

Electro-magnetic induction methods for mapping permafrost along northern pipeline corridors

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Electro-magnetic induction methods have been used to map permafrost over more than 1000 km of northern gas-pipeline corridors over the past five years. The soil conductivity data obtained is integrated with other geological and geotechnical information in order to 1) identify optimal borehole locations, 2) map extent of permafrost degradation in areas of cultural disturbance, and 3) map lateral and vertical extent of permafrost between boreholes. Electro-magnetic induction instruments induce an electric current in the ground. The magnitude of the induced current depends on the conductivity of the soil. Soil conductivities can often be ten times higher for unfrozen ground than for frozen ground.

Several inversion techniques are used to establish the conductivities of the different frozen and unfrozen soil strata. The more useful methods use borehole information and the "geometric factor" approach. When integrated with borehole and other site-specific geological and geotechnical information, the conductivity data has provided much valuable information on the lateral and vertical extent of frozen soil along the pipeline corridor.

Depuis cinq ans, on emploie les méthodes d'induction électromagnétique pour cartographier le pergélisol sur une longueur de plus de 1000 kilomètres, le long du couloir du gazoduc construit dans le Nord. On a intégré les données sur la conductivité des sols, à l'information géologique et géotechnique 1) pour identifier l'emplacement optimal des sondages, 2) pour cartographier l'étendue de la dégradation causée par le pergélisol dans les zones où la végétation se développe difficilement et 3) pour cartographier l'extension latérale et verticale du pergélisol entre les sondages. Les instruments d'induction électromagnétique servent à induire un courant électrique dans le sol. L'intensité du courant électrique dépend de la conductivité du sol. Parfois, la conductivité du sol peut être dix fois plus élevée dans le sol non gelé que dans les sols gelés.

On emploie plusieurs techniques d'inversion pour établir la conductivité des diverses strates de sol gelé ou non gelé. Les méthodes les plus efficaces font appel à l'information obtenue avec les sondages, et à la méthode des "facteurs géométriques". Lorsqu'on les a intégrées aux sondages et aux autres études géologiques et géotechniques du site, les données sur la conductivité nous ont fourni des informations précieuses sur l'extension latérale et verticale du pergélisol le long du couloir du gazoduc.

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Introduction

The design of gas pipelines and related facilities in northern areas requires a detailed knowledge of the distribution of permafrost in the shallow subsurface (<15 m depth). Since vast areas of remote and rugged terrain are to be investigated, fully integrated exploration programs involving geological, geophysical, and geotechnical studies are presently being used. The roles of geological and geophysical methods in these programs are primarily to identify and categorize variations in terrain. Boreholes, fulfilling definite exploration objectives, may then be located in an orderly fashion. The subsurface conditions reported from boreholes can often be used to predict conditions in adjacent areas where geophysical data indicate similar terrain.

Over the past five years, shallow electro-magnetic (EM) survey lines totalling more than 1000 kilometres have been run in conjunction with these exploration programs. This paper discusses the application of shallow EM survey methods to map the distribution of frozen ground, some of the interpretive methods used, and illustrative examples.

Study Area

EM surveys have been conducted to delineate the distribution of frozen ground along five major proposed northern pipeline corridors. These routes (Figure 1) are

- 1) Alaska Highway Natural Gas Pipeline:
 - a) in Alaska — about 500 kms of survey from Prudhoe Bay to the Alaska-Yukon boundary,
 - b) in southern Yukon — about 450 kms of survey from the Alaska-Yukon boundary to Watson Lake, and
 - c) in northern British Columbia — about 50 kms of survey from Lower Post to Fort St. John;
- 2) Dempster Lateral Natural Gas Pipeline, in central to northern Yukon and north-western N.W.T. — about 30 kms of survey from Whitehorse to Inuvik; and
- 3) Canadian Arctic Gas Pipeline project (abandoned), central to southern Mackenzie Valley — about 300 kms of survey from Fort Norman to the N.W.T.-Alberta border.

Most of these areas lie within the discontinuous permafrost zone (Brown 1967). Many sites are remote

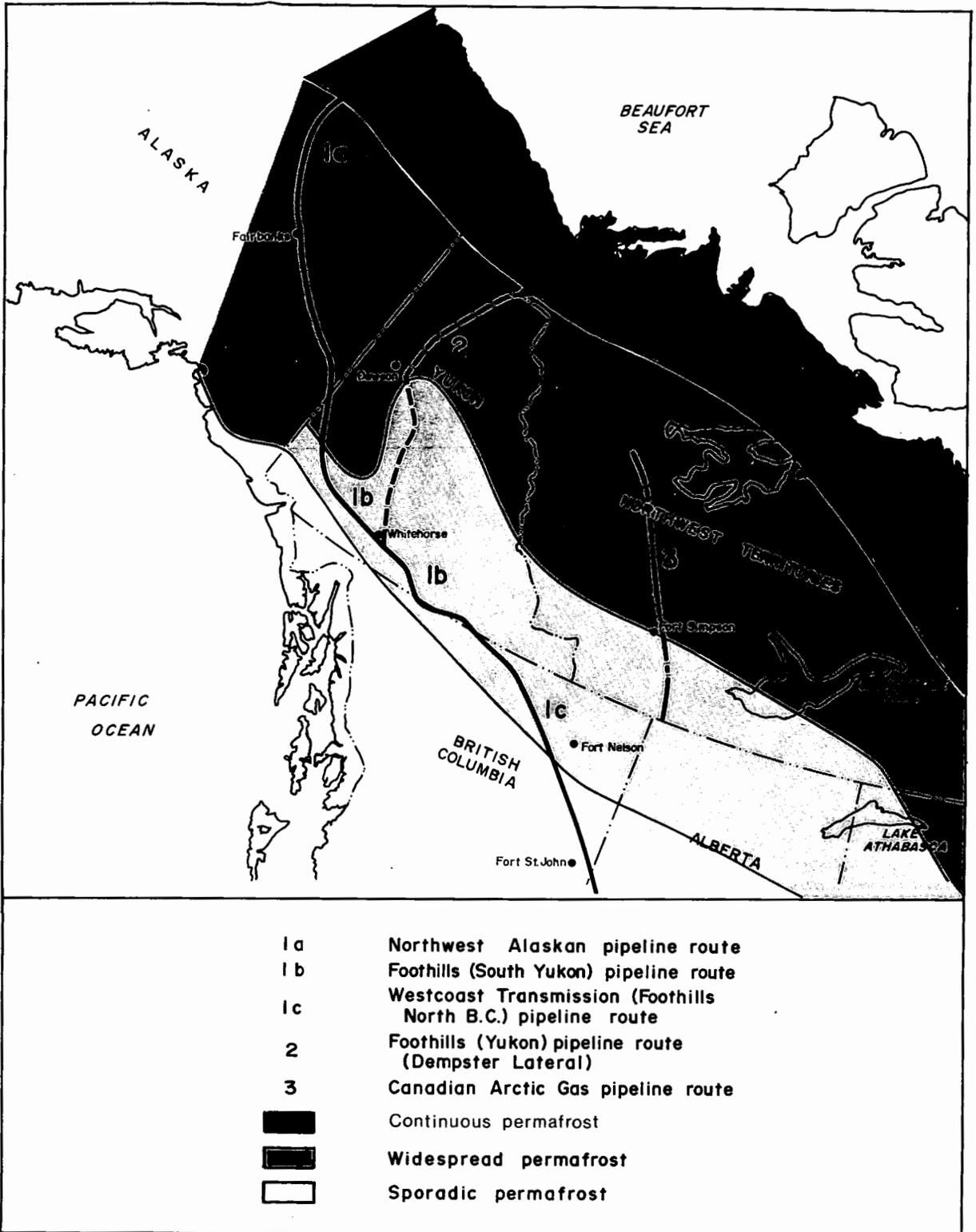


FIGURE 1. Location map of study areas (after Brown 1967 and Ferrians 1965).

and situated in rough terrain. Access to sites may be better in the summer or winter, depending on the number and frequency of stream crossings, lakes, and bogs.

Objectives of Electro-magnetic Surveying

Most of the EM surveys along pipeline corridors in permafrost terrain have been undertaken to aid in pipeline routing and design. The surveys are tailored to meet three primary objectives:

- 1) Locating suitable unfrozen and frozen terrain to be probed with test borings. This allows boreholes to be placed to meet specific requirements, e.g. gathering ice-rich soil samples.
- 2) Mapping the extent of permafrost degradation and locating frozen-unfrozen soil boundaries at crossings of roadways, other pipelines, burned areas, and naturally occurring thermokarst and taliks. Such information is often useful for estimating the need and cost of special design requirements in construction.
- 3) Mapping the lateral and vertical extent of unfrozen or frozen terrain along the lines surveyed. This allows a near-continuous profile of the shallow subsurface to be prepared between boreholes. The profiles are often used as a guide when planning future exploration programs.

Instrumentation

The equipment used for shallow EM surveying are the Geonics terrain conductivity meters, the EM31 and EM34-3. The EM31 has two coils mounted on a rigid (collapsible) fibreglass boom. Coil separation and frequency of operation are 3.66 m and 9.8 kHz, respectively. It weighs about 9 kg and is operated by one man. The instrument is used to give information on the conductivity stratification in the upper six metres using both horizontal and vertical coplanar coil configuration in which horizontal and vertical refer to the plane of the coil.

The EM34-3 is a two-man version of the EM31. It has two, eighty-centimetre coils connected by a reference cable. Loop separations of 10, 20, or 40 m can be used. The frequency of operation for each of the separation is 6.4, 1.6, and 0.4 kHz, respectively. Measurements can be taken with either vertical or horizontal coplanar loop configurations. The instrument is influenced by soil strata extending well below six metres and is used for determining the background conductivities over which the EM31 measurements are taken. For northern pipeline work the EM34-3 is generally used with the vertical loop configuration and 20 m separation to extend information

on the conductivity stratification to about 15 m depth.

This equipment exhibits a number of features that enhance its use for northern pipeline surveys, namely, portability and ruggedness, survey productivity, good resolution, reliable operation over a wide range of air temperatures, linearity between meter reading and ground conductivity over a large range of ground conductivity values, and relatively simple interpretative techniques for ground with conductivity stratification.

Soil-Conductivity Relationships

In permafrost-free terrain, the soil types of the Unified Soil Classification System may be identified by characteristic conductivity values. From the standard relationship between soil type and conductivity, three important conclusions can be drawn (Figure 2):

- 1) for distinct soil types, the conductivity generally increases as particle size decreases (fine sands are an exception to this rule);
- 2) for mixed soil types, the conductivity increases as the percentage of clay-size material increases; and
- 3) the conductivities for specific soil types may overlap. It is precisely because of this overlap that geological and geotechnical information and an appreciation of site-specific observations, such as the vegetation, topography, and drainage are always required to guide the interpretation of EM measurements.

In permafrost terrain, frozen and unfrozen soils of the same type may have substantially different electrical conductivities (Figure 3). Important is the fact that the ratio of unfrozen-to-frozen soil conductivity is often greater in fine-grained soils than in granular soils. The accuracy of mapping frozen-unfrozen

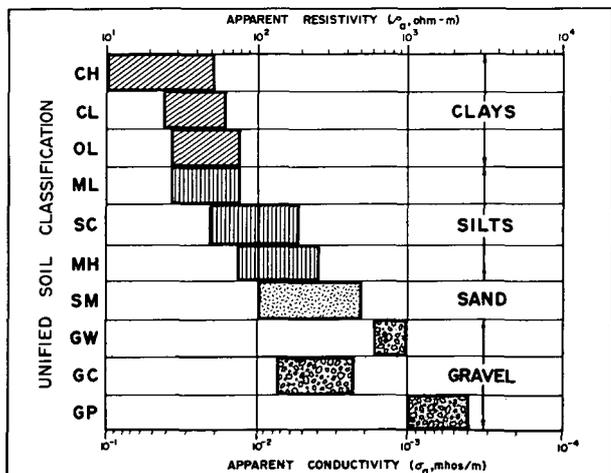


FIGURE 2. Conductivity versus soil type.

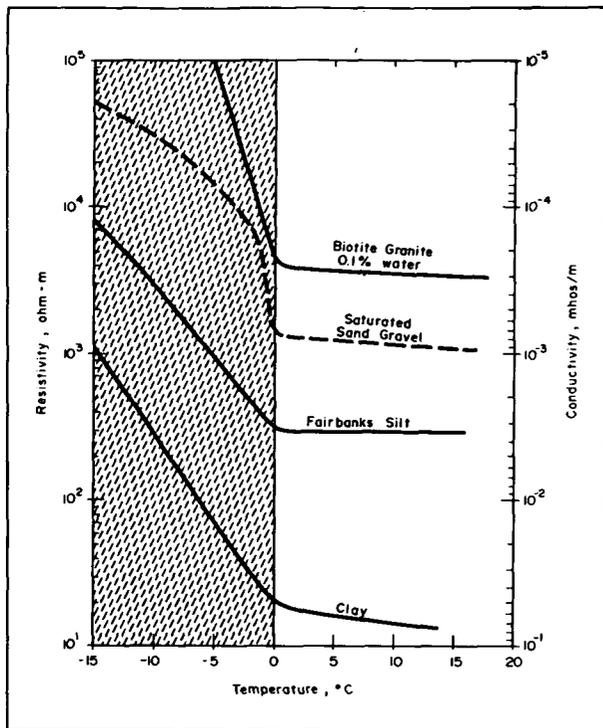


FIGURE 3. Conductivity versus temperature (after Hoekstra and McNeill 1973).

boundaries in a soil generally increases as this ratio increases.

The conductivity of frozen soils may be very much less than that indicated by the previous figure, depending upon ice content (Figure 4). High ice contents may reduce conductivities to below 1 mmho/m. These low values are not readily measured with the equipment used, due to low signal-to-noise ratios in this range. Consequently, EM conductivity surveys have been less successful in predicting the ice content of soils. For a more complete discussion of the electrical properties of soils and rocks, McNeill (1979) should be consulted.

Electromagnetic Induction Method

The conductivity of the ground may be mapped from the surface by several different methods. For surveying along northern pipeline routes, the electromagnetic induction method is used because of its many advantages.

In the electromagnetic induction method, current flow is induced in the ground by the oscillating magnetic field of a magnetic dipole transmitter, which consists of a loop antenna through which an oscillating electric current is forced. The transmitted, or primary, oscillating magnetic field induces horizontal eddy currents in the subsurface. These eddy currents, in turn, produce a secondary oscillating magnetic field.

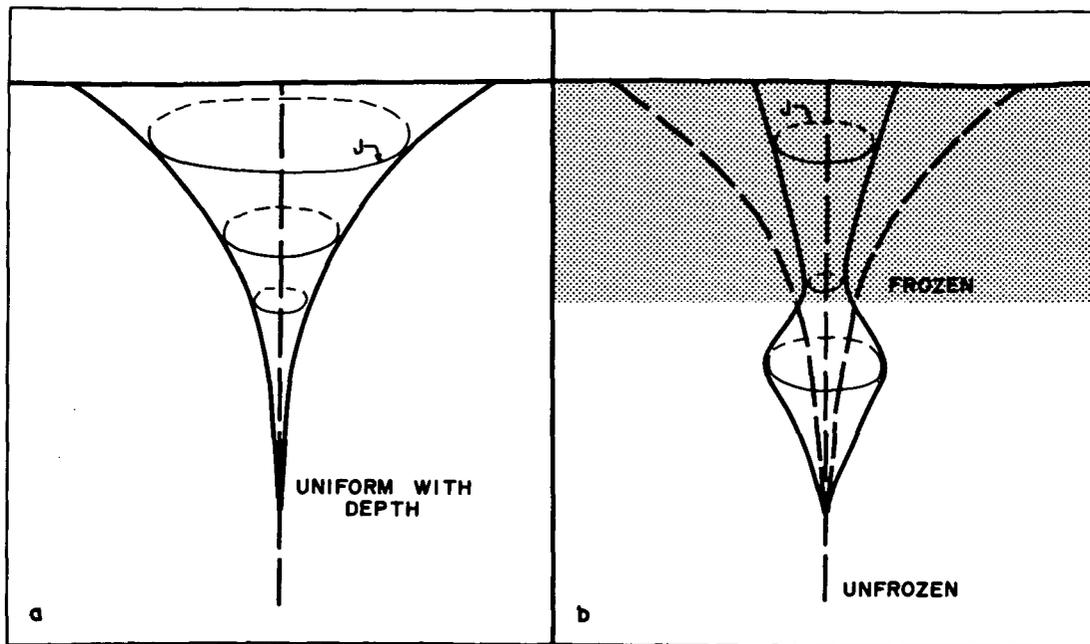


FIGURE 5a. Eddy current distribution (J) for ground of conductivity uniform with depth. b. Eddy current distribution (J) for layered ground, conductor below.

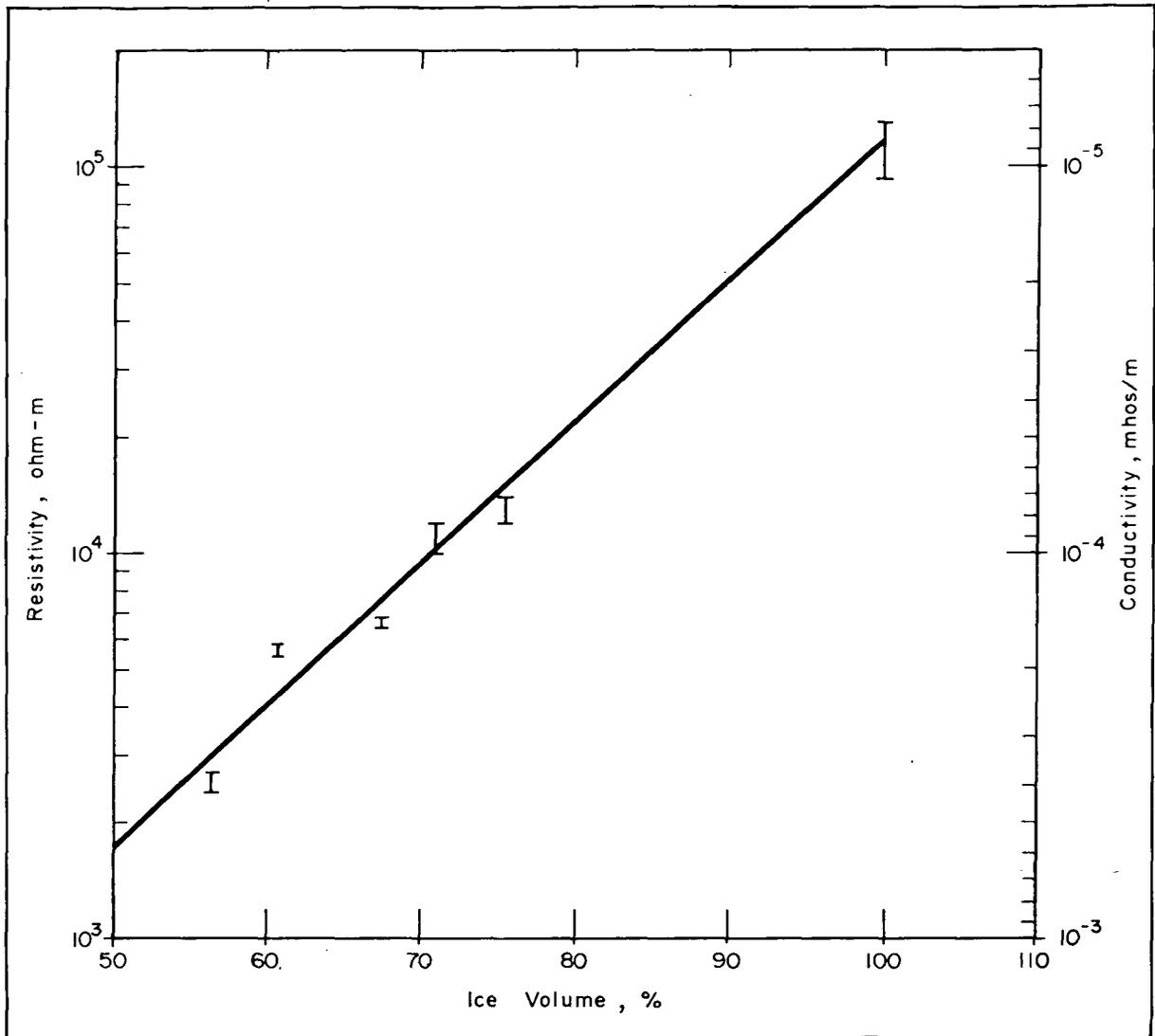


FIGURE 4. Conductivity versus ice content (after Hoekstra and McNeill 1973).

The instruments operate in steady state. Therefore, the electromotive force induced in the receiver coil is proportional to the total (primary and secondary) magnetic field. The effect of the primary magnetic field is electronically cancelled within the instrument. The quadrature phase of the secondary magnetic field can be shown to be linearly related to the ground conductivity, over a wide range of ground conductivities, under conditions fulfilled within the design of the instruments. Details are available in McNeill (1980).

The amount of eddy current flow at each point in the ground is proportional to the product of primary field intensity and local soil conductivity. The primary field decreases rapidly with depth, so that over terrain uniform in conductivity, the amount of cur-

rent flow also decreases with depth (Figure 5a). The conductivity measured over homogeneous ground will be the true conductivity plus calibration error. The conductivity measured over layered ground (Figure 5b) is termed the apparent conductivity. For layered ground, the apparent conductivities measured with instruments having different exploration depths will not be the same. Their relative values enable a qualitative assessment of the conductivity stratification in the ground to be made. The exploration depth of an instrument is dependent on the spacing between transmitter and receiver, the orientation of the loops and, to a lesser extent, the frequency of operation and layering in the ground.

Layered Earth

To study the instrument response above layered earth the geometric factor approach is used. The geometric factor is the normal primary field strength below any depth in the subsurface. This approach assumes that each layer in the subsurface acts independently, so that eddy currents induced in one layer do not significantly affect eddy current flow induced in adjacent layers. The assumption holds well at the low values of terrain conductivity usually encountered in northern areas.

The advantage of this approach is that the secondary magnetic field measured at the surface over layered ground can be considered as a simple summation of contributions by horizontal strata. The summation, in terms of apparent conductivity, is given by

$$[1] \quad \sigma_a = \sum_{i=1}^n \sigma_i (R_i - R_{i-1})$$

where σ_a is the apparent conductivity given by the instrument,

σ_i is the conductivity of the i th layer, and

R_{i-1}, R_i are the geometric factors of half-space bounded by the top and bottom of the i th layer.

This relation can be simplified in terms of the geometric factor so that:

$$[2] \quad \sigma_a = \sum_{i=1}^n R_{i-1} C_i$$

where R_{i-1} is the geometric factor for the half-space bounded by the top of layer i , and

$C_i = \sigma_i - \sigma_{i-1}$ is the conductivity difference between the i th layer and the $(i-1)$ th layer.

For the case of two layers ($n=2$)

$$\sigma_a = R_0 C_1 + R_1 C_2$$

where R_0 is the geometric factor at ground surface,

R_1 is the geometric factor at the interface of interest,

$C_1 = (\sigma_1 - 0)$ where 0 approximates the conductivity of air, and

$$C_2 = (\sigma_2 - \sigma_1).$$

Geometric factors are a function of instrument parameters and depth only. For horizontal coplanar loops (vertical coplanar magnetic dipoles) they may be determined from the relation

$$[3] \quad R_H(D) = (D^2 + 1)^{-1/2}, \text{ and}$$

for vertical coplanar loops (horizontal coplanar magnetic dipoles) from

$$[4] \quad R_V(D) = [D + (D^2 + 1)^{1/2}]^{-1}.$$

The parameter ' D ' is equal to twice the depth, d , divided by the coil separation, s , i.e.

$$[5] \quad D = 2d/s.$$

The geometric factor functions for both loop configurations are shown in terms of this parameter, D , (Figure 6).

For a given loop spacing and configuration, an estimate of the effective exploration depth for each instrument mode can be determined. The effective depth of exploration is an arbitrary value that may be defined as the depth to which the primary (exciting) field falls to $1/e$ (~ 37 per cent) its value at the surface. Consideration of this value allows one to qualitatively determine the conductivity stratification in the ground.

In Table 1 are listed the effective depths of exploration and the symbolism used for each instrument mode in the examples that follow.

Terrain Models

For the purposes of interpretation, the apparent conductivity data is analyzed considering models representative of the terrain. The results of numerous boreholes suggest that the distribution of frozen ground during summer and winter surveys may be generally modelled as shown in Figure 7. The thickness and conductivity of each layer must be determined such that the apparent conductivities calculated for the model match the apparent conductivities observed.

For each of the seasonal models in Figure 7, the middle case (three layer case) is the most complex. It

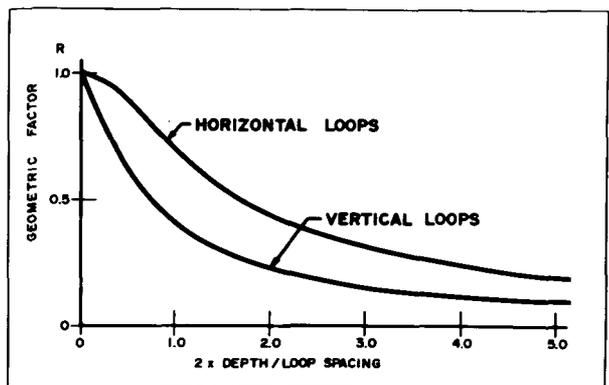


FIGURE 6. Geometric factors for horizontal and vertical loops.

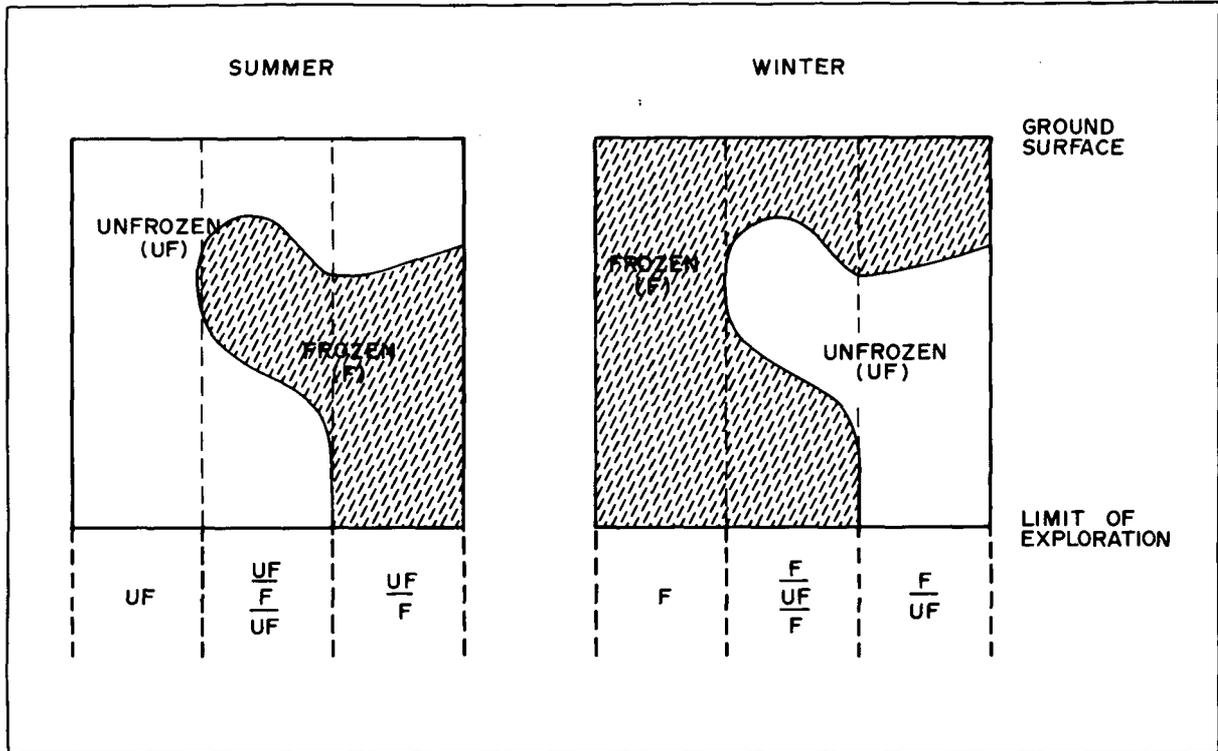


FIGURE 7. Terrain models.

simplifies to either of the two other cases, depending upon the thickness of intermediate layer, as it varies from nil to greater than the limit of exploration.

The upper layer in each model may encompass only the active layer or a combined thickness of active layer and thermally similar underlying soils. Vertical changes in soil type do not complicate the model layering if the soil-type boundaries coincide with the boundaries between frozen and unfrozen ground. Many of the examples cited reflect this condition. There may be difficulty in the interpretation of results over terrain where changes in soil type do not coincide with thermal boundaries or where the layering of

frozen and unfrozen strata is more complex than indicated in the models above.

Methods of Interpretation

The interpretation of apparent conductivity data, when delineating the distribution of frozen ground, generally falls into two stages. The preliminary stage involves a qualitative assessment of the terrain for the purpose of locating boreholes. In this regard, the interpretation is constrained by considering the conductivity stratification evident from the measurements, the terrain model anticipated and the geological conditions present. An appreciation for site-specific observations such as vegetation, topography, and drainage is important at this stage since the interpreter may eliminate certain unfrozen but low-conductivity anomalies, that could be confused with the presence of frozen ground, before they are drilled.

A few examples are described from surveys where EM methods have suggested the presence of permafrost using the above procedures. Subsequent boreholes have confirmed frozen ground conditions. The boundary line between frozen and unfrozen ground (bottom part of figures) is determined during the next

TABLE 1. Effective exploration depth for magnetic induction instruments

Instrument		Depth (m)
EM31(VG)	(vertical loops, ground level)	2.1
EM31(HZ)	(horizontal loops, hip level)	3.7
EM31(HG)	(horizontal loops, ground level)	4.6
EM34-3 (10 m)	(vertical loops, 10 m coil separation)	5.5
EM34-3 (20 m)	(vertical loops, 20 m coil separation)	11.5

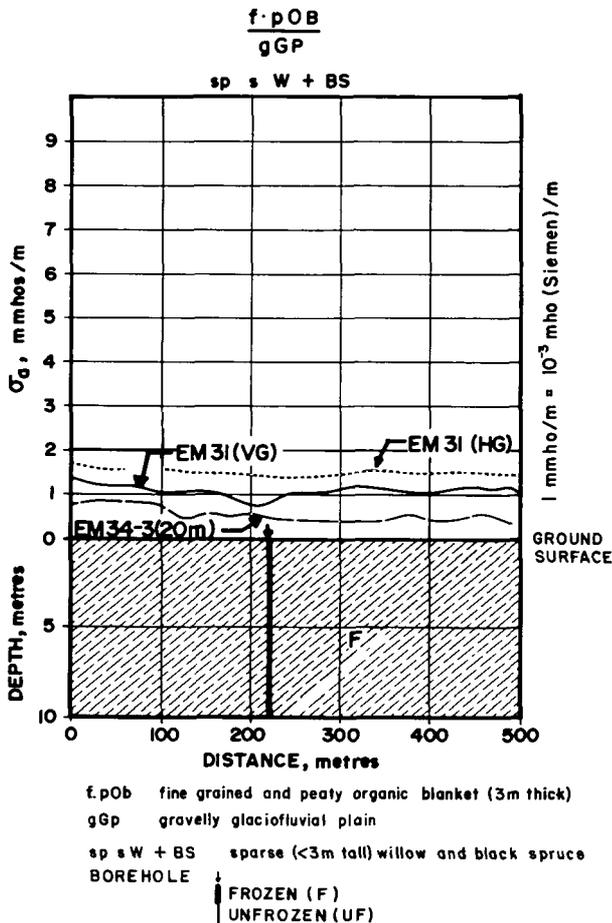


FIGURE 8. Continuously frozen in winter.

stage of interpretation, after placement of the boreholes.

Measurements taken during winter at a site across Snag Creek Flats near the Alaska border in the Yukon are illustrated in Figure 8. Fine-grained soils and organic materials lie up to three metres thick over gravelly outwash in this area, and only sparse stands of short black spruce and willow are present. The low and uniform conductivity measurements indicate no unfrozen zones. A borehole could be conveniently located on a trail, in a clearing, etc., along this line and still encounter similar soil and thermal conditions.

Measurements taken during winter at a site across Pine Creek, Yukon Territory, in discontinuously frozen ground are illustrated in Figure 9. The site lies over a lake plain and creek flood-plain. The location and extent of frozen zones are identified with conductivity lows and are confirmed by the boreholes. White spruce are generally found in unfrozen and moderately to well-drained environments. However, due to

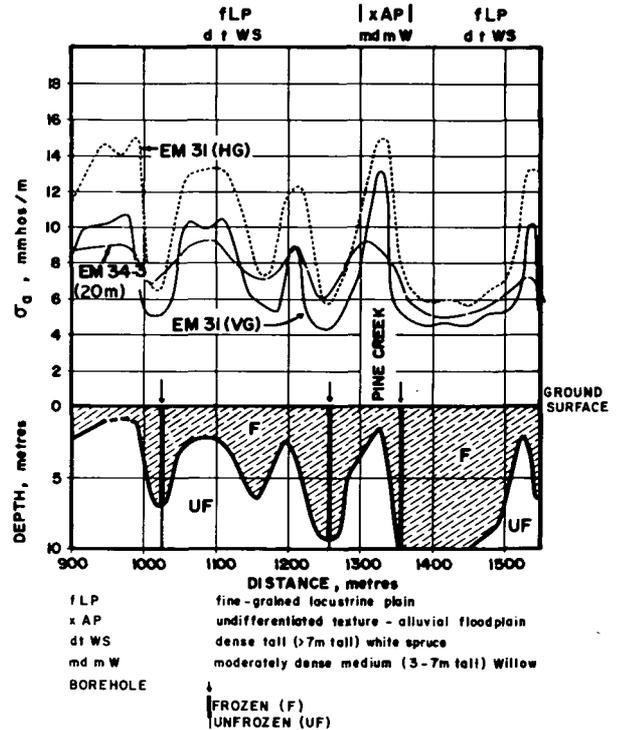


FIGURE 9. Discontinuously frozen in winter.

shading by the spruce, permafrost may develop in sporadic fashion. At this location, analysis is facilitated by the relatively large contrast in frozen and unfrozen fine-grained soil conductivities.

Measurements over a discontinuously frozen area surveyed in summer are illustrated in Figure 10. The site lies across a poorly drained lake basin. Permafrost is expected to border the marshy area. The boreholes at stations 4 + 40 and 7 + 20 indicate that frozen and unfrozen soils can be associated with the respective low and high conductivity levels apparent in the data.

A frozen-unfrozen soil transition, surveyed during summer, is illustrated in Figure 11. The site lies across fine-grained alluvial deposits bordering Edith Creek, Yukon Territory. The conductivity highs at the left of the figure represent the extent of the thaw bulb adjacent to Edith Creek. The variation in the shallow-looking EM31(VG) data is due primarily to the presence of the conductive unfrozen active layer. In such areas, where the presence of a conductive active layer serves to mask the response from lower, more-resistant soils, surveys would be best performed in winter when this active layer would be frozen.

The second stage of the interpretation deals with extrapolation of conditions found at boreholes to other areas along the survey lines. The general

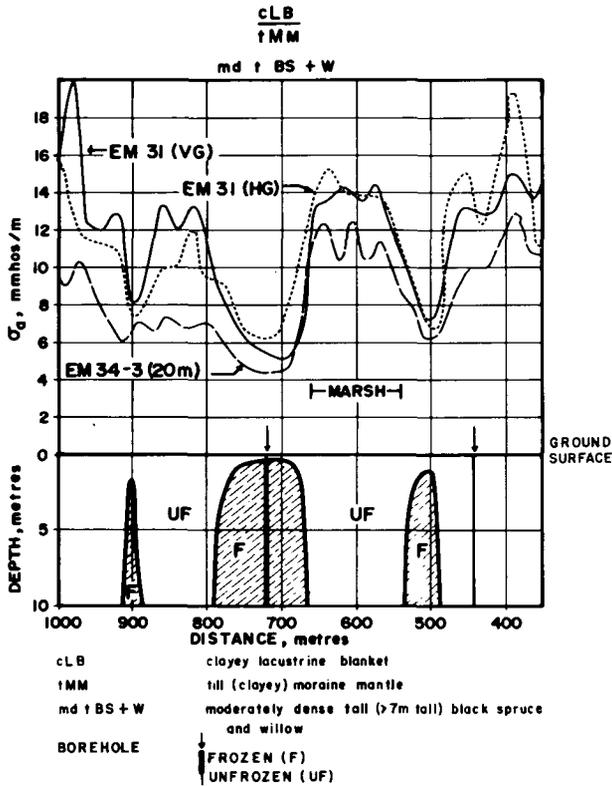


FIGURE 10. Discontinuously frozen in summer.

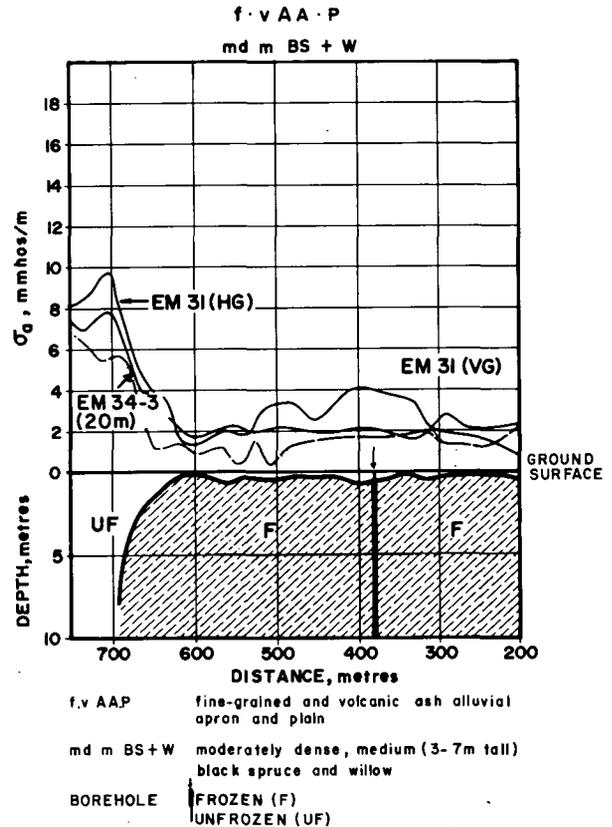


FIGURE 11. Unfrozen-frozen boundary in summer.

approach is to determine the conductivity for each significant layer in the subsurface from the apparent conductivity data and layer thicknesses reported at the borehole. These soil conductivities are assumed to remain relatively constant away from the borehole so that changes in the observed apparent conductivity are due only to variations in the thicknesses of the layers. Borehole or other direct information on the subsurface is required at this stage since it is generally not possible to determine reliable values for both depth and ground conductivity even when several measurements are made with different coils spacings and orientation.

Application of model parameter (soil conductivities) is restricted to terrain with expected similarities in stratigraphy and soil type. Terrain typing boundaries, mapped by project geologists on project alignment sheets, are used as a guideline for determining the lateral extent of usefulness for each model developed. Often these terrain boundaries are evident, either as sharp or as gradual changes, on the observed conductivity profiles.

Methods available to determine the subsurface layer conductivities are outlined.

Conductivities Determined Without Borehole Control

There are essentially three methods of determining usable conductivity values where no borehole control is available. These include:

- (i) the use of standard values for the expected soil type;
- (ii) direct observation of frozen and unfrozen soil conductivities at location where the soils are expected to be reasonably homogeneous to the depth of exploration; and
- (iii) the use of frozen and unfrozen soil conductivities from other locations where the soils are expected to be similar and for which the conductivities have been determined from borehole findings.

Interpretations made without the benefit of borehole control may be misleading. They are prepared on the assumption that conductivity lows probably represent frozen ground. Where no boreholes are placed to confirm the preliminary interpretation the interpreter may find himself caught up in any of the pitfalls described later.

Conductivities Determined using Depths Reported in Boreholes

"Inversion" techniques are necessary to determine the conductivity of frozen or unfrozen soil types from the apparent conductivities and layer thicknesses reported from boreholes. These techniques will produce results that are more or less reliable, depending mainly upon the variation in subsurface conditions with distance from the borehole.

The relation between measured apparent conductivity, the geometric factor (depth), and layer conductivity (equation 2) can be written as

$$\sigma_a = R_0 C_1 + R_1 C_2 + R_2 C_3 + \dots$$

One such equation can be written for each instrument measurement at each borehole in similar terrain.

a) Two-Layer Case

The two-layer case is the simplest situation for layered ground. Consider two different instrument measurements at a given borehole, resulting in two different equations

$$\text{(instrument 1)} \quad \sigma_a^{(1)} = C_1 R_0^{(1)} + C_2 R_1^{(1)}$$

$$\text{(instrument 2)} \quad \sigma_a^{(2)} = C_1 R_0^{(2)} + C_2 R_1^{(2)}$$

Since the R_0 and R_1 are known from the borehole log and the instrument parameters, the equations can be solved simultaneously for C_1 and C_2 , in turn giving σ_1 and σ_2 .

In some situations, there may be only measurements from one instrument at two, or more, boreholes located in geologically similar terrain. For the two-borehole case, the questions are

$$\text{(borehole 1)} \quad \sigma_a^{(1)} = C_1 R_0^{(1)} + C_2 R_1^{(1)}$$

$$\text{(borehole 2)} \quad \sigma_a^{(2)} = C_1 R_0^{(2)} + C_2 R_1^{(2)}$$

These equations may again be solved simultaneously to determine C_1 and C_2 , and σ_1 and σ_2 . When more than two boreholes are available, the solution is over determined. A "best fitting" solution may be determined using a least-squares method. The system of equations in this instance is

$$[6] \quad \begin{pmatrix} n & \Sigma R_i \\ \Sigma R_i & \Sigma (R_i)^2 \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} \Sigma (\sigma_a)_i \\ \Sigma R_i (\sigma_a)_i \end{pmatrix}$$

where n is the number of boreholes,
 R_i is the geometric factor of the interface for an instrument at each borehole,
 $(\sigma_a)_i$ is the apparent conductivity for an instrument at each borehole,
 C_1, C_2 are relatable to σ_1 and σ_2 , and the summation is over $i = 1$ to n .

Graphically, the observed apparent conductivities can be plotted on the vertical axis and the geometric

factors for the first layer thickness plotted on the horizontal axis. There will be one point for each instrument at each borehole. The best fitting line through these points will have a slope of C_2 and a conductivity intercept at C_1 .

b) Multi-Layer Case

The least-squares approach may be easily extended to solutions for multi-layered ground. Again, from equation 2;

$$\sigma_a = C_1 R_0 + C_2 R_1 + C_3 R_2 + \dots$$

With n layers there are n unknowns, C_1, \dots, C_n . Considering j different instrument readings at k different boreholes there will be $j*k > n$ equations. These may be solved using multiple linear regression methods to determine the C_i and, hence, the conductivity σ_i , for each layer.

Care must be taken to assure that these "best fitting" conductivity values are physically meaningful. Most pitfalls can be avoided with common sense. Poor values of conductivity for deeper layers may result unless an instrument with a large depth of exploration is used. Also, conductivities for thin layers will be difficult to determine.

The three-layer case can often be simplified to a combination of two-layer cases using two assumptions:

- (i) that the instrument used to determine the thickness of the first layer is not influenced by contributions from the third layer; and
- (ii) that the instrument used to determine the surface of the third layer is not influenced by contributions from the first layer or is influenced uniformly across the profile by the first layer.

The accuracy obtained using this method increases with an increase in the ratio of the second layer to first layer thickness.

Pitfalls

EM methods do not directly locate frozen ground. Rather, the presence of frozen ground is only inferred from the apparent conductivity measurements and experience in an area. There are many situations in which other terrain- and non-terrain-related factors combine to produce results that could be mistaken for permafrost. A few examples follow.

Dry Sand and Gravel

In measurements taken across outwash plain near Beaver Creek, Yukon Territory, (Figure 12), the feature of importance is that the conductivities measured over frozen and unfrozen segments of the line are very nearly identical. At this site, the transition from

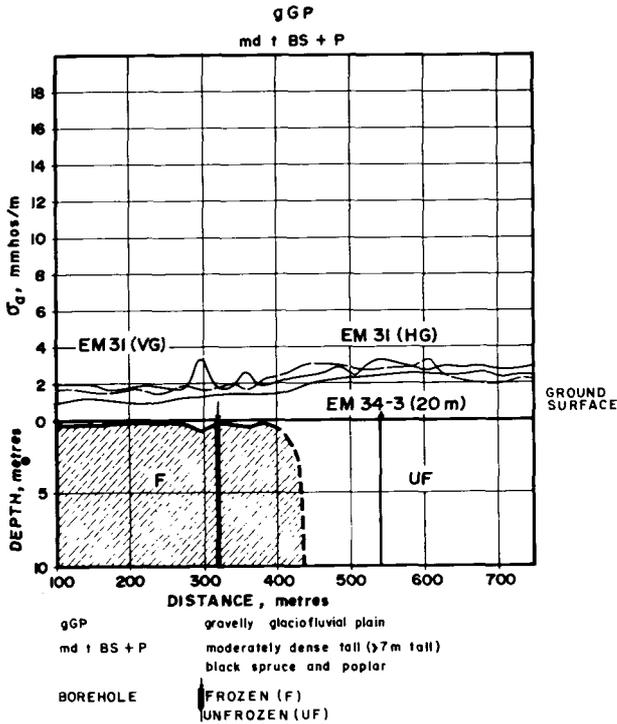


FIGURE 12. Dry sand and gravel.

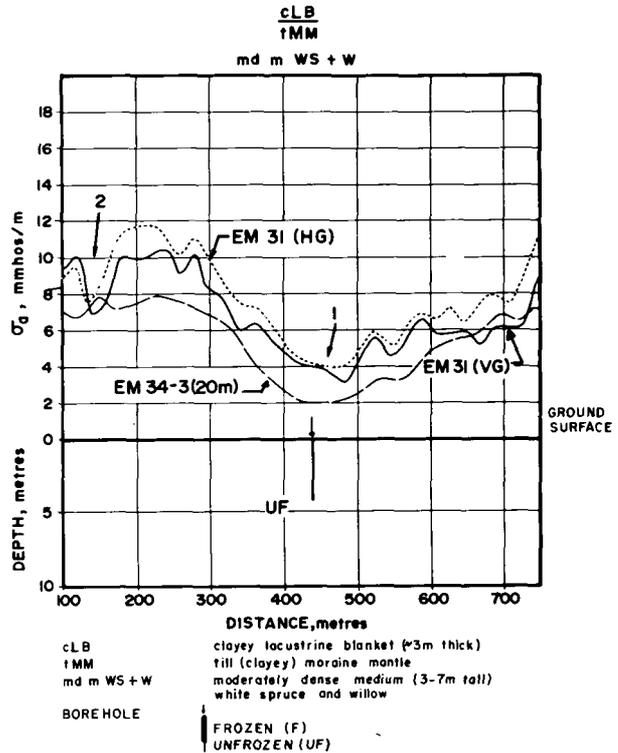


FIGURE 13. Near-surface bedrock.

frozen to unfrozen soils is best evidenced by the 1 mmho/m increase in the EM34-3 data at about station 4 + 30. Without borehole control it is impossible to reliably determine the frozen to unfrozen soil transition on the basis of EM measurements alone.

Stringers of sand, low profile dunes, or beach ridges in otherwise fine-grained areas may also be mistaken for frozen soil. Knowledge of the tree types and size, as well as the micro-relief in an area can do much to identify sandy anomalies before they are drilled.

Bedrock

Near-surface bedrock is often a complicating factor in EM surveying. The measurements illustrated in Figure 13 are across an area located close to that depicted in Figure 10. The segment labelled '1' shows stratification and conductivity values similar to those of the frozen areas (see Figure 10). At this location the ground was unfrozen with bedrock at shallow depth. The anomaly denoted as '2' is caused by near-surface soils and may be a sandy area or an area having a shallow, thin zone of frozen ground.

Cultural Features

Northern pipeline routes often cross frozen terrain that has been disturbed by the activities of man. The major disturbed corridors are those of the Alaska

Highway and the Haines-Fairbanks pipeline. EM surveys in the vicinity of these features often give the impression that unfrozen ground occurs to great depths. The apparent conductivity measurements have been shown not to be entirely terrain related. However, useful data may be obtained following proper survey procedures.

i) Alaska Highway

The Alaska Highway is a disturbed corridor under which frozen ground would be expected to be absent or deeper than in surrounding undisturbed terrain.

In Figure 14, on the left side are measurements from a summer survey across the Alaska Highway. From the large conductivity increases across the Highway, unfrozen ground to large depth could be expected, but the boreholes do not confirm this. The winter survey results, on the right hand side of the same figure, were from about 40 m away at the same crossing and indicate a much shallower thaw bulb. This discrepancy could be due to the fact that road salts used for road compaction and dust control are in solution during the summer and frozen during the winter. The salts serve to mask the true ground conductivities, and surveys across the highway would be best run during the winter months. For surveys performed during the summer, EM34-3 (20 m) measure-

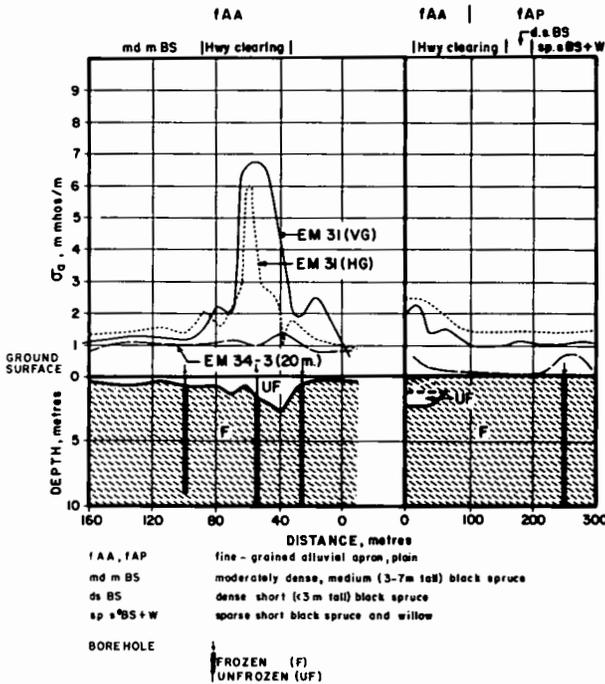


FIGURE 14. Alaska Highway.

ments taken perpendicular to the highway direction may provide the only useful data.

ii) Haines-Fairbanks Pipeline

Typical EM measurements across the ten-inch Haines-Fairbanks pipeline, which is still present on the ground surface along much of the pipeline route in Alaska and the Yukon Territory, are given in Figures 15 and 16. The proposed gas pipeline is routed next to, or along, the Haines-Fairbanks pipeline corridor for significant distances. Magnetic induction measurements made along the corridor have two problems to contend with: First, the presence of the metal pipe; and secondly, the vertical frozen-unfrozen interface near the corridor edges.

Data has been obtained from adjacent to, and across, the Haines-Fairbanks pipeline at many locations along the route. The horizontal and vertical loop mode measurements at one such crossing are illustrated (see Figure 15). Evident in the figure is the large EM31 (HG) response compared to the low and more uniform EM31 (VG) and EM34-3 (20 m) responses, except at the crossing of the pipe. Typical EM31 (VG) and (HG) mode responses at another crossing of the Haines-Fairbanks pipeline are also illustrated (see Figure 16). The EM31 (HG) measurements again show abnormally high values when compared to the low and uniform vertical loop mode measurements.

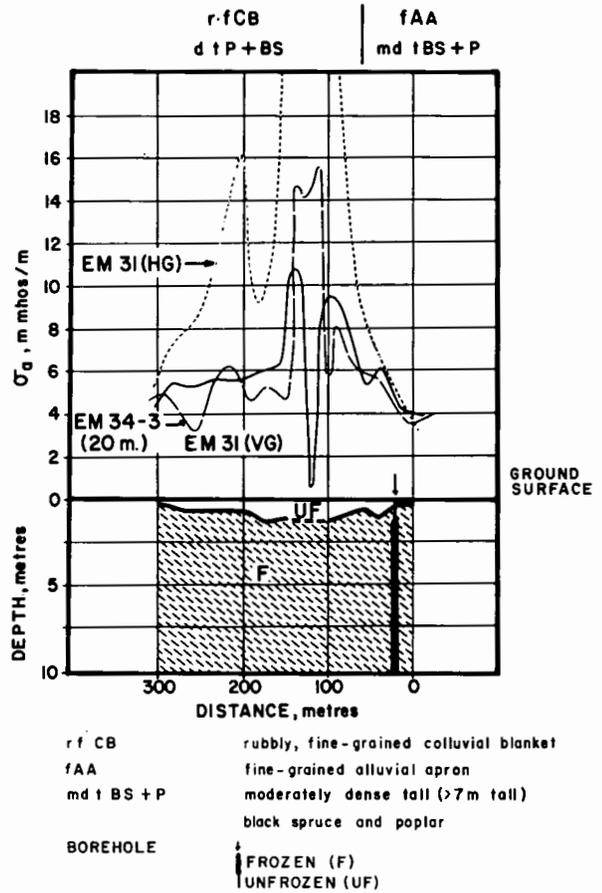


FIGURE 15. Haines-Fairbanks Pipeline.

It is now thought that horizontal loop mode measurements with the EM31 are not useful terrain conductivity indicators when taken within 15 m of the pipe. However, such measurements may still be useful as a guide to show the relative amount of pipe influence on vertical loop measurements taken close to the pipe. Vertical loop measurements are thought to give reliable estimates of ground conductivity when not closer than 10 m to the Haines-Fairbanks pipeline.

Conclusions

EM surveys provide a rapid, and cost-effective, initial exploration tool with which to locate targets for more-direct sampling methods. The technique also provides a means for extrapolating information on soil conditions and thickness of frozen and unfrozen soil strata between boreholes. In frozen ground, EM surveys are often better suited to finding unfrozen anomalies in fine-grained soils as compared to granular soils. Determination of the ice content of soils is

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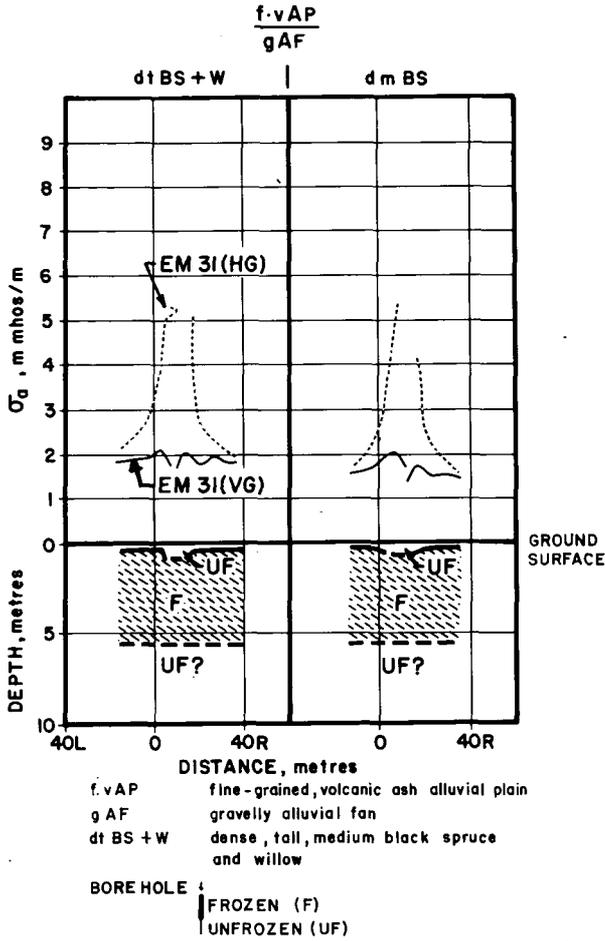


FIGURE 16. Haines-Fairbanks Pipeline.

not considered to be within the capability of the EM equipment available at present.

Interpretation must always have input from site-specific observation and other available geological and geotechnical data. When this is available, confusing situations, arising in granular soil, or where bedrock is near the surface, or where man has altered the terrain, can often be resolved.

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