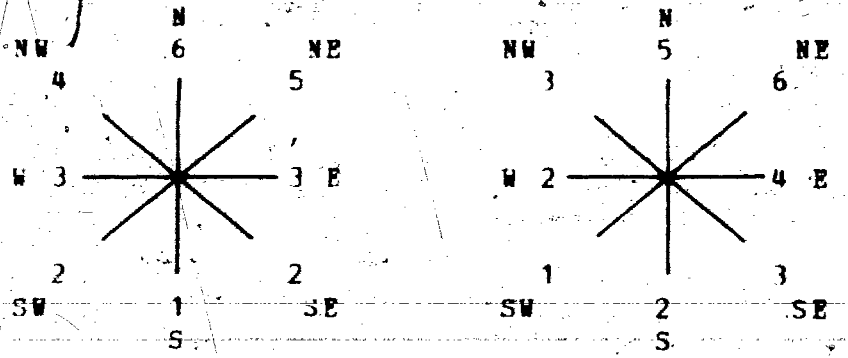
CODE	ELEVATION	ELEVATION (Mackenzie)
1	less than 1500 ft (475 m)	0 - 200 ft (61 m)
2	- 2000 ft (610 m)	- 400 ft (122 m)
3	- 2500 ft (762 m)	- 600 ft (183 m)
4	- 3000 ft (914 m)	- 700 ft (213 m)
5	- 3500 ft (1067 m)	- 800 ft (244 m)
6	over 3500 ft	- 900 ft (274 m).

Table 4: Codes for the Variable Elevation.

This definition of categories is different from Crampton's since elevations in the Mackenzie Valley vary much less than along the Dempster route which crosses mountain ranges, river valleys and a great upland plain, varying from sea level to almost 5,000 (1,524 m) (Table 4).

4. Aspect:

Aspect is known to be an important variable influencing the presence of permafrost for it influences the amount of solar radiation received at the surface. It can happen that frozen ground exists on northly slopes while the opposing southerly slopes are free of permafrost (Brown, 1970) due to the insolation potential of either slope. Aspect was determined on site with a compass, adjusted for declination, and recorded. The problem of coding this information is to place the eight major points of the compass in a six fold category system. Tables of daily solar radiation values on surfaces for specific aspects, slopes and latitudes show that with constant slope and latitude, the radiation is symmetric about a north-south axis. This assumes constant, or at least a similar moisture conditions at the surface throughout the day, but dew, formed in the cool of the night, must be burned off in the morning and so there is less radiant energy available to heat the ground than later in the day. The difference is only slight but it is suggested that it is enough to permit a non-symmetrical coding of the northwest and northeast true compass points (Table 5). Aspect is coded low to high with more frequequent incidence of permafrost, as indicated in the literature. Crampton's code structure is used for the Mackenzie data.



(Mackenzie)

Table 5: Codes for the Variable Aspect.

5. Slope:

The Mackenzie data are coded, one degree of slope for each class, with class six being any slope greater than six degrees. This proved highly successful for this terrain; a broad flat valley. However, the Dempster is much more diversified in relief.

CODE	DEGREES OF SLOPE	SLOPE (Mackenzie)
1	0 - 2	1°
2	3 - 6	2°
3	7 - 9	3°
4	10 - 12	4°
5	13 - 21	5°
6	22 and over	6°

Table 6: Codes for the Variable Slope.

The literature cites three degrees of slope to be important for the initiation of downslope movement (Brown and Grave, 1978; Strang, 1973; U.S. Dept. Interior, 1976), eight degrees is suggested by Zoltai and Pettapiece (1973), while Code (1973) cites instances of flow on fire damaged slopes of four degrees. Klohn Leonoff Ltd. (1979) consider 0 to 3% as flat, 3 to 10% as low, 10 to 20% as medium and over 20% as steep. With these figures in mind, and having plotted frenquency tables of the data, the above code structure was assigned.

6. Landform Genesis:

Landform genesis, as it is conceived here, should be treated as an areal descriptor of the surrounding locale. It is the sum of the immediately perceptible topography, and a gross estimate of the genesis of the substrate material. The class 'organic' describes peat plateaus and sheltered hummocky terrains with deep organic layers and pingos. 'Glacial lacustrine' encompases valley bottoms of fine materials, and 'glacio-fluvial' implies valley sides of river terrace sandy materials. 'Morainal' includes sites of granular material on valley sides, and hummocky terrain of open and exposed areas with resultant thin organic horizons. 'Lineated slopes' include areas of strong relief with obvious movement and sorting of materials on the slopes.

CODE	LANDFORM GENESIS	LANDFORM
1	Organic - peat plateaus, hummocks, deep organics, pingos.	Peat
2	Glacial Lacustrine - valley bottoms, fines.	Alluvial-Lacustrine
3	Glacio-fluvial - valley sides, terraces, sandy materials.	Deltaic
4	Morainal - valley sides, open hummocks, gravels, thin organics.	Morainal
5	Lineated Slopes - large relief, sorting, surface gravels.	Slopes
6	Till venere over bedrock.	Till.

Table 7: Codes for the Variables Landform Genesis and Landform (Mackenzie).

The final class includes areas of barren rock and open, exposed divides with a thin cover of open tussocks over coarse materials. The codings by Crampton (1981) were used as a base for the present structure. Changes were made to accommodate the diversity of terrain in the Yukon traverses and facilitate and simplify the field work.

7. Depth:

Depth to the sample, below the surface, was coded in six inch (15.2 cm) increments (Table 8). It was virtually impossible to hand-auger beyond five feet (1.5 m) in even the lightest of organic clays. Permafrost, if present to five feet and beyond, was invariably found within two feet of the surface. Only two of 160 sites sampled in the Dempster-Klondike set were found to have active layers between three and five feet thick. Because the sampling was conducted in July and August it is assumed that the active layer depth was close to its maximum.

CODE	DEPTH (Dempster-Klondike)	DEPTH
1	0 - 6 ins (15.2 cms)	0 - 5 ft (1.5 m)
2	- 1 ft (30.5 cms)	- 10 ft (3.0 m)
3	- 1.5 ft (45.7 cms)	- 15 ft (4.5 m)
4	- 2 ft (61.0 cms)	- 20 ft (6.1 m)
5	- 2.5 ft (76.2 cms)	- 25 ft (7.6 m)
6	over 2.5 ft.	over 25 ft.

Table 8: Codes for the Variable Depth.

Permafrost at five to six feet was determined by probing only. The thickness of the permafrost was seldom determined if thicker than 18 inches (46 cms), simply because it took so much time and effort to core through. However, thin lenses with interspersed taliks were noted. In engineering terms, if permafrost is found only below two metres then the site is considered 'unfrozen' (Klohn Leonoff Ltd., 1979). Thus the codes in the first list were used for the Dempster-Klondike Highways data set, and in the second list, those devised by Crampton, were used for the Mackenzie and Dempster Corridor data sets.

8. Texture:

Texture of the sample coded low to high with increasing grain size. The classes are sufficiently broad for hand texturing in the field to be accurate (Burdick et al., 1978), while at the same time concise enough for general engineering purposes (Assoc. Comm. Soil and Snow Mechanics, 1955). All samples were double checked during the laboratory analysis. The variables texture above and texture below are used to describe the textural changes in the horizons ofer the profile. The Canadian Soil System or Unified Scale is reported for comparison and convenience.

CODE	TEXTURE	UNIFIED SCALE
1	Organic soil	PT
2	Organic silts and clays	OH/OL
3	Inorganic silts and clays	CH/CL
4	Inorganic silts and clays with fine sand	MH/MI
5	Clayey and silty sands and gravels	SC/GC/SM/GM
6	Sands, gravels and bedrock	SP/GP/SW/GW.

Table 9: Codes for the Variables Texture, Texture of the Layer Above and Texture of the Layer Below.

Organic materials at the surface act as an insulator and are particularly effective in preserving the permafrost from atmospheric heat. At the southern fringe of the distribution of permafrost, in the Sporadic Zone, permafrost is to be found only in peatlands. Thermal conductivity of dry peat is very low so that in summer, when the top surface is dried, the heat penetration below the surface is curtailed resulting in less seasonal thawing than in nearby non-peatlands. In winter the peat becomes saturated and no longer being a great insulator, it freezes. The soil being relatively warmer than the air, the vertical heat flux is in an upward direction and the soil looses heat to the atmosphere. If the energy balance is consistently at a deficet the temperatures of the ground will be negative and permafrost results.

Finer textures of materials reduce the volumes of air trapped in the soil, the thermal conductivity is larger so that permafrost is more likely to be found present in silts than sands. The finer textured materials also retain moisture better and thermal conductivity is enhanced by the presence of moisture which is subsequently increased when the moisture forms ice (Sellers, 1972).

9. Vegetation:

Vegetation has been repeatedly considered as the single most important parameter for predicting the occurrence of permafrost, though often it has proven unreliable. However, there is no denying the usefulness of vegetation as a parameter in combination with other variables for prediction. The code structures used here arose from field experience and a broad literature search. It is based primarily upon the general findings of permafrost and vegetation associations observed in air-photo analysis, and intuitive interconnections developed by fieldwork on ecosystems by several, but chiefly by Bliss (especially (ed.) 1973 and 1980). The classes proceed low to high with suspected increases in insidence of permafrost. The associated soils and drainage are reported to help the reader visualize the various environments, and thereby emphasize the differentiation in the coding structure.

CODE	VEGETATION	DRAINAGE	SOILS	VEGETATION
1	White & Black Spruce Balsam Poplar Closed forest	well to imperfect	Brunisols	Hardwoods
2	White & Black Spruce Birch, Moss Open forest	well to imperfect	Brunisols to Regosols	Conifers
3	Black Spruce Moss	imperfect	Fibrisols to Gleysols	Lichen-treed
4	Lichen Moss	well to imperfect	Regosols	Lichens
5	Tall Shrubs Drunken Black Spruce	imperfect to poor	Gleysols to Fibrisols	Sedges-treed
6	Hummocks & tussocks Wet sedges	poor	Gleysols to Fibrisols	Sedges.

Table 10: Codes for the Variable Vegetation with its Associations and Vegetation (Mackenzie).

Additional Variables

Other variables were considered for inclusion in the analysis but not employed. One was the depth of the active layer, but the various data sets were collected at different times, seasons and years and were thus considered incompatible. There was no simple method of including a time variable, either to account for the variation in active layer, or as a variable to account for past disturbance.

Fire history was contemplated but the necessary records simply did not exist. This was also the case for climatic variables. The records of temperatures, precipitation and wind were too dispersed over the area for a valuable contribution to the analysis. One potential climatic variable is insolation potential. Computed from slope, length of day, percent sunlight per day and angular displacement of the sun, and presented in units of energy over time, this could be a powerful variable. Various computations were attempted, but all proved unwieldly and never instilled a firm conviction that they added any more information to the analysis than aspect and slope. Snowcover is another variable influencing local permafrost variations for it insulates the ground in winter inhibiting frost penetration and if preserved late in the spring can also impeed warming of the ground. Snowfall regime and duration on the ground are important factors especially south of the treeline in discontinuous permafrost (French. 1976) but for the breath of this study such data are not available. Drainage constitutes an important omission from the variety of variables used. Water bodies possess a high specific heat. In continuous permafrost lakes that do not freeze to the bottom in winter have an unfrozen ground layer beneath. If the water body is large enough an unfrozen window may exist all the way through the permafrost. In a few cases the results have indicated small amounts of ice in what should be prime conditions for high ice content in the permafrost. The suspicion is that there is a lack of moisture present to form the ice. If there was some measure of available subsurface drainage this problem might be explained and the suspicions confirmed or rejected, but it has not been possible to undertake the necessary field work.

Another omission in the analysis is fire history. Much, if not all, the study area has been burned over at some time, to the extent that for the Central Yukon mixed stands of black and white spruce can be considered the climax forest for it is unlikely that a mono-specific black spruce stand will have enough time to develop between fires (Strang and Johnson, 1981). The effect of fire on permafrost is dependent on the nature and dampness of the vegetation and the speed at which the fire passes through the area (French, 1976). Rapid fires in damp areas may burn only the trees and the effect on permafrost will be negligible. On the other hand if the vegetation is dry and the fire moves slowly the ice-rich will thaw, thermokarst may develop and the active layer will thicken. Other than a recent paper by Johnson and Strang (1982) there is little information on fire history in the Yukon. For the Mackenzie some studies were done but only on a site specific level (Bliss, 1980).

Taking the lead from Heginbottom et al. (1978), structure of icy permafrost was initially input as the dependent variable in the analysis (Table 11). The coding was derived from Pihlainen and Johnston (1963) and their work on types of ice in frozen ground. It was rejected in preference to ice content because it was limited in scope due to the smaller number of classes (but see Crampton, 1981).

CODE	GROUP	STRUCTURE
1	Nf	Frozen soil, ice not visible, poorly bonded
2	Nb	Well bonded, low saturation to excess ice.
3	Vx	Individual ice crystals or inclusions
4	Vc	Ice coatings on particles
5	Vr	Random or orregularly oriented ice formations
6	Vs	Stratified or dictinctly oriented ice formations
7	ICE	Ice with soil inclusions
8	ICE	Ice without soil inclusions.

Table 11: Codes for the Variable Structure.

Random numbers from 1 to 6 were generated and used in place of the variables elevation and aspect when those variables were seen to be secondary influences as indicated by ANECSY output. The reasons for this action were: to test for 'garbage in' and 'garbage out' phenomena in the program and to assure recognition of spurious relations by having an example to go by. Odd results were obtained; the most powerful predictor was a two variable and not a four variable interaction as had always been the case for four cycle analysis. The resultant matrices were confusing, identifying spurious relations as dominant interactions. In addition the check results were erratic. It was concluded that the random number sets identified themselves as meaningless by presenting such idiosyncrasies.

Revised Codes

Summarising, the codes were based on Crampton (1981), but revised and altered in many cases. Latitude was changed for the Dempster-Klondike data because the data spread farther south and not as far north as that of the Mackenzie Valley. Elevation and slope were altered because the routes travered differ in the amplitude of relief. The influence of aspect on permafrost is interpreted slightly differently than by Crampton. Landform genesis was substantially re-defined in an attempt to make it more specific to the Dempster route. Depth of the sample as a variable was changed because of the different field procedure, and vegetation was expanded to make it more specific, and also to include information on associations (Bliss, 1980).

Techniques of Analysis

Initially perceived as simply a way of getting to know the data sets, the preliminary statistical analysis came to be an integral part of the work, providing a surprising amount of information. The scattergrams and the correlation figures provided a measure of the interdependence of the variables, and were an excellent reference when the strength of the interrelationships between the variables in the program were analyzed.

Scattergrams

Using Release 8 of the Statistical Package for the Social Sciences (SPSS, 1979) scattergrams were produced for each independent variable on the dependent variable; ice content of permafrost. Scattergrams were also produced for each variable on every other variable. The results were examined manually and visually at a variety of scales in an attempt to isolate the clustering and patterns, and to preview linear and non-linear trends.

Correlations

Pearson's product-momement coefficients were automatically produced with the Scattergram Program and so these were used initially. Later Kendall's Tau was computed as possibly a more appropriate measure. Kendall's Tau is a technique for producing standardized coefficients based on the amount of agreement between two sets of ordinal rankings. It is used when a large number of cases are classified into a small number of categories. The absolute value of tau generally tends to be less than Pearson's R coefficent. The signifigance of tau is determined by comparing tau to a normal distribution with standard deviation. A two-tailed test of significance was used. The standard error of the estimate is equivalent to the standard deviation of the residuals. For the computational formulae of these statistics see Nie (1980). Kendall's Tau was found to be, as expected, slightly smaller in absolute value than Pearson's. In terms of direction and significance both computations proved virtually the same.

Regressions

Linear regression statistics were produced with the scattergrams, including correlation coefficient, two-tailed tests of significance, standard error, intercept and slope of the line. Some of these are reported for each of the data sets.

In the coding for ice content, code 1 represents unfrozen material. In order to see how the correlation coefficients react, all unfrozen sites were excluded in a second computer run of the data. The rationale for this action was to focus more closely on the ice content rather than the distribution of the permafrost. By excluding those unfrozen sites the regression equation became a predictive model of the conditions that promote higher ice contents in permafrost. These results are also reported.

Using the SPSS programs once again, a multiple linear regression was run. All ten of the independent variables were regressed upon ice content in a stepwise fashion.

Because regression analysis requires a higher order of measurement than the coded variables, dummy variables were created for a second multiple regression procedure. Dummy variables are created by treating each category of the nominal variable as a dummy variable and assigning scores for all cases depending on their presence or absence in each of the categories (Nie, 1980). Since dummy variables have arbitrary metric values of 0 and 1 in each category, they are dichotomous and may be treated as interval variables and thereby inserted in the regression equation by way of a category versus variable matrix (Draper and Smith, 1966). It is necessary however to impose additional constraints on the parameters of the regression equation otherwise it would be unsolvable, the last dummy variable being completely determined by the rest. Among the possible constraints the most useful are; to set the constant term of the equation to zero or to omit one of the dummies from the the equation. If several systems of multi-categoried variables are involved the best procedure is to delete one dummy variable from each system (Suits, 1957). The excluded category does not mean a loss in information as each category is represented by a unique combination of the dummy variables. The excluded category is referred to as the reference category (Nie, 1980), in this case, category 6 for each variable. Suits (1957) declares that there is nothing artificial about the creation of such variables. He suggests that they may, in some sense, be more properly scaled than otherwise conventionally measured variables for in the event of curvature the use of linear regresion yields biased estimates. By dividing variables into a set of dummy variables, unbiased estimates are obtained since the regression coefficents of the dummies conform to the curvature.

In an effort to keep this part of the analysis under some control the procedure was as follows: all the dummies were regressed upon ice content, then the variable whose dummies contributed least was excluded. The remaining dummies were regressed upon ice content and again the least contributor identified: in essence a stepwise regression in a backward direction. It was continued until the regression equation proved significant in F-value at the 0.001 level. Only the final outputs are reported and discussed.

Analysis of Ecological Systems

The final stage in the analysis is ANECSY. It is a statistical program based on multiple regression of dummy variables but novel to such an analytical approach is the processing of the data and creation of combination variables or surrogates. The procedure is outlined below.

On inputting the data a percentage of sites is deleted from the working body of the data. This is the check sample and is kept separate for later use, its size and selection procedure are user-defined.

Each independent variable has been classified into the same number of discreet categories, six in this case, to allow for their equitable treatment within the analysis. The average of measured ice content is then calculated for each category.

For each possible combination of two independent variables a two-dimensional, 6X6 matrix, is constructed, embracing all combinations of their categories. The measured ice contents are recorded in the appropriate cell of the matrix representing the particular conditions at each site. The large data base assures that every cell contains some observations. Means of ice content are computed for each cell and are ranked and divided into six classes of ice content. The cells are numbered 1 to 6 according to their new classification creating a surrogate value. Thus the category combinations or matrix cells for each two-variable combination are equated with a class of ice content. This type of re-scaling procedure is a practical way of defining a surrogate variable acting for the two independent variables and avoids the problem of the exponentially expanding number of cells in the interacting variable matrices. Categorized into six classes of ice content the surrogates serve as input into the analysis in addition to the single variables.

For each possible combination of three variables a similar routine is adapted as for the two-variable combinations. And again a 6X6X6X6 matrix is constructed for each possible four-variable combination, to permit calculation of surrogates classified in terms of six categories of ice content for processing with single, two- and three-variable surrogates.

Though there is only the mathematical limit of multi-variable combinations, it has been found from earlier trials during the development of ANECSY, that the four-variable analysis is close to the optimum for interpretation. Higher powers become too abstract and convoluted. Other problems of computer time and storage come into effect at this point reducing the efficency.

In the analysis the surrogates of each variable and variable combination are regressed in dummy fashion on the dependent variable ice content. All surrogates are input into the analysis simultaneously but the best predictive model, in terms of explanation of the variance, has been consistently the four-variable interactions. The three most significant interactions are reported for each data set.

The check sample is then employed to evaluate the results. Prediction of ice content is based on the calculation of the best fit for the environmental character of a site in the check sample and the analysis results. The strength of association between ice content of the particular site in the check sample and that predicted by the results is then reported. The search for an analytical tool capable of employing combination variables is an ongoing process: ANECSY continues to evolve and develop.

The Assumptions of Classical Regression Models

The assumptions of the classic linear regression models are;

1. No measurement error in the values of the dependent and independent variables,
2. The relationships between the dependent and every independent variable are linear,
3. Each conditional conditional distribution of the disturbance term has a mean of zero,
4. The variance of the conditional distribution of the disturbance term is constant for all such distributions, ie. Homeoscedasticity assumption,
5. The values of the disturbance term are serially independent, ie. Autocorrelation assumption,
6. The variables are independent of one another, ie. Multicolinearity assumption,
7. The conditional and marginal distributions of each variable are normal.

(after Poole and O'Farrell, 1971)

For the Mackenzie Valley and Dempster Corridor data sets the measurement errors in the dependent variable were kept to a minimum by setting a standardized method of computing ice content of the frozen samples. For the independent variables one can only depend on the expertise of the workers in the field.

The Dempster-Klondike data set has the advantage of having been collected by only one individual and the sampling procedure was outlined prior to field reconnaissance. It should be noted however, that measurement error in regression can be ignored if the sole objective of the regression analysis is to predict the values of Y to a given set of X values.

The linearity assumptions in points two and six are the greatest problems associated with the use of regression analysis for environmental studies. The relationships outlined later in the scatterplots (Figs. 6 to 12), are not linear and some of those reported in the tables of correlation coefficents (Tables 12 to 14) indicate their non-linear nature by large standard errors. Such is generally the case for environmental data. But the point of presenting the results of this analysis is to show the problem of non-linearity of interrelationships and to offer some solutions, for dummy variables do not require a linearity assumption in regression (Suits, 1957).

Points 3, 4 and 5 all involve the pattern of disturbances. It is impossible to test directly the validity of the assumptions of the characteristics of the disturbances as the disturbances are unobservable (Poole and O'Farrell, 1971). Tests may, however, be carried out on the pattern of residuals in an attempt to estimate the pattern of disturbances (Draper and Smith, 1966). SPSS facilitates plotting the residual (ie. the differences between the observed values with the corresponding predicted values obtained from the regression equation) versus the predicted values obtained from the regression equation. A 'horizontal band' about the predicted Y values indicates no abnormality and this was the case for most of the residual plots.

The assumption of normality in the conditional and marginal distributions of each variable is not binding if the data sets are large. On the other hand large sample sets create problems themselves of spurious correlations and statistical versus practical significance (Draper, 1968). The problem of occurrence of spurious relations depends on the number of independent variables and their intercorrelations. With ten uncorrelated independent variables the probability of obtaining at least one spurious correlation is approximately the probability of a type 1 error times 10. If we set the test statistic at 0.01 the probability is 0.1, or with a test statistic of 0.001 the probability is 0.01. Where there is intercorrelation between the independent variables the probability is less but still considerably larger than the test statistic (Draper, 1968). Thus the test statistic must be kept stringent wherever possible. With regard to the second problem, the magnitude of the correlation required for statistical significance, this depends directly on the sample size. The probability of obtaining a statistically significant sample correlation coefficent when in fact two variables are uncorrelated remains constant with increasing sample size, but the magnitude of the correlation considered to be statistically significant decreases. Thus in an attempt to avoid type 2 errors a harsh cutoff of r greater than or equal to 0.20 was used for intervariate correlations before being considered to have potential practical significance, and this was increases to 0.30 for inter-dummy variable correlations. With consistent application of these indicators confidence in the correlations can be maintained.

A last point should be made here, this in regard to analysis of variance. Although analysis of variance and multiple regression analysis are interchangable in the case of categorical independent variables, multiple regression analysis is superior or the only appropriate method of analysis when, as applies to this thesis; (a) the independent variables are both continuous and categorical; (b) when cell frequencies are unequal and disproportionate and (c) when studying trends in data, linear, quadratic and so on (from Kerlinger and Pedhazur, 1973, pp.114-5; Cohen and Cohen, 1975, pp.186-8).

On the Use of Regression

It was found most difficult to interpret the output of a four-variable interaction from ANECSY without some indicator of the dynamics of the interrelationships involved. The scattergrams were employed to search for recognisable trends between the variables. Correlation coefficients were employed for indicating strength and significance of the relations.

Still there was a 'gap' evident between intercorrelations of variables by twos and the four variable interactive output. In an attempt to fill such a void and gain insight into the trends of the relationships the regressions were employed. Multiple regression was perceived primarily as an indicator of the relative dominance of the variables in potential explanation of the distribution of icy permafrost. It was recognised that the levels of measurement of the variables was inadequate and so the dummy variables were created. The results of the regression analysis are never the less presented for they fulfill the need for direction in translating the ANECSY output matrices. It is hoped that the regression results are accepted for what they are meant to be; exploratory.

The Analysis Procedure in Outline

For convenience a flow chart of the analytical procedure has been drawn up (Fig. 5). There are three data sets. Each datum is a record of the ice content and the ten associated variables for a sample. Each of the independent variables is coded from one to six. In addition each data set has a sub-set comprising only those sites that are frozen. This is a modified dependent variable and is termed CDICE(1). Scattergrams and correlations were computed for the dependent variable and the modified variable against each independent variable. Then each independent variable was run with every other independent variable. Kendall's Tau rank correlations were computed and are reported.

Scattergrams with CDICE(1) were visually no more informative than the originals and are therefore not reported. Lin~~ear~~ and multiple regressions were computed with both CDICE and CDICE(1) as dependent variables. Other variables were not used as dependent variables in turn because

- the focus of this thesis is permafrost and ice content and
- the data is in coded form, ordinal level, and is inapplicable for regression analysis, and
- the regressions were done to fill an information gap to be used very tentatively as indicators of trends and not to identify causal relationships.

At this point the data were reviewed once more and modified. Dummy variables of the independent variables were created as described earlier so as to increase the level of measurement. Correlation coefficients and multiple regressions were computed once more. Finally the Analysis of Ecological Systems program was run for the three initial data sets only. The results were compared to the other statistical procedures, primary and secondary interactions identified and possible occurrences of synergy outlined.

Summary

The data cover three areas; the Mackenzie River Valley of western N.W.T., the Dempster Corridor and the Dempster-Klondike highways of the Yukon Territory. The latter set was collected specifically for this work, whereas, the others were adapted from alignment sheets of the proposed gas pipeline routes.

Variables used in the analysis were; latitude, elevation, aspect, slope, landform genesis, depth to the sample, texture of the stratum above, texture of the sample, texture of the stratum below and, lastly, vegetation. The dependent variable was ice content of the permafrost. Other variables were tried, but rejected. The coding structures were based on those of Crampton and a review of the literature. In many cases the codes were designed to fit the situations involved, to be extractable from the field data and, importantly, to be meaningful to prospective users.

The proposed statistical procedures to be employed and assessed are; correlations, linear regressions, multiple regressions with and without dummy variables and finally Analysis of Ecological Systems.

DATA SETS	**ANALYTICAL PROCEDURES**	
Mackenzie Valley N=2322 N(1)=2032	Scattergrams	CDICE vs each var Intervariable
Dempster Corridor N=1700 N(1)=1369	Correlations	CDICE vs each var Intervariable CDICE(1) vs each var Intervariable N(1)
Dempster-Klondike N=434 N(1)=154	Linear Regression	CDICE vs each var CDICE(1) vs each var
	Multiple Regression	CDICE vs all vars CDICE(1) vs all vars
	Dummy Variables	
	Correlations	CDICE vs each dummy Interdummies CDICE(1) vs each dummy Interdummies N(1)
	Multiple Regression	CDICE vs all dummies CDICE(1) vs all dummies
	ANECSY	
	ANECSY	Four-variable combination

Fig. 5: Outline of the Analysis Procedure.

IV. RESULTS

The results of each step in the analysis are presented in this chapter. Firstly the scattergrams are outlined for selected interactions. The intervariate correlations are reported next with a discussion on those proving significant. The multiple regressions are then presented. The discussion then proceeds with creation of the dummy variables and a review of their interactions. Then the multiple regressions employing the dummy variables are presented. Finally the Analysis of Ecological Systems program results are tabulated and discussed.

Scattergrams

Using the subroutine Scattergram of SPSS Release 8 (Nie, 1975), eleven variables were plotted against one another, and for each plot, simple statistics were obtained. These comprised Kendall's Tau, its significance test, the standard error of the estimate and the coefficients a and b in the linear regression equation. A two-tailed test of significance was selected. Standard error of the estimate is also known as the standard deviation of the residuals. For more details and the computational formulae of these statistics see Nie (1975).

For the Mackenzie Valley

(a) Ice Content vs Texture (Fig. 6)

Ice content ranges from 1 through 21, and texture, 1 through 6 inclusive. Tau = -0.372 significant at the 0.1% level and standard error of 2.329. Ice content is inversely related to texture. Both the plot and correlation coefficent suggest there is an inverse relation between ice content and texture, that is ice content of permafrost increases with finer textures, though the plot also indicates the relationship is only somewhat linear at best. In the literature it is accepted that frozen organics and fine textured soils such as silts and clays often contain high proportions of ice in permafrost and that sandy materials are less susceptible to ice accumulation. But nowhere is it suggested that this relation is purly linear in nature. It is even possible that the relation between ice accumulation and texture of the soil is not continuous over the full range of possible textures. It is not possible to verify this speculation in this analysis, however, due to the limited number of categories in the variable.

(b) Ice Content vs Latitude (Fig. 7)

With Tau = 0.186, significant at better than 1% and a standard error of 2.610, the indications are of a significant but weak linear relationship. Investigating the plot in the upper values of ice content it may be seen that latitude 1 and 4 have few occurrences of high ice whereas in latitudes 3 and 6

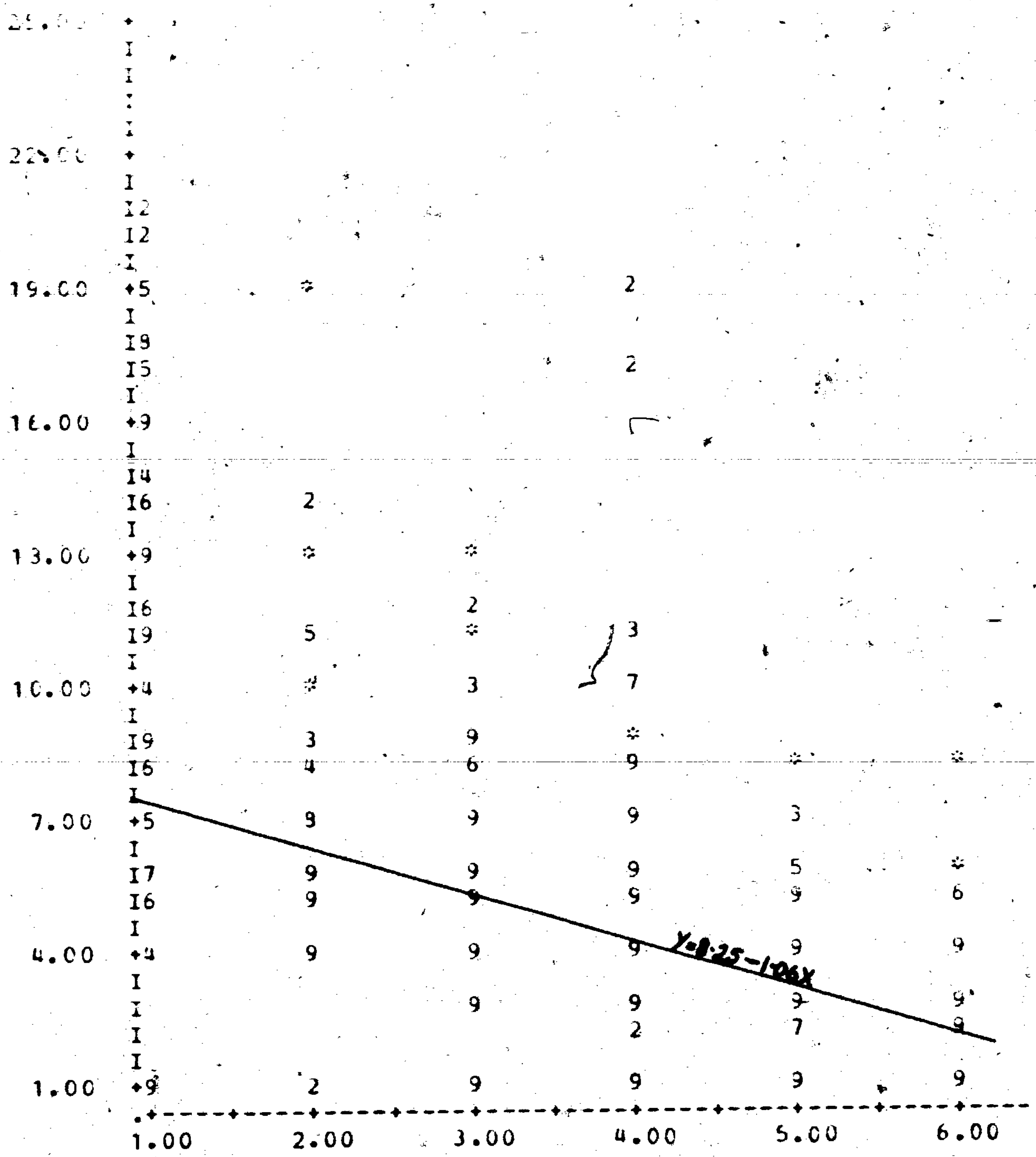


Fig. 6: Ice Content vs. Texture in the Mackenzie Valley.

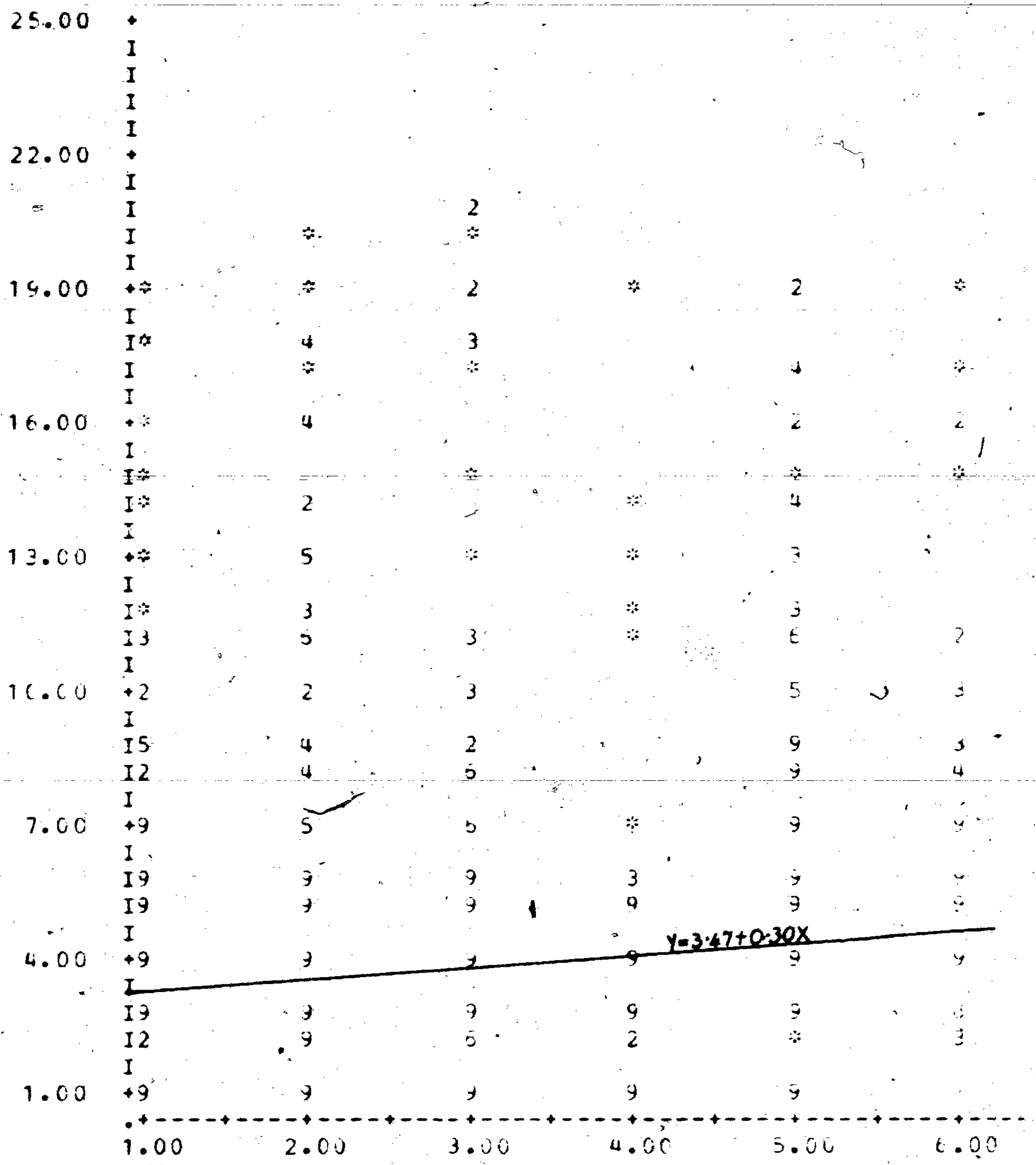


Fig. 7: Ice Content vs. Latitude in the Mackenzie Valley.

they are more frequent and still more frequent in latitudes 2 and 5. So a change in ice contents from low to high latitudes might read as follows; an area of low ice contents at 60° to 61°N, climbing to a peak of high ice content at 62° to 63°N. From here there is a steep decline, minimizing at 63° to 64°N, whereupon there is another rapid rise to a high at 64° to 65°N. Then there begins a gradual fall off once more. This is definitely not a linear relationship and because the curve shows two maximum and one minimum points the simplest curve that could fit is a fourth order curve (cf. Fig. 13).

(c) Latitude *vs* Elevation (Fig. 8)

With only six categories to each variable and such a large sample, population cells are mostly overfilled. This situation occurs often under such a graphing procedure and very little information of value can be detected within the visual component of the scattergram. Otherwise Tau = -0.38, significant at better than 1%, so high latitudes are associated with low elevations. Because the Mackenzie Valley trends northward this is no more than one would expect.

For the Dempster Corridor

(a) Ice Content *vs* Vegetation (Fig. 9)

In this data set there occurs some of the highest ice contents recorded, code 24 or 1165 to 1280% by weight. The inverse relationship is very weak but significant at the 1%

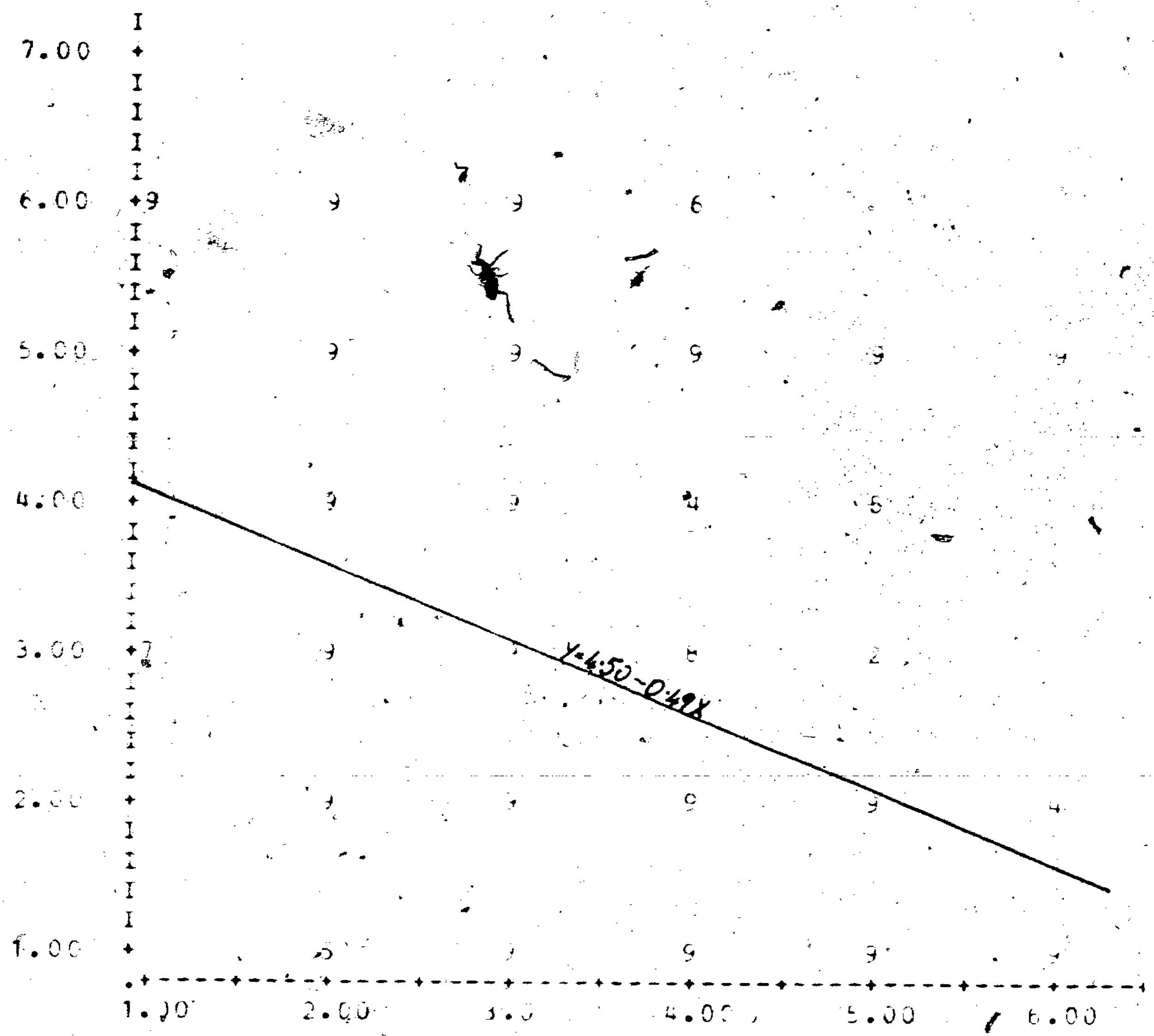


Fig. 8: Latitude vs. Elevation in the Mackenzie Valley.

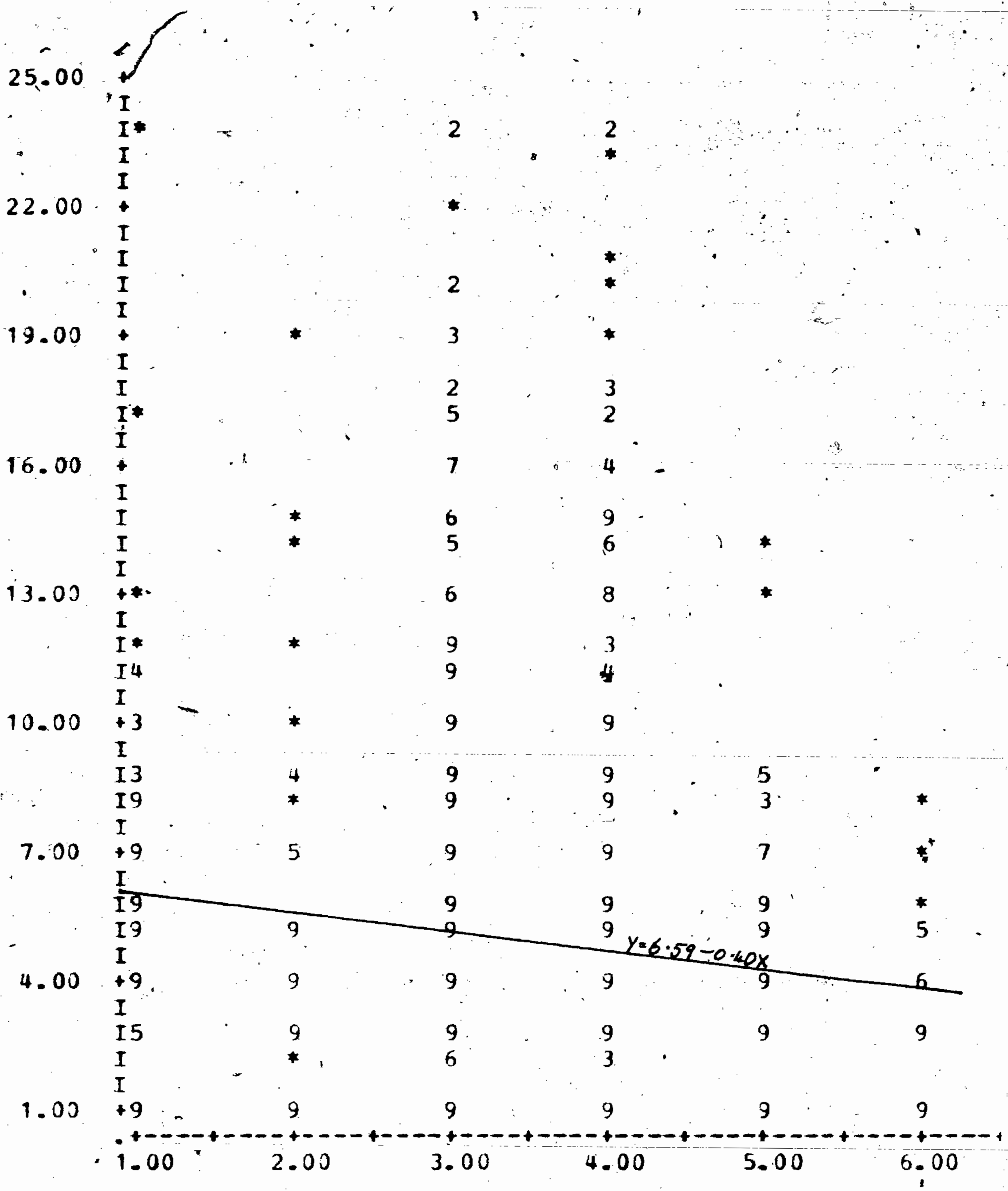


Fig. 9: Ice Content vs. Vegetation in the Dempster Corridor.

level. The highest ice contents occur most frequently under black spruce with moss covered floors (vegetation 3), and beneath thick lichen and moss covers (vegetation 4). From field experience these are the expected cases. The thick moss covers are often indicatative, though not always, of shallow icy permafrost in the North. The moss tends to insulate the ground beneath thus promoting and preserving ice formation. Mono-species stands of black spruce take a long time between fire damage to develop (Strang, 1982) and possibly this extended undisturbed period aids in the development of icy permafrost.

(b) Aspect vs Vegetation (Fig. 10)

Though the relationship is significant, less than 3% of the variance is explained. Aspect was coded low to high with suspected permafrost occurrence as indicated in the literature of previous studies, i.e. northerly facing slopes contain permafrost more often than southerly slopes. Vegetation was coded on similar basis, i.e. the hummocks and tussocks and sedge lands often poorly drained are suspected of containing permafrost more often than forests of white and black spruce and balsam poplar. So the expected relationship between aspect and vegetation, being coded in this way, is a positive correlation with northerly slopes related to the occurrence of hummocks and tussocks. But such is not the case here. The null relationship between ice content and aspect and the small relation between

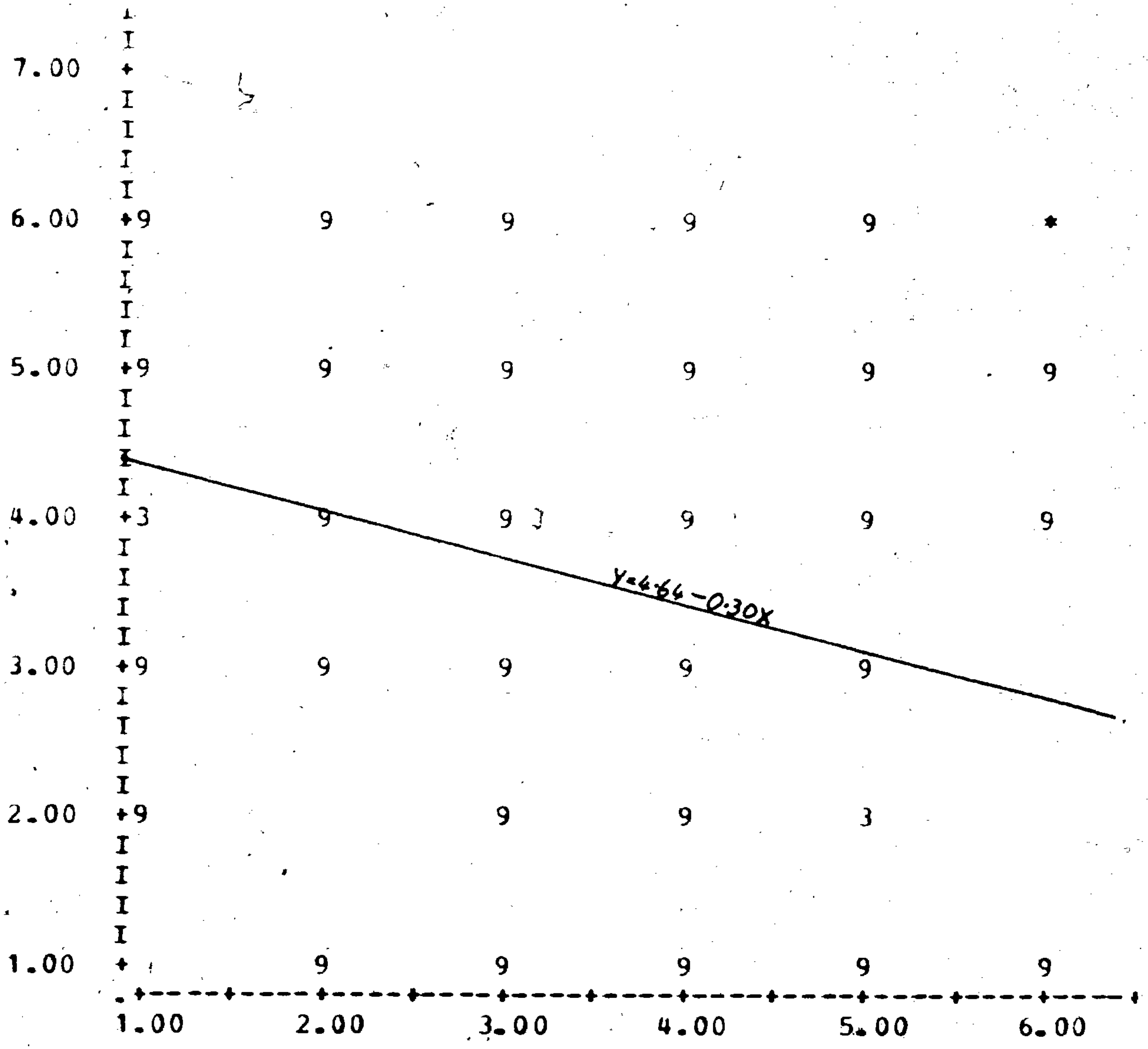


Fig. 10: Aspect vs. Vegetation in the Dempster Corridor.

ice content and vegetation belie the assumptions outlined above and leave expectations on the intervariable level unfulfilled. On the other hand it is possible that bias in the site selection is being indicated here. The oil companies gathered data along the proposed pipeline route which had major constraints imposed upon it during planning. The Dempster Lateral route was situated along the upper dry parts of ridges and avoided low lying wet areas. Recource to the original data is required to assess if this bias exists in fact.

For the Dempster-Klondike Highways

(a) Ice Content (modified) vs Depth (Fig. 11)

With Tau = -0.303, significant at 0.001, this is the strongest relationship after the textural variables. Computing category means (14.5, 11.8, 8.2, 7.8, 8.6 and 7.1) reveals a logarithmic type curve for which the regression line proves to be a good approximation for the low and mid values of depth. From the plot it is evident that frozen ground is more predominant at shallow depths, i.e. the active layer is most often shallow, with the ice content greater at or near the top of the permafrost.

(b) Landform Genesis vs Vegetation (Fig. 12)

The correlation is weak and not significant. Because of the empty areas in the plot, one is tempted to speculate that there are relationships here. Only black spruce with moss and hummocks

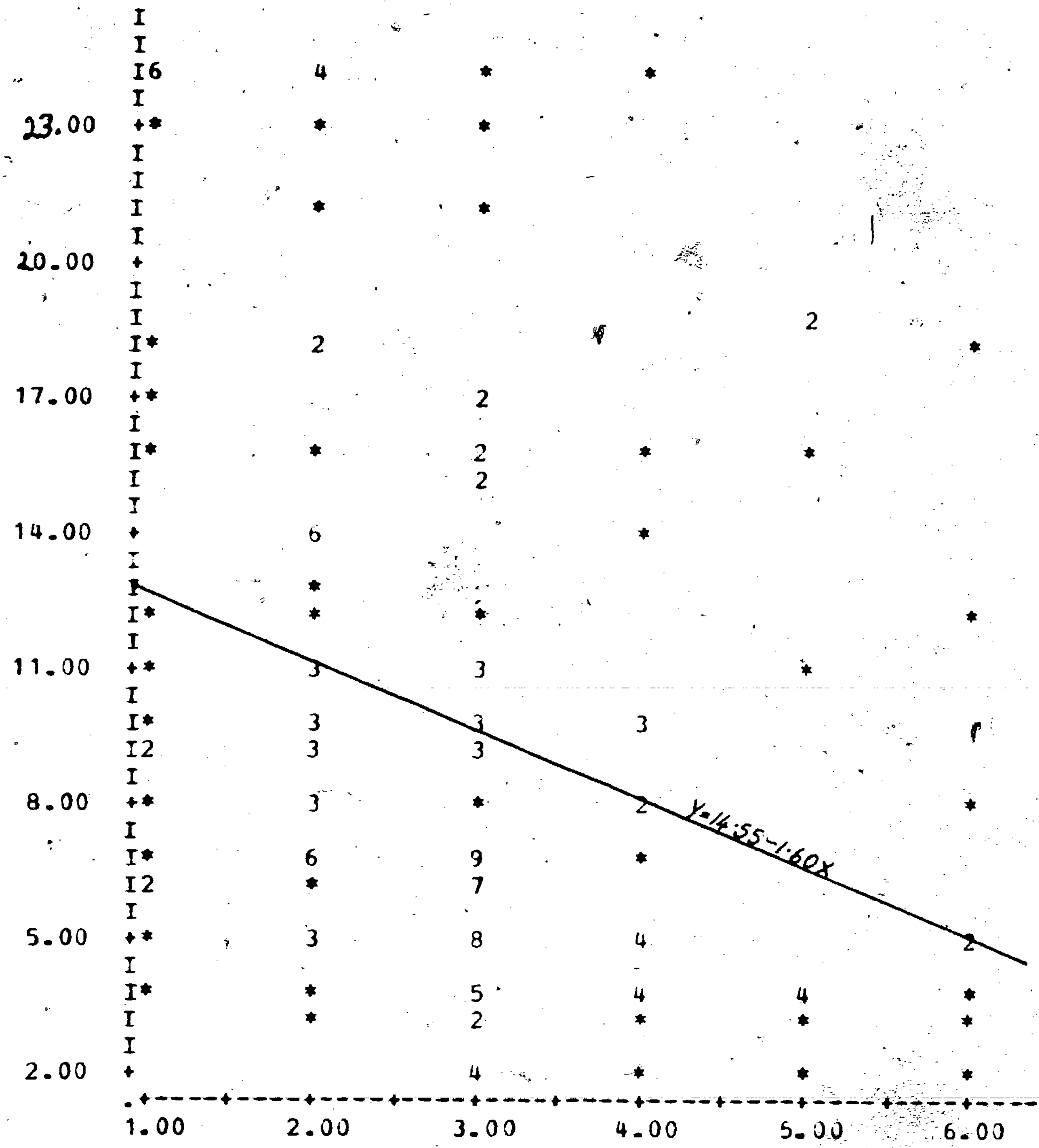


Fig. 10: Ice Content (modified) vs. Depth in the Dempster-Klondike Highway.

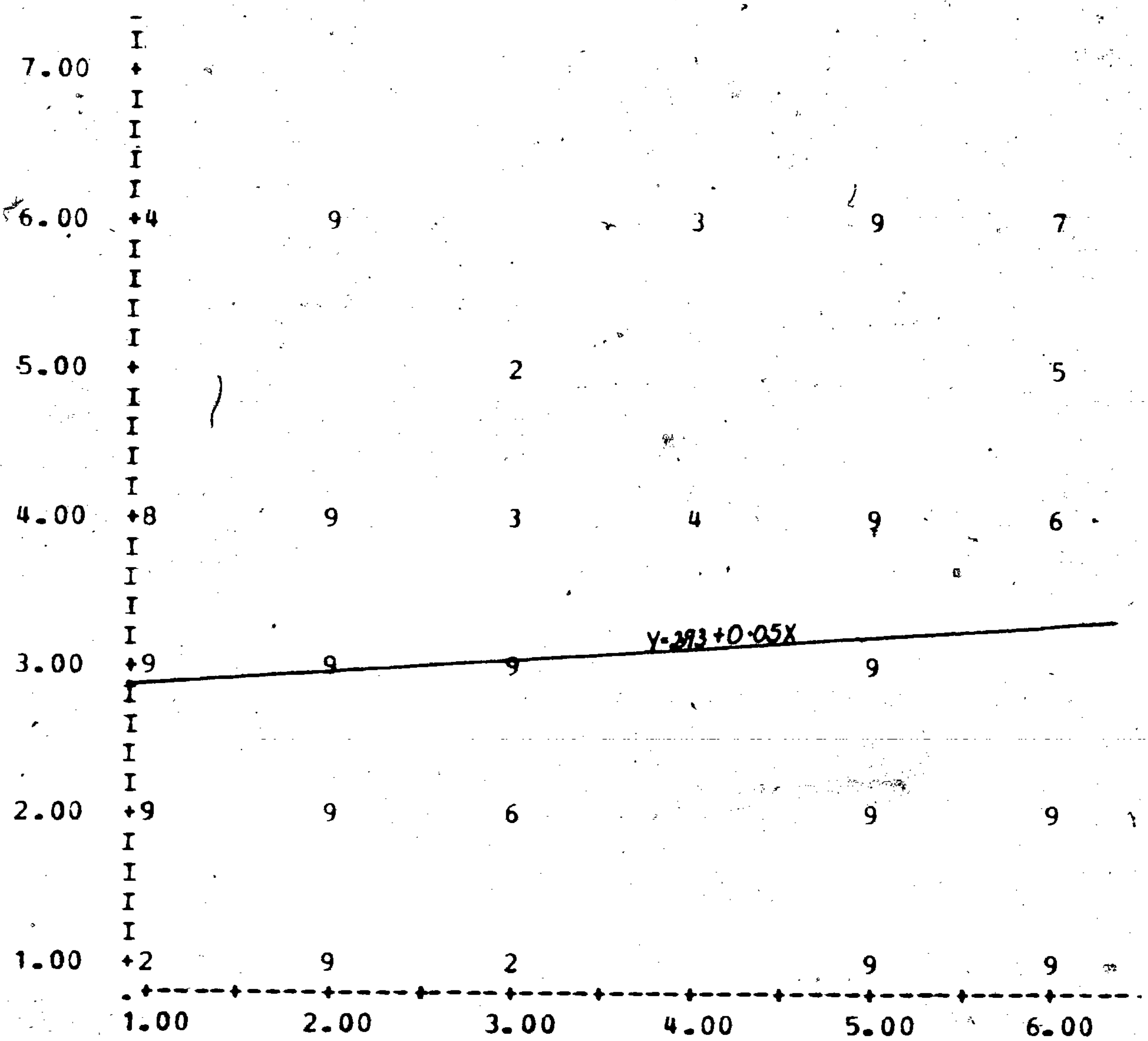


Fig. 12: Landform Genesis vs. Vegetation in the Dempster-Klondike Highway.

or tussocks are to be found on lineated slopes; lichen and moss covers are limited to morainal and till landforms. Such mutually exclusive, non-graduated relationships are not well represented in these statistical formats.

In general scattergrams provide a useful display of the data at the initial stages, clustered and dispersed data are discernible and a visual estimate of the linearity or non-linearity is sometimes possible. In the cases presented here it can be seen that texture, latitude, vegetation and landform genesis each have a particular relation to ice content and they are by no means simple linear curves. Though the trends are not defined specifically in terms of the best fitting curve there are indications of the type of trends existing between the independent variables. Relations are sometimes surprising; where a positive relation would be expected between aspect and vegetation this proved not to be the case. But for this, at least, the constraints on data gathering are suspect.

Inter-Variate Correlations

Descriptive statistics, correlation coefficients, two-tailed tests of significance and standard errors of the estimate were assembled in tabular form (Tables 12, 13, 14) for each of the data sets.

	lat	elev	aspect	slope	lndfm	depth	text	texta	textb	veg
CDICE	0.19 2.61 0.00	-0.05 2.66 0.01	0.07 2.65 0.00	-0.03 2.66 0.10	0.01 2.64 0.71	-0.19 2.60 0.00	-0.37 2.33 0.00	-0.37 2.39 0.00	-0.32 2.48 0.00	-0.08 2.65 0.00
lat		-0.38 1.55 0.00	-0.19 1.59 0.00	0.04 1.65 0.04	0.19 1.62 0.00	-0.06 1.65 0.00	-0.06 1.65 0.00	-0.06 1.65 0.00	-0.05 1.65 0.50	-0.10 1.65 0.00
elev			0.05 1.19 0.00	-0.16 1.17 0.00	0.05 1.19 0.01	-0.03 1.19 0.06	-0.19 1.66 0.00	-0.17 1.17 0.00	-0.19 1.16 0.00	-0.11 1.18 0.00
aspect				-0.01 1.46 0.54	0.04 1.46 0.01	0.02 1.46 0.31	-0.06 1.45 0.00	-0.05 1.45 0.01	-0.05 1.45 0.01	-0.02 1.46 0.14
slope					-0.03 1.06 0.08	0.02 1.06 0.20	0.06 1.06 0.00	0.05 1.06 0.01	0.05 1.06 0.01	0.26 1.06 0.00
lndfm						-0.04 1.67 0.03	-0.02 1.68 0.15	-0.04 1.67 0.03	0.01 1.68 0.47	-0.05 1.68 0.00
depth							0.12 1.30 0.00	0.25 1.25 0.00	0.07 1.31 0.00	0.07 1.31 0.00
text								0.70 0.86 0.00	0.80 0.78 0.00	0.16 1.19 0.00
texta									0.60 1.08 0.00	0.14 1.36 0.00
textb										0.15 1.14 0.00
CDICE (1)	0.15 2.47	-0.02 2.49	0.05 2.49	-0.09 2.49	0.01 2.47	-0.26 2.41	-0.41 2.41	-0.42 1.21	-0.33 2.33	-0.11 2.49

Tau
Std Err
Sig (2)

1.0f

2of2

slope					-0.03	0.02	0.06	0.05	0.05	0.26
					1.06	1.06	1.06	1.06	1.06	1.06
					0.08	0.20	0.00	0.01	0.01	0.00
lndfm						-0.04	-0.02	-0.04	0.01	-0.05
						1.67	1.68	1.67	1.68	1.68
						0.03	0.15	0.03	0.47	0.00
depth				Tau			0.12	0.25	0.07	0.07
				Std Err			1.30	1.25	1.31	1.31
				Sig (2)			0.00	0.00	0.00	0.00
text								0.70	0.80	0.16
								0.86	0.78	1.19
								0.00	0.00	0.00
texta									0.60	0.14
									1.08	1.36
									0.00	0.00
textb										0.15
										1.14
										0.00
CDICE	0.15	-0.02	0.05	-0.09	0.01	-0.26	-0.41	-0.42	-0.33	-0.11
(1)	2.47	2.49	2.49	2.49	2.47	2.41	2.41	1.21	2.33	2.49
	0.00	0.23	0.01	0.00	0.53	0.00	0.00	0.00	0.00	0.00

Table 12: Correlation coefficents, standard errors of the estimate and two-tailed significance test results for data from the Mackenzie River Valley.

	lat	elev	aspect	slope	lndfm	depth	text	texta	textb	veg
CDICE	0.13 3.66 0.49	-0.01 3.68 0.80	-0.00 3.65 0.29	-0.02 3.54 0.13	0.03 3.54 0.00	-0.21 3.54 0.00	-0.49 2.94 0.00	-0.44 3.14 0.00	-0.45 3.04 0.00	-0.13 3.65 0.00
lat		-0.22 1.40 0.00	-0.04 1.48 0.03	-0.09 1.47 0.00	-0.06 1.48 0.00	0.15 1.46 0.00	0.05 1.48 0.00	0.04 1.48 0.06	0.02 1.48 0.43	-0.03 1.47 0.12
elev			0.12 1.63 0.00	0.07 1.64 0.00	-0.18 1.61 0.00	-0.03 1.65 0.13	-0.03 1.65 0.08	-0.03 1.65 0.13	-0.01 1.65 0.56	-0.06 1.64 0.00
aspect				0.00 1.68 0.83	-0.13 1.65 0.00	-0.12 1.67 0.00	0.04 1.68 0.02	-0.00 1.68 0.98	0.06 1.68 0.00	-0.17 1.64 0.00
slope					0.22 0.81 0.00	-0.10 0.82 0.00	0.12 0.81 0.00	0.06 0.82 0.00	0.12 0.81 0.00	0.14 0.81 0.00
lndfm						-0.09 1.67 0.00	0.06 1.68 0.00	0.04 1.69 0.06	0.07 1.68 0.00	0.05 1.68 0.02
depth				Tau Std Err Sig (2)			0.28 1.51 0.00	0.40 1.42 0.00	0.22 1.54 0.00	0.07 1.59 0.00
text								0.68 0.99 0.00	0.80 0.83 0.00	0.11 1.49 0.00
texta									0.59 1.23 0.00	0.11 1.63 0.00
textb										0.10 1.50 0.00
CDICE	-0.08	0.11	0.01	-0.00	-0.02	-0.40	-0.61	-0.57	-0.54	-0.08

10f

slope					0.81	0.82	0.81	0.82	0.81	0.81
					0.00	0.00	0.00	0.00	0.00	0.00
lndf						-0.09	0.06	0.04	0.07	0.05
						1.67	1.68	1.69	1.68	1.68
						0.00	0.00	0.06	0.00	0.02
depth				Tau			0.28	0.40	0.22	0.07
				Std Err			1.51	1.42	1.54	1.59
				Sig (2)			0.00	0.00	0.00	0.00
text								0.68	0.80	0.11
								0.99	0.83	1.49
								0.00	0.00	0.00
texta									0.59	0.11
									1.23	1.63
									0.00	0.00
textb										0.10
										1.50
										0.00
CDICE	-0.08	0.11	0.01	-0.00	-0.02	-0.40	-0.61	-0.57	-0.54	-0.08
(1)	3.38	3.37	3.41	3.41	3.39	3.12	2.52	2.73	2.73	3.40
	0.00	0.00	0.76	0.94	0.26	0.00	0.00	0.00	0.00	0.00

Table 13: Correlation coefficents, standard errors of the estimate and two-tailed significance test results for data from the Dempster Corridor.

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	lat	elev	aspect	slope	lndfm	depth	text	texta	textb	veg
CDICE	0.09 5.67 0.02	-0.04 5.72 0.34	0.09 5.73 0.03	0.05 5.71 0.24	-0.14 5.70 0.00	0.18 5.73 0.00	-0.03 5.64 0.51	-0.03 5.68 0.52	-0.20 5.46 0.00	-0.12 5.66 0.00
lat		-0.25 1.71 0.00	-0.16 1.80 0.00	-0.01 1.83 0.82	0.09 1.80 0.02	-0.15 1.80 0.00	-0.14 1.79 0.00	-0.14 1.80 0.00	-0.18 1.77 0.00	0.14 1.81 0.00
elev			0.10 1.57 0.01	0.21 1.53 0.00	0.03 1.58 0.48	0.07 1.58 0.07	0.06 1.58 0.10	0.08 1.58 0.05	0.07 1.57 0.06	0.20 1.53 0.00
aspect				0.24 1.44 0.00	-0.10 1.50 0.01	0.00 1.51 0.97	0.01 1.51 0.81	0.00 1.51 0.99	0.00 1.51 0.93	0.00 1.51 0.95
slope					0.10 1.43 0.01	-0.02 1.44 0.56	-0.02 1.44 0.70	0.03 1.44 0.46	0.03 1.44 0.38	0.06 1.44 0.15
lndfm						-0.04 1.38 0.29	0.11 1.38 0.00	0.11 1.38 0.01	0.20 1.38 0.00	0.02 1.38 0.60
depth							0.47 1.36 0.00	0.41 1.39 0.00	0.31 1.45 0.00	-0.08 1.59 0.05
text								0.48 1.36 0.00	0.50 1.27 0.00	-0.11 1.62 0.01
texta									0.42 1.03 0.00	-0.08 1.18 0.06
textb										-0.17 1.60 0.00
CDICE	0.08	0.03	-0.03	0.08	-0.15	-0.30	-0.52	-0.31	-0.38	0.15

Tau
Std Err
Sig (2)

1of

2of2

slope					0.10 1.43 0.01	-0.02 1.44 0.56	-0.02 1.44 0.70	0.03 1.44 0.46	0.03 1.44 0.38	0.06 1.44 0.15
lndfm						-0.04 1.38 0.29	0.11 1.38 0.00	0.11 1.38 0.01	0.20 1.38 0.00	0.02 1.38 0.60
depth				Tau Std Err Sig (2)			0.47 1.36 0.00	0.41 1.39 0.00	0.31 1.45 0.00	-0.08 1.59 0.05
text								0.48 1.36 0.00	0.50 1.27 0.00	-0.11 1.62 0.01
texta									0.42 1.03 0.00	-0.08 1.18 0.06
textb										-0.17 1.60 0.00
CDICE (1)	0.08 6.32 0.22	0.03 6.39 0.64	-0.03 6.38 0.96	0.08 6.33 0.18	-0.15 6.38 0.02	-0.30 6.04 0.00	-0.52 5.28 0.00	-0.31 6.02 0.00	-0.38 5.73 0.00	0.15 6.28 0.01

Table 14: Correlation coefficents, standard errors of the estimate and two-tailed significance test results for data from the Dempster-Klondike Highway.

To study these coefficients more closely Kendall's Tau is reported where the absolute value of Tau is greater than or equal to 0.19 and the significance is better than 0.1% (Tables 15, 16, 17). Across the three data sets the major common relations are depth versus texture above, texture of the sample versus texture above, texture of the sample versus texture below and texture above versus texture below. Thus there appears to be strong interrelationships between the textural variables and depth in the profile. Where soils are shallow the profile is generally consistent; organically charged materials over bedrock. Where soils are deep, as in valley bottoms the profiles are characterized by organic materials grading to silts and fine sands below. Because the profiles are predictible in this way, depth should show correlation with textures.

Latitude and elevation are inversely related for all data too. The relation is particularly strong for the Mackenzie Valley as expected, however, the same explanation (valley trend) may not be advanced for the Yukon because the transits cross varying terrains with differing valley orientations. On the other hand the correlations represent only about 6% explanation of the variance which might well be accounted for by simply moving northward to the coast.

Investigations of intervariable independence by studying significant but null relations, i.e. absolute Tau less than 0.10

RELATION		R	RELATION		R
CDICE	lat	0.19	CDICE(1)	depth	-0.26
CDICE	depth	-0.19	CDICE(1)	text	-0.41
CDICE	text	-0.37	CDICE(1)	texta	-0.42
CDICE	texta	-0.37	CDICE(1)	textb	-0.33
CDICE	textb	-0.37			
lat	elev	-0.38	lat	elev	-0.37
lat	aspect	-0.19	lat	aspect	-0.21
lat	lndfm	0.19	lat	lndfm	0.19
elev	text	-0.19	elev	slope	-0.19
elev	textb	-0.19	elev	text	-0.21
slope	veg	0.26	elev	texta	-0.19
depth	texta	0.25	elev	textb	-0.21
text	texta	0.72	slope	veg	0.29
text	textb	0.80	depth	texta	0.27
texta	textb	0.60	text	texta	0.69
			text	textb	0.78
			texta	textb	0.58

Table 15: Kendall Tau, where R is greater than the absolute value of 0.20 and a significance of better than 0.1%, for the Mackenzie River Valley.

RELATION		R	RELATION		R
CDICE	depth	-0.21	CDICE(1)	depth	-0.40
CDICE	text	-0.49	CDICE(1)	text	-0.61
CDICE	texta	-0.44	CDICE(1)	texta	-0.57
CDICE	textb	-0.45	CDICE(1)	textb	-0.54
lat	elev	-0.22	lat	elev	-0.35
slope	lndfm	0.22	depth	text	0.31
depth	text	0.28	depth	texta	0.43
depth	texta	0.40	depth	textb	0.28
depth	textb	0.22	text	texta	0.66
text	texta	0.68	text	textb	0.81
text	textb	0.80	texta	textb	0.61
texta	textb	0.59			

Table 16: Kendall Tau, where R is greater than the absolute value of 0.20 and a significance of better than 0.1%, for the Dempster Corridor.

RELATION		R
CDICE	textb	-0.20
lat	elev	-0.25
elev	slope	0.21
elev	veg	0.20
aspect	slope	0.24
lndfm	textb	0.20
depth	text	0.47
depth	texta	0.41
depth	textb	0.31
text	texta	0.48
text	textb	0.50
texta	textb	0.42

RELATION		R
CDICE(1)	depth	-0.30
CDICE(1)	text	-0.52
CDICE(1)	texta	-0.31
CDICE(1)	textb	-0.38
lat	elev	-0.37
lat	aspect	-0.22
lat	depth	-0.23
elev	slope	0.19
aspect	slope	0.31
lndfm	textb	0.20
depth	text	0.28
depth	texta	0.35
depth	textb	0.34
depth	veg	-0.24
text	texta	0.45
text	textb	0.59
text	veg	-0.22
texta	textb	0.43
texta	veg	-0.25
textb	veg	-0.22

Table 17: Kendall Tau, where R is greater than the absolute value of 0.20 and a significance of better than 0.1%, for the Dempster-Klondike Highways.

RELATION		R	RELATION		R
CDICE	elev	-0.05	CDICE(1)	slope	-0.09
CDICE	veg	-0.08			
lat	depth	-0.06	lat	depth	-0.05
lat	text	-0.06	lat	text	-0.05
lat	texta	-0.06	lat	texta	-0.05
lat	textb	-0.05	lat	textb	-0.05
lat	veg	-0.10	lat	veg	-0.08
elev	aspect	0.05	elev	lndfm	0.05
elev	lndfm	0.05	slope	texta	0.08
aspect	lndfm	0.04	slope	textb	0.09
aspect	text	-0.06	lndfm	texta	-0.05
aspect	texta	-0.05	depth	textb	0.08
aspect	textb	-0.05	depth	veg	0.07
slope	text	0.06			
slope	texta	0.05			
slope	textb	0.05			
lndfm	veg	-0.05			
depth	textb	0.07			
depth	veg	0.07			

Table 18: Kendall Tau where R is less than the absolute value of 0.10 and a significance of 1%, for the Mackenzie Valley.

RELATION		R	RELATION		R
			CDICE(1)	lat	-0.08
			CDICE(1)	veg	-0.08
lat	slope	-0.09	lat	depth	0.09
lat	lndfm	-0.06	lat	texta	0.10
lat	text	0.05	elev	slope	0.10
elev	slope	0.07	elev	depth	-0.07
elev	veg	-0.06	elev	text	-0.07
aspect	textb	0.06	elev	texta	-0.07
slope	texta	0.06	aspect	depth	-0.10
lndfm	depth	-0.09	aspect	text	0.07
lndfm	text	0.06	aspect	textb	0.07
lndfm	textb	0.07	slope	text	0.09
depth	veg	0.07	slope	textb	0.09
textb	veg	0.10	lndfm	depth	-0.07
			lndfm	textb	0.07
			lndfm	veg	0.07
			depth	veg	0.07

Table 19: Kendall Tau, where R is less that the absolute value of 0.10 and a significance of 1%, for the Dempster Corridor.

RELATION		R	RELATION		R
			elev	aspect	0.10
			aspect	lndfm	0.10
			lndfm	slope	0.10

Table 20: Kendall Tau, where R is less than the absolute value of 0.10 and a significance of 1%, for the Dempster-Klondike Highways.

and significance better than 1%, proved fruitless as there was no common thread to the relations amongst all data sets (Tables 18, 19, 20). However within the separate data sets some points are of note. For the Mackenzie, depth and the textural variables are independent of latitude, aspect and slope. Vegetation is independent of latitude, landform genesis and depth. Along the Dempster Corridor indications of independence are less clear. Vegetation is independent of elevation, depth and texture below. That vegetation is independent of so many variables in the differing situations is surprising as some relation to latitude and elevation is to be expected. The lack of relation to depth is a function of the latter's mode of measurement because obviously for a series of samples through one site profile the depth will change but not the vegetation at the surface. This is true for depth and all the surface features.

Under the constraints of a modified data set the situations for latitude and depth remain the same for the Mackenzie, however, for aspect the relations become non-significant. For the Dempster Corridor the landscape variables of elevation, aspect, slope and landform genesis show increased independence of the textural and depth variables.

For the Mackenzie and Dempster Corridor, ice content is significantly inversely related to depth and all three textural variables (Tables 15, 16, 17). The interesting part is the case for the third data set. Here, ice content is related only to texture of the layer below. The relation to depth is just beyond the limits set for Tau, but is minor and non-significant for texture and texture above. However, when ice content is modified by assigning unfrozen cases as missing, then all four variables become significant and are strongly inversely related. The results now complement each other for all three data sets. Latitude is the only other variable with a relation to ice content of consequence and then only in the Mackenzie Valley but note that it becomes lost when ice content is modified. This indicates a non-linear change in ice with movement northwards.

Finding significant null or independent relations to ice content proved difficult (Tables 18, 19, 20). Only elevation and vegetation appeared for the Mackenzie and none appeared for either of the other data sets. For the modified ice content, slope was indicated in the Mackenzie, latitude and vegetation for the Dempster Corridor and once again Dempster-Klondike had none reported.

Multiple Regressions

Multiple regression statistics were obtained using the subroutine Regression, from the programs in SPSS8. The ten variables were regressed upon ice content. Explanation potential for the distribution of ice content varied from 44% for the Dempster Corridor, through 29% for the Mackenzie Valley, to 12% for the Dempster-Klondike Highway (Tables 21, 22, 23).

VARIABLE	MULT R	R2	CH R2	PEARSON	B	F Sig
text	0.482	0.232	0.232	-0.482	-0.767	0.001
lat	0.501	0.251	0.019	0.189	0.258	0.001
texta	0.518	0.268	0.017	-0.439	-0.283	0.001
depth	0.526	0.277	0.009	-0.207	-0.215	0.001
aspect	0.532	0.283	0.006	0.067	0.156	0.001
veg	0.536	0.287	0.004	-0.049	0.121	0.001
					6.747	
	F=155.524		F Sig=0.001			

Table 21: Summary table, multiple regression of the Mackenzie Valley data.

VARIABLE	MULT R	R2	CH R2	PEARSON	B	F Sig
text	0.602	0.363	0.363	-0.602	-0.902	0.001
lndfm	0.625	0.390	0.028	0.126	0.441	0.001
lat	0.643	0.413	0.023	0.103	0.430	0.001
textb	0.658	0.424	0.011	-0.563	-0.426	0.001
texta	0.663	0.432	0.008	-0.522	-0.313	0.001
elev	0.664	0.439	0.007	0.022	0.199	0.001
					7.694	
	F=220.828		F Sig=0.001			

Table 22: Summary table, multiple regression of the Dempster Corridor data.

VARIABLE	MULT R	R2	CH R2	PEARSON	B	F Sig
textb	0.301	0.090	0.090	-0.301	-1.328	0.001
depth	0.346	0.120	0.029	0.028	0.679	0.001
veg	0.363	0.130	0.012	0.157		0.050
slope	0.376	0.141	0.009	-0.083		
elev	0.384	0.147	0.006	-0.043		
					7.191	
	F=21.797		F Sig=0.001			

Table 23: Summary table, multiple regression of the Dempster-Klondike Highways data.

A stepwise regression procedure was employed. The inclusion criteria were, F score better than 0.01 and tolerance of at least 0.001 (Nie, 1975). These were purposefully kept non-restrictive so as to permit as many variables to enter the equation as possible for, as indicated earlier, the purpose of the regression procedure was to gain insight into the dynamics between ice content of the permafrost and the environment and not in obtaining an optimum predictive equation. Once computations are completed a return to a strict F test of 0.001 is made in reporting the results. The rationale for this action is to allow freedom in analysis while keeping control over type 1 and type 2 errors within the results. It is an attempt to balance the incentive for identifying secondary influences against the possibility of acquiring insignificant and spurious relationships.

An explanation potential of around 29% in six variables was found for the Mackenzie, beyond this partial F was not significant at 0.001 for new variables. Texture dominates the equation but latitude proves important too. For the Dempster Corridor the explanation potential is much higher, at about 44%. This is again in six variables with texture predominant but with landform genesis second. Dempster-Klondike has the least explanation potential of 12% but in only two significant variables; texture below and depth.

Comparing the Pearson R with the Kendall Tau (Tables 12, 13, 14) correlations for the variables in the regression it can be seen that there are differences in the absolute values as indicated earlier: the Pearson coefficients being the larger. Notice that the high correlation scores do not guarantee inclusion in the regression. Once texture is included the possibility of substantially adding to the explanation potential is slight for the variables texture above and texture below. So the secondary influences on ice content are begining to be identified here. This is a major change from the study of correlations aone. However, from the change in R^2, the results show that the addition of these secondary influences into the stepwise regression over and above the initial inclusion of the textural variable accomplishes little in explaining the variance associated with ice content. Therefore though the secondary influences might be begining to be identified they are not given much weight and there is no consideration of cumulative influences in the environment. Textural and to some extent locational variables are being presented as all-important for predicting ice content of permafrost with biological and geomorphological variables of lesser importance.

Ice content was modified by excluding unfrozen sites and the multiple stepwise regression was again calculated. The changes were quite dramatic (Tables 24, 25, 26). The explanation of the variance increased in every case; dramatically so for the Dempster Corridor. Obviously the unfrozen sites in this data set are obscuring the dynamics between permafrost and its environment. In all data sets texture and depth proved to be the

VARIABLE	MULT R	R2	CH R2	PEARSON	B	F Sig
text	0.513	0.263	0.263	-0.513	-0.845	0.001
depth	0.542	0.294	0.031	-0.262	-0.271	0.001
elev	0.555	0.307	0.013	0.013	-0.264	0.001
texta	0.567	0.320	0.013	-0.467	-0.296	0.001
lndfm	0.573	0.328	0.008	0.127	0.136	0.001
					10.008	
	F=198.174		F Sig=0.001			

Table 24: Summary table, multiple regression of the modified Mackenzie Valley data.

VARIABLE	MULT R	R2	CH R2	PEARSON	B	F Sig
text	0.672	0.452	0.452	-0.672	-1.131	0.001
depth	0.692	0.479	0.027	-0.403	-0.256	0.001
lndfm	0.703	0.494	0.015	0.101	0.295	0.001
elev	0.711	0.506	0.011	0.152	0.222	0.001
texta	0.718	0.516	0.011	-0.600	-0.342	0.001
					10.230	
	F=290.705		F Sig=0.001			

Table 25: Summary table, multiple regression of the modified Dempster Corridor data.

VARIABLE	MULT R	R2	CH R2	PEARSON	B	F Sig
text	0.562	0.316	0.316	-0.562	-2.809	0.001
depth	0.583	0.339	0.024	-0.323		0.010
textb	0.588	0.345	0.006	-0.441		
					17.149	
	F=70.151		F Sig=0.001			

Table 26: Summary table, multiple regression of the modified Dempster-Klondike Highways data.

primary influences (though depth was not significant at the 0.001 level in partial F for the Dempster-Klondike it is still reported). Note too that the significant variables comprising the equations for the Mackenzie and Dempster Corridor are the same albeit in a different order. Elevation, landform genesis and texture above are proposed as the secondary influences and a general model is appearing.

Creation of Dummy Variables

Regression assumes that the effects of the independent variables are additive, that is, the relationship between dependent and independent variables is the same across all values of the remaining independent variables. This has consequence for the level of measurement of the variables and the linearity of the relationships. While the latter is considered beyond the scope of this study the former can be relieved quite quickly by the development of dummy variables. As stated earlier dummy variables may have arbitrary metric values of 0 and 1 and can therefore be treated as interval level variables and inserted in a regression equation remembering that it is necessary to exclude one of the dummies for each variable by creating a reference category.

For all 10 independent variables, dummies were created, i.e. for latitude: lat 1, lat 2, lat 3, lat 4 and lat 5 were created. Each dummy was given the value 1 where it appeared.

Thus if a site had latitude of 3 then the dummies for that site all score 0 except lat 3 which scores 1.

Dummy Variable Interactions

Means are computed in the process of finding correlations but these means represent the proportion of cases recording the presence of that particular dummy variable. So lat1 has a mean of 0.2416, or 24.16% of the 2322 cases in the the Mackenzie Valley data set, i.e. there are 561 sites between 60°-62°N. This information on frequencies was found useful in judging the relative importance of relationships in the correlation matrices and are reported here (Tables 27, 31).

Pearson correlation coefficents were computed for each dummy variable with every other dummy variable prior to the regression. Where two dummies originate from the same variable their coefficents are negative. This is but a measure of their mutual exclusion and therefore has little interest here. Below are reported the correlation coefficents greater than an absolute value of 0.30 for all data (Tables. 28, 29 and 30) and the number of records to each cell is also reported as a source of evaluation. There are no significance tests computed by SPSS for the Pearson correlation coefficents in this case. However knowing R and N, an F test is available by using

$$F_{1,N-2} = \frac{R^2}{1-R^2}(N-2)$$

Dummy Variable	MACKENZIE VALLEY		DEMPSTER CORRIDOR		DEMPSTER-KLONDIKE	
	Cases	Mean	Cases	Mean	Cases	Mean
lat1	561	0.2416	277	0.1629	132	0.3041
2	566	0.2438	265	0.1559	95	0.2189
3	407	0.1753	260	0.1529	49	0.1129
4	143	0.0616	601	0.3535	42	0.0968
5	477	0.2054	154	0.0906	51	0.1175
lat6	168	0.0724	143	0.0841	65	0.1489
elev1	65	0.0280	160	0.0941	54	0.1244
2	755	0.3252	96	0.0565	60	0.1382
3	815	0.3510	229	0.1347	70	0.1613
4	371	0.1598	456	0.2682	124	0.2857
5	182	0.0784	113	0.0665	55	0.1267
elev6	134	0.0577	645	0.3794	71	0.1636
aspect1	173	0.0745	362	0.2129	36	0.0829
2	98	0.0422	100	0.0588	100	0.2304
3	40	0.0172	247	0.1453	113	0.2604
4	467	0.2011	367	0.2159	57	0.1313
5	698	0.3006	435	0.2559	76	0.1751
aspect6	846	0.3643	189	0.1112	52	0.1198
slope1	1221	0.5258	674	0.3965	54	0.1244
2	720	0.3105	792	0.4659	102	0.2350
3	252	0.1085	162	0.0953	103	0.2373
4	60	0.0258	52	0.0306	84	0.1935
5	9	0.0039	20	0.0118	62	0.1429
slope6	59	0.0254	0	0.0	29	0.0668
lndfm1	822	0.3540	673	0.3959	43	0.0991
2	209	0.0900	135	0.0794	125	0.2880
3	392	0.1688	332	0.1953	104	0.2396
4	355	0.1525	242	0.1424	111	0.2558
5	439	0.1891	192	0.1135	7	0.0161
lndfm6	106	0.0457	125	0.0735	44	0.1014
text1	119	0.0512	121	0.0712	165	0.3802
2	66	0.0284	316	0.1859	76	0.1751
3	1083	0.4664	313	0.1841	77	0.1774
4	475	0.2046	466	0.2741	43	0.0991
5	361	0.1555	196	0.1153	41	0.0945
text6	218	0.0939	288	0.1694	32	0.0737

Table 27: Cases and means for Dummy Variables.

Dummy Variable	MACKENZIE VALLEY		DEMPSTER CORRIDOR		DEMPSTER-KLONDIKE	
	Cases	Mean	Cases	Mean	Cases	Mean
texta1	307	0.1322	320	0.1882	301	0.6935
2	62	0.0267	305	0.1794	41	0.0945
3	975	0.4199	283	0.1665	50	0.1152
4	444	0.1912	391	0.2300	20	0.0461
5	339	0.1460	166	0.0976	19	0.0438
texta6	195	0.0840	235	0.1382	3	0.0069
textb1	61	0.0263	91	0.0535	43	0.0991
2	55	0.0237	289	0.1700	94	0.2166
3	1119	0.4819	315	0.1853	106	0.2442
4	479	0.2063	436	0.2565	47	0.1083
5	363	0.1563	220	0.1294	63	0.1452
textb6	445	0.1055	348	0.2047	81	0.1866
veg1	195	0.0840	157	0.0924	42	0.0968
2	299	0.1288	127	0.0747	135	0.3111
3	404	0.1740	492	0.2894	39	0.0899
4	668	0.2877	659	0.3876	7	0.0161
5	462	0.1990	176	0.1035	154	0.3548
veg6	294	0.1266	85	0.0500	57	0.1313

Table 27(cont.): Cases and means for Dummy Variables.

RELATION		R	CELL
CDICE	text1	0.59	119
CDICE	texta1	0.47	307
CDICE	textb1	0.45	61
lat1	elev2	-0.38	5
lat1	elev4	0.37	224
lat1	elev5	0.31	127
lat1	veg1	0.33	137
lat2	veg6	0.32	177
lat4	lndfm3	0.42	111
lat6	elev1	0.54	58
slope1	lndfm4	-0.30	60
slope2	lndfm4	0.39	261
slope6	lndfm3	0.32	54
slope6	veg5	0.32	59
lndfm1	veg4	-0.34	68
lndfm2	text6	0.32	82
lndfm2	texta6	0.33	79
lndfm4	veg4	0.48	282
lndfm5	veg3	0.34	192
lndfm6	text6	0.36	61
lndfm6	textb6	0.40	70
depth1	text1	0.31	101
depth1	texta1	0.51	255
text1	texta1	0.55	111
text1	textb1	0.49	43
text2	texta2	0.63	41
text2	textb2	0.71	43
text3	texta3	0.78	902
text3	texta4	-0.34	53
text3	texta5	-0.33	22
text3	textb3	0.84	1011
text3	textb4	-0.40	35
text3	textb5	-0.37	11
text4	texta3	-0.37	32
text4	texta4	0.75	367
text4	textb3	-0.40	43
text4	textb4	0.80	400
text5	texta3	-0.32	17
text5	texta5	0.77	281
text5	textb3	-0.38	13
text5	textb5	0.85	315
text6	texta6	0.78	165
text6	textb6	0.84	197
texta1	textb1	0.33	49
texta2	textb2	0.52	31
texta3	textb3	0.70	872
texta3	textb4	-0.34	44
texta3	textb5	-0.31	23
texta4	textb3	-0.31	72
texta4	textb4	0.63	325
texta5	textb3	-0.33	27
texta5	textb5	0.68	256
texta6	textb6	0.69	157

Table 28: List of the correlation coefficents for dummy variables in the Mackenzie Valley data set.

RELATION		R	CELL
CDICE	lndfm5	0.39	192
CDICE	text1	0.56	121
CDICE	text2	0.32	316
CDICE	texta2	0.42	320
CDICE	textb1	0.51	91
CDICE	textb2	0.33	289
lat1	elev3	0.65	176
lat1	veg2	0.41	89
lat3	elev6	0.45	232
lat3	veg1	0.36	87
lat4	elev4	0.51	344
lat4	depth6	0.38	162
lat4	veg4	0.32	361
lat5	elev1	0.66	108
lat6	elev2	0.72	87
elev4	slope3	0.31	112
elev4	lndfm4	0.31	148
elev4	text6	0.31	164
elev4	texta6	0.31	143
elev6	aspect5	0.31	275
aspect3	depth6	0.47	115
aspect5	slope2	0.31	319
aspect5	veg1	0.34	113
lndfm4	veg4	0.46	227
lndfm5	text1	0.38	66
lndfm5	textb1	0.38	56
depth1	texta1	0.44	219
text1	texta1	0.50	109
text1	textb1	0.70	75
text2	texta2	0.69	233
text2	textb2	0.86	268
text3	texta3	0.69	221
text3	textb3	0.79	261
text4	texta4	0.66	319
text4	textb4	0.79	381
text5	texta5	0.67	127
text5	textb5	0.71	151
text6	texta6	0.81	219
text6	textb6	0.84	275
texta1	textb1	0.43	82
texta2	textb2	0.64	208
texta3	textb3	0.61	203
texta4	textb4	0.59	286
texta5	textb5	0.59	121
texta6	textb6	0.72	218

Table 29: List of the correlation coefficents for dummy variables in the Dempster Corridor data set.

RELATION		R	CELL	RELATION		R	CELL
lat1	elev4	0.37	71	depth1	texta1	0.34	141
lat1	lndfm3	0.33	60	depth6	texta1	-0.32	9
lat4	veg6	0.33	20	text1	texta1	0.42	155
lat6	elev1	0.41	29	text2	textb2	0.30	37
lat6	lndfm5	0.31	7	text4	textb4	0.31	17
lat6	lndfm6	0.50	30	text6	texta5	0.41	1
elev4	lndfm3	0.35	59	text6	textb6	0.54	30
elev5	veg5	0.35	44	texta1	textb2	0.30	90
elev6	lndfm4	0.33	41	texta1	textb6	-0.37	27
lndfm3	veg3	0.31	26	texta5	textb6	0.36	16
depth1	text1	0.52	110				

Table 30: List of the correlation coefficents for dummy variables in the Dempster-Klondike Highways data set.

But for F(1,N-2) to be significant at the 0.1% level, where N is greater than 122, it must be greater than 10.83. Therefore, working the formula backwards, for the Mackenzie Valley, with N=2320, R will be significant when it is greater than an absolute value of 0.07 and for the modified version of the data set, with N=2032, R must also be greater than an absolute value of 0.07. For the Dempster Corridor the cutoff values of R are 0.08 (where N=1700) and 0.09 (where N=1369). Likewise the values of R for the Dempster-Klondike, 0.16 (where N=434) and 0.26 (where N=154) will be significant at the 0.001 level.

For the Mackenzie Valley the correlations indicate those relations that would be expected by virtue of the fieldwork. Low latitudes of 60°-62°N are associated with the higher elevations and not with the lower elevations. Which is as one would expect considering it is a valley trending from south to north. High latitudes of 67°-68°N are strongly associated with the low elevations. Glacio-fluvial landforms are common at mid-latitudes and are characterized by steep slopes, often such slopes are covered in tall shrubs and dwarfed black spruce. Morainal materials have low slopes and are generally covered by lichen and mosses. Not surprising, tills near bedrock are characterized by textures of sands and gravels but so are glacial-lacustrine landforms, which is surprising. Organics occur near the surface and among the contorted interrelationships of textural dummy variables there appears to be only one distinct statement; that the soils are texturally consistent from site to site or homogenous through the profiles.

The Dempster Corridor, in its southern most part, is categorized by mid-elevations covered by white and black spruce with birch in open canopy forests and moss covered floors. Moving northward to 63°-64°N elevations are higher and white and black spruce forests with closed canopies are to be found on gentle northeasterly slopes. Around 64°-65°N morainal landforms composed primarily of sands and gravels are found with moderate slopes at mid-elevations and are often covered by lichens and mosses. Further north again and the elevations decrease towards the Mackenzie Delta.

The Dempster-Klondike Highways study area at low latitudes is characterized by mid-elevations and glacio-fluvial landforms covered by black spruce and mosses. In the northern portion elevations are low and lineated slopes and thin tills predominate. Where glacio-fluvial landforms are found at mid-elevations, at higher elevations landforms are often morainal.

From an overall perspective coefficents greater than an absolute value of 0.30 are positive, few are negative. This indicates that one may find 'a little of everything' throughout the areas. The absence of a characteristic is less definitive than its presence.

On modifying the data bases, in the Mackenzie the situation remains much the same. Thus the conditions for the formation of permafrost are not dramatically different from those characterizing unfrozen sites.

In the Dempster Corridor analysis small changes occur such as lineated slopes being common at low latitudes or morainal landforms at high elevations being associated with mid-latitude regions. But new interrelations between mid-latitudes and mid-elevations and textures are evident. It appears that frozen soils composed of inorganic silts and clays with fine sands do not occur in these regions and that sands, gravels and bedrock are more frequent. Possibly the general tendency in this area is for ground materials to be unfrozen except where the soils are shallow.

The relationships in the Dempster-Klondike change dramatically. Because the sample size has shrunk so much, from 434 to 154, the frequency of occurrences within each cell is small. Some cells of the 6X6 matrices must, even in the best of circumstances, have an expected frequency of less than five thereby questioning the validity of the inter-dummy variable correlations. Empty cells are a fact of trends in the ecosystem analysis for there will always be mathematically defined situations that do not exist in the field. However, with large populations it is acceptable to have some cells empty because the trends are evident, but for small populations the trends are less obvious.

To summarize then, the dummy variables associated with ice content in the Mackenzie are textural, i.e. organic material at all levels in the profile. For the modified data set the associations with fine textures prove stronger and in addition depth becomes important so that the tendency is for icy permafrost to develop at shallow depths.

For the Dempster Corridor the situation is more complex. The association of permafrost with organics is broader including organic silts and clays even at depth. Lineated slopes are also indicated as being susceptable to permafrost accumulation. In the modified data base the situation is similar. New are the relations to latitude, depth and some textures. Icy permafrost is most prevalent between 63°-64°N, occurs most often at shallow depths and is rarely encountered in sands and gravels.

For the Dempster-Klondike there are no significant relationships between dummy variables and ice content. However icy permafrost is related to organic textures throughout the profile and not to inorganic silts and clays with fine sands.

Dummy Variable Regression

Note that because there are no occurences of dummy variable slope6 in the Dempster Corridor, slope5 must be excluded in the multiple regression of dummy variables to become the reference category. Both must be excluded where the modified data set is employed, as must texta5 and texta6 in the modified data set of the Dempster-Klondike.

The dummies were used as input for the stepwise multiple regression procedure. The least contributing variable was identified and its dummies extracted from the regression. The least contributor was defined as the variable whose dummies were inputed after all other variables had at least one dummy already in the equation. The process was repeated until the F statistic for the regression equation was significant at the 0.001 level.

Though the B coefficients are reported they do not represent a one to one correspondence with their companion dummy variable. The coefficients represent a complex matrix of dummy variable combinations (Nie, 1975; Blalock, 1960; Draper and Smith, 1966). Because there are so many dummy variables in the regression, breaking down the results further is beyond the scope of this work. For similar reasons the partial F statistic for the dummy variables is meaningless at this stage and so it too is not reported. The emphasis is on the final R^2 as an indicator of explanation potential.

The dummy variable multiple regressions (Tables 32, 33, 34) are similar to the earlier regression (Tables 21, 22, 23) in that the F statistic is significant where the dummies of the same variables are input. That is, for the Mackenzie data the F statistic is significant for a equation with dummies of the six variables input and is not significant when the dummies of the seventh are added (Table 32). So the same variables are identified as important. The major new item is the level of

Dummy Variable	MACKENZIE VALLEY		DEMPSTER CORRIDOR		DEMPSTER-KLONDIKE	
	Cases	Mean	Cases	Mean	Cases	Mean
lat1	472	0.2323	164	0.1198	42	0.2727
2	452	0.2224	164	0.1198	32	0.2078
3	360	0.1772	227	0.1658	11	0.0714
4	128	0.0630	520	0.3798	16	0.1039
5	452	0.2224	151	0.1103	23	0.1494
lat6	168	0.0827	143	0.1045	30	0.1948
elev1	65	0.0320	157	0.1147	20	0.1299
2	700	0.3445	90	0.0657	20	0.1299
3	663	0.3263	154	0.1125	29	0.1883
4	305	0.1501	404	0.2951	45	0.2922
5	175	0.0861	102	0.0745	23	0.1494
elev6	124	0.0610	462	0.3375	17	0.1104
aspect1	148	0.0728	300	0.2191	10	0.0649
2	86	0.0423	96	0.0701	29	0.1883
3	18	0.0089	149	0.1088	39	0.2532
4	407	0.2003	327	0.2389	23	0.1494
5	608	0.2992	361	0.2637	30	0.1948
aspect6	765	0.3765	136	0.0993	23	0.1498
slope1	1046	0.5148	545	0.3981	17	0.1104
2	637	0.3135	651	0.4755	35	0.2273
3	227	0.1117	126	0.0920	35	0.2273
4	55	0.0271	43	0.0314	35	0.2273
5	9	0.0044	4	0.0029	19	0.1234
slope6	58	0.0285	0	0.0	13	0.0844
lndfm1	731	0.3597	549	0.4010	22	0.1429
2	165	0.0812	71	0.0519	57	0.3701
3	352	0.1732	237	0.1731	28	0.1818
4	295	0.1452	230	0.1680	26	0.1688
5	403	0.1983	190	0.1388	2	0.0130
lndfm6	86	0.0423	92	0.0672	19	0.1234
text1	109	0.0536	112	0.0818	34	0.2208
2	64	0.0315	296	0.2162	51	0.3312
3	986	0.4852	245	0.1790	35	0.2273
4	405	0.1993	369	0.2695	20	0.1299
5	308	0.1516	124	0.0906	11	0.0714
text6	160	0.0787	223	0.1629	3	0.0195

Table 31: Cases and means for dummy variables with modified ice content.

Dummy Variable	MACKENZIE VALLEY		DEMPSTER CORRIDOR		DEMPSTER-KLONDIKE	
	Cases	Mean	Cases	Mean	Cases	Mean
texta1	281	0.1383	269	0.1965	102	0.6623
2	61	0.0300	290	0.2118	22	0.1429
3	875	0.4306	216	0.1578	16	0.1039
4	382	0.1880	314	0.2294	8	0.0519
5	292	0.1437	100	0.0730	6	0.0390
texta6	141	0.0694	180	0.1314	0	0.0
textb1	56	0.0276	89	0.0650	23	0.1494
2	54	0.0266	270	0.1982	40	0.2597
3	1023	0.5034	258	0.1885	37	0.2403
4	409	0.2013	351	0.2564	19	0.1234
5	310	0.1526	138	0.1008	14	0.0909
textb6	180	0.0886	263	0.1921	21	0.1364
veg1	160	0.0787	117	0.0855	8	0.0519
2	237	0.1166	73	0.0533	48	0.3117
3	389	0.1914	481	0.3514	11	0.0714
4	610	0.3002	571	0.4171	1	0.0065
5	390	0.1919	100	0.0730	59	0.3831
veg6	246	0.1211	27	0.0197	27	0.1753

Table 31(cont.): Cases and means for dummy variables with modified ice content.

VARIABLE	MULT R	R^2	B
text1	0.586	0.344	6.802
texta1	0.613	0.375	1.212
lat5	0.635	0.403	-0.433
text2	0.645	0.417	3.263
veg3	0.654	0.428	0.383
aspect3	0.661	0.438	-2.427
text3	0.666	0.444	1.275
text4	0.675	0.456	1.158
lat4	0.678	0.460	-1.901
veg2	0.680	0.463	-0.573
lat1	0.682	0.466	-1.513
text5	0.684	0.468	0.562
lat2	0.685	0.470	-1.408
lat3	0.692	0.478	-1.411
aspect1	0.693	0.480	-0.755
aspect5	0.695	0.483	-0.477
aspect4	0.695	0.485	-0.443
aspect2	0.697	0.485	-0.465
depth5	0.698	0.486	0.101
depth3	0.698	0.487	-0.449
depth4	0.698	0.488	-0.418
texta2	0.699	0.488	-0.526
texta3	0.699	0.489	-0.146
depth2	0.699	0.489	-0.292
depth1	0.699	0.489	-0.193
veg1	0.699	0.489	-0.236
veg4	0.699	0.489	-0.164
veg5	0.700	0.489	-0.131
texta4	0.700	0.489	0.026
			4.833

F=75.759 F Sig=0.001

Table 32: Summary table, dummy regression of the Mackenzie Valley data.

VARIABLE	MULT R	R^2	B
text1	0.559	0.312	5.639
text2	0.683	0.467	1.923
lat1	0.704	0.496	-3.190
lndfm5	0.731	0.534	1.871
textb1	0.742	0.550	3.214
lat2	0.750	0.562	-1.991
lat4	0.759	0.576	-1.835
texta5	0.764	0.584	-0.091
textb2	0.768	0.589	1.474
textb4	0.771	0.594	0.832
textb3	0.775	0.600	0.469
elev5	0.778	0.606	1.854
elev4	0.781	0.610	0.923
lndfm2	0.784	0.615	-0.802
texta2	0.786	0.618	1.050
texta1	0.789	0.622	0.784
lndfm4	0.790	0.624	0.593
text3	0.791	0.625	0.858
text4	0.791	0.626	0.608
elev3	0.791	0.626	0.395
text5	0.792	0.627	0.379
lat3	0.792	0.627	-0.308
texta3	0.792	0.627	-0.156
lndfm3	0.792	0.627	0.144
elev1	0.792	0.627	-0.504
elev2	0.792	0.628	-0.587
lat5	0.792	0.628	-0.186
lndfm1	0.792	0.628	0.036
			3.948

F=104.378 F Sig=0.001

Table 33: Summary table, dummy regression of the Dempster Corridor data.

VARIABLE	MULT R	R^2	B
textb1	0.259	0.067	6.923
depth1	0.329	0.108	-1.785
textb2	0.395	0.156	4.064
textb3	0.432	0.187	2.611
depth3	0.437	0.191	2.294
depth4	0.440	0.193	2.166
depth2	0.442	0.195	1.368
depth5	0.445	0.198	1.636
textb4	0.445	0.198	0.185
			1.615
	F=11.618		F Sig=0.001

Table 34: Summary table, dummy regression of the Dempster-Klondike Highway data.

VARIABLE	MULT R	R²	B
text1	0.682	0.465	6.943
texta1	0.710	0.504	1.129
text2	0.725	0.526	3.132
text5	0.732	0.536	0.106
lndfm5	0.737	0.544	1.224
elev1	0.740	0.547	1.267
lndfm1	0.742	0.551	0.709
elev2	0.745	0.555	0.494
depth1	0.747	0.558	0.319
depth2	0.748	0.560	0.156
lndfm3	0.749	0.562	0.535
elev3	0.750	0.564	0.347
text3	0.751	0.571	0.922
text4	0.756	0.573	0.932
lndfm2	0.757	0.574	0.645
texta2	0.757	0.574	-0.692
lndfm4	0.758	0.575	0.322
depth5	0.758	0.575	0.167
depth4	0.758	0.575	-0.176
texta5	0.758	0.575	-0.131
depth3	0.758	0.575	-0.117
texta4	0.758	0.575	-0.177
			2.536

F=129.407 F Sig=0.001

Table 35: Summary table, dummy regression of the modified Mackenzie Valley data.

VARIABLE	MULT R	R^2	B
text1	0.645	0.416	7.854
text2	0.746	0.571	3.227
texta1	0.774	0.598	1.532
text4	0.782	0.612	1.576
text3	0.793	0.629	1.519
lndfm5	0.798	0.636	1.598
elev3	0.802	0.644	-1.166
texta2	0.806	0.650	0.887
elev5	0.808	0.653	0.754
lndfm3	0.809	0.655	0.595
lndfm4	0.811	0.658	0.864
text5	0.812	0.659	0.557
elev2	0.813	0.661	-0.670
lndfm2	0.813	0.661	-0.252
elev1	0.814	0.662	-0.484
elev4	0.814	0.663	-0.296
depth1	0.815	0.664	0.734
depth2	0.815	0.665	0.586
depth3	0.816	0.665	0.441
depth4	0.816	0.666	0.371
lndfm1	0.816	0.666	0.290
texta4	0.816	0.666	0.102
depth5	0.816	0.666	0.119
texta5	0.816	0.666	-0.065
			2.786
	F=129.407		F Sig=0.001

Table 36: Summary table, dummy regression of the modified Mackenzie Valley data.

VARIABLE	MULT R	R^2	B
text1	0.487	0.237	8.765
text2	0.594	0.353	4.157
text3	0.606	0.367	0.343
text4	0.606	0.367	-2.100
text5	0.608	0.369	-2.182
			7.000
	F=17.317		F Sig=0.001

Table 37: Summary table, dummy regression of the modified Dempster-Klondike Highway data.

explained variance. For the Mackenzie the potential explanation rises to 49% with dummies, 63% for the Dempster Corridor (Table 33) and 20% for the Dempster-Klondike (Table 34). This indicates that the regression by dummies is adding substantially to the power of explanation.

Once again the dependent variable was modified and the regression with dummy variables computed (Tables 35, 36, 37). The significant dummies matched the variables of the earlier stepwise regression (cf. Tables 24, 25, 26). The highest explanation potentials thus far were obtained: 58% for the Mackenzie, 68% for the Dempster Corridor, and 37% for the Dempster-Klondike Highways.

By way of summary then, throughout the levels of analysis, textural variables predominate, particularly texture of the sample. As the type of analysis becomes more refined there are four points to note:

1. The prediction equation becomes more consistent.

   In the final regression both texture and depth are the most important variables.

2. Depth below surface, as a variable, is identified as the major secondary influence of the ice content of permafrost. after texture (Tables 24, 25, 26).

   It seems that high ice content permafrost is generally formed close to the surface. Explanations of this may centre around hydrological aspects of the environmental factors either in terms of availability of moisture to form ice or a combination of moisture retention by organics (Tables 35, 36, 37) and impermeability of the frozen substrate inhibiting infiltration. These indications are consistent with the impressions gained during field work in the Dempster and Klondike areas.

3. Other secondary influences become more apparent.
   Unlike texture and depth no other single variable is common to all regression equations at one level of analysis. Various influences appear at different levels in the analysis and for differing data sets. Elevation and landform-genesis are significant variables in the Mackenzie and Dempster Corridor as is another textural variable (Tables 24. 25).

4. The level of explanation increases consistently but the field applicability does not.
   Single variables at best explain 18% of the variance in the ice content of permafrost in the Mackenzie Valley, 37% in the Dempster Corridor and 26% in the Dempster-Klondike area. Multiple regression with dummy variables, on the other hand, explains 58%, 67% and 40% respectively. However with texture and depth dominating the regression equations the models are not applicable to alternative data sources: ground core sampling continues as a prerequisite to route evaluation.

Analysis of Ecological Systems

With ten independent and 375 computed surrogate variables and ice content as the dependent variable, the analysis were run to determine the most important predictor of ice in the Mackenzie River Valley, the Dempster Corridor and the Dempster-Klondike Highways. The results are presented in the tables below.

A combined four-variable interaction consistently proved more powerful as a predictor, than one-, two- or three-variable interactions, so that each analysis reports a four-variable interaction. In the tables, N/Cell indicates the number of data points in the particular matrix cell. There are N data points, Na was used in the analysis and Nch was used in the check procedure. Of course N = Na + Nch. There are ten Primary variables, 45 Secondary surrogates ($^{10}C_2$), that is the two-variable combinations, and so forth, with three and four-variable combinations giving a total of 385 input variables for the analysis. Each variable has six categories. The predicted ice content is given in the form of an intercept, which may then be translated back to a percentage of total weight (Table 2).

Mackenzie River Valley Analysis

In the Mackenzie Valley (Table 38) the least ice content, less than 5% by weight of soil, occurs in well drained sands and gravels of unsorted and moderately sorted morainal and till landforms, having northeasterly aspects beneath black spruce and moss covered floors, and in coarse-grained lineated northwest facing slopes under a lichen cover.

Large amounts of ice, 3.5 to 6 times the weight of soil, occur in organic soils of south southerly facing peat plateaus with a cover of tall shrubs and "drunken" black spruce, or in organically charged silts and clays of north facing glacio-lacustrine sediments with an open canopy forest cover of black and white spruce, birch and poplar.

While moderate amounts of ice, are to be found in in fine inorganic silts and clays perched on coarse tills or bedrock where the slopes face west or east and have a closed canopy forest cover of spruce and poplar or they are to be found in fine to sandy glacio-fluvial deposits (possibly layered) with southerly aspects and exposed hummocks and tussocks.

INTERCEPT	LANDFORM	ASPECT	TEXTURE	VEGETATION	N/CELL
0.28	4 Morainal	5 NE	6 Sand, Gravel & Bedrock	3 Black Spruce & Moss	965
2.60	5 Lineated Slopes	4 NW	5 Clay/Silt Sands & Gravels	4 Lichen & Moss	774
5.82	3 Glacio-flivial	1 S	4 Inorganic Silt/Clay w Sand	6 Hummocks and Tussocks	47
10.27	6 Till on Bedrock	3 W/E	3 Inorganic Silts & Clays	1 Closed Spruce & Poplar	29
12.49	1 Organics	6 N	2 Organic Silts & Clays	5 Shrubs & drunken Bl. Spruce	25
15.35	2 Glacio-lacustrine	2 SW/SE	1 Organic	2 Open; Birch Spruce & Moss	18

Four variable analysis of 385 variables; 10 primary variables, 45 secondary, 120 tertiary and 210 quaternary surrogates.
N=2322, Na=1859, Nch=464.
R^2=0.657 on 1x4 variable cycle.
R^2=0.402 on 1x4 variable check sample (20%).

Table 38: ANECSY; Mackenzie River Valley.

Important points to note are:

a. ice content increases with finer textures.

This relationship, between higher ice contents and the fine-textured soils of the substrate in the Mackenzie Valley is well documented (Brown and Grave, 1978; Brown and Johnston, 1964).

b. Glacio-lacustrine deposits cntain the greatest amounts of ice.

It has been found for the northern Mackenzie Valley (Dome Petroleum Ltd. et al., 1982) that glacio-lacustrine silts and clays usually contain up to 50% ice by volume. Where ground is moderate to well drained the soils are Regosols to Brunisols and the vegetation consists of back spruce and feather moss, but when drainage is poor to imperfect gleysols are most and the cover is of open black spruce with sedges and moss. In varved clay deposits ice typically occus as uniform layers between successive layers.

c. Neither aspect nor vegetaion seem to have a consistent pattern with ice content of permafrost.

Aspect has been widely studied and it has been cited as an agent influencing permafrost presence. It is reported that north facing slopes have, in general, more ice than those facing south (Brown, 1965b; Harris, 1981). This analysis shows northern slopes as having ice but no more than on other aspects. Possibly, southerly aspects promote availibility of moisture to form ice in the substrate with melting of the first light snowfalls in the Fall.

Though vegetation alone is not completely reliable as a predictor (Roberts-Pichette, 1973), nevertheless it has a strong influence on the formation of permafrost. It is no surprise, then, to see the variable vegetation occuring in the interactions; equally, it is not surprising to see that vegetation types within the results show no consistent patterning with ice content.

d. The presence of ice in permafrost increases in deep soils of fine or organic textured landforms, but moderate amounts of ice are to be found in thin shallow organic soils on bedrock.

Code (1973), McRoberts and Morgenstern (1973) and Strang (1973) observed in the Mackenzie Valley the occurrence of lacustrine sands overlying clays and silts. They found that ice lenses tended to develop at the interfaces. If there has been any disturbance, allowing the ice lens to melt, then because of the large amounts of moisture released the soil exceeded its liquid limit and began to flow on slopes as low as one degree. Headward erosion and mass movement can be self-promoting in such situations. Such areas are therefore considered highly sensitive to disturbance. Crampton (1981) determined that the interface was generally to be found at the 5.5 m (18 ft) mark in the profile.

The variable latitude is conspicuous by its absence. In the literature northerly position is considered a major influence on permafrost as it is so tied with temperature. A portion of the results produced by this analysis is a listing of the interactions in the order of their correlation value. From this listing the first mention of latitude in a four-variable interaction is; latitude, landform, texture and vegetation. The surprising fact is that it comes in 28th place with an R=0.582.

Interesting as the single variables are, within the four-variable interaction and conceding that isolating a single variable within an interaction is the conventional method of studying the interactions and relationships, nevertheless it must be remembered that the behaviour of the components does not predict the character of a synergistic interactive multi-member surrogate variable. To separate a component part from a synergistic interactive is to divest the multi-variable of some, possibly all, of its potential for explaining the distribution of the dependent variable.

The Dempster Corridor Analysis

The Dempster Corridor results (Tables 39) indicate that unfrozen and low ice conditions occur in sands and gravels, on low slopes with predominantly southerly aspects, covered by closed canopy forests composed of spruce and poplar. Low ice conditions, less than 20% by weight, are to be found in coarse textured soils of moderate slopes and east or west aspects with a cover of moss and black spruce.

High ice contents, ranging from four times the weight of soil to ice features that may reach seven times the weight of soil, are found in organic soils with steep northerly slopes covered by open birch and spruce with a thick moss floor. High ice contents may be found in organically charged silts and clays with steep southeasterly and southwesterly slopes and covered by a "drunken" black spruce forest. Moderate amounts of ice, up to twice the weight of soil may be found in soils of inorganic silts and clays, some with fine sands present, beneath low and moderate slopes of northerly aspects covered in a low level vegetation of lichens or mosses or hummocks and tussocks.

The results once again indicate the predominance of texture in influencing the formation of ice and permafrost and that organics and fine textured soils promote greater ice contents. Slope is significant, the higher slopes associated with the most ice. Aspect too is important. The most ice is formed with northeasterly aspects, and slightly less under south-eastern and south-western aspects. It is possible that the availability of moisture for the ice formation is in question again, for drainage and snow cover have been cited as important influences (Brown, 1978).

INTERCEPT	ASPECT	SLOPE	TEXTURE	VEGETATION	N/CELL
0.23	1 S	2 2°	6 Sand, Gravel & Bedrock	1 Closed Spruce & Poplar	454
3.64	3 W/E	4 4°	5 Clay/Silt Sand & Gravels	3 Black Spruce & Moss	300
6.69	4 NW	1 1°	4 Inorganic Silt/Clay w Sand	6 Hummocks and Tussocks	307
10.10	6 N	3 3°	3 Inorganic Silts & Clays	4 Lichen & Moss	196
13.34	2 SE/SW	5 5°	2 Organic Silts & Clays	5 Shrubs & drunken Bl. Spruce	88
17.05	5 NE	6 6°	1 Organic	2 Open; Birch Spruce & Moss	15

N=1700, Na=1360, Nch=340.
$R^2=0.755$ on 1x4 variable cycle.
$R^2=0.581$ on 1x4 variable check sample (20%).

Table 39: ANECSY; Dempster Corridor.

The Dempster-Klondike Highways Analysis

Low ice content conditions in permafrost in the Dempster-Klondike region (Tables 40) are found in latitudes 61°-62°N and 64°-65°N, at mid-elevations 475-762 m (1500-2500 ft) at depth of 30.5-60 cms (1-2 ft). High ice, 5.5 to 9 times the weight of soil, may be found at 62°-63°N and 65°-66°N, in middle and upper elevations (762-1067 m) (2500-3000 ft) of northeasterly and southerly aspects. The ice is formed at very shallow depths or alternatively at depth and, because the ice content can be so large, lenses of virtually pure ice may exist. Modrate amounts of ice, of less than three times the weight of soil, are present at latitudes 63°-64°N at either the highest (over 1067 m) (over 3500 ft) or the lowest (less than 475 m) (less than 1500 ft) elevations on northerly to northwesterly slopes at either very shallow depths or greater depths.

The results suggest that latitude has a strong influence on ice content. However, it does so in a non-linear fashion (Fig. 13). The greatest ice is found between 65° and 66°N, or around the Ogilvie River area, and a secondary peak occurs about 63°to 64°N or around Carmacks. Ice then decreases to the north and south of each area. The greatest rate of ice accumulation occurs immediately to the south of the plotted peaks or maxima points. Behaviour like this may indicate transitions from one environmental pattern of permafrost to another: at around 62°N, permafrost changes from scattered bodies to a discontinuous distribution, and at about 65°N it is continuous. This is in fair agreement with the analysis of the Mackenzie Valley (Crampton, 1981). In the Mackenzie the transition is situated between Norman Wells and Fort Norman (64°-65°N), and the discontinuous permafrost dissipates to scattered occurrences around Fort Simpson (61°-62°N).

There appears no obvious pattern to aspect. It is not a direct or simple relationship to ice content of permafrost. For elevation, moderate ice contents are present at either the lower or the higher values while less icy permafrost is to be found at the low to middle range. It is the middle to upper elevations where the highest ice contents are indicated. Such conditions may be related to valley forms but the diesected nature of the terrain may be obscuring the relationship. The data were collected along a transit that is limited by road access. A bias is included then, for the roads are positioned along ridges. While this is an advantage for work on pipeline routings for they will follow very similar routes, it is a disadvantage for speculation on causality and interrelationships with ice formation in permafrost. To determine the full effects of this bias requires further investigation and more extensive fieldwork than is possible in this study.

The results otherwise indicate that the highest ice contents are to be found near the surface and decrease with depth, however high ice content permafrost may also be encountered at about 60 cms (2 ft). The shallow icy permafrost is probably related to the presence of organics. The validity of the second peak in ice content is open to question, however, because the variable has a very small range. It is unfortunate that hand augering proved so difficult when gathering the data.

This is the first model presented that does not include the variable texture. The required data input can be obtained from maps and air photographs and the model may be successfully employed as a first level investigation indicating areas of high ice content permafrost where further detailed work is necessary.

Summary of the Levels of Analysis

Scattergrams, Correlations and Linear Regressions

Scattergrams and linear regression statistics indicate few of the interrelations between the environmental variables are linear in form. The plots in some cases indicate a closer approximation to the true form. Because of the codings, the large data base and the limitations of the program the visual component is obscured by the overfilled cells. The computations of correlation coefficients confirm that there are interrelationships between the factors comprising the ecosystems in northern Canada. Intervariate correlations showed the textural variables and depth to be tightly interdependent.

INTERCEPT	LATITUDE	ASPECT	ELEVATION	DEPTH	N/CELL
0.13	1 61°-62°N Whitehorse	3 W/E	2 1500-2000 feet	4 1.5-2 feet	225
5.17	4 64°-65°N Dawson City	2 SW/SE	3 2001-2500 feet	3 1-1.5 feet	47
7.76	3 63°-64°N Stewart Crossing	4 NW	6 over 3500 feet	6 2.5 ft and deeper	29
10.72	6 66°-67°N Eagle Plains	6 N	1 less than 1500 feet	2 0.5-1 feet	23
15.22	2 62°-63°N Carmacks	1 S	5 3001-3500 feet	5 2-2.5 feet	17
19.65	5 65°-66°N Ogilvie River	5 NE	4 2501-3000 feet	1 0-0.5 feet	6

N=430, Na=347, Nch=87.
R^2=0.712 on 1x4 variable cycle.
R^2=0.429 on 1x4 variable check sample (20%).

Table 40: ANECSY; Dempster-Klondike Highways.

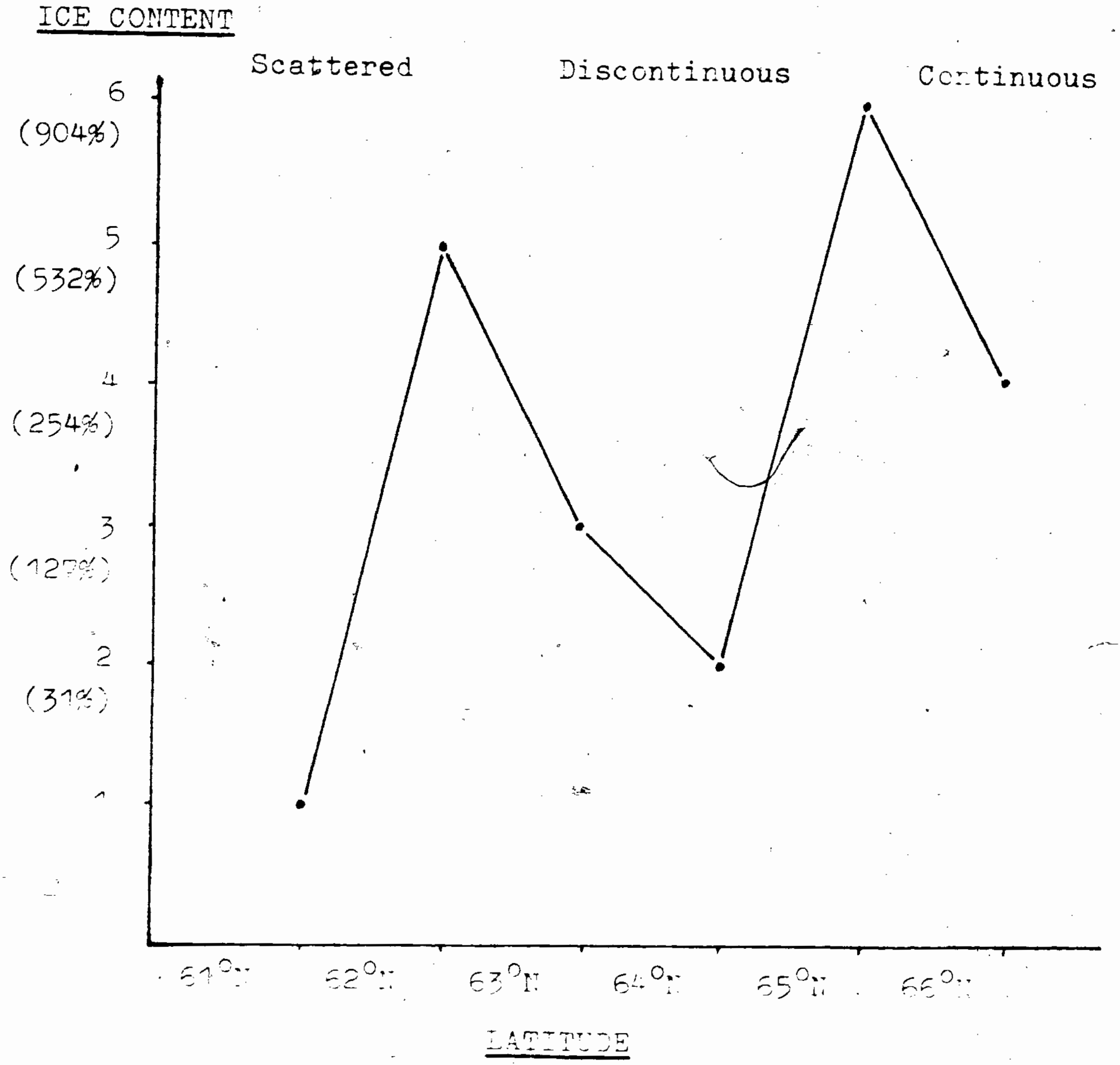

Fig. 13: Ice Content vs. Latitude for the Dempster-Klondike.

With modifications to the data set these same interdependencies occurred but the landscape variables became more independent of the textural group. The usefulness of such information lies in assessing the validity of the regression assumptions in later procedures rather than in modeling itself.

The regression of single variables on ice content of permafrost proves to be low in explanation potential. While explanation potential increases with modifications of the data sets, it is still not very high, that is to say not reaching a preferred point of 50% explanation of the variance. The maximum is 37% for CDICE(1) and texture in the Dempster corridor.

Texture of the substrate is the least useful model for the prediction of permafrost in the field as it requires site specific analysis and/or drilling. In the Mackenzie valley data set the only alternate is the variable latitude but for this, explanation is only 3.6% making it virtually useless.

Multiple Regression

Textures again comprise the prime variables in the models. Latitude is important in the Mackenzie, landform-genesis in the Dempster Corridor and depth in the Dempster-Klondike Highway as secondary influences. Explanation potential increases with this step but applicability to the field is still hampered by the dominance of textural variables. Though explanation increased over single variable analysis the incremental additions to R^2

with the inclusion of secondary variables are small, indicating how unsympathetic regression is to this environmental situation.

On modifying the data sets a general model of texture and depth appeared, consistent across all data sets, for the first time. The explanation potential touched the 50% mark for the Dempster Corridor. But the criticism of field applicibility remains.

Multiple Regression with Dummy Variables

For both the normal and the modified data sets the same variables proved to be significant as in the multiple regression analysis without dummy variables. The difference is in the power of the explanation. Use of the dummy variables aleviates, to some extent, the problems of assuming linear relationships between the dependent and independent variables resulting in higher explanation potentials.

Simple regression statistics and correlation coefficients indicated that the ice content is inversely correlated with texture, and that ice structures are formed towards the surface rather than at depth. The criticism of the results lies mainly in their inability to isolate the secondary influences. Multiple regression studies are all hampered by the persistent dominance of texture as a prime predictor. It appears that depth and latitude are the next most powerful predictors, but this is not conclusive. The criticism of these studies centre about their lack of field applicibility and user orientation: the regression models require drilling. Though the requirements for an ideal method of analysis are not fulfilled the continual increase in explanation with each step is comforting.

Analysis of Ecological Systems

In assessing the models produced by ANECSY, it can be seen that they are complex and difficult to summarize, however, they do predict the occurrence of permafrost, outline the primary variables and indicate those of lesser power, all with a respectible degree of accuracy and confidence. Texture being so dominant no real advances in solving the economic problems of northern route appraisal have been made: the regression model requires drilling. But ANECSY aleviates the problem by providing a choice of models with varying confidence limits as indicated by the R^2. It is therefore possible to choose a model suitable to the user's data base. ANECSY is capable of providing information necessary for allowing re-orientation of the planning focus from one of pure economics to one more ecologically based. It may also be seen that ANECSY can fit easily into the present framework of environmental leglislation, and not only can ANECSY aid in early route selection, field reconnaissance and assessment of proposed linear development features it may also be used to advantage in predicting the possible outcomes of mitigation procedures. ANECSY produces multi-variate models, and indicates those areas where synergistic forces may be at work.

From the results of the Dempster-Klondike Analysis the zones of each distribution type of permafrost becomes evident (Fig. 13). Within these zones the transition belts are distinctive as the areas of greatest change in ice accumulation and decline; 62°N and 65°N respectively. It is postulated that these areas are choice for synergistic-type processes. They are characterized by their tenuous nature and environmental sensitivity. Any enforced alteration here can have dramatic consequences, so development must be done slowly and with care.

The models produced are potentially adaptable to any data bases available. They are user-oriented for both field work and engineering planning. They are adaptable to the various northern projects; pipelines, whether gas or oil, power-line routes, roads etc., those projects characterized by their extended linear nature.

It is suggested that the program is cost-efficent. It may be used at a variety of levels of analysis for reconnaissance and planning and it may result in less field drilling than the methods presently available. With adaption to a personal computer the program will be a mobile tool of analysis and the addition of a mapping package would make handling the results easier. This program has the potential of being a very powerful tool of analysis with very positive consequences for environmental impact analysis.

V. CONCLUSIONS

Disturbing frozen ground can lead to thermokarst, subsidence and slumping. The degree of reaction to disturbance is related to the ice content of the permafrost. A predictive model for the occurrence of permafrost and its ice content is required by those involved in the development of the North. Clues to the permafrost exist in the morphology of the landscape, the texture and hydrology of soils and the vegetation cover. Most studies have confined their enquiries to analyzing changes in one variable with relation to permafrost. But, because of the information such studies have provided, it is now possible to look at a whole series of variables comprising the northern ecosystems, their interrelationships and their combined relations to permafrost. This thesis is an assessment of a method which attempts to do just that. The results of both the assessment and the program itself have consequences for many aspects of permafrost studies in Northern Canada.

Distribution of Permafrost

It has been suggested that Brown's model of the zones and conditions of permafrost be altered so that the Mackenzie Delta be included in discontinuous permafrost (Gill, 1973). The results here indicate that the Delta should be considered an outlier of discontinuous permafrost in its own right and not just a northerly extension. The reason is that south of the Delta there exists a belt of continuous permafrost. The area between Fort Norman and Norman Wells (65°N) has the highest ice content in the Mackenzie Valley and then falls off to the north and south. The same or at least similar, conditions exist for the Dempster area (66°N) of the Yukon (Fig. 13), where the northerly latitudinal displacement might be explained by Pacific Ocean influences. This indicates such permafrost conditions are not a local phenomenon, but that there is continuous permafrost in a belt that isolates the Delta from southern discontinuous conditions.

The rates of change in ice content are greatest in these fall-off areas. Because of the presence of discontinuous permafrost in the Delta there is a transition between discontinuous and continuous permafrost northward and again to discontinuous permafrost. What might be an orderly change is constricted by the presence of the Delta and the transition is forced and thereby more rapid. Conctricted transitions like this can have a potential for change greater than general expectations. Because of this potential extra care must be sought in planning and development.

Variables for Analysis

No single model to predict ice content, for the study areas as a whole, could be found in this analysis, nor, it seems, for the complete length of a transit. Therefore, as has been suggested in the literature, it is here concluded that models must be created for small localized sections at a time, although the scale which might prove most efficient is a question for further study.

The only common explanation of ice content between the models was the textural components. Although the specific textures associated with high ice contents vary somewhat with environmental conditions it is, nonetheless, plainly obvious that the dominant influence on the formation of icy permafrost in the substrate is texture. In some ways it is unfortunate that texture is so dominant. Firstly, it has overshadowed the less powerful influences of other variables and, secondly, textural information requires drilling. But drilling is the most expensive field surveying method, and first level prediction using less costly data would be a real asset to development by reducing planning and exploration costs and ultimately, by altering the focus to to one of a more ecological viewpoint in turn reducing long term maintainence costs.

Suggestions for Further Research

The program ANECSY is continually being updated and developed thus it is recognised that the present version does have problems and limitations. The analysis is sensitive to the coding structures. Just how sensitive is unknown and must be studied. A methodical study under controlled conditions of both data and variables should be exercised. Variables should be given a greater number of classes. Scattergrams would then become more useful. Non-linearity (and of course linearity) may be identified in these plots, as will curvilinear relationships. The results of this style of analysis would be enhanced by an increase in the number of classes so that a way of 'opting-out' would be available. It is suspected that sometimes classes are forced into their matrix position simply because there is no alternative. Also an option in the program whereby true frequencies of variable cases in matrix cells could be output is advised, as opposed to the present system where they are computed by hand. Empty cells could then be readily identified, indicating interrupted trends and weakened variables.

Large populations covering large areas and many different environs create questionable results in tests of significance. This causes problems in evaluating correlation coefficents, null relation indicators and the independence of the variables. Some solution should be found, as simple linear regression coefficents provide the first level of information as to which variables may ultimately make up the predictive model. Where significance of the results is questionable, confidence in the predictive model wanes.

Scattergrams and correlations are an important part of the study if only because they aid interpretation of a more complex analysis. The study of four-variable interactions is difficult and there is a strong possibility of error in interpretation of the output matrix. There is then, a need to study the two- and three-variable predictors so as to be able to decipher the higher orders of analysis. It would also be useful for understanding synergism if, in selected cases, certain variables were displaced in favour of others in the higher level combinations.

A system of priority levels for variables in the analysis is required so that different combinations of different groups or types of variables, field or office oriented, may be analyzed. With a companion mapping package the program could be combined with map-oriented route analysis and landscape sensitivity analysis. The maps could be adjusted to suit any variable and data block within reason.

There are other possibilities for the synergistic models that are worth investigation. There is the possibility that the analysis could model frost heave potential since in low ice content, fine-grained soils frost susceptibility is probably related to moisture availibility.

A Final Statement

The single variable and multi-variate analytical techniques presented in this thesis are incapable of predicting the presence of permafrost and its ice content with as great an explanation of the variance as the combination variable technique Analysis of Ecological Systems. The notable advantages of the ANECSY program are the variety of predictive models produced, the field applicabiliy to reconnaissance and northern surveys for linear development and the capacity to outline occurrances of synergistic interactions in the environment. The enhanced sensitivity to various databases allows flexibility in input requirements, thereby reducing the need for expensive and time consuming core drilling and sampling in the initial stages of inquiry. The models produced by ANECSY, therefore, better provide for the needs of route selection procedures than those of conventional methods.

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