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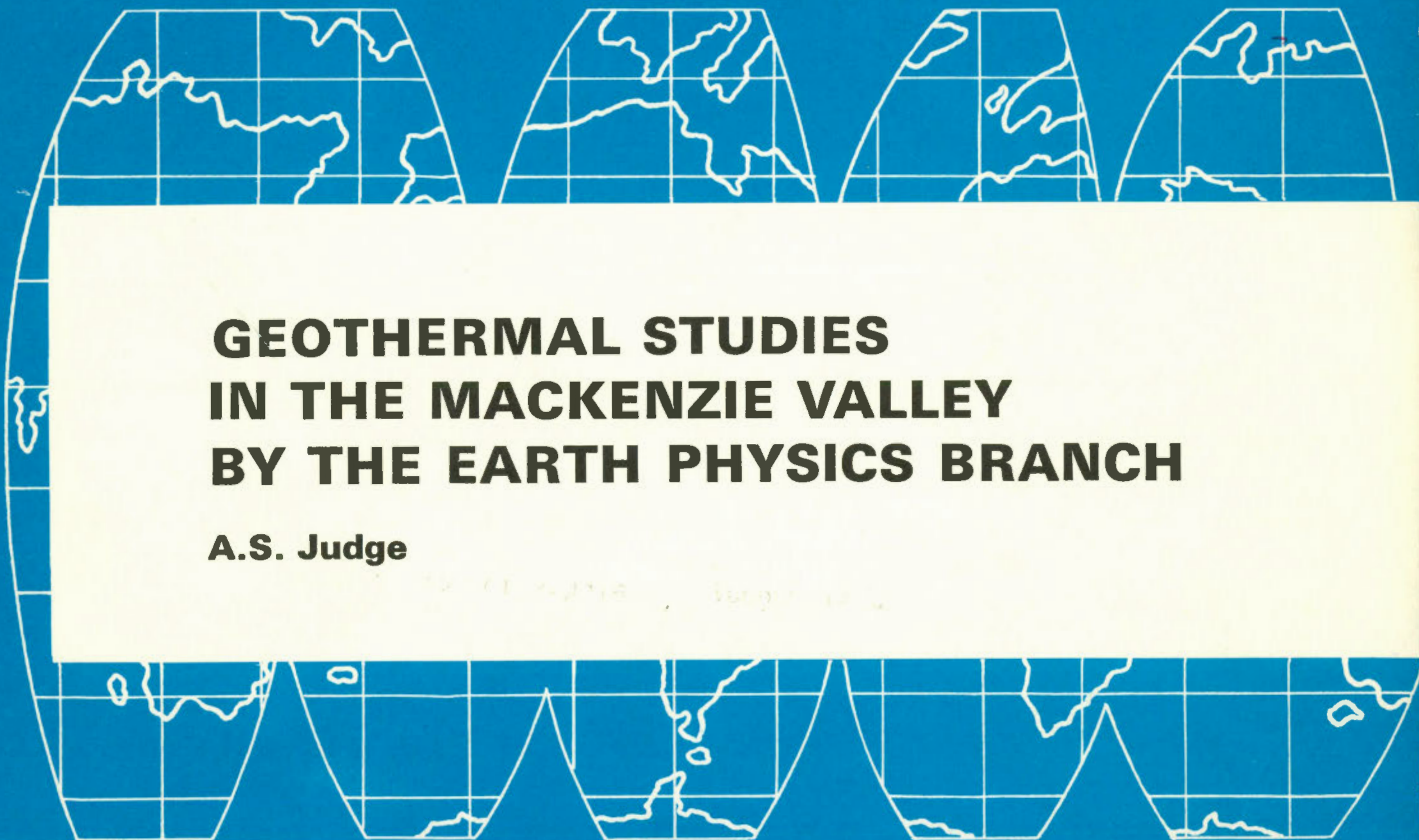
Earth Physics Branch
Direction de la physique du globe

Geothermal Service of Canada

GEOTHERMAL STUDIES IN THE MACKENZIE VALLEY BY THE EARTH PHYSICS BRANCH

A.S. Judge



Geothermal Series Number 2
Ottawa, Canada 1975

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ABSTRACT

As part of the Environmental-Social Program, Northern Pipelines, the Earth Physics Branch of the Department of Energy, Mines and Resources has carried out field observations of both the shallow and deep thermal regime of the Mackenzie Valley, conducted laboratory measurements of the thermal properties of subsurface soils and rocks, both frozen and unfrozen, has examined theoretically the thermal effects resulting from changes in the surface energy balance and compared these results with some observed temperature profiles.

Such studies are necessary for an adequate assessment of the environmental impact of proposed northern construction and development.

Through the existing program of the Earth Physics Branch, the work on the thermal behaviour of permafrost areas will continue to add to the volume of available data and enhance our understanding of the phenomena.

RÉSUMÉ

Dans le cadre du Programme écologique et social, Pipelines du Nord, la Direction de la physique du globe du ministère de l'Energie, des Mines et des Ressources a effectué des observations à faible et à grande profondeur du régime thermique de la vallée du Mackenzie et a étudié en laboratoire les propriétés thermiques des sous-sols et des roches, gelés et non gelés. La Direction a étudié de façon théorique les effets thermiques consécutifs à des modifications dans le bilan énergétique à la surface et a comparé ces résultats avec certains profils de température obtenus par observation.

Ces études sont nécessaires pour parvenir à une évaluation adéquate des effets que peuvent exercer sur l'environnement les travaux de construction et de développement projetés dans le Nord.

Par l'intermédiaire de la Direction de la physique du globe, les travaux sur le comportement thermique des régions à pergélisol continueront à fournir des données supplémentaires et à améliorer notre compréhension du phénomène.

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GEOTHERMAL STUDIES IN THE MACKENZIE VALLEY BY THE EARTH PHYSICS BRANCH

A.S. Judge

1. Introduction

Permafrost is by definition a thermal phenomenon and is said to exist when earth materials are held at temperatures of below 0°C for several years or more. Whether a solid rock is at negative or positive temperatures is not significant because little change occurs in its mechanical or thermal properties. The significance of the 0°C arises from the phase change between the liquid and solid phases of the common substance, water, that occurs at that temperature. Changes in the physical properties accompanying the phase change cause many of the engineering problems in permafrost terrains. The most dramatic results of these effects are seen in the near-surface unconsolidated materials. Judge (1974b) has described some of the resulting effects in the surficial deposits.

Whether or not permafrost exists at a location or whether it could be created is a result of a complex interaction of energy sources, interior and exterior to the solid earth. The nature of the earth's energy balance and how it governs the distribution of permafrost has been described by Jessop (1972), Judge (1973a) and Judge (1974b). Basically, the important factors are the present and past mean annual surface temperatures, the terrestrial heat flux, the thermal properties of the earth materials present, the amount of moisture present in those materials and its phase properties. Superimposed on this are the annual and other periodic and aperiodic effects that attenuate with depth at a rate dependent on the frequency and the thermal diffusivity. Under some circumstances heat conduction may no longer be the dominant heat transfer mechanism and moisture may migrate through the material at a rate dependent on the temperature and pressure gradients and the hydraulic conductivity.

The keys to understanding the danger imposed by introducing temperature changes at the surface are a knowledge of the present thermal regime and a prediction of the thermal regime resulting from the new situation. The thermal properties are required to deduce the speed at which change will occur and its extent.

In the program described here emphasis has been placed on:

1) measuring the temperature distribution in the subsurface, both spatially and temporally, at several locations in the Mackenzie Valley and Delta,

2) measuring the thermal properties of soils and rocks from the region, and

3) developing simple conduction models with which to investigate the effect of surface temperature changes.

Partial funding for the program was provided through the Environmental-Social Program, Northern Pipelines, of the Task Force on Northern Oil Development. Assistance with logistic support was provided by the Geological Survey of Canada, by the Polar Continental Shelf Project, as well as by several oil companies. Boreholes were made available by several oil companies, the major of which were Gulf Oil Canada Limited and Shell Canada Limited, by several mining companies and by the Geological Survey of Canada. To these and to all of the students and pilots who have assisted at various stages of this work, we offer our grateful thanks.

PART I

2. Objectives and achievements

The potential for damage to the northern environment as a result of northern development projects, such as pipelines, is twofold. Both the construction of the pipeline and associated structures and its eventual operation present substantial problems. In order to design both phases in such a way as to maintain the integrity of the land surface and the pipeline, the engineer needs basic information on the present thermal environment. Such required information includes ground temperatures on both a local and, in the case of a pipeline, a regional scale, the absence or presence of permafrost, the thermal and physical properties of typical earth materials, and the local terrestrial heat flux. Ground temperature information, from both disturbed and undisturbed sites, aids in assessing the maximum effect of surface changes on ground temperatures, and measurements of thermal properties over a range of temperatures aid in establishing the rate at which surface changes are translated to the subsurface. Numerical or analytical simulations aid in establishing both these rates and the natural rates of change due to changes in climate.

These four components, present ground temperatures, the earth's heat flux, thermal properties of earth materials and the ability to determine the thermal effects of temporal change in these parameters, have constituted the basic studies carried out by the Earth Physics Branch. The need to study these parameters has required considerable development of both instrumentation and methodology.

2.1 Instrumentation and methodology

2.1.1 Temperature

During the course of this program, 37 new drill sites have either been instrumented with multi-thermistor strings or have been preserved as open holes for subsurface temperature measurements. The 20 deep sites range from maximum depths of between 300 and 1160 m and the 17 shallow ones from 11 to 60 m. The methods and techniques of constructing suitable equipment for instrumenting and preserving drill-holes for such observations, for data acquisition and methods of data reduction and analysis have been described in earlier reports (Judge, 1973a, 1973d, 1974b).

The measured temperature results from holes to depths in excess of 125 m have been given by Judge (1974b), Taylor and Judge (1974b), Judge and Taylor (in preparation, 1975), and those at the shallow sites by Judge (1974b) and Judge and Taylor (in preparation, 1975).

As is apparent from reference to a series of temperature profiles measured at the deeper sites (see, for example, Taylor and Judge, 1974b), many profiles are not yet in thermal equilibrium with the undisturbed rock. The nature of this thermal disturbance due to drilling, how it is complicated by the presence of ice and how the undisturbed temperature of the rock or soil may be calculated from a series of profiles has been discussed in some detail by Judge (1974a), Taylor and Judge (1974a). Judge (1974b) has discussed the equilibrium return of the shallower holes. Ice need not, however, be present at temperatures below 0°C and it is often more important to know if materials are frozen rather than whether they are below 0°C. Jessop and Judge (1975) and Judge and Jessop (in preparation, 1975) have shown that it is possible to determine the base of the frozen section from temperature logs taken shortly after the completion of drilling, provided the material penetrated possesses high ice content and the time of circulation of, and the temperature of, the circulated drilling fluids are sufficient to partially melt the walls of the drillhole.

The drilling of holes solely for temperature observations is a very expensive proposition. Seismic shot-holes are, however, drilled routinely over much of northern Canada. Their use has been investigated as a means of acquiring a wider distribution of information on the mean annual surface temperature (Judge, 1974c).

2.1.2 Thermal conductivity

Measurements of the thermal conductivity of earth materials have been made on 400 samples representing a wide variety of soils and rocks from the Mackenzie Valley. The methods and techniques of making such determinations, many of them on frozen materials ranging in temperature from -2 to -20°C, have been described by Judge (1972a, 1973c, 1974b). Equipment suitable for field or laboratory, transient or steady-state determinations has been discussed in some detail.

Judge (1974b) has shown that a modified "geometric" model can be successfully used to calculate conductivity provided the conductivity of the grain material, the moisture content and the ice-to-water content with temperature is known. Judge and Taylor (in preparation, 1975) have used this to calculate *in situ* conductivities from measurements on drill cuttings.

2.1.3 Numerical model studies

The use of numerical simulations in permafrost terrains was described by Jessop (1973) who simulated the temperature distribution in layered media due to recent changes in surface temperature. A one-dimensional finite difference heat conduction model has been used by Judge (1974d) to investigate the aggradation and degradation of permafrost in the Beaufort Sea. The model can simulate realistically the variable thermal properties of multi-layered media and the variable temperature range over which latent heat is released or absorbed in materials of differing lithologies. Judge and Taylor (in preparation, 1975) have used the model to investigate the thermal response in the subsurface resulting from surface temperature changes such as might result from recent climatic change in the Mackenzie Valley or from similar man-induced changes.

2.2 *Regional surface temperatures and permafrost distribution*

Discussion of the results of the temperature observations has been given by Jessop (1970), Judge (1973c; 1974a, b, d) and Judge and Taylor (in preparation, 1975).

The thickness of permafrost throughout the Mackenzie Valley is highly variable, as shown in Figure 1, responding to a wide range of mean annual surface temperatures and temperature gradients. Surface temperatures, shown in Figure 2, range from 1.6°C to -9°C and subsurface gradients from 10 to 84 mKm^{-1}, leading to permafrost thicknesses from 0 m in the south to in excess of 560 m in the north. In the immediate vicinity of the Mackenzie Valley, permafrost as far north as 67°N does not exceed 80 m maximum and mean surface temperatures are generally warmer than -3°C. Mean surface temperatures and permafrost thickness in this southern area are almost as variable on a local scale as on a regional. In the vicinity of Yellowknife, surface temperatures vary from -1.8° to 1.5°C and permafrost ranges from 0 to 80 m. In the Fort Good Hope area, surface temperatures range from -0.1° to -2°C and permafrost varies from 33 to 48 m. Similarly in the Norman Wells area, surface temperatures vary from -0.7° to -3.1°C and permafrost thickness from 26 to 70 m. These can be compared with maximum and minimum values for the region of 1.6° and -3.1°C and 0 and 80 m, respectively.

Local variations can generally be related to surface conditions at the site. It was observed, for example, that in general peat-covered areas have a surface temperature of 1 to 3K lower than the warmer bare rock outcrops. Burnt peatlands, not yet heavily revegetated, provided an exception and are generally warmer than normal peat-covered areas. Marginal permafrost areas such as these inevitably contain substantial thicknesses of partially frozen or unfrozen materials at temperatures below 0°C, particularly in silt and clay lithologies. The southern regions of relatively warm permafrost correspond to mean air temperatures of between -3.9° and -7.6°C. North of 67°N permafrost thickens rapidly from about 100 m in the vicinity of Fort McPherson to in excess of 500 m in the northern part of the Mackenzie Delta. The young parts of the Delta with permafrost thicknesses of 20 to 90 m are an exception to this general thickening. Mean surface temperatures are again highly variable and values of -2° to -10°C are found, corresponding to mean air temperatures of between -8° and -13°C. The higher surface temperatures ranging from -0.4° to -4.0°C are found within the young delta and reflect the complex interactions of a young surface undergoing periodic flooding. Outside this region, surface temperatures range from -3° to -8.8°C, and are generally in the range of -5° to -9°C in the old delta. The very thick permafrost in the northern region, particularly on Richards Island and the Caribou Hills, corresponds closely to the low snowfall area (<76 cms), whereas south of Inuvik the average is from 120 to 170 cms.

The very great importance of winter snow cover in ameliorating winter ground temperatures, and thus contributing to a mean annual ground temperature 3° to 8°C above the mean annual air temperature, has been illustrated by Judge (1974b). Ground temperatures at a depth of 0.3 m were compared with air temperatures at the same locality for a period of 11 months. In mid-winter of that period when air temperatures were consistently in the range of -20° to -45°C, ground temperatures beneath 10 to 15 cms of snow did not fall below -9°C. Also, fluctuations of air temperature of 20K over periods of up to one week were almost entirely damped out.

The active or frost-prone layer immediately below the surface varies in thickness from as much as 15 m in exposed bedrock to 0.6 m beneath a peat cover. This illustrates particularly well the insulating qualities of high water contents at the surface. Similarly, where overburden covers the bedrock, the depth of the active layer is generally only 0.6 to 2.0 m. Correspondingly, the mean annual range of near-surface temperatures varies from 32K on exposed bedrock to as low as 2.4K in peat terrain. This is in comparison with ranges of the mean annual air temperatures of 45K. The depth to "zero" amplitude of the annual temperature wave is highly dependent on the mean annual range of near-surface temperatures and reaches a maximum in excess of 15 m at exposed bedrock sites and averages 10 m through the region.

Evidence exists of long-term surface temperatures changes of as much as 2 K, probably due to a combined change of climate and vegetation. The effect of recent mean surface temperature changes is observed as a reduction or even inversion of the shallow temperature gradient. The change in mean surface temperature is given approximately by the difference between the surface temperature intercept,

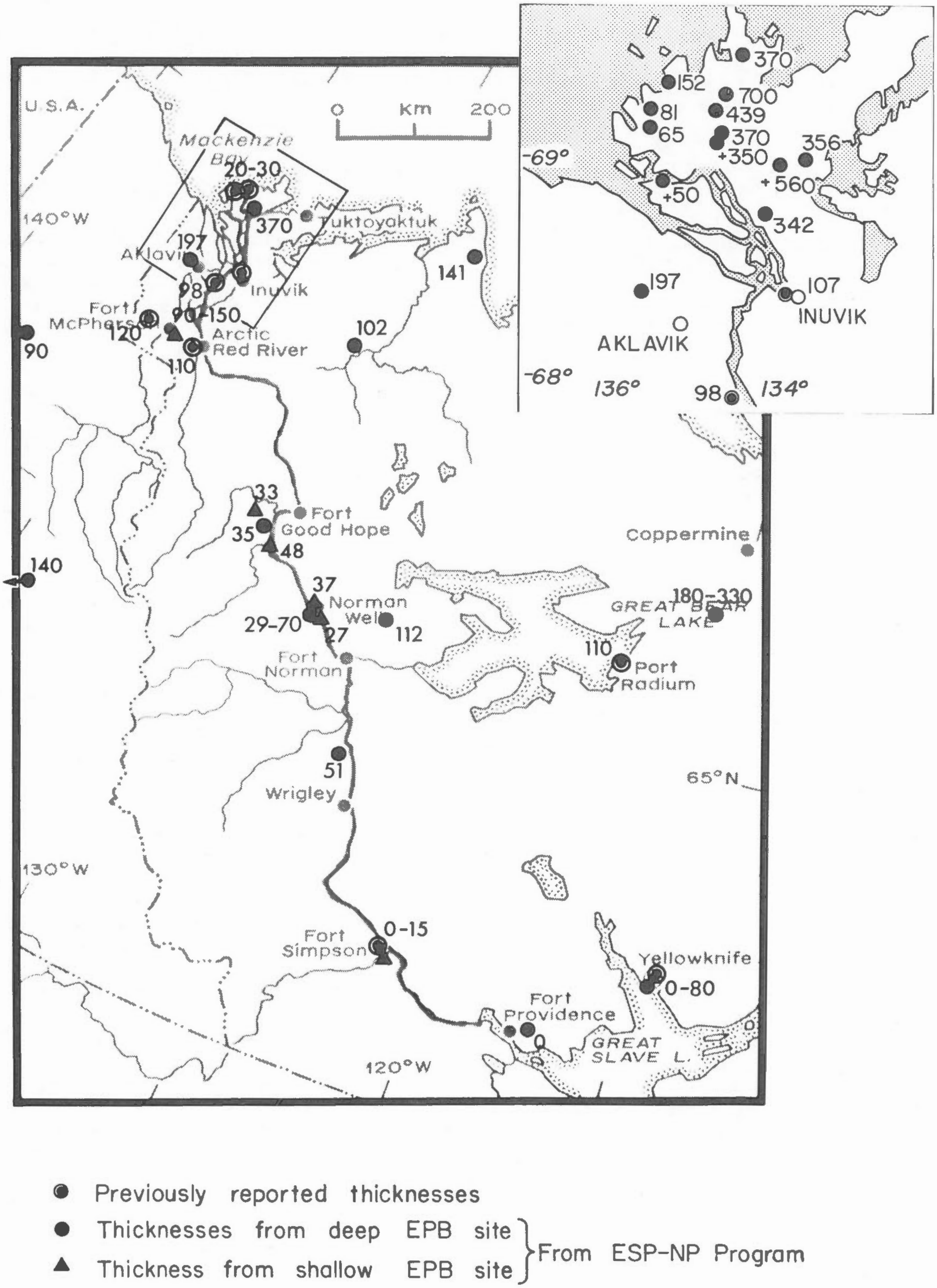

Figure 1. Distribution of permafrost and thickness in m across the Mackenzie Region.

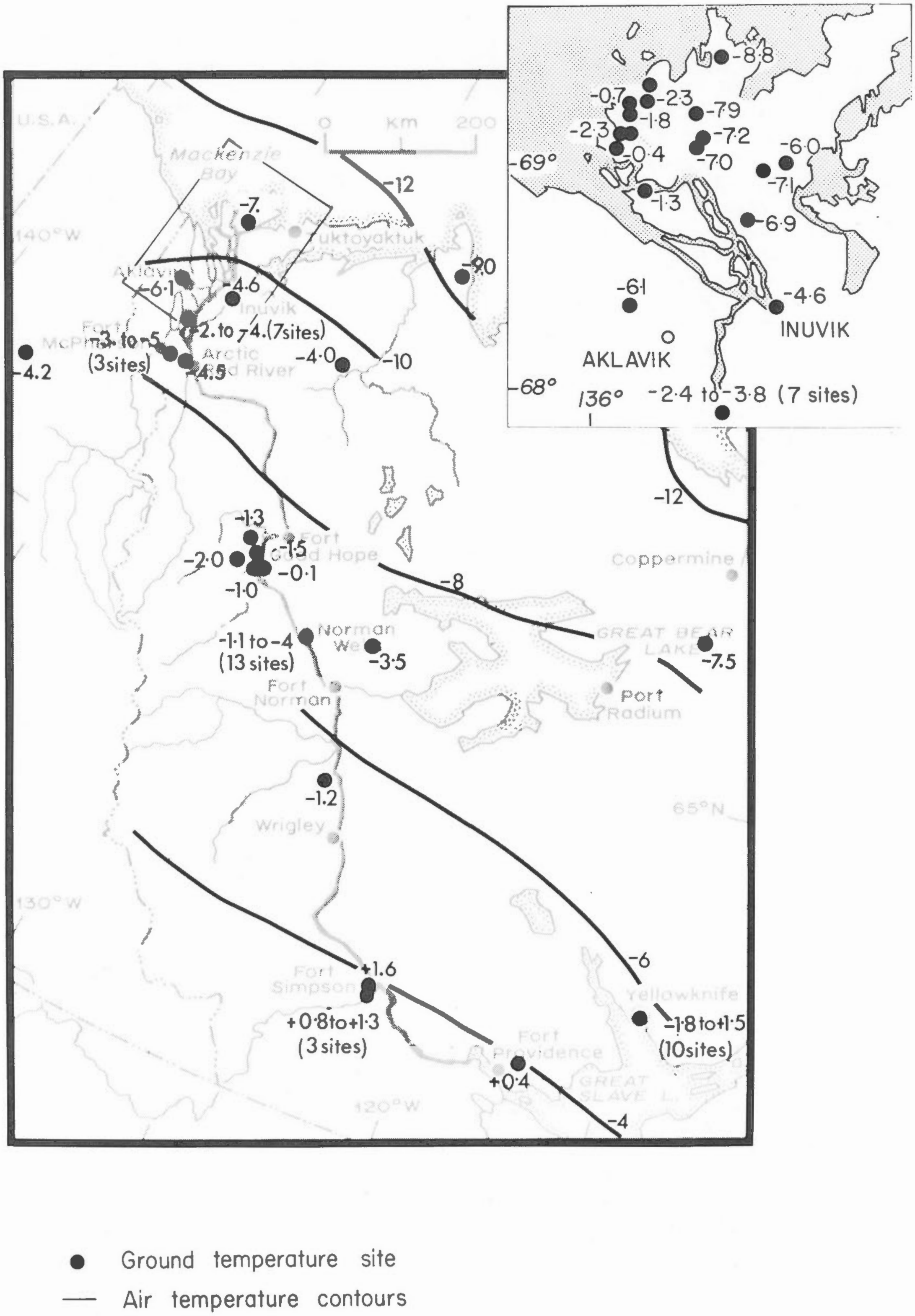

Figure 2. Comparison of mean air and ground temperatures in °C across the Mackenzie Region.

determined by extrapolating the temperature gradient from the zone where it is linear, and the present surface temperature intercept. Observed maximum differences are as much as 2K at Fort Providence, 3K at Norman Wells and 2K at Fort Good Hope, but they vary considerably at different locations and generally penetrate to depths of less than 100 m. In general, they must reflect changes that have occurred in the past 100 years. Changes of this magnitude and time scale have occurred in mean annual air temperatures throughout much of the northern hemisphere and are revealed extensively in ground temperature profiles in southern Canada.

Some observations have been made of the subsea thermal regime in the offshore portions of the Mackenzie Delta (Judge 1974d; Judge *et al.*, in preparation, 1975). Observations in general support two different scenarios in different parts of the Delta, reflecting the very different thermal histories of the areas. Common to both are present mean bottom water temperatures of above 0°C and similarly high sediment temperatures except on exposed bars or in water shallow enough to freeze to the bottom in winter. In both areas sediments are generally unfrozen to depths of 30 m or more, with the exception again of bars and shallows. This is where the similarity ends. In the one area, Mackenzie and Shallow Bays, very little, if any, permafrost occurs at depth, whereas offshore of the old delta relict, degrading permafrost several hundreds of metres thick exists.

On the basis of the thermal conditions described above, the Mackenzie Valley and Delta may be divided into several regions as shown in Figure 3. The simplest divisions are north and south of 67°, although the area east of Norman Wells rightly belongs with the northern area. The area south of 67° in which permafrost is marginal in nature may be further divided into two zones: Zone I, a southerly one where positive mean annual surface temperatures are frequently observed, i.e., permafrost is not continuous, and Zone II, a northerly one where mean annual surface temperatures are generally negative but not all soil types are frozen. Permafrost thickness in this area is generally less than 50 m in thickness and does not exceed 80 m. North of 67° mean surface temperatures are, in general, below -4°C, but fall rapidly to -9°C at the Arctic Coast. Corresponding permafrost thickness in this northern region lies between 90 and 700 m. The northerly and easterly regions may then be divided into several subregions, Zones III and IV. An exception to the divisions is the young Mackenzie Delta where surface temperatures are slightly below zero and permafrost is marginal. It is most similar to region II in Figure 3, although for different reasons.

2.3 *Thermal properties of soils and rocks*

The results of the thermal conductivity measurements have been presented and discussed by Judge (1974b) and Judge and Taylor (in preparation, 1975). Briefly, thermal conductivities measured on 300 samples of bedrock materials range from 0.6 $Wm^{-1}K^{-1}$ for poorly compacted shales to 3.5 $Wm^{-1}K^{-1}$ in granites and pegmatites. Densities range from 2.2 Mgm^{-3} in sandstone to 3.0 Mgm^{-3} in greenstone. The lowest porosities measured were 0.2 per cent in greenstones and ranged up to 25 per cent in sandstone. Similar measurements were made on 90 samples of frozen unconsolidated sands, silts and clays over a range of temperatures. Mean thermal conductivities average 1.2 ±.4 $Wm^{-1}K^{-1}$ for frozen clays, at moisture contents between 8 and 167 per cent to 1.9 ±.4 $Wm^{-1}K^{-1}$ for the frozen sands with 19 to 32 per cent water contents. Silt lies intermediate in thermal conductivity, depending upon the composition. Thermal conductivities in general increase by less than 10 per cent over the temperature range -2.5 to -10°C. Several samples, however, exhibit a large increase of conductivity at -2.5°C, apparently consistent with a modification of the soil structure as the ratio of ice to water present decreases. The variation of thermal conductivity with temperature appears well represented by a simple "geometric" model requiring a knowledge of the conductivity of the mineral grains, of the total moisture content and the proportion frozen at any temperature. Such models also offer a means of estimating the thermal conductivity of earth material from measurements made on drill cuttings.

Table I lists some typical results for earth materials encountered in the Mackenzie Valley.

Although no direct laboratory determinations of the thermal diffusivity of the materials have been made, Judge (1974b) has shown how values can be derived.

2.4 *Terrestrial heat flow*

Several determinations of the terrestrial heat flux have been made in the Mackenzie Valley region. These results have been summarized by Judge (1973a, 1974a). Values of close to 82 mWm^{-2} were measured in the northern Yukon, the Anderson Plain and the Cape Bathurst area in contrast to values of 54 mWm^{-2} measured

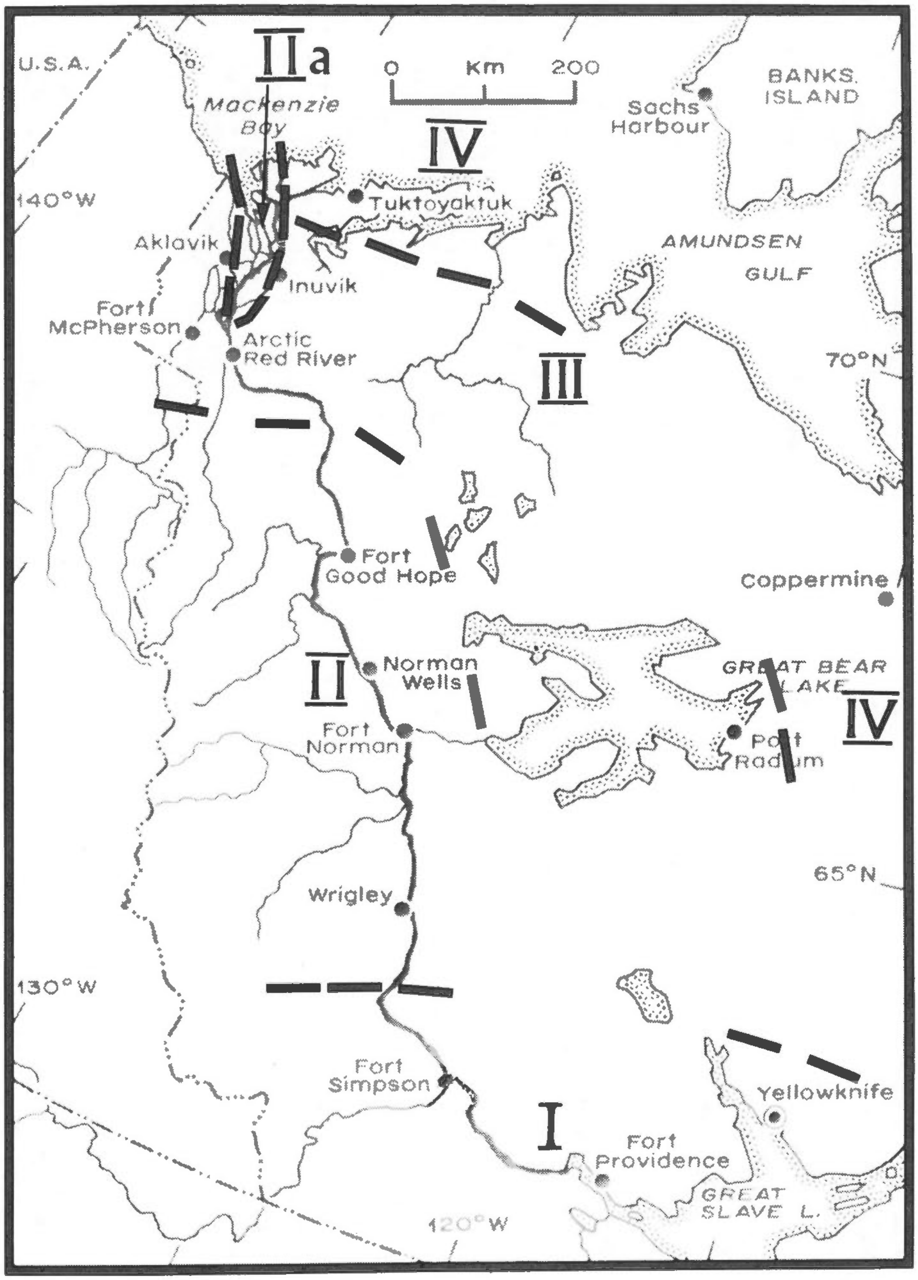

Figure 3. Preliminary thermal zones in Mackenzie Valley (see text for explanation).

TABLE I

Thermal Conductivities of Bedrock in Mackenzie Region

Site	Formation and Lithology	Mean Thermal Conductivity $Wm^{-1}K^{-1}$	Range	Mean Density Mgm^{-3}	Range	Porosity Per Cent	Range	No. Samples
Yellowknife EPB No. 105	P¢ - Greenstones, tuffs, lavas	3.2	1.1-2.7	2.96	2.66-3.22	0.2	-	108 c[1]
EPB No. 66	P¢ - granites, pegmatites	3.5	2.9-4.1	2.64	2.58-2.69	0.4	0.1-0.9	51 c
Norman Wells IOE samples	Imperial - shales, sandstones and siltstones	1.63	1.11-2.54	nm[3]	nm	nm	nm	5 c
	Canol - shales	1.31	1.09-1.52	nm	nm	nm	nm	3 c
	Kee scarp - limestones	2.37	1.9-2.6	nm	nm	nm	nm	3 c
NW No. 3	Imperial - shales	0.6	-	nm	nm	nm	nm	3 c
Fort Good Hope FGH No. 2	Cretaceous - shales	1.2	-	nm	nm	nm	nm	1 c
Eagle Plains EPB No. 62	Upper Devonian - sands, shales	1.8	1.3-3.2	nm	nm	nm	nm	9 d[2]
	Imperial - sandstones, siltstones and shales	1.5	1.4-1.5	nm	nm	nm	nm	2 d
	Canol - limestones	1.7	-	nm	nm	nm	nm	1 d
	Bear Rock - carbonates	1.8	-	nm	nm	nm	nm	1 d
Anderson Plains	Imperial - siltstones sandstones	1.8	1.2-2.3	2.62	2.48-2.78	1.5	0.1-2.7	32 c
	Canol - shales, siltstone	1.4	1.1-1.9	2.49	2.29-2.80	1.0	0.4-1.4	4 c
	Hume - carbonates	1.6	1.6-1.7	2.68	-	0.3	-	2 c
Mackenzie Delta EPB No. 63	Unconsolidated sand, silts	1.4 unfrozen	-	2.2	-	25	-	16 d
	and clays	2.1 frozen	-	2.2	-	25	-	16 d
Coppermine River Muskox	peridotites and gabbros	2.5	1.7-3.4	nm	nm	nm	nm	46 c

Footnotes:

c measurements on core samples
d measurements on drill cuttings
nm parameter not measured or not reported

on the exposed Shield. In general, the terrestrial heat flow along the Mackenzie Valley is fairly uniform and high in relation to much of the rest of Canada. To the west, the high values continue, whereas to the east lower values, more typical of shields, are found.

2.5 *Theoretical studies of the thermal regime*

The numerical techniques described in 2.1.3 have been used by Judge (1974d) to predict the permafrost thickness and distribution in the Beaufort Sea using physical parameters derived from deep holes in the Mackenzie Delta and a surface history derived from the literature. An important feature of the analysis is the demonstration of how heat flow measurements within and below the frozen section can be used to determine the surface temperature history and the extent of thermal disequilibrium.

Relict permafrost up to several hundreds of metres thick, mostly at temperatures between 0 and -1° C, may occur offshore of the Tuk peninsula and the northern delta below a water depth of as much as 80 m in response to eustatic changes of sea level many tens of thousands of years ago. Because of the rather different surface histories, this is not true of Shallow Bay nor of the Yukon coast east of Herschel Island. These differences in the thermal character of the subsurface have been confirmed by onshore borehole observations. Permafrost is observed to be aggrading in the young sediments of the onshore parts of Shallow and Mackenzie Bays (MacAulay *et al.*, in preparation, 1975). Rapid coastal recession of the Beaufort Sea shoreline may lead to thick permafrost in the nearshore areas. Results of numerical simulations have been shown to be consistent with observations from drilling in Kugmallit Bay at the exit of the east channel of the Mackenzie (Judge *et al.*, in preparation, 1975).

Similar numerical techniques have been applied to problems of permafrost aggradation and degradation in the Mackenzie Valley (Judge and Taylor, in preparation, 1975). For example, permafrost in a drained lake bed in the northern delta may accumulate by as much as 35 m in a period of 20 years. Conversely, if surface temperatures increase by 2K, as Judge (1974b) has shown to have occurred naturally, permafrost may degrade by as much as 90 m in a period of 100 years and may completely disappear in the marginal areas.

PART II

3. Implications of the results

As was reported by Judge (1974b) and confirmed by more recent observations (Judge and Taylor, in preparation, 1975), mean surface temperatures in much of the Mackenzie Valley south of 67°N are between 0° and -3°C. It is this range of temperatures that is of most concern from an engineering point of view because

a) a small change of temperature may greatly change the ice-to-water content of a frozen soil, and

1) change the volume occupied by the soil,
2) change its mechanical and thermal properties, and

b) various soil lithologies may or may not be frozen or partially frozen, depending on pore pressures and pore-water salinities, leading to possible moisture migration because of

1) permeable soil,
2) high local hydraulic gradients.

In the areas where mean temperatures are marginally below zero, a small increase in surface temperature may greatly degrade the permafrost, accompanied by

1) increased active layer development,
2) formation of thermokarst in areas of previously high ice content,
3) formation of palsas where peat insulates the subsurface,
4) mass flows on slopes and banks, and
5) changes in the flow patterns of surface and groundwater.

A small reduction in the surface temperature and a consequent aggradation of permafrost may result in

1) local heaving of the land surface,
2) formation of ice lenses and ice wedges,
3) changes in the vegetation, and
4) changes in the flow patterns of surface and groundwater.

Similar effects will also occur to the north of 67°, but to a much smaller extent because initial temperatures are well below 0°C. Thus, the general surface response will be confined to a change in the depth of the active layer and the corresponding geomorphological responses.

3.1 *Natural changes to the thermal environment*

In section 2.2, observations suggesting recent increases in surface temperatures have been described. If these increases were widespread, as little as 100 years ago the region described in Figure 3 as I belonged in II, etc., and may have been accompanied by quite drastic geomorphological changes. The effect of these changes on the thick permafrost of regions III and IV would be very small in comparison. Examination of historical records would confirm this. Changes of air temperature by 1 to 4K are observed throughout much of the northern hemisphere and are revealed in long-term meteorological records. Apparent accompanying changes in the shallow thermal regime are observed throughout most of Canada east of the Rocky Mountains. Current evidence also suggests that this warming period is now past its peak and a cooling period has commenced. If the changes are periodic in nature, general cooling may continue for several more decades. This time scale is certainly significant from an engineering standpoint.

3.2 *Man-made changes to the thermal environment*

Similar effects to those discussed in 3 and 3.1 will result from man-made changes to the environment. Such changes occur more rapidly, are more localized in extent, and may cause similar but restricted changes to landforms.

As is discussed in sections 3 and 3.1, the total effect of a change of surface temperature may be quite drastic, particularly in zones I, II and IIa. Changes in the thermal regime occur rapidly by heat conduction alone, as is illustrated in section 2.4. In assessing the thermal disturbance and its consequences in a human context, two aspects are important: the effect of the disturbance on the local environment and the effect of the changes caused to the environment on engineering structures. On a local scale, the immediate consequences of man-made changes may be far more serious than those resulting from natural changes.

An aspect of the pipeline construction might be used as an illustration. The creation of a right-of-way by removal of vegetation will generally increase the surface temperature and may initiate the various surface effects listed in section 3. The end result could be to create a selective path for the movement of surface-and groundwater, in fact, a "water-rich" environment and a more permeable soil. A chilled pipe inserted within the right-of-way may therefore be more subject to heave damage due to moisture migration to, and ice buildup around the pipe, than if no right-of-way had been cleared.

4. Conclusions

The thermal regime of the Mackenzie Valley and Delta has been investigated both by field observations of ground temperature and by field and laboratory measurements of thermal conductivity of both frozen and unfrozen rocks and soils. As a result of these studies, it is concluded that:

1) The mean annual surface temperatures along the Mackenzie Valley range from 1.6° to -8.8°C. Local spatial variations of up to 3K are found. Mean surface temperatures are consistently above the mean annual air temperature by 3 to 8K.

2) Much of the Mackenzie Valley up to 67°N is at mean surface temperatures between 0 and -3.0°C. It is over this temperature range that the largest changes in the physical properties of moist unconsolidated soils occur.

3) The difference between surface and air temperatures is largely explained by the insulating qualities of the winter snow cover, the time of onset, of persistence and the total thickness of the snow cover. Although winter air temperatures frequently fall below -40°C, measured surface temperatures south of 67°N rarely fall below -10°C.

4) The mean annual range of near-surface temperatures varies from 32K on exposed bedrock to as low as 2.4K in a wet peat terrain. In contrast, the range of mean annual air temperature is 45K.

5) Large variations were noted in the depth of penetration of the annual wave. At exposed bedrock sites, the depth at which the annual amplitude is reduced to 0.1K is in excess of 15 m. At moist sites with thick overburden, the depth is half as great.

6) The active or frost-prone layer varies in thickness from as much as 15 m on exposed bedrock to 0.6 m through a peat cover. Where overburden covers the bedrock, the active layer development is reduced to 0.6 m to 2.0 m.

7) Considerable observational evidence exists for an increase of about 2K during the past century in the mean surface temperature. This

may be variously attributed to changes of climate, to the effects of forest fires and to the effects of development.

8) Geothermal gradients in the region vary from 10 mKm^{-1} through rocks of the Canadian Shield to 84 mKm^{-1} through shales of the Mackenzie Valley.

9) Corresponding permafrost thicknesses range from 0 m in the south of the region to in excess of 500 m in parts of the Mackenzie Delta. Locally, the largest variations occur between the older and younger parts of the Delta.

10) Measured thermal conductivities of overburden materials average 1.9 $Wm^{-1}K^{-1}$ for frozen sands with a water content of 19 to 32 per cent, and 1.2 $Wm^{-1}K^{-1}$ for frozen clays with water content of 8 to 167 per cent. The frozen conductivities are generally up to 30 per cent higher than the unfrozen values. Little variation was noted in the conductivity of individual samples over the temperature range of -2.5° to -10°C.

11) Bedrock materials vary more widely in thermal conductivity. Measured values range from 0.6 $Wm^{-1}K^{-1}$ in poorly compacted shales to as high as 3.5 $Wm^{-1}K^{-1}$ in Precambrian granites. Variations are largely a factor of lithology and porosity.

5. Recommendations

From the studies made as part of this program, a regional picture of the spatial and depth variations in the thermal regime has emerged. The most significant information from an engineering viewpoint is the thermal state both south of 67°N and in the younger parts of the Mackenzie Delta. It is apparent that the present state is one of only quasi-equilibrium as there is considerable evidence for surface temperature changes of several degrees having occurred in this century. Changes of this magnitude have occurred quite generally in the northern hemisphere and are revealed in ground temperature profiles and long-term meteorological records. While such changes are not important in engineering design in southern Canada, they are very important in the marginal permafrost areas where small changes in surface temperatures may have drastic effects on the geometry of the land surface. It is therefore recommended that observational programs be repeated at five-year intervals at presently instrumented shallow sites to determine the long-term trends and that similar monitoring programs be established elsewhere if the proposed gas pipeline is constructed. Further measurements are still required of the thermal properties of frozen and unfrozen soils from northern areas in order to develop an adequate data base. This should be coupled with detailed physical studies of the transition between the state of freezing and of thawing. In the work described here, it has been assumed that the dominant mechanism of heat transfer is conduction. However, moisture migration is important under certain circumstances and its role requires further investigation.

6. Publications

Jessop, A.M. 1970. How to beat permafrost problems. *Oilweek*, 12th January 1970.

Jessop, A.M. 1972. Heat flow and permafrost. *Bull. Can. Inst. Min. Met. 65*, p. #45-48.

Jessop, A.M. 1973. Terrestrial heat flow and permafrost. *NRC Tech. Mem. 108*, p. #57-59.

Jessop, A.M. and Judge, A.S. 1974. Temperature and heat flux measurements through permafrost as a geophysical tool. *Proc. Symp. Permafrost Geophysics. NRC Tech. Mem. 113*, p. #17-27.

Judge, A.S. 1972a. Geothermal studies conducted in conjunction with the Geological Survey of Canada drilling project at Fort Good Hope, N.W.T. *Proc. Can. Northern Pipelines Res. Conf., NRC Tech. Mem. CRCC 12498*, p. #161-162.

Judge, A.S. 1972b. Predicting the depth of permafrost. *Oilweek*, 17th July 1972.

Judge, A.S. 1973a. The prediction of permafrost thickness. *Can. Geotech. J., 10*, p. #1-11.

Judge, A.S. 1973b. Deep temperature observations in the Canadian North. *North American Contrib., 2nd International Permafrost Conf.*, NAS/NRC, Washington, p. #35-41.

Judge, A.S. 1973c. Measurement of thermal conductivity of earth materials. *Proc. Symp. Thermal regime and measurements in permafrost, Tech. Memo. No. 108, Assoc. Comm. Geotech. Res., NRC*, p. #26-31.

Judge, A.S. 1973d. Ground temperature measurement using thermistors. *Proc. Symp. Thermal regime and measurements in permafrost, Tech. Memo No. 108, Assoc. Comm. Geotech. Res., NRC*, p. #13-22.

Judge, A.S. 1973e. Selected bibliography of heat flow measurements and subsurface temperatures in the Canadian Arctic and

Alaska. *Proc. Symp. Thermal regime and measurements in permafrost*, Tech. Memo. No. 108, Assoc. Comm. Geotech. Res., NRC, p. #54-59.

Judge, A.S. 1974a. Geothermal measurements in northern Canada. *Proc. Symp. Geology of the Canadian Arctic*, GAC/CSPC vol., p. #301-312.

Judge, A.S. 1974b. Thermal regime of the Mackenzie Valley: Observations of the Natural State Report. *Environmental-Social Committee on Northern Pipelines, Rept. No. 73-38*, 175 p.

Judge, A.S. 1974c. Summary report to Environmental-Social Committee on Northern Pipelines, *Internal Report*, 4 p., April 1974.

Judge, A.S. 1974d. The occurrence of offshore permafrost in northern Canada. In: *Beaufort Sea Symposium, Arctic Inst. N. America*, San Francisco, p. #427-437.

Taylor, A.E. and Judge, A.S. 1974a. Return to equilibrium of permafrost observation holes in northern Canada. *EOS*. 55, p. #424.

Taylor, A.E. and Judge, A.S. 1974b. Canadian geothermal data collection - Northern Wells 1955 to February 1974. *Geothermal Service of Canada Series, No. 1*, 171 p.