ELECTROMAGNETIC INDUCTION MEASUREMENTS IN PERMAFROST TERRAIN FOR DETECTING GROUND ICE AND ICE-RICH SOILS

FINAL REPORT

By

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PREFACE

Geophysical methods which allow remote sensing of subsurface soil features have gained mixed acceptance with geotechnical engineers. Problems have usually stemmed from two areas; 1) the high level of specialized expertise required to obtain and interpret geophysical data and 2) complicated and/or inconclusive interpretations of the geophysical data which are not directly applicable to the engineering problem at hand. This report, however, discusses a relatively inexpensive, highly portable remote sensing instrument that is simple to operate and, as indicated by a number of case studies, can provide useful information.

The purpose of this report is to introduce geotechnical engineers and geologists to a practical tool intended to augment, but not replace present foundation exploration methods. Apparent ground resistivity as measured by the Geonics Ltd. EM-31 device can often be directly correlated to borehole information or other forms of "ground truth" at a foundation site. For example, such correlations may key on depth to bedrock, overburden thickness at a gravel source, soil moisture content or gravel layer thickness. Of even greater interest perhaps to the Alaskan geotechnician are correlations demonstrated within this report between permafrost features and resistivity data. permafrost Relative to investigations, the EM-31 has been successfully used to detect massive ice features and estimate soil-ice contents. Outside of proprietary industrial reports this publication contains the most extensive assembly of case studies (22) presently available that describe application of the EM-31 to engineering problems. It is hoped that the report will spark the interest of geotechnical engineers and geologists which will lead to a routine utilization of the EM-31 or EM-31 type devices in Alaska.

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ABSTRACT

Permafrost is a unique geotechnical material that poses severe engineering and environmental problems for surface construction and for petroleum, mineral, water and hydroelectric power development. This report addresses the detection and characterization for geotechnical purposes of shallow permafrost and ground ice with an electromagnetic induction method.

The operating principles of the instrument used (Geonics EM-31) are described and field operational techniques are discussed from a practical, layman's point of view. The instrument measures near-surface resistivity and thus may be employed to detect lateral differences in subsurface conditions such as hydrologic flow, bedrock, gravel deposits, etc., as well as ground ice and permafrost. Vertical differences may also be detected.

Investigations at twenty-two sites in permafrost and non-permafrost areas throughout Alaska are presented in case history form. Interpretation of the EM-31 data are based on available boreholes, drill samplings, aerial photography and terrain maps as well as operator-noted, on-site conditions. The case histories include surveys of numerous highway and airstrip rightof-ways, potential gravel borrow sites, geothermal areas, pipelines, areas of peat, farmland, thermokarst and patterned ground and others. The results show that permafrost and ground ice can be reasonably well-defined by the EM-31 system in diverse settings. Aquifers in permafrost areas are sometimes detectable, but the technique appears to be less successful, although still useful in some cases, in delineating sand and gravel deposits which are needed for paving.

Measurements made through several seasons at two sites suggest that late winter and early spring, when the absolute near-surface resistivities

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are highest are not necessarily the optimal period to detect ice-rich soils. The optimal period for detection of such soils depends on the resistivity contrast which in turn depends on the temperature profile, moisture content and other factors in the ice-rich soil and surrounding area.

Based on the case histories and other experience, it is recommended that the EM-31 or equivalent electromagnetic induction devices operable by one man be used routinely as a reconnaissance tool prior to extensive drilling <u>at sites suspected of harboring ice-rich permafrost soils</u>. The drilling program can then be designed on the basis of the results of the induction survey and in consultation with others (e.g., geologists).

Proper implementation of the above recommendation can only be accomplished by a person familiar with geophysical methods. It is therefore recommended that the Research Section of the Alaska Department of Transportation and Public Facilities (ADOTPF) employ a geophysicist whose task would be to oversee work and advise ADOTPF on electromagnetic and other geophysical methods that have proved useful in permafrost and ground ice detection.

INTRODUCTION

Permafrost underlies approximately three-quarters of the land area of Alaska, most of the continental shelf of the Beaufort Sea, parts of the shelf in nearshore areas of the Chukchi and Bering Seas and some of the alpine areas of the contiguous 48 states and Hawaii. Where permafrost contains massive ice or is ice-rich, severe environmental and engineering problems can result if it thaws. These problems were frequently encountered during the construction of the Trans-Alaska Pipeline System. In addition, Alaskan highways, railroads, airports, buildings and houses sometimes show the disastrous results that can occur when ice-rich permafrost thaws. Solutions to these problems are avoidance and specialized construction techniques. However, both solutions require a knowledge of the permafrost distribution, especially the precise position and extent of massive ground ice and ice-rich permafrost. This knowledge must be based on the ability to detect the presence of permafrost and ground ice, a problem for exploration geophysics. In the broadest sense, exploration geophysics includes both surface and borehole methods applied to the problems of detecting permafrost and ground ice and determining their properties.

The problems in permafrost detection that can be addressed by exploration geophysics are those related to:

- 1. Establishing the presence or absence of permafrost.
- 2. Determining the distribution (horizontal and vertical extent) of permafrost including the position of the top and bottom of permafrost (equivalently, its thickness).
- 3. Determining the presence and extent of massive ground ice and ice-rich permafrost.
- 4. Establishing the properties and thickness of the active layer on a seasonal basis.
- 5. Measuring the physical and mechanical properties of permafrost and ground ice in-situ.

6. Miscellaneous environmental and engineering problems such as locating groundwater in permafrost terrain, detecting thawed zones for purposes of electrical grounding, selecting pipeline and highway routes through permafrost terrain etc.

Permafrost geophysics problems have been reviewed by Ferrians and Hobson (1973), by several authors in Collett and Brown (1974) and at recent symposia on permafrost (Permafrost Geophysics-Vancouver, B.C., 1976 and Saskatoon, Saskatchewan, 1977; Third International Conference on Permafrost, Edmonton, Alberta, 1978; Fourth International Conference on Permafrost, Fairbanks, Alaska, 1983).

Detection methods generally rely on some surface expression of the permafrost, on the properties of ground ice and their contrast with surrounding soils, and on changes in the physical and mechanical properties of a soil on freezing. Methods that have been used to detect permafrost and ground ice include the so-called traditional methods (e.g., surface expression in the form of vegetation, patterned ground, etc.); drilling, sampling and borehole logging (including thermal logging); seismic reflection and refraction; gravity profiling; and various electromagnetic methods. No one method will work for all problems since material contrasts depend on material type, water and ice content, temperature, pore water composition, and other parameters. A major problem for exploration geophysics is to select the proper instrument for the problems and conditions being investigated.

One of the most promising geophysical methods for detecting permafrost and ground ice is the use of the electromagnetic induction method for measurements of the electrical resistivity (equivalently conductivity) of permafrost terrain. The method has also proved to be useful in studies of groundwater, geothermal systems and for delineating certain material types.

This report describes the magnetic induction method, as employed in the EM-31 instrument, and the experimental details of its use. Case histories illustrating the application of the method to exploration geophysics problems in Alaska are given. Recommendations on the use of the method for investigating scientific, environmental and engineering problems are made. The majority of the examples discussed in this report involve permafrost terrain, however a few cases from non-permafrost terrain are also discussed.

The following two sections discuss the general operating principles of the electromagnetic induction device and the effects of temperature, salinity, moisture and other factors on the electromagnetic induction measurements. The remaining sections include a description of experimental methods, specific case histories, a discussion, and recommendations.

Electromagnetic Induction Method

This method is based on the observation that an electromotive force (emf) is generated along a closed circuit (e.g., a coil) when the circuit is immersed in a time-varying magnetic field (Faraday's law of electromagnetic induction).

In the context of geological structures, such as horizontally stratified earth, a closed circuit should be understood to mean any closed path within the material which is threaded by a time-varying magnetic induction field. Along such a closed path, an electromotive force (emf) proportional to the time rate of change of the integrated magnetic flux through the area $(d/dt \int \vec{B} \cdot d\vec{A})$ is induced and as long as there are no parts of this path that have infinite resistance, a time-varying electric

current will flow. Note that although in some rare geophysical settings, the so-called displacement current may have a magnitude comparable to the free conduction current, it can be ignored in most circumstances.

The temporal behavior of this induced current depends not only on the inducing magnetic field, but also on the resistance, circuit inductance and circuit capacitance. For an extended body such as the earth, the current and other quantities must be specified in terms of volumetric and areal quantities (e.g., current density, resistivity, etc.). As in the case of a simple circuit with resistive, inductive and capacitive elements, which is coupled inductively to a primary field, the induced current, hence the secondary magnetic field generated by the current, will not be in phase with the primary field.

For geophysical applications, it is the secondary magnetic field which is generated by the current induced in the earth that is the important parameter to be monitored. This time-varying magnetic field will depend, through the induced emf and induced current, on the electrical characteristics of the underlying material. Since magnetic fields are vector quantities, the orientations of the inducing field and the secondary induced field are also important in assessing the electrical characteristics of the subsurface material.

Although naturally occurring magnetic fields such as the disturbance associated with magnetic storms and magnetic micropulsations (small periodic change in the main geomagnetic field) can be used to probe the earth, the electromagnetic induction technique in geophysical exploration refers to an active system consisting of a primary inducing coil (transmitter) and a secondary pickup coil (receiver).

Two categories of instrumentation exist - those whose secondary signal is analyzed in the frequency domain and those that are analyzed in the time domain. In the frequency domain system, the primary inducing field is usually a sinusoidal signal, and the secondary induced sinusoidal signal amplitude and/or phase angle are analyzed. In time domain (or transient) systems, on the other hand, the primary field is pulsed and the secondary signal is sampled at various times after the primary signal is turned off, but prior to a second pulse of the primary field. This report concerns itself with the application of the Geonics, Ltd. EM-31 frequency domain device which has a fixed frequency, fixed receiver coil - to transmitter coil spacing, and fixed, coplanar coil orientation. Greater information on shallow subsurface structures can be gained with variable frequency, variable coil separation devices, such as the EM-34 also built by Geonics, Ltd. However, the portability and reduced complexity afforded by a fixed coil separation and fixed frequency makes the EM-31 very useful for geotechnical purposes.

The receiver coil of the EM-31 instrument (and others like it) detects (again by Faraday's law) both the secondary field and the primary field. The extent of coupling through the air of the primary field with the receiver coil can be determined, since the phase of the primary field, orientation and coil separation are known. The primary field can thus be eliminated leaving only the signal of the secondary field which is generated by the induced current within the earth. The EM-31 is designed in such a manner that for reasonably resistive (low conductivity) materials such as permafrost and ice, the secondary field is nearly 90° out of phase with the primary field. That is, the inductive and capacitive

elements can be ignored because of the high resistivity of the subsurface material and relatively low frequency of the instrument.

For the fixed geometry and frequency of the EM-31 and known relative orientation to the ground surface, it is a relatively straightforward matter to determine the effect on the receiver coil of the circuits induced by the primary field in a thin slab of material coplanar with the surface of the ground. The response of the receiver coil to the induced current in the thin slab may be integrated over a homogeneous, resistive half-space taken to represent the earth. This integrated response is called the cumulative response function and depends on the orientation of the coils relative to the surface as well as the resistivity of the ground and the frequency of the signal. Figure 1 shows the cumulative response functions, $R_{y}(z)$ and $R_{H}(z)$, versus depth for the two standard orientations of the coils of the EM-31, respectively, namely with coil planes parallel to the ground surface (or axes perpendicular) and coil planes perpendicular to the surface (or axes parallel to the surface). The response functions are normalized, as are the depths, with respect to intercoil spacing.

The curve labelled $R_{\gamma}(z)$ (= $1/(4z^2 + 1)^{1/2}$) in Figure 1 may be interpreted in the following way for a uniform earth: the response function at depth z will give the contribution to the measured conductivity from all material below that depth. Thus, at z = 0, the response function value is that for <u>all</u> the material below the instrument or $R_{\gamma}(z) = 1$, so that the apparent conductivity for a uniformly conductive earth is $\sigma_a = \sigma$ $R_{\gamma}(z) = \sigma$. The same interpretation may be made of $R_{\rm H}(z)$ (= $(4z^2 + 1)^{1/2} - 2z$).



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Figure 1. Cumulative response functions for EM-31 in the normal (coil axes vertical, V) and rotated (coil axes horizontal, H) positions (McNeil, 1980a).

If the resistivity varies with depth and can be represented by a layered model (e.g., an active layer over uniform permafrost, permafrost consisting of several layers of different soil, permafrost and ice layers, etc.) then the response curve again may be used to evaluate the conductivities by noting that the response function at any depth is associated with only the material below that depth. Thus, for a two layer case the apparent conductivity is $\sigma_a = \sigma_1 (1 - Ry(z)) + \sigma_2 Ry(z)$, where σ_1 is the conductivity of the upper layer and σ_2 that of the underlying permafrost. This equation holds for the instrument when it is oriented with its coil axes vertical and a similar equation with $R_{V}(z)$ replaced with $R_{\rm H}(z)$ holds in the case when the coil axes are horizontal, so that, provided the first layer thickness is known, the unknown conductivities may be calculated. Alternatively, it is possible to raise the instrument above the ground, keeping the coil orientation constant and obtain two or more equations relating apparent conductivity to a three layer case, one of which is an air layer with $\sigma \approx 0$, and solve the equations for the unknown conductivities knowing the first layer thickness.

The maximum effective penetration depth for the EM-31 is claimed by the manufacturer to be about 7-8 m (20-25 ft), although Figure 1 suggests the $1/e^{th}$ value is attained at about z = 1.3 or a depth of z' = zs (s = $3.66 \text{ m} \approx 12$ ft, the intercoil spacing) = $4.76\text{m} \approx 16$ ft in the vertical mode. Thus, material deeper than perhaps 7 m (~ 23 ft) will contribute very little to the apparent conductivity unless its conductivity is extremely high relative to the surface layer(s).

As with other electrical and electromagnetic methods, if the depth of the first layer is unknown, curve matching may also be used to infer the thicknesses and conductivities using the EM-31. This requires several

measurements to be made as a function of height above the ground and plotting σ_a/σ_1 versus the height h above ground for different ratios of σ_2/σ_1 , where σ_1 and σ_2 are reasonable estimates of the first and second layer conductivities (see McNeill, 1980a).

In practice there will always exist lateral inhomogeneities of the subsurface materials in terms of soil or rock type, moisture content, temperature and other factors which will lead to differences in electrical properties. The EM-31, being a relatively short-ranged device, is capable of detecting lateral inhomogeneities in conductivities to within 5% to 10% accuracy. If the dimensions of the inhomogeneity in an otherwise uniform background are one or two times the intercoil spacing, the EM-31 will give a conductivity value for the material as if it essentially occupied all of the half-space. Near the edges of the inhomogeneity, however, the readings of the instrument will be extremely variable because the currents will generally be concentrated near the contact between the differing materials. Indeed, the instrument may give a negative conductivity reading over the center of a conductive buried linear mass of width smaller than the intercoil spacing, because the net secondary field signal may become 180° out of phase in time relative to what the instrument has been designed to detect.

Dependence of Electrical Parameters on State of Material

The electrical properties of rocks and soils depend on several factors among which are rock or soil type, porosity, moisture content, salinity and temperature.

The electrical conductivity of earth materials is especially sensitive to the amount of free water that may exist in the pore spaces

of the materials. Electrical conduction through most rock and unconsolidated material for a given electromotive force would be very small were it not for the presence of free water and dissolved salts which allow conduction to occur electrolytically through the fluid-filled pores. Electrical current may also flow through a material by electronic conduction as in a copper wire or by dielectric conduction. Generally, however, these modes of current conduction are small for most earth materials and the current flow is dominated by electrolytic conduction at the inducing field frequencies of interest.

A great deal of work has been done in determining the porosity of rocks, especially petroleum-associated rocks, which in turn can be used to estimate the resistivities of the rocks if the voids are filled with fluid water (see, for example, Keller and Frischknecht, 1966 and Grant and West, 1965 for reviews on this subject). Little comparable work has been done, however, in determining the relationship between void spaces in a soil and the electrical resistivity, when the interstitial water is partially frozen. Some work on void spaces in freezing soils has been summarized by Johnston et al., 1981; also the report summarizes some work done on the resistivity of a few soil types in Alaska as a function of temperature near the freezing point. Figure 2 shows the results of resistivity measurements around the freezing point obtained by Hoekstra et al., (1974) for saturated Fairbanks silt, peat and silt mixed with organic materials.

The graph of resistivity versus temperature for Fairbanks silt given in Figure 2 clearly shows why it is possible to differentiate frozen saturated silts from unfrozen saturated silts using the electromagnetic induction methods. For common permafrost temperatures in the Fairbanks area



Figure 2. Resistivity of Fairbanks silt and other geotechnical materials as a function of temperature (after Hoekstra et al., 1974). Note the abscissa should be shifted to the right by 0.2C.

(~ -2°C (28°F)), the resistivity is about a decade greater than that of the unfrozen permafrost material. Ice can be some 10 to 1000 times as resistive as water (see Johnston et al., 1981), which indicates that interstitial ice plays an important role in the determination of soil resistivities.

It should also be noted in Figure 2 that the resistivity does not rise in a precisely stepwise manner as the temperature decreases past the freezing point of water. This is a consequence of the existence of unfrozen water in the pore spaces of the soil matrix, even when the temperature is below the freezing point of water, due to surface and curvature effects and presence of solutes within the water, which depress the freezing point of water in localized volumes. Some water in the pore spaces may not freeze until the temperature is far below the freezing point of pure water.

Water having no dissolved salts has an extremely high resistivity ($\sim 10^5$ ohm-m at 25°C; see discussion in Eisenberg and Kauzmann, 1969), since very few water molecules are in an ionic state. With the addition of as little as 0.1 parts per thousand (by weight) of sodium chloride (about the same as natural stream water) the resistivity decreases by about a factor of 10^3 to less than 10^2 ohm-m at 25°C (Keller and Frischknecht, 1966). By contrast, normal sea water has a salinity of about 35 parts per thousand parts of solution (Mason, 1952).

The effect of various types of salts in water is to produce dissociated ions which can move in the presence of an electric field, thereby constituting a current flow, termed electrolytic conduction. To be more precise, in the presence of an electric field, such as an emf generated by a relatively low frequency (several tens of kilohertz) electromagnetic induction field, the salt ions will reach a terminal velocity in less than 10^{-6} seconds.

The coherent motion of such ions constitutes the electrolytic current equal to the product of the number density (or concentration), charge of each ion and mobility (~ terminal velocity) averaged over all ionic species (see Keller and Frischknecht, 1966).

The mobility of the dissociated ions in a water solution is a gradually decreasing function of decreasing temperatures which gives rise to an increasing resistivity. As subfreezing temperatures are encountered, a portion of the water may freeze, effectively increasing the resistivity rather rapidly in the frozen fraction. However, salts will be rejected from the ice and if the water is within a fine-grained soil matrix, the resulting brine may form interconnected films that can continue to allow current conduction. Surface forces in the interstitial spaces consisting of adhesion and capillary action surrounding the soil particles must be overcome during the freezing process so that the increase of resistivity with decrease of temperature is relatively gradual.

The temperature dependence of the resistivity of permafrost and the active layer must always be considered when making resistivity measurements, whether by electrical (DC) or electromagnetic methods. This is especially the case in much of Alaska south of the Brooks Range where permafrost temperatures at shallow depths are often warmer than $-3^{\circ}C$ (26.6°F).

Much work has been done in measuring other electrical properties of earth materials such as the electrical polarizability (hence the dielectric constant), magnetic permeability and natural electrical potentials. Most of this work has been done to facilitate mineral and petroleum exploration and is of little concern relative to electromagnetic methods of detecting permafrost and associated ground ice. However, studies of the dielectric

constant of soils as a function of temperature near the freezing point are of interest in radar work because there is a large contrast in the dielectric constant between the frozen and unfrozen soil which can be utilized in detecting ice-rich soils (Delaney and Arcone, 1982).

In summary, relative to permafrost and ground ice detection by means of electromagnetic induction devices, the moisture content, salinity and temperature of a soil are extremely important in governing the resistivity of the material. Salinity is not usually taken into account except in coastal areas and around hot springs where water mineralization is extensive.

EXPERIMENTAL PROCEDURES

In this section, the operational procedures for the use of the Geonics EM-31 will be discussed. Specific items that will be covered include: (1) physical description of equipment icluding specifications; (2) description of how the instrument is operated; (3) discussion of calibration procedures, instrumental drift and potential problems that may be encountered; (4) description of survey techniques; and (5) a description of data reduction and interpretation.

Description of equipment

The manufacturer's specifications are tabulated in Table 1. Physically, the EM-31 is a box with two booms of diameter 5 cm (\approx 2") extending to either side with a total length of about 4 m (13 ft). The center of mass of the instrument is near the center of the box so that it can easily be carried about at hip level (1 m) with a shoulder strap attached to the box. The apparent conductivity can be read by the operator off the meter on the top face of the instrument box.

Instrument operation

Assuming the instrument has been calibrated, it is a relatively straightforward matter to make a measurement of the apparent conductivity. Once the proper scale has been chosen for the area of interest, with the instrument at hip height (\approx 1 m (3.28 ft)), the meter can be read to obtain the apparent conductivity of the ground in mmhos (millimhos)/meter. Orienting the instrument with the meter face up makes the axes of the coplanar coils vertical to the ground surface; rotating the instrument box 90° around the long axis of the boom aligns the axes of the coplanar coils parallel to the ground surface. The boom axis should always be parallel to the ground surface, although misalignment by a few degrees will not affect the reading substantially.

The instrument may be laid on the ground to take additional readings which generally will be higher, since, in the hip position, the intervening air gap is sensed as a layer having zero conductivity. As indicated previously, additional measurements with height will allow determination of layer thicknesses and conductivities by curve matching methods.

Normally, the instrument is used at hip height in the vertical axis mode which provides the greatest penetration. For these reasons, the instrument is electronically calibrated in such a way as to give the true apparent resistivity (for a layered earth) directly at 1 meter above the ground (hip height) in the vertical axis mode.

Calibration, drift and other instrumental problems

Although the instrument is factory calibrated prior to shipping, certain functional checks should be undertaken prior to field work. These functional checks are somewhat different for more recent models of the EM-31, because some adjustment controls that existed in the earlier

model are now fixed and internal to the system. The operation manual which accompanies each instrument should be consulted for the necessary functional checks.

Absolute calibration of the instrument to read the true apparent resistivity cannot be readily accomplished, if the factory adjustments have been altered by aging of components or other changes, because sites are required where the conductivity is known and uniform to reasonable depths and lateral extents. However, a standard site may be established immediately upon receipt of the instrument and readings made at ground level and hip height for the 'normal' (vertical dipole or horizontal coplanar mode) and 'rotated' (horizontal dipole or vertical coplanar mode). Assuming nothing has altered the 'true' calibration in the transit from the factory, these initial reference readings can be used to determine whether the instrument continues to be properly adjusted. For earlier models, the instrument could be adjusted, using a quadrature phase compensation control, back to the reference readings, if drift of internal origin occurred.

Unfortunately, selection of a site for calibration checks is especially difficult in Alaska, because of the great variation of soil resistivity with temperatures close to the freezing point. To be used throughout the year, the temperature and moisture profiles with depth in the soil at the site would need to be reasonably constant in time, which clearly is not the case.

Alternatively, the instrument may be raised high above the ground on a wooden platform or ladder and adjusted to read a value equal to the value read at the ground times the response function (see previous section on the electromagnetic induction method) for a depth equal to the height above the ground. This assumes there is not very much variation of the resistivity

with depth below ground level, although the calibration will not generally be very sensitive to this assumption unless the surface layer(s) is (are) highly conducting.

Another method of checking the absolute calibration is to make measurements over a deep body of reasonably conductive water from a wooden boat or a rubber raft. Since the temperature profile and conductivity can be readily established by in-situ measurements, absolute integrated conductivity can be determined and compared with the EM-31 readings, and the meter can be adjusted accordingly.

Instrumental drift of short duration (a few minutes to several hours) whose source may be either internal or external may also occur. The internal source appears to be related to battery usage and warmup time. The instrument should be left on for at least 20 minutes before any readings are taken to allow time for warmup. This depends upon ambient temperature, with longer times required for lower temperatures. Figure 3 shows the results of drift measurements on three separate EM-31 units made over a period of 6 hours; units 1 (ADOTPF) and 3 (private) have identical manufacturer specifications, having been built after 1979 when the operating frequency was changed from 39.2 to 9.8 KHz. The range of the drift for all three instruments is under 8 parts in 200 (< 5%). Both the shorter-term fluctuations (\sim 30 minutes) and longer termed changes (1-3 hours) do not seem well correlated between instruments so that these variations appear to be entirely instrumental in origin. Although the manufacturer suggests that the batteries have a lifetime of 20 hours under continuous use, repeatability tests with unit 2 (the Geophysical Institute EM-31) indicate the batteries may degrade within a period of 6 to 8 hours of continuous use in cold weather. Since battery costs are generally only a very small fraction of



Figure 3. Instrumental drift of three different EM-31 units over a six hour period.

field surveys, our practice has been to replace the batteries after 6 to 8 hours or 1 day of use. Figure 3 suggests that the newer models may be more stable even after 6 hours of operation, so that the batteries may not have to be replaced for several more hours. The extremely low temperatures in Alaska are a serious constraint on battery lifetime. While such conditions require more frequent replacement of batteries, the instrument functions down to -50C.

Very short term drifts can sometimes be noted even as the meter of the EM-31 is being read. Such drifts, generally only seen during the springsummer months, are related to thunderstorm activity which peaks in the afternoon to evening period. Nothing can be done about such drifts except to avoid surveying when local thunderstorm activity is high. (Energy from more distant thunderstorms such as those that occur in the tropics can be channeled to the high latitude regions via the earth-ionospheric cavity. This energy is generally low and more impulsive and does not generally affect the EM-31). The electrical surges associated with auroral substorms can also influence the EM-31, although to a lesser extent than the local thunderstorm activity.

Some man-made sources of electromagnetic noise may also sometimes interfere with the EM-31. The electrical systems of cars and other vehicles and intermittent operation of electrical motors produce transients which also interfere with the EM-31. Power lines do not generally affect the operation unless leakage discharges, usually associated with very wet weather, occur or when the instrument is under the lines. It is good practice to avoid areas where power lines and other electric currentcarrying wires exist or at least take into consideration the potential

such sources when interpreting the data from these areas if they cannot be avoided.

Surveys of areas with wire fences, buried cables, wires, pipes and large metallic objects such as corrugated roofing sheets can lead to erroneous mapping of the ground resistivity. Linear objects such as culverts can often be identified by the negative-going signature they produce when a profile is measured transverse to the long axis. In general, the use of the EM-31 in such areas is difficult. However, the device can be specifically employed to detect buried metal objects. Survey Techniques

The EM-31 being a lightweight, portable non-contacting device is wellsuited for rapid terrain reconnaissance. Before any type of survey is undertaken, however, lines should be "brushed out" where vegetation is thick. For preliminary reconnaissance, brush removal may actually be needed only at the survey point itself, since exact line of sight is not generally required. In traversing very heavily wooded areas and thick brush, the extended booms of the EM-31 may prove to be unwieldy so that access lanes to specific survey points may be required. While the instrument is fairly rugged, care should be taken when moving over rough terrain, especially in cold weather, to prevent to prevent sudden stresses on the booms which may cause them to snap.

In very preliminary reconnaissance surveys of right-of-ways and other sites, exact positioning of the EM-31 survey points relative to the boundary of the site may not be needed. However, it is good practice to determine the exact location of one or more EM-31 survey points and the bearing of one or more EM-31 profile lines relative to the boundaries

which normally will have been sited in by a surveyor and marked with stakes beforehand.

In terrain with unknown subsurface materials, it is wise to make a preliminary EM-31 survey by walking the area or line of interest and noting the locations where the conductivity readings change rapidly from point to point. (Elevation, vegetation, presence of water and other factors should also be noted at this time). The distance between survey points should be dictated by this preliminary survey. That is, the survey points should be more closely-spaced where conductivity readings change rapidly. The minimum spacing for permafrost problems usually does not need to be closer than 1.5 m (\approx 5 ft) and a 3 m (\approx 10 ft) spacing is probably more than adequate for most reconnaissance surveys.

To minimize complicating the recording of data in a field situation, a systematic line of points or set of approximately rectangular grid points should be set up prior to taking data. Each point should be clearly marked with flagging tape on available trees or shrubs or with stakes or other survey markers. Distances between points should be measured off with as long a tape as possible and the desired intervals marked. An alternative way of marking grid points, if more permanent marking is not needed, is to spray a brightly colored paint on tree trunks, shrubs or even on the surface of the snow in winter.

The survey should always begin at a survey point that is easily accessible from different directions. This point may be used as a reference to which all subsequent values will be referred in order to remove any drifts that may occur. The time at which the reading is made should be recorded to the nearest minute and no more than 20 to 30 minutes should elapse between readings at the reference point. For normal walking times

between points along lines cleared of brush and time for reading and recording the measurements, this corresponds to about 15-30 readings spaced 3 m (\approx 10 ft) apart between readings at the reference point. The number of readings possible per unit time may be greatly reduced in heavily wooded areas, thick undergrowth or over very steep terrain.

Typically the direction of brush clearing dictates the orientation of the booms in the horizontal plane. Over a layered earth, the azimuth of receiver and transmitter coils in the horizontal plane will make no difference. However, where conductivity varies over a short lateral distance (say, 3 m (\approx 10 ft)), some care must be exercised in orienting the booms, because the secondary induced signal may not be a maximum for that particular orientation of the booms. It is therefore a good idea to rotate the boom 90° in the horizontal plane from the initial direction and obtain normal (coil axes vertical to ground) and rotated (coil axes parallel) values. Indeed, if the orientation of booms is parallel to an object like a thin dike or culvert, the conductivity measurements will show very little contrast from those of the surrounding soil, whereas a large contrast will be seen if the booms are oriented perpendicular to the strike of the object. Shallow-buried objects with horizontal dimensions larger than one to two times the intercoil spacing and having sufficient contrast in conductivity relative to the surrounding matrix will be detectable with the EM-31 regardless of boom orientation, if the grid spacing is small (3 m or 10 ft). When surveying, the orientation or azimuth of the booms with respect to the survey boundaries, should always be noted, as well as the end location of the transmitting coil with respect to the traverse.

In summary, prior to making a survey with an EM-31, lines ideally should be cleared of brush and survey points should be marked at a spacing of about 3 m (10 ft). Terrain slope, vegetation, presence of thermokarsts, moisture conditions, geology and other physical surface features should be noted. The booms should be oriented in the same manner at each survey point, although additional information may be gained by rotating the entire unit by 90° in a horizontal plane. Detection of very isolated objects like culverts will require close grid spacing and proper orientation with respect to the strike of the object. When making a survey, a reference point should be chosen and readings retaken at the point within a period of 20 to 30 minutes to allow elimination of drift when the data is reduced.

Data Reduction and Interpretation

The EM-31 gives a reading of the apparent conductivity of the underlying material in mmhos/m (millimhos/m). The term 'apparent', as may be inferred from the previous discussions, is used in this context to denote 'bulk' rather than a value for the conductivity over a relatively small volume of the material. Indeed, the EM-31 in the vertical mode (coil axes vertical) senses the conductivity of a roughly hemispherical volume with diameter about twice the intercoil spacing (2 x 3.66 m or 2 x 12 ft). It should be understood, however, that the material at and near the surface tends to contribute the greatest amount to the readings and that inhomogeneities within the volume range may have a profound effect on the measured apparent conductivity.

Figure 4 (after McNeill, 1980b) shows the apparent conductivity along a profile perpendicular to the strike of a thin conductive dike. The curve

<u>EM 34-3</u>

VERTICAL DIKE RESPONSE

Vertical dipoles, 20meter intercoil spacing



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is calculated for the Geonics EM-34 but can be scaled-down to the EM-31 coil-spacing. The profile clearly shows that a point measurement on the surface of the ground may lead to an apparent conductivity reading which is very small, zero or even negative depending on the position relative to the dike. It is thus clear from this example that a great deal of care must be exercised when interpreting the EM-31 data. Qualitatively, culverts, buried cables and other materials of small dimensions in the direction of the traverse but large lateral dimensions may produce similar results.

In field situations, one would expect the dimensions of inhomogeneities in the earth to be large relative to coil spacing, and temperatureregulated conductivity variations, such as those between thawed and unthawed zones, to occur reasonably gradually with distance. Thus, one would assume in an EM-31 survey that regions of low apparent conductivity represent true low conductivity areas and those that have high apparent conductivity to be regions of true high conductivity.

Two types of reconnaissance surveys have been undertaken. Several case histories of these will be described in a subsequent section. The first type is simply a quick reconnaissance profile survey to ascertain the need for further investigation or for other purposes such as studying the seasonal dependence. The second type is a more complete gridded survey pinpointing regions of high and low conductivity in a particular area. The procedure for reducing the raw data will now be described.

As indicated previously, drift should be removed by use of the measurements made at a reference point. The simplest procedure is to interpolate linearly for the correction values for times between reference point readings. Occasionally, atmospheric electrical activity may occur which

will not be obvious to an observer in the field. Relatively rapid drift of readings at the reference point may occur. If this drift occurs linearly over the interval between reference readings, it may be removed. However, in some instances the drift may occur in an impulsive fashion over the same period as the reference readings, leading to a positive or negative bias to all the readings over the period. Such externally caused variations will appear in contour plots of the conductivity (or resistivity) values in a gridded survey as linear features, if the survey is conducted along co-linear points of the grid.

Assuming the drift has been successfully removed, the data should be converted to apparent resistivity which by convention is used instead of conductivity. For readings in mmhos/m, the conversion to resistivity ρ_a is $\rho_a = (1000/\sigma_a)$ ohm-m. The data can be plotted as a function of distance along a reconnaissance traverse, or for a gridded survey, the data may be contoured giving isointensity contours of resistivity.

The line plots are especially useful for picking out regions along a traverse with anomalously high or low resistivity. On some occasions, these readings have been used as a guide to drilling and sampling, although a more complete and thus somewhat more time-consuming gridded survey should be the basis for any drilling that may follow.

There are many versions of contour programs that exist for computer calculations of isoresistivity contours. The one that has been employed in discussing case histories in the following section is the SURF II program (Sampson, 1978). There is an optional feature in the program that allows isometric (perspective) representation of the resistivity (or other parameter) as a function of height above a reference plane. Both the isoresistivity and the isometric (3-dimensional representation) are valuable

visual aids in delineating regions of high and low resistivity. In practice, the coordinates of a point and its resistivity values(s) are tabulated on the computer. Various parameters that can be chosen allow the interval of contouring, labelling, area of the mapping, plot size and other parameters to be varied.

Some caution must be exercised in the interpretation of the results of an automated contouring program such as SURF II. Suppression and deletion of data, or data with uneven distribution may cause the contours to look very different from the case when more data points are available. At the least, however, the plotting of data can give a good idea of the lateral homogeneity of the underlying material.

Interpretation of any data is often very subjective. It is for this reason that all surface and subsurface information that is available in the area of interest should be used in the interpretation. When drilling information is available, it should give site-specific information such as whether the underlying material is ice-rich or unfrozen, whether there are aggregates such as gravel or solid rock and other ground truth which will aid the interpretation of the resistivity measurements. Often, surface expressions of ice-rich soils can be found in the over-lying flora, with small scrub, spruce and other brush usually indicating poorlydrained, colder soils. Geological information tied together with surface data must always be correlated with the resistivity measurements. However, preliminary electromagnetic induction measurements should precede drilling. Such measurements allow better control of the drilling program, to maximize the potential information that can come from any subsurface investigation, including a more comprehensive EM-31 survey that may follow some initial drilling.

It is not always possible to reoccupy remote sites either for additional drilling or for resurveying with the EM-31. Since drilling is in general much more expensive per data point, than using the EM-31, economics would dictate that the EM-31 be used first at such remote sites. Under these circumstances, it is wise to prepare for the survey with a geologist knowledgeable about the general characteristics of the underlying material of the site or right-of-way. A detailed plan is required with identification of areas with potential ice-rich ground being made in consultation with the geologist. At the site, the EM-31 crew (one person, but preferably two at a remote site) should graph the isoresistivity contours by hand so that potential areas of ice-rich soils may be resurveyed if necessary. The EM-31 crew should give a reasonably comprehensive evaluation of the site such that a follow-up drilling crew may use its time to maximum effectiveness.

CASE HISTORIES

In this section, several surveys and sets of surveys made with the EM-31 will be described. Some are typical reconnaissance type surveys over terrain with minimal available ground truth, while a few others are over terrain with fairly extensive information including temperature, drilling, sampling and the like. Also, some nearby sites in the Fairbanks area were repeatedly surveyed to observe seasonal effects.

Because the EM-31 is a shallow-sounding device, it is well-suited for studies of the active layer, delineation of thawed and unthawed ground, locating near-surface ice-rich permafrost and massive ground ice and other problems unique to high latitude regions. It can be a particularly useful adjunct to traditional methods of subsurface investigation required

prior to the construction of highways, buildings and other structures that are to be built over land that is potentially thaw-unstable. Another useful application of the EM-31 for the construction industry is to locate and delineate borrow pit areas. Accordingly, several surveys that are described have been undertaken to prove feasibility and to improve the techniques of using the EM-31 in field situations involving construction sites of one type or another. Other surveys include those of an archaeological site, geothermal areas and an artificial ground ice mass.

The case histories are grouped according to usage of the EM-31 for (1) basically unfrozen materials, namely, detection and mapping of contact between rock material types, mapping of aquifiers and saline zones in geothermal areas, detecting buried entrances and strike of caves at an archaeological site and detection and delineation of borrow pit sites, (2) basically frozen materials, namely, detecting differences in permafrost due to differences in moisture, temperature and/or material types, detecting ice-rich permafrost and massive ground ice masses and defining contact zones between frozen and unfrozen materials and (3) miscellaneous case histories involving ground water detection, peat site delineation, (Some examples of EM-31 surveys of residential sites and mining etc. sites have been discussed by Jurick and McHattie, 1982 and McHattie and Jurick, 1982. Reconnaissance surveys with the EM-31 over a wide variety of terrain along the proposed Northwest Gas Pipeline Corridor have also been made (P. Hoekstra, 1982; private communication).

In each of the subsequent case histories the following items will be given 1) survey location, 2) purpose of survey, 3) date of survey, 4) description of terrain, 5) description of known subsurface conditions, 6) graphs of data and 7) interpretation and discussion of results.

Case History No. 1 Latouche Harbor

Location: The site of the survey is in the township of Latouche on Latouche Island adjacent to Montague Strait on the southwestern exit of Prince William Sound.

Purpose: To identify location of materials suitable for constructing a small boat harbor (rip rap seawall)

Survey Date(s): May, 1982

Terrain: Area of survey is a hillside extending approximately 102-150 ft. (31-46 m) from edge of Latouche Island with a maximum elevation of 95 ft (29 m).

Subsurface Conditions: Information from 6 boreholes, surface outcroppings and a seismic survey of the area show there is an overburden of humus and muskeg (≈ 3-6 ft; 0.9 - 1.8 m), gravel and silty sand in some areas and weathered and jointed shale/argillite and graywacke over the less-jointed and weathered shale and graywacke basement rock.

- Data Plots: Figure 5 shows the results of the resistivity survey. There are two high points in the elevation located at (140, 120 ft; 43, 37 m) and 310, 30 ft; 95, 9 m) with height above sea level > 95 (26) and > 80 ft (24 m), respectively.
- Interpretation: The resistivity survey appears to have detected the more conductive, moisture-laden overburden of thick humus. A seismic survey taken over the area suggests the overburden of humus plus till/weathered rock is quite thick exceeding 20 ft. (6 m) in many places. Thus, if the seismic data are to be believed, the resistivity values are likely to be representative of the underlying solid bedrock in only a few areas. The duck-shaped low resistivity region


Figure 5. Isoresistivity contours of Latouche Island-Harbor material site in the township of Latouche.

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appears to be a drainage area from upslope (the bottom of Figure 5) while the high at (320, 40) corresponds reasonably well with the elevation high and also perhaps a thinning of the overburden. (For further details of this site see "Geotechnical Report for Latouche Harbor, Latouche Island", Alaska, Project #K32409, ADOT/PF Central Region, September, 1982, prepared by Weaver et al.)

Case History No. 2 Pilgrim Springs Geothermal Area

Location: Pilgrim Springs, a geothermal area on the Seward Peninsula approximately 72 km (45 miles) north-northwest of Nome, Alaska. Purpose: To map conductivity anomalies as indicators of subsurface aquifers and saline zones.

Survey Date(s): June, 1979 and July, 1980.

- Terrain: Relatively flat and tundra-like with numerous small lakes and ponds near the Pilgrim River. Vegetation demarcates frozen from unfrozen ground - brush where unfrozen, tundra where frozen.
- Subsurface Ground is unfrozen and silty in the geothermal area. Groundwater Conditions: is very saline with conductivities, σ_W , of the soil pore water as high as 1 mho/m.
- Data Plots: The conductivity contours from a grid of data at 10 m intervals along E-W lines separated by 100 m are shown in Figures 6 for the horizontal coplanar mode σ_H (lower panel) and vertical coplanar mode σγ (upper panel) of the EM-31, respectively. (Note that the subscripts H and V for the conductivities denote orientation of the planes of the coils: H for the horizontal and V for



Figure 6. Isoconductivity contours of Pilgrim Springs geothermal site. The upper panel labelled σ_V gives the contours for the vertical coplanar mode and the lower that for the horizontal coplanar mode σ_H . Note subscript V and H here and in Figures 7, 8 and 9 have opposite meaning from those of Figure 1 (and subsequent discussions) where V denotes vertical dipole and H horizontal dipole orientations.

vertical with respect to the earth. The H and V correspond to coil axes vertical and horizontal with respect to the earth respectively). The hot water discharge of Pilgrim Springs comes from a pool near 30E, 30S. All distances are in meters and conductivity contours in mmhos/m. As a more explicit comparison of the measurements using the two orientation modes of the EM-31 (dipoles vertical and horizontal), Figure 7 shows line plots of $\sigma_{\rm Y}$ and $\sigma_{\rm H}$ along the transect at 400S.

Interpretation: These data have been discussed in detail by Osterkamp et al., (1983) (See also Turner and Forbes, 1980) and by Osterkamp and Gosink (1984). The main conclusion from the surveys shown in Figure 6 is that regions of anomalously high conductivity tend to correlate with regions of high thermal flux, implying that these are regions where cells of convecting hot water bring the heat to the surface. Saline materials are also deposited nearer the surface in these plumes as the water cools. Figure 7, which shows a profile over one section of the area surveyed, indicates that the conductivities are higher at shallower than at deeper depths ($\sigma_V > \sigma_H$) suggesting there is concentration of hot salty materials nearer the surface.

Case History No. 3 Pilgrim Springs Airstrip

- Location: New Pilgrim Springs airstrip extending from about (0,100S) to (150W, 350S) of Figure 6.
- Purpose: To delineate thermal convective hydrologic flow by the use of conductivity (resistivity) data.



Figure 7. Conductivity profiles for vertical coplanar mode V and horizontal coplanar H along the 400 S grid line of Figure 6.

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Survey Dates:	June, 1979 and July,	1980.
Terrain:	See Case History No.	2.
Subsurface	See Case History No.	2.

Conditions:

Data Plots: Figure 8 (upper panel) shows the conductivity profile for the horizontal coplanar (σ_V) and vertical coplanar (σ_H) orientations of the EM-31 along the center line of the new Pilgrim Springs airstrip. The 0 point corresponds to the point (0,100S) of Figure 6. Figure 8 (lower panel) also shows the corresponding temperature contours to a depth of 4.5 m (~ 15 ft) taken at 20 m (~ 66 ft) intervals over the same survey line.

Interpretation: These data have been discussed in detail by Osterkamp et al. (1983) and by Osterkamp and Gosink (1984). As in the previous case, the EM-31 survey has clearly delineated a region of high heat flow indicating, in the context of the Pilgrim Springs geothermal area, that there is likely to be a hot water plume just beneath the airstrip surface at about 100 m (328 ft) along the profile. This is suggested by the relatively higher values for $\sigma\gamma$ compared with σ_H directly over the hottest point along this profile.

Case History No. 4: Chena Hot Springs

Location: This geothermal area is located approximately 80 km (50 miles by air east-northeast of Fairbanks, Alaska.

Purpose: To determine location of thermally convective hydrologic flow by use of conductivity (resistivity) measurements of the EM-31. 36



Figure 8. Conductivity profiles σ_V and σ_H (vertical and horizontal coplanar orientations, respectively) along centerline of new Pilgrim Springs airstrip (upper panel) and isotemperature contours to the 4.5 m depth along the same line.

Survey Dates: August, 1979 and May, 1980.

Terrain: Site is located at the floor of a narrow river valley along Monument Creek, a tributary of the North Fork of the Chena River. The site at about 1500 ft (457 m) above sea level is surrounded by 500-2000 ft (152-610 m) peaks. Subsurface Groundwater temperatures are much cooler and the groundwater Conditions: much less saline than those encountered at Pilgrim Springs (Case Histories No. 2 and 3) with maximum T \simeq 65°C and laboratory measurement of water conductivity $\sigma_{W} \approx 60$ mmhos/m. The near surface material is mainly alluvial in origin consisting of sand, gravel, silt and large angular boulders. The parent materials are primarily the metamorphic rocks and granitic plutons of the Yukon-Tanana upland. Data Plot(s): Figure 9 shows EM-31 and temperature measurements on a 140 meter profile across a hot spot and a warm stream carrying overflow from the hot springs. The hottest temperature was found at the 2.5 m (8.2 ft) depth at 19S along the profile. The stream is located between 7S and 12S. Interpretation: The conductivity shows a clear peak correlating well with the location of the hottest area and the transecting stream. However, unlike the Pilgrim Springs data, the conductivity in the vertical axis (horizontal coplanar mode labelled $\sigma_{\rm H}$) orientation is larger than that of the horizontal axis (vertical coplanar mode labelled oy) orientation. This apparently is a consequence of the lower temperature and the lower salinity found at the Chena Hot Springs site compared to the Pilgrim Springs



Figure 9. Conductivity profiles oy and o_H (vertical and horizontal coplanar orientations, respectively) along a 140 m line across a hot spot and warm stream at Chena Hot Springs and temperature at 1 m depth along the same line.

site. (Other details of this site may be found in Osterkamp et al., 1983 and Wescott and Turner, 1981).

Case History No. 5: Porcupine River Archaeological Site

- Location: Site is located approximately 120 km by air from Fort Yukon between John Herberts Village and Burnt Paw on the Porcupine River.
- Purpose: Locate caves in bedrock on a hillside covered with talus and delineate cave entrances. There is evidence that ancient man inhabited this region and caves of the type found on the hillside are prime candidates for use as shelters. Survey Date: June, 1981.
- Terrain: The area surveyed is on a south-facing talus slope along an abandoned meander, now a slough, of the Porcupine River. The slope is approximately 40° from horizontal. Some bedrock outcrops protrude from the talus.
- Subsurface Conditions: Dutcroppings are limestone and the talus on the slope consists primarily of limestone rubble and a thin layer of organic material. Removal of rubble from the entrance of one cave suggests the limestone extends to considerable depth, probably well below the 75% detection limit of the EM-31. Data Plot(s): Figures 10, 11, 12 and 13 show the resistivity contours obtained using the EM-31 at one meter spacing in the vertical and rotated orientations on the ground and at hip height, respectively, over the area containing possible cave dwelling sites. Distances are in meters. Outcroppings (OC) and other features are shown by dotted lines in Figure 12. At the time of the survey only one cave site located



Figure 10. Isoresistivity contours of Porcupine River Archaeological site in normal mode (= vertical dipoles = horizontal coplanar) at ground level.

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Figure 11. Isoresistivity contours of Procupine River Archaeological site in rotated mode (= horizontal dipoles = vertical coplanar) at ground level.



Figure 12. Isoresistivity contours of Procupine River Archaeological site in normal mode at waist level together with mappings of vegetation, limestone outcrops, caves, etc.



Figure 13. Isoresistivity contours of Porcupine River Archaeological site in rotated mode at waist level.

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at about W21,N18 (-21,18) had been excavated to any degree. The ground normal readings appear to show the best correlation with known cave sites; accordingly the discussion below will concentrate on those data, which also show the the greatest contrast between low and high resistivity areas. Except for the outcroppings, the talus slope was relatively Interpretation: smooth. There appears to be little in the way of resistivity contrast between the surrounding talus materials and the outcrops as indicated by the resistivity contours whose trends do not seem to significantly deviate when passing through the outcrop boundaries. Tunnels and cavities in the earth will in general produce higher resistivity readings. However, if they are filled with water or very wet rubble, they may in fact give lower resistivity readings than the surrounding areas. This latter possibility appears to be the case with the cave located at (+12, +18) (see Figure 12), which has a minimum resistivity of less than 300 ohm-m and the areas to the southeast and southwest which apparently are the subsurface drainage channels for the cave which was very wet. There is a higher resistivity area at (-22,+16) near the excavated cave at (-21,+16) indicating the resistivity readings are giving a reasonable estimate of the cave's location. However, the known cave at (+20,+20) (see Figure 12) does not seem to be reflected in the resistivity contours (see Figure 10). There are several other areas in Figure 10 showing high resistivity; these are located at (+8, +20), (+28, +14), (+4, +9) and (+10, -10)

The first of these appears promising as the poten-+12). tial location of a dry cave, sealed with talus material and with no indication of its existence in surface features. The second high resistivity area at (+28, +14) also appears to be a possible location for a hidden cave. The last two high resistivity areas seem to be related to the drainage path of the cave at (+12, +18) and may indicate connecting caves that are dry. The resistivity lows in the top lefthand corner of Figure 10 appear to be related to the higher moisture, unfrozen soils and the tree-covered area (see Figure 12) which differs from the limestone talus slope. Some of the resistivity lows on the talus slope may be caves that are filled with very wet rubble. Our interpretation of the resistivity highs being potential locations of dry caves must be regarded as tentative since it is also possible for a cave to be filled with pure ice and give relatively high resistivity readings. Due to a reduction in funds and man-power, no work on the potential cave sites has been done recently.

Case History No. 6. Ugashik Airport

Location: Site is approximately 300 km SW of Anchorage, Alaska by air at the proposed new airstrip of Ugashik Village near the head of Ugashik Bay on the Alaska Peninsula facing Bristol Bay.

Purpose: Map resistivity of proposed borrow site adjacent to proposed all-weather airstrip to delineate materials suitable for surfacing.

Survey Date: January 7-9, 1982

Terrain: The airport site is located in a relatively flat area near the banks of the Ugashik River. The general area is marshy and relatively low in elevation (≈ 20 m (~ 66')) above sea level while the village and airstrip are on somewhat higher ground (≈ 25 m (~ 82')) with isolated exposed outcrops of rock.

Subsurface Conditions: Slightly higher elevation and occasional nearby bedrock outcrops indicate that silt, sand and gravel overburden near the airstrip may be thinner than over adjacent marshy areas. However, boreholes along the airstrip (bearing 77.5° north of east) and along the eastern border of the borrow site, whose southern border is 100'. (30.5 m) north of the airstrip centerline, indicate that the underlying material at deeper depths (5 ~ 10' (2 ~ 3 m)) is relatively well-drained sand and gravel.

Date Plot(s): Figure 14, 15 and 16 show the results of the survey over the potential borrow site. The grid spacing used was 50' (~ 15 m), so that 119 separate readings were taken over an area 800 x 300 ft. (244 x 91 m). This spacing was deemed sufficient for mapping a borrow site, since considerable material is generally required and smaller scale anomalies possibly corresponding to suitable paving material would not be of economic interest. Figure 14 and 15 give the isoresistivity contours in the waist-high, normal and rotated positions, while Figure 16 shows the isointensity contours of the ratio of the rotated to normal readings.



Figure 14. Isoresistivity contours of proposed Ugashik airport borrow site in normal mode at waist level.



Figure 15. Isoresistivity contours of proposed Ugashik airport borrow site in rotated mode at waist level.

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Figure 16. Isointensity contours of the ratio of rotated to normal resistivity values at proposed Ugashik airport borrow site.

Interpretation: Both normal and rotated readings show the same general trends. The most prominent difference is the resistivity peak centered near (3350, -100) in the normal position (Figure 14). This shows up in the ratio of resistivities. Figure 16, as a low at the same location. Areas where resistivity is high may indicate a location of bedrock or dry gravel and sand. Based on Figure 1 the ratio of rotated to normal apparent conductivities at hip height $(\sim 1 \text{ m})$ should be about 0.67 for a uniform earth so that the ratio of apparent resistivities should be about 1.48. Nearly all the contours of Figure 16 exceed 1.48 in value indicating the surface layers are generally more resistive than the slightly deeper layers. This may indicate the surface layers were fairly cold, possibly frozen and/or they were relatively dry compared with deeper layers. However, the fact that the low at (3350, -100) is less than 1.48 in resistivity ratio does not seem interpretable as a region of either warm unfrozen material or moist area close to the surface, since Figure 15 does not seem to show an unusually low resistivity area at this position. It is more likely that the deeper layers are more resistive at the position. It is therefore concluded that there is resistive material centered near (3350, -100) at lower depths. There is also a resistive structure located near (3200, -200), which protrudes closer to the surface. This structure is possibly connected to the more deeply lying structure at (3350, -100). Thus, the most likely location

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for surfacing material within the survey area appears to be in the vicinity of the peaks at (3350, -100) and (3200, -200) and the region between them.

Case History No. 7 Togiak Airstrip and Borrow Site

Location: At the head of Togiak Bay some 325 km west southwest of Anchorage by air in the western Bristol Bay region. Purpose: Map resistivity of proposed borrow site to define materials suitable for Togiak airport paving and survey airstrip area for detecting anomalous zones.

Survey Date(s): April 4-9, 1982

Terrain: Airstrip is located a few hundred feet inland from Togiak Village which consists of beach front dwellings. Site appears to be on the inland side of an ancient spit (a former bay mouth beach, Bascom, 1964). The marshy area inland of the spit appears to have been filled in by peat and silt deposits from overflow of Togiak River whose mouth now exits into Togiak Bay some 2-3 miles east of Togiak. The elevation of the airstrip and village is $< 7 \text{ m} (\sim 23')$. The potential borrow site is located on a ridge $< 50 \text{ m} (\sim 164')$ in height approximately 2 miles northwest of Togiak across the marshy area which lies to the north of the airstrip.

Subsurface Conditions: Airstrip site is on the edge of the inland side of the spit area which consists of sands and gravels. A typical soils profile obtained from drilling data indicates the airstrip site is underlain by peat from 0'-3', sands and gravelly sands from 3'-10' and clays and clayey silt from 10' to

some depth. Numerous ponds occur in the marshy area, with some ponds occurring in the site of the proposed airstrip. Peat in the marshy area ma be as deep as 15'. A branch of a creek draining the general area cuts through the airstrip site. The relatively narrow strip where the village and airstrip are located between the ocean and marsh suggest the water table is very shallow. Test holes in the area of the EM-31 survey show that the hillside borrow pit site is overlain by organic silt to a depth of about 0.5' - 2'(0.15 - 0.61 m), silt and gravelly silt from depths of 2.5' - 4.0' (0.76 - 1.22 m) and silty gravel from the second interface down to bedrock which varied in depth from 6' (1.83 m) to 14' (4.27 m) except for a single hole where bedrock was not encountered in the 20' (6.1 m) hole. There was also a covering of snow of up to 3' (0.91 m) with a few open patches.

Data Plots: Figures 17 and 18 show the isoresistivity contours of the borrow site in the normal and rotated positions, respectively, while Figure 19 shows the contours for the normal (upper panel) and rotated position (lower panel) for the new airstrip site. All distances are in feet and the grid spacing for taking data was 50' (15.24 m) for the borrow site. For the airstrip site, measurements were taken along the long edge (2650' ≈ 808 m) of the area and then 6 lines of data were taken perpendicular to this line to the west-northwest starting with the long line as the base. These were located at 0, 475, 821, 1235, 1505 and 2505.

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Figure 17. Isoresistivity contours of borrow site for proposed Togiak airstrip in normal mode at waist level.

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The lowest resistivity (< 400 ohm-m) of the proposed borrow Interpretation: pit site is centered about (1080, 280) in the normal waist high mode (Figure 17). This corresponded to an area of melted snow indicating the occurrence of a flux of heat by conduction or by hydrologic flow such as a spring. Nine test holes were located in the band defined by $0 \le y \le$ 100' and 100' < x < 1550', that is, the bottom 100' (30.48) m) strip extending between 100' (30.48 m) to 1550' (472.44 m) from left to right. Of these, five encountered bedrock at 8' (2.44 m) or less, while the other four hit bedrock at 11' (3.35 m) or greater. Only one of the latter four was associated with resistivity greater than 440 ohm-meter, whereas the other three holes plus three more holes were located in areas where resistivity was 420 ohm-m or less. The five holes where bedrock was encountered at 8' or less were all associated with resistivity of 440 ohm-m or greater. Thus, it would appear that suitable borrow material is located closest to the surface where resistivity is highest. Figure 18 derived from measurements of the EM-31 in the rotated mode (dipole axes horizontal) shows similar resistivity contours to Figure 17. The readings in both orientations are high relative to the amount of silt present even if it were frozen, but warm, indicating that the silty gravel and bedrock at lower depths are influencing the readings to a great extent.

The results of the survey at the airstrip site are quite different from the borrow site. The resistivities

shown in Figure 19 are extremely low; indeed they are lower than the readings encountered at Chena Hot Springs (Case History No. 4). This may be the result of two factors - the possible presence of salty porewater and/or the presence of a highly conductive layer of material such as clay. It is likely that the former is the case since the airstrip site is no more than a fraction of a mile from the sea. Areas, where no isoresistivity contours exist, occur because there were an insufficient number of data points for the contour program to interpolate across these areas. These areas were avoided due to the presence of open water. A detailed comparison of contours in the normal and rotated positions, for the airstrip site shown in Figure 19 indicates there is an almost one-to-one correspondence between features at the two depths of penetration. This indicates that the lateral inhomogeneities in material type and porosity occur gradually unlike, for example, a dike or other sharply-defined geologic structure. A result of this type gives further evidence that the subsurface material was deposited more or less uniformly as in the case of a spit or other marine deposit.

Case History No. 8. Northway-Alcan Highway

Location: Approximately 249-261 road miles (400-420 km) from Fairbanks on the Alcan Highway. There were two sites; one near Milepost 1264.5 across from the Northway Motel and the other near Milepost 1266.0 (see Engineering and Soils Report of Alaska Highway Miles 1256 to 1270, Project

Number IR-I-OA1-1(3), (4) A-37632 Interior Region DOTPF, prepared by G. Brazo, June 1983).

Purpose: To map soil resistivity as an indicator of the location of potential thaw unstable material and bedrock along proposed realignments of Alcan Highway.

Survey Date(s): June 9 and June 11, 1981

Subsurface

- Terrain: Transition zone between Tanana lowlands and Tanana uplands. Area is on north side of the Tanana Valley, south of the confluence of the Chisana and Nabesna Rivers which converge to form the Tanana River proper. The road and proposed realignments are located along the base of the rounded foothills a few meters to tens of meters above the floodplain of the valley floor.
- Conditions: The hills are composed of granitic bedrock overlain by an overburden of grüs (up to 20' (7 m)), a residual granitic soil varying in consistency from silt to boulder size aggregate materials plus wind blown silt and sand. The depth of the wind blown silt varies considerably from near zero to as much as 30' (10 m) on the southeastern slopes leeward of the prevailing winds that deposited the silts. This description is typical of the sites studied. Data Plots: The grid spacing was 50' (15.24 m) for both sites along the established curved centerlines of the realignments and also along parallel lines 50' to each side. Additional data were taken along survey lines used to establish the proposed realigned section; data were also taken generally

transverse to these lines in the larger of the two areas near Milepost 1266. Figure 20 shows the isoresistivity contours derived from the normal readings for the site located near the Northway Lodge at about Milepost 1264.5. The location of some boreholes are indicated by a cross superposed on a circle. The year the hole was drilled is given by the first two numbers, while the number of the hole in a particular series of holes is given by the last three numbers. Figure 21 gives the isoresistivity contours for the realignment site near Milepost 1266.

Figures 20 and 21 offer an interesting contrast in the Interpretation: differences in resistivity that can occur when the surface layers (< 6' (\sim 2 m)) are basically frozen or unfrozen. The first area surveyed near Northway Lodge (Milepost 1264.5) is essentially on a south-facing slope and boreholes made in fall 1980 indicate the permafrost table to be near the 10' (3.048 m) depth over most of the area. By late spring the thaw depth had already proceeded to a depth of about 5' (1.524 m) over most of the area. By contrast. the second site near Milepost 1266 is on a hillside facing west-northwest and boreholes made in fall 1980 and in spring 1981 indicated that the active layer is not very thick. Indeed, the depth of thaw was generally less than 1' (0.3048 m) when the boreholes were drilled in the spring of 1981. Subfreezing ground temperatures are not the only controlling factor in these contrasting surveys. The borehole logs indicate a significant difference in material



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type, in that, windblown silt predominates in the overburden of the 1264.5 site whereas grus in the form of sandy silt occurs at the 1266 site. However, with similar moisture contents the ground temperatures should be the dominant factor. The variation in resistivity within each area is difficult to explain. In Figure 20, the higher resistivity area in the lower right hand corner, within the 180-190 ohm-m contours, corresponds to a relatively-flat, benchshaped area. The area to the left (west) and extending to the top above the 180-190 ohm-m contour is at an elevation of 10'-15' (3-5 m) above the bench-shaped area. The low resistivity area (< 160 ohm-m) which cuts across the road alignment is apparently associated with a thinning of the overburden over the granitic bedrock as suggested by boreholes in the area.

The resistivity distribution at the site near Milepost 1266 (Figure 21) is even more difficult to explain. The highest resistivity area (> 370 ohm-m) centered at about (1090, 540) appears to correspond to an outcrop of bedrock. This is unlike the case at 1264.5 where thinner overburdens appear to be related to lower relative resistivities. This may be caused by a difference in ground temperature or the presence of massive ice at the 1266 site although there were no boreholes in the high resistivity zone to confirm this. Other boreholes do show the presence of massive ice and very ice-rich soils in the area of this realignment, particularly to the left side of the plot

(the left side corresponds to the northerly direction). The top of the figure is generally the higher elevation. direction, although there is a gradual decrease in elevation to the left of the figure. The entire area is sparsely covered by relatively large birch trees to the north (left side) and spruce to the south at higher elevations (top or east) belying the conventional wisdom that large trees do not grow where permafrost and massive ice occur. These trees apparently occur where the soil is reasonably welldrained in between areas of extremely ice-rich soils.

Case History No. 9. Dot Lake Material Sites

Location: Three sites near Dot Lake, Alaska about 220 km (137 miles) southeast of Fairbanks by air along Alaska Highway. Purpose: Map resistivity in gravel pit areas to delineate materials suitable for paving.

Survey Dates: May 21-22, 1981

- Terrain: All three sites are adjacent to the Tanana River flood plain next to the Alaska Highway which skirts the southern edge of the Tanana River Valley. Trees are stunted in most areas although there are a few stands of trees that show reasonable growth indicating good drainage.
- Subsurface Conditions: The underlying material is mainly sand and gravel some of which is of cobble and boulder size. These glacially outwashed materials are at least 5 m (16') thick. The permafrost table is some 1.5 - 5 m (5-16') and possibly deeper in some areas of the three sites.
- Data Plots: Figures 22, 23 and 24 show the resistivity contours in the normal mode for the three sites. The spacing for the



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Figure 24. Isoresistivity contours for waist-high, normal mode at borrow material site 62-2-060-2 near Dot Lake.

measurements was 50' (15 m) and the grids exactly rectangular in shape. Site 62-2-066-2 (Figure 22) is located about 8.9 km (5.5 miles) north of Dot Lake off the northern side of the Alaska Highway, while sites 62-2-062-2 (Figure 23) and and 62-2-060-2 (Figure 24) are located 3.6 km (2.25 miles) and 10.9 km (6.75 miles), respectively, south of Dot Lake off the southern side of the highway. The data in the rotated mode at waist height show very similar magnitude and distribution and are thus not shown here. Also a complete set of measurements was taken at ground level in both modes which again show similar distributions and magnitudes; these are not shown here but the results will be discussed below.

Interpretation: Test pits were dug with a backhoe at the two southern sites (062-2 and 060-2) in August, 1980 and test holes were drilled in site 066-2 in late June, 1982. The drilling logs at site 066-2 show there is some silt (< 1 m (3')) overlying two layers of gravel apparently deposited during different epochs of time to a depth of 4 m (12') or greater. Both gravel layers are very coarse with cobble and boulder size inclusions; they are distinguished by sand content... the upper layer containing large amounts of sand. The underlying material at the other sites, 62-2 and 60-2, is basically a sandy gravel similar to the layer found at site 66-2, although an occasional sand layer was found to separate the sandy gravel layers. All sites were covered with vegetation at the time of the EM-31 surveys. There

was secondary growth to the right of the X = 200' (61 m) (Figure 24) in site 60-2, while site 66-2 had been cleared previously to the left of $X = 400^{\circ}$ (122 m) (Figure 22), material removed and then had been used as a dump site. Only the data to the right of perhaps X = 500' (152 m) in site 66-2 are thus valid as indicators of natural conditions. The low resistivity area centered near (375,-200) (see Figure 22) corresponds to a dump site for scrap metal. At the time of the surveys, the active layer was only at the initial stage of thawing. Thus, relatively high resistivities would be expected. The test holes made in June, 1982 in 66-2 (Figure 22) show the material is probably frozen in the wooded part (to right of $X = 400^{\circ}$ (122 m)) down to at least a depth of 5 m (15'). Figures 22, 23 and 24 are relatively featureless and fairly high in apparent resistivity suggesting the gravel is fairly uniform and possibly frozen and/or fairly dry. Site 60-2 shows the highest resistivity (Figure 24) which perhaps is an indication that the ground there was colder. Indeed the test pits dug in August, 1980 to the left of a diagonal drawn from (250,0) to 400,-300) show the ground was frozen at 3 m (10') or shallower while the test pits to the right of the diagonal show no frost down to a depth of 5 m (15'). The resistivity contours also clearly show there is a decline in resistivity from left to right across the diagonal. Test pits dug in August, 1980 near 62-2 show no frost down at least to about 4 m (12'). The resistivity contours of

this site (Figure 23) seem to indicate either a thinner frozen layer and/or warmer ground temperatures. The lower resistivity readings in the upper right hand corner correspond to a difference in elevation; this area is about 2 m (6') lower and may be an area where ground water is closer to the surface. Figure 22 for site 66-2 shows the lowest general resistivity readings of all. This may be a reflection of the presence of the silt layer previously described, but also may be due to relatively warmer ground temperatures as indicated by the test holes drilled in June, 1982 which showed no frost in a layer 1.5 m (5') thick starting at a depth of about 2.3 m (7.5'). As discussed previously in the section on the electromagnetic induction method, it is possible to determine the resistivities of a layer by taking measurements at various heights and knowing the layer thickness. Here we do not have sufficient information on layer thicknesses at the time of the survey to give an exact account of all the layer resistivities. However, since measurements were made at both hip height and at the ground we can infer whether the surface layer is more or less resistive than the underlying layers. The data taken at site 62-2 and 60-2 at ground level in the rotated position are almost universally lower in resistivity than the ground level measurements in the normal This implies first, that the ground resistivity position. is nonuniform with depth and second, that the surface layer has a significantly lower resistivity than the layer

beneath it. Since the layer closest to the surface may be thawed to a few inches and and definitely warmer than the deeper layers at this time of the year, this result may be a reflection of the annual variation in temperature of the ground.

Case History No. 10. Hiland Drive Soil Resistivity

Location: Site is located between Anchorage and Eagle River on the north side of Mt. Gordon Lyon facing the Eagle River and the township of Eagle River, Alaska.

Purpose: To map soil resistivity along proposed realignment of Highland Drive as indicator of bedrock and hydrologic flow. Survey Date(s): May 25-29, 1981

Terrain: The area is on the steep northern slopes of Mt. Gordon Lyon at an elevation ranging from about 148 m (485') near the western end just off the Glenn Highway to an elevation of 273 m (895') near the eastern end of the road realignment. The length of the realignment surveyed was 2591 m (8500'). Subsurface Conditions: The materials in the area are generally classified as glacial moraine and talus materials. Boreholes show the subsurface strata to consist of sandy silt to gravel containing cobbles and boulders. Very large boulders or outcrops of bedrock were also evident at some locations along the realignment. The boreholes drilled in April, 1981 show only a very thin layer of frozen material (< 0.7 m (~ 2')) and apparently

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no permafrost occurs in the area.

- Data Plots: Two sets of gridded data were taken over two shorter sections of the realignment. These data are not of great interest and are not shown here. A long reconnaissance line of data generally spaced 100' apart except over more interesting areas where 50' spacing was used was taken along the center line of the realignment and is shown in Figure 25. Both normal and rotated values are given in the lower panel and the normal values repeated for clarity in the upper panel of Figure 25.
- Twenty-four boreholes were drilled near the center line Interpretation: of the realignment. The low resistivity readings between stations 52+00 and 60+00 (an 800' length) in the normal readings appear to be related to the near-surface occurrence of bedrock (< .7 m (2')) which is very weathered. Visual inspection along the survey line indicated areas that were wet correspond to areas of lower resistivity. Moisture measurements of some borehole samples show the moisture tended to be higher in areas where the relative elevation is lower: these areas were also associated with lower resistivity as might be expected. The low resistivity readings (see Figure 25) occur between stations 68+00 and 78+00, 113+00 and 119+00 and 128+00 and 135+00. The latter two areas show relatively low resistivity ratios of the shallow to deep (rotated to normal orientations) readings; for a uniformly resistive half-space, this ratio should be about 1.5. In these areas the ratio is smaller indicating the deeper material tends to be more resistive



Figure 25. Resistivity profile lines along a realignment of Highland Road near Eagle River; upper panel---waist-high normal mode and lower panel---waist high rotated and normal modes.

than the surface layers. However, the data between 68+00 and 78+00 clearly give a much smaller ratio at most points and even ratios of 1.00 or less at 3 data points. This indicates the surface layer is significantly more conductive (less resistive) than the lower layers. It may thus be inferred that the hydrologic flows through the latter two sites occur more deeply than that at former site between 68+00 and 78+00.

Case History No. 11. Marshall, Alaska Airport Site

- Location: Approximately 2-3 miles north of Marshall, Alaska on the Poltes Slough of the Yukon River. Marshall is located about 800 km (500 miles) southwest of Fairbanks, Alaska and 120 km (75 miles) north by air from Bethel, Alaska. Purpose: Define ice rich areas and possible areas of hydrologic
- flows at the site of a proposed airstrip using resistivity data.

Survey Dates: March 17-18, 1982

- Terrain: Area is located on edge of Yukon-Kuskokwim lowland region at an elevation of less than 20 m (66') above sea level. The airport is to be located parallel to the banks of Poltes Slough over tundra-like terrain incised by a small creek and even smaller drainage channels from highlands to the north and east.
- Subsurface Conditions: Unditions: Subsurface materials consist of an organic layer (from about 0.7 m (2') to nearly 2 m (6') thick), silt and gravel. Bedrock (schist and greenstone), weathered in spots, occurs at a depth of 3 to 6 m (10-20').

- Data Plot(s): Figure 26 shows the isoresistivity contours derived from the EM-31 measurements with the instrument in the normal (coil axes vertical) position. The data consisted of a grid of values along the main runway alignment spaced 100' (30.5 m) apart along the center line and 75' (22.9 m) to each side of the center line plus a single line of data 100' (30.5 m) apart along the center line of the alternate runway shown by the straight diagonal line drawn from the upper left hand corner to the lower right hand corner.
- Interpretation: Test holes drilled in March and April, 1982 and subsequent laboratory testing of samples show the foundation materials in the area of the proposed airstrip are predominantly frozen and very moist. Most of the mineral soil is silt though in some locations gravels and sands were encountered. The resistivity readings should be dominated by the saturated, frozen or unfrozen organics near the surface and the silt layer, typically the mineral layer above bedrock. As indicated by Figure 26, the resistivity ranges from a low of less than 150 ohm-m centered near (4000,+100) to a high of greater than 400 ohm-m centered near (200,-100). The test holes show these contrasting, resistivity values arise because there are distinctly frozen and distinctly unfrozen soils in the area. The high resistivity area centered at (200,-100) suggested that there was solid ice and extremely ice-rich soil at this location; this was subsequently confirmed by drilling! The low resistivity region near (4000,+100) is associated with basically

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unfrozen ground except for an annually frozen layer of 0.7 m (2') or less. A topographic map and aerial photography show that lower resistivity areas are coincident with larger vegetation such as trees and taller willows while the higher resistivity areas coincide with tundralike vegetation and poorly drained areas. The lower resistivity areas at the top margin of the area surveyed correlate extemely well with the positions of drainage channels to the edge of the slough which varies from about 90 m (300') to 180 m (600') in distance from the top edge of Figure 26. There is an extremely steep gradient in resistivity, changing by more than 225 ohm-m in a distance of less than 60 m (200') centered near (3050, - 800). The air photo shows the lower resistivity area to be related to a larger drainage channel which bisects the area of interest from the east (the lower part of the figure) to the west (upper part). Since no test holes were drilled in this area, the reason for the steep resistivity gradient is not known, but it may be related to the dip of bedrock in the general area, which from sewer and water excavations in Marshall and air photos appears to be predominantly northward with strike predominantly east-west. A dike of bedrock or permafrost may be inhibiting groundwater flow from right to left, thereby producing a relatively steep thermal and moisture gradient.

Case History No. 12 CRREL Farmers Loop Road Site

Location: The site is located approximately 3.2 km (2 miles) north of Fairbanks, Alaska at about 1.6 km (1 mile) Farmers Loop Road on the CRREL (Cold Regions Research and Engineering Laboratory, U.S. Army) Experimental Site (see Arcone, et al., 1979, for other surveys made near this site). Purpose: To investigate subsurface resistivity as an indication of permafrost.

Survey Date(s): April 22, 1980

Terrain: This site is located on alluvium on the lower part of the Tanana uplands just adjacent to the Tanana River flood plain. The terrain slopes upward to the northeast. The area of the EM-31 survey was previously cleared of trees and recleared of larger secondary growth shortly before the the survey.

Subsurface Conditions: Generally the subsurface soil is classified as Minto silt loam, a grayish-colored silt containing very small amounts of organic matter. This silt is mainly a wind blown soil initially deposited at higher elevation and subsequently redeposited near the base of foothills by erosion processes. The overburden of Minto silt (Rieger et al., 1963) may be many meters thick in some areas and can contain massive ice. Data Plot(s): Figure 27 gives the isointensity contours over the area surveyed (1200 x 140' \approx 37 x 43 m). This data is derived from measurements taken in the normal position at intervals of 20' (6.1 m).



Figure 27. Isoresistivity contours for waist-high, normal mode at the CRREL Farmers Loop site near Fairbanks.

Interpretation: At the time of the year the data was taken (late April), it would be expected that the active layer had not thawed appreciably. Despite this, the area centered around (120, 20) near the southwest corner (lower right) already shows very low resistivity readings suggesting that this isolated area is unfrozen to some depth below the active layer. The anomalously high resistivity region centered around (80, 40) is believed to be the result of an erroneous reading. The general trend towards higher resistivity values from right to left and bottom to top, i.e., towards the northeast roughly corresponds to the increase in elevation in these directions. Apart from the anomalous region around (80, 40) and the unfrozen zone around (120, 20), the values over the remainder of the area clearly indicate the subsurface material is frozen and apparently has a high moisture (frozen) content. Reference to Figure 2 of this report indicates that Tanana silt (Minto silt is probably similar) has a resistivity of 600 ohm-meter at -5C or colder. Since it is not likely the permafrost in the Fairbanks area is this cold to appreciable depths, the most likely source of the extremely high resistivity is ice-rich permafrost (and/or very dry soil). The low resistivity area may be due to groundwater seepage and/or related to removal of vegetation and subsequent maintenance of the cleared area for a long period of time.

Case History No. 13. University of Alaska, Farmers Loop Site

- Location: This site is located off Farmers Loop Road across from the east entrance (Taku Drive) of the University Campus property partly on University of Alaska lands and partly on privatelyheld land.
- Survey Dates: October 19-20, 1978 and October 2, 1979.
- Purpose: The main purpose of this series of measurements was to determine the response of the EM-31 to patterned ground, disturbed areas and other surficial features over permafrost terrain.
- Terrain: The general area studied is on the nearly flat portion of the Chena/Tanana alluvial plain and is vegetated by scrub spruce and other typical low growing fauna. Aerial U-2 photos indicate there is patterned ground in the vicinity of the EM-31 profile lines. Some of the area had been cleared a few decades ago as indicated by berm piles and the presence of trails, but some immature secondary growth has returned to the area.

Subsurface Conditions: The soil in the area is classified as Goldstream silt loam, a fine-textured silt. It may contain layers of sand and sandy loam and also patches of Tanana silt-like loam. The general description of the area by Rieger, et al., 1963 indicates Lemeta peat may occur in the area in relatively small depressions. However, it is known from other sites that peat deposits may be overlain by silt and show no surface expression.

- Figures 28, 29, 30 and 31 show profiles of the resistivity Data Plot(s): at about a 10' (\sim 3 m) spacing along lines designated A, B, C and D, respectively. Line A was directed roughly east-west from the eastern edge of Farmers Loop Road 140' $(\sim 43 \text{ m})$ into an area that is apparently undisturbed except for a trail which crossed the line. B is also an east-west line with a total length of 290' (~ 88 m) displaced about 400'-500' (~ 122-152 m) north of A, starting and ending in an undisturbed area. Line C is a line of 140' (~ 43 m) length directed roughly northsouth, crossing line B in the same undisturbed area. Line D began in an undisturbed area and ended in an area orginally cleared of vegetation. D was paced off rather than measured exactly for a total of 54 paces (~ 162' or 49 m). The data includes the complete set of measurements made along each line on 10/19/78 and one or both of the two sets of measurements made on 10/02/79. Also included in Figure 30 are the ground level data taken along line C on 10/20/78. The locations of the boundaries of patterned ground where ice wedges usually occur, trails and other surface features are noted on each of the plots.
- Interpretation: The occurrence of polygonally-patterned ground, melt holes and man-made disturbances appears to have made the profiles taken over the area extremely complex. Such differences in surface features are indicative of lateral inhomogeneities in ground temperature, moisture content and/or soil type and hence in ground resistivity. Probing measurements in



Figure 28. Resistivity profiles along an approximate east-west transect starting near the eastern edge of Farmers Loop Road just north of the Taku Drive entrance of the University of Alaska, Fairbanks. Surface features along the transect are also noted. The data for both normal and rotated modes are shown for two dates.



Figure 29. Resistivity profiles for both normal and rotated modes for two dates along an east-west transect approximately parallel to transect of Figure 28, but displaced to the north. Surface features are also noted.



Figure 30. Resistivity profiles for both normal and rotated modes in the same general area as Figure 28, but directed north-south. Two separate sets of measurements for one date are shown as well as the ground level and waist-high readings for two other dates. Surface features are also noted.



Figure 31. Resistivity profiles for both normal and rotated modes in the same general area as Figure 28. This rough east-west profile was measured in paces and crossed into a disturbed area. Surface features are also noted.

a nearby area show the permafrost table was probably 24" (~ 0.6 m) or less in late September 1978 so that one may expect the thaw depth in October to be similar. If the lateral inhomogeneities are large-scale (at least 1 to 2 times the intercoil spacing, 3.66 m = 12 ft), the conductivity (resistivity) determined by the EM-31 will essentially be that of a layered earth. It is a relatively easy matter to determine whether the upper layer of a two-layer earth is more conductive than the basement material, by placing the EM-31 <u>on the ground</u> in the normal (vertical dipole) and rotated (horizontal dipole) positions. For a homogeneous earth, $\sigma_{aV} = \sigma_1 (1-R_V) + \sigma_2 R_V$

= σ_1 = σ_2 and σ_{aH} = $\sigma_1(1-R_H)$ + σ_2R_H = σ_1

= σ_2 , respectively, for the apparent conductivities in the normal and rotated orientations. For a two-layer earth, if $\sigma_1 > \sigma_2$, then $\sigma_{aH} > \sigma_{aV}$; similarly for σ_1 < σ_2 , $\sigma_{aH} < \sigma_{aV}$. At waist height, the magnitude of σ_{aV} is always larger than that of σ_{aH} for a homogeneous earth with a ratio σ_{aV}/σ_{aH} of about 1.5) or a two layer earth with upper layer conductivity less than the lower ($\sigma_1 < \sigma_2$). However, for a two-layer earth with $\sigma_1 > \sigma_2$, the apparent conductivity σ_{aV} in the normal orientation may be less than equal to or greater than the apparent conductivity σ_{aH} in the rotated orientation. The primary reason for this is that the response function (see Figure 1) for the instrument in the rotated position has a steeper slope (hence ($R_H(1) - R_H(2)$) is larger than

 $(R_V(1) - R_V(2)))$ over a certain range of depths than the response in the normal position. With regard to the data of 10/19/78 and 10/02/79 and the following case history, the upper layer should generally be more conductive than the lower layer; the data also shows a wide range of conductivity ratios (σ_{aV}/σ_{aH}) indicating the existence of thaw depth variations, conductivity differences and lateral inhomogeneities in temperature, moisture, ice content and soil type or combinations of all these factors. The lower resistivity readings (higher conductivity) at the beginning of Line A (Figure 28) corresponds to the location of the eastern edge of Farmers Loop Road which clearly forms a disturbed area with a large thaw bulb. Within 40-50 ft (12.2 - 15.2 m) of the road the resistivities are close to typically undisturbed values. Note also both the 10/19/78 and 10/02/79 data show similar variations, although their magnitudes differ. The larger resistivity values encountered on 10/19/78 than on 10/02/79 may be due to cooler ground temperatures or to some differences in calibration of the instrument. There seems to be no strongly systematic signature in the normal position of the instrument for ice wedges assumed to be at the boundaries of the patterned ground areas; of seven wedges noted in Figures 28-31, three show positive change (greater resistivity) relative to the surrounding terrain while the other four show little or no change. In the rotated position, there appears to be a somewhat more systematic

signature with six of the seven wedges showing a negative change (lower resistivity). It is interesting to note that the ground level readings taken on 10/20/78 along Line C (Figure 30) show a strongly positive resistivity change over the presumed position of a wedge in the normal orientation and a negative change in the rotated position. Also these data show the rotated resistivities over most of the profile are lower than the normal resistivities confirming the existence of a thawed layer with lower resistivity above permafrost. The precise reason for the apparent lack of a definitive signature for the ice wedges in the normal position at waist level is unknown, but it is believed to be due to the presence of a more moist active layer above the ice wedge, which masks out the higher resistivity of the ice wedge itself, such that the apparent resistivity is not much different from the surrounding area. The melt holes observed along lines A-D (Figures 28-31) also do not appear to have a definitive signature, and, although one might expect a lower resistivity, the resistivities are actually larger over four of five identified melt holes for the normal orientation of the instrument at hip height than they are over the surrounding terrain. Three of the five melt holes show also increased resistivity in the rotated position. They may be associated with areas of exceptionally high moisture such that the underlying material is ice-rich and hence more resistive, but by the same token, they should require a longer period

in the Fall for refreezing of the thawed layer. The trail which crosses both Line A (Figure 28) and Line B (Figure 29) produces a strong perturbation on the profile of Line B, but very little perturbation on that of Line A. The reason for this difference in response is unknown, but may be related to a minor difference in elevation such that ground water may accumulate near the trail where it crosses Line B. It is interesting to note for the 10/19/78 data that the resistivity change in the rotated position on the Line B profile (Figure 29) is considerably larger than the change in the normal position where the trail crosses the profile (x = 50 ft (15.24 m)). Indeed, the absolute magnitude of the resistivity is smaller in the rotated position. For a two layer earth, this implies that the overburden is thin < 1 m = 3.28 ft) and probably that it has a much higher conductivity (lower resistivity) than the basement material. At waist height, the response function in the rotated position (see Figure 1) falls off more rapidly than that in the normal position for a narrow range of first layer depths (≈ 1 m) such that provided the first layer conductivity is large enough, it is possible for measured conductivity to be larger in the rotated than in the normal position. Line D (Figure 31) crosses a boundary between an undisturbed area and a disturbed area. This profile shows there is only a slight difference between the two areas in terms of resistivity at this time of the

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year. In fact, the disturbed area exhibits a higher resistivity in both orientations, although one might initially assume that such a disturbance should lead to a greater thaw depth and a greater conductivity. The higher resistivity in comparison with the undisturbed area implies the disturbed ground is colder and/or drier. In summary, the profiles of Figure 28-31 are complicated due to the presence of lateral inhomogeneities in subsurface conditions (and surface vegetation as well). Such data suggests that early Fall, when the active layer is probably near maximum thickness, is not the best time for efficient use of the EM-31 due to difficulties in interpreting the data.

Case History No. 14 College Road Peat Site.

Location: This site is located on University land about 0.2 mile (0.32 km) to the north of College Road. The access road is approximately 0.8 mile (1.3 km) from the intersection of College Road and University Avenue/Farmers Loop Road. Purpose: To determine the response of the EM-31 to a typical area of peat in the Fairbanks area.

Survey Date: September 27, 1978.

Terrain: The general area is relatively flat and poorly-drained with occasional depressions where peat has formed. Distinct boundaries in the vegetation occur where spring runoff has formed channels and accumulated in shallow ponds and lakes or where mineral soil is directly beneath the existing, living surface vegetation as distinct from the site of peat bogs.



Figure 32. Resistivity profiles for normal and rotated modes over a peat bog north of College Road approximately 1.61 km (1 mile) from University of Alaska by road. The thaw depth along the profile and surface features are also noted.

Subsurface The area studied is the site of a peat bog formed by infilling Conditions: of a shallow lake about 0.5×0.3 miles (0.8×0.48 km) in dimensions. The depth of the peat (classified as Lemeta peat) measured by drilling to the base at one site is about 3 m (\sim 10'). The areas surrounding this and other areas of peat consist primarily of Goldstream silt loam (Rieger, et al. 1963). This classification applies to typical surface soils down to ten meters or somewhat more in depth; however, other boreholes drilled to nearly 200' (~ 61 m) have revealed the existence of interbedded gravel layers and peat below a thin layer of surface soil. Data Plots: Figure 32 shows the resistivity obtained with the EM-31 along a profile crossing the areas of interest. The survey line is directed approximately east-northeast to westsouthwest over 240' (73 m) of the peat bog and then about 80' (24 m) over a stream channel into an area of silt. Depth probing measurements using a steel rod were made to determine the thaw depth; these are also plotted in Figure 32 in inches (1" = 2.54 cm). The location of the stream channel and other features are noted for comparison with the resistivity and depth of thaw readings. Interpretation: There appears to be a clear correlation of the depth of thaw with the EM-31 readings in the rotated position, but no systematic correlation with depth for the normal position along the length of the profile. The log books indicate the thaw depth is correlated with shading produced by trees being shallower where shading is greatest. There

are small groups of scrub spruce growing on the peat bog and a much denser and larger growth of spruce at the eastern edge of the bog near the stream channel indicated in Figure 32. Birch trees, which grow where drainage of ground water is reasonably good, predominate along the stream channel, itself. The channel is well-defined in both rotated and normal positions. For contrast, the survey should have been extended over an area where silt is known to exist, but where no drainage channel occurs. Unfortunately, the stream channel centered near 110E is located to the left of the center between two areas of Lemeta peat, which are separated by about 300' (91 m). Thus, the profile does not cover an area of poorly-drained frozen silt, except possibly at the flanks of the stream channel, sufficiently far from the stream. These areas on both sides of the stream do exhibit higher resistivity indicating a difference in soil type and/or soil temperature. The resistivity in the rotated orientation tends to be lower than that of the normal resistivity for many points along the profile. As has been indicated previously in Case History No. 13, this may be due to a combination of lower first layer resistivity and an appropriate range of first layer thickness (< 1 m), such that the difference in response function of the first layer in the rotated position is larger than that in the normal position of the instrument. Evidently, both criteria are met here since the depth of thaw is much less than a meter and the existence of a thaw

layer implies the surface layer is more conductive (less resistive) than the frozen basement material. The fact that the rotated readings are lower than the normal ones over the stream channel must be interpreted to imply the unfrozen surface layer in the stream channel is much less resistive than the underlying frozen material, because the depth of thaw is about 1 meter (39.37"), close to the limit of a first layer thickness that can give a reversal of the dominant resistivity values. That is, a thaw thickness exceeding about 1 meter will always give a normal reading which is less than the resistivity reading in the rotated position at waist height.

Case History No. 15. Glennallen, Alaska TAPS Site

- Location: The site is located about 9 miles (14.5 km) north of Glennallen, Alaska near the Gulkana Airport. The area surveyed is adjacent to the TAPS (Trans-Alaska Pipeline System) right-of-way where borehole information is available (see Trans-Alaska Pipeline System Special Soil Profile Study - Copper River Basin, Alaska, prepared by R & M Engineering and Geological Consultants, June, 1970).
- Purpose: To compare borehole and electrical resistivity measurements in an area containing clayey frozen materials.

Survey Date: October 25, 1978

Terrain: The terrain is typical of the upland portion of the Copper River Basin in an area with poor drainage. The general area is relatively flat with dense stands of very short to medium tall spruce, willow, birch and aspen. Numerous ponds and lakes exist in the area of the survey proper.

Subsurface Conditions: The area is underlain by permafrost. Borehole samples show the subsurface materials are peat, clayey silt and silty clay with occasional traces of sand, gravel and cobbles to depth of at least 10 meters (~ 30').

- Data Plots: A profile was made along a series of boreholes drilled in 1969 and 1970 along the then proposed route of the TAPS pipeline. Subsequent construction placed the pipeline about 150' (46 m) to the east of the proposed pipeline route (at the location of the survey which extended from about Station 6356 + 00 to about Station 6369 + 00 (i.e., 636,900' from Valdez, Alaska, the terminus of the pipeline). The pipeline crosses the Glenn Highway between Glennallen and the intersection of the Glenn and Richardson Highways at about Station 5905 + 00 (590,500' or 111.8 miles (180 km) from Valdez). Figure 33 shows the result of this 1300' (396 m) survey. Resistivities in both the normal and rotated positions are shown and vegetation boundaries and other surficial features are noted.
- Interpretation: This site has been studied in somewhat greater detail using both magnetic induction (EM-31) and low frequency radio wave signals by Arcone et al. (1978), although our survey includes data from the instrument in the rotated position which were not included in the earlier report. Arcone et al. (1978) show a cross-section of subsurface conditions from the R & M report, mentioned previously, indicating the subsurface soils and moistures encountered by the drill samples. The normal readings of our survey



Figure 33. Resistivity profiles for normal and rotated modes along Trans Alaska Pipeline System (TAPS) site near Glennallen. Some surface features and borehole locations are also indicated.

are very similar in every detail to those of Arcone et al. and therefore, like ours, disagree with how one may interpret the resistivity relative to some of the borehole data. In particular, TH-36 (477.0' along our profile line) shown on Figure 33 indicates there is a high ice content (> 20%, visible) beginning at a depth of about 5' (1.5 m) extending to a depth well below 15' (4.6 m) while a hole 25' (7.6 m) to the north (at 452.0' on our profile) shows ice content > 20% from 2' (.6 m) to 15' (4.6 m). One would expect this area to exhibit significantly higher resistivity than the area to the north between stations 1.5 and 4.0 where boreholes indicate much smaller amounts of visible ice occur. Boreholes were drilled in three phases using various methods including split spoon and even a 3' (.9 m) diameter auger. Drilling occurred in October, 1969, February, 1970 and June, 1970. The interpreted profile of ice content and soil type with depth shown in the R & M report and also reproduced in Arcone et al. (1978) appear to contain only information from the boreholes drilled in the first two phases, although the loggings from the boreholes drilled later do appear in the R & M report. Some of the later boreholes designated TH-36A, B and D, only about 6' (~ 2 m) from the area of TH-36 itself apparently do not show the high visible ice content seen in TH 11-36. We are therefore led to conclude from the evidence of the resistivity measurements and the boreholes drilled in June, 1970 that there is either an

error in interpretation of the ice content at shallow depths for the earlier boreholes located in and around the vicinity of TH 11-36 or that the locations of the holes drilled in June, 1970, namely TH 11-36 A, B and D are not actually near TH 11-36. Alternatively, the EM-31 surveys which were conducted several years later, may not have been correctly located relative to the boreholes. However, except for the observations of ice content in TH 11-36 there is a general correlation of high ice content at shallow depth with high resistivity. Also there is some correlation between vegetation and resistivity as might be expected, with the cleared area correlated with low resistivity, the shaded area with high resistivity and the occurrence of the lake, which has a thawed area underneath it, showing the lowest resistivities along the profile. Also according to the borehole measurements the occurrence of silty clay, which should lead to generally lower resistivity values since it tends to be more conductive, is apparently not distinguishable from clayey silt, with ice content of the subsurface soil being the dominant factor. The resistivities are fairly low particularly between stations 1.30 - 5.60 and also 9.10 - 10.50 indicating the ground is not frozen to very great depths or that a deeper subsurface layer is strongly conductive in the former area and possibly that there is well-drained soil near the latter as evidenced by the occurrence of taller spruce there.

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Case History No. 16. Delta Barley Site

Location: Approximately 17 miles (27 km) east of Delta Junction, Alaska along the Alcan Highway and just west of Sawmill Creek on one of the several University of Alaska, Agricultural Experiment Station (AES) plots in the Delta-Clearwater area.Purpose: To determine the characteristic signature of a small diameter (≈ .5' = .15 m) fuel pipeline crossing a portion of the Delta Agricultural Project lands.

Survey Date(s): October 24, 1978

- Terrain: The survey area is located in the Tanana Valley lowlands and is generally flat. The profile was conducted across the abandoned small-diameter, pipeline which once carried fuel between Haines, Alaska and Fairbanks. Trees were removed when the pipeline was laid but secondary growth has returned. Vegetation was also removed on the northern edge of the profile which was conducted into a Delta AES plot.
- Subsurface Conditions: The site is underlain by thick beds of gravel with a rather thin layer of topsoil consisting of organic silt (~ 1'-3' (0.3-0.9 m)) and organic matter. At the time of the survey, probing showed the depth of the active layer to be greater than 4' (1.22 m) in the wooded area. Freezing from the top was about 0.15' to 0.5' (0.05 to 0.15 m).
 Data Plot(s): Figures 34 and 35 show the resisitivity profiles obtained from the normal and rotated orientations, respectively, at waist and ground heights. The profiles extend over 330' (100.6 m) starting from the northern end which is on the AES Delta Experimental plot. The direction of the profile



Figure 34. Resistivity profiles for normal orientation at waist and ground levels at Delta Barley site near Delta Junction. Surface features and other information are noted.

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Figure 35. Resistivity profiles for rotated orientation at waist and ground levels at Delta Barley site.
was from the northeast to the southwest. Vegetation and other boundaries are noted.

The readings in the normal position (Figure 34) show a Interpretation: wide range of resistivities. The most prominent feature of the profiles is the great decrease of resistivity over the pipeline and associated clearing. As discussed previously, a conducting dike or a cylindrical conductor buried at shallow depths may produce a negative conductivity reading directly over the conductor provided its thickness is less than the spacing between receiver and transmitter coils. Thus, the meter values at station 2.5 were not recorded because the instrument is only calibrated to read positive apparent conductivity values. If data had been taken at closer spacing as the point directly above the pipeline was approached, the resistivity would continue to decrease and then begin to rise perhaps reaching infinite resistivity at two points symmetric with the centerline of the pipe provided the conductivity contrast between pipeline and soil matrix is large and it is not buried very deeply. Theoretical calculations show the effect of a dike or buried pipe should decrease to negligible levels at two or three times the intercoil spacing. However, if the conductivity of the host material is small, a conductive body may have a disproportionately large effect on the resistivity even at these distances. This is apparently the case with the profiles of Figure 34 to perhaps within some 50' (15.4 m) (or 4.16 times the intercoil spacing) of the

pipeline centered at 2.5. Clearly within this interval the signature of the pipeline dominates the profile: outside of this range, to the north (0 to 200'), there are fluctuations in the ground normal data that are large indicating more local sources affect the profile. There is a gradual decrease between 0 and 200' in all the profiles and there is no clear demarcation in resistivity between the wooded and cleared areas. This suggests there is a gradation in the underlying materials whose moisture content is not the dominant factor, since one would expect a higher resistivity in the shaded, wooded section. One interpretation is that the underlying gravel is relatively dry and graded with distance from the pipeline with coarser materials on the north side of the profile (nearer the origin). A similar though much less spectacular variation with distance is seen in the rotated position (Figure 35).

Case History No. 17 UAF-AES Farm Site

- Location: The site is located on the University of Alaska, Fairbanks, Agricultural Experiment Station farmland almost due south of the Geophysical Institute and just north of Geist Road to the east of the meteorological shelter.
- Purpose: To compare the electromagnetic response of areas where the permafrost table is known to be relatively deep (> 20' 6.1 m)) with areas where the permafrost table is relatively shallow (\approx 6' (1.8 m)) and to study the seasonal responses of the two areas.
 - Survey Date(s): September 21, October 19 and December 11, 1978 and September 27 and March 15, 1979.

- Terrain: The area is in the Tanana Valley flood plain. It was once heavily wooded, but part of the area studied was cleared approximately 30 years ago for agricultural purposes. Subsurface Conditions: The subsurface soil is primarily alluvial in origin and is classified as Tanana silt loam. The depth to bedrock in a nearby area is about 25' (7.6 m). Removal of the vegetation and continuous cultivation have allowed the permafrost table to be lowered to approximately 24' (7.6 m) and beyond. In undisturbed areas adjacent to the fields and in areas where vegetation has been allowed to return over a long period of time, the permafrost table is 3-6' (1-2 m) or less.
- Data Plot(s): Figures 36 and 37 show the profiles obtained along east-west transects over cleared land and into a basically undisturbed area. The plots in Figure 36 are the normal and rotated profiles for 9/21/78, 9/27/79, 10/19/79, and 3/15/79. Figure 37 shows the normal and rotated profiles for 12/11/78. The data obtained with the instrument on the ground on 12/11/78 and 3/15/79 are also shown. The positions of vegetation and other boundaries are noted. Figure 38 shows profiles obtained on the same dates as those shown in Figures 36 and 37 for north-south transects in the same general area.
- Interpretation: The EM-31 was calibrated prior to taking each set of measurements. Assuming the instrument was properly calibrated, an examination of Figures 36 and 37 shows there is a systematic change in resistivity with time as

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Figure 36. Resistivity profiles for waist high and one set of ground level readings in the normal and rotated modes for several dates in 1978 and 1979. The profiles for a west-to-east transect across cleared and undisturbed land at the University of Alaska Agricultural Experiment Station (UAF-AES) are shown.



Figure 37. Resistivity profiles for waist high and ground level readings in the normal and rotated modes for late fall, 1979 at the UAF-AES for the same transect line as in Figure 36.



Figure 38. Resistivity profiles for waist high and some ground level readings in the normal and rotated modes for several dates in 1978 and 1979. These profiles are for a north-to-south transect across cleared land and over an area of secondary growth at the UAF-AES in vicinity of the Figure 36 transect.

the ground temperature decreased from late summer to late winter conditions. However, it is clear by comparing the early fall data with the winter data in Figures 36 and 37 that parts of the profiles are affected differently by seasonal change as may be expected from the differences in surface cover materials present. This can be seen in the area of the berm located between stations 130 and 140. In the late summer-early fall profiles, the resistivity over the berm has a distinct peak in the normal orientation and a slight decrease in the rotated mode. This may be interpreted as indicating the temperature beneath the berm is significantly colder than the surrounding areas, especially the cleared area between stations 0 and 130. The insulating effects of the berm are apparently even greater than that of the natural, undisturbed vegetation of the woods to the right of station 140. It is interesting to note that as the cold wave penetrates the ground, the steep change of resistivity between 120 and 130 (Figures 36 and 37) in the waist normal position present in early fall disappears by December being replaced by a more gradual change. However, the berm is still seen as a distinct lateral boundary in resistivity in the ground normal position (Figures 36 and 37), indicating at deeper depths there is still a significant temperature difference between the soils directly beneath the berm and the cleared The 1978 and 1979 data in early fall (Figure 36) area. are very similar showing that there is repeatability in

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the measurements. There is a peak at station 170 (Figure 36) in the resistivity measured in the rotated position which may be interpreted as an area of colder and/or a drier, near-surface soil. The response of the EM-31 in the north-south transects are similarly affected by season (Figure 38). The transect carries the profiles from the cleared area through what appears to be an area of secondary growth, primarily willow. It is expected that the permafrost in this area will not be as well shaded as an area containing undisturbed tall spruce such as that covered by the east-west profiles (Figures 36 and 37). Corresponding to this interpretation, we see the resistivity in the area of the willows (Figure 38) is lower than that in the area of the spruce of the east-west transects (Figure 36), implying warmer surface layer soil temperature and a deeper permafrost table. Alternatively, the subsurface soils may differ somewhat between the locations of the spruce and willows. The anomalous changes between stations 30 and 70 are probably due to buried cables, one of which was observed at the surface at station 40. In summary, both the east-west and north-south profiles show resistivity values which correlate reasonably well with the expected depth of the permafrost table and with the seasonal thickness of the active layer and temperature profile with depth. Finally, the measurements in the fall appear to show the surface layers are more resistive than the underlying layers even in the woods where the permafrost table

is presumed to be about 6' (~ 2 m). This may be inferred from the ratio of rotated to normal resistivities which is about 1.60 to 1.80 (see Figure 36 between stations 190 to 240). As indicated previously, at hip height this ratio is about 1.48 for a uniform earth, greater than 1.48 for a more resistive first layer and less than 1.48 for a conductive first layer. Thus, it appears groundwater has percolated downward leaving the cooling, but yet unfrozen surface layer relatively dry; alternatively, there may be a fairly highly conductive layer at depth.

Case History No. 18: West Dock Prudhoe Bay

Location: Near the West Dock at Prudhoe Bay on the Beaufort Sea coastline.

Purpose: To determine the effect of a high conductivity layer on the EM-31.

Survey Date: May 31, 1979.

Terrain: The terrain is typical of the land-sea boundary in the North Slope region of Alaska that is, it is relatively flat, dotted with numerous lakes on land and has a very shallow continental shelf extending many tens of kilometers offshore.

Subsurface Conditions: Deeper materials consist of sands and gravels, but these are generally beyond the effective penetration depth of the EM-31. The very nearshore region of Prudhoe Bay is extremely shallow only 1 ~ 2 meters (< 6.1') within 400 meters (1312') and deepening to about 30 meters (~ 100') beyond 500 meters (1640'). At the time of the year of survey the ice was about 1 m thick nearshore and less than

2 meters beyond 400-500 meters from shore. Beneath the ice in the nearshore region the thawed layer, consisting of sand and gravels saturated with briny sea water, was only about 1-2 meters thick within 400 meters of shore. Data Plots: Figures 39 and 40 show the data along a profile extending from 100 meters (328') inland to 700 meters (2297') out onto the ice. Both ground and waist measurements are shown in the normal and rotated orientations with the inland portions shown as insets.

Interpretation: Except at the 80 meter point in the inland portion of the profiles shown in the insets of Figures 39 and 40, the ratio of normal resistivity to rotated resistivity both on the ground and at waist level is lower than expected for a uniformly resistive half space. In fact, the inland ground readings suggest the surface layer is more resistive than the more deeply lying material, since the ratio of normal to rotated readings is generally less than 1.0. It is interesting to note that the resistivity is fairly low $(\sim 200-400 \text{ ohm-m})$ for North Slope conditions where the deeper depth resistivities may be several thousand ohmmeters. This suggests there may be a layer of fairly saline soil beneath the topmost layers of snow, ice and surface vegetation. Such a saline layer could be formed by percolation downward of seawater carried on shore by storm surges. The high values of conductivity (low resistivity values) seaward of the shoreline at about station 100 are expected, since the frozen sea ice is only about 1 to 2 meters thick and the underlying slush/seawater mixture



Figure 39. Resistivity profiles for waist and ground level normal mode from a point 100 m inland (inset) to 700 m offshore near the West Dock at Prudhoe Bay.

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Figure 40. Resistivity profiles for waist and ground level rotated mode corresponding to normal mode survey of Figure 39.

under the near shore ice and the cold seawater further out would be expected to have a reasonably high conductivity even though their temperatures are very close to freezing. However, the response of the EM-31 is extremely non-linear with the apparent conductivity eventually decreasing with increasing true half space conductivity when the instrument is on the ground. This occurs because the skin depth decreases with increasing conductivity (and also with frequency) such that in the limit of infinite conductivity when the induced currents flow only in the thin boundary layer which is mathematically coincident with the dipole loops, no net field (primary and secondary) will be observed by the receiver coil. On the other hand, when the instrument is not located immediately adjacent to the conductive material which is the case here when the instrument is at hip height and on the surface of the one-to-two meter thick ice, the indicated conductivity may be considerably higher than that indicated when the seawater layer is immediately adjacent to the plane of the loops. For the latter situation, the maximum possible indicated conductivity for the EM-31 (operating frequency 39.2 KHz) is 81 mmhos/m (resisitivity 12.3 ohm-m) in the normal orientation (vertical dipoles) for a true conductivity of about 280 mmhos/m (resistivity 3.6 ohm-m). True conductivities lower or higher than 280 mmhos/m will be indicated by values less than 81 mmhos/m when the instrument is lying on the highly conductive material in the normal orientation.

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It may be inferred from Figure 39 that many of the measured conductivity values are greater than 81 mmhos/m suggesting there is a high conductivity layer at some depth beneath the surface of the ice. Unfortunately, it is not possible to model these data using the response functions shown in Figure 1 which are only applicable under the condition that $\sqrt{\mu_0}\sigma fs^2\pi \ll 1$ where μ_0 = permeability constant, σ = conductivity, f = operating frequency and s = intercoil spacing distance. However, some idea of the nature of the conductive layer may be obtained from the following argu-Seaward of station 500, the sea ice is about 1.8 m ments. $(\sim 6')$ thick and there is seawater to a depth of about 10 m (3.5'), while between stations 100 and about 400, the sea ice is about $1 \mod (3')$ with a 1 to $2 \mod (3' \ to \ 6')$ layer of slushy seawater beneath the ice. If one models this using the curves supplied with the EM-31 instrument assuming the surface ice layer and the seabed have zero conductivity. one finds the conductivity of the seawater outside Station 500 to be about 125 mmhos/m and that of the slushy seawater inside station 400 to be about 325 mmho/m. At standard temperatures, seawater has a conductivity of about 5 mhos/m and at 0°C laboratory measurements indicate the conductivity should decrease by no more than a factor of 2 to about 2.5 mhos/m (2500 mmhos/m). Thus, the results from the profile disagree by an order of magnitude or so from expected values. Also there is a disagreement between the calculated values obtained for typical conditions

seaward of station 500 and landward of station 400 further indicating the models based on the Geonics supplied curves which hold for lower conductivities are in error. Unfortunately, the fixed-core, fixed-frequency system of the EM-31 does not allow probing with depth to resolve the conductivity, although given the depths of the seawater layer and the two point measurements (ground and waist levels) with height from the sea water, it might be possible to obtain a better estimate of the seawater conductivity. This, however, is beyond the scope of this report.

Case History No. 19: Tanana River Ice Revetment Site

- Location: This site is located near the south end of Fairbanks International Airport just adjacent to the Tanana River, where an ice revetment was constructed in an attempt to prevent erosion at a sharp bend of the Tanana River. Purpose: To correlate EM-31 data with known subsurface conditions. Survey Date: April 10, 1979.
- Terrain: The area is located on the Tanana Valley flood plain which is incised by numerous stream and slough channels both new and ancient. Given sufficient time, old channels are refilled with peat and/or covered by silt during episodes of flooding. The survey line was approximately parallel to the banks of the Tanana River with some measurements made at the edge of the water. The area is primarily vegetated with scrub forests of spruce, willow and birch with occasional stands of taller trees where the ground is generally unfrozen and well-drained.

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The near surface soil surveyed in the area is classified mainly Subsurface Conditions: as Bradway sandy loams, a poorly drained sandy soil, although some patches of Tanana soil, a more silty soil. also occurs along the survey line (Rieger et al. 1963). Borehole samples taken by the U.S. Army Corps of Engineers show the area is underlain by various grades of sand with silty sand and organic silt predominating near the surface and sandy gravel at depths greater than about 3 m (10 ft). Peat and organic silt were no more than about 0.6 m (2 ft) thick along the survey line and considerably thinner as indicated by most boreholes along the survey line. Data Plots: Figure 41 shows the resistivities in the normal orientation at hip and ground levels along a profile line aligned along a series of boreholes. Temperature measurements were made on February 15, 1979 at various depths in most of these boreholes and the depths at which the OC isotherm are located are also shown along the profile. The EM-31 measurements in the rotated position show similar variation and are therefore not shown here.

Interpretation: The profile of resistivity correlates well with the depth to the OC isotherm as can be seen by a cursory examination of Figure 41. In February, the ground near the surface is very cold; however, if, the air temperature is high and there is a lack of insulating snow and surface vegetative mat, the temperature in the surface layers should begin to rise with increasing solar zenith angle. It is clear from this example that temperature is the dominant factor



Figure 41. Resistivity profiles for waist and ground level normal mode at Tanana River Ice Revetment site at southwest corner of Fairbanks International Airport. The depth of the OC isotherm measured in several boreholes and surface features are also shown.

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controlling resistivity. The boreholes AP 18 and AP 19 were the closest to the banks of the river after breakup in May, 1979 and AP 19 had the coldest, near-surface temperature with T \simeq - 14C at a depth of about 0.6 m (1.9'). There is considerable variation of the depth to the OC isotherm over the profile. This is probably due to differences in the subsurface soils and also to the presence of shading trees as indicated in Figure 41. The position of the OC isotherm has by now (1984) been greatly altered by the proximity of the profile line to the river (< 5' $\sim 10'$ in some locations) which from aerial photos taken in 1951 was approximately 200 m (600' \sim 700') east of the present stabilized position (stabilization was achieved by a permanent concrete revetment - the ice revetment was unsuccessful). This gives an erosional rate of over 7 m (21') per year! The ratios of normal to rotated (not shown here) conductivities show values expected of a two layer situation where the surface resistivity is higher than that of the more deeply lying material. In summary, this case shows the ground temperature is the controlling factor in resistivity all other factors being equal or at least similar.

Case History No. 20: South Fairbanks Expressway-Proposed Alignment

Location: This site is the proposed location of the south Fairbanks Expressway which will allow through traffic a direct route to bypass the southern edge of the downtown Fairbanks, Alaska core area by connecting the Parks Highway to the Richardson Highway.

Purpose: An EM-31 time reconnaissance survey was conducted along a 12,000' (3658 m) section of the alignment to determine areas of frozen and ice-rich soils in conjunction with borehole data.

Survey Date: December 7, 1981

Terrain: The general area is considered part of the Tanana River floodplain. Its location between the west-southwesterlyflowing Chena River and the westerly-flowing Tanana River east of their confluence and the relatively low elevation of the area suggests it has been subjected to frequent episodes of flooding by both rivers. Numerous streams, sloughs and infilled channels can be noted in aerial photographs of the area. The vegetation varies from low alpine-like ground cover to birch and spruce 25' (7.6 m) and taller. The survey line crossed numerous trails, many abandoned, and maintained roads. Such man-made disturbances are often associated with metal debris, power and telephone lines and other, often-times hidden sources of erroneous signal.

Subsurface Conditions: As evidenced by surface vegetation and a series of 30 boreholes drilled along the alignment during a period from late September to late November, 1981, the subsurface temperature and moisture regimes and layering of the soils are complex. The near-surface materials vary from totally

silt or sandy silt to sand and gravel to a depth of 15' (4.7 m) or more underlying a thin 3' to 5' (0.9 to 1.5 m)layer of silt. Generally the courser materials are found nearer the base of the boreholes mostly drilled to 15' (4.7 m). although two deeper boreholes showed alternating sequences of course and fine materials. Moisture contents determined from borehole samples vary from a low of about 2% at a depth of about 7' (2.1 m) in one hole to a high of nearly 70% at 2' (0.6 m) at another hole. No massive ice was encountered in drilling permafrost zones. The active layer depth was about 2' - 6' (0.6 - 1.8 m) where permafrost occurred, but in some locations the permafrost table was 9' (2.7 m) or more. Data Plots: Figures 42 and 43 show the normal and rotated resitivities along a 2400' (732 m) section of the total 12,000' (3658 m) reconnaissance survey. The remainder of the survey shows similar results; a summary of the entire resistivity survey and borehole data may be found in a report to ADOTPF by Shannon and Wilson, Inc. (Project No. F-035-6(12) Parks Highway - Airport Road to Peger Road, Materials Investigation, Fairbanks, Alaska, January, 1983).

Interpretation: The occurrence of permafrost and its absence along this section of the reconnaissance line are fairly well-defined by high and low resistivity values, respectively, as indicated by borehole data schematically drawn on Figures 42 and 43. Estimates of the extent of permafrost (PF) are indicated as are areas that are thought to be thawed. Permafrost with a table less than 10' (3.1 m) appears to

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Figure 42. Resistivity profiles for waist level normal and rotated modes along proposed alignment of South Fairbanks Expressway from station 41 (x 100') from Airport Road to station 53 (x 100'). Borehole information and surface conditions are also indicated.

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Figure 43. Resisitivity profiles for waist high normal and rotated modes along the proposed alignment (Figure 42) from station 53 to station 65 together with borehole and surface information.

produce resistivity of 300-350 ohm-meters or higher in the normal orientation at waist height (see boreholes B8, B10 and B11), a fact which is used here to define the extent of permafrost. It should be noted that the boreholes, which were drilled prior to the EM-31 survey, were not favorably sited to detect permafrost in some locations. For example, permafrost is likely to be located between stations 45 and 47 and between 57 and 59 where no borehole data are available. It should also be noted that there is a reasonably good correlation between vegetation and permafrost with trees being associated with permafrost in most cases. However, there appear to be thawed zones even in areas of tree growth as indicated by boreholes B6 and B9. The occurrence of roads and trails also disturbs the natural setting as can be seen by the trails and roads centered near stations 63+20. 62+20, 59+80, and 43+10. Also as expected, active drainage channels tend to be associated with thaw bulbs as is observed at station 48+80. In conclusion, the reconnaissance EM-31 survey correlates well with the results obtained by borehole sampling and observations; ideally, an EM-31 reconnaissance survey should be made prior to the drilling of boreholes to maximize detection of ice-rich soils.

Case History No. 21: Engineer Creek Roadcut

Location: This site is approximately 7 miles (11.2 km) north of Fairbanks along a realignment of the Steese Highway on the north side of a hill adjacent to Engineer Creek. This site has been described in detail by Osterkamp et al. (1980).

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- Purpose: The Engineer Creek roadcut provided a unique opportunity to correlate the location and extent of ice masses observed during the road cutting phase of construction with geophysical measurements made prior to the roadcut. In addition, a series of EM-31 measurements were made on a nearly monthly basis for more than a year to observe the effects of seasonal variation and changes caused by the roadcut. A few sets of observations were also made along the roadbed after completion of the roadcut.
- Survey Date(s): October 14, 1977 and various dates between September 1978 and October 1979.
- Terrain: At its highest point, the area where the roadcut was placed had an elevation of about 1160' (354 m) and at its lowest point near the end of the cut the elevation was about 890' (271 m). The last 600' to 700' (183 to 213 m) of the nearly mile long (1500 m) cut section is of interest here. The relatively gently-sloping hillside (slope ~ 9%) is northwest facing with medium to small birch near the upper part of the area studied, gradually grading to predominantly black scrub spruce at the lower end.

Subsurface Conditions: Prior to roadcutting, holes were drilled along and parallel to the proposed centerline of road. These detected the presence of massive ice imbedded in an overburden of silt with thickness 20-30' (6-9 m). The basement material is Birch Creek schist which may be weathered for several tens of feet. According to Rieger et al. (1963) the soils along the section of the roadcut of interest vary from Fairbanks silt loam

(FaD) at the top of the hill, Saulich silt loam (SuC) and Goldstream silt loam (GtB) near the bottom of the hill and on the alluvium nearer Engineer Creek. Although the soil has been identified as the B type of the Goldstream series which has a slope of 3 to 7%, the original EM-31 survey lines actually appear to have been conducted over an overburden of Goldstream silt loam (GtC), which has a slope of 7-12%. The survey within the cut after completion of the roadbed was conducted over a thin overburden of pavement materials over weathered schist of unknown depth on the upper part of the profile lines and over paving material plus backfill to a depth of as much as 20' (6 m) at the lower (northernmost end) end.

Data Plots: A single profile line near the edge of the proposed Engineer Creek roadcut was established in August, 1976 for the purpose of detecting ground ice with a sensitive gravimeter. Subsequently, two parallel lines were established to the west of the original line in October, 1977 to evaluate the use of the EM-31 and other electrical/electromagnetic methods of detecting ground ice. The results of the EM-31 surveys along the three lines 400' (121.9 m) long labelled A, B and C are shown in Figure 44 together with a schematic of the cross-sections of ice masses made from detailed observations of the cutting operation done during a week long period in November, 1977. Measurements were made with the instrument at waist height in the normal (vertical dipole) position with the instrument boom both parallel to

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Figure 44. Resistivity profiles for waist high normal mode along three parallel lines (A, B and C) at Engineer Creek roadcut realignment of Steese Highway made prior to construction; the two profiles shown for each line were made with booms parallel to the line and perpendicular. A schematic of the ground ice cross-sections along lines A and B are also shown.



Figure 45. Isoresistivity contours along first 130' (39.6 m) of the grid of values obtained from the three profile lines of Figure 44. The lateral extents of the ice masses and ice-rich soils from Figure 44 are also shown.

(crossed data points) and perpendicular to the lines. Figure 45 shows a portion (130' (39.6 m)) of the three profiles plotted in terms of isoresistivity contours. Figure 46 and 47 give the normal and rotated readings for several sets of surveys over line C conducted nearly monthly from September, 1978 to October, 1979. A section of the road was completed by subcutting (to remove massive ice detected during exploratory drilling) and backfilling. Line surveys of this area were made to examine the differences in resistivity of the backfill in winter and summer. The results of these surveys for the waist high normal orientation are shown in Figure 48.

Interpretation: The site has been studied using various geophysical techniques including electrical, electromagnetic induction and surface impedance methods by Osterkamp et al. (1980) and also by Arcone et al. (1979) based on ground truth data reported by Osterkamp et al. (1980). More detailed background information on the original subsurface conditions and subsequent conditions after the road was built may be found in a study of the detection of ice masses using a sensitive gravimeter (Kawasaki et al., 1983b). In the present report we summarize some of the previous data and interpret the results of a more extensive set of EM-31 measurements. Figure 44 summarizes the EM-31 results of Osterkamp et al. (1980). These data show there is good correlation between the locations of ice-rich soils and ground ice masses and the high resistivity areas along the

Figure 46. Resistivity Figure 44 fo made. These drainage. R These show seasonal for several Roadcutting destroyed profiles for waist dates effects in high | 1978lines and normal 1979 after possib A and B mode $\overline{<}$ e along line the roadcut y alteration C of was of



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Figure 47. Resistivity profiles for waist high rotated mode corresponding to normal mode of Figure 46.



Figure 48. Resistivity profiles in spring and summer along edge of outbound lane within the Engineer Creek roadcut in waist level normal and rotated modes. Ground level normal and rotated mode profiles for the spring date are also shown.

EM-31 profiles. At the time the profiles were taken, there was about 0.02 m (~ 1") of snow on the ground and the underlying vegetative mat was dry and unfrozen. The thaw depth was probably near maximum at this time and measured about 0.5 m (~ 2'). Air temperatures were generally somewhat warmer than normal at least up to the time the surveys were taken (Climatological Data - Alaska, V64, NOAA-EDS, National Climatic Center, Asheville, N.C., 1978 - see also V62, V63 and V65), so that the ground temperatures were probably not unusually different from typical early fall conditions. The three parallel profile lines were 15' (4.6 m) apart and the ice cross-sections shown in Figure 44 indicate the general shape and extent of the ice masses were similar along lines A and B. Figure 45, which is an iso-intensity contour plot constructed from data obtained along the first 130' (39.6 m) of profile lines A, B and C starting from station 460+00, shows the locations of the edges of the ice-rich soil and ground ice mass in relation to the iso-intensity contours (note that the lateral distance is greatly exaggerated). It may be inferred from this figure that the deeper ground ice mass and the zone of ice-rich soil lying at shallower depth coalesce in the lateral (to the profile) direction, although it is unknown whether they actually coalesce in the vertical direction. The roadcut was made in November, 1977 with the edge of the cut nearly directly over line B; thus only line C, the westernmost of the original three lines, re-

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mained intact. After completion of the roadcut, the Geophysical Institute acquired an EM-31 (the surveys done in October, 1977 were made with an instrument borrowed from R & M Consultants) and this instrument was employed in intermittently monitoring line C over the course of a year starting in September, 1978. Twelve such surveys were made over line C from September, 1978 to October, 1979. However, due to uncorrectable drift and apparent instrument reading errors only 7 of these were suitable for analysis. Figures 46 and 47 show the waist high resistivity measurements in the normal (vertical dipoles) and rotated (horizontal dipoles) positions with the booms aligned parallel to the profile line. The curves are labelled serially from 1 to 7 starting with the date of 10/18/78 and ending 10/04/79. We note there is a progressive change of resistivity with seasons as is seen in Figure 46 and to a lesser extent in Figure 47. However, the seasonal variation does not differ by more than a factor of two (curve 7 is not considered in this statement because it appears the calibration on this date was not conducted properly) which is unlike the results obtained by Arcone et al. (1979), whose data over line C in April 1977 differ from those in September, 1977 by factors ranging from 2 to 20. With an overburden assumed to be silt above the ground ice of about 2 m (6.1')it does not seem possible to have such a large contrast in resistivity unless this surface layer was extremely cold and/or very dry. Since the March and April, 1977 air

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temperatures are not much different from the March, 1979 temperatures, the difference in the results of the two studies are not well understood. However, there are two differences in the topographic setting of the two surveys-the first being that our seasonal data is over line C not line A where the spring-late summer surveys of Arcone et al. (1979) were done and the second and perhaps the major difference is that our surveys presented in Figures 46 and 47 were done after the roadcut was completed. This latter difference would be reflected in the electromagnetic induction profiles in several ways including an increased contrast in summer and winter ground temperatures at shallow depths, possible changes in the drainage patterns, hence frozen and unfrozen water distribution, and the change from an approximate half-space configuration to an approximate quarter-space configuration. Because the ice masses appear to be laterally oriented to the profile lines and appear to extend westward beyond line C, it should be expected that the EM-31 profiles after roadcut construction would be similar both in shape and magnitude. However, comparison of Figures 44 and 46 show that although there are some similarities, there is a much broader and higher peak centered around 464+50 after than before the roadcut. The relatively broad peak centered near 462+60-70 in Figure 44 (see also Fig. 45) has disappeared in Figure 46 in the summer-fall data (curves 1, 2 and 6); this is partly due to the slight lowering of the resistivity

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of this peak, but it is primarily due to the relatively large, but differential increases of all the resistivity values between about stations 463+70 and 465+30. The general shape of the profiles is more or less maintained throughout the winter-spring period with little alteration as can be seen in both Figures 46 and 47 (unfortunately, no measurements were made in the rotated position in 1977; thus it is unknown just how much the pre-roadcut profiles in this orientation might have changed). This implies there were no drastic differential changes of the drainage patterns, hence, subsurface moisture distribution during the period September, 1978 to October, 1979; however, this does not preclude the possible occurrence of major changes in drainage during the 1978 melt season, which through an increase of subsurface moisture in the form of ice may have increased differentially the overall resistivity along the profile. Another possibility is that the change from essentially a half-space to a quarter-space configuration may have significantly altered the current conduction paths in and around the ice-rich soils and ground ice masses such that the resistivity profiles were also altered. We favor this affect as the major source of the changes, although some alteration of the profiles should have resulted from the changes in drainage. Comparison of Figures 46 and 47 shows there is considerable scatter in the data points both seasonally and point by point on the same profile in the rotated values between 462+00 and

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463+50. This scatter probably implies a greater variance of moisture content at shallow depths along the first 150' (45.7 m) of the profile lines than along the remainder of the profile, but that at the deeper depths of penetration afforded in the normal orientation of the instrument, the effect of the near surface variance in moisture is small. In conclusion, Figures 46 and 47 show there is a relatively systematic variation of resistivity with season, while a comparison of Figures 44 and 46 shows that the resistivity profiles may have been altered by the roadcut by changes in the eddy current conduction paths and by some changes in the drainage patterns.

Although surfacing had not been completed by August, 1978, the road base had been completed. Of particular interest to us in terms of potential settlement was the lower part of the subcut which was sub-excavated to remove most of the ice-rich soils and weathered bedrock and backfilled with graded roadcut material from further up the hill. Figure 48 shows the results of surveys made along the eastern edge (outbound lane from Fairbanks) of the roadbed in August, 1978 and April, 1979 in the waist high normal (open circles) and rotated modes (closed circles) in the lower panel and the ground level survey in the upper panel. Note the pavement surface was laid sometime after August, 1978. Profiles down the centerline and along the western edge (inbound lane towards Fairbanks)
were also made, but are not shown here, since they were very similar to the resistivity profile along the outbound lane. Figure 49 (adapted from Kawasaki et al. 1983a) shows the results of a gravity survey over the same profile line together with the proposed road cross-section along the centerline of the roadbed. The road section 'as built' is probably reasonably close to the cross-section designed as shown in Figure 49. We note there is a 2' (0.6 m) culvert buried at a depth of about 3' (1 m) near station 459+15at its eastern (outbound) edge: it enters the roadbed at about 458+90 at its western (inbound) edge. The culvert is close to 100' (30.5 m) long so that its orientation relative to the profile line is essentially perpendicular. Each data point in Figure 48 is 10' (3.05 m) apart; there are no data points shown at station 459+10, because the EM-31 went off scale there. This coincides with the location of the culvert; however, although the shapes of the curves in Figure 48 around station 459+10 are reasonably consistent with a conductive cylinder perpendicular to the EM-31 profile line (Keller and Frischknecht, 1966), the half-width of the signal of over 100' (30.5 m) is not consistent with the culvert as the primary cause. It appears that there is a peak in resistivity between stations 457+10 and 460+30 upon which is superposed a signature of a more highly conductive zone which includes the culvert. This may be caused by infiltration of moisture around the pipe and flow through the underlying weathered schist

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bedrock from west to east underneath the road. The more resistive region (aside from the conductive zone associated with the culvert) between about stations 457+00 and 460+00 appears to correlate with the slightly positive deviations in the gravity readings from a straight line drawn between the gravity values at stations 456+60 and 461+25 (see Figure 49). A higher gravity reading implies higher subsurface density which in turn implies lower moisture content; thus the relatively higher resistivity values should be associated with less weathered Birch Creek schist with lower moisture content than the surrounding materials. Figure 49 also shows the approximate cross-section and location of the subexcavated region, while Figure 48 shows a region of slumping or settlement (see Project Report F36122 on the settlement of the Steese Highway subcut by M. Reckard, ADOTPF) corresponding to the location of the subexcavated region that had occurred some four years after the pavement was laid. Inspection of the August, 1978 profiles in Figure 48 indicates that northward (to the right) of station 460 the roadbed and underlying base are fairly uniformly stratified, there being only gradual variations of resistivity with distance. Such relatively gradual variations are in keeping with the fairly deep, graded backfill in this area. It may be noted in the right half of Figure 48 that aside from a few data points, which appear to have been erroneously read in the ground level surveys, there are two distinct bands formed by the



Figure 49. Schematic of 'as built' roadbed, together with gravity values along the same line as Figure 48 (after Kawasaki et al., 1983a).

normal and rotated data, one between about stations 460 and 461 and the other between stations 461 and the ends of profile lines. These are best seen in the waist level surveys and appear to approximately coincide with the locations of the beginning of the backfilled region and the area of slumping. It is unknown whether there already were signs of slumping at the time of the 4/25/79 survey. but the banded structure to the right of about station 461, which can be characterized by higher normal to rotated conductivity ratios than those between 460 and 461, is already evident in the 8/28/79 data even before final paving occurred. The ratio of normal to rotated conductivities is generally higher to the right of 461 than between 460 and 461. Indeed except for one data point (at 462+90), all the ratios between 460 and 463+50 are less than 1.48 indicating that the surface layer is more conductive than the underlying layers. The resistivity values in the waist-high, normal orientation in August, 1978 (Figure 48) are characteristic of unfrozen material in the surface layers. It is interesting to note, however, that even in the late winter-early spring period (4/25/79) the conductivity ratios are less than 1.48 indicating the upper layers are more conductive than the lower layers across the backfilled region. If the profile line was well protected from direct exposure to solar radiation as in the case of a line through forested terrain, the data between 461 and the ends of the profile lines could not

strictly be interpreted in terms of seasonal air temperature differences, since the upper layers in early spring should be less conductive than the deeper layers. This suggests other factors are affecting the surface layer conductivity including infiltration of spring runoff water on the north side of the road and greater surface temperaures from longer periods of exposure to solar radiation of the southwest-facing north side of the roadcut. Indeed, the conductivity ratios at stations beyond 461 are nearly all greater than 1.48 both along the centerline and along the inbound edge of the roadbed in the surveys made in August, 1978 mentioned previously but not shown here. These indicate the surface layers are drier and/or colder at this time in these locations than along the outbound lane edge. The centerline ratios are even larger than the ratios along the inbound edge again suggesting moisture infiltration played the dominant role in producing the ratios along the profiles. With the locations of the inlet (at 458+90 of the inbound side of the roadbed) and outlet (at 459+15 of the outbound side) of the culvert, this interpretation of the resistivity variations is consistent with an enhancement of moisture in the subcut backfill material along the edge of the outbound land, somewhat lower moisture along the edge of the inbound lane and relatively dry, near-subsurface materials along the centerline. The transport of heat is implicit to moisture infiltration into the backfilled materials of the subcut.

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Precisely how the resistivity readings beyond station 460 are related to the slumping or settlement of the pavement starting at about 461+30 is unknown. However, as indicated previously, there is a clear transition in conductivity ratios between stations 461 and 462 and a corresponding increase in settlement also between 461 and 462. In comparing the 4/25/79 profiles with the 8/28/78 profiles (Figure 48), one interpretation might be that the settlement was caused by thawing of the subcut backfill such that the normal orientation, deeper sounding readings beyond station 462 taken in April, 1979 would indicate relatively greater conductivity than in the less-thick, transitional backfill area between stations 461+50 and 462. That is the somewhat greater conductivity (lower resistivity readings in the normal mode beyond 461+30 in the April data) is caused by the greater total amount of thawed backfill which has a deeper depth.

The major results of the EM-31 surveys at Engineer Creek may be summarized as follows: (1) the EM-31 readings do not differ much more than a factor of two with seasons. Most of this difference is attributable to ground temperature changes, although some effect from seasonal or even transient changes in moisture drainage patterns after roadcut completion may be involved; (2) the differences in the pre-cut and after-cut EM-31 profiles along the same line may be due to changes either in the thermal conditions, drainage (moisture) distribution or electrical current conduction paths. This

latter change probably has the greatest effect in changing appearance of the profiles, although the magnitudes of the resistivities are not seriously altered; (3) the measurements along the roadbed over sections excavated to the bedrock are generally quite variable probably due to differences in the topographic surface of the bedrock or depths of weathering in the bedrock. Where the backfill was fairly deep, little variation with distance was noted both in the rotated and normal waist-high orientations. Although the variation was small over the backfilled region, there was a definite, systematic difference in the profiles over the transitional backfill region versus that over the thicker part. The profile taken in April, 1979 (early spring) shows lower resistivity in the normal position over the full backfill zone versus that of the transitional zone indicating warmer temperatures and/or greater moisture at depth. The opposite is the case for the August, 1978 profile; this possibly indicates a greater amount of melting has occurred under the more deeply backfilled zone or simply that the greater thickness of backfill there allows for a larger overall amount of moisture.

Case History No. 22: Artificial Ground Ice Mass Site

Location: The artificial ground ice mass was constructed during the winter of 1980-1981 in an underutilized, wooded area of the University of Alaska, Fairbanks, Agricultural Experiment Station (AES) 0.7 miles (1.13 km) from the Geophysical Institute building approximately 2100' (640 m) northwest

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of the intersection of Geist Road, Chena Pump Road and the Parks Highway and 200' (61 m) from the northern shoulder of the Parks Highway. The location, construction and other information on the ice mass are detailed in Gruol et al. (1981) and Kawasaki et al. (1983a).

- Purpose: The purpose of the electromagnetic surveys done in the vicinity of the ice mass was to verify the utility of the shallow-sounding electromagnetic induction technique for detecting ground ice masses under well-known subsurface conditions. The artificial ground ice mass was specifically built as a known target to evaluate various geophysical detection methods.
- Survey Dates: May, June and September, 1981 and January, February, March, May, June, July and August, 1982.
- Terrain: The area where the ice mass was constructed is on the Tanana-Chena floodplain, approximately 600' (183 m) east of the confluence of the Happy Creek and the old Cripple Creek drainage ditch. The site is relatively flat with small to medium spruce trees predominating. Stumps of up to 1' (.3 m) in diameter were noted in the area indicating that large trees had been removed from the site, but that the vegetative mat had probably been left intact judging from its thickness of about 5" (.13 m) Approximately 60 tree rings were counted on one cross-section of a tree, cut to allow the ice mass to be built, suggesting the area had been undisturbed for as much as 60 years. Although the ice mass is in a relatively flat area, there is a very

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slight but noticeable slope dipping to the west towards the Parks Highway and Cripple Creek beyond. The low spot adjacent to the Parks Highway embankment is generally very wet during spring runoff and summer rainfall. The area of the ice mass and access road was cleared of trees in an approximately rectangular shape of dimensions 12' x 150' $(3.7 \times 76.2 \text{ m})$. The relatively large width of clearing was required for access of a backhoe which was used to dig the trench in which the ice mass was constructed. The east-west (geographically-oriented) trench had the basic shape of a right parallelipiped except for some ramping at both ends and a slightly larger width to a depth of about 1.5 m (\sim 5') along 5 m (16.4') of the eastern end. The dimensions of the trench are 34 x 0.69 x 4.4 m (111.6' x 1.3' x 10.5'), while the ice after burial is 1.2 m (3.9')below the surface. Thus the thickness of the ice is 3.2 m (10.5'). Examination of the sidewalls to the 4.4 m base of the trench indicated the silt (identified by Rieger et al., 1963 as the Tanana type silt loam) was relatively uniform except in the first 1.2 m (4') where there occurred small ice lenses between 0.6 and 1.2 m (2' and 4') deep and brown silt down to a depth of $3.1 \text{ m} (10^{\circ})$ indicative of staining by organic matter. A borehole drilled about 85' (25.9 m) deep, 20 m (65.6') from the long axis of the ice mass, showed the silt extends down to about 50' (~ 15 m) where a 5' (1.5 m) gravel layer was encountered. Gravellysand and sand occur between 55' and 70' (16.8 m and 21.3

Subsurface Conditions:

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m) and from 70' (21.3 m) to the base of the hole, the material is sandy silt. At the time this borehole was drilled in March, 1981, the ground was estimated to be frozen to a depth of at least 70' (21.3 m). The ice mass was constructed by freezing layers of water in place over a three month period of time during the winter of 1980-1981. The location, physical and electrical parameters and other pertinent data are summarized in Tables 2 and 3 taken from Kawasaki et al. (1983). We note that due to long exposure of the sidewalls of the trench to extremely cold temperatures, the temperature profiles with depth in vicinity of the ice mass should initially have been substantially different from the surrounding areas. Temperatures periodically measured in a borehole drilled through the ice mass in late 1981 to a depth of 29' (9.5 m) and also in the deeper borehole mentioned above indeed show that the temperatures near the ice mass were colder in the first 5-10 m (\sim 16' - 33') of depth during 1982; however the temperatures at these depths at both sites did not differ much by summer, 1983. Because the thermal conductivity of ice differs somewhat from that of the surrounding finegrained soils (about 2.2/m-°K for ice and about 2.0 or less for fine-grained soils with reasonable water contents (Slusarchuk and Watson, 1975), we would expect the thermal profiles to differ even after a guasi-stationary state is attained. In addition, clearing of the area and cutting through the vegetative mat at the time of trenching significantly disturbed the area, in that, for part of the year

the ice mass site is not shaded and melt water from the snowpack and rain more readily infiltrate to the mineral soil there. Although we have attempted to mitigate some of the more serious of these problems by protecting the ice mass with peat, styrofoam and seeding of grasses, it is clear that there will be some differences in near surface temperatures and moisture which will be reflected in turn in the apparent resistivity as detected by the EM-31.

Data Plots: Figures 50-59 show the isointensity contours of apparent resistivity in the normal (vertical dipoles) position at the waist level for grids of readings obtained over an area containing the ice mass. Except for Figures 50 and 60 which cover a 40 m x 40 m (131.2' x 131.2') area the arid size is 40 m x 60 m (131.2' x 196.9'). The grid spacing was not held uniform in the north-south direction being more closely-space over the ice mass (0, \pm 2, \pm 5, \pm 10, \pm 20 from the long axis of the ice mass) and spaced generally in multiples of 2.5 m in the east-west direction. In Figures 54 and 59 the position of the ice mass is drawn It extends from 0 east to 34 east in Figure(s) 50 in. (and 60) and 10 east to 44 east in Figure(s) 51 (through 59 and 61 through 67); thus the line 0 east of Figure 50 corresponds to 10 east in Figure 51. Figures 60-67 are plots obtained from the waist rotated readings corresponding to the normal readings of Figures 50-59 except for two of the surveys when rotated readings were not made. Figure

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CROUND RESISTIVITY (OHM-METERS) B10515WN ICE MASS

TIME 10.38,24

DATE 08/06/82

PLOT NO.

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Figure 50. Isoresistivity contours for waist high normal mode over artificial ice mass at University of Alaska, Agricultural Experiment Station (UAF-AES) for 5/15/82. The vertical line 20E corresponds to the line 30E in subsequent figures (see Figure 54 for the relative position of ice mass and the orientation of the grid). Note that the grid spacing was uniform except over the ice mass along the 20E line.



CROUND RESISTIVITY (OHM-METERS) B10605HN ICE MASS PLOT NO. 1 DATE 08/06/82 TIME 10.24.51

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Figure 51. Same as Figure 50 except for enlarged grid, denser gridpoints over ice mass and later date.

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Figure 52. Same as Figure 51, but for later date.



CROUND RESISTIVITY (OHM-METERS) 821101WN ICE MASS PLOT NO. 1 DATE 02/24/84 TIME 14.00.58



OROLNO RESISTIVITY (OHM-METERS) 820209WN ICE MASS PLOT NO. 1 DATE 08/13/82 TIME 11.31.57







GROUND RESISTIVITY (OHM-METERS) 820312WN ICE MASS

TIME 10.54.22

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DATE 08/06/82

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OROLNO RESISTIVITY (OHM-METERS) 8205044N ICE MASS PLOT NO. 1 DATE 08/06/82 TIME 09.56.56

Figure 56. Same as Figure 51, but for later date.



CROLND RESISTIVITY (OHM-METERS) B20618WN ICE MASS

Figure 57. Same as Figure 51, but for later date.



OROLNO RESISTIVITY (OHM-METERS) 820716WN ICE MASS PLOT NO. 1 DATE 08/03/82 TIME 08.18.09

Figure 58. Same as Figure 51, but for later date.



GROUND RESISTIVITY 10HM-METERS | 82 0812WN ICE MASS PLOT NO. 1 DATE 08/13/82 TIME 11.23.45

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Figure 59. Same as Figure 51, but for later date.

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 Normalized
 GROUND RESISTIVITY (CHAPTERERS) \$1051518 F.H.

 N
 PLOT N. : 1
 CATE 00/16/02
 TIME 08.27.12

Figure 60. Isoresistivity contours in waist high rotated mode for 40 x 40 m grid over artificial ice mass for 5/15/82. Grid points along line 20E (abcissa)are denser over ice mass.



NZ GROUND RESISTIVITY (CHM-METERS) 8109\$44.R I.M.
PLOT NO. 1 DATE 06/09/82 TIME 16.17.14

Figure 61. Same as Figure 60 except for enlarged grid, denser grid points over ice mass and later date. The line 30E corresponds to line 20E of Figure 60.



Figure 62. Same as Figure 61, except for later date.



GROUND RESISTIVITY (CHM-METERS) EMS202094R I.M.

Figure 63. Same as Figure 61, except for later date.

GROUND RESUBILIVITY 10444 METERS) EMBENSIER I.H. PLOTIND. 1 DATE 08/04/82 TUPE 11.28.25











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GROUNT RESISTIVITY 10HM-METERS) S206184R I.M. PLOT NO. 1 DATE 06/21/82 TDAE 12.45.58



Figure 66. Same as Figure 61, except for later date.

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Figure 67. Same as Figure 61, except for later date.

GROUND RESISTIVITY (OHM-METERS) B10515WN ICE MASS PLOT NO. 1 DATE 08/06/82 TIME 10.48.34



Figure 68. Same as Figure 50, except additional grid points have been removed from line 20E. Note considerable difference in appearance of contours near the line 20E.

68 gives the data for the May, 1981 survey in the waist high normal position with some data points left out as a test of the contour program.

Conceptually, the idea of creating an isolated, artificial Interpretation: ice mass of known parameters for use as a target in investigating various geophysical devices and methods for detecting ground ice is very appealing. However. constraints arising from the large size of the object in question, logistical difficulties and weather-related problems have produced, a target that is not free from the effects of unnatural surface and surface-related disturbances. Thus, it should be understood that the data presented here represent the results of measurements on an artificial ice mass that has not yet reached true quasiequilibrium or stationary conditions of temperature and moisture. In each of the examples shown, an exact understanding of all of the results requires detailed measurements of ground temperatures and moistures which were neither available everywhere nor simultaneously with the EM-31 induction measurements. However, a general understanding of the results should be expected since the temperature, moisture, active layer depths and other parameters were monitored periodically and the shape of the ice mass and dimensions of the disturbed area are Although somewhat limited, these data are much known. more complete than have been obtained at any other of our sites where EM-31 measurements have been made. Figures

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50-59, which were derived from the waist normal measurements made from May, 1981 to August, 1982 clearly, show behavior that is unexpected. That is, the rather distinctive signature of the ice mass observed in Figures 50-52 is not observed in Figures 53-56, but then can be seen again in Figures 57-59. The observed signature in the rotated position is also unexpected, Figure 60 showing a somewhat higher resistivity in the vicinity of the ice mass than the surrounding area, no detectable signal in Figures 62-64 and a somewhat lower resistivity around the ice mass in Figures 61 and 65-67. These results should be interpretable in terms of temperature, moisture and active layer thickness differences near and away from the ice mass plus the fact that the ice mass generally has a higher resistivity than the surrounding silt. (We note that Figure 50 shows a rather peculiar "dog bone" shaped structure; this arises from the closer grid-spacing used along the line 20E than those along 0, 10, 30 and 40E. Figure 68 shows the isoresistivity contours obtained when the additional data points were removed). Comparison of the normal and rotated plots for those cases in which the area of the ice mass is clearly defined by isointensity contour lines appear to suggest the apparent area of the disturbance is larger in the rotated plots (about 7.3 m (24'), twice the width of the cleared area). However, this is actually an artifact of the contour intervals chosen as indicated by a more detailed look at the raw data, which show there are side

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lobes of lower resistivity centered at 15S and 25S or \pm 5 m $(\pm 16.4')$ from the 20S line in the normal data. The relatively lower resistivity values in the area of the ice mass in the rotated position obtained during summer months imply a lower resistivity in the upper layer. Most of the ratios of normal to rotated resistivities are in fact less than 1 in the ice mass area. Probing tests and measurements with the impulse radar (Kawasaki and Osterkamp, 1981) indeed indicate the active layer in and around the ice mass to be significantly deeper, about 4' (1.2 m) versus about 2'-3' (0.6 - 0.9 m) in the more shaded, undisturbed areas during late summer. The active layer over the ice mass is also significantly wetter during most of the summer period. Thus, although the ice mass for temperatures slightly colder than 0°C is expected to be much more resistive than the surrounding undisturbed silt areas, the thicker active layer is more conductive. The net effect evidently is to produce an apparent resistivity lower than the background in the rotated position and higher in the normal position. EM-31 measurements were made along a profile perpendicular to the trench just after it was dug and before any water had been deposited to build the ice mass. These (not shown here) indicate the signature of the trench is a fairly broad high in resistivity in both the normal and rotated instrument orientations.

These results on a vertical resistive dike are similar to the those obtained over a conductive dike or

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semi-infinite conductive half sheet (see Keller and Frischknecht, 1966, p. 392) for the normal (horizontal coplanar coils or dipoles vertical) and the rotated (vertical coplanar coils or dipoles horizontal) orientations. The fact that a thin resistive dike produces similar profiles to a thin conductive dike may be qualitatively understood by noting that close to the dike eddy currents induced in the ground will tend to be channeled parallel to the dike whether it is conductive or resistive relative to the surrounding material. The data of May 15, 1981 (Figures 50, 60 and 68) indicate the resistivity of the ice mass area in the rotated position is only slightly higher than the surrounding area. This implies the ice mass region had become significantly more conductive, although still less so than the surrounding areas after completion of the ice mass and just after the end of breakup. At this time the active layer was probably no more than about 1' (~ 0.3 m) thick, but it was very wet. Such a layer is conductive relative to the undisturbed area. Keller and Frischknecht (1966) (p. 343) give the response curves for a buried plate which show the change in resistivity should be negative relative to the surrounding areas in the rotated orientation and positive in resistivity in the normal orientation. On comparing Figure 50 with Figure 52 and 60 with 61, we infer that the difference in signal (there being a relative decrease in resistivity over the ice mass region in Figure 61 from

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that in Figure 60) is caused by the increase in conductivity near the surface of the disturbed region. Thus, we may consider the signature of the ice mass region at this time as a composite of two distinct structures, a near surface plate conductor and a vertical resistive dike of limited depth. The fact that Figure 60 shows a higher resistivity over the ice mass may be attributed to the fact that the trench area at depth was very cold at this time and the surface thaw zone relatively thin so that the signature of the deeper material in the form of a resistive dike was dominant.

Temperature measurements taken in two boreholes one through the ice mass and the other in the woods in early 1982 show that the ice mass region was about 0.25C colder at a depth from 4 to 10 m (13' to 30') and deeper, but as much as 3 to 4C warmer in the upper 4 m (13') during late January, February and March, early 1982 than in the wooded aera. By late April and May the upper layers had warmed such that the temperature was warmer by only about 0.5C at 1.5 m (4.9') through the ice mass than in the borehole in the undisturbed area. Given temperature as the only variable affecting resistivity, the apparent resistivity obtained with the EM-31 in vicinity of the ice mass and in the undisturbed areas should be similar with the warmer temperatures at shallow depth, but colder temperatures deeper near the ice mass and vice versa in the undisturbed area. Such dissimilar temperature profiles together with

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other factors such as moisture appear to have led to the results obtained in early 1982 shown in Figures 54-55 and 62-63 where the ice mass is not delineated in one or both orientations. The January 11, 1982 isoresistivity contours (Figure 53) for the normal orientation do show the high resisitivity area around the ice mass indicating the colder temperatures (associated with higher resistivity) at deeper depths at this time more than compensates for the warmer upper layer (lower resistivity) so that there is a contrast between the ice mass and the undisturbed On the other hand, by May 4, 1982 (Figure 65) areas. shortly after breakup, the very near surface depth of the ice mass area apparently had become conductive enough to just begin to produce a distinctive ice mass signature in the rotated orientation, but it was not conductive enough to be detected in the normal orientation (Figure 56). During the summer of 1982 (Figures 57-59 and 66-67), the signatures for the ice mass area in the rotated and normal orientations are quite prominent.

While this discussion may imply a qualitative understanding of the ice mass signature in late winter-spring, 1982, the fact that the ice mass region is actually a three-dimensional anomaly should be taken into account; this phenomenon will be discussed more fully below.

Temperature measurements were continued through the summer of 1982 and a few times during 1983. These measurements were not spaced closely enough in time to
monitor the progress of the temperature wave through the ice mass and in the undisturbed area. However, it is clear that by late spring 1983 the 0.25C temperature difference at shallow depths had disappeared. We would thus have expected rather different isoresistivity maps of the area, but unfortunately no measurements were made during 1983 to confirm this. The temperature measurements in late spring and late summer 1982 show similar temperature profiles through the ice mass and undisturbed areas, except, of course, the 0.25C temperature difference at intermediate depths (4 ~ 10 m). Thus, through the summer months in 1982, the cold and more resistive ice mass together with the conductive sheet representing the deeper active layer above the ice mass appear to have produced a definite signature in the isoresistivity maps.

We note it is possible to obtain a reasonable understanding of the effects of temperature on resistivity from the temperature profiles assuming a knowledge of the resistivity and layering of the underlying material. In the low induction number range to which the EM-31 (see McNeill, J. D., 1980a) is applicable, we may write the apparent conductivity for an N-layered earth as:

$$\sigma_a = \sum_{n=1}^{N} \sigma_n (R_{n-1} - R_n)$$

where $R_n = 1/(4Z_n^2 + 1)^{1/2}$ in the normal orientation and $R_n = (4Z_n^2+1)^{1/2} - 2Z_n$ in the rotated orientation and σ_n refers to the conductivity of the nth layer with base depth Z_n . Note that $R_0 = 1$ and $R_{\infty} = 0$. If there are no

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discontinuities in temperature or resistivity and no lateral boundaries, the sum may be written as an integral:

$$\sigma_a = \int_0^\infty \sigma(z) dR(z)$$

If the material type and temperature profile are known, we can in principle obtain $\sigma(z)$ from the temperature dependence of the resistivity of the material. There, are of course, several other factors which must be considered, among the most important, of which, is the moisture content of the material, which are neglected here. We have numerically integrated the above equation for the normal orientation by obtaining a conductivity profile with depth from the curve of temperature versus resistivity measured for Fairbanks silt by Hoekstra et al. (1974) (see also Figure 1 of this report). The apparent resistivity calculated is 313 ohm-m for a temperature profile taken in February, 1982 and a similar value (318 ohm-m) for another profile taken in April, 1982. It was assumed in these calculations that below 23 m (75.5') the conductivity was uniform at 16.67 mmhos/m. Although somewhat low, the resistivity values obtained above for the February and April, 1982 temperatures are within the range of values (~ 230-480 ohm-m) in the normal orientation (Figures 53-56) for this period.

A numerical integration was also carried out for the temperature measurements obtained through the ice mass assuming lateral homogeneity. Because the near surface

temperatures through the ice mass were warmer than through the undisturbed area the calculated integrated apparent resistivity -- 228 ohm-m in February, 1982 -- is lower than in the surrounding areas. As mentioned previously the temperature at 4-10 m through the ice mass was about 0.25C colder at this time; this difference only adds about 8 ohm-m to the 228 ohm-m signal. We note that the surface layer near the ice mass region was likely to be ice-rich at this time (February-May, 1982). Generally an ice-rich soil has a higher resistivity than the same soil with lower moisture content. However, it appears the generally warmer soil temperatures near the surface of the disturbed area to a depth of about 4 m (13.1') in which the ice mass is embedded may have produced a combined resistivity signature with little or only a small contrast from the surrounding undisturbed area during this period. We are at this time unable to understand completely the signatures or more correctly, the absence of signature of the artificial ice mass.

In summary, the ice mass and surrounding area was detectable during the early part of its existence by virtue of the higher resistivity associated with ice and with the colder frozen soils immediately surrounding it. The ground in and around the ice mass area has subsequently warmed and it would appear the basic signature of the ice mass is actually dominated by the thaw zone associated with the area that was disturbed during construction of

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the ice mass. The ice mass and surrounding area ($\sim \pm 1.83$ m (6') from the projection at the surface of the long axis of the ice mass) may be considered a buried vertical resistive dike with a lower boundary plus a horizontal slab or sheet with long axis coinciding with the projection of the long axis of the ice mass at the surface. The surface sheet or more exactly a slab can be significantly more conductive than or about as conductive as the surrounding undisturbed area depending on the season. The conductive slab produces a signature qualitatively similar to the vertical dike when the instrument is in the normal (horizontal dipolar) orientation, but is opposite and apparently dominates the signature in the rotated orientation. It appears that due to the geometry, temperature profile and ice content in late winter-early spring, the net effect of the slab-on-dike model is to produce a null signature. The seasonal variation in the signature of the ice mass cannot be the result of the measured temperature profile differences alone.

IMPLEMENTATION

This report section presents suggested implementation policies and procedures intended to promote utilization of the research findings of this study within the Alaska Department of Transportation and Public Facilities (DOT&PF). Implementation recommendations were generated through departmental review of the completed research study and were authored by the DOT&PF research project manager.

It should be noted that the specific device name "EM-31" is used here in a sense. These recommendations are directed toward application of the EM-31 itself or functionally similar instruments which may become available.

General Policy:

DOT&PF engineering policy should require that the EM-31 be <u>considered</u> for use during preconstruction soil investigations on all DOT&PF roadway, airfield and facilities related projects. It should be applied to any project having problems or suspected problems of a type which are amendable to investigation and interpretations based on ground resistivity data.

Training:

Representatives from the geotechnical staff of each DOT&PF region should receive intensive training in the acquisition, analysis and interpretation of EM-31 data. The trainees will become the seat of EM-31 expertise within their respective regions, responsible for further training of local geologists and engineers who will have specific project level involvements.

It is proposed that the initial "seed" training session be held in Fairbanks before May of 1985 so that the EM-31 can be regionally utilized by the beginning of the 1985 construction season. The training session will be sponsored, arranged, and funded by the DOT&PF Research Section and presented by the report authors and DOT&PF Research Section staff members.

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The training period will be one (1) day. Research Section responsibilities will further include periodic reviews of scientifical and engineering literature in the subject area of ground resistivity applications. This continued research effort will provide improvements in applications of EM-31 data to engineering problems.

Equipment:

Each regional geotechnical section will be supplied with at least one EM-31 type unit. Each geotechnical section will also supplied with a data graphics program, compatible with locally available computer equipment, which will enable generation of isorestivity contour plots similar to those shown in this report. It is expected that funding for all equipment associated with EM-31 implementation will be provided through regional budgeting. DOT&PF Research Section presently has one EM-31 unit which can be loaned within the Department (see information contact person listed below).

The purchase price (as of this writing) of an EM-31 is approximately \$10,000. An excellent contour plotting program for an IBM-PC type computer system will cost \$400 - \$600. A total basic equipment package for the 3 DOT&PF regions would therefore cost about \$32,000. This initial capitol investment would easily be recouped by a single EM-31 aided discovery of a massive ice feature on a single building foundation site.

Field Application of the EM-31:

EM-31 measurements will be obtained according to the equipment manufacturers instructions and the guidelines contained in this report. Data will be collected during reconnaissance or centerline foundation investigations on a routine basis prior to roadway or airfield construction. Sites for proposed building type facilities will be surveyed using the EM-31 over a closely spaced sampling grid which will include the structures entire plan area.

In addition to any other data locations, resistivity measurements will always be obtained at pits, holes, trenches, etc., where ground truth is available.

Analysis and Interpretation of Data:

Methods for utilizing EM-31 data are discussed within the body of this report. Procedures pertaining to specific field site types are covered within the case histories section.

Information Requests:

Information regarding this report or the proposed implementation plan can be obtained by contacting:

Robert L. McHattie Department of Transportation and Public Facilities Division of Planning/Research Section 2301 Peger Road Fairbanks, Alaska 99701

Telephone: (907) 479-2241 or 479-4650

Mail Stop: 2554

SUMMARY AND CONCLUSIONS

This report summarizes the results of a number of EM-31 loop-loop electromagnetic induction surveys conducted over a wide variety of terrain types in Alaska. Although the 22 sites investigated here in case history form do not by any means represent an exhaustive compendium of Alaskan terrain types, they are generally located where much human activity has already occurred or will occur, namely, along river valleys of interior Alaska and some coastal sites. Many of the 22 case histories represent a single occupation of a site, but a few of the others represent multiple occupations to evaluate seasonal effects and other factors influencing terrain resistivity.

Information on potential subsurface conditions at each site from all sources, including exploratory drilling, borehole-temperature logs, area air temperature readings, surface vegetation, geologic, soil and topographic mappings, aerial photography, etc., has been integrated with the EM-31 measurements whenever possible. The case studies confirm that EM-31 measurements are reasonably good indicators of whether shallow ground ice and permafrost are present or absent. The EM-31 instrument is also useful in detecting areas of shallow bedrock and in mapping borrow site materials, although its use for these purposes is not as promising as that for ground ice and permafrost detection because of the limited depth of detection and the smaller inherent conductivity (resistivity) contrasts. As indicated by some of our case histories, another application is for studying geothermal systems in permafrost terrain and seawater intrusions. Mineralized geothermal water and seawater conductivities produce significant and detectable contrast from the conductivity of surrounding terrains even when the flow occurs beneath the surface of the ground.

Sequences of surveys made to study seasonal effects at three sites near Fairbanks, Alaska show that the annual cold wave penetration into the ground profoundly influences the apparent resistivities. As expected there is a general increase of resistivity as ground temperatures decline, however, the decrease can be significantly non-uniform depending on surface vegetation, drainage patterns and other factors. It is believed from the studies given in this report that the pattern of subsurface drainage has the greatest influence on summer ground resistivity in the sense that water which accumulates in the near-surface soil dominates the conductivity readings in the summer. Near surface liquid water, conversely, allows for a lower apparent ground resistivity than surrounding, less-moist areas in late summer-fall when the active layer is thickest.

As has been indicated in this report, the ground temperature profiles may be such that there is little difference in apparent resistivity between say an EM-31 measurement made in February and another in April despite the fact that the surface layer in February may be much colder than that in April. This is because below some depth, the temperature may generally be colder in April than in February. While the relationship between resistivity and temperature of silt is non-linear (Figure 2), as is the response function of the EM-31 with depth (Figure 1), it is clear that the curvatures of the temperature profiles with depth in February and April are such that the total apparent resistivities may be similar in magnitude.

The non-uniqueness of the apparent conductivities (resistivities) determined by the EM-31 brings to mind the question of what season of the year one should make such electromagnetic induction measurements for detecting frozen ground, ice-rich soils and ground ice. The case histories discussed here do not answer this question satisfactorily, although Arcone,

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et al. (1979) and Osterkamp et al. (1980) suggest from Engineer Creek data that the early spring period may be the time when the largest contrast is observed between ice-rich zones and surrounding terrain. Our data over the same area (Case History No. 21) and over the artificial ice mass (Case History No. 22) suggest that there should be a reasonable and detectable contrast between ice-rich zones and surrounding areas even during late summer-early fall. Indeed the artificial ice mass was not detectable in late spring; however, as mentioned previously, the surface disturbance over the artificial ice mass makes any conclusive statement concerning detectability with season at this site difficult.

It should be noted that the resistivity of massive ground ice by itself should not vary much with the range of typical subfreezing ground surface temperatures found in interior Alaska (see Hobbs, 1974 for a discussion of the conductivity of ice), whereas the resistivity of moist silt can vary an order of magnitude between -10C and 0C (Figure 2). With only the first $3 \sim 4$ m of the ground undergoing say a 5C decrease in temperature from late summer to early spring, the apparent resistivity probably should not change by more than a factor of 2 or 3. In the undisturbed area of the ice mass site where relatively uniform silt occurs to a depth of 25 m, the range of EM-31 resistivities measured is from about 160 to about 480 Ω -m. This indicates relative uniformity of moisture with depth with season.

In summary, this study shows that the EM-31 electromagnetic induction device is capable of distinguishing permafrost from areas with unfrozen soils and of detecting zones of ice-rich soils and ground ice masses embedded in a frozen soil matrix of otherwise uniform frozen moisture content. The large contrast in resistivity between these isolated zones and the frozen soil matrix is due to the high resistivity of the frozen solid moisture.

RECOMMENDATIONS

Several methods of geophysical exploration currently widely-used in the oil and mineral industries are suitable for use in solving geotechnical problems in the arctic regions. Among these are the gravity method for detecting massive ground ice, neutron flux and other downhole methods for determining soil moisture content, lithology, etc., impulse radar for mapping interfaces in frozen soil and rock, and various electrical and electromagnetic induction methods for subsurface resistivity measurements. The EM-31 electromagnetic induction device discussed in this report is especially useful for relatively shallow resistivity measurements of subsurface materials.

Permafrost exists as a distinct geotechnical material by virtue of the occurrence of subfreezing mean annual ground surface temperatures. The mean annual air temperatures for the past few years in interior Alaska have been higher than the average of the preceding 30 years (Bowling, 1982). A general warming of this type would lead to melting of permafrost which has serious implications to surface construction as indicated by Osterkamp (1982). Thus, proper foundation design of buildings, roads and airstrips to be built in the future may require more thorough pre-construction geotechnical investigations. Geophysical methods along with existing traditional site investigation methods are cost effective in providing a more detailed knowledge of subsurface conditions than can be provided by drill sampling alone.

The case histories of the use of the EM-31 described in this report show clearly that the instrument is well-suited for reconnaissance resistivity surveys of terrain that is suspected of harboring permafrost, massive ground ice and ice-rich soils. The ruggedness, portability and

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ease of operation of the EM-31, as well as other factors, make the instrument a valuable adjunct to traditional methods of detecting or mapping permafrost and ice-rich soils, such as drilling. <u>It is therefore recommended that the EM-31 (or equivalent non-contacting device) be used routinely on sites</u> of new construction such as highway right-of-ways, airstrips and buildings. The EM-31 measurements may be used as a guide for initial drilling or to pinpoint the extent of frozen, ice-rich soils first detected by drilling. A preconstruction EM-31 survey together with judicious use of drilling could potentially reduce costs while at the same time supplying a more comprehensive inventory of subsurface conditions of a site.

As with any geophysical data, the successful interpretation of EM-31 measurements requires a thorough knowledge of the instrument and of any potential subsurface conditions that <u>may</u> be found in surface expressions of such conditions, namely vegetation, topography, geologic features and others. If available, drilling information should be used to calibrate the EM-31 data. Operative and interpretive expertise using the EM-31 must be developed in order to utilize the resistivity surveys to the fullest.

Our experience over the past several years indicates that implementation of the above recommendations and suggestions can only be properly accomplished by a geophysicist familiar with geophysical methods in general. With respect to highways and public facilities, it is therefore further recommended that the Research Section of the Alaska Department of Transportation and Public Facilities (ADOTPF) employ a geophysicist whose role would be to advise ADOTPF on the use and interpretation of geophysical methods for detecting ground ice and permafrost.

ACKNOWLEDGMENTS

The surveys discussed in this report covering six years of study have been conducted with the aid of a large number of personnel including students, faculty, ADOTPF staff and private sector employees. We would especially like to thank R. Jurick, D. Esch, R. McHattie, G. Brazo and W. Slater, all of the ADOTPF, staff of R & M, Consultants, Inc., R. Abbott of Shannon and Wilson, Inc. and R. Gaffi, V. Gruol and G. Walker of the Geophysical Institute. We would also like to thank C. Burnett of the Geodata Center of the Geophysical Institute for providing assistance in tracking down aerial photographs of some of the sites studied. Funding for support of the work described herein were provided by the National Science Foundation, Division of Polar Programs under Grant Number DPP78-27641 and the State of Alaska, Department of Transportation and Public Facilities, Research Section under Project numbers 82IP79 and F26152, TA#8-82. Funding for some borehole loggings were provided by the U.S. Department of Energy under Grant Number DE-AS19-83BC10797.

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TABLE 1

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Specifications-GEONICS EM-31

Measured Quantity	Apparent conductivity of ground (millimhos/m)
Conductivity Range*	3, 10, 30, 100, 300, 1000 millimhos/m
Instrument Noise Level	< 0.1 millmhos/m
Measurement Accuracy	± 5% at 20 millimhos/m
Measurement Precision	± 2% of full scale
Primary Field Source	Self-contained Dipole Transmitter
Operating Frequency*	9.8 kHz
Secondary Field Sensor	Self-contained dipole receiver
Intercoil Spacing	3.66 m (12 ft)
Power Supply	8 C cells (approx. 20 hrs. continuous operation)
Weight	9 kg (19.8 1bs)
Dimensions Console Boom	24 x 20 x 18 cm (9" x 8" x 7") 3.66 m (12.2 ft) extended 1.4 m (4.5 ft) stored

*Early versions have a range from \approx 0-1 to 300 millimhos and an operating frequency of 39.2 kHz.

TABLE 2

Artificial Ice Mass*

Purpose:	Artificial, known target for geophysical detection of massive ground ice.				
Location:	University of Alaska-Fairbanks Agricultural Experiment Station				
Construction Date:	Trench - 11/24 and 25/1980 Ice Mass - 12/01/80 - 3/09/81 Mean daily temperature < 1.0°F (-17.2°C)				
Method	Natural freezing of water mainly from University of Alaska Well #11 - 16,795 gallons				
Configuration:	Right parallelepiped - E-W orientation				
Dimensions:	1.2 m (3.9 ft)				
Resistivity:	Permafrost - Winter ≈ 350 ohm-m Summer ≈ 220 ohm-m				
Resistivity of w	well water: ≈ 14 ohm-m				
Dielectric Const	cant (Relative): Permafrost = 4 to 5 Ice ≈ 4				

*See Gruol et al., 1981; Kawasaki et al., 1983a

TABLE 3

Tanana Soil - Properties*

Engineering Indices

	Classification		Frag- ments		Percentage passing sieve number			<u> </u>	Plas-
SDA texture	Unified AASHTO	> 3 inches	4	10	40	200	Liquid limit	ticity index	
ilt loam	ML	A-4, A-5	0	100	100	90-100	70-90	35-45	NP-10

Physical and Chemical

Clay < 2 mm	Moist bulk density	Permeability	Available water capacity	Soil reaction	Shrink-swell potential
Pct	<u>G/cm³</u>	<u>In/hr</u>	<u>In/in</u>	рH	
5-10	1.335-1.55	0.6-2.0	0.18-0.23	5.6-7.3	Low

*Source: USDA Soil Conservation Service, "Soil Survey of Totchaket area, Alaska, October, 1980. See also Kawasaki et al., 1983a

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