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Interpretation of Geophysical Well Logs in Permafrost

Final Report

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ABSTRACT

This report is a collection of information on the interpretation of well logs and borehole geophysical surveys in permafrost. The body of the report is preceded by an executive summary that gives the highlights of the report in condensed form. The introductory chapter contains background information that is fundamental to the understanding of well log applications in permafrost, including definitions and descriptions of well logs, permafrost, and related terms, and illustrations showing the extent of permafrost in Alaska. Chapter 2 presents information on physical properties of permafrost that relate to well log interpretation, including porosity and pore-filling media (water, ice and air), and their effects on thermal properties, electrical properties and acoustic properties. Chapters 3-8 describe the following types of well logs in detail, including measurement principles and methods, procedures for calibration and interpretation, and identification of special problems related to permafrost: thermal logs, electric logs, sonic logs, nuclear logs, magnetic logs, and miscellaneous (caliper and drilling) logs. Chapter 9 gives information on three types of borehole geophysical surveys, electrical resistivity, seismic velocity, and borehole gravity, with emphasis on the increased depth of investigation afforded by these surveys as compared with well logs. Chapter 10 describes a number of specific applications, including the identification of lithology in permafrost, characterization of the thermal regime and the thermal properties of permafrost, petroleum exploration and production, mining applications, and geotechnical applications. A concluding chapter summarizes the information contained in the body of the report and includes a table that gives an overview of the relative value of various borehole geophysical measurements that can be used for delineating and characterizing permafrost. Conclusions of the report are that a number of standard borehole measurement techniques have been tried and proven in permafrost and can be used effectively to delineate and characterize earth material penetrated by the borehole. However, there are several well logging techniques that have special potential for detecting permafrost that have not been tested: dielectric constant, sonic waveform, televiewer, and nuclear magnetic resonance. Borehole electrical and seismic surveys have potential for detecting permafrost at large distances from the borehole, and these techniques need further development and refinement to take full advantage of their capability.

PREFACE

The purpose of this report is to provide earth scientists and engineers with the information needed to properly analyze and effectively interpret well logs in permafrost. Thousands of well logs have been made in Arctic areas for petroleum and mineral exploration and for geotechnical evaluation of construction sites in permafrost, yet no single document is available that explains how to interpret these measurements. The authors have attempted to collect information from a variety of sources and to present it in a format that is convenient to use as a text and as a reference. A primary source of information was the technical literature published in professional society journals, transactions of symposia, and in text books. All of these sources are cited and listed at the ends of chapters in the report. Another source of information was direct experience with borehole measurement data obtained with equipment procured or developed by the University of Alaska for application to problems in permafrost. The authors based some of their findings on studies of commercial logs, mainly from oil and gas exploration boreholes in permafrost areas in Alaska. Some of the techniques of well log interpretation that are described were developed through research of the staff and students of the Geophysical Institute of the University of Alaska.

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EXECUTIVE SUMMARY

Well logs are graphs of geophysical measurements vs. depth that are made by lowering probes into boreholes on wireline cables. The holes may be drilled for petroleum or mineral exploration, or for geotechnical investigations of construction sites. Well logs provide information on the character of earth material along the borehole wall by sensing its thermal, electrical, magnetic, sonic, nuclear, and mechanical properties. Some of these properties change drastically when ice replaces water in the pore spaces of soil or rock. The mechanical strength of soil increases substantially, sonic velocity may double, and electrical resistivity may increase several orders of magnitude. Both water and ice can coexist in the pores of earth materials, causing their physical properties vary continuously from one extreme when they are completely frozen to the other when completely thawed. In order to make the most of well logging in permafrost which is defined as ground that remains below $0^{o}C$ for two or more years, the log analyst must have a good understanding of these variations so that he can select the suite of logs that provides the most meaningful information for the exploration or evaluation problem at hand, and so that he can interpret the logs accurately in spite of the many pitfalls that exist.

Thermal Logs

Borehole temperature measurements provide the only direct indication of the presence of permafrost. It is difficult to determine permafrost temperatures in boreholes soon after drilling because the drilling process generates and distributes heat along the borehole walls. After a period of time (weeks to years) the temperature in the borehole approaches equilibrium with the undisturbed material, so that true temperature can be estimated by extrapolating the curve representing time-spaced measurements. Highly accurate measurements showing the profile of ground temperature vs. depth and its variation with time, can be obtained by installing multisensor cables in boreholes semi-permanently, and measuring them periodically after equilibrium is attained. Analyses of these temperature profiles can provide information on the position of the permafrost base, permafrost thickness, freezing point depression at the permafrost base, heat flow, thermal properties of the permafrost, porosity and past ground surface temperature changes.

Electric Logs

Electric logs provide information on the electrical properties of earth materials and on natural potentials that are generated by electrochemical and electrokinetic effects caused by interactions between fluids in the borehole and fluids in the soil or rock. These potentials are recorded on the SP (self potential) log which represents the dc (direct current) potential between an electrode on the borehole probe and another planted a few cm below the ground surface near the hole collar. SP logs sometimes indicate the presence of permafrost by showing a negative drift when going from unfrozen to frozen ground. However, they are not very reliable indicators, because sometimes they are erratic in frozen zones, and sometimes they are rendered useless by telluric noise associated with the aurora.

Electrical resistivity logs can be made by either of two methods: (1) the contact electrode technique in which probes are equipped with electrodes that make electrical contact with the rock along the borehole wall, usually through conductive fluid (drilling mud) in the borehole, or (2) the induction technique, in which probes contain coils that transmit and receive electromagnetic energy at frequencies of 20-50 kHz (kilohertz), inducing currents that are proportional to the conductivity of the ground surrounding the borehole. The contact electrode technique can measure a broad range of resistivity (1-10,000 ohm-meters or more), but it is subject to errors caused by anomalous borehole conditions such as washouts and caving along the walls of the borehole. The induction technique is less sensitive to borehole conditions, but it is less accurate when measured resistivities exceed 1000 ohm-meters. Both techniques are usually capable of detecting the anomalously high resistivities associated with permafrost, with the deep induction log generally preferred because of its large radius of investigation and relative insensitivity to borehole conditions. Resistivity measurements can be used to estimate the porosity of unfrozen rock if it is fully saturated with pore fluid of known resistivity.

The dielectric constant log is a relatively new technique that measures the dielectric constant of the formation by the propagating electromagnetic energy of very high frequencies, 25-1100 MHz (megahertz) along the borehole wall. These logs were developed to distinguish oil from water in petroleum reservoir rocks by the large contrast between the dielectric constant of water (80) and oil (2-4). They are also potentially capable of distinguishing ice from water because of the low dielectric constant of ice (3-4) and therefore should be very useful for geotechnical applications as well. However, the depth of investigation is very shallow (a fraction of a meter) which may not be deep enough to penetrate the thawed zone that usually occurs around petroleum drill holes in permafrost. The technique has not been tested in permafrost, so its effectiveness for detecting frozen rock has not been established.

Induced polarization (IP) logs are made with probes having electrodes that make electrical contact with the formation through conductive borehole fluids. They are sensitive to metallic sulfide minerals and clays that have high cation exchange capacities (e.g. smectite), which distort the current waveform that is transmitted into the rock. These logs should also be sensitive to permafrost which is known to produce high IP values in laboratory measurements. However, field tests of the logging technique have not been made in permafrost, so its usefulness for detecting permafrost is unproven. Because of the sensitivity of IP measurements to metallic sulfides, these logs are usually used for mineral exploration and not for oilfield investigations.

Sonic Logs

Sonic logging probes transmit sonic pulses of high frequency (10-50 kHz) through the borehole fluid and into the formation to examine its mechanical properties. After the pulses travel a known distance through the formation, they are picked up by one or more receivers on the logging probe, and the sonic pulses are converted to electrical signals that are amplified and analyzed to determine the velocity, amplitude, and distortion of the sonic signals that propagate through earth materials.

The velocity log records the compressional wave velocity by detecting the first arrivals of sonic energy at the receivers. The measured velocity can be used to compute formation porosity if the velocities of the rock matrix and the pore fluid are known. If the pores contain ice instead of water, the measured velocity increases significantly, especially in high porosity materials.

Sonic amplitude logs are often combined with velocity logs to measure the degree of attenuation of sonic energy as it passes through the formation. Fractures in the rock attenuate the signal severely, particularly if they are open and uncemented. Rocks containing ice instead of water transmit sonic pulses with relatively little attenuation, and therefore they provide a qualitative indication of the presence of permafrost.

Waveform logs can be interpreted to obtain the elastic moduli of rock because they show the arrival of shear waves as well as compressional waves in the wavetrain that is recorded vs. time. Dynamic elastic moduli are functions of compressional and shear wave velocities, and of bulk density which can be determined from the density log. Waveform logs are also very sensitive to fracturing which causes not only a decrease in amplitude but also a decrease in frequency. Although waveform logs have not been tested in permafrost, they should show an increase in both amplitude and frequency, particularly in the shear wave, because of the stiffening effect of ice.

Televiewer logs transmit a beam of very high frequency sonic energy (~2 MHz) that is used to examine the borehole wall for fractures and other flaws caused by drilling and natural sources of stress. The beam rotates about a vertical axis as the probe is pulled up the hole, so that a high resolution sonic image of the reflectance of the hole wall is obtained. If the effects of permafrost are present at the hole wall (i.e. spalling and caving of soft formations), the televiewer log should be able to detect them, although it has not been tested in this application.

Nuclear Logs

Nuclear logging probes measure nuclear radiation from naturally occurring radioactive isotopes (potassium-40 and uranium-thorium daughter isotopes), or from radiation transmitted into the formation by artificial sources contained in the probe.

Natural gamma ray logs measure gamma rays from natural isotopes in the formation, and can be used to indicate lithology, because clays and shales are usually more radioactive than sands and sandstones, which in turn, are generally more radioactive than limestones and dolomites. Gamma ray logs are also useful in exploring for uranium and thorium and other minerals that may be associated with anomalous concentrations of these isotopes. Gamma ray logs are unaffected by permafrost. However, massive ground ice in frozen silts can be detected by its lack of radioactivity.

Gamma-gamma density logging measurements are sensitive to the electron density of the formation, which is related to its bulk density by a calibration factor that varies only slightly with differences in rock type. These differences can be taken into account by making corrections for the effective value of Z/A (atomic number/atomic weight) of elements in the formation. Density logs are useful for indicating lithology in oilfield applications, and for detecting coal and metallic sulfides in mineral exploration. Density logs can also be used to compute the porosity of water-saturated rocks if their grain densities are known. Density logs are not significantly affected by the presence of permafrost. However, ice-rich permafrost and massive ground ice an be detected by their affect on density.

Litho-density logs, sometimes called P_e (photoelectric effect) logs are sensitive to variations in the effective atomic number of the formation, and they are not significantly affected by variations in formation density. They are made with a detector that is sensitive only to gamma rays with energies lower than 125 keV (kilo electron volts) which are selectively absorbed photoelectrically as a function of the effective atomic number of the formation. The response of the low energy detector is normalized to that of a high energy detector, so that the effect of variation in the electron density of the formation is removed. Litho-density logs are not affected by permafrost.

Neutron logs are made with probes that contain a source of neutrons and a neutron or gamma ray detector. Neutrons from the source enter the formation where they interact with nuclei of any atoms that they encounter. Neutron absorption logging probes primarily measure the effects of hydrogen nuclei which have large scattering and absorption cross-sections for neutrons. These probes contain detectors that measure the neutron flux which exists at some distance from the source (0-70 cm). Since most of the hydrogen nuclei that affect the measurement occur in the pore water in the rock, these logs are used to estimate the porosity of saturated, unfrozen rocks. The hydrogen density of ice is lower than that of water, and this coupled with the 'excavation' effect causes the neutron log porosity index to be slightly lower for rocks containing ice rather than water. Because of this phenomenon, neutron porosities can be crossplotted against gamma-gamma log densities to identify frozen soils and rocks with high porosities.

Neutron 'lifetime' logs are made with neutron generators that produce pulses of 14 MeV (million electron volt) neutrons. Sensitive time-gated gamma ray or thermal neutron detectors are used to measure the capture gamma rays or thermal neutron flux that decays with time during the quiescent period following the neutron pulse. The thermal neutron decay time is primarily a measure of the amount of chlorine (sodium chloride) present in the formation fluid, and thus can be used to distinguish oil from saline water. Spectral gamma ray detectors can be used to identify capture gamma rays representing silicon and oxygen, making the log sensitive to lithology. An important attribute of neutron 'lifetime' logs is their ability to be run in cased holes, which makes them useful for investigating old cased wells. Neutron 'lifetime' logs are not affected by permafrost.

Neutron activation logs are made with probes containing isotopic sources of neutrons or neutron generators that activate the nuclei of atoms in the formation. A spectral gamma ray detector is used to measure the amplitude and the energy of spectral peaks that are diagnostic of various elements (copper, nickel, gold, silver, etc.). The technique has been developed because of its potential value in mineral exploration, but it is still considered experimental. Neutron activation logs are insensitive to permafrost.

Magnetic Logs

Magnetic susceptibility logs respond to the presence of ferromagnetic minerals in rocks near the borehole, and are used to detect susceptibility anomalies that are associated with some types of mineral deposits. They are not affected by permafrost.

Borehole magnetometer logs can be used to measure the Earth's magnetic field and to detect distortions that are caused by magnetic minerals in ore pods near the hole. They can also be used to determine the direction of magnetic polarization of layers of volcanic rocks. They are insensitive to permafrost.

Nuclear magnetic resonance logs measure the concentration of hydrogen nuclei in 'free' fluid in rocks. 'Free' fluid refers to water or oil that is 'free' to move about because (1) it is not restricted by surface tension effects close to mineral grains, (2) it is not combined with minerals in the form of water of hydration, and (3) it has a viscosity less than about 500 centipoise. The measurement is made by applying a strong dc magnetic field in the borehole for a short period of time which lines up the hydrogen nuclei (spinning magnetic dipoles) in the 'free' fluid. After the magnetic field is removed the dipoles precess in unison in response to the torque arising from the Earth's magnetic field, and produce an electromagnetic signal of a characteristic frequency. The intensity and duration of the signal, which is picked up by a sensing coil in the probe, indicate the amount and type of 'free' fluid in the formation. The technique was originally developed to measure permeability and to distinguish oil from water by the difference in the relaxation time of the electromagnetic signal. It is also theoretically capable of distinguishing ice from water, but this has not been demonstrated by field testing.

Miscellaneous Logs

Caliper logs simply record hole diameter vs. depth. They are used for making borehole corrections for quantitative interpretation of nearly every other type of geophysical well log. They sometimes indicate the presence of permafrost in soils and poorly consolidated rocks by detecting sloughing and caving that may occur in the thawed zone near the borehole wall.

Mud logs are made during oilfield drilling to detect hydrocarbons that are picked up by the circulating drilling fluid when the drill bit penetrates petroleum-bearing rocks. Mud logs have been helpful in detecting gas hydrates that occur within and below permafrost.

Drilling parameter logs are records of penetration rate, bit pressure, and drill rotation rates. They are made routinely on oilfield rigs, and occassionally on the smaller rigs that are used for mineral exploration and geotechnical studies. They indicate changes in lithology that affect the ease of drilling and respond to ice lenses in permafrost.

Borehole Geophysical Surveys

Borehole geophysical surveys penetrate deeper into the formation than well logs, and therefore they are not seriously affected by anomalous conditions near the borehole. Furthermore, they may be used to 'see' anomalous conditions that exist at great distances from the borehole. Borehole electrical resistivity surveys have been used to sense high resistivities associated with salt domes and gas reservoirs that are hundreds of meters away from the measurement borehole. Although these surveys have not been used extensively for detecting permafrost, they offer considerable potential.

Downhole seismic surveys are made to obtain velocity vs. depth profiles for interpreting surface seismic surveys. However, as a byproduct of these surveys, they have been successful in identifying and delineating permafrost.

Borehole gravity meter surveys provide highly accurate values of the average bulk density of formations, and are used to solve oil well completion problems and to detect oil in formations that cannot be evaluated reliably with well logs. Borehole gravity surveys are unaffected by permafrost. However, gravity meters have been used to detect near-surface ice-rich permafrost and massive ground ice.

Applications

Well logs and borehole geophysical surveys have been applied to numerous problems in permafrost environments, including the detection and characterization of permafrost, ice-rich permafrost, massive ground ice, and the thermal regime, the identification of lithology, and the determination of density, porosity and other physical properties.

Petroleum applications include determining the velocity and density of major stratigraphic units for interpreting seismic reflection surveys, and providing physical property information needed for the successful completion of oil wells in the Arctic. Gas hydrates have been identified by interpreting combinations of well logs made on the Northern Slope of Alaska.

Mining applications include the detection and delineation of coal and metallic ores, and the characterization of overburden. In some cases well logs have been used to make in situ assays of mineral deposits.

Geotechnical applications include detection and delineation of permafrost, identification of massive ice, prediction of thaw consolidation, and determination of thermal and mechanical properties of permafrost that affect construction and long term stability of engineering structures.

Table 0.1, which summarizes information from chapter 11 of the report, shows the principal applications of various borehole measurements and their capability for delineating permafrost.

The table indicates several well logging and borehole survey techniques that have considerable potential in permafrost applications, but need further testing before their applicability can be fully established. Well logs in this category are the dielectric constant log, the sonic waveform log, the televiewer log, and the nuclear magnetic resonance log. Borehole geophysical surveys that need more research, development and testing are the electrical resistivity, seismic velocity and gravity meter techniques.

Table 0.1 — Summary of Borehole Measurements and Permafrost Applications

BOREHOLE MEASUREMENT TYPE	PERMAFROST DELINEATION CAPABILITY	ROCK OR SOIL CHARACTERIZATION property	accuracy	SECTIONS OF REPORT
THERMAL LOGS	*****	temperature, heat flow, thermal properties, por	variable	3.4 10.1
ELECTRIC LOGS:				
Self potential	*	lith, Rw	variable	4.1 10.1 10.5
Electrical resistivity:				
contact	***	lith, Rt	good	4.2 10.1
induction	****	por, pf	good	4.3 10.1 10.5
Dielectric constant	pp	fluids, pf	experimental	4.5
Induced polarization	*	clay, sulfides	qualitative	4.4 10.1
SONIC LOGS:				
Velocity	***	lith, por, pf	good	5.1 10.1
Amplitude	*	lith, por, pf	qualitative	5.2
Waveform	ppp	mod, fracs, pf	good	5.3
Televiewer	p	fracs, pf, ice	qualitative	5.4
NUCLEAR LOGS:				
Natural gamma ray	-	lith, uranium,ice	good	6.1
Gamma-gamma density	-	dens, lith,ice	good	6.2 10.1
Gamma-gamma P_e	-	lith	good	6.2 10.1.1
Neutron porosity	*	por, lith	variable	6.3 10.1
Neutron 'lifetime'	-	oil, gas, water	variable	6.3
Neutron activation	-	min	experimental	6.3
MAGNETIC LOGS:				
Susceptibility	-	ferromag min	good	7.1
Earth's field	-	mag polarity	experimental	7.2
Nuclear mag resonance	ppp	free fluid, pf	experimental	7.3
MISCELLANEOUS LOGS:				
Caliper (hole diameter)	**	caving	variable	8.1 10.1
Drilling mud	-	hydrocarbons	good	8.2.1
Drilling parameters	*	hardness, pf, ice	variable	8.2.2
BOREHOLE GEOPHYSICAL SURVEYS:				
Electrical resistivity	pppp	Rt, por, pf	good	9.1
Seismic velocity	ppp	velocity, pf	good	9.2 10.4
Gravity meter	-	density, ice	good	9.3

Symbols and abbreviations:

*	proven capability (*=least *****=greatest)
p	potential capability (p=least ppppp=greatest)
-	no capability (unaffected by permafrost)
Rw	electrical resistivity of pore water
Rt	electrical resistivity of rock or soil
lith	lithology
por	formation porosity
pf	permafrost
mod	dynamic elastic moduli
fracs	fractures
ice	ice-rich permafrost and massive ice
dens	formation density
min	minerals
mag	magnetic

1.0 INTRODUCTION

1.1 Geophysical Well Logs

Geophysical well logs are recordings of geophysical measurements made by probes containing sensors that measure the properties of soil and rock penetrated by boreholes in the earth. The probes are lowered and raised in the borehole by a wireline cable that is used to transmit the measurements to a control module and recording system at the ground surface. Well logs are usually strip-chart records of measured data that are plotted vs. depth as the probe is lowered or raised in the borehole. They are sometimes recorded on magnetic tape or disk, with data acquisition and editing controlled by a computer which can be used to manipulate the data, apply corrections and analytical algorithms, and replot the log after processing. Computers are commonly used with oilfield logging equipment which is usually mounted in large trucks or tracked vehicles. On the other extreme, light-weight, portable logging equipment is used for mineral exploration in remote areas where the equipment has to be hand carried or flown in by helicopter. This type of equipment is relatively simple and usually does not include a computer or magnetic recording capability.

The purpose of obtaining geophysical well logs is to investigate the properties of earth materials, either to find and evaluate deposits of petroleum, coal and other minerals, or to determine the physical and mechanical properties of soil and rock at construction sites and to predict their behavior during and after construction.

A limited number of texts are devoted exclusively to geophysical well logging (Dakhnov, 1959; Pirson, 1963; Guyod and Shane, 1969; Keys and MacCary, 1971; Hilchie, 1978; Hoffman, et al., 1981; Asquith and Gibson, 1983; Bateman, 1985; Hearst and Nelson, 1985). Some books on geophysics and physics contain chapters or sections on well logging (Nettleton, 1940; Keller and Frischknecht, 1966; Dobrin, 1976; Telford et al., 1976; Parasnis, 1979; Barnes, 1980; Clayton, 1983). However, most of the information on well logging is published in short papers in journals and in transactions of symposia. The Society of Professional Well Log Analysts' bimonthly journal The Log Analyst and Transactions of the Annual Logging Symposia are completely dedicated to papers on well logging as are the journals and transactions of the Canadian Well Logging Society. Journals such as Geophysics (Society of Exploration Geophysicists), Geophysical Prospecting (European Association of Exploration Geophysicists), the Journal of Petroleum Technology, and publications of the Society of Petroleum Engineers, often carry articles on well logging.

All of the major oilfield well logging service companies (Dresser Atlas, Gearhart Industries, Schlumberger, Welex, and others) publish descriptive brochures and interpretation manuals for their well logging tools and techniques, and these are generally available at no cost.

Companies that manufacture mineral and geotechnical logging equipment for sale or lease (Comprobe, Mt. Sopris, OWL Technical Associates, Simplec, and others), or provide well logging services through contract (BPB, Century, Colorado Well Logging, EDCON, PGT, and others) also provide free descriptive literature on their products and services.

Most well logging techniques and analytical procedures have been developed for use in temperate climates where earth materials are not frozen. Therefore, a great deal of the literature that is available on well log interpretation is only valid for determining the properties of unfrozen rock and soil. In recent years, more effort has been directed toward developing the resources of arctic and subarctic regions of the world. A unique aspect of these efforts is that they have taken place in terrain that is largely underlain by permafrost. In permafrost regions, ice is a common component of earth materials, and where it occurs, it drastically alters the physical properties of earth materials that well logs measure. Existing interpretational procedures need to be revised to make them relevant and valid in permafrost areas.

This report focuses on the special problems of interpreting geophysical well logs in permafrost.

1.2 Permafrost and Ground Ice

Permafrost, a term coined by Muller (1947), is permanently or perennially frozen ground. It underlies about 1/5 of the land area of the Earth and about 3/4 of the land area of Alaska (Péwé, 1982). It also occurs in most of the continental shelf of the Beaufort Sea north of Alaska. 'Perennially frozen', which is the term now commonly used to describe permafrost, means frozen for a time period of two years or more. 'Frozen' refers to ground temperatures less than $0^{o}C$. 'Ground' means earth materials (soil, peat, rock, ice, etc.), but excludes glaciers. Generally, no consideration is given to soil texture, water or ice content, degree of cementation, lithology, salt content, etc. The definition is a thermal one (temperature $< 0^{o}C$) and is a necessary condition for the ground to be frozen. However, temperatures may have to be considerably lower than $0^{o}C$ for the ground to contain ice, since the freezing point of water may be depressed because of pressure, salinity, and soil particle effects (surface and curvature). These factors also lead to situations where both ice and water can coexist in equilibrium in a soil or rock matrix. Since the physical and mechanical properties of ice and water differ substantially, the properties of permafrost may be expected to be quite different from those of unfrozen ground. In addition, where ice and water can coexist in equilibrium, the ground properties may be expected to change in a continuous fashion through the freezing point. These are important considerations for interpreting well logs since the logs record the physical properties of permafrost, and many of the physical properties depend on the relative amounts of ice and water.

Permafrost develops by freezing of the ground from the surface downward when the surface is subjected to cold temperatures. This thermal condition of the ground extends to about 670 m (2200 ft) in the North Slope area of Alaska and to only a few meters at its southern limits along the southern coasts of Alaska (Osterkamp et al., 1985). Under steady state conditions at the Earth's surface, the approximate equilibrium thickness of permafrost can be obtained from the Fourier heat conduction equation:

$$X \approx \frac{K}{J} \Delta T \qquad (1.1)$$

where X = equilibrium thickness of permafrost (m),

K = thermal conductivity of the ground (W/m^oC)

J = geothermal heat flow (W/m^2)

ΔT = difference between 0^oC and the mean annual surface temperature (MAST)

The quantities on the right side of Equation 1.1 are influenced by climate, precipitation, vegetation, nature of the ground surface, local geology, soil type, lithology, presence of bodies of water and other surficial and subsurface conditions.

Alaska can be divided into three general zones with regard to permafrost conditions: continuous, discontinuous and non-permafrost zones (Ferrians, 1965). Alaska's non-permafrost zone includes parts of the Alaska Peninsula, the southern coasts along the Gulf of Alaska, and Southeast Alaska. Permafrost is generally absent in these areas except at high elevations.

The continuous permafrost zone includes Alaska's North Slope, the Brooks Range, the north side of the Seward Peninsula and parts of the Yukon River drainage. Its southern boundary is poorly defined. However, continuous permafrost can usually be expected north of the -5^oC mean annual air temperature (MAAT) isotherm. The continuous zone is characterized by permafrost that is continuous in distribution and thickness except near and under large bodies of water or other features such as geothermal areas. Its thickness on the North Slope ranges from less than 200 m to about 670 m (650-2200 ft). Osterkamp and Payne (1981) have developed the map of the thickness of ice-bearing permafrost determined from well log data, on the North Slope shown in Figure 1.1. A schematic temperature profile from the Prudhoe Bay area is shown in Figure 1.2 (Lachenbruch et al., 1982). This profile demonstrates the presence of deep permafrost, a past mean annual surface temperature (MAST) of about -11^oC, and a warming trend of about 2^oC during the last century which is illustrated by the curvature in the top 160 m (525 ft) of the temperature profile.

There is also an extremely strong gradient in MAST and permafrost temperatures across the Arctic Coastal Plain. For example, the MAST warms about 2^oC in the 26 km (16 miles) from the West Dock at Prudhoe Bay to the Deadhorse Airport, and it warms about 4.5^oC in the 113 km (70 miles) from the West Dock to Happy Valley (Osterkamp, unpublished data). Special well completion procedures are required to produce hot oil through this permafrost which is close to its melting temperature.

Discontinuous permafrost extends roughly from the Yukon-Tanana drainage southward nearly to the southern Alaska coasts. This southern boundary is thought to coincide approximately with the -1^oC MAST isotherm (Brown and Pewe, 1973). Discontinuous permafrost is characterized by large ground areas which are free of permafrost. The vertical distribution may also be discontinuous with unfrozen layers (taliks) and even large amounts of liquid water present

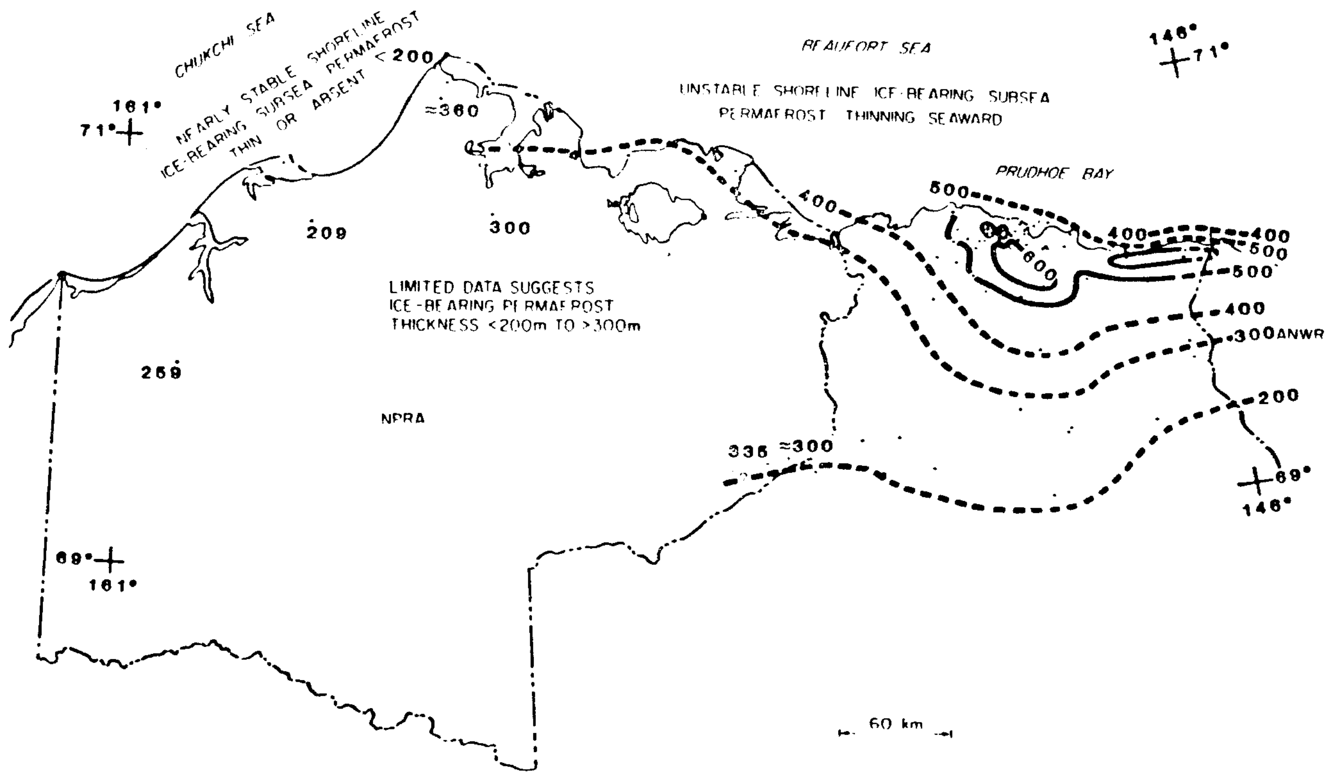

Figure 1.1 -- Depth to the base of ice-bearing permafrost in northern Alaska as determined from well log data (after Osterkamp and Payne, 1981).

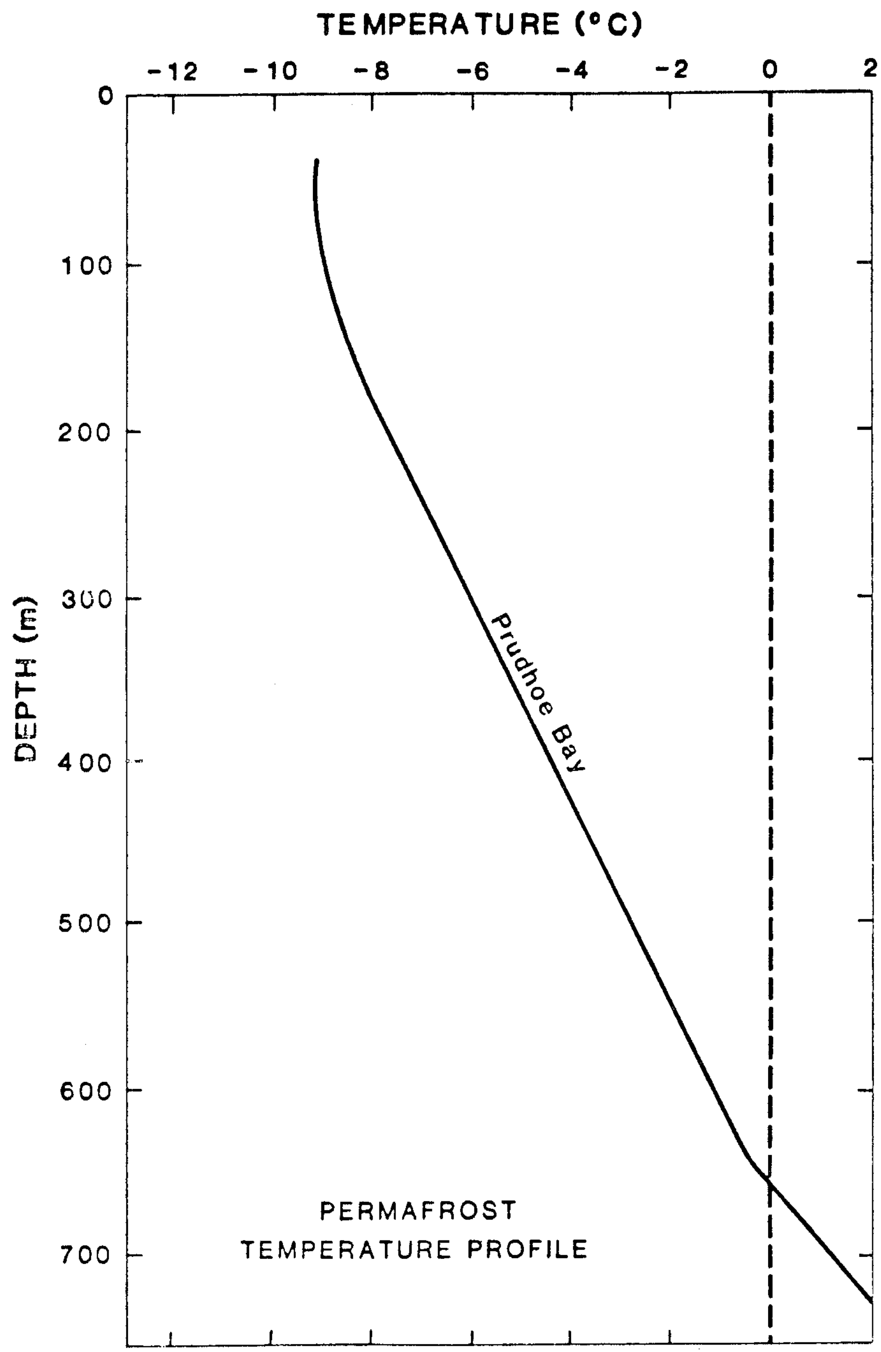

Figure 1.2 -- Temperature profile in permafrost near Prudhoe Bay, Alaska (after Lachenbruch, et al., 1982).

within the permafrost. Generally, the permafrost thickness in the discontinuous zone is less than 100 m (328 ft). The temperature profile in Figure 1.3 was obtained in discontinuous permafrost near Fairbanks (Osterkamp, 1984). This profile shows that the ice-bearing permafrost thickness is about 40 m (131 ft) with a past MAST of about -0.9°C. The curvature in the upper 25 m (82 ft) suggests a warming of the ground surface during the past decade. It also illustrates the extremely warm ground temperatures, within 0.4°C of thawing in this case, for much of the permafrost in the discontinuous zone. These warm permafrost temperatures make the permafrost in the discontinuous zone very susceptible to thawing by any increase in temperature at the ground surface, such as that caused by destruction of the vegetative mat, or by an increase in MAST.

Ground ice refers to any type of underground ice. It can be found in all types of permafrost including gravels and bedrock (Mackey and Black, 1973). There is considerable lateral and vertical variability in the amount of ground ice in permafrost even within relatively small areas. Permafrost problems commonly involve ground ice (e.g., thawing, settlement, slope stability, bearing capacity, well casing design, etc.), and it is an important consideration in the location and design of foundations, well completion procedures and in the construction and performance of engineering structures in permafrost areas. When permafrost is ice-rich (i.e., the ground ice volume exceeds the soil pore space) or contains massive ground ice, then severe engineering and environmental problems occur if it is caused to thaw. Solutions to these problems generally include avoidance and specialized construction techniques. Application of these solutions requires information on the occurrence, distribution and properties of the permafrost. A variety of geophysical methods can be used to develop this information, and geophysical well logs are among the most useful. Clearly, the detection, delineation and determination of the properties of ice-rich permafrost and massive ground ice are important objectives that can be achieved through the interpretation of well logs.

1.3 Applications

Practical applications of well logging can be divided into three major categories: petroleum, minerals, and geotechnical. Oil and gas logging can be accomplished most effectively by well logging service companies that offer the equipment and experienced personnel needed for logging deep wells quickly and efficiently. Speed and efficiency are important considerations because of the high cost of stand-by time for the drilling equipment and drillers during logging.

Mineral and geotechnical logging can be accomplished by service companies that are equipped for logging relatively shallow, small-diameter wells with light-weight portable or mobile equipment, or by mining and construction companies with their own specialized equipment and personnel.

In all three applications, oilfield, mineral and geotechnical, the key to obtaining a useful final result lies in proper interpretation of high quality well logs.

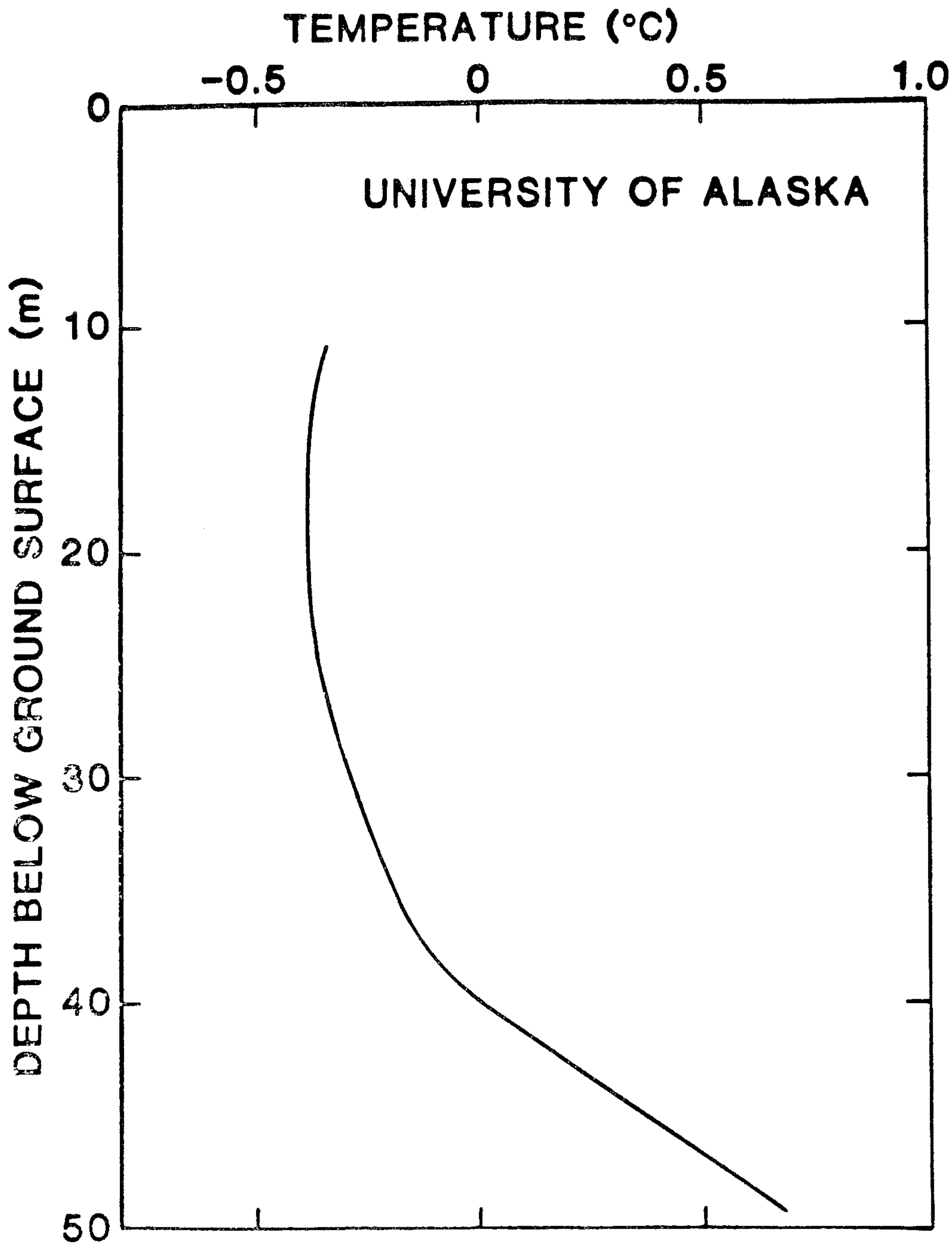

Figure 1.3 -- Temperature profile in discontinuous permafrost near Fairbanks, Alaska (after Osterkamp, 1984).

1.3.1 Petroleum Applications

Information on permafrost which can be obtained from geophysical well logs is useful in all phases of petroleum exploration and development. For example, seismic data must be corrected for the thickness of the relatively 'fast' permafrost layer which may be variable locally. Oil well drilling, completion and production procedures require information on permafrost temperatures, thickness and properties. An assessment of the potential occurrence and distribution of gas hydrates requires information on the thickness and temperature of the permafrost. Gas hydrates can also be detected with geophysical well logs (Collett, 1983). These considerations are especially important in offshore areas since most subsea permafrost is at its melting point. Any thermal disturbance caused by drilling or production activities will cause some ice in the permafrost to thaw. The potential for thaw subsidence and excess pore pressures increases with the thawing.

1.3.2 Mineral Applications

The existence of ice in soil or rock pore spaces causes the seismic velocity and electrical resistivity of soil and rock to increase, making it difficult to use electrical and seismic surface geophysical techniques for finding and delineating placer deposits that occur below frozen sediments overlying alluvial channels or depressions in bedrock. Because the sediments are generally much more porous than the bedrock, they usually contain more ice, which in turn results in a greater increase in their acoustic velocity and resistivity relative to that of bedrock. As a result, the velocity and resistivity contrasts between the frozen sediments and bedrock may not be sufficient for clear delineation of the bedrock surface by seismic and electrical methods. It is sometimes possible to find the channels or depressions using a combination of seismic and electrical techniques and special interpretation procedures. In any case, permafrost makes exploration by these techniques more difficult, and more dependent on having accurate values of velocity and resistivity for interpretation of field data. Accurate values can be obtained from well logs, which also provide information on the variability of velocity and resistivity with depth within the two media. This information is valuable in two ways: (1) it helps the geophysicist make a decision as to whether seismic and electrical surveys have enough promise of success to make them worthwhile, and (2) if so, how the field exploration program and interpretation procedure should be planned to provide the best possible final result.

Mining is generally more difficult and expensive in permafrost. In the case of surface mining, the earth materials overlying the mineral deposit must be removed to provide access to the 'pay' zone, and this sometimes requires thawing the overburden to make excavation by heavy equipment possible. In order to decide whether thawing is cost effective, it is necessary to have an accurate profile of the type of material overlying the mineral deposit, the degree of freezing within it, and the strength of the frozen material. This information can be obtained by trial and error through a pilot study (small, local excavation), or by geophysical well logging. Well logging is generally less expensive and can sample a larger area than a pilot study, and therefore can be expected to be more effective.

In the case of the underground mine that requires a shaft, adit or incline to gain access to the 'pay' zone, permafrost can make initial construction of the entryway easier and less expensive if the ground that must be penetrated is unconsolidated or poorly consolidated in its unfrozen state. However, such an entryway in permafrost may weaken with time due to the thermal disturbance caused by the heating associated with mining operations. Again, well logs can provide valuable information on the profile of permafrost and lithology over and around the mineral deposit so that an optimum location can be chosen for the entryway. This information can also be used in the design of insulation and refrigeration systems to prevent thawing that could dangerously weaken the entryway and other parts of the mine system.

1.3.3 Geotechnical Applications

Site investigations for engineering structures such as roads, pipelines, airfields, buildings, coastal facilities etc., require information about permafrost that can be obtained from geophysical well logs. For example, the local presence or absence of permafrost can be confirmed with well logs from boreholes. Most geotechnical problems are related to the presence of ice-rich permafrost or massive ground ice which can be detected with the proper well logs. Potential thaw consolidation can also be evaluated, and under some conditions, the relative amounts of ice and water can be obtained from analysis of well logs. Some of the physical and mechanical properties of permafrost that are useful for foundation design can also be determined from well logs.

As petroleum exploration and production moves into offshore areas, the geotechnical problems associated with these activities will be severe. Construction of islands, drilling pads, docks, causeways and especially subsea pipelines in warm and salty subsea permafrost will create a host of new geotechnical problems. Geophysical well logging may be expected to play a key role in the evaluation and solution of these problems.

1.3.4 Special Considerations

The logging of deep holes drilled for petroleum exploration and production in arctic areas has proceeded in much the same fashion as for temperate regions with due consideration for cold weather and remoteness of sites. However, mineral and geotechnical applications are generally conducted with tighter budget constraints. Consequently, there is a need for lightweight and compact tools and instruments capable of operating under severe environmental conditions.

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1.5 List of Acronyms

MAAT Mean annual air temperature
MAST Mean annual ground surface temperature

2.0 PERMAFROST PROPERTIES RELATED TO WELL LOG INTERPRETATION

2.1 Soil Water in Permafrost

Marked physical and mechanical changes accompany the phase change of soil water to ice. These changes produce strong variations in the thermal, electrical, mechanical, and other properties of a soil or rock on freezing. Consequently, well logs that detect these properties are especially useful for detecting permafrost and ground ice and in determining their properties. The transition from the water to the ice phase is not necessarily abrupt and usually occurs over a temperature range rather than at a distinct temperature. Therefore, water and ice can coexist, in equilibrium, in permafrost. The fractional unfrozen water content by weight is

$$W = a\ T^{b} \tag{2.1}$$

where a and b are empirically-determined constants characteristic of each soil and T is the temperature in degrees centigrade (Anderson and Morgenstern, 1973). In coarse-grained soils, W is very small, however, in fine-grained soils, W can be large as shown in Figure 2.1. This means that the changes in the physical and mechanical properties of a coarse-grained soil on freezing will be much more abrupt (occur over a smaller temperature range) than for a fine-grained soil. When water and ice coexist in permafrost, the degree of ice bonding between soil particles may be reduced in comparison to the case where ice is present without the water phase. For temperatures close to the melting point, the permafrost may be ice-bearing but not necessarily ice bonded. This effect produces a transition temperature zone at the lower surface of the ice-bearing permafrost characterized by decreasing ice-bonding downwards through the ice-bearing permafrost. The transition zone may range from a few meters in coarse-grained soils to about 60 m (200 ft) in finer-grained soils containing salty pore water (Osterkamp and Payne, 1981).

The temperature difference between the base of the ice-bearing permafrost and the $0^{o}C$ isotherm is the freezing point depression (FPD) of the soil pore water caused by pressure, chemical (salt) and soil particle effects. If it is assumed that the factors producing FPD are additive, then the equilibrium temperature of a soil, water and ice system is given by

$$T_o = 0.0100 - T_p - T_c - T_s\ (^{o}C) \tag{2.2}$$

where the first term on the right side is the triple-point-of-water (TPW) and T_p, T_c, and T_s are the temperature corrections for pressure, chemical and soil particle effects, respectively (Osterkamp, 1985). If the ice point is used as a reference (the equilibrium temperature of pure ice and pure air-saturated water at one atmosphere of pressure) then

$$T_o \simeq - T_p - T_c - T_s. \tag{2.3}$$

If the soil is water saturated, then the pressure on the ice and water phases may be assumed to be equal and if equilibrium prevails, the pressure correction becomes

$$T_p \approx BP \tag{2.4}$$

where B is the Clausius-Clapeyron slope (0.00751°C $atmos^{-1}$) and P is the pressure on the ice and water in the pore spaces. If P is known or can be assumed to be the hydrostatic pressure at a given depth from the soil surface, then Equation 2.4 can be used to calculate T_p. For example, at a depth of 600 m, T_p = 0.44°C. The assumption of P being the hydrostatic pressure at the base of the ice-bearing permafrost is thought to be valid for most of the North Slope. Unfortunately, the thermal disturbance caused by drilling produces a thawed zone around the well-bore where thaw consolidation with possible pore pressure reductions may occur. Gas hydrate decomposition and freeze-back pressures can cause pressures in excess of hydrostatic (Perkins et al., 1974), thus increasing T_p. Normally, in the absence of gas hydrates, pore pressures at the base of permafrost should not be significantly different from hydrostatic pressures.

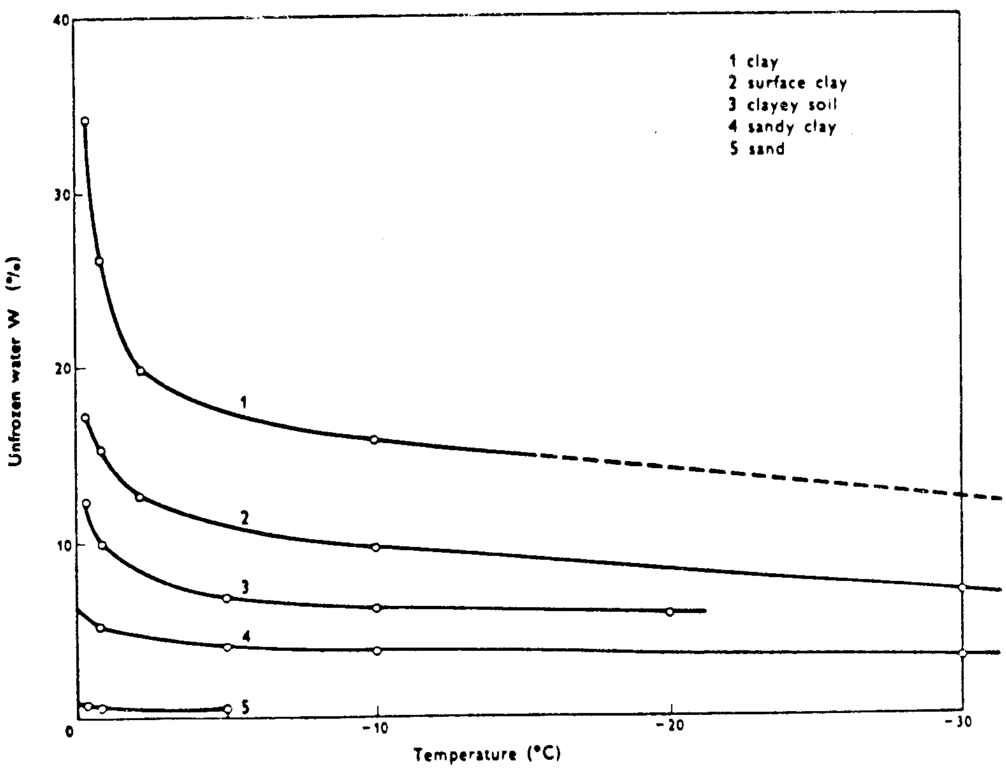

Figure 2.1 -- Variation of unfrozen water content of frozen soils with changes of temperature (after Tsytovich, 1957).

T_c depends on the solute concentrations in the soil pore water. The most common salt in the pore water at depth is NaCl. When the salt concentrations are known, the FPD values can be calculated from them or obtained from their phase diagrams. In the common case, where the ionic concentration ratios are similar to sea water, the chemical FPD can be calculated from

$$T_c \simeq 0.0137 + 0.051990\ S + 0.0000225\ S^2\ (^{\circ}C) \qquad (2.5)$$

where S is the salinity of the soil pore water in parts per thousand (ppt) (Doherty and Kester, 1974). According to Howitt (1971) the salt concentration within the permafrost is highly variable. One measured salinity value at the base of ice-bearing permafrost was 14 ppt which makes $T_c \approx 0.75^{\circ}$ C according to Equation 2.5. If the variations of salt concentration within the permafrost are indicative of variations at its base then T_c may range from almost zero to more than 1.8°C in the permafrost near Prudhoe Bay.

Osterkamp and Payne (1981) suggest that the temperature correction associated with soil particle effects can be obtained by inverting Equation 2.1 so that

$$T_s = \left[\frac{W}{a}\right]^{\frac{1}{b}} \qquad (2.6)$$

For saturated silts and coarser-grained soils $T_s \approx 0.01^{\circ}$ C or less while for very fine-grained clays T_s could exceed several degrees Celsius.

Obviously, it is impossible to make a reliable estimate of T_o in a well-bore at the base of ice-bearing permafrost given the uncertainties of thawing and associated pore pressure reductions, freeze-back pressures, gas hydrate presence and decomposition, pore water salt concentrations, and soil type and saturation levels. Nevertheless, under certain conditions and given supplementary information from well logs, it may be possible to obtain at least a rough estimate of T_o. For example, in the Prudhoe Bay field, the soils are generally saturated sands, gravels or silts and, in the absence of gas shows on the mud log, this suggests that hydrostatic pressure and chemical effects dominate T_o.

2.2 Thermal Properties

2.2.1 Thermal Conductivity

The thermal conductivity of permafrost is used to interpret thermal logs in permafrost including both temperature and temperature gradient logs. Experiments on heat flow indicate that the heat flux in a material at a point across a surface is

$$\vec{J} = -K\,\vec{\nabla}\vec{T} \qquad (2.7)$$

where K is the thermal conductivity coefficient and $\vec{\nabla}\vec{T}$ denotes differentiation along the outward-drawn normal to the surface. Equation 2.7 states that the heat flux across a surface is proportional to the temperature gradient with the proportionality coefficient being the thermal conductivity. Methods and apparatus used for measuring the thermal conductivity of permafrost include the guarded hot plate, divided bar, and probe methods (Farouki, 1982; Hoekstra et al., 1973) with the probe method being the most common.

Factors which have a significant effect on the thermal conductivity of a soil-water-ice-air matrix include soil type, temperature, water content, porosity, and density. The effects of these factors on the thermal conductivity of frozen and unfrozen soils have been reviewed recently by Farouki (1981, 1982). A number of graphical and analytical methods for obtaining the thermal conductivity of frozen and unfrozen soils have been compiled and presented in these reviews.

Lachenbruch et al. (1982) used the geometric mean method to calculate the thermal conductivity of saturated permafrost and obtained good agreement between calculated values and measured values obtained with a probe. According to this method, the thermal conductivity of the frozen soil-water-ice matrix is

$$K_f = K_i^{\phi} K_g^{1-\phi} (K_w/K_i)^{\phi'} \qquad (2.8)$$

where K_i is the thermal conductivity of ice, K_g is the geometric mean conductivity of mineral soil grains, K_w is the thermal conductivity of water, ϕ' is the volume fraction of liquid water in the frozen sample and ϕ is the volume fraction of water in the thawed sample (porosity). The volume fraction of ice in the frozen, saturated sample

$$\phi_i \approx \phi - \phi'. \qquad (2.9)$$

Equation 2.8 is especially useful since it accounts for the effect of unfrozen water on K in saturated permafrost, which is a common occurrence. Figure 2.2 is an example of the variation of K in a partially frozen soil. Typical values of thermal conductivity for use in Equation 2.8 are given by Lachenbruch et al. (1982).

2.2.2 Thermal Diffusivity

The thermal diffusivity of permafrost is defined as

$$\kappa \equiv \frac{K}{\rho c} \qquad (2.10)$$

where K is the thermal conductivity, ρ is the bulk density and c is the specific heat capacity. Very few measurements of the thermal diffusivity of permafrost have been made. κ is not a strong function of temperature except at negative temperatures near $0^{\circ}C$ where the presence of an unfrozen water phase can cause c to increase strongly. When the values for K decrease, the net result is that κ decreases as the permafrost temperature approaches the melting point. Figure 2.3 (Hoekstra and McNeill, 1973) shows this behavior for a clayey sand. A common procedure for obtaining values for κ is by calculating them from the data of Kersten (1949). Johnston (1981) and Lunardini (1981) have assembled these calculations in graphical form.

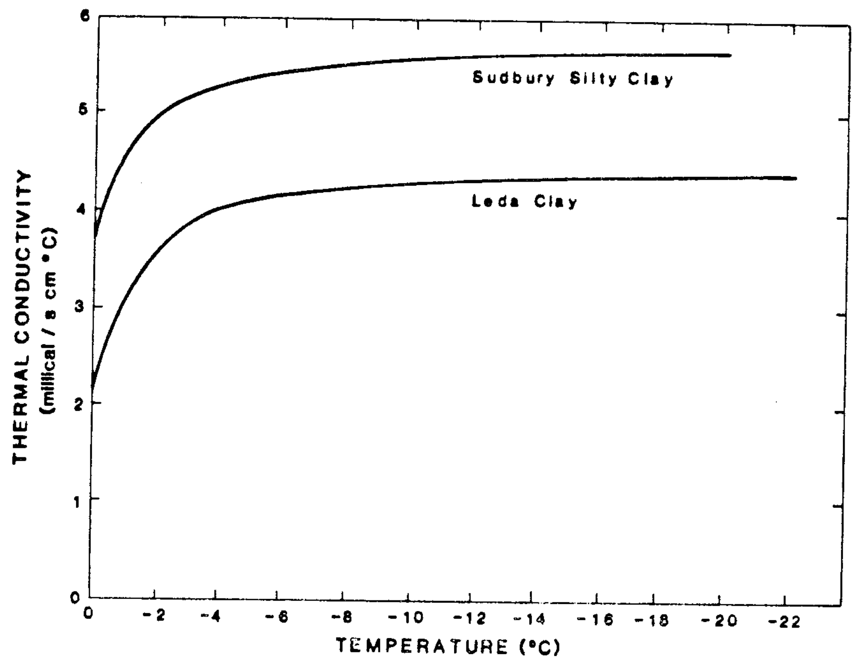

Figure 2.2 -- Thermal conductivity variation with temperature in two fine-grained frozen soils (after Penner, 1970).

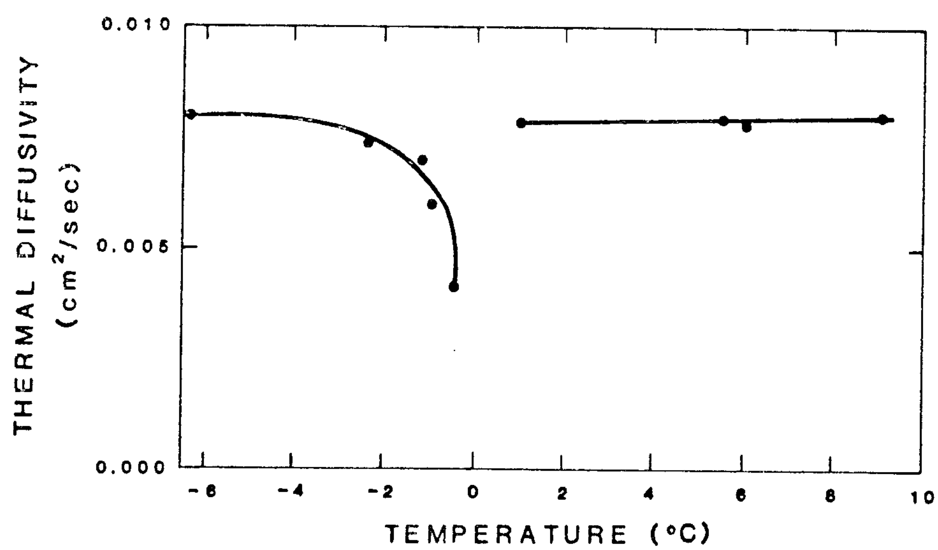

Figure 2.3 -- Thermal diffusivity of a clayey sand as a function of temperature (after Hoekstra and McNeill, 1973).

2.3 Electrical Properties

The electrical parameters of earth materials such as resistivity, dielectric constant (relative permittivity), loss tangent and electric polarizability depend on many factors including soil or rock type, porosity, moisture content, pore water salinity, temperature and frequency of the electromagnetic signal. Thus, the values of the electrical parameters encountered in ordinary earth materials even of the same type may have a substantial range.

The polarization of earth materials by means of impressed electric fields (induced polarization) and naturally occurring polarization (self-potential) may have importance in some përmafrost work, although only a few papers have appeared in the literature along these lines (e.g., Snegirev, et al., 1973; Frodlov, 1973; Sidirova and Fridrikhsberg, 1973). The dielectric is related to the polarizability of earth materials including subsurface ice. Borehole radar and other high-frequency electromagnetic methods which rely on the contrast between the dielectric constant of frozen and unfrozen water have been used to detect permafrost and associated ground ice (Rodney, et al., 1983). Various borehole electrical and electromagnetic methods have also been used to detect permafrost and ground ice by determination of the subsurface resistivity.

The utility of electrical borehole geophysical methods for detecting permafrost and ground ice depends on the great contrast that can exist between an earth material that is frozen and the same material when unfrozen. This in turn implies that it is the reduction of the liquid water in an earth material through freezing and conversion to ice that causes the contrast. The effects on the resistivity, dielectric constant and electrical polarizability of earth materials on freezing are discussed below.

2.3.1 Resistivity

Electric current conduction through most rocks and unconsolidated materials for a given electromotive force would be very small were it not for the presence of free water and dissolved salts which allow electrolytic conduction to occur through the pore fluids. Thus, since electrolytic conduction plays the dominant role in electrical conduction in soils and unconsolidated materials, it is assumed that the resistivity is a function of the porosity of the rock. Archie's law, an empirically-derived equation, relating porosity to resistivity for saturated rocks, is

$$R_o = aR_w\phi^{-m}, \qquad (2.11)$$

where R_o is the bulk resistivity of the material, R_w is the resistivity of the water in the pores, ϕ is the porosity expressed as a fraction per unit volume of material and m and a are empirical parameters approximately equal to 2 and 1, respectively, that can be determined from laboratory measurements of samples (Keller and Frischknecht, 1966).

2.3.2 Effects of Unfrozen Water Content

When more than one ionic species of solute is present, the resistivity of water is given by:

$$R_w = \frac{1}{\sum_i C_i \Lambda_i} \qquad (2.12)$$

where Λ_i is the conductance of the ith ionic species in mhos/m^2 and C_i is concentration of the species in equivalents/m^3 (Park, 1964).

The dependence of the resistivity on temperatures above the freezing point for an earth material saturated with electrolyte is given by

$$R(T) = R_o/[1 + \alpha\ (T-T_o)] \qquad (2.13)$$

where R_o is the resistivity at some reference temperature T_o and α is the temperature coefficient of resistivity (Keller and Frischknecht, 1966). The temperature dependence arises from the increase in mobility of the electrolyte ions with temperature due to a decrease in viscosity. Since for most electrolytes, α is about 0.025 per degree centigrade, the resistivity, say for a 10°C change near the freezing temperature, will only give a fractional change of $R/R_o \approx 0.8$; thus, this temperature dependence is not of much interest relative to the effect of freezing of pore water which has a much larger effect on the ionic mobilities.

Because conduction through earth materials occurs primarily electrolytically through the pore water, it may be thought that soil water conductivity by itself governs the resistivity. However, the interaction of the material and pore space surfaces with the soil water can also affect electrolytic conductivity. In clay materials especially, which may have a large ionic exchange capacity, ions can be supplied to the soil water by desorption of exchangeable cations adsorbed on the clay particles, which decrease the soil water resistivity (Waxman and Smits, 1968; Olhoeft, 1977). The conductance of the electrolyte in the first few molecular layers adjacent to the soil particle surface can also be affected due to a slight net surface charge associated with preferred fracturing planes which places atoms of one type at the surface of the fracture plane.

The foregoing primarily considers the resistivity of earth materials when the pore spaces are completely saturated with electrolyte. Due to the nature of the interconnection of the water film between adjacent pores, two separate situations may arise when the pore spaces are not fully saturated depending on whether the amount of saturation is less than or greater than some critical value. The critical value is the level of saturation for which an interconnected film of electrolyte occurs over all the internal surface of the material. Empirical formulas relating resistivity to the amount of electrolyte in the pore spaces expressed as a fraction, S_w, of the electrolyte volume to pore space volume have been developed (Keller and Frischknecht, 1966) for unfrozen soils.

For the case that the fraction S_w is greater than the critical value, S_{wc}, but less than 1, for a continuous, interconnected film of electrolyte

$$R_o = a\, R_w\, \phi^{-m}\, S_w^{-n_1}, \quad S_{wc} < S_w < 1, \tag{2.14}$$

where the factor $a\, R_w\, \phi^{-m}$ is the resistivity for complete saturation, i.e., Archie's law, and n_1 is an empirical parameter (desaturation factor) which has a value of about 2 for most materials.

If S_w is less than S_{wc}

$$R = a\, R_w\, \phi^{-m}\, b\, S_w^{-n_2}, \quad S_w < S_{wc}, \tag{2.15}$$

where the factor $a\, R_w\, \phi^{-m}$ is the resistivity for complete saturation and b and n_2 are empirical parameters with values in the approximate ranges 0.05-0.5 and 4-5, respectively. There is a fairly dramatic change in resistivity around the critical value S_{wc} as indicated by the range of values for this case relative to the case when $S_w > S_{wc}$.

The modification of Equation 2.11 to account for salt rejection in a freezing soil has been considered by Hoyer, et al. (1975). They obtain

$$R' = FR_w'\, S_w^{-n}, \tag{2.16}$$

where F is the formation factor and R_w' is the resistivity of the unfrozen water in the pore spaces. The derivation of Equation 2.16 assumes complete salt transfer from the ice which has formed to the water that remains unfrozen.

With F given by $F = R_o/R_w$ and the assumption that the ratio of the electrolyte volume to the pore space volume is related to solute resistivities below and above the freezing temperature by $R_w' = R_w\, S_w$, Equation 2.16 becomes

$$R' = a\phi^{-m} R_w'\, S^{-n}, \tag{2.17}$$

or

$$R' = R_o\, S'^{\,-n}. \tag{2.18}$$

In arid regions, surficial materials tend to be very dry and hence one might expect the surficial resistivity to be high. However, the opposite is usually the case, because the lack of precipitation prevents rapid loss of exchange ions from clay soils, while upward-directed moisture migrating from the water table may continuously deposit salts near the surface upon evaporation. The annual precipitation is fairly low in most areas of Alaska north of the Alaska Range, but the region cannot be considered arid in the usual sense because the groundwater in the active layer is frozen for most of the year, groundwater percolation may be retarded by permafrost and cool summertime temperatures may reduce evaporative losses. However, the upper layers of permafrost immediately below the active layer tend to be very resistive even when the moisture content is high, because the pore spaces have a high fractional ice content which prevents electrolytic conduction and also because there may be massive ground ice present.

As indicated, there is a strong dependence of the resistivity of earth materials on temperature near the freezing point. Figure 2.4 shows the results of Hoekstra and McNeill (1973) for the resistivity of laboratory samples of granite, sandy gravel, Fairbanks silt and clay as a function of temperature over a range of nearly 30^{o}C around the freezing point. The fact that the resistivity variation near the freezing point is not as abrupt as might be thought is attributable to the gradual change in the relative amounts of unfrozen water and ice at temperatures less than the freezing point.

2.3.3 Frequency Dependence

The foregoing discussion of resistivity in material media is restricted to electrical conduction under static or quasi-static conditions of the imposed electric field. Under such conditions, the resistivity is the reciprocal of the conductivity, σ_{dc}, where dc denotes the static or steady state conductivity. In addition, the dielectric permittivity and magnetic permeability are real, static quantities. However, for time-varying fields, the conductivity, permittivity (or equivalently dielectric constant) and magnetic permeability (or equivalently susceptibility) may change drastically from the static case due to the various mechanisms for conduction, electric polarization and magnetization. These mechanisms are material dependent and enter into the solutions of the wave equations governing the propagation of electric and magnetic fields via the constitutive relations $\vec{D} = \varepsilon\vec{E}$ and $\vec{B} = \mu\vec{H}$ and the equation relating current density to electric field, $\vec{J} = \sigma\vec{E}$.

The conductivity, permittivity and permeability are all frequency dependent. This may be qualitatively understood by noting that the responses of charged particles and electric and magnetic multipoles to time varying fields may depend on charge magnitudes, ionic mass, molecular orientation and many other factors. Futhermore, the macroscopic response of a material to a time-varying field will depend on the manner in which the electric charges and magnetic dipoles of the material interact collectively among themselves and with the neutral parts of the material. An example of this is the distortion or polarization of water molecules, which have permanent dipole moments, in a time-varying field and the difference that arises in the phases of the resulting electric and magnetic fields due to interaction with the surrounding medium.

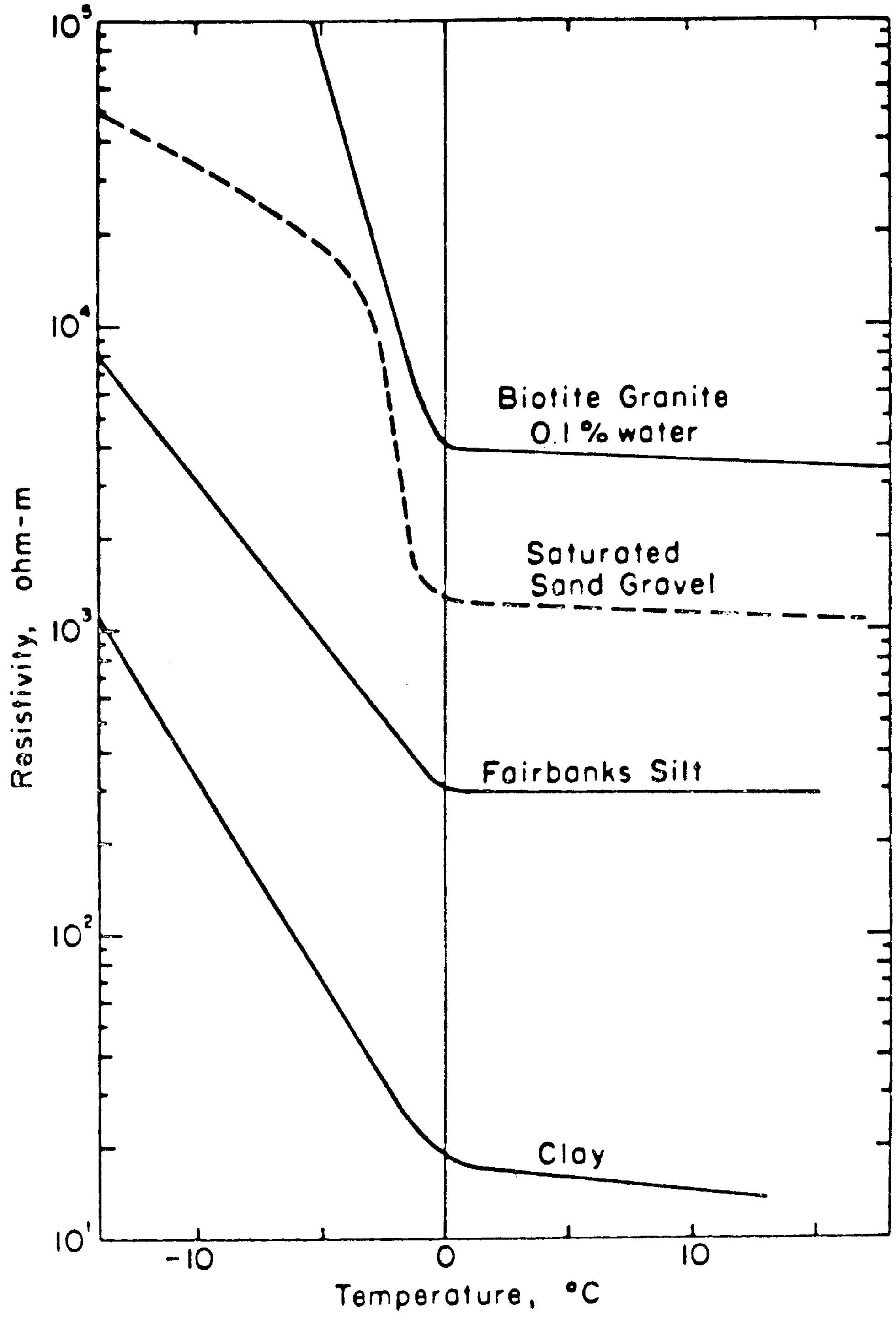

Figure 2.4 -- Resistivity of laboratory samples of granite, sandy gravel, silt and clay as a function of temperature near the freezing point (after Hoekstra and McNeill, 1973).

Because a material can produce phase differences between the electric and magnetic fields of a propagating wave, energy losses may occur independent of ohmic losses which are related to the conductivity, σ_{dc}. Such a wave may attenuate in the medium due primarily to dielectric losses. Olhoeft (1975; 1977), Delaney and Arcone (1982) and Arcone (1984) discuss electromagnetic propagation and energy loss in permafrost materials.

Olhoeft (1977) has studied electrical losses in terms of the loss tangent which is the ratio of real part of the conductivity to the imaginary part of the conductivity. This is equivalent to the ratio of the 'effective' conductivity (which contains a contribution from the imaginary part of the complex permittivity as well as the dc conductivity, σ_{dc}) to the quantity $\omega\epsilon'$. The dielectric constant is defined as the real part of the permittivity divided by the 'free' space permittivity ϵ_o. Delaney and Arcone (1982) studied the imaginary part of the complex dielectric constant ($= \epsilon/\epsilon_o$), referring to it as the dielectric loss term.

The complex conductivity and dielectric constant of permafrost materials are largely controlled by the unfrozen water content and the temperature. Figure 2.5 shows an example from Olhoeft (1977) of resistivity and loss tangent measurements as a function of frequency made on a sample of frozen clay at two different temperatures and two different field strengths. Note

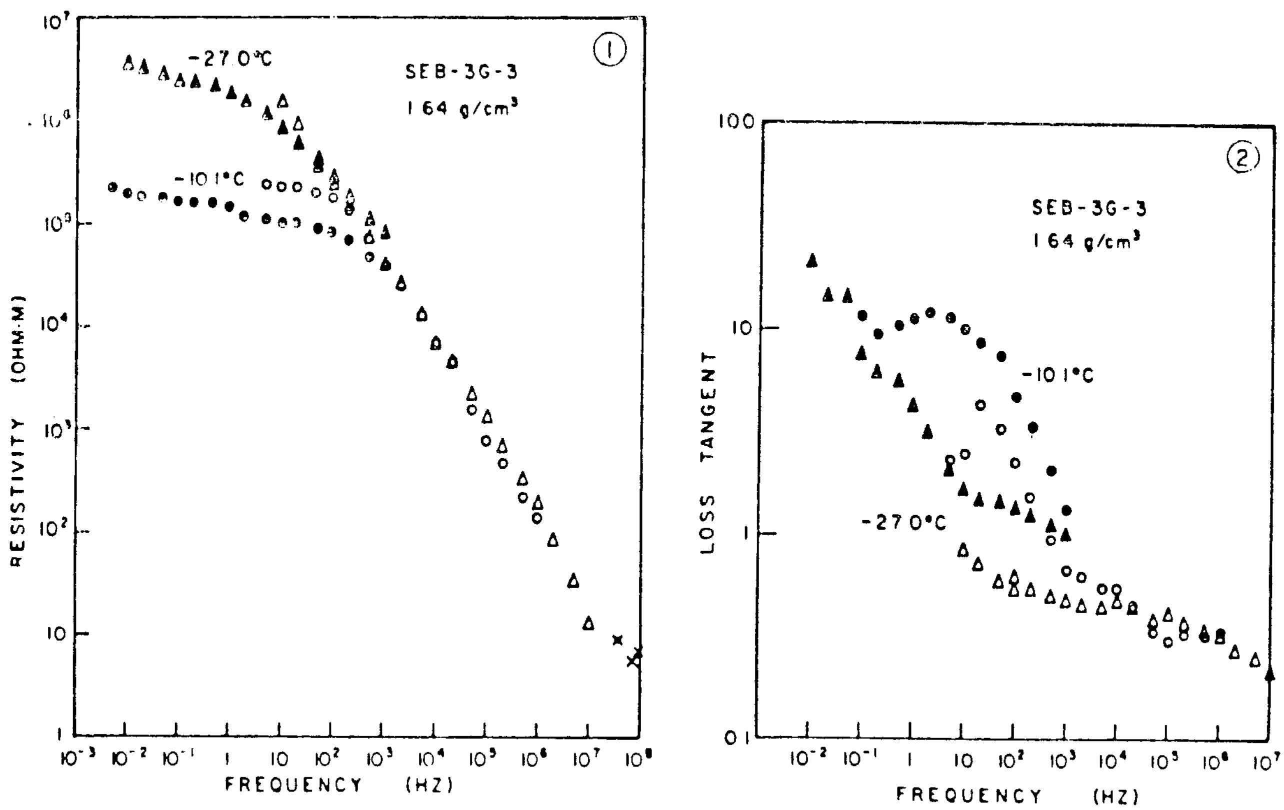

Figure 2.5 -- Left: Real resistivity vs. frequency at -27°C (triangles) and -10.1°C (circles for 0.0022 V/cm (open symbols) and 22 V/cm (closed symbols) for natural clay core at 1.64 g/cm^3; Right: Total loss tangent vs. frequency for the same sample (after Olhoeft, 1977).

the relatively abrupt decrease of the resistivity at around 1 kHz for the sample at -10.1°C which contrasts with the smoother change with frequency for the loss tangent. Figure 2.6 is an example from Delaney and Arcone (1982) showing the change of the dielectric constant and loss term with temperature in Fairbanks silt for various moisture contents.

It is important to note that theory and measurements show that dielectric effects must be taken into account when using borehole induction tools for resistivity measurements in the kilohertz range. This is true because resistivity is defined as the reciprocal of conductivity and if the conductivity is complex it must contain a loss term due to dielectric effects.

Measurements of the dielectric constant made with high frequency wireline tools such as the one described by Rodney et al. (1983), can be used to assess moisture content or to infer other parameters. Such tools operate in the low megahertz range. Arcone (1984) and Arcone and Delaney (1984) have measured dielectric properties of permafrost in a tunnel through permafrost at Fox, Alaska and at other sites near Fairbanks, Alaska using a radar unit operating in the 100 MHz range. This series of measurements was made using cross borehole techniques to correlate dielectric properties with temperature, grain size and ice content.

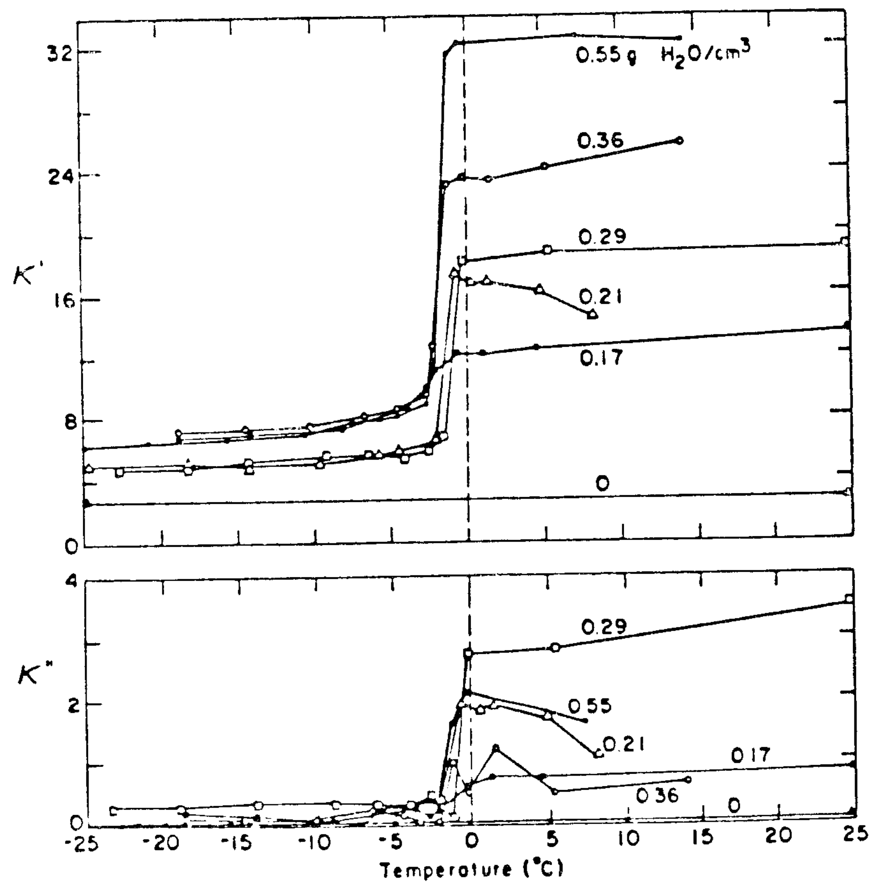

Figure 2.6 -- Dielectric constant and dielectric loss factor of Fairbanks silt as a function of temperature for five moisture contents at 0.5 GHz (after Delaney and Arcone, 1982).

2.4 Seismic-Acoustic Properties

Interpretation of acoustic or sonic borehole logs requires information on the associated wave velocities in permafrost. Parameters that influence the compressional and shear wave velocities in soils and rocks include grain size, lithology, water content, ice content, temperature, porosity, pore structure, confining pressure and degree of cementation (Garg, 1973; Vinson, 1978). Velocities of various subsurface materials have been obtained during seismic surveys by standard refraction or reflection methods and in laboratory experiments. Table 2.1 gives compressional wave velocities in frozen and unfrozen soil and rock (Roethlisberger, 1972). Since water and ice have very different elastic constants, wave velocities may be expected to vary with water and ice content and, therefore, with temperature especially near the melting point. Figure 2.7 illustrates the variation of compressional wave velocities with temperature (Nakano and Froula, 1973).

Table 2.1 -- Compressional wave velocities in permafrost [after Barnes (1966); Roethlisberger (1972); Garg (1973); King et al. (1974)].

Material	Locality (Reference)	Seismic velocity km/s		Approx. temp. °C
		Frozen	Unfrozen	
Silt and organic matter	Fairbanks, Alaska (Barnes)	1.5-3.0	0.6-1.2	-1
Gravel	Fairbanks, Alaska (Barnes)	4.0-4.6	1.8-2.3	-1
Glacial till	McMurdo Sound, Antarctica (Roethlisberger)	3.0-4.3	0.5-1.5	-20
Shale and sandstone	Alaska (Barnes)	2.5-2.6	1.5-2.1	-9
Limestone	Bedford (King et al.)	6.1	4.8	-8
Limestone	Warminster (King et al.)	5.65	4.3	-5
Sandstone	Berea (King et al.)	5.75	4.0	-9
Sandstone	Boise (King et al.)	5.1	3.3	-1
Iron Ore	Schefferville (Garg)			
(a) unaltered		6.1	3.0	-1
(b) altered		5.5	1.4	-1

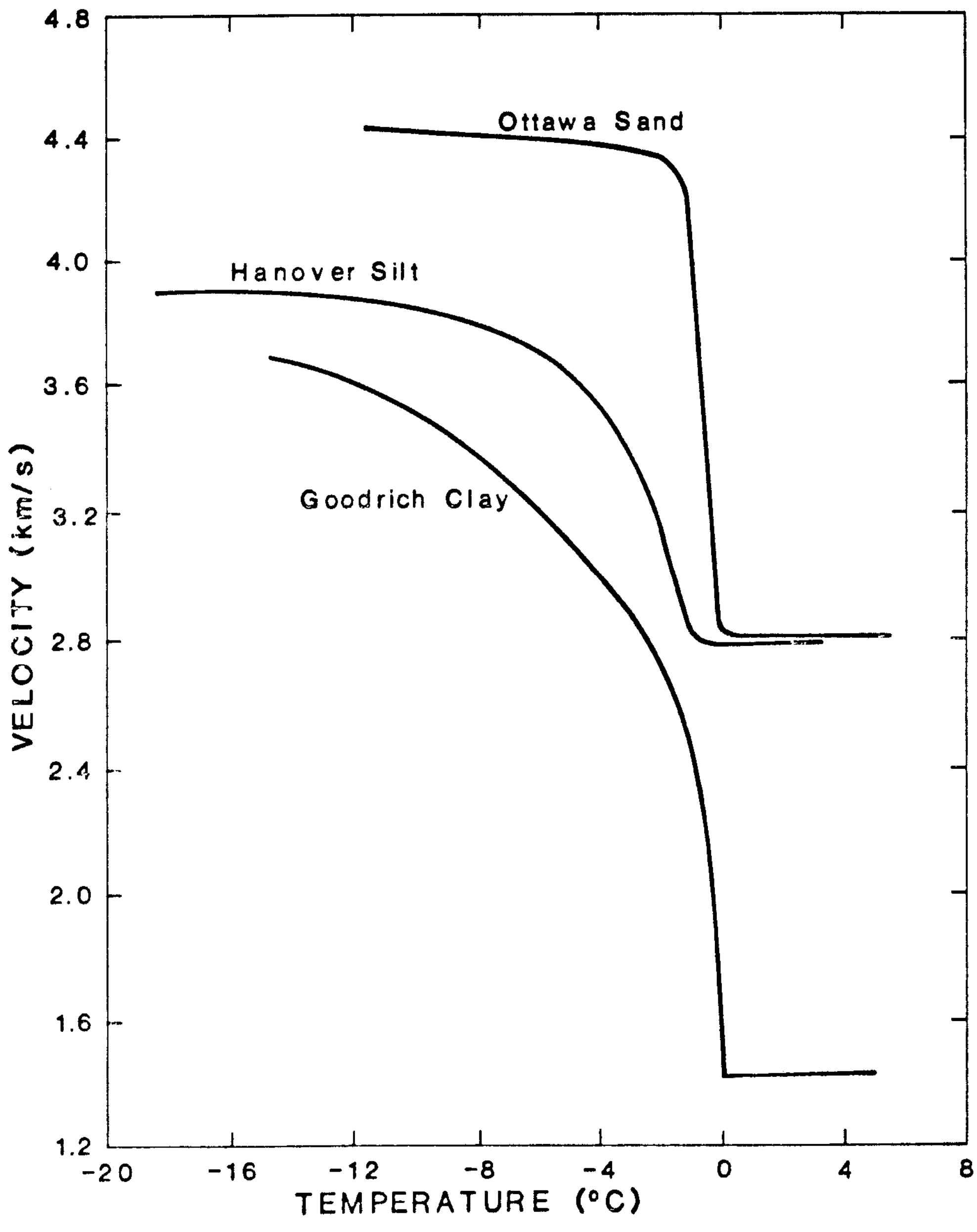

Figure 2.7 -- Compressional wave velocity vs. temperature under fully saturated conditions (after Nakano and Froula, 1973).

2.5 References

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2.6 List of Acronyms

FPD Freezing point depression
TPW Triple-point-of-water

3.0 THERMAL LOGS

3.1 Introduction

A thermal log is a record of temperature or temperature gradient vs. depth. The log can be discrete (i.e. values measured at specified depths) or continuous, and in digital or analog form. Thermal logs are very important in permafrost investigations because many of the problems associated with permafrost involve changes in permafrost temperatures. Permafrost is defined on the basis of temperature (< $0^{o}C$) and time (two years or more) so that the only sure way of detecting it is by measuring its temperature. Permafrost problems commonly include thawing, settlement, and erosion as a result of surface disturbance; creep, flow and fracture as a result of mechanical loading; and the presence and flow of groundwater. Some specific examples include loss of support for buried pipes, embankment settlement, and roadway or airfield cracking due to thaw consolidation; slope stability, creep of piles and foundations, and tensile and compressive forces on well casings; and formation of icings on roads and in buildings. Temperature measurements are necessary for evaluating these problems and for predicting whether or not they might occur in a proposed drilling or construction project. Permafrost temperatures are also useful in assessing its physical and mechanical properties and in investigating heat and mass transport processes within permafrost.

3.2 Methods and Instrumentation

A temperature measuring system consists of a thermal sensor, instrumentation for measuring the thermometric property of the sensor, a method for converting the thermometric property of the sensor to temperature and a method for calibrating the sensor. In addition, a borehole logging system requires a probe and cable.

3.2.1 Sensors

Sensors for permafrost temperature measurements include mechanical devices such as liquid-in-glass thermometers, Wise (1976); Osterkamp (1977), resistance devices (e.g., thermistors, resistance temperature devices or RTD's), voltage devices (e.g., thermocouples, integrated circuit devices), and others. Misener and Beck (1960) suggest the use of maximum thermometers for some temperature measurements in permafrost. Misener and Beck (1960), Robertson et al., (1966), Beck (1963), Raspet et al. (1966), Lachenbruch et al. (1962), Hansen (1963), Osterkamp (1970), Judge (1973), Reiter et al. (1980), Osterkamp and Harrison (1976), and Osterkamp (1984), have described a variety of methods using thermistor sensors. The use of thermocouples in permafrost temperature measurements has been described by Johnston (1963) and Jurick (personal communication, 1977). In recent years, thermistors have become the most widely used sensors for precision temperature measurements in permafrost and are used almost exclusively in logging apparatus (Osterkamp, 1985). Therefore, this section will focus on their use for permafrost temperature measurements.

Thermistors are small, rugged, reliable, and inexpensive sensors that can be calibrated to a high degree of precision. Close fitting interpolation equations exist for relating thermistor resistance to temperature (e.g., Steinhart and Hart, 1968). In addition, it is possible to make very precise resistance measurements under field conditions. Thermocouples are often used in multisensor cable installations where reliability and low cost are important and where high precision is not necessary. While other types of sensors could be useful in permafrost temperature measurements, there does not appear to have been any concerted effort to adopt them for this purpose.

Permafrost temperature measurements are usually made with a logging method or with multisensor cables permanently installed in a borehole. The drill hole may be open or cased; however, a cased hole is preferred. There is little danger of a logging cable becoming stuck and multisensor cables can be recovered and replaced when the hole is cased. However, some geotechnical applications preclude the use of a cased hole. With the logging method, a sensor is attached to the end of a cable which is lowered in increments or continuously down the drill hole. The thermometric property of the sensor is measured at selected depths or a continuous recording is made to determine the temperature. Care must be taken in the selection of thermistor sensors to ensure that proper time constants and heat dissipation constants are obtained and that the thermistors are compatible with the cable and measuring instruments. Guidelines for thermistor probe design show that the product of probe density, volume, and specific heat capacity should be minimized to minimize the probe time constant (Osterkamp, 1985). Logging cables are selected to minimize size, weight, and stiffness while avoiding large corrections for lead resistance. Three and four conductor cables eliminate the need for applying corrections for lead resistance.

3.2.2 Instruments

The instruments used for determining temperatures in permafrost are those generally used for measuring electrical resistances and the small voltages of a thermocouple. These include Wheatstone bridges, Kelvin bridges, digital voltmeters (DVM), digital multimeters (DMM), potentiometers, and a variety of electronic indicators. Some of these instruments are direct reading in temperature while others read only resistance or the emf which must be converted to temperature.

Bridges and potentiometers utilize the null method of measurement and are available as battery-powered, portable, precision measuring instruments. They usually have low temperature coefficients and can be sealed against moisture. A disadvantage is that they require manual balancing for each reading which is tedious and difficult to do for long periods of time under adverse ambient conditions. DVM's and DMM's are also available as battery-powered, portable, precision measuring instruments. Their digital readout does not require manipulation by the observer so that changes in readings can be conveniently monitored and recorded. However, these instruments appear to be more susceptible to malfunction in cold or wet environments. Consequently, bridges and potentiometers are usually used for the most precise temperature measurements in permafrost.

A more detailed discussion of instrumentation for temperature measurements in permafrost is provided by Osterkamp (1985).

3.3 Calibration

Calibration of a temperature sensor consists of a determination of values for its thermometric property at a number of known temperatures. A means for interpolating the values over the temperature range of interest and for converting these values to temperature is also required. Known temperatures are provided by fixed points or by comparison to temperature standards in a controlled temperature environment. Equations are available for converting thermometric values to temperature. Additional general information on the calibration of temperature sensors can be found in Benedict (1977), ASTM (1981), and Osterkamp (1985).

3.3.1 International Practical Temperature Scale -- 1968

Current temperature measurements in science and industry are based on the International Practical Temperature Scale of 1968 (IPTS-68) adopted by the International Committee of Weights and Measures (CIPM, 1969). IPTS-68 consists of a series of fixed points to which numerical values have been assigned and designated standard instruments and standard interpolation equations for defining the scale between the fixed points have been selected. The most important primary fixed point for permafrost temperature measurements is the triple-point of water (TPW), the equilibrium temperature between the solid, liquid and vapor phases of pure water at a pressure of 4.58 mm of mercury (TPW = 273.16°K = 0.0100°C). A specially constructed platinum resistance thermometer (PRT) is the standard interpolating instrument in the range of permafrost temperatures. Temperatures between fixed point temperatures are obtained from interpolation formulae which establish the relation between the resistance of the PRT and values of the IPTS-68 (CIPM, 1969).

There are several possible methods, based on the IPTS-68 for calibrating and maintaining the accuracy of a permafrost temperature measuring system. All methods rely on either fixed points or on a controlled temperature environment (usually a refrigerated liquid bath) with a standard thermometer for determining the temperatures.

3.3.2 Fixed Points and Comparison Methods

The only primary fixed point in the range of temperatures usually found in permafrost is the TPW defined as 0.0100°C. Several useful secondary points are shown in Table 3.1.

Table 3.1. Secondary reference points for the International Practical Temperature Scale -- 1968 (CIPM, 1969)

Sublimation point of carbon dioxide	-78.476°C
Melting point of mercury	-38.862°C
Ice point	0.000°C
Triple point of phenoxybenzene	+26.87°C
Melting point of gallium	+29.771°C

The ice-point (0.000°C) is an inexpensive and convenient fixed point for calibration purposes and for verifying calibrations in the field. It is also used extensively as the reference junction environment for thermocouple systems.

Detailed information for the preparation of ice baths and precautions in their use are found in Osterkamp (1985).

Permafrost temperature measuring systems can be calibrated to high accuracies using fixed point cells. The procedure involves a determination of thermistor resistances in several fixed point cells. An interpolation and conversion equation is then used with the constants in the equation determined by the known temperatures of the fixed points. The accuracy of the fixed point method can be better than 0.01°C.

The most common method of calibrating thermistors or other sensors of permafrost temperature measuring systems is by comparison to a standard thermometer in a well-stirred liquid bath. The accuracy of this method depends on the accuracy of the standard thermometer and the ability of the observer to bring the thermistor and the standard thermometer to the same temperature in the bath. Circulating controlled temperature baths are available that can maintain temperatures constant to ±0.01°C or better. Raspet et al. (1966) described a bath that could maintain temperatures constant to ±0.002°C.

The experimental procedure for calibration by comparison with a standard thermometer involves placing the standard thermometer and the thermistor in close proximity in a well-stirred, refrigerated, temperature-controlled bath. At each calibration temperature the reading of the standard thermometer and the resistance of the thermistor is obtained.

3.3.3 Conversion and Interpolation Methods

The calibration procedure for thermistors produces a set of calibration points which are the thermistor resistances and their corresponding temperatures. A method is needed to convert thermistor resistance to temperatures and to interpolate between calibration points.

Several equations describe the relationships between temperature and thermistor resistance (Robertson et al.,1966; Steinhart and Hart, 1968; Johnson, 1970; Judge, 1973). However, the relatively simple and precise equation of Steinhart and Hart (1968) is recommended over other equations. In this equation, the reciprocal of the temperature, in degrees Kelvin,

$$1/T = A + B \log R + C (\log R)^3, \qquad (3.1)$$

where A, B, and C are constants and R is the thermistor resistance at temperature T. Equation 3.1 has been tested against about one hundred other relationships and has been found to be consistently superior.

Steinhart and Hart (1968) have also shown that the best experimental strategy is to extend the calibration range beyond the range in which measurements are to be made. Extrapolation beyond the calibration range leads to rapidly deteriorating accuracy.

When three calibration points are available, Equation 3.1 can be used to algebraically determine the three coefficients, A, B, C, for each thermistor. If a greater number of calibration points are available, then a computer least squares fit algorithm can be used to determine the coefficients.

Once the coefficients have been determined, thermistor temperatures can be calculated directly using Equation 3.1. Alternatively, when less accuracy is required, a graph or a table of thermistor resistances vs. temperatures can be produced using Equation 3.1. Robertson et al. (1966) have developed a procedure involving interpolation of tabulated resistance and temperature values which allows temperatures to be determined to a certainty of $0.01^{o}C$.

3.4 Interpretation

3.4.1 Data Reduction

The measured temperature data consist of a set of thermistor resistances and depths and the times at which they were measured. A number of corrections are necessary to obtain the true in situ temperature profile. Depth measurements are usually made with respect to a convenient reference depth (e.g., the top of the casing), however, the usual datum is the ground surface. This correction requires only a simple subtraction of the height of the reference point above the ground surface from the measured depths. Corrections for cable stretch are not required when using a cable counter, but the depth going down the hole should be compared to the depth obtained coming out of the hole, and corrections should be applied for any discrepancy caused by the cable slipping through the metering system.

For precise work the measured resistance values should be corrected for instrument drift, temperature coefficient of the instrument, effects of temperature gradients on the instrument, etc. If a very low temperature coefficient resistor is used as a standard, by measuring it at the time of calibration and then again at the time of the field measurements, then corrections can be made for instrument error.

If the calibration procedure eliminates the effects of cable resistance (as with 3 or 4 terminal measurements) and the same method is used in the field, then no additional correction for cable resistance variation with temperature is necessary. There is an error involved when using two-conductor cables; however, when the cables are short (30 m or less) the error is small.

When the above corrections have been applied to the raw data, the corrected thermistor resistances can be converted to temperatures using Equation 3.1. The resulting measured temperature profile is the in situ profile.

The in situ profile may not be the equilibrium profile because of the thermal disturbance associated with drilling which may require a long period of time to dissipate. Lachenbruch and Brewer (1959) have shown that the borehole and thermal disturbance of drilling can be treated as a continuous line heat source. The axial temperature due to a constant heat source Q applied for a time, s, is

$$T = T_o + \frac{Q}{4\pi K} \ln \left(\frac{t}{t-s}\right) \qquad (3.2)$$

where T_o is the initial temperature in the permafrost, K is the thermal conductivity, t is the time measured from the start of drilling and s is the time required for drilling to a given depth. It follows from Equation 3.2 that if the drill hole temperature, T, at some depth, is graphed with ln [t/(t-s)], then a straight line with intercept T_o (the temperature before drilling) should result. Additional details and examples are given in Lachenbruch and Brewer (1959).

Ground surface temperature disturbances (water bodies, roads, buildings, etc.) and topographical changes may distort the temperature profile by lateral heat flow and changes in surface temperature. For some purposes (e.g. heat flow measurements), it is desirable to correct the temperature profile to a flat earth condition with no surface disturbances. Lachenbruch (1968) and Gold and Lachenbruch (1973) describe the methods.

When the in situ equilibrium temperature profile has been corrected for surface and topographical disturbances, then the resulting profile can be used for a variety of thermodynamic calculations and can be directly compared to other corrected equilibrium temperature profiles.

3.4.2 Analyses

The analyses of temperature profiles in permafrost are complex tasks and only an outline of the methods can be given here. For additional details the reader should consult the references.

Permafrost is defined on the basis of temperature ($< 0^oC$) and time ($>= 2$ years). Therefore, a determination of its presence or absence requires temperature measurements for two years or more. In practice, inspection of one equilibrium temperature profile is all that is normally used. This procedure works well because ground temperatures, particularly below the depth of annual freezing, change very slowly with time. Problems arise near the permafrost table where temperatures must be monitored for a two year period to determine whether permafrost is present or absent and its level in the ground. Problems can also arise when the temperature data are of low accuracy. For example, permafrost warmer than -0.5^oC is common in the interior of Alaska and, using measurements with an accuracy of $\pm 0.5^oC$, it would be difficult to decide on the presence or absence of this permafrost. More accurate measurements are needed in these cases.

Figure 3.1 is an example of temperature profiles in warm permafrost. The ice-bearing permafrost base at a depth of approximately 25 m can be determined from the equilibrium temperature profile obtained after the drilling disturbance has dissipated. However, consider the profile measured eight days after drilling. It demonstrates that the approximate depth to the ice-bearing permafrost base, 25-26 m, can also be determined very soon after drilling from the change in slope of the temperature curve as it passes through the base of the ice-bearing permafrost. The reason is that as long as there is any ice, the temperature around the drill hole must remain at the melting point of the ice-water-soil mixture. The position of the permafrost table (its top surface) is more difficult to determine from these temperature data. It is usually obtained from an actual physical probing of the soil with a rod and from temperature measurements made during late summer or early fall.

Temperature gradients can be obtained directly from the temperature profiles. This determination is best made with an equilibrium temperature profile. However, Lachenbruch and Brewer (1959) have shown that, in a very disturbed hole, the gradient defined by a least squares line, 67 days after the completion of drilling, was only 5 per cent greater than the probable equilibrium value. At this time, the measured temperatures were still about 2^{o}C greater than the equilibrium value.

The mean annual ground surface temperature (MAST) is obtained by extrapolating the lower linear portion of the equilibrium temperature profile to the surface. For example, the permafrost in Figure 3.1 has a MAST of about -0.7^{o}C. The relationship between mean annual air temperature (MAAT) and MAST is not usually known. It is difficult to determine because of surface effects (e.g., snow cover, vegetation) and the presence of the active layer. In addition, the numerical modeling results of Goodrich (1978) suggest that the effect of a snow cover and the active layer may be to displace the true MAST from the extrapolated value.

Permafrost thicknesses, determined by the position of the 0^{o}C isotherm, do not usually correspond to the thicknesses of ice-bearing or ice-bonded permafrost which may be up to 60 m (200 ft) less than the permafrost thicknesses on Alaska's North Slope (Osterkamp and Payne, 1981).

Figure 3.1 shows that the equilibrium temperature, T_o, is approximately -0.12^{o}C at the base of the ice-bearing permafrost at this site. At this depth, $T_p \cong 0.02^{o}$C, and, therefore, the sum of T_c and T_s must be $\cong 0.10^{o}$C. However, information on the solute type and concentration or on T_s are not available to help separate chemical and soil particle effects at this site.

Gold and Lachenbruch (1973) have shown that, for saturated materials, the water content (volume fraction), for permafrost in equilibrium with the climate, is

$$\phi = 0.72 \ln \left(\frac{G_t}{G_f}\right) \qquad (3.3)$$

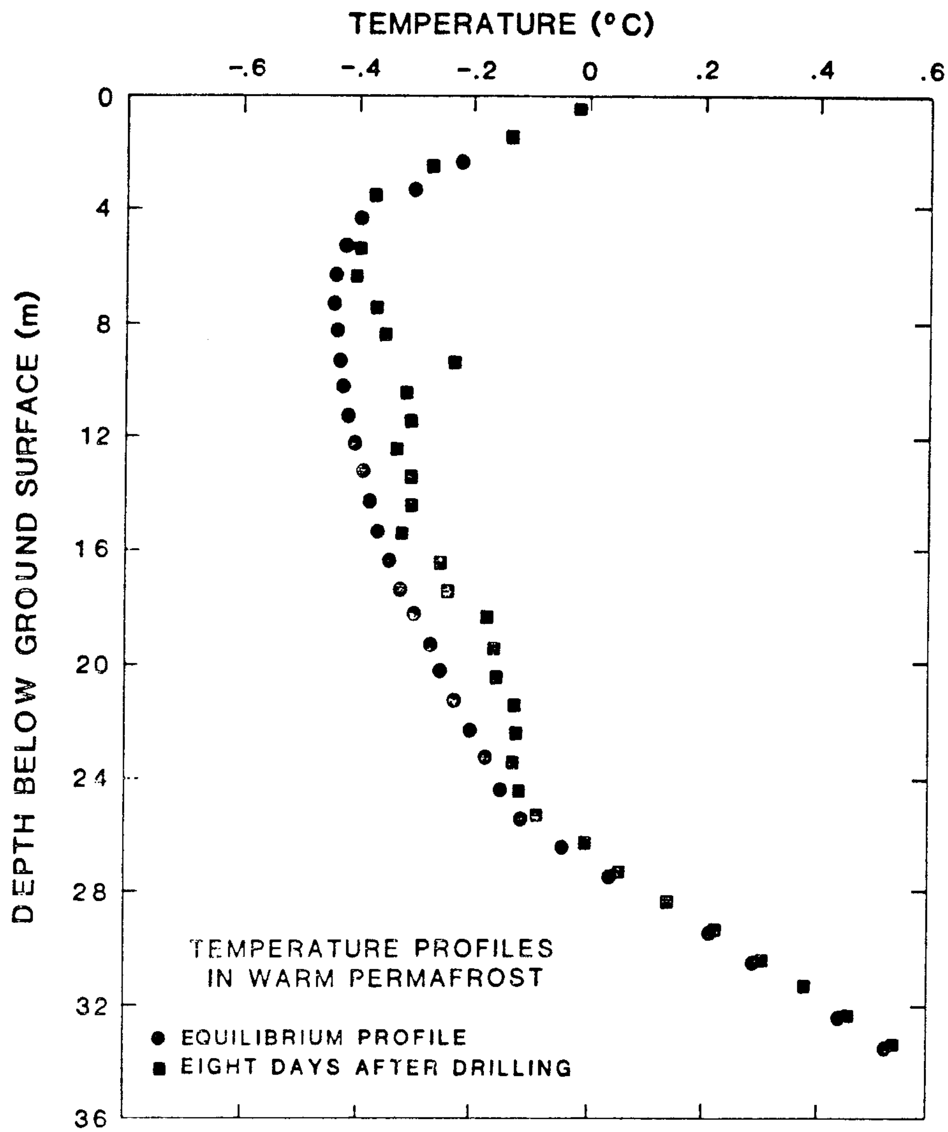

Figure 3.1 -- Temperature profiles in warm permafrost (after Osterkamp, 1985).

where G_t and G_f are the geothermal gradients in the thawed soil under the permafrost and in the permafrost, respectively. This condition probably holds for most of the deeper permafrost on Alaska's North Slope (Lachenbruch et al., 1982) but not for some of the discontinuous permafrost south of the Brooks Range (Osterkamp, 1983). Since the geothermal gradients are related to the thawed and frozen thermal conductivities, then

$$\frac{K_f}{K_t} \approx 4^{\phi}. \tag{3.4}$$

Gold and Lachenbruch (1973) also provide other relationships of the thermal conductivity and thermal diffusivity to ϕ.

If the thermal properties of the thawed and frozen material are known (e.g. from direct measurements) then the heat flow into the base of the permafrost and in the permafrost can be determined from the heat conduction equation.

$$Q_t = -K_t\ G_t \tag{3.5}$$

and

$$Q_f = -K_f\ G_f \tag{3.6}$$

where Q_t and Q_f are the heat fluxes in the thawed and frozen material, respectively, K_t and K_f are the corresponding thermal conductivities, and G_t and G_f, the geothermal gradients.

The preceeding paragraphs briefly describe some of the analyses that can be applied to permafrost temperature profiles. Another large class of analyses, that will not be included here, involve the application of the theory of heat conduction to permafrost. This is possible because the ice in the pore spaces of permafrost prevents the transport of matter (water or moisture) which ensures that the heat transport will be primarily conductive. This fact has been exploited by investigators to determine the effects of natural processes and anthropogenic activities on permafrost (Gold and Lachenbruch, 1973).

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3.6 List of Acronyms

ASTM	American Society for Testing and Materials
CIPM	International Committee on Weights and Measures
DMM	Digital multimeter
DVM	Digital voltmeter
IPTS	International Practical Temperature Scale
MAAT	Mean annual air temperature
MAST	Mean annual ground surface temperature
PRT	Platinum resistance thermometer
RTD	Resistance temperature device
TPW	Triple-point of water

4.0 ELECTRIC LOGS

Electric logs are records of electrical potentials, either natural earth potentials, or potentials that are artificially produced by electric current applied to the rock near the borehole. These logs are made to investigate the electrical properties of the formation which reflect its physical and lithologic characteristics. The electrical properties of earth materials and the fundamentals of electric logging are described by Keller and Frischknecht (1966).

4.1 Self Potential (SP) Logs

SP logs are galvanic contact-type electric logs that measure the natural potentials that exist in boreholes filled with conductive fluid (water or drilling mud). These logs are made with a passive probe containing only one electrode, and a surface electrode grounded near the hole collar. They require conductive fluid in the borehole, and they cannot be made in cased holes. SP logs record the electrical potential that exists between the probe electrode and the reference ground electrode. A general discussion of the sources and the meaning of SP anomalies is given by Pirson and Wong (1972).

4.1.1 Principles

SP is largely electrochemical in origin, being generated by the difference in the concentration and type of ions in the borehole fluid and in the pore fluid of the formation. A secondary source of SP is electrokinetic potential, or streaming potential, that is generated by the flow of borehole fluid into the formation, or by the flow of pore fluid from the formation into the borehole in response to a difference in fluid pressure between the two. A third source of SP, the redox potential, is generated between two fluid-filled media that have different oxidation-reduction potentials. All of these sources of SP are additive and cannot be distinguished from one another on the basis of the SP log alone.

4.1.2 Methods

Because the SP measurement is so simple, requiring only two electrodes, one electrode on the probe, the other at the ground surface (both usually made of lead), and a dc (direct current) voltmeter to measure the potential between them, SP is usually combined with some other electric logging measurement (single-point resistance, resistivity, or IP) which also uses electrodes that make electrical contact with the borehole fluid. In practice, the same electrode used to pick the potential for one of these other measurements is commonly used to detect SP. Since SP is a slowly varying dc potential and the other logging potentials are represented by fixed frequency square-wave or sine-wave signals, the two signals can be separated by a simple R-C (resistance-capacitance) filter.

4.1.3 Calibration

Calibration of the SP log can be accomplished in the field with a dc voltage source that is connected to the two electrodes and is switched to various positive and negative levels to check the SP measurement ranges for accuracy and linearity over a typical maximum range of -1000 to +1000 mV.

Internal electronic adjustments are made, if necessary, to make the measured potentials correct.

4.1.4 Interpretation

SP logs are usually recorded with a floating or unknown position of zero potential because of electrode polarization and electrochemical effects in the vicinity of the surface ground electrode that produce potentials of undeterminable polarity and magnitude. An artificial offset voltage of arbitrary value is applied to counteract these potentials to bring the recorded SP on scale. In order to make measurements of SP quantitative, a reference level of potential, known as the 'shale base line' is established by the log analyst at the most negative excursions of the log trace. The shale base line represents the SP generated by thick, pure shales which generally give about the same SP response regardless of depth or geologic formation. Positive SP deflections referenced to the shale base line generally represent sandy shale, sandstone, or carbonate rocks. These deflections, measured in mV, are related to the resistivity of the mud filtrate (measured on a sample of fluid squeezed from the drilling mud) and the resistivity of the formation water by

$$SP = -K \log \frac{R_{mf}}{R_w} \qquad (4.1)$$

where SP = SP log deflection, mV,

K = constant for liquid-liquid junction potential for saline solutions of different concentrations and different ions species; for NaCl solutions, K = 64.3 + .239 TC, TC = temperature, ^{o}C, (K = 60 + 0.133 TF, TF = temperature, ^{o}F),
R_{mf} = mud filtrate resistivity, ohm-m,
R_w = formation water resistivity, ohm-m.

Equation 4.1 can be solved for R_w (which is a parameter required for estimating porosity from resistivity logs) by graphic methods (Schlumberger Well Surveying Corp., 1966) or by numerical methods and charts based on the concept of the formation factor (Pirson, 1963; Schlumberger Ltd., 1979; Schlumberger Well Services, 1985)

$$F = R_o/R_w \qquad (4.2)$$

where F = formation factor,

R_o = formation resistivity, ohm-m,
R_w = formation water resistivity, ohm-m,

and Archie's formula (see also Section 2.3) for saturated formations,

$$F = a\ \phi^{-m} \tag{4.3}$$

where a = empirical constant, approximately 1,
m = empirical exponent, approximately 2,
ϕ = fractional porosity of the formation.

Equation 4.2 and 4.3 can be combined to form Archie's law:

$$R_o = a\ R_w \phi^{-m} \tag{4.4}$$

which applies to formations that are completely saturated with water. In partially saturated formations the following formula can be used to estimate the bulk resistivity of the rock.

$$R_o = a\ R_w \phi^{-m} S_w^{-n} \tag{4.5}$$

where S_w = fraction of total pore space occupied by pore water,
n = empirical constant, approximately 2.

Equation 4.5 is a generalized form of Equations 2.14 and 2.15 introduced in Section 2.3.2. These equations are valid in rocks that have low clay content, such as clean sandstones, limestones, and most igneous rocks. However, rocks that contain significant amounts of clay minerals behave in a nonlinear way because of the double-layer of ions that form around wetted clay minerals. A number of semi-empirical formulas with additional terms have been developed to take this effect into account, although at the present time most of them are controversial. A discussion of this so-called shaly-sand problem, and a comparison of the various formulas is given by Worthington (1985).

Before SP deflections can be used to estimate the porosity of low-clay rocks, corrections must be applied for the effects of formation temperature, thin beds, and invasion (Schlumberger Ltd., 1979; Schlumberger Well Services, 1985).

4.1.5 Special Problems

SP logs record natural potentials that are primarily caused by electrochemical reactions between the fluid in the borehole and the fluid in the formation. In permafrost, where the water in the formation is partially or totally frozen, these reactions are sometimes abnormal, causing the SP log to show variations that cannot be repeated from run to run, and that appear to be unrelated to lithology. In some cases, however, the SP log shows a negative drift when going from unfrozen to frozen sections of the formation, and this effect can be used to identify the permafrost boundary (Desai and Moore, 1968). Freezing potentials that could cause interpretation problems may also exist at phase boundaries in permafrost (Hanley and Rao, 1981).

4.2 Resistance and Resistivity Contact Logs

Galvanic contact resistivity logs (in contrast to non-contacting induction logs) are made with probes containing one or more electrodes that make electrical connection with the wall rock either through the fluid in the borehole (water or drilling mud), or by direct contact through scratcher or roller electrodes. Probes designed to make electrical contact with the borehole fluid cannot be used in holes that contain air, oil-base mud, or any other type of non-conductive borehole fluid. Probes that contain scratcher or roller electrodes can be used to obtain resistance and resistivity logs in dry holes (Dakhnov, 1959; Casey et al., 1958; Snegirev, 1983). Neither type of probe can be used in holes that contain metallic or plastic casing because it interferes with the flow of electrical current between the probe and the formation. A general discussion of galvanic contact electric logs is given by Keys and MacCary (1971).

4.2.1 Principles

An electrical current of known and constant value is applied to two electrodes, at least one of which is located on the downhole probe. The other electrode is sometimes located on the logging cable above the probe or at the ground surface near the hole collar. The source current is generally a square wave or sine wave of low frequency, typically in the range 1 to 100 Hz. The current flows into the formation through the borehole fluid or through the scratcher-roller electrodes, generating an electrical potential that can be detected by two other electrodes, at least one of which is also located on the probe.

The single-point resistance log is a special case in which only two electrodes are used; one on the probe and the other at the ground surface. The electrical potential measured between the two electrodes is proportional to electrical resistance between them when the applied current is held constant, as shown by Ohm's law:

$$E = IR \qquad (4.6)$$

where E = potential,
I = current,
R = resistance.

The objective of the single-point resistance measurement is to detect variations in the electrical resistivity of the formation. However, single-point resistance logs are also affected by the contact resistance at the electrodes, by the resistivity of the borehole fluid, and by variations in the diameter of the borehole, all of which are undesirable because they produce anomalies that can be misinterpreted as formation effects. In general, multiple-electrode resistivity logs are more useful than single-point resistance logs because they are relatively free of these undesirable effects, and therefore they provide a better representation of the variation of electrical properties of the formation that reflect lithologic changes. However, single-point resistance logs have one special advantage over resistivity logs; they have very sharp depth resolution and can be used to pick lithologic bed boundaries to an accuracy of 13-25 cm (5-10 in), whereas resistivity logs show a gradational change over distances of 30 cm (12 in) or more in the vicinity of bed boundaries. Furthermore, single-point logs are useful for making stratigraphic correlations between boreholes in areas where geologic formations are continuous.

Resistivity logs record the apparent resistivity of rock near the borehole in units of ohm-meters. Resistivity is a physical property of a material that is independent of shape and size, and is related to resistance much as bulk density is related to weight. Although resistivity logs are affected adversely by variations in hole diameter, by flushing of permeable rocks near the borehole, by invasion of borehole fluid into the formation, and by adjacent beds with sharply contrasting resistivities, corrections can be applied to reduce errors from these sources by use of charts or computer algorithms (Schlumberger Ltd., 1979; Schlumberger Well Services, 1985; Scott, 1978). In the case of unfocused resistivity logs made with four electrodes, the apparent resistivity is

$$R_a = \frac{E}{I} \cdot \frac{4\pi}{1/AM - 1/BM - 1/AN + 1/BN} \qquad (4.7)$$

where R_a = apparent resistivity, ohm-m,

E = potential measured between electrodes M and N, volts,
I = current applied to electrodes A and B, amperes,
AM = spacing between electrodes A and M, meters,
BM = spacing between electrodes B and M, meters,
AN = spacing between electrodes A and N, meters,
BN = spacing between electrodes B and N, meters.

For the normal electrode configuration (described below) this formula simplifies to:

$$R_a \approx \frac{E}{I} \cdot 4\pi AM \qquad (4.8)$$

because all of the electrode spacings other than AM effectively approach infinity (considered to be 10 to 20 times the spacing AM).

Focused resistivity logs use auxiliary electrodes above and below the measuring electrode to focus the measuring current into the formation in the form of a horizontal sheet ranging in thickness from 8 to 30 cm (3 to 12 in). This sheet of current does not spread out significantly until it has penetrated several feet into the formation. The apparent resistivity determined by focused resistivity logs is related to measured E/I by an empirical geometry factor that is a function of electrode size and configuration (Pirson, 1963). The geometry factor for focused logs can be estimated by use of physical models or approximation formulas (Keller and Frischknecht, 1966).

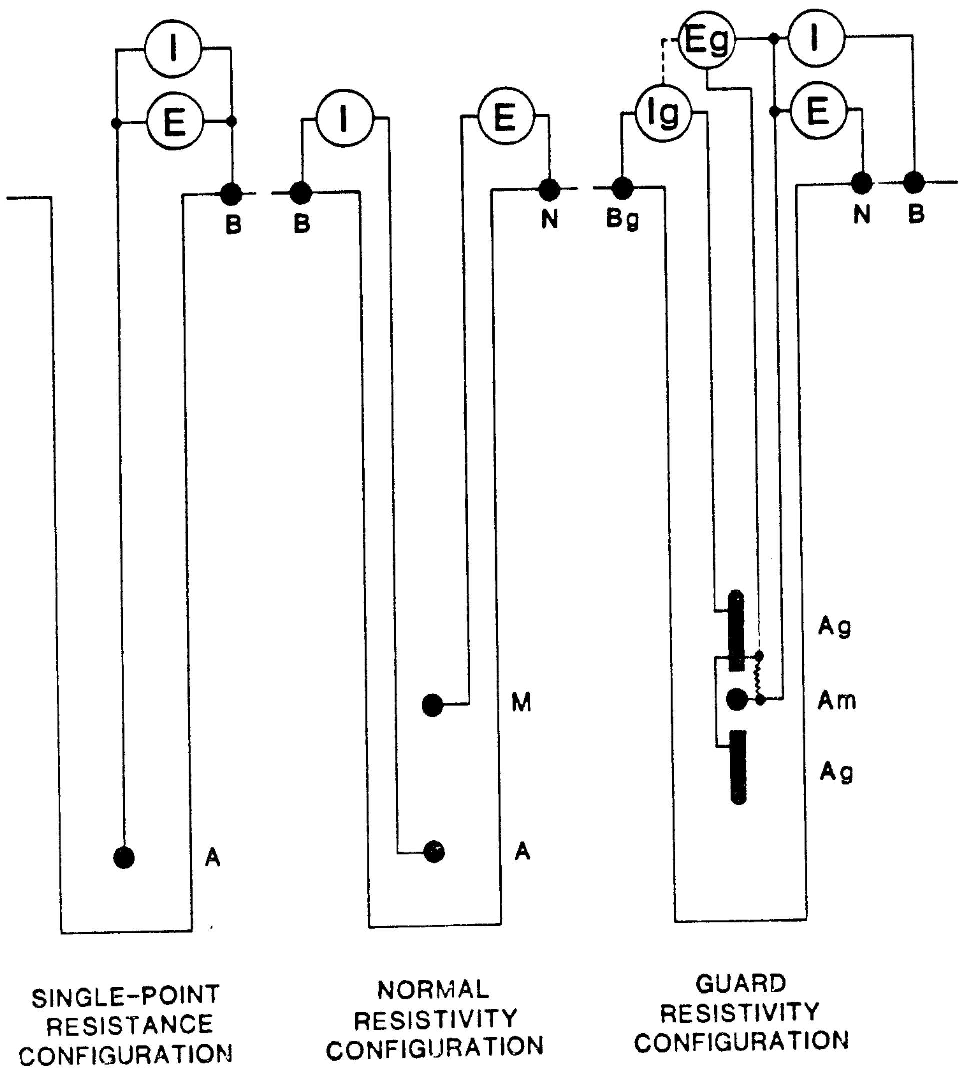

Figure 4.1 -- Electrode configurations used to make resistance and resistivity logs. Current electrodes are labeled A and B, potential electrodes are labeled M and N. The current source is labeled I, and the potential measurement circuit is labeled E. In the guard configuration, the guard electrode current source is labeled Ig, and the amount of current fed to the guard electrodes is controlled by a feedback circuit (dashed lined) which keeps the voltage Eg between electrodes A and A_m as close to zero as possible. The measurement current source, I, is held constant, producing the measurement voltage E.

4.2.2 Methods

Three configurations of electrodes that are commonly used to measure electrical resistance and resistivity are shown in Figure 4.1. The single point resistance configuration is the simplest in terms of probe construction and electronic circuitry, consisting of a passive probe (probe containing no electronic circuitry) with only one electrode (the other electrode being grounded at the surface near the hole collar), and a control module that is essentially a low-frequency ac (alternating current) ohmmeter. Depth of investigation is approximately equal to five times the diameter of the electrode on the logging probe, which is usually 2.5 to 5 cm (1 to 2 in), making the depth of investigation 13-25 cm (5 to 10 in). The vertical resolution is approximately the same as the depth of investigation.

The normal configuration, which is commonly used to make unfocused resistivity logs, is also rather simple, requiring a passive probe containing only two electrodes and a control module that provides a source of constant current, a potential-measuring circuit, and a rectified dc output. If the source current is a square wave, rectification of the potential signal is usually synchronized with the source waveform to reduce noise and improve measurement accuracy. Two electrode spacings are commonly used to make normal logs, 41 and 163 cm (16 and 64 in), called short and long normals. Logging measurements using these two spacings can be made simultaneously by use of a probe containing one current electrode 'A', and two potential electrodes, 'M_1' and 'M_2' spaced 41 and 163 cm (16 and 64 in) away from the 'A' electrode, respectively. The depth of investigation is approximately equal to the electrode spacing, AM, so that logs made with two electrode spacings, provide resistivity data at two depths of investigation and two levels of vertical resolution, also approximately equal to the electrode spacings. The short normal spacing gives sharper depth resolution, and is therefore preferable to the long normal spacing for picking bed boundaries. However, the long normal log gives apparent resistivity values that are closer to the true resistivity for thick beds (beds that are 10 times the electrode spacing AM) because it has a greater depth of investigation, and is therefore less affected by borehole conditions (e.g., anomalous resistivities associated with the borehole fluid, the flushed zone, and the invaded zone). If a resistive bed is thinner than the electrode spacing of the normal configuration probe, then the apparent resistivity measured between the bed boundaries is severely distorted and cannot be used to estimate true resistivity (Keller and Frischknecht, 1966).

Focused resistivity logs (guard, laterologs, and spherically focused logs) are more complex than other resistivity logs, and are made with probes equipped with 3 to 9 electrodes and downhole electronic circuitry. However, some focused logs, particularly the guard log, combine the best attributes of the single-point and the normal log configurations; sharp bed definition and a quantitative measurement of formation resistivity. Furthermore, the apparent resistivity that is measured by the focused log is generally much closer to true resistivity than the resistivity measured by the normal configuration log. Hence, corrections for borehole conditions are smaller, and the final result is more accurate. Focused resistivity logs are particularly useful when the borehole fluid is highly conductive, a condition that adversely affects both single-point resistance logs and unfocused resistivity logs by providing a path of low resistance up the borehole, causing a significant corrections include probe electrode diameter, hole diameter from a caliper log, and mud resistivity measured on a sample of drilling mud. In porous, permeable rocks it is necessary to apply corrections for anomalous resistivities in the flushed zone and in the invaded zone. These parameters can be determined by measuring the resistivity of filtrate squeezed from a mud sample, and by interpreting micro-focused resistivity logs. The effects of bed thickness and adjacent beds can also be taken into account by the use of charts or computer algorithms. In the third stage of interpretation, the estimated values of true resistivity are related to lithology by a knowledge of the resistivities of formations in the area, and by reference to other geophysical logs (gamma ray, SP, etc.) or to geologists' logs based on drill core or cuttings. Ranges of resistivity for various types of saturated, unfrozen rock and soil are given for various geologic ages in Table 4.1. It should be noted that in permafrost environments, the resistivity of frozen rock and soil may increase several orders of magnitude above the values given for unfrozen rocks in Table 4.1 (see Table 2.1). Finally, the porosity of unfrozen formations and the volume fraction of unfrozen water in partially frozen formations can be estimated by using Archie's law with the interpreted values of true resistivity, and the value of resistivity of formation water determined from the SP log (see Section 4.1.4). It should be noted that in permafrost environments the SP log cannot be used reliably to determine the resistivity of formation water.

4.2.5 Special Problems

There are practical and operational problems associated with making resistance and resistivity logs in permafrost. In shallow investigations, the holes are usually augered or drilled dry to avoid thermally disturbing the permafrost, and probes with scratcher or roller electrodes are used to make electrical contact with the formation. The surface of the ground may be solidly frozen, making it difficult to make good electrical contact with the surface ground electrodes (Snegirev, 1983). In deep investigations, holes may have to be cased to prevent unconsolidated material from caving when warm drilling fluid melts the ice that gives it strength. If caving occurs in uncased holes, as it often does in permafrost zones in poorly consolidated rock, the hole diameter may become so large that corrections can not be made by use of standard charts and computer algorithms, and so the true resistivity of the formation cannot be accurately estimated (Petersen et al., 1985). It is important to run a caliper log along with the resistivity log to detect zones of enlarged hole diameter that may severely limit the accuracy of the interpretation.

4.3 Induction Logs

Induction logs measure the resistivity of rock and soil adjacent to the borehole without making galvanic electrical contact with the borehole fluid and the formation. Therefore, they do not require conductive fluid in the borehole, and can be run in dry holes and in holes containing any type of fluid (oil-base drilling mud, conductive mud, or water). They can also be run in holes lined with plastic casing. They are effective in making quantitative measurements of formation resistivity as long as the resistivity is not too high. The accuracy of the measurement decreases rapidly as the apparent resistivity increases above 100 ohm-meters, and becomes practically meaningless above 1000 ohm-meters. A general description of various types of induction logs is given by Pirson (1963).

4.3.1 Principles

Induction logging probes contain transmitting and receiving coils, at least one of each, which produce and detect sinusoidal electromagnetic fields of relatively high frequency (20-50 kHz). The transmitted electromagnetic signal produces eddy currents in the formation that flow in circular loops in planes perpendicular to the axis of the probe. These ground currents create a magnetic field that is sensed by the receiving coil in the probe. The strength of the magnetic field is proportional to the conductivity of the formation through which the currents flow. Therefore the amplitude of the signal that is detected by the receiving coil is a measure of formation conductivity, which is recorded on the induction log in units of mhos/meter. Since resistivity is the reciprocal of conductivity, resistivity can be computed and plotted on the same log in units of ohm-meters which are more familiar and meaningful to most log analysts.

4.3.2 Methods

Several different coil configurations, ranging from simple two-coil to complex six-coil systems have been developed by well logging service companies. Two of these configurations are shown in Figure 4.2. Although two coils are adequate for making the basic induction measurement, the additional coils are effective in focusing the response of the tool to minimize the adverse effects of anomalous resistivities in the borehole and in the flushed and invaded zones, and to reduce errors in the apparent thickness and resistivity of high resistivity formations caused by the presence of adjacent beds with low resistivities. Two different spacings of the basic transmitter-receiver coil pair are commonly used, 69 and 102 cm (27 and 40 in), which provide two depths of investigation and two levels of vertical resolution. The depth of investigation of induction logs varies with the resistivity of materials in the zone of measurement (borehole fluid, flushed zone, invaded zone, and undisturbed formation), increasing if resistivities are high, and decreasing if they are low, but typically ranging from 2 to 5 times the spacing of the main transmitter-receiver coil pair. This results in depths of investigation of about 1.4-3.4 m (4-11 ft) for the shorter coil spacing, and about 2-5 m (7-17 ft) for the longer spacing. Because of its deep penetration, the 102 cm (40-in) spacing log, commonly called the ILd log, has been found to be particularly advantageous for evaluating permafrost lithologies (Osterkamp and Payne, 1981; Petersen et al., 1984).

4.3.3 Calibration

Calibration can be accomplished in the field with test loops of copper tubing that are placed around the sensing coils before the probe is run in the borehole. The loops are designed to represent specific values of formation conductivity. A calibration point representing zero conductivity is obtained by hanging the probe in air above the ground and away from any metal objects that might produce conductive anomalies.

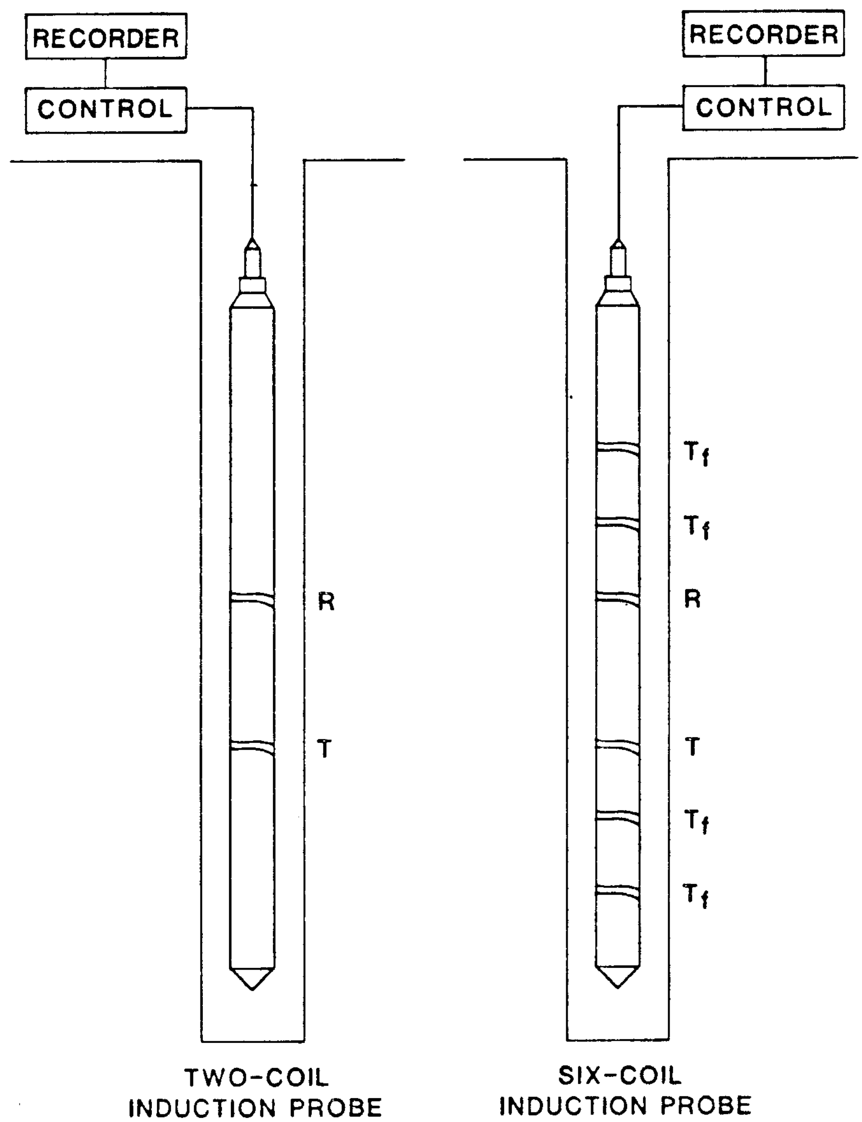

Figure 4.2 -- Coil configurations used to make induction logs. Receiver coils are labeled R, transmitter coils are labeled T. The coils labeled T_f in the six-coil induction probe are auxiliary focusing coils.

4.3.4 Interpretation

Induction logs are interpreted in three stages. First, the logs are scanned to locate zones of special interest that are selected for quantitative interpretation. Second, departure curves or computer algorithms are used to make corrections for the effects of hole diameter measured by the caliper logs, bed thickness, and the resistivity of borehole fluid and adjacent beds (Schlumberger Well Surveying Corp., 1966; Schlumberger Ltd., 1974, 1979; Bateman and Konen, 1977). Third, the corrected values of resistivity are related to lithology by knowledge of the resistivities of formations in the area, taking into account the effects of permafrost that cause the resistivities of frozen rock and soil to increase.

4.3.5 Special Problems

The response of induction logs to formation resistivity is nonlinear and relatively inaccurate for resistivities greater than 100 ohm-meters (Snegirev, 1983). In permafrost environments, where resistivities commonly exceed 100 ohm-meters, induction logs may give only semi-quantitative results. However, these logs have the advantage over contact-type electric logs of being usable in dry holes, in holes filled with oil-base mud, and in holes lined with plastic casing. Under these conditions they may provide useful information on formation resistivity even if this information is only semi-quantitative. Induction logs that do not penetrate deeply into the formation may be uninterpretable in zones where the borehole is enlarged by caving (Petersen et al., 1985).

4.4 Dielectric Constant Logs

Dielectric constant logs are similar to induction logs in that they are made with probes containing coils that transmit and receive high-frequency electromagnetic energy. However, the operating frequency of dielectric constant probes (25-1100 MHz) is several orders of magnitude higher than that of induction probes (20-50 kHz). At these high frequencies the transmitted wave reaches the receivers by propagation rather than by induction, and the signal is affected by the dielectric constant of the formation as well as by its conductivity. The development of dielectric constant logs was motivated by the large difference between the relative dielectric constant of water (about 80) and that of oil (2-4), and by the difficulty in distinguishing oil-bearing formations from those containing low-salinity water by use of conventional induction logs (Dresser Atlas, 1981). The dielectric constant log is considered potentially useful in permafrost environments because of a similarly strong contrast between the relative dielectric constant of water and that of ice (80 and 3-4, respectively). The dielectric constant of ice depends on temperature and measurement frequency, but at frequencies of 60 kHz and greater, it ranges from about 3 to 4 for all temperatures (Keller, 1966). A general discussion of the principles of dielectric logging is given by Poley et al. (1978).

4.4.1 Principles

The dielectric constant of rock and soil measured at high frequencies is primarily a function of fluid content (dependent on porosity in saturated rock), fluid type (oil or water), and if it is water, whether it is frozen or liquid. The relative dielectric constant of the rock matrix is much lower than that of water, ranging from 4-6 for sandstones to 7-11 for carbonates (Cox and Warren, 1983), so that the rock matrix has only a secondary effect on the measured dielectric constant. Because the frequency of electromagnetic energy used to make dielectric logs is very high, the depth of investigation is very small, 2.5-38 cm (1-15 in), and therefore the measurement is subject to the effects of anomalous conditions close to the borehole, such as rugosity, mudcake, fluid invasion, and in the case of permafrost, the possible presence of a thawed zone and caving.

4.4.2 Methods

Dielectric constant logs are made with probes containing one or two transmitter coils and two receiver coils. Coil spacing depends on the measurement frequency, and ranges from a few cm or a few inches for the Schlumberger tool which operates at 1100 MHz, to about a meter (3 ft) for the Dresser Atlas tool that operates at 47 MHz. The Schlumberger tool uses a wall-contact pad that contains two transmitter coils and two receiver coils, that are pressed against the borehole wall to increase penetration of the signal into the formation. Because of the very high frequency of the Schlumberger tool, the depth of investigation is only a few cm (an inch or two) and the attenuating effect of high-conductivity material close to the pad may make the signal too weak to produce reliable data (Shen et. al., 1984). The Dresser Atlas tool is less sensitive to borehole conditions because it operates at a lower frequency and uses larger coil spacings of 79 and 99 cm (31 and 39 in) between a single transmitter coil and two receiver coils on a conventional sonde (not a wall-contact pad). The depth of investigation of the Dresser Atlas tool is about 38 cm (15 in). Both systems measure the amplitudes of the signals picked up by the two receivers and the phase difference between them. These basic measurements are converted to propagation time and attenuation in the case of the Schlumberger log, and to relative dielectric constant and resistivity by the Dresser Atlas system.

4.4.3 Calibration

Dielectric constant logging systems can be calibrated by use of test tanks filled with water having different salinities (Cox and Warren, 1983), and in the field by hanging the probe in air to obtain a reference point representing a relative dielectric constant of one and signal attenuation of zero.

4.4.4 Interpretation

Dielectric constant logs may be interpreted by use of procedures developed and described by experimenters and well logging service companies (Shen et. al., 1984, Cox and Warren, 1983, and Dresser Atlas, 1981). These procedures, which are designed to detect the presence of oil, may be applied using computer programs developed by service companies. Since the dielectric constant of frozen water and oil are similar, these interpretation procedures may also apply to logs made in permafrost where the primary objective may be to identify rock units that contain ice.

4.4.5 Special Problems

Because of the shallow penetration of high frequency electromagnetic energy, dielectric constant logs are adversely affected by materials with anomalous electrical properties that occur close to the measurement coils. Reliable logs may be made with the Schlumberger system only if the following conditions are met: the borehole should be smooth with mudcake less than 1 cm (3/8 in) thick, and the resistivity of the zone of investigation should be greater than 0.3 ohm-meter (Shen et. al.,1984). Although dielectric constant logs made with the Dresser Atlas tool are less sensitive to borehole conditions, the accuracy of the measurement is improved if the resistivity of material close to the probe is not anomalous with respect to the resistivity of the undisturbed formation. It may be possible to measure the dielectric constant with the Dresser Atlas tool through plastic casing, but this has not yet been demonstrated by field tests. In permafrost environments, the thawing and caving that commonly occurs at the borehole wall may seriously limit the usefulness of the dielectric constant log. However, the dielectric constant log has not been tested extensively in permafrost environments, so its effectiveness has not been established.

4.5 Induced Polarization (IP) Logs

IP logs are galvanic contact electric logs that measure the chargeability of rocks and soils. They are made with probes containing two or more electrodes made of lead, platinum, or silver-silver chloride. Like SP logs, IP logs require conductive fluid in the borehole, and they cannot be made in cased holes. IP logs respond to concentrations of minerals that enhance the chargeability of rocks and soils, particularly metallic sulfides and clays of the smectite family that have high cation exchange capacities. A general discussion of IP logging is given by Snyder et al. (1977).

4.5.1 Principles

IP measurements can be made in the time domain or in the frequency domain. Time domain measurements are made with current applied to the logging electrodes in the form or a modified square wave with an 'off' time following the positive and negative half-cycle 'on' times. Frequency domain measurements are made with the current applied in the form of a sine wave. In both cases the frequency is low, typically in the range of 0.5 to 5 Hz. Potential electrodes are used to pick up the potential created by the flow of current in the formation near the borehole. Anomalously high levels of IP that are produced by metallic sulfide minerals and active clays affect the shape and phase of the potential waveform. In time-domain measurements the shape of the potential waveform is distorted and takes the form of a gradual decay during the current 'off' time, instead of an abrupt return to zero that would occur in the absence of anomalous IP. This decay is measured by integrating the potential in a time window that begins shortly after the current is turned off and ends before it is turned back on again. The integrated voltage is averaged for the positive and negative half cycles, and is normalized by dividing it by the average 'on' time potential which varies in proportion to the apparent resistivity of the formation. Units of measurement of time-domain IP are mV/V (millivolts/volt) where the numerator represents the integrated voltage during the current 'off' time, and the denominator represents the normalizing voltage measured during the current 'on' time. In frequency-domain measurements, anomalously high IP causes the potential waveform to shift in phase with respect to the current waveform. The unit of measurement of IP in the frequency domain is the milliradian. Figure 4.3 shows the difference between time domain and frequency domain IP waveforms and illustrates the effect of anomalous IP in both cases.

4.5.2 Methods

Three electrode configurations that are commonly used to make IP logs are illustrated in Figure 4.4. The normal configuration is the simplest, with only two electrodes on the logging probe, one current electrode and one potential electrode. The other two electrodes are grounded at the surface, or alternatively, one of them, usually the current electrode, may be located on the logging cable above the probe where it makes contact with the borehole fluid. A disadvantage of the normal configuration is that the spacing between the two potential electrodes is very large, making the IP measurement susceptible to electromagnetic noise from power lines, radio antennas, lightning storms, and strong telluric currents from any source, including the aurora. Other electrode configurations used for IP measurements (dipole-dipole and Wenner) are less susceptible to noise because both potential electrodes are located close together on the probe.

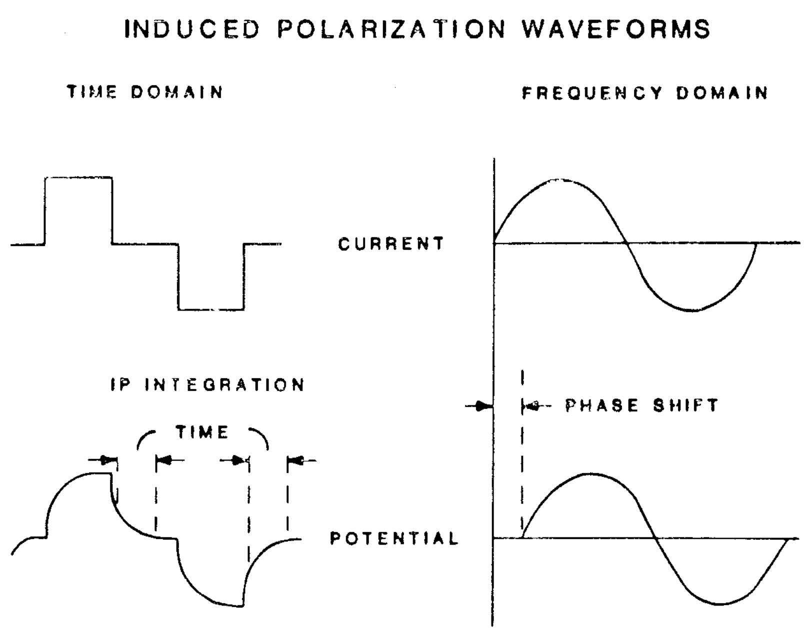

Figure 4.3 -- Induced polarization (IP) waveforms showing exaggerated IP effects for time domain and frequency domain potential waveforms.

IP logs are usually made with passive probes and control modules that contain all of the electronic circuitry necessary for current waveform generation and potential waveform analysis. However, some advanced IP logging probes contain electronic circuitry for analyzing the potential waveform downhole, which avoids waveform distortion, coupling effects and noise that may be introduced when the potential signal is sent up the logging cable.

Most IP systems provide a means of balancing out SP (spontaneous potential) that is picked up by the potential electrodes. This is necessary because SP causes a voltage shift in the IP signal that may put it beyond the linear range of amplification of the signal analysis circuitry. The depth of penetration and vertical resolution of IP logging measurements is approximately equal to the electrode spacing AM (Figure 4.4).

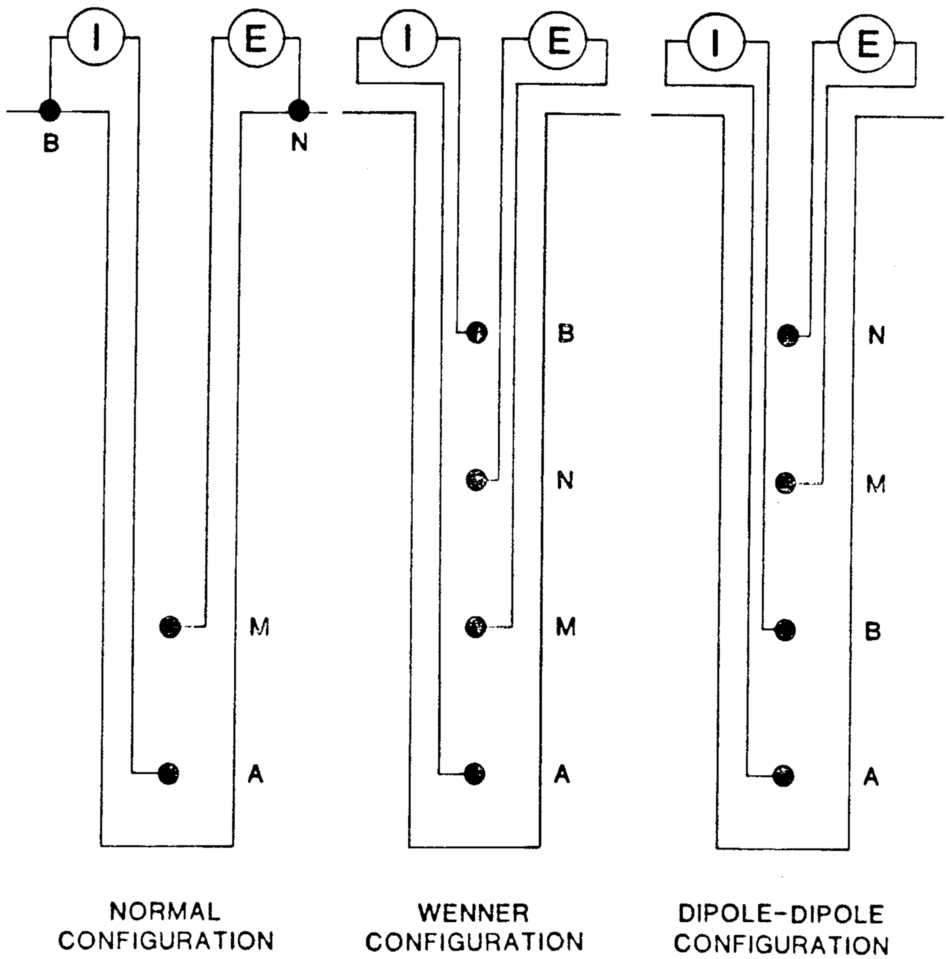

Figure 4.4 -- Electrode configurations used to make induced polarization (IP) logs. Current electrodes are labeled A and B, potential electrodes are labeled M and N. The current source is labeled I and the potential measurement circuit is labeled E.

4.5.3 Calibration

IP logging systems may be calibrated in the field by use of resistance networks similar to those used for calibrating resistivity systems (described in Section 4.2.3), except that they contain a variable capacitance (such as a decade capacitor box) that is connected in series with the variable resistance that represents formation resistivity. The combined resistance and capacitance creates a predictable phase shift in the potential signal for calibrating frequency-domain systems, and a known potential decay during the current 'off' time for calibrating time-domain systems. Some IP logging systems contain built-in electronic circuits for checking calibration before and after logging.

4.5.4 Interpretation

Interpretation of IP logs requires some knowledge of the lithology and mineralogy of the area being investigated. IP logs cannot be interpreted uniquely without this knowledge, because anomalies produced by low concentrations of disseminated metallic sulfide minerals, for example, may look the same as those caused by high concentrations of active clays with high cation exchange capacities. However, very strong IP anomalies (more than 100 mV/V or 100 milliradians) generally can be correctly interpreted as representing concentrations of metallic sulfide minerals, particularly if the anomalous zones are thin and erratically distributed with depth. Clay minerals tend to be more uniformly distributed in host rocks than sulfide minerals, although concentrations of anomaly-producing clays sometimes occur in very thin beds. Interpretation of IP logs can be improved significantly if drill core is available from at least one borehole in the area under investigation. The core can be examined to determine the cause of IP anomalies at specific depths, and relationships between mineralogy and IP response can be established and used as a guide for interpreting other IP logs in the area. A study of the relationship between frequency-domain IP anomalies and metallic sulfide content of cores is described by Glen and Nelson (1979). Worthington and Collar (1982) describe the relationship between IP and shaliness. Permafrost usually enhances the IP effect because when the interstitial water begins to freeze, the concentration of ions in the unfrozen pore fluid close to rock grains increases, causing the chargeability of the rock to increase (Olhoeft, 1975). As the salinity of the unfrozen water increases, the freezing point is depressed, which tends to prevent all of the pore water from freezing. However, if the amount of unfrozen water is very small, the pore ice surrounding the individual grains may freeze solidly enough to isolate them electrically, sharply reducing the IP effect.

4.5.5 Special Problems

Operational problems associated with IP logging in permafrost are the same as those associated with other types of electric logging, and involve the requirement of filling the borehole with conductive fluid and making good electrical contact with the ground surface when ground electrodes are used. In permafrost zones, caving of the rock adjacent to the borehole may limit the depth of investigation severely, causing IP anomalies from the formation to be weakened or even vanish.

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4.7 List of Acronyms

IP Induced polarization
ILd Induction log, deep penetrating
R-C Resistance - capacitance
SP Self (or spontaneous) potential

5.0 SONIC LOGS

Sonic logging probes investigate the elastic properties of the formation by transmitting sonic pulses that travel through the formation at shallow depths parallel with the borehole. The wavetrains that are produced by the pulses are picked up by receivers, and either the travel times representing the first arrivals or the wavetrains themselves are recorded on the log. A collection of papers on sonic logging has been assembled in the Society of Professional Well Log Analysts' reprint volume, Acoustic Logging (Timur et al., 1978), including one on the velocity of compressional waves in permafrost (Timur, 1968).

5.1 Velocity Logs

Sonic interval transit time logs are made with probes that measure the time required for a sonic compressional pulse to travel a specific distance through the formation adjacent to the borehole. Because the reciprocal of interval transit time is velocity, these logs are commonly called velocity logs. Conventional sonic tools require fluid in the borehole in order for the sonic pulse to propagate between the probe and the formation. It is possible to make sonic logs in cased holes only if the casing is firmly cemented to the formation. Uncemented casing reverberates when the transmitted pulse hits it, producing high amplitude ringing that obscures the arrival of pulses traveling through the formation. This effect is used in cement bond logging (described in Section 5.2) to detect zones where the casing is poorly bonded to the formation.

Special dry-hole sonic tools have been developed by the Southwest Research Institute (Suhler et al., 1978) and by King et al. (1978). These tools can determine shear as well as compressional wave velocity, but they must be clamped to the borehole wall, making logging very time consuming.

5.1.1 Principles

Interval transit time logs are made with probes containing one or two transmitters and two or more receivers. The transmitted compressional pulse propagates outward through the borehole fluid into the formation, where it is critically refracted along the borehole wall and travels through the formation toward the receivers about a meter (several feet) away. The receivers, usually spaced 0.3-1 m (1-3 ft) apart, pick up a component of the pulse that is refracted back toward them through the borehole fluid. The interval transit time is the difference in the time of the first arrival of the pulse at two receivers, normalized by dividing it by the receiver spacing, and recorded in units of μs/m or μs/ft. Because interval transit time is strongly dependent on porosity, sonic logging has become one of the primary borehole techniques for estimating formation porosity. In addition, sonic logs are useful for detecting the presence of fractures in rock close to the borehole. Fractures severely attenuate the sonic signal, causing an erratic error condition called 'cycle skipping' that is easily recognized on the interval transit time log. Cycle skipping may also be caused by borehole effects related to extreme rugosity, washouts, and caving. It is important to run a caliper log in order to detect these borehole conditions so that their effect will not be mistaken for fracturing.

5.1.2 Methods

Various configurations of sonic transducers are used in sonic logging, two of which are illustrated in Figure 5.1. The transmitters are magnetostrictive or piezoceramic devices that produce pulses with a center frequency in the range 10-40 kHz. The receivers are broadband transducers, either magnetostrictive rings or piezoceramic cylinders, that respond to changes in fluid pressure by producing proportional voltage variations. Transmitters and receivers are both covered with flexible, abrasive-resistant rubber or plastic sleeves that transmit sonic signals, but prevent borehole fluid from entering the probe. The section of the probe that separates the transmitters from the receivers is usually made of a low-velocity material or a slotted metal housing that attenuates sonic signals, preventing them from traveling directly along the probe housing from the transmitter to the receivers. Sonic probes are equipped with centralizers that keep them approximately centered in the borehole. This is necessary to prevent the signals from arriving at the receivers out of phase, which would occur if the length of the ray path in the borehole fluid differed from one side of the probe to the other. The spacing between transmitters and receivers on sonic probes determines the depth of investigation of the sonic signal. Short spacings of a meter or less (two or three feet) between the transmitter and the receiver result in shallow penetration of only 5-8 cm (2-3 in) (Baker, 1984). This shallow penetration is satisfactory for logs made in hard rock environments where the rock adjacent to the borehole is usually not significantly eroded or fractured by the drill bit. However, in soft formations, particularly those in permafrost, the drilling process often causes moderate to severe damage to depths of 10 cm (4 in) or more in the formation. When this condition occurs, long-spaced sonic logs with transmitter-receiver spacings of 5 m (15 ft) or more are required to penetrate deeply enough to measure the properties of the undisturbed formation (Williams et. al., 1984).

5.1.3 Calibration

Interval transit time logging probes can be calibrated in test pits containing simulated formations with known sonic velocities. A calibration point for water, approximately 656 μs/m (200 μs/ft) can be obtained by suspending the probe in a trough filled with water. Sonic probes cannot be calibrated by these techniques at the well site, and generally there is no need to do so because probe calibration depends mainly on transmitter-receiver spacings that are fixed and can not change. Most control modules are equipped with test signal generators that produce simulated receiver signals for checking the operation of automatic pulse arrival detection circuitry.

5.1.4 Interpretation

Interval transit time logs are interpreted in two stages. First the log is scanned to find anomalous sections that do not appear to represent valid interval transit times. Valid times range from 131 to 656 μs/m (40 to 200 μs/ft) equivalent to a velocity range of 7620-1524 m/s (25,000-5,000 ft/s). Transit times of 656 μs/m (200 μs/ft) or greater indicate that the sonic pulse traveled through the borehole fluid rather than through the formation, either because the formation velocity was lower than the fluid velocity, or because the signal traveling through the formation was severely

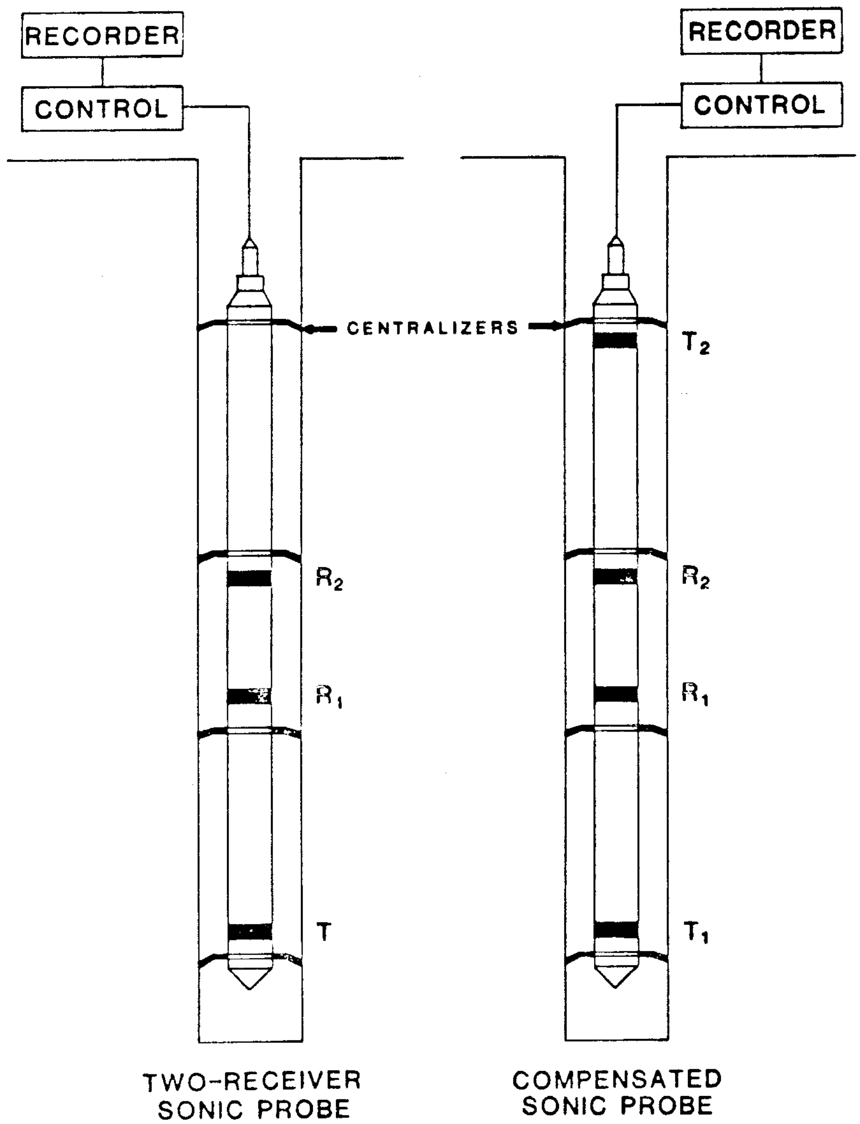

Figure 5.1 -- Sonic probes used for measuring interval transit time. Transmitters are labeled T and receivers are labeled R. The transmitters T_1 and T_2 of the compensated probe are fired alternately, and the interval transit time measured between the two receivers R_1 and R_2 is averaged for each pair of transmitter firings.

attenuated by fracturing or by borehole rugosity and washouts. Fracturing and borehole roughness may also cause cycle skipping which can be recognized by its wild appearance and abrupt fluctuation between two levels of recorded transit time. One level represents the correct transit time, and the other represents a cycle skip which causes the apparent transit time to be in error by one or more full periods of the frequency of the received signal (e.g. 50 μs for a 20 kHz signal), which would be recorded as an apparent error of 82 μs/m (25 μs/ft) after being normalized for a receiver spacing of 0.6 m (2 ft). The second stage of transit time log interpretation involves relating the log values to lithology, which requires some knowledge of formation velocities in the area. The porosity of the lithologic units of interest can be estimated by using a relationship suggested by Wyllie et al. (1956), known as the 'time-average formula':

$$\Delta t = \phi \Delta t_f + (1 - \phi)\Delta t_{ma} \qquad (5.1)$$

where Δt = interval transit time, μs/m or μs/ft,
ϕ = fractional porosity,
Δt_f = interval transit time for the pore fluid,
Δt_{ma} = interval transit time for the rock matrix.

A modification of the 'time average formula' takes into account the effect of ice in permafrost (Timur, 1968):

$$\Delta t = S_w \phi \Delta t_f + (1 - S_w)\, \phi \Delta t_i + (1 - \phi)\, \Delta t_{ma} \qquad (5.2)$$

where S_w = volume fractional of ϕ occupied by water,
Δt_i = interval transit time for ice.

The interval transit times for the rock matrix and the pore fluid and ice are the reciprocals of the compressional velocities of these media, converted to units of μs/m or μs/ft. Table 5.1 gives interval transit times and velocities of various earth materials and several fluids and gases. Application of the time average formula is discussed in detail by Guyod and Shane (1969), and by Pirson (1963).

5.1.5 Special Problems

Since conventional sonic logs require fluid-filled boreholes, the problem of rugosity and caving in zones of thawed permafrost may cause severe cycle skipping, making it important to run a caliper log along with the sonic log. An interpretational problem occurs in permafrost because the velocity of ice is close to the velocity of the rock matrix for many rock types. Therefore Wyllie's time-average formula cannot be used reliably to determine the porosity of frozen or partially frozen rocks that contain mixtures of ice and water in the pore space. However, this problem has the potential for being turned into a technique for detecting permafrost. If porosities obtained from the sonic log (ignoring the effect of ice) are plotted against porosities obtained from the density log (which is less affected by ice), points representing frozen zones should fall far from the 45-degree line of perfect correlation, whereas points from unfrozen zones should fall close to the 45-degree line. If the porosity of the formation can be determined from some other source of information such as the density

Table 5.1 — Typical interval transit times and compressional wave velocities for various unfrozen water-saturated earth materials, ice, fluids, and gases (after Guyod and Shane, 1969; Press, 1966)

	Interval transit time (microseconds/foot)		Velocity (feet/second)	
Earth materials	Porous material	Matrix	Porous material	Matrix
Alluvium	152-610	----	6,560-1,640	------
Sandstone	62.5-87.0	52.9	16,000-11,500	18,900
Shale	58.8-143	----	17,000-7,000	-------
Limestone	54.0-76.9	49.8	18,500-13,000	20,100
Dolomite	50.0-66.7	43.5	20,000-15,000	23,000
Granite	51.8-63.5	51.8	19,300-15,700	19,300
Ice	76.3-305	76.3	13,100-3,280	13,100
Fluids				
Water (pure)	208		4,800	
Water (200 g/l NaCl)	182		5,500	
Drilling mud	167		6,000	
Petroleum	238		4,200	
Gases (at normal temperature and pressure)				
Air	909		1,100	
Methane	667		1,500	

log, and if the formation velocity is not too close to the velocity of ice, then the volume fraction of pore space occupied by ice in permafrost can potentially be determined from Equation 5.2.

5.2 Amplitude Logs

Sonic amplitude logs record the amplitude of the transmitted sonic signal arriving at one or more of the receivers on the logging probe. In general, they are made with probes that are similar or identical to those used to make interval transit time logs (Section 5.1).

5.2.1 Principles

The amplitude of a sonic signal that travels through rock adjacent to a borehole is a measure of the ability of the rock to transmit acoustic energy. Acoustic transmissivity generally increases as rock density and bedding thickness increase, and as porosity and fracturing decrease. In oilfield environments, rocks containing gas are less transmissive than those containing oil which are less transmissive than those containing water. Borehole rugosity, washouts, and caving are conditions that may severely attenuate the sonic signal, obscuring the effects of the formation. Therefore it is important to run a caliper log in addition to the sonic amplitude log to determine if and where these conditions exist.

5.2.2 Methods

Amplitude logs are usually made simultaneously with interval transit time logs, and may be recorded as individual amplitude levels at the two receivers, or as the ratio between them, which represents the attenuation of the sonic signal. An exception is the cement bond log, which is a special sonic amplitude log that is usually made with a probe containing only one transmitter and one receiver, and is used to examine the quality of the bond between casing and the formation, and to detect channeling behind the casing.

5.2.3 Calibration

Amplitude logs are usually not calibrated, but are recorded on relative or arbitrary scales representing the voltage outputs of individual receivers, or the ratio of the voltage outputs of two receivers.

5.2.4 Interpretation

Sonic amplitude logs can be related to lithology in a semi-quantitative manner by reference to other logs and through knowledge of the geology of the area. They are usually used along with interval transit time logs to infer the presence of fractures that cause cycle skipping and reduce amplitudes. In the special case of the cement bond log, high amplitude indicates a poor bond with possible channeling between casing and the formation, and low amplitude indicates a good bond. In permafrost environments, sonic amplitude logs may be helpful when used with interval transit time logs for identifying frozen rock, which can be expected to produce higher than normal amplitudes as well as higher than normal velocities.

5.2.5 Special Problems

Holes drilled in permafrost tend to cave when warm drilling mud thaws the formation close to the borehole. Attenuation of sonic amplitude due to caving can be just as severe as attenuation due to fracturing. Therefore, it is important to refer to a caliper log to identify zones of caving so that they will not be incorrectly interpreted as zones of fracturing.

5.3 Waveform Logs

Sonic waveform logs are recordings of the waveform picked up by one or more of the receivers on a sonic probe. They are usually displayed in variable intensity format where tones of gray ranging from black to white represent the amplitude of the signal. In contrast to conventional velocity logs which only record the interval transit time of the compressional wave, waveform logs display the compressional wave, the shear wave (or pseudo Rayleigh wave), and the Stoneley wave (or tube wave). Occasionally waveform logs also show diffraction and reflection patterns caused by discontinuities along the borehole wall and in the formation. Shear wave velocity is required for estimating the elastic moduli of the formation in engineering studies, and anomalously low values of shear wave amplitude and velocity suggest the presence of fractures. Theoretically the Stoneley wave velocity can be used to estimate formation density (Geyer and Myung, 1970), although this technique is not commonly used, probably because it is easier and more reliable to get formation density from the gamma-gamma density log (Section 6.2). The Stonely wave has been used to determine the velocity of the shear wave in low velocity formations where the shear wave is not observed on the wavetrain (Liu, 1984), and to detect fractures (Paillet, 1983; Hardin and Toksöz, 1985).

5.3.1 Principles

Waveform logs are like seismic records in that they display amplitude variations as a function of time for a wavetrain arriving at a specific receiver location. In the case of the waveform log, the transmitter and the receiver move up the hole together, and occupy a series of close-spaced stations at contiguous depths. Waveform logs contain more information relating to the elastic properties of the rocks than any other type of log. All of the elastic moduli are functions of compressional and shear wave velocities which can be estimated from waveform logs, and density which can be determined separately from a density log. These moduli are important in engineering and geotechnical studies where strength and deformational characteristics of earth materials must be predicted.

5.3.2 Methods

Waveform logs can be made with the same probes that are used to obtain interval transit time logs. However, if the transmitter-receiver spacings are too short, the compressional wave, shear wave, and tube wave may overlap, making it difficult or impossible to distinguish one from another. In order to improve the separation between the different wave modes, it is desirable to use a probe with a transmitter-receiver spacing of at least 1.5 m (5 ft). Some waveform probes have been developed with spacings as large as 6 m (20 ft) (Williams et al., 1984), and others have as many as 12 receivers (Lamont-Doherty, 1985)

5.3.3 Calibration

Waveform logs do not require calibration, although their response can be checked in test pits containing simulated formations with known compressional and shear wave velocities and attenuation characteristcs.

5.3.4 Interpretation

Waveform logs are interpreted in two different ways, depending on the objective of the logging program. If the objective is to determine the elastic properties of rocks penetrated by the borehole, the first step is to pick the arrival times of compressional and shear waves at depths of specific interest, avoiding zones that may be adversely affected by anomalous borehole conditions. Then the arrival times are corrected for the time of travel through the borehole fluid if the waveform is available for only one transmitter-receiver spacing. The interval transit time between receivers at two different spacings is determined if dual-spacing waveform logs are available. Computer techniques for extracting compressional and shear wave transit times from dual-receiver waveform logs have been described by Willis and Toksöz (1983), and by Scott and Sena (1974). Next, the corrected travel times are converted to velocity by dividing them into the appropriate spacing, and elastic moduli are computed from the following formulas (Geyer and Myung, 1970):

$$\text{Poisson's ratio:} \quad \sigma = \frac{0.5(V_p/V_s)^2 - 1}{(V_p/V_s)^2 - 1} \qquad (5.3)$$

$$\text{Young's modulus:} \quad E = K\, 2\rho\, V_s^2\, (1 + \sigma) \qquad (5.4)$$

$$\text{Bulk modulus:} \quad B = K\, (\rho\, V_p^2 - 4/3\, \rho\, V_s^2) \qquad (5.5)$$

$$\text{Shear modulus:} \quad G = K\, \rho\, V_s^2 \qquad (5.6)$$

where V_p = compressional wave velocity, ft/sec,
V_s = shear wave velocity, ft/sec,
ρ = bulk density, g/cm^3,
K = constant, 0.01355, converts moduli to units of psi (pounds per square inch).

If the objective is to detect fractures, the compressional and shear wave amplitudes are compared in zones of interest. In general, shear waves are more severely attenuated by fractures than compressional waves, sometimes so much so that shear waves can not even be recognized in the wavetrain. When they can be recognized, fracturing delays their arrival more than that of compressional waves, providing additional evidence of their presence. Fractures usually cause a decrease in the frequency as well as the amplitude of compressional waves and shear waves.

In permafrost environments one would expect shear wave velocities and amplitudes to be much higher in zones of frozen rock than in unfrozen rock because of the stiffening effect of ice. One would also expect the velocity and amplitude of shear waves to increase more than the velocity and amplitude of compressional waves, because the frictional losses that ordinarily reduce shear wave velocity and amplitude would be sharply reduced. These relationships have not been verified experimentally yet, but if they are tested and found to be true, they could form the basis of a new technique for identifying permafrost.

5.3.5 Special Problems

Problems of making waveform logs in permafrost are the same as for other types of sonic logging; the hole must be filled with fluid unless a dry-hole sonic probe is used, and caving may occur if the fluid thaws the ice in poorly consolidated rocks, making it difficult to transmit sonic energy from transmitter to receiver through the formation. Caliper logs can be used to identify zones of borehole damage where waveform logs may be too severely attenuated to be interpreted.

5.4 Televiewer Logs

Televiewer logs produce high frequency sonic images of the borehole wall which show fractures, bedding planes and mechanical flaws in the rock along the wall that are produced by drilling and stress-induced spalling. They have been applied sparingly to special problems in oilfield, mineral and geotechnical studies, usually related to fracture detection. Because televiewer logs are difficult and expensive to run, they have not become available from service companies on a routine basis. The borehole must be filled with fluid to carry the high frequency sonic signal between the probe and the borehole wall.

5.4.1 Principles

The televiewer log is made by scanning the borehole wall with a beam of high frequency sonic energy. The beam is reflected back to the transducer in the probe where the borehole wall is smooth, but is absorbed and scattered by rough features or by depressions produced by fractures or other mechanical flaws. The log provides an image that is similar in appearance to an impression packer that is cut vertically and spread out flat for observation. The principles of televiewer logging are discussed in detail by Zemanek et al. (1969).

5.4.2 Methods

Televiewer probes contain a high frequency transducer that rotates about the vertical axis of the probe at about 3 revolutions/second, emitting sonic pulses that are beamed outward toward the borehole wall. The transducer is housed in an oil-filled chamber in the probe that is sealed off from the borehole fluid by a plastic shell that is transparent to the sonic pulses. The predominant frequency of the pulses is about 2 MHz, and they are transmitted at a rate of about 2000 per second. The transducer is gated so that it can be used as a receiver of energy reflected back from the borehole wall. The reflected sonic pulse is converted to an electronic signal that is sent up the cable to a recorder (oscilloscope-camera or videotape) in the logging truck. A magnetometer in the probe is used to sense when the beam crosses magnetic north, and the output signal is triggered to start its sweep at this point. The probe is centralized in the hole and is moved upward at a speed of about 15 ft/min so that the scanning beam follows a tight spiral path along the borehole wall.

5.4.3 Calibration

The amplitude of the output signal of the televiewer log is adjusted by the operator to produce a signal with the proper intensity to map features along the borehole wall. Therefore no precise calibration is necessary.

5.4.4 Interpretation

Interpretation of televiewer logs consists of inspecting the image and searching for fractures or other features of interest. Plane features such as fractures that cut across the hole at a high angle appear as sinusoidal curves on the image. The dip of these features can be determined by measuring the vertical distance between the peak and the trough and relating it geometrically to the hole diameter. Strike can be determined by noting the azimuthal direction of the trough (Zemanek et al., 1969). Breakouts caused by stress-induced spalling of rock on opposite sides of the hole are indicated by vertical shadows that are 180° apart on the image (Zoback et al., 1985). Shadows of this type may also be produced by boreholes with elliptical cross sections, so it is important to obtain good independent-arm caliper logs of the hole to distinguish the two effects. Interpretation procedures in a variety of rock types are discussed by Paillet et al. (1985).

Although televiewer logs have not been used to detect permafrost boundaries, it is believed that they might be effective in this application under certain conditions where spalling along the borehole wall is associated with the contact. It may also be possible to identify massive ice in the borehole with televiewer logs.

5.4.5 Special Problems

If spalling of poorly consolidated permafrost sediments is very severe and covers a large vertical interval in the hole, the borehole wall might be too rough and irregular to reflect a televiewer signal at all, and in this case it would be impossible to determine the exact location of the permafrost boundary. In consolidated sediments and in hardrock environments, thawing caused by drilling might obscure the permafrost signature.

Since the technique has not been tested in permafrost, its usefulness and applicability are conjectural.

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6.0 NUCLEAR LOGS

Nuclear logs record the intensity of nuclear radiation, either natural or artificially induced, that is picked up by detectors in the logging probe after it has traveled a short distance (a few centimeters to a maximum of about a few meters) through the formation. The types of induced radiation used in well logging (gamma rays and neutrons) generally have sufficient energy to penetrate steel and plastic casing, so that these logs can be made in cased holes with only moderate degradation in accuracy if appropriate corrections are applied. Nuclear logs can be made in holes that are filled with any type of fluid or gas. A collection of papers on nuclear logging is published in the Society of Professional Well Log Analyst's reprint volume Gamma Ray, Neutron and Density Logging (Lawson et al., 1978).

6.1 Natural Gamma Ray Logs

Natural gamma ray logs record the intensity of gamma radiation from natural sources in the earth, specifically, from isotopes in the radioactive decay series of uranium and thorium, and from potassium. Gamma ray logs can be made in open or cased holes containing any type of fluid or gas. They are diagnostic of lithology, particularly in sandstone-shale sequences, and are useful for correlating strata from hole to hole in an area under study.

6.1.1 Principles

Most unstable radioactive isotopes emit gamma rays when they decay and form other isotopes. In earth materials, three isotopes contribute significantly to the gamma ray logging measurement; bismuth-214, which is a decay product of uranium, thallium-208, a decay product of thorium, and potassium-40, which is present in minerals rich in potassium such as feldspar, and in feldspar-derived sediments such as shales and clays. Clays also have a tendency to adsorb uranium ions dissolved in ground water, making them more radioactive than most other rock-forming minerals. Gamma ray logging probes contain detectors that register the intensity of the gamma ray flux in the borehole, and this flux reflects the concentration of gamma-emitting isotopes in the formation. If the energies of the gamma rays are also measured, it is possible to estimate the concentrations of each of the three natural sources of gamma radiation, potassium (K), uranium (U), and thorium (Th). This type of gamma ray log is called a 'KUT' log, or gamma ray spectral log.

6.1.2 Methods

Two types of detectors are commonly used in gamma ray probes; Geiger tubes and scintillation detectors. Geiger tubes are less sensitive to gamma radiation than scintillation detectors, but they have the advantage of being relatively simple, rugged, and capable of operating at high temperatures. Scintillation detectors, which are more fragile, consist of a scintillation crystal, usually sodium iodide, and a photomultiplier tube that is optically coupled to it. The amplitude of scintillation pulses depends on the energy of gamma rays, so that scintillation detectors can be used to make gamma ray spectral logs, whereas Geiger tubes cannot. Pulses that are obtained from either Geiger tubes or scintillation detectors are amplified and shaped by electronic circuits in the probe before they are sent up the cable. When they arrive at the logging truck the pulses are counted over a specific period of time by ratemeters or scalers that produce an output voltage or numerical readout that represents count rate (counts per second), which is the quantity that is generally recorded by mineral and geotechnical logging systems. Oilfield logging systems usually record gamma radiation in API units (American Petroleum Institute units) which can be obtained by multiplying count rate by an empirically derived calibration factor.

6.1.3 Calibration

Calibration of gamma ray logging probes can be accomplished in calibration pits that contain artificial formations with known levels of gamma radiation. Calibration pits that contain zones of radioactive concrete that simulate oilfield lithologies are available to the public at the University of Houston. These pits were built under the auspices of the American Petroleum Institute for determining calibration factors for converting gamma ray count rates to API units (American Petroleum Institute, 1974). Other artificial pits are available in Grand Junction, Colorado for determining calibration factors for converting gamma ray count rates to equivalent uranium grade and for calibrating gamma ray spectral probes (Wilson and Stromswold, 1981). These pits are maintained by the U.S. Department of Energy (DOE) and are also available to the public (Mathews and others, 1978). The Geological Survey of Canada maintains a gamma ray logging facility near Ottawa, Ontario which can be used to derive uranium logging calibration factors, and to calibrate gamma ray spectral probes (Killeen, 1978).

6.1.4 Interpretation

Gamma ray logs are interpreted in different ways, depending on whether they are being used in oilfield studies, or for mineral investigations (uranium, thorium, base metals, coal, etc.). In oilfield studies, gamma ray logs can be related to lithology by using Table 6.1 as a guide. More specific relationships can be established in specific environments by reference to existing correlations between gamma ray logs and lithology in the area. In mineral exploration applications, gamma ray log anomalies can be converted to equivalent uranium grade (percent eU_3O_8) by use of charts and overlays (Scott et al., 1961), or by computer algorithms (Conaway and Killeen, 1978; Scott, 1963). Accurate in-situ uranium assays from gamma ray logs require corrections for instrumental dead time (Crew, 1979; Scott, 1980), for borehole diameter in fluid-filled holes (Mathews et al., 1978), and for steel casing, if present (Conaway et al., 1979).

In base metal exploration, anomalously high gamma ray response is sometimes associated with metallic sulfide deposits, making the gamma ray log useful for indicating and delineating mineralization.

Coal is usually characterized by an anomalously low gamma ray response, although coal may become uraniferous under special geologic conditions that exist in some locations (uranium-rich ground water seeping through high-permeability coal over long periods of time). Under normal conditions where coal has an anomalously low gamma ray response, the gamma ray log can be

Table 6.1 — Natural gamma ray API units associated with various rock types and ice (Hilchie, 1978)

Rock type	Gamma ray log API units
Sandstone	10-30
Shale	80-140
Limestone	0-5
Dolomite	5-20
Anhydrite	0-30
Halite	0
Ice	0

used to estimate ash content of the coal by means of empirical near-linear relationships where ash content increases as gamma ray response increases (Hoffman et al., 1982).

In geotechnical evaluations of permafrost, the natural gamma ray log is useful for finding and identifying massive ice in silts. The ice can be recognized by its anomalously low level of gamma radiation compared with that of silt (Petersen et al., 1985).

Clay and silt-sized particles that occur in fine-grained sediments tend to adsorb radioactive ions from water during the sedimentation process before compaction reduces permeability to very low values. Therefore, gamma ray response can often be used as a semi-quantitative indicator of the volume fraction of clay content (Heslop, 1974), which in turn can be cross plotted against properties of other logs to possibly help estimate the content of unfrozen water in permafrost that is attributable to soil particle effects.

Interpretation of gamma ray spectral logs for oilfield and mineral applications is straightforward after corrections are made for gamma ray scattering effects (Stromwold and Wilson, 1981; Killeen and Cameron, 1977). Potassium, uranium and thorium values that are obtained from the corrected logs are related to lithology by empirical correlations established for the study area.

6.1.5 Special Problems

Although caving in boreholes drilled in permafrost reduces the gamma ray flux detected by the probe in fluid-filled holes, errors due to caving are less significant in the case of gamma ray logs than for most other logs. Corrections can be applied for hole diameter effects by use of charts or formulas and information from the caliper log. All things taken into account, the natural gamma ray log is probably less affected by problems associated with permafrost than any other log.

6.2 Gamma-Gamma Density Logs

Density logs record the apparent density of rocks by use of a probe that sends gamma rays into the formation and measures the portion that reach the detector a few tens of centimeters away before being absorbed. They can be made with or without fluid in the borehole, and can even give quantitative results if the hole is cased, as long as there are no large gaps or open annular spaces between the borehole wall and the casing. Unfortunately, gaps and spaces often occur, making the density log only qualitative under these conditions.

6.2.1 Principles

Each time a gamma ray interacts with an orbital electron of an atom in a rock, it changes direction and thus, loses some of its energy. This is known as Compton scattering. If a rock is very dense, gamma rays traveling through it lose a great deal of their energy by Compton scattering, and many of them become so weak that they are absorbed photoelectrically before they can travel more than a few centimeters. If a rock is not very dense, there are fewer orbital electrons in the travel paths of the gamma rays, and they have a better chance of traversing a given distance through the rock without being weakened and absorbed. This phenomenon is the basis of gamma-gamma density logging. Although the scattering of gamma rays depends on the density of electrons, not atoms, and the absorption of gamma rays depends on their energy as well as the density of electrons, most earth materials contain atoms which, on the average, have ratios of atomic number to atomic weight (Z/A) that are very close to 1/2, so that the average bulk density of most rocks can be related to average electron density by a constant. Therefore, if a gam gamma logging probe is properly calibrated, its readout (counts per second) can be converted to the apparent bulk density of limestone, which has a Z/A ratio of 1/2 to a very high degree of approximation, and corrections can then be applied for rocks with anomalous Z/A ratios (Gearhart-Owen, 1970). The principles of gamma-gamma density logging are fully discussed in a definitive paper by Tittman and Wahl (1965) and a more recent paper by Czubek (1983).

A recent addition to the standard density log is the litho-density or P_e log. Instead of measuring the effects of Compton scattering, the P_e log measures the photoelectric absorption effect by detecting gamma rays with energies lower than 125 keV (kilo electron volts), and normalizing the low energy response to the response of the standard high energy detector which depends on the electron density of the formation. The resulting log represents the 'index of effective photoelectric absorption cross section' which increases as the average atomic number of the formation increases. Because of normalization, the P_e log is not significantly affected by variations in porosity, but responds primarily to differences in lithology which are associated with differences in the average atomic number of the formation (Gardner and Dumanoir, 1980). Principles of litho-density logging are discussed by Bertozzi et al. (1981).

6.2.2 Methods

There are two basic types of probes that measure electron density (Compton scattering effect); those that have collimated sources and detectors, and those that do not. Both types use isotopic sources of gamma rays, commonly cesium-137, sealed in a metal capsule. Collimation is achieved by surrounding the source and the detector with high-density shielding material (lead or tungsten) with a port on one side which allows gamma rays to travel in to the detector or out from the source. Collimated probes are pressed against the formation by a bow spring or caliper arm so that gamma rays are beamed directly into the rock and are backscattered to the detectors with a minimum distance of travel through the borehole fluid. This probe design reduces the adverse effects of borehole rugosity and abrupt changes in hole diameter. These effects are further reduced by use of dual detectors spaced several inches apart in 'borehole compensated' probes. In these probes the detector that is closest to the source (near detector) is more severely affected by borehole conditions than the one far from the source (far detector), so that the near detector response can be used to correct the far detector readout for borehole conditions by use of compensation algorithms (Scott, 1977, Scott et al., 1985). The three basic probe designs described above are illustrated in Figure 6.1. Uncollimated density probes are very sensitive to borehole conditions and cannot be used to obtain accurate densities unless the borehole is smooth-walled and has a constant diameter.

Litho-density probes that measure P_e response as well as electron density contain an additional detector that is sensitive only to low energy gamma rays.

6.2.3 Calibration

Density probes are calibrated by use of test pits containing simulated or quarried rocks of known density (Snodgrass, 1976; Mathews et al., 1985). Calibration is usually checked at the well site by use of aluminum, magnesium, and plastic calibration blocks with known tool responses. The system sensitivity is adjusted, if necessary, to compensate for small changes in response.

The litho-density is calibrated so that the output is:

$$P_e = (Z/10)^{3.6} \qquad (6.1)$$

where P_e = index of effective photoelectric absorption cross section,
Z = effective atomic number of the formation (Gardner and Dumanoir, 1980).

6.2.4 Interpretation

Density logs made with mining and geotechnical equipment are usually recorded in units of counts per second. Interpretation of these logs begins with converting measured count rate to apparent density by use of calibration formulas, and in the case of compensated density logs, applying the appropriate compensation algorithms. Oilfield service company logs are usually recorded directly in apparent density units, with calibration and compensation formulas applied by the electronics in the logging truck, or by

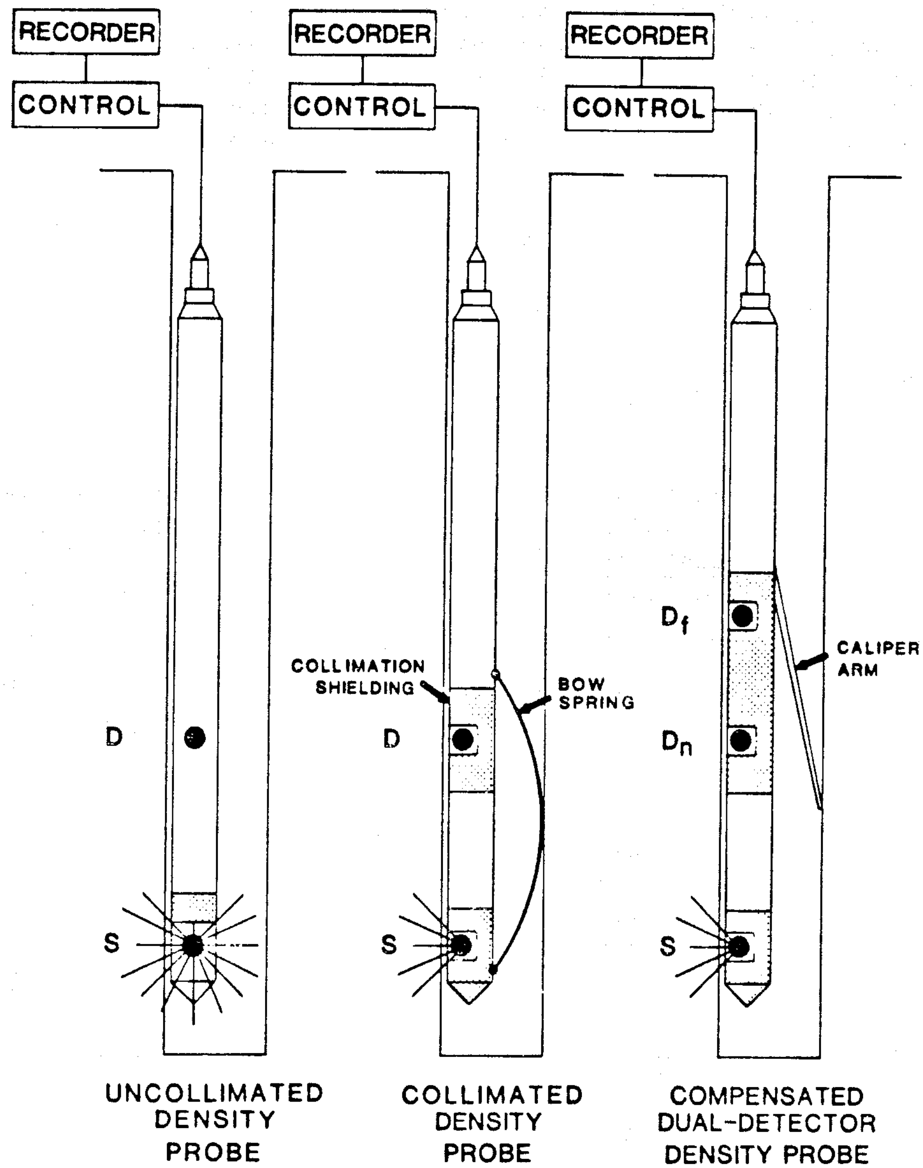

Figure 6.1 -- Gamma-gamma density probes with different source-detector arrangements. Gamma ray sources are labeled S and detectors are labeled D. For the compensated probe, D_n is the near detector and D_f is the far detector.

an onboard computer. The next step is to compare the density log with the caliper log to locate zones of severe borehole rugosity, washouts, or caving that cause apparent density readings to be low. These zones are noted and excluded from quantitative analysis. The valid sections of the log are then related to lithology by knowledge of formation density in the area under study. Typical ranges of density for various earth materials are listed in Table 6.2 along with Z/A ratios. Corrections are applied, if necessary, to apparent densities of lithologic units containing minerals with anomalous Z/A ratios (e.g. coal, metallic sulfides) using the technique described by Hoffman et al. (1982). Formation porosity can be estimated by use of the following formula (Pirson, 1963) if grain density is known or can be estimated (see Table 6.2):

$$\phi = \frac{D_g - D_b}{D_g - D_f} \qquad (6.2)$$

where ϕ = Fractional porosity,
D_g = Grain density,
D_b = Bulk density,
D_f = Pore fluid density,

Table 6.2 -- Bulk densities, grain densities and Z/A ratios of various earth materials and saturants (after Daly and others, 1966; Gearhart-Owen Industries, 1970)

Earth material	Saturated bulk density (g/cm^3)	Grain density (g/cm^3)	Z/A Ratio
Sand, silt, clay	1.44-1.93	----	0.4990
Sandstone	2.17-2.65	2.65	.4990
Limestone	2.37-2.71	2.71	.5000
Dolomite	2.75-2.80	2.85	.4994
Granite	2.52-2.81	----	------
Basalt	2.70-2.85	----	------
Dunite	3.20-3.31	----	------
Coal	1.35-1.60	----	.5134 -.5201
Pyrite	----	5.06	.4850

Saturants	Density (g/cm^3)	Z/A Ratio
Water (pure)	1.00	.5551
Water (200,000 ppm NaCl)	1.15	.5401
Petroleum	0.70-1.00	.5703 -.5778
Ice (pure)	0.92	.5551

Because of the low density of ice (0.92 g/cm^3), density logs can be used to identify massive ice that sometimes occurs in permafrost environments (Petersen et al., 1985). If the pores of a rock are saturated with a mixture of ice and water, the bulk density of the rock is given by the following formula (Petersen, 1985):

$$D_b = D_g (1 - \phi) + [D_w S_w + D_i(1 - S_w)] \phi \qquad (6.3)$$

where D_b = bulk density of the rock,
D_g = grain density of the rock,
ϕ = fractional porosity,
D_w = density of water (1.00),
D_i = density of ice (0.92),
S_w = volume fraction of ϕ containing water.

This formula can be used to estimate the effect of ice on density log measurements in permafrost. It is evident that unless the fractional porosity is very high and most of the pore space is occupied by ice rather than water, the bulk density of rock is not greatly affected by permafrost. Hence, the density log can be used as a reliable indicator of the true porosity (Equation 6.2), independent of the ice content in the pores.

Litho-density logs are interpreted by use of mineral matrix analysis charts which relate P_e output to formation mineral makeup, and hence lithology (Gardner and Dumanoir, 1980).

6.2.5 Special Problems

Density logs are adversely affected by caving that commonly occurs in boreholes drilled in permafrost. Therefore it is important to run caliper logs to identify zones where caving may cause density readings to be invalid. Borehole effects may override and obscure formation response on logs made with uncollimated density probes.

6.3 Neutron Logs

Neutron-neutron logs record the effects of rocks on neutrons that radiate into the formation from a source on the logging probe, and are backscattered to a detector also located on the probe. Since hydrogen atoms are strong thermalizers of fast neutrons, and strong absorbers of thermal neutrons, the neutron-neutron log can be used to estimate the porosity of water-saturated rocks. Since neutrons can penetrate steel and plastic casing, neutron logs can be made in cased holes.

There are two approaches to the design of neutron probes for measuring formation water content (porosity in saturated rocks). One approach uses a relatively short spacing between source and dectector, typically 0-7 cm (0-3 in) (Troxler Electronics Laboratory, 1980), the other a relatively long spacing, 35-70 cm (14-28 in) (Kantor, 1955; Tittman, 1956a). In the case of the short-spacing tool, hydrogen atoms in the formation thermalize the fast neutrons radiating from the source, making them detectable by the thermal neutron sensor in the probe. This configuration is usually used in 'soil-moisture' probes (Troxlers) that are inserted into metal tubes with pointed, sealed tips that are driven into the ground. As the water (hydrogen) content of the soil increases, more and more neutrons are thermalized closer to the thermal neutron detector, so that the neutron count rate increases as soil moisture increases. The key to the success of the 'soil-moisture' probe measurement is that the tubes have a fixed and constant diameter just slightly larger than the probe, are dry (filled with air), and there are no large water-filled gaps between the soil and the tube driven into it. Under these controlled conditions, the probe response can be related to soil moisture by calibration in media having known moisture content. Troxler-type 'short-spacing' neutron-neutron probes have the advantage of being lightweight and portable for shallow measurements in remote areas. However, if a short-spacing neutron probe is used in a water-filled, rugose borehole of the type usually encountered in oil and mineral exploration, the response of the probe cannot be reliably related to rock water content. Under these conditions it is necessary to use a 'long-spacing' neutron probe.

When 'long-spacing' neutron probes are used, the formation thermalizes most of the fast neutrons issuing from the source before they reach the detector. The number of neutrons detected by the thermal neutron dectector in the probe decreases as the water content of the rock increases because more and more thermal neutrons are absorbed by the hydrogen (water) in the formation before they reach the detector. All commercial neutron-neutron porosity tools used in well logging (single detector, dual-detector compensated, and sidewall epithermal tools) are the 'long spacing' type for which neutron response decreases as formation water content increases (Tittman, 1956a).

The fundamentals of neutron porosity logging are presented in a series of three papers by Tittle (1961), and Tittle and Allen (1966) and Allen et al. (1967). A good collection of papers that describe practical applications is contained in the Society of Professional Well Log Analysts reprint volume Gamma Ray, Neutron and Density Logging, compiled by Lawson et al., (1978). J. Tittman's lectures (Tittman, 1956a and 1956b), which are reprinted in that volume, are particularly helpful for understanding neutron interactions with matter in well logging applications.

Pulsed neutron 'lifetime' or 'dieaway' logs are made with a neutron generator that produces pulses of 14 MeV (million electron volt) neutrons, and time-gated neutron and gamma ray detectors. These logs are used in oilfield applications where they can distinguish salt water from oil and gas in the pore space of reservoirs because of their sensitivity to chlorine, and can detect the relative amounts of silicon and oxygen in the formation, from which lithology can be inferred. A good collection of papers on pulsed neutron logging is presented in the Society of Professional Well Log Analysts reprint volume, Pulsed Neutron Logging (Hoyer et al., 1976).

Neutron activation logs are made with either neutron accelerator sources that produce pulsed 14 MeV neutrons, or by isotopic sources that produce a broad spectrum of neutrons of lower energy, and a spectral gamma ray detector. These logs have been developed experimentally for quantitatively detecting specific elements (gold, silver, copper, nickel, etc.), but they have not found widespread commercial usage yet, largely because of the complexity and cost of the equipment required to make the measurement. One exception is the use of neutron activation to measure uranium directly rather than by the conventional measurement of natural gamma radiation from daughter isotopes that may not be in secular equilibrium with uranium. In this application the neutron flux causes U-235 and U-238 in the formation to fission, and the delayed or prompt fission neutrons are detected after activation takes place (Humphreys et al.,1983; Duray 1982).

6.3.1 Principles

Probes that measure porosity by the neutron-neutron method use an isotopic source that produces a flux of fast neutrons that are moderated to epithermal energies (0.5 eV to several eV) and thermal energies (<0.025 eV) by hydrogen atoms in water in the borehole and in the formation (Tittman et al., 1966). The number of neutrons that reach the detector per unit time depends primarily on the concentration of hydrogen atoms in the formation, which in turn, depends on the porosity of the rock and its degree of saturation. With proper calibration, neutron-neutron logs can be used to estimate the porosity of water-saturated rocks with reasonable accuracy as long as extraneous neutron absorbers such as boron, chlorine and other strong absorbers of neutrons are not present in significant concentrations. Since ice has a lower hydrogen index than water, neutron logs can be used to infer the presence of ice in porous rocks, and in some cases, where neutron-neutron response is cross plotted with gamma-gamma density log response, the results can be used to estimate the ice-water ratio (Petersen et al., 1985).

6.3.2 Methods

Neutron-neutron 'long-spacing' logs are made with three basic types of probes; single-detector, compensated dual-detector, and sidewall epithermal-detector. The design of these probes is illustrated in Figure 6.2. All three types use an isotopic source of neutrons, usually americium-241 mixed with beryllium (Am-Be), sealed in a small metal capsule. Alpha particles emitted by Am-241 interact with nuclei of beryllium atoms, converting them to C-12, and releasing an excess neutron in the process. Neutrons that are generated by this reaction have energies of several MeV and are considered 'fast' neutrons. The simple single-detector probe uses a thermal neutron detector (helium-3 tube) that is spaced 40-50 cm (15-20 in) from the source that has a strength of 1-6 Ci (Curies). The compensated dual-detector probe is usually pressed against the side of the hole with a bowspring, and is equipped with two thermal neutron detectors at different spacings from the source. The dual-detector spacings are larger than the source-detector spacing of the single-detector probe, and the source strength is much greater, typically 16 Ci. The large spacings increase the depth of investigation, and the large source decreases the statistical variation of the log readings. A compensation algorithm is applied to the count rates from the two detectors to reduce errors caused by borehole effects. The sidewall epithermal neutron probe uses a skid containing both the source and the detector which are pressed against the borehole wall, reducing the effect of adverse borehole conditions. The detector in the skid is shielded so that neutrons with energies less than about 0.4 eV are excluded, reducing the sensitivity of the probe to strong thermal neutron absorbers (e.g. boron and chlorine) that might be present in the borehole fluid, pore fluid, or rock matrix.

6.3.3 Calibration

Neutron probes can be calibrated in pits containing artificial or quarried rocks with known porosities. The API pits at the University of Houston contain quarried blocks of limestone from three different formations that have porosities of 1.9, 19 and 27 percent (Belknap et al., 1959). Field calibration devices made of plastic or containing chambers that can be filled with water can be used at the drill site to check the calibration of the probe. Adjustments are made to bring the system back into calibration if necessary. Neutron-density crossplots are useful for calibrating neutron logs in specific formations where densities and porosities can be determined accurately from drill core.

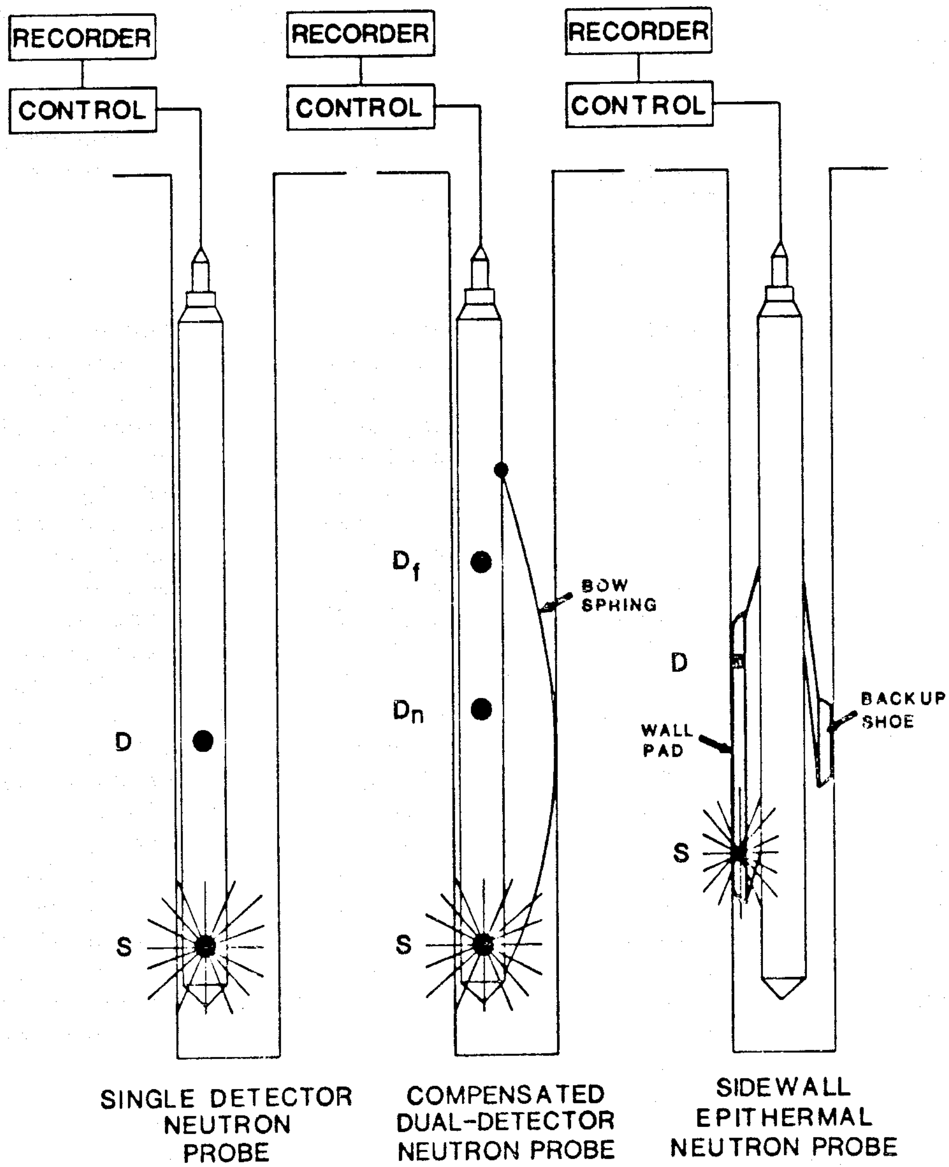

Figure 6.2 -- Neutron-neutron probes with different source-detector arrangements. Neutron sources are labeled S and detectors are labeled D. For the compensated probe, D_n is the near detector and D_f is the far detector.

Most oilfield neutron logging systems are now calibrated to record logs directly in neutron porosity index units for one or more of the three major sedimentary rock types; sandstone, limestone, or dolomite, although some systems still record logs in neutron API units (American Petroleum Institute, 1974). Most logging systems designed for mining and geotechnical applications record neutron logs in counts per second.

6.3.4 Interpretation

Neutron log interpretation begins with inspection of the caliper log to identify zones of severe borehole damage due to washouts or caving that might invalidate the neutron log readings. These zones, if present, are excluded from further analysis. Then intervals on the neutron log that represent lithologic units of interest are selected for quantitative analysis. If the neutron log is recorded in count rate units, the log readings in the selected intervals are converted to API units by use of an empirically derived calibration factor, and then to neutron porosity index units by use of charts or computer algorithms that require matrix lithology and hole diameter as input parameters (Gearhart-Owen, 1970; Scott, 1984). An example of such a chart is shown in Figure 6.3. However, even when neutron tools are carefully calibrated, the estimation of porosity by use of the neutron log alone is somewhat uncertain (Schlumberger, 1972). Crossplots of neutron porosity and measurements obtained from other logs, particularly density and resistivity logs, are commonly used to identify the lithologic character of the rock matrix, to infer the presence of oil or gas (Schlumberger, Ltd., 1974), and to aid in identifying permafrost (Petersen, 1985).

6.3.5 Special Problems

Neutron-neutron logs are sensitive to adverse borehole conditions such as extreme rugosity, washouts, and caving, all of which increase the apparent porosity by reducing the measured count rate. Of the three types of neutron probes, the single-detector probe is most severely affected by borehole conditions. Both the single-detector and dual-detector probes give anomalously high porosity readings if strong absorbers of thermal neutrons (e.g. chlorine and boron) are present in abnormally high concentrations in the borehole fluid, pore fluid, or in the rock matrix. The neutron logging measurement is sensitive to all forms of water; water of hydration in alteration minerals as well as water in the pore space. In mineral exploration, where porosities are often very low, the effect of bound water in hydrated minerals can dominate the neutron log, causing porosity estimates to be too high (Nelson and Glen, 1975). In permafrost environments, apparent porosities are reduced by the presence of ice which has a lower hydrogen density than water (0.92 vs. 1.00), and by the 'excavation' effect of ice (Segesman and Liu, 1971). This can be used to an advantage to identify zones containing pore ice by cross-plotting gamma-gamma density and neutron porosity index values (Petersen, 1985).

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7.0 MAGNETIC LOGS

Magnetic logs have been available for many years, but they have been used only sporadically and experimentally for solving special problems in oilfield and mineral deposit exploration and evaluation. There are three types of magnetic logs: magnetic susceptibility, magnetic field, and nuclear magnetic resonance (Telford et al., 1976). Magnetic susceptibility logs measure the degree to which a formation becomes magnetized when subjected to a magnetic field (i.e., the Earth's field) as a result of the magnetic minerals it contains. Magnetic field logs measure one or more components of the Earth's magnetic field in the borehole. Nuclear magnetic resonance logs measure the amount of free hydrogen in pore fluid (water or oil) in the formation.

7.1 Magnetic Susceptibility Logs

Magnetic susceptibility logs respond to ferromagnetic minerals such as magnetite, ilmenite, maghemite, and pyrrhotite. Magnetite and ilmenite often occur in high concentrations in iron ore, while maghemite and pyrrhotite sometimes occur in low, but anomalous concentrations in association with copper, nickel, uranium and other metallic ores. Low-sensitivity susceptibility logging equipment has been developed for assaying iron ore deposits in situ, and has been used successfully in taconite deposits containing more than 25 percent iron (Zablocki, 1974). High sensitivity systems have been developed that can detect magnetite in concentrations as low as a few parts per million (Scott et al., 1981; Emilia et al., 1981). Magnetic susceptibility logs are not affected by borehole fluid unless it contains particles of magnetic minerals in suspension, and logs can be run equally well in dry or fluid-filled holes. Logs can not be run in holes containing metallic casing, but fiberglass or plastic casing does not adversely affect the measurement.

7.1.1 Principles

Magnetic susceptibility probes are similar to induction conductivity probes (see Section 4.4) in that they both contain a coil that generates an electromagnetic field that penetrates into the formation. However, the frequency of the electromagnetic field used for susceptibility logging is much lower, typically 1000 Hz, which increases the sensitivity of the measurement to variations in magnetic susceptibility and decreases its sensitivity to conductivity.

7.1.2 Methods

Two different coil configurations have been used in magnetic susceptibility logging: The solenoid (single coil) and the transmitter-receiver (two coil) arrangements. The solenoid configuration is by far the more common, and has been described by Broding et al. (1952) and George and Scott (1982). The solenoid is usually wound on a high-permeability cylindrical core chosen for its temperature stability. In order to further reduce temperature drift, the coil assembly may be placed in a temperature regulated chamber in the probe (Emilia et al., 1981; Scott et al., 1981). The section of the probe containing the coil is covered with a shell made of electrically insulating material such as fiberglass or ceramic. The solenoid is connected to an induction bridge that is balanced for zero output in air.

The susceptibility log is a recording of the amplitude of the out-of-phase component of the off-null bridge signal which is nearly a linear representation of the magnetic susceptiblity of the formation. Depth of investigation is approximately equal to the length of the solenoid.

The design of the two-coil magnetic susceptibility probe is similar to that of the two-coil induction probe (see Figure 4.2). The advantage of the two-coil susceptibility system over the solenoid system is its relative insensitivity to borehole diameter and formation resistivity effects when coil spacing is optimized (Anderson, 1958). A disadvantage is that it is more difficult to design and construct than the solenoid system. The depth of investigation of the two-coil system is approximately equal to the coil spacing.

7.1.3 Calibration

Calibration of magnetic susceptibility logging systems can be accomplished with the use of concrete models or quarried rock models such as those described by Snodgrass (1976) and Mathews et al. (1978). The susceptibility of the models can be determined by making laboratory measurements of drill core samples obtained when the test holes are drilled in the models. Logging equipment can be checked in the field for valid calibration by placing calibration loops around the sensing coil. The loops contain reactive components that simulate known levels of magnetic susceptibility.

7.1.4 Interpretation

Magnetic susceptibility logs are interpreted in different ways, depending on the type of application and the information sought. If the objective is to obtain quantitative assays of iron contained in iron ore, an empirical relationship must be obtained between measured susceptibility and iron content determined from laboratory measurements of drill core (Zablocki, 1974). If the objective is to detect low-level, but anomalous concentrations of ferromagnetic minerals associated with copper sulfide deposits or other non-ferrous minerals, then interpretation is based on the deviation of susceptibility from background levels and from the normal variability of suceptibility in the formations where the deposits are likely to occur (Scott and Daniels, 1976). This requires logging representative boreholes in areas that are not anomalous.

7.1.5 Special Problems

Magnetic susceptibility logs are relatively free of problems associated with permafrost because the susceptibility of earth materials is independent of temperature within the range of temperatures encountered in boreholes in the Arctic. Susceptibility logs can be made in dry holes or in holes filled with any type of non-magnetic fluid. They are unaffected by casing as long as it is non-conductive and non-magnetic. Hole diameter corrections are required and can be determined empirically from susceptibility logging measurements made in test pits (Scott et al., 1981). Drift may occur if the temperature of the sensing coil cannot be kept constant because of extremely low ambient temperatures. If temperature drift is not too severe, corrections can be applied to minimize the error (Scott, 1984).

7.2 Magnetometer Logs

Magnetometer logs measure one or more components of the Earth's magnetic field in the borehole. They can be used to detect and locate magnetic ore bodies, and to determine the direction of polarization (normal or reversed) of volcanic flow and other strongly polarized rock units (Scott and Olson, 1985).

7.2.1 Principles

The Earth's magnetic field is distorted in the vicinity of pods or concentrations of ferromagnetic minerals, particularly if they are strongly polarized. This distortion can be mapped by making magnetometer measurements in boreholes that intersect or pass nearby the disturbing body. Modeling techniques can be used to estimate the location and size of the body if the direction and intensity of polarization is known. The direction of polarization of volcanic flow rocks can be determined from borehole magnetometer measurements made in holes that pass through the magnetized layer.

7.2.2 Methods

Magnetometer logs are made with probes containing one or more sensors, usually fluxgate elements. In holes that are nearly vertical, the magnitude of the vertical component of the Earth's field can be measured directly by a fluxgate element suspended as a pendulum inside the probe. A three-component fluxgate magnetometer with orthogonal fluxgate elements and sensors that measure probe orientation can be used to determine the direction and magnitude of the Earth's field. Logs made with this type of probe have been used to map iron ore bodies (Levanto, 1959; Bergdahl, 1963), and to determine the direction of polarization of volcanic rocks (Scott and Olson, 1985).

7.2.3 Calibration

Borehole magnetometers are usually calibrated by reference to a station magnetometer used as a secondary standard. A better, but more difficult and expensive technique, is to use Helmholtz coils to apply magnetic fields of known magnitudes and directions, and to relate the probe readout to these values.

7.2.4 Interpretation

Interpretation of borehole magnetometer measurements begins with computing the magnitude of the measured field from the probe readout by applying the proper calibration factors and correction factors. If the probe has orientation sensors (e.g., inclinometers and a gyroscope), and if it measures three orthogonal components of the magnetic field, both the direction and the magnitude of the Earth's field can be computed. Then modeling programs can be used to estimate the size and position of the anomalous magnetic source (Silva and Hohmann, 1981).

7.2.5 Special Problems

In polar regions the Earth's magnetic field often fluctuates because of the aurora, causing magnetometer measurements to be noisy, and leading to a degree of uncertainty in the interpretation of magnetometer measurements. Errors in borehole magnetometer measurements caused by these fluctuations can be reduced by making simultaneous magnetic field measurements with a station magnetometer near the site of the borehole. The station magnetometer readout can be used to correct the borehole measurements for minor flutucations, and to determine if and when the magnetic noise is too severe to make meaningful measurements. The presence of permafrost has no effect on borehole magnetometer measurements.

7.3 Nuclear Magnetic Resonance (NMR) Logs

The borehole NMR measurement examines the formation for hydrogen nuclei that are 'free' to move about without mechanical restriction. Water and oil in open pores in permeable rocks contain 'free' hydrogen nuclei, while water of hydration associated with clay minerals, water in direct contact with rock grains, and hydrocarbons with viscosities greater than about 500 centipoise, do not (Brown and Neuman, 1980; 1982). The NMR log should also be able to distinguish water from ice in porous, permeable rocks, although the technique has not been tested in this application.

7.3.1 Principles

'Free' hydrogen nuclei in pore water or oil can be visualized as tiny bar magnets or magnetic dipoles that spin continuously around the long axis of the magnet and move about in a random fashion so that the net magnetic field produced by the motion of all of the magnets together is zero. In NMR logging, all of the hydrogen nuclei dipoles are lined up in the same direction by a strong dc magnetic field that is applied for a few seconds. When the dc magnetic field is removed, all of the spinning dipoles precess in unison in response to the pull of the Earth's magnetic field, and for a short period of time an alternating magnetic field is generated at the precession frequency of the dipoles. After a few tenths of a second the hydrogen dipoles return to random motion, and the net magnetic field becomes zero again. During the period of time that the dipoles are precessing in unison, the amplitude of the alternating magnetic field, which is sensed by a coil in the logging probe, is proportional to the concentration of 'free' hydrogen dipoles in the formation. The relaxation time required for the dipoles to return to random motion depends on the type of fluid. For water the relaxation time is generally less than 300 ms, but for oil it is more than 600 ms, making it theoretically possible to distinguish oil from water. A discussion of the principles of NMR logging is given by Brown and Gamson (1982).

7.3.2 Methods

The NMR log is sensitive to 'free' hydrogen in the borehole fluid as well as 'free' hydrogen in water or oil in the formation. In order to remove the effect of the borehole fluid, powdered magnetite and other chemicals are added to the drilling mud and circulated before the log is run (Brown and Neuman, 1980; 1982). Two logging runs are usually made. During the first run the 'free fluid index' is recorded to identify zones containing 'free' hydrogen contained in liquid water or oil in the formation. A second run is made with the probe held stationary at depths of interest to determine whether the liquid is water or oil by observing the relaxation time of the NMR signal. An excellent guide to planning NMR logging is given by Brown and Neuman (1982).

7.3.3 Calibration

The 'free fluid index' log is calibrated to read out in free fluid index numbers (FFI) which represent the fraction of pore space occupied by 'free fluid' in the formation (Pirson, 1963).

$$FFI = \frac{V}{EG} \qquad (7.1)$$

where FFI = 'free fluid index',
V = initial precession voltage measured,
E = environmental factor (a function of T, H, and I),
T = temperature,
H = Earth's magnetic field,
I = inclination of H with respect to the tool,
G = tool geometric factor.

7.3.4 Interpretation

According to Pirson (1963), when the FFI exceeds 6 percent, the formation can be expected to be sufficiently porous and permeable to produce fluid, and the type of fluid (water or oil) can be determined by measuring the relaxation time. The relaxation time for saline water ranges from 50 to 300 ms, while the relaxation time of oil and gas exceeds 600 ms. Zones with FFI less than 6 percent may be interpreted as shales, tight sands, or permafrost. Crossplots of FFI and porosity computed from density logs (which are relatively insensitive to pore spaces filled with ice rather than water) should indicate whether or not porous formations are frozen. However, it should be noted that this technique has not been tested in permafrost environments.

7.3.5 Special Problems

NMR logs are very sensitive to hole diameter variations, and therefore caliper logs are usually run simultaneously (Brown and Neuman, 1982). Since NMR logs have not been tested in permafrost environments, their value for identifying permafrost is conjectural. They are difficult and expensive logs to run, even under good environmental conditions, which probably accounts for their slow development since the early 1960's. They are still considered experimental and need to be developed and tested further before being evaluated in terms of their usefulness in permafrost applications.

7.4 References

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8.0 MISCELLANEOUS LOGS

Logs in the miscellaneous category include caliper logs that provide a continuous record of borehole diameter, hand written lithology logs based on observations of drill cuttings and cores, and automatic recordings of mechanical parameters associated with drilling.

8.1 Caliper Logs

One of the most important steps in the quantitative analysis of geophysical well logs is the application of corrections for hole diameter. Accurate corrections require continuous readings of hole diameter over the entire depth range covered by the geophysical logs, and these readings can only be obtained from high-quality caliper logs. Furthermore, some well logs give invalid readings in zones where the borehole wall is severely damaged by the drilling process. In permafrost, holes drilled for geotechnical purposes by augering or rotary-air drilling methods in competent materials generally remain open. However, holes tend to cave in dry coarse-grained permafrost and when ice-bonded materials are thawed by warm drilling mud. It is necessary to detect and identify areas where caving has occurred by inspection of the caliper log so they can be excluded from analysis rather than being interpreted erroneously. In some cases, the caliper log alone has been used to detect the base of permafrost (Osterkamp and Payne, 1981). Caliper logs are also useful for making stratigraphic correlations from hole to hole, because rugosity and washouts that appear as hole diameter anomalies often provide characteristic signatures of specific formations.

8.2 Drilling Logs

Drilling logs are made by the driller or geologist at the well site who observes and describes the drill cuttings or cores as they are obtained, and notes the depth interval that they represent. These logs provide a preliminary description of the lithology of formations penetrated by the drill, and are useful for relating the response of geophysical logs to lithology.

8.2.1 Mud Logs

Mud logs are routinely run in petroleum exploration drilling to detect the presence of hydrocarbon gases that flow into the drilling fluid when oil or gas bearing formations are penetrated. They are useful for identifying zones of potential production of oil or gas, and are helpful in explaining anomalous readings on well logs caused by hydrocarbons. Mud logs have proven to be very useful for detecting gas hydrates occurring within and directly below permafrost on the North Slope of Alaska (Osterkamp and Payne, 1981; Collett, 1983).

8.2.2 Drilling Parameter Logs

Drilling records of penetration rate, bit pressure, and rpm reflect the hardness and ease with which the formation may be drilled which, in turn, varies with rock type and the degree of consolidation and induration of the formation. Therefore, these records can be used along with well logs to infer lithology and to pick the depths of contacts between soft and hard formations. In permafrost, massive ice can sometimes be identified by the ease and speed of drilling when it is encountered.

8.3 References

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9.0 BOREHOLE GEOPHYSICAL SURVEYS

Borehole geophysical surveys are made to obtain information on the gross or average physical properties of formations penetrated by boreholes, particularly electrical resistivity, seismic velocity and density (borehole gravity). Two cross-hole techniques using resistivity and seismic measurements for mineral exploration have been described by Scott et al. (1975). Other techniques that have greater ranges and require only one borehole are discussed in the following sections.

9.1 Borehole Electrical Resistivity Surveys

Borehole resistivity surveys made with wide-spaced electrode arrays are effective for determining the average resistivity of thick lithologic units without significant measurement errors caused by borehole effects. Runge et al. (1969) describes a technique known as 'ULSEL' (ultra long spaced electric log) that has been used to detect the presence of salt domes (high resistivity) at distances up to 760 m (2500 ft) from a borehole. The electrodes are arranged in a normal array with AM spacings ranging from 23 to 305 m (75-1000 ft) on a long bridle (insulated cable). Similar devices would probably be useful for locating the edge of permafrost from a hole drilled in unfrozen ground some distance away. Although the technique has not been tested for finding the boundary of permafrost at depth, the high-resistivity of permafrost should produce anomalies similar to those associated with salt domes, and therefore the technique would probably be successful in this application.

Another long-range electrical measurement technique called 'telelog' uses surface current electrodes to generate an electromagnetic field that is sensed by potential electrodes on a probe lowered into a borehole (Gabillard et al., 1971). Typical spacings used for the surface electrodes and probe electrodes are 100 m (330 ft) and 1.6 m (64 in) respectively. The surface current electrodes are aligned radially with respect to the borehole, and are stepped outward from the borehole to distances of 2000 m (6560 ft) or more along radial lines. The technique has been used successfully to locate the edge of a gas reservoir in France up to 900 m (2950 ft) away from a borehole. Since permafrost commonly produces resistive anomalies at least as large as those associated with gas reservoirs (about 10:1), the technique should also be capable of detecting the edge of permafrost at depth.

Another variation of this technique uses a current electrode in the borehole and another on the ground surface sufficiently far away to be considered effectively at infinity. The current applied to these electrodes generates a field that is detected by orthogonal potential dipole electrodes that are positioned along radial lines emanating from the borehole, or in a rectangular grid (Daniels and Dyck, 1984). Because the measurements are made with orthogonal potential dipoles, the results can be plotted as two-dimensional vectors, and these can be used to interpret the location, size, and resistivity contrast of subsurface anomaly-producing features by computer modeling techniques.

Various inductive techniques using current loops on the ground surface and pickup coils in boreholes have been developed for mineral prospecting (Daniels and Dyck, 1984), and these techniques probably would be equally useful in permafrost applications.

9.2 Borehole Seismic Velocity Surveys

Borehole velocity surveys provide information on the average velocity of compressional waves over large depth intervals in formations penetrated by boreholes. This information is required for accurate interpretation of seismic reflection surveys. The surveys are made with cables containing pressure detectors at intervals of 3-30 m (10-100 ft). The detector cable is lowered into the borehole, with the uppermost detector at the top of the shallowest depth of interest. An explosive charge is detonated in a shallow hole near the collar of the borehole being surveyed, and a seismic record is made of the response of the detectors to the arrival of the compressional wave. Then the cable is lowered in the borehole so that the uppermost detector is at the same position that was occupied by the lowermost detector when the first record was made, and another explosive charge is detonated. This process is repeated until the entire hole has been surveyed. A plot of arrival time vs. depth is made, from which interval velocities and overall average velocities are determined (Dobrin, 1976). In permafrost environments, these surveys can detect high velocity anomalies associated with frozen formations. Downhole velocity surveys have an advantage over velocity logs when used for this purpose, because they penetrate deeply into the formation, avoiding thawed zones that commonly occur close to the borehole wall and sometimes prevent sonic logging pulses from reaching the undisturbed, frozen formation.

9.3 Borehole Gravity Meter Surveys

Borehole gravity surveys can be interpeted to obtain very accurate values of the bulk density of thick, flat-lying lithologic units. Measurements of gravity are made at the tops and bottoms of units of interest, and density is computed from the following formula after corrections have been applied for terrain, borehole and regional gradient effects;

$$\bar{\rho} = (F - \Delta g/\Delta z)/4\pi k \qquad (9.1)$$

where $\bar{\rho}$ = average bulk density of the lithologic unit,
F - free-air vertical gradient,
Δg = difference in gravity between top and bottom of lithologic unit,
Δz = difference in depth between top and bottom of lithologic unit,
k = universal gravitational constant.

Densities computed from borehole gravity surveys may be accurate to ±0.01 g/cm^3 or better, depending on the inherent reading accuracy of the meter, the accuracy of corrections, and the thickness of the lithologic unit that is bracketed by gravity measurements.

Most borehole gravity meters in use today are modifications of the geodetic gravity meter developed for surface gravity surveys. In principle they are horizontal pendulums with long periods of oscillation ($\geq$15 s). The theory of operation of these meters is given by Nettleton (1976).

Smith (1950) and McCulloh (1966) have discussed the fundamentals of borehole gravity measurements and corrections, and Rasmussen (1975) and Robbins (1979) have described applications to petroleum and coal exploration and evaluation, respectively. A comprehensive discussion of borehole gravity equipment, data analysis, interpretation, and application is given by Beyers (1982).

Borehole gravity surveys are slow and expensive to run, often requiring one or two full days to complete, with equipment costing over a half million dollars. Therefore, they are generally reserved for applications where the determination of bulk density to a high degree of accuracy is very important and economically justified, mainly in oil well completion studies. They are not affected by permafrost except to the extent that the density of ice is lower than the density of water. They should be capable of detecting ice-rich permafrost and massive ground ice because of their low densities.

9.4 References

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10.0 APPLICATIONS

10.1 Lithology

A knowledge of the lithological parameters of permafrost is essential for the determination of many of the thermal and mechanical parameters needed for well completions, mining analysis and geotechnical site evaluation. Lithological parameters to be determined include soil type and texture, depth to the table and base of the ice-bonded permafrost, and fractional volumes of soil, ice, and unfrozen water.

10.1.1 Soil Type and Distribution

The soil type can be determined from cores, mud logs or drill cuttings. However, continuous coring can be expensive and partial coring gives an incomplete picture of a section. Due to the lag between the time that the drill penetrates a lithological unit and the time that the mud or cuttings come to the surface and the dispersion of the cuttings while coming to the surface, it is sometimes difficult to determine the depth and spatial distribution of any particular lithological unit from a mud or cuttings log.

Continuous wireline logs provide valuable data for a determination of the apparent thickness of the different units and, according to Delfiner et al. (1984), most geologists and engineers accept the fact that wireline logs provide reliable information on lithology.

In non-permafrost logging, lithology is usually determined from a single log or a combination of logs. Since the presence of permafrost affects the response of some logs, it is important to know which logs are affected and how they are affected.

The SP (self potential) log is used for the delineation of lithological units, but does not always correlate with the lithology in a consistent manner in permafrost. However, the SP log has been noted to have a negative drift with decreasing depth through the base of the ice-bearing permafrost (Desai and Moore, 1968; Hnatiuk and Randall, 1977; Pollard and Nash, 1971). The SP response is affected by telluric currents that are sometimes caused by the Aurora Borealis (Northern Lights) which occurs quite frequently in permafrost regions. When large telluric currents affect the SP, the log may be rendered useless (Hilchie, 1982). However, Hoyer et al. (1975) suggest running SP logs in permafrost, despite this possibility, so as to not lose a potentially valuable source of information.

Resistivity logs are sometimes used to delineate lithological units in unfrozen formations. However, in permafrost, the resistivity of a soil or rock is dependent on the unfrozen water content which in turn is dependent on temperature. Since the temperature in permafrost typically varies with depth, interpretation of the resistivity log may be unclear when identifying similar lithological units at different depths or when correlating the same unit at different depths from logs of a number of boreholes. The deep induction log is the preferred resistivity device for logging in oil wells because it has a large radius of investigation (Hnatiuk and Randall, 1977; Osterkamp and Payne, 1981; Petersen et al., 1985).

Snegirev (1973) reports that IP (induced polarization) generally increases when soil freezes, with coarse-grained frozen soils having the maximum IP. The IP decreases with increasing fineness of the soil. Hence, IP effects in frozen soils are different from those in unfrozen soils where IP attains a maximum which is a function of clay concentration and clay mineral type (Keller and Frischknecht, 1966). Snegirev (1973) also reported that combined resistivity and IP surveys clearly delineate sections of ground with increasing ice.

Gamma log response is generally linearly related to the fractional volume of clay-sized particles in sedimentary deposits (Heslop, 1974) and is not affected by freezing. Therefore, it can be used to differentiate fine-grained silts, shales and clays from coarser-grained sands, gravels, consolidated bedrock and massive ice. Petersen et al. (1985) found that an artificial ice mass buried in Fairbanks silt had a very low gamma count rate compared to the silt. King (1983) showed that for unconsolidated permafrost samples from the Canadian Arctic the unfrozen water content increases linearly with the fraction of clay-sized particles for a given porosity and temperature. As the unfrozen water content of a particular soil increases, the resistivity decreases (Hoyer et al., 1975). Thus, in permafrost, the resistivity can be expected to decrease with increasing gamma count rate. Hoyer et al. (1975) used a combination of the gamma and deep induction resistivity logs to interpret the lithology of the ice-bearing permafrost for a well on the North Slope of Alaska and their interpretation agreed reasonably well with core data. If the gamma log is complicated by the occurrence of uranium mineralization, a gamma ray spectral log should be run.

Caliper and borehole geometry logs can be used to indicate ice-bonded sands, gravels, clays, and fine-grained sediments. A thawed annulus around the borehole often results from drilling and the subsequent circulation of the relatively warm drilling muds (Desai and Moore, 1968). Unconsolidated, thawed sands and gravels will tend to slough into the borehole causing severe enlargement of the borehole (Hoyer et al., 1975; Osterkamp and Payne, 1981; Petersen et al., 1985). The plasticity of clays and fine-grained sediments may cause them to creep into the borehole and decrease the diameter of the borehole. Thus, borehole diameters larger than gauge often indicate ice-bonded sands and gravels, whereas diameters smaller than gauge often indicate clays and fine-grained sediments. The borehole geometry log often correlates with the gamma log from wells through the ice-bearing permafrost from the North Slope of Alaska. However, some sands and gravels will not cave upon thawing and some clays and fine-grained sediments will cave; hence, the borehole geometry log should not be used alone to interpret lithology. However, the borehole geometry log is essential for determining borehole corrections for the other wireline logs that are sensitive to borehole diameter. In some cases the caving of the borehole in permafrost can become large enough to make corrections meaningless, and it is important to know where these zones occur so that the invalid data can be identified and discarded.

Problems associated with the thawing and sloughing of the borehole wall may possibly be circumvented by using logging tools that are incorporated into the drill stem (Hendricks et al., 1984). With these tools, known as MWD (measurement while drilling) devices, the formation is logged before the thermal disturbance becomes significant. The data from MWD tools may be stored in resident memory, or transmitted to the surface acoustically through the drilling mud, or electrically through special drill rods containing insulated conductors.

The acoustic, or sonic velocity, log has been used as an indicator of lithology, but it is greatly affected by ice content. Generally, in wells from the North Slope of Alaska, the acoustic log shows sands and gravels as high velocity sections and clays and fine-grained sediments as lower velocity sections. Osterkamp and Payne (1981) noted that sections above the permafrost base often showed a decrease in velocity on the acoustic log which was attributed to a decrease in ice content with depth. The acoustic log has a relatively small radius of investigation and is affected by the thawed annulus and the size of the borehole in caved sections. Severely caved sections of a log can appear as low velocity layers, often accompanied by cycle skipping. Unfortunately, caving usually occurs in the ice-bonded sands and gravels that have been thawed by the drilling mud, and severely caved sands and gravels may be mistakenly interpreted as low-velocity clays and fine-grained sediments. Thus, the acoustic log is not a reliable indicator of lithology in permafrost when used alone. Some of the adverse effects of borehole geometry can be alleviated by using a borehole compensated sonic or a long spaced sonic tool (Hoyer et al., 1975).

The density log is only slightly affected by ice in the pore spaces (Petersen, 1985) and can be used to identify massive ice and ice-rich soils (McKay and O'Connell, 1976). In boreholes where severe caving may have occurred, it is necessary to run a caliper log with the density log. Petersen et al. (1985) examined density logs from boreholes where the caving in some sections was so severe that the density tool decentralizing arm could not hold the tool against the borehole wall. In these sections, the density log hangs free in the borehole and only measures the drilling mud density. In logs from boreholes in non-permafrost areas, low density materials are generally interpreted as coals; caution must be exercised to avoid confusing low density coals with ice-rich soils, massive ground ice or severely caved boreholes.

The P_e (index of the effective photoelectric absorption cross section) of the formation is theoretically insensitive to porosity. Brock (1984) shows that for pure quartz, $P_e = 1.81$, for 35% porous quartz, $P_e = 1.54$ when water saturated and $P_e = 1.76$ when saturated with methane. Since the density difference between methane and water is much greater than the difference between ice and water, the P_e log should be insensitive to ice and traditional interpretation methods should be valid. Hence, it should be possible to use the P_e log as an indicator of the mineral matrix in permafrost.

Since the density and P_e logs are only slightly affected by ice in the pore spaces, traditional P_e vs. density crossplot lithology interpretation techniques should be approximately correct.

The neutron log is affected by ice. Since the hydrogen density of ice (0.92) is lower than that of water (1.00), and because of the 'excavation' effect in ice, a neutron tool that has been calibrated for use in water-filled formations, will see pure ice as a medium with a porosity of approximately 72% (Petersen, 1985), and formations with ice contained in the pore spaces will show anomalously low apparent neutron porosities. Thus, conventional neutron-density crossplots cannot be used to determine lithology in permafrost. A caliper log should be run with the neutron log when caving of the borehole is suspected because borehole diameter corrections are quite large for most types of neutron logs.

10.1.2 Detection of Permafrost

Because permafrost is defined by temperature, the temperature log is the only log that can determine the presence or absence of permafrost. However, permafrost does not usually present a geotechnical problem or a geophysical anomaly unless it contains excess ice in the pore spaces or massive ground ice. This section addresses the problems associated with the detection of ice-bearing permafrost.

Ice-bearing permafrost can be differentiated from unfrozen sediments on temperature logs by the difference in thermal gradient caused by the differences in the thermal conductivity of water as opposed to ice (Lachenbuch et al., 1982). However, when unfrozen water is present, the change in the thermal gradient across a phase boundary may be very gradual, making it difficult to determine the exact position of the boundary (Osterkamp and Harrison, 1982).

The depth to the base of the ice-bearing permafrost is best determined from the deep induction resistivity log. However, acoustic or sonic velocity logs are also helpful in substantiating the base determined from the resistivity log (Desai and Moore, 1968; Pollard and Nash, 1971; Osterkamp and Payne, 1981). Hnatiuk and Randall (1977) state that downhole seismic surveys made with crystal pressure detectors mounted on a cable lowered into the borehole can also be used to confirm the depth to the base of the ice-bearing permafrost as indicated by well logs. Walker and Stuart (1976) detected a low velocity, unfrozen zone within the permafrost from a crystal cable survey; a zone that was not indicated by the sonic or resistivity logs.

Because of caving in ice-bearing permafrost, the caliper log is often a useful tool for substantiating the thickness of the ice-bearing permafrost as determined from the resistivity log (Pollard and Nash, 1971; Osterkamp and Payne, 1981).

A crossplot of gamma-gamma density vs. neutron porosity can be used for the delineation of ice-bearing soils (Petersen, 1985), However, this technique is complicated by the fact that changes in lithology, gas and organics content can also affect the neutron and density log responses. The density-neutron crossplot can also be used for the determination of the true porosity and the unfrozen water content of the permafrost.

10.1.3 Density, Porosity and Ice-Water Content

The gamma-gamma density log has received such a wide acceptance for density determinations that it is usually referred to as the density log. The apparent density determined by a tool calibrated in unfrozen soils is only slightly affected by the presence of ice or air in the pore spaces (Petersen, 1985) and therefore the density log can be used for preliminary calculations without corrections.

If the densities of the soil or rock grain particles and material contained in the pore spaces are known, porosity can be calculated from density log data (McKay and O'Connell, 1976; Petersen, 1985). If the soil or rock density deviates far from the density for which the tool was calibrated, the photoelectric absorption log trace, P_e, can be used to determine the soil or rock type and, hence, its grain density (Brock, 1984). The photoelectric cross section per unit volume can also be used to estimate porosity directly (Brock, 1984).

If the resistivity of the unfrozen water is known, the volume fraction of unfrozen water can be found using Archie's Equation (Desai and Moore, 1968). Hoyer et al. (1975) have developed an equation to calculate the unfrozen water content of permafrost if the resistivity of the same soil is known in an unfrozen state. The ice content for saturated soils can be calculated from the porosity and unfrozen water content.

King (1983) emperically showed that the volume fraction of unfrozen water varied linearly with acoustic velocity for unconsolidated permafrost samples from the Canadian Arctic, independent of the ice and soil matrix content. Hence, the acoustic and resistivity logs both respond to the unfrozen water volume fraction of the permafrost, and thus, acoustic velocity data could potentially be used with resistivity data to determine the salinity of the unfrozen water in permafrost.

Petersen (1985) showed that the density vs. neutron crossplot can be used to determine total porosity and the fraction of unfrozen water and, for frozen peats, the fractions of ice, organics and mineral materials. When gas or organics are contained in the pore spaces in conjunction with ice and unfrozen water, a combination of three logs (density, neutron and acoustic) is necessary to determine the fractional volumes of four soil constituents (ice, water, soil matrix, and gas or organics).

10.2 Thermal Regime and Thermal Properties

The use of temperature logs to determine the thermal regime of permafrost and to obtain information on its thermal properties is described in Section 3.4. This section addresses some additional experimental methods and the relation of the logs to temperature logs.

Borehole heating experiments have been used to determine the thermal conductivity of permafrost (Osterkamp and Harrison, 1985). The experimental method is based on conductive heat transfer theory. However, the method is subject to error if latent heat effects associated with melting some of the pore ice are present.

Thermal diffusivity of the permafrost can be obtained from measurements of the natural temperature variations (e.g., McGaw et al., 1978).

The volumetric heat capacity can be calculated from the volume fractions, densities and specific heats of the components of the permafrost (Anderson and Morgenstern, 1973). Volume fractions of the permafrost components can be found using the techniques outlined in the section above on lithology. Heat capacity can also be determined if the thermal conductivity, density and the thermal diffusivity are known.

10.3 Mechanical Properties - Elastic Moduli

If valid values for bulk density, shear wave velocity, and compressional wave velocity can be obtained, then Young's modulus, bulk modulus, shear modulus, and Poisson's ratio can be calculated (Kowalski, 1978). Bulk compressibility is calculated as the reciprocal of the bulk modulus. Akimov (1973) reported that, in Bol'shezemel'skaya tundra, longitudinal waves varied between 0.6 to 4 km/s, V_p/V_s (ratio of compressional wave velocity to shear wave velocity) varied between 1.9 to 2.4, dynamic Young's modulus varied from 0.1×10^4 to 2.6×10^5 kg/cm^2 and Poisson's ratio varied between 0.23 to 0.5.

10.4 Petroleum Exploration and Production

More money is spent on the seismic method than any other geophysical prospecting method used in the search for petroleum. Yet, in the Arctic, seismic prospecting is handicapped by the existence of a high velocity permafrost layer. Since the base of the ice-bearing permafrost is not sharply defined, seismic records do not show a distinct reflection at the base. Hence, the high velocity and seismically undefined permafrost can affect the seismic records of potential reservoir formations that exist deep below the permafrost base. The problem is especially acute in offshore areas where subsea permafrost of variable thickness occurs with very little contrast between the relatively warm frozen material and the adjacent unfrozen material.

The depth of the base of the ice-bearing permafrost must be determined in order to correct the seismic records for the high-velocity permafrost layer. The acoustic velocities of layers within the permafrost must be known as well. The crystal (pressure detector) cable survey can provide both (Walker and Stuart, 1976). Potentially, the VSP (vertical seismic profile) method could also give velocities in the ice-bearing permafrost and provide better insight into the structure of the permafrost than the crystal cable. Both methods have the advantage over the acoustic logs in that they avoid the problems of the thawed and sometimes caved annulus around the borehole.

In the analysis of the seismic data, it is often desirable to calculate reflection coefficients for the lithology encountered which requires a knowledge of density as well as velocity. Hence, the density log should be run in conjunction with velocity surveys.

10.4.1 Arctic Well Completion

Goodman (1977) outlined the basic permafrost data requirements for the completion of wells in the Arctic. The required data were broken down into three categories: lithology, thermal properties, and mechanical properties summarized in Table 10.1.

Most of the parameters in Table 10.1 have been addressed in Sections 10.1, 10.2, and 10.3. Some of the parameters that are specific to well completion will be discussed in this section.

Table 10.1--Permafrost data requirements for completion of wells in the Arctic (after Goodman, 1977).

Lithology	Thermal Properties	Mechanical Properties
1. Soil type and distribution	1. Thermal conductivity of thawed/frozen permafrost*	1. Bulk compressibility of thawed permafrost
2. Depth of permafrost table/base	2. Heat capacity of thawed/ frozen permafrost*	2. Shear modulus of thawed permafrost
3. Porosity	3. Heat of fusion*	3. Young's modulus of frozen permafrost
4. Density	4. Initial geothermal temperature distribution	4. Poisson ratio of permafrost*
5. Ice content		5. Cohesive yield strength*
6. Unfrozen water content		6. Angle of internal friction*
7. Hydrate content		7. Fracture gradient
8. Hole washout size		8. Pore pressure*

*Can be estimated from lithology.

Natural gas hydrates can be detected using the induction or resistivity and the mud gas logs. The sonic, caliper, SP, and neutron logs can also be useful (Collett, 1983; Stewart and Weaver, 1983). Since hydrates have a hydrogen index of 1.07 to 1.13 (Collett et al., 1984) and a sonic velocity of 0.88 relative to ice at -10^{o} C (Whiffen et al., 1982), there is a difference between ice-saturated sediments and hydrate-saturated sediments on the neutron and sonic logs for a given porosity. Collett et al. (1984) have shown that the sonic-neutron crossplot has good potential for the quantitative analysis of gas hydrates. The density-neutron crossplot also has potential because the density log responds primarily to the true porosity and the neutron log gives low apparent porosity if ice is contained in the pore spaces (hydrogen density of ice = 0.92), and high apparent porosity if hydrates are present instead of ice (Segesman and Liu, 1971). When gas hydrate content is to be determined within the permafrost, the possibility exists for both water and ice to exist in the pore spaces along with the hydrates. A potentially useful method of determining the fractional volume of all three components in the pore spaces would be a three dimensional density-sonic-neutron analysis. When the hydrates occur below the base of the ice-bearing permafrost, resistivity and SP logs may provide the information needed to estimate water and hydrate content.

Bulk compressibility is calculated as the reciprocal of the bulk modulus which can be calculated from shear and compressional wave velocities from a sonic log (Kowalski, 1978). Goodman (1977) suggested that bulk compressibility of thawed permafrost and Young's modulus of frozen permafrost are the two dominant mechanical properties needed for arctic well completion. Young's modulus was cited as being insensitive to the angle of internal friction and it was recommended that the angle of internal friction be estimated from a knowledge of lithology.

Harrison and Osterkamp (1981) and Osterkamp and Harrison (1985) report a method of obtaining pore pressure profiles in the subsea permafrost sediments at Prudhoe Bay, Alaska. They used a pneumatic pressure transducer at the tip of a probe that was hammered into the sediments.

In unfrozen areas, the pore pressures at depths greater than 600 m (2000 ft) have been estimated from the sonic velocity or resistivity of shale beds (Hottmann and Johnson, 1965). Since the sonic velocity and the resistivity of shale beds in permafrost are dependent on ice content, which is in turn dependent on temperature, these methods will probably not work for permafrost well logging. S. P. Godbole of the Petroleum Engineering Department, University of Alaska (personal commun., 1984) has used the gamma log response of shale beds to estimate the pore pressure in permafrost.

10.5 Mining Applications

When examining the factors that determine the economic feasibility of developing a mine, the grade of ore in the deposit and cost of removing any overburden are of prime importance.

10.5.1 Ore and Coal Delineation and Grade Estimation

Estimation of the extent and grade of mineral deposits should be based on logs that are not greatly dependent on the ice content of the ore body. SP, IP and resistivity logs are significantly affected by the existence of ice in the pore spaces. On the other hand, magnetic field and magnetic susceptibility logs (Telford et al., 1976) are independent of ice content. Photoelectric absorption and neutron activation logs should also be useful for the estimation of the ore grade independent of ice content.

Logging for coal in permafrost presents a special problem because many of the properties of coal that allow it to be defined in the unfrozen setting are not as anomalous in a frozen environment. Coal beds are often delineated by their high resistivity, but ice-bearing permafrost also has a very high resistivity. Therefore, it may be difficult to distinguish low density coals from ice-rich soils. Acoustic velocities are low in unfrozen coals, but may be high in hard frozen coals. Coals are usually characterized by a low natural gamma count rate which, in permafrost may also be indicative of massive ice. Daniels et al. (1983) showed that IP correlated with the sulfur content of a Wyoming coal. However, a high IP can also be associated with ice rich gravels (Snegirev et al., 1973).

Petersen (1985) determined the fractional volumes of ice, organic peat and ash by using a density vs. neutron crossplot of data from logs through a frozen peat bog. Since coal and peat are of similar elemental composition, it should be possible to differentiate coals from ice-rich soils on a density vs. neutron crossplot. However, Petersen (1985) used the theoretical neutron response described by Segesman and Liu (1971) which models the neutron response on the basis of the hydrogen index, H (the hydrogen density of the material in the pore spaces relative to water index). For coals, $H \approx 0.5$ and the theory of Segesman and Liu (1971) predicts a low apparent neutron porosity for coals, relative to ice-rich soils. Schlumberger (1974) states that coals are characterized by high apparent neutron porosities due to their high carbon content. Further work and experience is needed before the parameters that define coal in permafrost can be established.

10.5.2 Overburden Composition

The overburden composition and depth are important parameters for estimating the cost of overburden removal. Lithology, thermal properties, and mechanical properties should be considered when defining the overburden composition.

Lithology and thermal properties of frozen overburden are needed to estimate its sensitivity to thawing, either for the purpose of thawing it before removal or to protect it for drift mining operations. Thermal properties to be estimated are the thermal conductivity, heat capacity, thermal diffusivity, and heat of fusion.

King et al. (1978) have designed an acoustic logging tool specifically for evaluating the quality of rock masses. The tool was used successfully in several Canadian nickel mines.

10.6 Geotechnical Applications

For geotechnical site evaluation the engineer must first determine if the permafrost site is thaw stable. If the site has been determined to be thaw unstable (i.e. the permafrost contains massive ground ice or is ice-rich) a decision must be made to either move to another site, thaw or excavate the existing permafrost, or to plan the construction so that it does not disturb the permafrost. Once the decision has been made to build on potentially thaw unstable permafrost the lithology of the permafrost and its properties should be determined. If the permafrost is to be thawed, a knowledge of the thermal properties of the permafrost is necessary. If the permafrost is to be excavated, the depth to thaw stable soils should be known. Construction techniques that avoid thawing of the permafrost usually involve pilings. Successful design of pilings in permafrost requires a knowledge of the soil type, ice and unfrozen water contents, unfrozen water salinity, depth to the permafrost table, and the undisturbed permafrost temperature distribution.

10.6.1 Thaw Consolidation

A knowledge of the soil type and porosity can be used to estimate the potential thaw strain of permafrost (Hanna et al., 1983). Soil type can be obtained from drill cuttings, and porosity can be calculated from the values of bulk density determined from a calibrated gamma-gamma density log (McKay and O'Connell, 1976; Petersen et al., 1985; Petersen, 1985). If bulk density, total porosity, ice and water contents are known, then the dry density can be calculated. Nelson et al. (1983) have correlated dry bulk density with thaw strain. Thaw strains can be integrated over depth to give an estimate of thaw consolidation.

10.6.2 Lithology Determination

Defining the lithological parameters of permafrost is essential for the calculation of many of the thermal and mechanical parameters needed for geotechnical site evaluation. Lithological parameters to be determined include a knowledge of soil type and texture, depth to the table and base of the ice-bonded permafrost, and fractional volumes of soil, ice, and unfrozen water. Miller (1984) describes a shallow geophysical borehole logging unit that was designed and built by the Alyeska Service Company for the trans-Alaska pipeline project. The logging unit was used by field engineers to provide information for calculating the dry bulk density of permafrost which was used to adjust the design of pilings on location.

For geotechnical site evaluation, the ice-bearing permafrost table can often be found by mechanical probing to the thaw front as the summer's melt of the active layer progresses.

10.6.3 Thermal Properties

If the permafrost is to be thawed a knowledge of its thermal properties must be obtained to estimate the energy required for thawing. Thermal parameters that should be obtained are the thermal conductivity, volumetric heat capacity, thermal diffusivity, latent heat of fusion, and the initial temperature distribution in the permafrost (see Sections 3.4 and 10.2)

10.6.4 Mechanical Properties - Elastic Moduli

The bulk modulus, shear modulus, Young's modulus, and Poisson's ratio of the permafrost are valuable engineering parameters and should be determined prior to construction (Akimov, 1973). Techniques for determining these parameters from well logs are discussed in Section 10.4.1 in relation to arctic well completion.

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10.8 List of Acronyms

IP Induced polarization
MWD Measurement while drilling
P_e Index of effective photoelectric absorption
SP Self (or spontaneous) potential
VSP Vertical seismic profile

11.0 SUMMARY AND CONCLUSIONS

Well logs and borehole surveys have been used successfully to delineate and characterize soil and rock formations in permafrost environments. Temperature logs provide the most useful and reliable information for identifying and delineating permafrost, because by definition, permafrost is ground that remains at a temperature below $0^{o}C$ for two years or more.

Since the electrical properties of earth materials containing ice are much different than those containing water, various types of electric logs are useful for detecting permafrost and identifying lithology in permafrost environments. Resistivity logs can be used to estimate porosity, and induced polarization logs can detect metallic sulfides associated with ore deposits.

Since sonic logs are also sensitive to rocks containing ice rather than water, they too can be used to detect and delineate permafrost. They can also be used to indicate lithology, porosity and fracturing. The sonic waveform log can be interpreted to obtain the elastic moduli of rocks. The televiewer log produces a sonic image of fractures and flaws that appear along the borehole wall.

Most nuclear logs are not affected by permafrost. However, the neutron porosity log is affected by the presence of ice, because ice has a lower hydrogen density than water and a significant 'excavation' effect. Therefore crossplots of neutron porosity vs. gamma-gamma density log values can be used to distinguish frozen from unfrozen soils and high porosity rocks. Density logs can be used to estimate formation porosity and to help identify lithology. Litho-density logs are particularly sensitive to lithologic variations. Neutron 'lifetime' logs can be used to distinguish oil from water in petroleum reservoir rocks. Neutron activation logs are being developed for detecting specific elements for mineral exploration.

Magnetic susceptibility and magnetometer logs are affected by ferromagnetic minerals, but not by permafrost. Magnetic logs can be used for mineral exploration and in mining applications. The nuclear magnetic resonance log has potential for distinguishing ice from water in the pore spaces of soil and rock, but has not been tested in this application.

Caliper logs measure borehole diameter which is essential for applying corrections to other geophysical logs. They also detect caving of soil and soft rock in permafrost zones that are thawed by warm drilling fluids. The drilling mud log detects combustible hydrocarbons, including gas hydrates, that are picked up as the drill penetrates zones containing hydrocarbons. Drilling parameter logs (speed, rpm, pressure, etc.) are useful for relating ease of drilling to lithology, and for indicating massive ground ice.

Borehole electrical surveys made with wide-spaced electrodes can detect the resistivity anomaly associated with permafrost, even if it occurs at a great distance from the borehole. Borehole velocity surveys penetrate much deeper than sonic logs, and can detect permafrost even when it is thawed near the borehole. Borehole gravity meter surveys can be interpreted to provide very high accuracy values of formation density and to detect massive ground ice. Gravity measurements are not affected by permafrost.

Table 0.1 summarizes the major types of borehole measurements and indicates their most important applications in permafrost environments, including their ability to delineate permafrost. Sections of the report that contain detailed information of each type of measurement are indexed on the righthand side of the table. This table is on page 7.

In conclusion, while many borehole measurement techniques have been tried and proven in permafrost environments, there are a few that have not been fully tested, but offer considerable potential. Well logging techniques that need further testing include: dielectric constant, sonic waveform, televiewer, and nuclear magnetic resonance. All four techniques have the potential for identifying and characterizing permafrost. Borehole surveys using electrical and seismic methods have been shown to be useful for identifying permafrost, but both techniques require further research and development to take full advantage of their ability to detect permafrost at large distances from the borehole and to detect and delineate ice-rich permaforst and massive ground ice.

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