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RÉSUMÉ

Les tensions électriques qui apparaissent pendant la congélation des sols naturels ont été mesurées dans deux zones de pergélisol: l'une située dans le sable saturé d'un lac asséché (Illisarvik) sur l'île Richards où il y a épaississement du pergélisol vers le bas à 5,65 m sous la surface du sol et l'autre dans un tertre de vase dans la zone active à Inuvik. On a mesuré, au moyen d'électrodes placées sur le front de congélation à Illisarvik, des tensions de pointe atteignant 1350 mV. À Inuvik, on a mesuré des tensions de congélation maximales atteignant 700 mV pendant la congélation de la zone active en hiver. On a également observé des indices de migration vers le bas et de congélation de l'eau au moment du début du dégel du terrain en surface au printemps.

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FIELD MEASUREMENTS OF ELECTRICAL FREEZING POTENTIALS IN PERMAFROST AREAS

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Electrical potentials developed during freezing of natural soils have been measured in two permafrost areas: one in a saturated sand in a drained lake (Illisarvik) on Richards Island where permafrost was aggrading downward 5.65 m below ground; the other, in a mud hummock in the active layer at Inuvik. Peak potentials of up to 1350 mV were measured on electrodes located on the advancing freezing front at Illisarvik. At Inuvik, maximum freezing potentials of up to 700 mV were measured as the active layer froze in winter. There was also evidence of downward water migration and freezing as the ground started to thaw at the surface in spring.

INTRODUCTION

The phenomenon of electrical potentials generated during freezing of aqueous solutions and other systems such as moist soils has been known for some time, although the exact mechanism of development is not fully understood. Several plausible explanations have been proposed for pure water and dilute aqueous solutions, but no such theory has been suggested for soils.

When water freezes on the surface of a solid, the dipole field of the oriented water molecules in the initial ice layer causes rotation and reorientation of the molecules in the liquid adjacent to the ice. An electrical double-layer of a few nanometers is formed at the interface between the frozen and unfrozen parts. It behaves like a semipermeable membrane, allowing one kind of charge to pass through more readily than the other, and causes selective incorporation of an excess charge of one sign in the frozen part and an equal and opposite charge in the unfrozen part. The potential developed in this way is commonly called the freezing electrical potential. During freezing, there is a tendency for water to migrate to the freezing front, and thus several electrokinetic effects (such as electrophoresis, electro-osmosis, streaming potential, and sedimentation potential) may also arise as a result of the relative motion between water and solid phase.

Early measurements of freezing potentials were carried out in water and in dilute aqueous solutions containing different kinds of ions, for example, alkali metals, ammonia, halogens, and hydroxyl ions (for early references, see Parameswaran 1982). The early investigations showed that the magnitude and sign of the freezing potential depend upon various factors, including the type of ion in solution, type and distance between electrodes, concentration of electrolyte solution, and rate of cooling.

Reports on the observation of freezing potentials in soils and rocks are meagre and inconclusive. Jumikis (1958) measured potentials of 40-120 mV during freezing of Dunellen silty soil (a glacial till) and suggested that such potentials could enhance moisture transport in the material. Korkina (1975) studied the freezing electrical potentials in suspensions containing particles of less than a micron and saturated with different kinds of ions such as Fe^{3+}, Ca^{++}, Na^{+}, and NH_4^{+}. The magnitude and polarity of the induced voltage depended on the density of the suspensions, type of particles, and type of ions. Under laboratory conditions, Borovitskii (1976) measured freezing voltages of 150-200 mV in argillaceous rocks, and Yarkin (1974, 1978) measured freezing voltages of up to 325 mV in powdered sand containing about 23% moisture and smaller freezing voltages in other soils. More recently, Hanley and Ramachandra Rao (1980, 1981) studied the effects of various cations on the generation of freezing potentials in a bentonite clay. The maximum potentials were in the range of 30-50 mV, and they concluded that the development of freezing potential and migration of moisture are closely associated phenomena, each influencing the other. Parameswaran (1982) has also reported laboratory measurements of electrical freezing potentials in water and soils under various rates of cooling. Ice-positive potentials of 4-12 V developed in pure water under rapid cooling; and in moist sands and soils ice-negative potentials of 100-200 mV were measured. Under slow cooling at -2.2°C reconstituted natural soils from permafrost areas showed freezing voltages of 200-300 mV. The freezing potentials in water could be due to a combination of those related to the phase change of water and those arising out of charge separation and ion incorporation from traces of impurities (known as Workman-Reynolds effect). In addition to polarization of water molecules and alignment of dipoles across the potential barrier at the freezing boundary, charges inherently present at the surface of mineral particles in soils could also contribute to the development of freezing potentials by exchange absorption processes.

The development of contact electrical potentials during freezing is of considerable importance in many construction problems in northern North America, the USSR, and Europe, where vast areas are underlain by perennially and seasonally frozen ground. Under the influence of an electrical gradient such as that caused by freezing, water is transported through frozen clay and silt towards the freezing front where segregated ice can form (Verschinin et al. 1949, Hoekstra and Chamberlain 1963). Such movement of water under the influence of geoelectric fields in the presence of a thermal gradient could also cause electro-osmotic drainage of unfrozen and frozen soils (Nersesova and Tsytovich 1966). The additional heave caused by such processes could necessitate special construction techniques for pipelines, foundations for buildings, and other structures in permafrost areas. Geoelectric fields generated near buried pipelines could also affect their cathodic protection.

FIELD STUDIES

Very few measurements of electrical freezing potentials under natural conditions have been published. The only documented report to the authors' knowledge is that of Borovitskii (1976), who measured the inherent electrical fields developed in the active layer between frozen and thawed parts in a permafrost region of the USSR. The measured values did not exceed 50 mV, although the value of the potential varied with depth in the ground. This he attributed to differences in quantity and direction of moisture movement. Mackay has also carried out measurements of the potentials developed in electrodes embedded to different depths in the active layer and in perennially frozen ground in three different areas of the Northwest Territories. When electrodes were placed in the active layer, he observed a potential change as the freezing front passed the electrodes. Values of potentials measured in the field were of the same order of magnitude as values measured in the laboratory on natural soils (Parameswaran 1982). This similarity of the freezing potentials measured in the laboratory and in the field prompted the authors to install field electrode assemblies in two permafrost areas and to measure freezing potentials in an attempt to understand the physical processes that occur during freezing of the ground. One chosen area was the middle of an artificially drained lake (Illisarvik) on Richards Island, N.W.T., where permafrost was aggrading from the top down (Mackay 1981). The other area was at Inuvik, N.W.T., where the active layer in a mud hummock was monitored. This paper describes the equipment and some of the results.

Illisarvik Lake Site, Richards Island

An electrode probe consisting of five plexiglas tubes, each 1.93 m long, 38 mm OD and 25 mm ID, was installed at the site, the middle of a drained lake, on 20 June 1981. Twenty-two copper electrodes in the form of circular bands (12.5 mm wide) were installed on the probe in suitable grooves 1 mm deep. The bottom electrode (numbered zero) was 89 mm from the tip of the plug closing the first tube. All the others, numbered 1 to 21 from the bottom upwards, were set 150 mm apart. A shielded coaxial cable (RG 174/U) was connected to each electrode through a slanted hole in the wall of the tube and the soldered joints were protected by epoxy resin. The tubes were designed to be joined with plexiglas couplings as they were installed.

Wires from the electrodes were connected to a rotary switch having 24 terminals (Figure 1b). The bottom electrode was connected to the common point (-); the others were connected to switch points 1 to 21. The central switch contact point was made the (+) terminal. The shields from all the cables were connected to the ground terminal, which was in turn connected to a grounding steel post at the lake site.

Two thermistor cables were installed near the electrodes for temperature measurements. The first cable had 12 thermistors (YSI 44033, calibrated to ±0.01°C at 0°C), each inside a soil salinity sensor (Soilmoisture No. 5100-A). These were embedded in a 30 mm diam PVC rod at 500 mm intervals. The rod (with salinity sensors) was installed in a hole drilled by water-jet 0.4 m from the electrode assembly (Figure 2). A second temperature cable with 26 thermistors (YSI 44033) spaced 150 mm apart was installed 4 m from the electrode assembly.

Depth of permafrost was 5.65 m when the electrodes were installed in June 1981. The uppermost electrode (21) was at a depth of 6.11 m and the bottom electrode (0) was 9.31 m below ground level (lake bottom). This placement ensured that the 0°C isotherm would soon reach the uppermost electrode. The material in which the electrodes were installed was a saturated sand with medium-to-fine grain size.

Inuvik Site

This site is about 3 km north of the town of Inuvik in an area of colluvium that has developed a pattern of mud hummocks. The electrode probe consisted of a PVC tubing (20.6 mm OD, 12.7 mm ID, 3 m long, closed at one end) on which 12 copper electrodes in the form of bands or rings (12.7 mm wide and about 1 mm thick) were installed in suitable grooves 150 mm apart. Coaxial cables were soldered to the electrodes and the wires were led out through a central hole and connected to the terminals of a rotary switch. The outer shields of the cables were grounded to a steel post at the site. A thermistor cable with 13 thermistors (YSI-44033) was also made. The electrode probe and the thermistor cable (Figure 3) were installed (by hand drilling) in August 1981 in the centre of a mud hummock about 2 m in diameter.

RESULTS AND DISCUSSIONS

Illisarvik Lake Site, Richards Island

Owing to the thermal disturbance of the ground caused by drilling and the resulting freeze-back, the readings taken in August 1981 are questionable and are not reported here. The Illisarvik site is relatively inaccessible and frequent readings were impossible, so that the next readings were taken 23 March 1982, 8 June 1982, and 12 August 1982. The temperature and freezing potential profiles for these dates are plotted in Figure 4(a-c). None of the three temperature profiles shows any change in gradient in crossing 0°C, from positive to negative temperatures. In Figure 4(a) there is a gradual change in the profile at about -0.1°C; and in Figure 4(b, c) a definite inflection point at -0.1°C. With little doubt this marks the freezing point depression so commonly observed in soils. The Illisarvik sediments consist mainly of sand, and the freezing point depression is slightly lower than might be expected. Since the sub-permafrost pore water has an increased salinity from ion rejection during permafrost aggradation, however, a freezing point depression below that of the original sands is to be expected. To illustrate, in the summer of 1982 the specific conductance of the pore water just below permafrost, as measured with the soil salinity sensors, was about 300 μohm^{-1} cm^{-1}; salinity had increased appreciably since the previous summer. Nearby measurements of heave of the ground surface suggest that most of the ice formed during the downward growth of permafrost was pore ice and not segregated ice.

Figure 4(a-c) shows plots of peak potentials and temperature gradients. On 23 March 1982 there was a very pronounced peak in the potential at 1.08 V at a depth just 15 cm below the 0 deg isotherm. As the temperature measurements were taken 0.4 m from the electrodes, the agreement seems good. By way of contrast, on 8 June 1982 the peak potential (about 1.35 V) occurred at a ground temperature of -0.1°C, the peak coinciding closely with the inflection point on the temperature curve. By 12 August 1982, however, the peak potential was unchanged at the same depth as on 8 June 1982, although permafrost had aggraded 50 cm and the ground temperature had decreased to about -0.4°C. In summary, the results from the Illisarvik site indicate that freezing potentials develop on electrodes located at the freezing front, but these results are by no means conclusive.

Inuvik Site

The Inuvik site contrasts with the Illisarvik site in soil type and the placement of the electrodes. Here the soil is a silty clay, with particles about 50 % finer than 0.002 mm and a specific surface area of about 120 m^2/g. The amount of unfrozen pore water in the clay, using the specific surface area method of Anderson and Tice (1972), is estimated at about 9 % at -5°C and 7 % at -10°C. Voltage and temperature readings were taken every two weeks by the staff of the Inuvik Scientific Resource Centre. Variations of voltage and temperature with depth below surface were much more predictable and systematic than those at the Illisarvik Lake site. Figure 5(a-e) shows the variations of voltage and temperature at various depths as the ground froze and thawed in the 1981-1982 season. At depths of 0.05 and 0.20 m, respectively, a freezing potential developed as the temperature passed through 0°C in the month of October 1981 (Figure 5(a,b)). The maximum freezing potentials developed were as high as 650 mV. As the ground temperature at these locations dropped in winter, the potential dropped too and remained at the lower level. In spring (May 1982), as the ground started to thaw and the temperature rose above 0°C, the potentials again rose to values of up to 700 mV. The interpretation of this potential is uncertain, but there is considerable evidence that during the summer thaw period water may migrate from the thawed active layer into the still-frozen active layer to freeze and increase the ice content (Cheng 1982, Mackay, in press; Parmuzina 1978, Wright 1981). A minor freezing potential may thus develop during the summer thaw period. This behaviour of meltwater, possibly percolating downwards and freezing to generate a freezing potential, was not observed at the electrodes at lower levels. For example, in Figure 5(c) the freezing potential on the electrode at a depth of 0.51 m below surface level rose to 700 mV as the ground temperature passed through -0.1°C. With further decrease in ground temperature the freezing potential remained unchanged. A slight drop in potential was noted when the temperature passed through 0°C in June 1982 as the ground thawed, but essentially the voltage was constant around 700 mV even when the ground started to freeze again in October 1982. The same type of behaviour was observed 0.96 m below ground level (Figure 5(d)).

Figure 5(a,b) shows the development of pronounced freezing potentials at depths of 0.05 and 0.20 m, respectively, in the upper part of the active layer where ice lensing commonly takes place. In addition, potentials at 0.51 and 0.96 m remained at 600-700 mV during the winter, after temperatures dropped below 0°C. Measurements carried out at Inuvik for many years have shown a prolonged and very gradual frost heave in the winter months long after the temperature has dropped below 0°C (Mackay et al. 1979). This suggests that, in winter, upward migration of unfrozen water from the freezing front into the frozen active layer could cause a minor freezing potential to develop. At levels close to the permafrost table, where ground temperature is maintained at or below 0°C, no freezing potentials developed on the electrode 1.42 m below ground level (Figure 5(e)). Figure 5(a-e) also shows that as depth increases below ground level the minimum temperature, as expected, becomes higher. For example, at 0.05 m the lowest ground temperature measured was -10°C, whereas at 0.96 and 1.42 m the lowest soil temperatures measured were -3.5 and -2.5°C, respectively.

CONCLUSION

Freezing potentials appear to have developed on electrodes installed in saturated sand at Illisarvik where the 0°C isotherm was that of an aggrading lower permafrost surface, but the results are inconclusive. Peak potentials of up to 1350 mV were measured on electrodes located on the advancing freezing front. At Inuvik, the electrodes were placed in the active layer on top of permafrost, in a silty clay. The electrodes in the upper part of the active layer where lens ice forms in the freeze-back period registered substantial increases in potential as the freezing front passed the electrodes. The maximum freezing potential measured here was about 500 mV when the ground temperature was about -0.1°C. There was also evidence of downward water migration and freezing, as evidenced by a rise in freezing potential at levels below the surface as the ground thawed at the surface. These field measurements indicate that by suitably modifying electrode probes and improving measuring techniques it is possible to locate and study the advancing freezing front and water migration at different levels below the surface as ground freezes and thaws.

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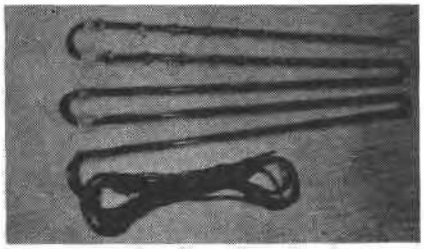

FIGURE 1(a) The Illisarvik electrode assembly.

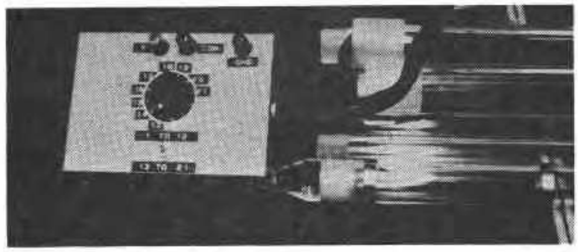

FIGURE 1(b) Switching box.

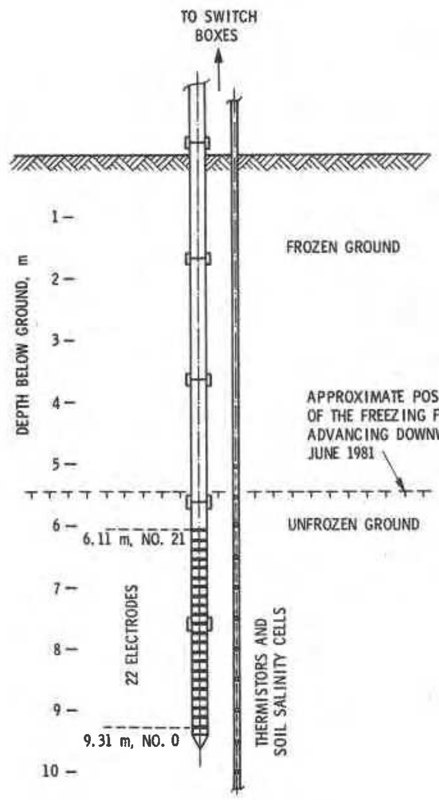

FIGURE 2 Schematic diagram showing the location of electrodes and thermistors after installation, Illisarvik site.

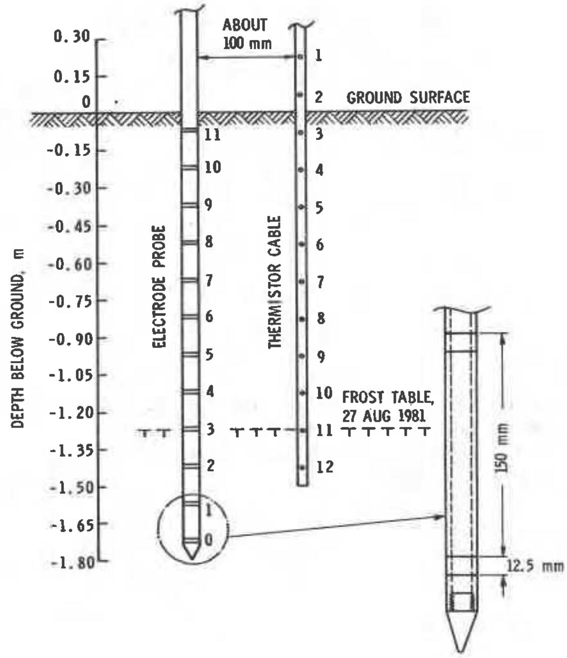

FIGURE 3 Schematic diagram showing the location of electrodes and thermistors after installation at the Inuvik site.

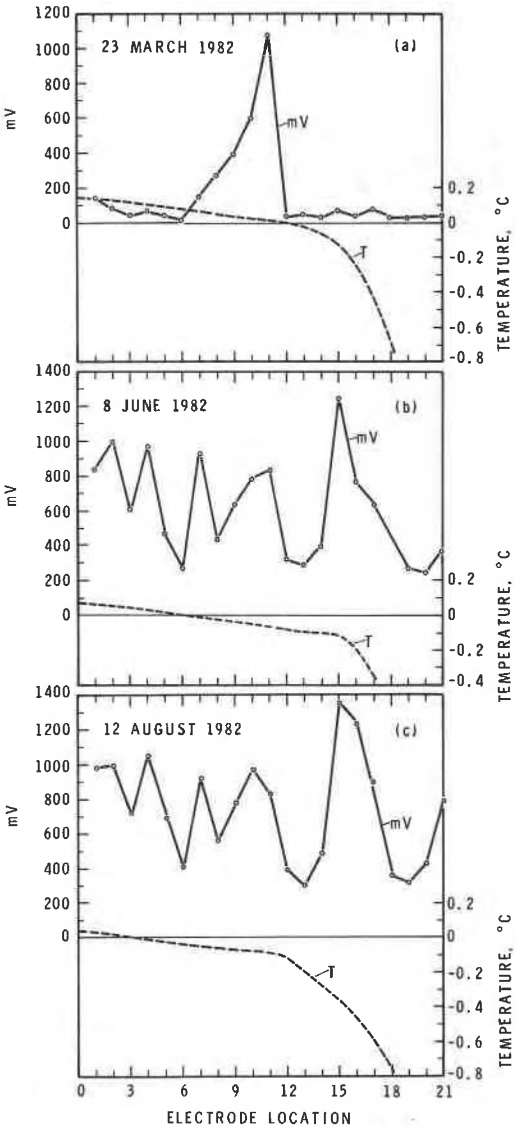

FIGURE 4 Variation of voltage and temperature with depth below ground surface at the Illisarvik site, (a) 9 months, (b) about 1 year, and (c) 14 months after installation.

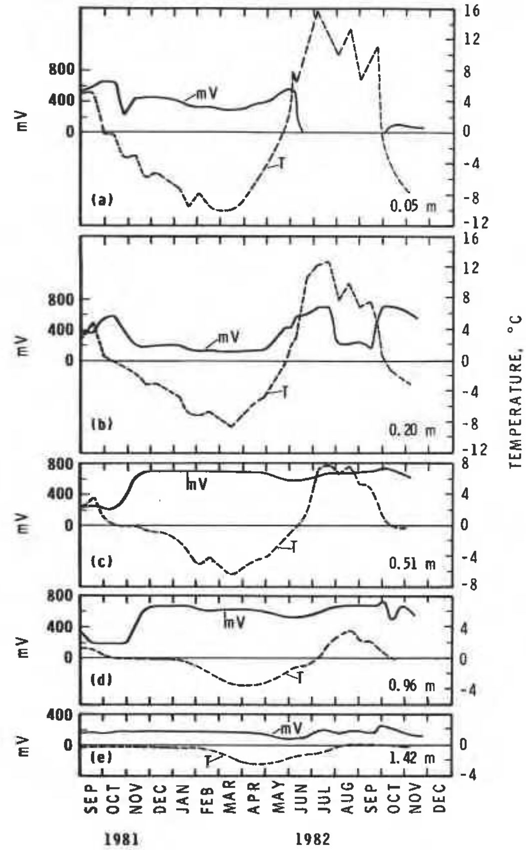

FIGURE 5 Variation of voltage and temperature with time at different depths below the surface, Inuvik site.