SPACE SCIENCES LABORATORY

N71-19108

PERMAFROST

NASA CR-116879

by

Jose Seixas Lourenco

and

Stanley H. Ward

Technical Report on
NASA Contract NAS 2-5078, Item 291

Covering the Period from July 8, 1968
through December 31, 1970

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Space Sciences Laboratory, Series 11 Issue 66

UNIVERSITY OF CALIFORNIA, BERKELEY

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PREFACE

To determine the physical properties of the media required to simulate the moon in model experiments, it is necessary to obtain a full understanding of the nature of the media with which one is dealing in the moon. *Permafrost* has been assumed as one potential ingredient of the lunar environment. What is permafrost? The following article provides a definition of permafrost, a discussion of its physical properties, and inferences concerning the manner in which it may be modeled.

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October 1970

SUMMARY

Some definite criteria for the occurrence of permafrost are established. It is shown that slight changes in temperature will upset the thermal balance that controls the occurrence of permafrost, thus causing changes in its thickness and extent.

Inhomogeneities, such as ice and brine inclusions and "taliks," which can produce changes in electrical conductivity of an area, are discussed.

It is inferred that, if permafrost does exist locally or ubiquitously in the lunar crust, it could very well exhibit the wide ranges of conductivity and dielectric constant as found on Earth. Therefore, the model studies of the moon should be consistent with these range variations.

PERMAFROST

Jose Seixas Lourenco and Stanley H. Ward

INTRODUCTION

Permafrost, or permanently frozen ground, is a widespread phenomenon in the northern parts of North America and Eurasia, and in Antarctica. Between 40 and 50 per cent of Canada's total land surface of 3.8 million square miles is underlain by permafrost. The total land area of the USRR exceeds 8 million square miles of which 47 per cent is underlain by permafrost. Altogether, about one-fifth of all the land area of the world is underlain by permanently frozen ground.

Although the existence of permanently frozen ground has been known for a long time, relatively little comprehensive and systematic work had been done in this field until about three decades ago when scores of Russian scientists began an intensive research effort, which already has brought extensive results. We know that there is a marked decrease in rock conductivity at temperatures below 0°C and that the electrical conductivity of permafrost can be as high as 1×10^{-3} mho/m. On the other hand, it is important that the extent, thickness, and electrical properties of permafrost be determined more intensively and extensively than heretofore.

The purpose of this report is to discuss the physical, mechanical, and electrical properties of frozen ground. The first sections consist of general descriptions of permafrost: thickness, formation and growth, climatic effects, and thermal regimes.

DEFINITION OF PERMAFROST

Permanently frozen ground, or permafrost, is defined as soil or other superficial deposit, or of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continually for a long time (from two to tens of thousands of years). Permanently frozen ground is defined exclusively on the basis of temperature, irrespective of texture, degree of induration, water content, or lithologic character.

Since it is defined on the basis of temperature, it may consist of any type of natural or artificial material, whether consolidated by ice or not. Ice is recognized as one of the most important components, and it is convenient to refer to the water content (generally, but not always, as "ice,") in terms of the available pore space. Thus, the material is "saturated" if it contains as much ice as pore space; it is "supersaturated" if it contains more ice than pore space; and it is "undersaturated" if it contains less ice than pore space. For practical purposes in the field, when exact moisture relationships are not available, it is relatively easy to distinguish these main types of materials with the aid of a hand lens (Black, 1954). Supersaturated material invariably contains visible ice in cement, granules, veinlets, and other forms that separate individual particles of rock or soil. Saturated rock has all pores filled with ice, and saturated sediment is firmly cemented with ice but lacks visible granules and veinlets of ice separating individual grains of the host material. Undersaturated material contains pores visibly lacking in ice and commonly is friable.

The phenomenon of permanently frozen ground is also known as "permanently frozen soil" or even "frozen soil"; but it is believed that the expression "permanently frozen ground" is the most appropriate, particularly as the permanently frozen condition commonly extends well below the level of soil and in many cases affects even a more or less solid bedrock. The expression permanently frozen ground, however, is usually replaced by the contraction "permafrost."

Ground with a temperature below 0°C but containing no ice as cementing substance is called "dry frozen ground." If it is permanent it is called "dry permanently frozen ground" or "dry permafrost." A list of terms pertaining to the frozen ground phenomena appears at the end of this report (from Muller, 1947).

PERMAFROST DISTRIBUTION AND AIR TEMPERATURE

Many investigators have made estimates of what mean annual air temperature is required to produce and maintain a permanently frozen condition in the ground, but there is much disagreement on this matter. One investigator reported that the southern limit of permafrost coincides very roughly with the 0°C mean annual isotherm (Terzaghi 1952). In Canada this certainly does not hold true, because this isotherm lies a considerable distance south of known areas of discontinuous permafrost. Another investigator reported that the mean annual air temperature required to produce permafrost varies many degrees because of local conditions and suggested that it is generally between 24°F and 30°F (Black, 1950). In a climatic hypothesis of the origin of permafrost, it was suggested that the southern boundary coincides approximately with the -2°C isotherm (Nikiforoff, 1928). West of Hudson's Bay there is some similarity between the position of the 25°F mean annual isotherm and the southern limit of permafrost. In the Yukon Territory, however, the 30°F isotherm lies much nearer the approximate southern limit. In Manitoba the known limit of permafrost cuts diagonally from the 25°F to the 30°F isotherm. In Ungava the permafrost limit lies far north of the 25°F isotherm, but in Labrador there appears to be some coincidence between this isotherm and the permafrost limit.

It is interesting that the isotherm for the mean annual temperature of -2°C lies south of the permafrost boundary in most of Canada, whereas in the USSR it lies considerably south of the permafrost boundary, but only in western Siberia. Thus, a large part of southern Siberia, northern Outer Mongolia, and Manchuria lies south of the -2°C isotherm and north of the permafrost boundary. The permafrost in this area is patchy and lies so deep that it is not in equilibrium with the present climate and must be a relict of a colder climate. The same situation may have existed in Canada.

Several factors may cause the permafrost to extend so far south in eastern Asia. The land mass of eastern Asia is much larger than that of North America, resulting in a more continental climate. In July the mean monthly air temperatures are about the same as those of northern Canada, but in January they are 20 to 30°F lower. This means both regions have similar thawing indices, but with much higher freezing indices and more favorable conditions for permafrost to form and persist in Asia than in northern Canada.

Attempts have been made in Canada to relate permafrost distribution and freezing indices. The freezing index for any locality is the yearly sum of the differences between 32°F and the daily mean temperature of the days with means below 32°F (Fig. 1, from Morgan and Maxwell, 1965).

A station with a high freezing index should have permafrost if its thawing index is low. If its thawing index is high, as in the interior of the continent where the climate is extreme, then summer heating with counteracting winter cooling and the formation of permafrost is inhibited (see Fig. 2, from Morgan and Maxwell, 1965). Similarly, a station with a low freezing index can have permafrost if its thawing index is also low, as in maritime localities.

It is evident that there is not a close relationship between permafrost distribution and air temperature. Because so many factors— climatic, surface, and geothermal— affect the occurrence of permafrost, prediction of its distribution cannot be based solely on this one climatic factor. Nevertheless, examination of the southern limit of permafrost as known at present and of air temperature patterns reveals the existence of a very broad relationship (Figs. 3 and 4, from Morgan and Maxwell, 1965).

FORMATION AND GROWTH OF PERMAFROST

Permafrost can exist, and therefore could have originated, only where the mean annual temperature is below 0°C. There are still some differences of opinion as to the exact minimum temperature required, but it is now generally agreed by most authors that permafrost first appeared during the refrigeration of the Earth's surface at the beginning of the Pleistocene or Ice Age, perhaps a million years ago. It is also generally believed that, during the subsequent periods of climatic fluctuations, corresponding changes must have taken place in the thickness and areal extent of permafrost.

Although the relict nature of permafrost appears to be established, it is equally certain that, at least in some areas, permafrost is forming during the present climate.

Several factors determine whether a soil will freeze permanently. Temperature of the air, precipitation, cloudiness, and direction of prevailing winds obviously affect surface layers; but covering, texture, water content, and degree and direction of exposure also play a part. All these factors influence the depth to which a wet soil freezes and the rate at which it freezes.

Apart from climate, the most important factor in promoting and preserving permafrost is the thermal conductivity of the soil. Different soils and rocks vary widely in their thermal conductivity, but because ice is a much better conductor than water, the freezing of any kind of soil invariably increases its conductivity. It follows, therefore, that the amount of heat transferred from a frozen soil to the air during a winter day will be greater than the amount transferred from the air through the unfrozen soil during a summer day, when the temperature ratio between ground and air is exactly reversed. The thermal conductivity of the ground cannot alter the temperature at which the ground begins to freeze, but it can greatly affect the rate of freezing, and the depth to which the frost penetrates. It would seem to have been the decisive factor in determining how far down in the ground the permafrost could extend before further accumulation became impossible— other than by a change of climate.

Let us try to explain the great thickness of permafrost in many places; i.e., its extent in depth to hundreds of feet below the level of present-day zero annual amplitude. We know that at various periods in the past the climate over a great part of the northern hemisphere has been very much colder than it is today. During any one of these cold ages the level of zero annual amplitude, which fluctuates slightly even during short-period climatic cycles, must have extended to a much greater depth than is possible under present conditions. One may reasonably conclude, therefore, that permafrost could become embedded to a very considerable depth during one or more of the harsher ages, yet not disappear entirely in the succeeding milder periods. During the milder periods, soil could accumulate over the permafrost and bury it still deeper, but this soil in turn would become permanently frozen when the climate deteriorated again (Fig. 5, from Jenness, 1969). In this way the permafrost could become thicker and thicker under successive cold and warm periods until, in the end, it reached a state of equilibrium, when any increase at the surface would be counterbalanced by a thawing at the base brought about by a rise of temperature with pressure. The depth at which this state of equilibrium would be reached depends on climate, soil, and other factors, and would therefore vary from one region to another.

This theory of permafrost growth readily explains the occasional presence of a belt of unfrozen ground (a talik), not on top of the present permafrost, but deep within it, far below the level of zero annual amplitude. It is hardly conceivable that underground water can force its way through already frozen soil and cause it to thaw out. This unfrozen belt, then, must represent either the lower part of an ancient active layer, which, in the course of a long mild period became so thick that a recurring cold age failed to freeze it to the bottom, or else it was an aquifer within that ancient layer that failed to freeze because of high mineralization or hydrostatic pressure.

MECHANICAL PROPERTIES OF PERMAFROST

Physical properties of frozen ground depend on the composition, texture, content of ice, and temperature of the frozen ground, but there is, as yet, no classification in which all these factors are taken into account. Furthermore, in engineering practice it is equally important to consider the properties of unfrozen or thawed ground.

Thawed ground is slightly different in its physical properties from ground that has not been subjected to freezing, even though they may be alike in composition, texture, and moisture content. This difference is, apparently, due to the fact that some time elapses before thawed ground "settles" or attains its normal structure, on which depends its ability to support a load.

It is an established fact that the compressive strength of ground frozen for the second time is considerable less than that of ground that has been frozen only once. Solid bedrock is comparatively little affected by freezing and is therefore, for the most part, left out of the consideration. The following discussion is devoted almost entirely to normally unconsolidated materials (as listed in Table 1, from Muller, 1947).

Ice fills some or all of the interstitial space between the mineral grains in frozen ground and acts as a cement. Mechanical properties of frozen ground, therefore, tend to approach those of ice. The relative strength of ice under different stresses depends on its structure, as well as the temperature and the nature of surrounding conditions. Compressive strength of ice also depends on the rate of increase of pressure and on the direction of forces with reference to the axes of ice crystals. Ice will withstand a much greater pressure if the force is directed parallel to rather than perpendicular to the long axis of a crystal. In ice formed over a body of water, the long axes of crystals are normal to the water surface.

The strength of ice varies over a large range, depending on its structure. River ice with well-developed structure has a compressive strength at -1.6°C of 127 Kg/cm^2 when a force is applied parallel to the crystal axis and only

74 Kg/cm^2 when a force is applied at right angles to this axis. Another property of ice, important in some engineering problems, is the bending strength of ice. Experimental data on this property is shown in Table 2 (from Tsytovich and Sumgin, 1937).

The bending strength of ice depends more directly on the orientation of crystals than is the case with other types of stresses. In general, the amount of deformation in ice is directly proportional to the load and inversely proportional to the coefficient of viscosity. It is shown in Figure 6 (from Tsytovich and Sumgin, 1937) that the coefficient of viscosity of ice varies markedly with temperature.

Frozen ground with pores completely filled with ice is susceptible to deformation, the amount of which varies with temperature and pressure. With the rise of temperature, the deformation of ice becomes more intense and its plasticity and flowage become more pronounced. When the ice begins to melt, the character of the ground underneath the ice is completely changed and its deformation is greatly intensified even without the application of additional load.

The compressive strength of frozen ground increases with the lowering of temperature. Compressibility of sand varies with the amount of moisture (ice) and reaches a maximum when the pores are completely filled with ice. The compressive strength of clays decreases with the increase of moisture content. The behavior of different frozen grounds under compression is illustrated in Table 3 and Figure 7 (from Tsytovich and Sumgin, 1937) and in Figure 8 (from Muller, 1947).

The shearing strength of frozen grounds depends primarily on temperature and, to a much less extent, on the content of moisture (ice) and the texture of the ground. The increase of moisture (ice) content tends to increase the shearing strength of the ground; but after a certain maximum addition of water (ice), tends to reduce the shearing strength of the material. See Tables 4, 5 (from Tsytovich and Sumgin, 1937), and Figure 9 (from Muller, 1947).

Thermal conductivity of ice is several times greater than that of water. Frozen ground, therefore, has a much higher thermal conductivity than the same ground in an unfrozen state. The coefficient thermal conductivity of ground is the quantity of heat in kilogram calories that pass through a surface of 1-square-meter of material during 1 hour to another surface of the same material 1 meter away, with 1 degree difference in temperature between the two surfaces.

The thermal conductivity of a given ground at different temperatures is variable. At temperatures below zero, the thermal conductivity in the frozen ground gradually rises, but at zero degrees centigrade there is a sharp drop; and with the further rise of temperature, the thermal conductivity again gradually increases. A similar relationship is also observed in water.

The results of investigations on the thermal conductivity of the most characteristic grounds, clay, sand, and of water are shown in Figure 10 (from Muller, 1947). From these graphs it can be seen that the thermal conductivity at the freezing point increases, on the average, 3.7 times for water, 3 times for sand, and 1.5 times for clay. It will be also observed that the thermal conductivity of sand is approximately half that of clay. Very little information is available on the thermal conductivity of peat, which is widespread in the Arctic regions. However, it is known that peat can absorb water up to 300% of its volume. It is therefore permissible to assume that the thermal conductivity of saturated peat will be close to that of water, which, in the range of temperatures from 0° to 20°C will be about 0.5 $kcal \cdot m/h/m^2/°C$, but in a frozen state it will be about 2.0 $kcal \cdot m/h/m^2/°C$. Dry peat, which is commonly used as an insulating material, has the thermal conductivity coefficient of 0.06 $kcal \cdot m/h/m^2/°C$ units. It will be thus seen that the thermal conductivity of peat will vary between wide limits depending upon the amount of moisture, compacting, and whether or not the material is frozen. It can be thus concluded that during summer a greater amount of heat is transferred through water-saturated peat into the underlying layers of soil than through dry peat. In winter, when water-saturated peat is frozen, the heat is transferred in the opposite direction from the soil into the air and the amount of heat passed into the air will thus be four times as great as the heat passed into the ground during the summer. When dried, this negative factor of loss of heat may be considerably decreased. From the above it can be easily seen that such an exchange of heat through peat will have a marked effect on the formation of permafrost.

The thermal conductivity of ground also depends on its structure. In grounds of similar texture, with a decrease of specific gravity, there is a decrease of thermal conductivity.

Thermal conductivity of different materials is given in Table 6 (from Bykov and Kapterev, 1940).

A METHOD FOR THE COMPILATION OF MAPS OF THE ELECTRIC CONDUCTIVITY OF ROCKS

The drafting of a detailed map of the electric conductivity of frozen rocks from in situ observations would require a tremendous number of observations. In practice, this type of mapping is not feasible.

Yakupov (1969) suggested a method for the compilation of maps of the electric conductivity and other physical properties of rocks; his method makes it possible to restrict the observations to relatively small, but carefully selected objects, as described below. According to Yakupov's method, a lithological map is the basis for the compilation of a map. Field observations, as well as other observations, are made in order to obtain comprehensive data on the rock properties and their dependence on lithological details.

This method was used to draw a map of the dc electric conductivity of frozen rocks in the Northeastern part of the USSR (Fig. 11, from Yakupov, 1969). The map characterizes the contemporary erosion profile and indicates the electric conductivity of the subjacent rocks in the region in which epigenetic multiple-veined ice formation has developed.

The basis for the map includes lithological as well as cryogenic structural features of the frozen layers. The composition of the sediment layer was determined from a particular rock variety which dominates in the profile. Facies changes within layers of the same age were established. Among the intrusive rocks, the most widely found granites and gronodiorites were singled out, along with ultrabasic, basic, neutral, and alkaline rocks. The porous sediments can be subdivided into four cryolithological groups: 1) syngenetically frozen alluvial sediments of river valleys in the mountain zones; 2) alluvial and lacustrine-alluvial sediments of the foothill lowlands, which were syngenetically frozen; 3) epigenetically frozen alluvial and lacustrine-alluvial sediments of the marsh lowlands; 4) epigenetically frozen sediments of the glacial group (glacial till, glacial sands, varved clays).

Data from measurements of the specific electric resistance of frozen rock from the parameter curves obtained by electric sounding with direct current were used for compiling the maps. Data on excavated rocks and on finely dispersed porous deposits with a large cryotexture had been obtained from the corresponding asymptotic sections of the electric sounding curves and were used for plotting the maps. Data on frozen porous deposits had been obtained from electric sounding curves recorded along sections in which the thickness of these deposits and their lithological composition were known from prospecting work; these data were also used for the maps.

Each set of measurements of the specific electric conductivity of rocks of a particular type was considered as a set of values of a statistical quantity. Whenever a sufficiently large number of measurements of the specific electric resistivity was available, empirical distribution functions were calculated for all lithological varieties of compact and porous rocks in both the thawed and frozen states; models of these distributions were determined.

The specific electric resistivity of a particular rock group was indicated on the map. To do this, the corresponding distribution function was used, taking into account the mineralization of the subterranean waters, metamorphism cryostructure, and other quantities. This estimate was then refined and checked against available data on the specific resistivity of rocks at particular locations. Naturally, the isolines usually coincided with the geological boundaries.

Due to sharp differences in the electric conductivity of frozen, porous sediments and solid rocks, the electric conductivity in situ is very irregular. With the scale used for the map (1:2,500,000), the distribution of the electric conductivity of rocks is smoothed out, and only regional differences visible in the schematic representation used in the figure are observed. There are two groups of regions: one with a relatively high resistivity, of the order of a few thousand ohm·m and the other with the resistivity of the order of 10:100,000. The first group of regions is mainly comprised of solid rocks; and the second, frozen porous sediments (primarily within the subartic lowlands). The second group of regions is not uniform in electrical conductivity.

The distribution of the electrical conductivities is mosaic-like, due to the large number of lakes with taliks underneath. The ratio of specific resistivities of porous sediments in the taliks underneath the lakes and in frozen sediments varies from 1:100 to 1:1000.

THE ELECTRICAL PROPERTIES OF PERMAFROST AND FROZEN ROCKS

Typical vertical distributions and thicknesses of permafrost are presented in Figures 12 and 13 (from Morgan and Maxwell, 1965). Departures from the typical models of Figures 12 and 13, such as ice and brine inclusions and taliks, produce marked changes in electrical conductivity of an area. Ice and brine inclusions and taliks are thus two inhomogeneities.

Taliks can be expected beneath lakes that do not freeze to the bottom during winter. For the North American Arctic, lakes deeper than 7 feet are in this category. Unfrozen layers will appear between the active layer and the permafrost.

Ice can occur in permafrost as coating on particles, or as layers or lenses. The amount of included ice varies with the material. Some estimates for various earth materials are tabulated below:

Material	Solid rock	Gravel	Sand	Peat	Organic material	Silty soil
Amount of included ice	much	much	much	much	little	little

Inclusions of brine in permafrost are very common. Earth material is never completely frozen, since pockets of brine are nearly always found in permafrost.

The electrical properties of rocks and soils; i.e., the electrical resistivity and dielelectric constant are greatly affected by the amount of water in the pores and the concentration of ions in solution. When the water freezes in the pores of a rock, large variations in the electrical properties may also be expected. A knowledge of these electrical properties of frozen rocks is necessary if geoelectrical methods are to be applied efficiently in areas of permafrost.

The freezing process in a rock and the effects of freezing on the electrical properties are complex phenomenon. Because of the many variables involved and some unknown factors, a qualitative rather than a quantitative approach should be used to evaluate experimental results.

Freezing in rocks begins at slightly below 0 °C and continues at almost constant temperature until two factors become important in lowering the freezing point of the remaining liquid: 1) increase in pressure exerted on the unfrozen liquid, and 2) increase in salinity of the unfrozen solution.

Pressure on the unfrozen solution may be partially caused by adsorption at the solid-liquid interface. These forces, mainly electrical, are particularly pronounced in clay-water systems because of the exchangeable cations lining the surface of the clay particles. The thickness of the adsorbed water layers and the magnitude of the adsorption forces depend on the nature of the solid and of the solution. The pressure is assumed to be the greatest at the interface and to decrease logarithmically with increasing distance from the solid. A complicating factor involved in these considerations is that water adsorbed on a clay particle has different characteristics from liquid water, and consequently, the effect of the adsorption pressure on the freezing point is not too clear.

An added pressure on the unfrozen solution is caused by the volume increase of the portion of the solution which has become frozen. Pressure caused by this volume change will be greater for infilling water of high purity.

The ions in solution also play an important role in the freezing-point depression of water. Figure 14 (from Hall and Sherrill, 1928) shows the freezing point of a sodium chloride solution as a function of concentration, at a pressure of 1 atmosphere.

Little information has been published on the electrical properties of rocks below 0 °C. Smith-Rose (1934) measured the dielectric constant and electrical resistivity of a soil sample at a frequency of 1,200 kHz, varying the temperature from +30 to -30 °C. Ananyan (1958) measured the electrical resistivity of fine-grained rocks, for various moisture contents, in the range from +20 to -40 °C. In most cases, the resistivity was found to increase slightly with decreasing temperature down to 0 °C. At this point, the resistivity increased by a factor of 10 to 100 in a range of only a few degrees, after which it continued to increase steadily with further decrease in temperature.

Measurements made by Dumas (1962) show that the electrical resistivity of sandstone cores follow the same trend with decreasing temperature. The resistivity first increases uniformly until the water in the pores starts to freeze. At this point, a sharp increase in resistivity occurs in a range of a few degrees, after which it continues to increase uniformly but at a much greater rate than it did above the freezing point (see Fig. 15, from Dumas, 1962).

Because of the sodium chloride in solution, the water in the pores of the rock starts to freeze slightly below 0 °C. The amount of increase in resistivity between 0 °C and -10 °C appears to depend on the porosity of the rock as well as on the salinity of the solution. Electrolytes with a higher salinity tend to diminish the amount of increase and flatten out the curve. A comparison of curves 3, 4, 5, and 6 of Figure 15 illustrates this point.

Dumas (1962) also measured the change in resistivity with frequency (see Fig. 16). In most cases, the resistivity decreases with an increase in frequency. This frequency-dependence of the resistivity, more pronounced at lower temperatures, is practically nonexistent above -5 °C. It is also more pronounced in rocks saturated with a solution of low salinity and in rocks having a low porosity.

Information on the electrical conductivity of rocks has also been published by Dostovalov (1947). Table 7 presents data showing the decrease in conductivity by a factor of 10 to 50 from +14 to -5 °C. Some values of resistivity are listed along with moisture content information in Table 8, (from Dostovalov, 1947).

Using the data presented on Table 8 on resistivity of rock and remaining moisture after freezing, Morgan and Maxwell (1965) have suggested the following empiral relationship to calculate the conductivity of a frozen rock:

$$\sigma_R = \frac{W}{300\ \sigma_I} \quad ,$$

where

σ_R = conductivity of frozen rock

W = remaining moisture after freezing

σ_I = conductivity of the ice in the rock.

The remaining moisture, as well as the conductivity of the ice, is not easily determined for a natural state rock in a permafrost region. From the above relationship, it is apparent that the remaining moisture is of particular importance and, for a frozen earth material, is dependent upon three factors: 1) the degree of saturation of the rock, 2) the salinity of the water and, 3) the character of the material (e.g., grain size, interconnections). The value of the dielectric constant, $\varepsilon/\varepsilon_0$, for frozen rocks is of considerable importance if electromagnetic methods are to be applied efficiently in areas of permafrost, because of the approximation involving the $\omega\varepsilon$ product.

For example, to calculate the effective conductivity for an electrically layered earth, Morgan and Maxwell (1965) assumed that $\sigma/10 > \omega\varepsilon$ for each electrical layer in the earth. Calculations, conveniently simplified if $\omega\varepsilon < \sigma/10$, are valid for all angles of incidence of electromagnetic energy.

In laboratory experiments, Dumas (1962) measured the effect of temperature variations on the dielectric constant of rocks in the range from +22 to -40 °C, for six sandstone cores of three different porosities and different concentrations of sodium chloride solutions.

One of the most significant features appears to be the rapid decrease of the dielectric constant with an increase in frequency, as shown in Figures 17, 18, and 19 (from Dumas, 1962). But, unlike the resistivity, this decrease in dielectric constant is most pronounced at room temperature, and becomes smaller at lower temperatures.

Variations with temperature are also indicated on the same curves, the dielectric constant decreases approximately linearly with a decrease in temperature, except in the range from +3 to -5 °C, where there is a pronounced discontinuity. For any temperature, the dielectric constant increases with an increase in the salinity of the solution and with an increase in the porosity of these particular samples. Other samples might exhibit a different behavior.

Using the measurements in conductivity and dielectric constant in sandstone samples, Morgan and Maxwell (1965) plotted the minimum values of conductivity as a function of $\varepsilon/\varepsilon_0$ such that $\omega\varepsilon < \sigma/10$ at 10 kHz (see Fig. 20). The behavior of $\varepsilon/\varepsilon_0$ with frequency and temperature support indications that the approximation $\omega\varepsilon < \sigma/10$ may be valid in permafrost regions in North America, at VLF. But, with temperature and frequency, the behavior of the dielectric constant and of the conductivity indicates that at frequencies below a few Hz, this approximation may not be valid in permafrost.

INFERENCES re. THE ELECTRICAL PROPERTIES OF PERMAFROST IN THE LUNAR CRUST

If permafrost does exist locally or ubiquitously in the lunar crust, it could very well exhibit the wide ranges of conductivity and dielectric constant found on Earth. As a first approximation, dc resistivities of order 10^4 ohm meters to 10^5 ohm meters at -40 °C might be reasonable for porous rocks, but values in the range 10^5 to 10^7 ohm meters seem possible for crystalline rocks. Great variability can be expected in conductivity, however, because of the probable variability of brine, syngenetic ice, and epigenetic ice in a hypothetical lunar environment which would permit these factors.

Dielectric constant at 10^2 Hz and -40 °C could readily fall in the range 10^2 to 10^3; but as frequency is increased, the dielectric constant should drop to 10 to 30 at 10^5 Hz.

The -40 °C temperature is reasonable at a depth of a meter or so below the lunar surface, but temperature is expected to rise with depth.

Ward, Jiraçek, and Linlor (1968) used dielectric constants and conductivities consistent with the above remarks in their model studies of the moon.

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GLOSSARY

Terms Pertaining to the Frozen Ground Phenomena
(Terms in lower case are provisionally regarded as unnecessary synonyms)

ACICULAR ICE (Fibrous ice, satin ice) - formed at the bottom of ice (near the contact with water); consists of numerous long crystals and hollow tubes of variable form having layered arrangement and containing bubbles of air

ACTIVE LAYER (Annually thawed layer) - layer of ground above the permafrost which thaws in the summer and freezes again in the winter (Equivalent to seasonally frozen ground)

ACTIVE METHOD (of construction) - method of construction in which permanently frozen ground is thawed and kept unfrozen at and near the structure

ACTIVE PERMAFROST (Active permanently frozen ground) - permafrost which, after having been thawed due to natural or artificial causes, is able to return to permafrost under the present climate

ADFREEZING - the process by which two objects adhere to one another owing to the binding action of ice as result of freezing of water

ADFREEZING STRENGTH - resistance to the force that is required to pull apart two objects which adhere to one another as a result of the binding action of freezing (In Russian reports this term is frequently used to mean TANGENTIAL ADFREEZING STRENGTH.)

agdlissartoq - Eskimo name for a frost-mound, lit., "the one that is growing," Pingorssarajuk

AGGRADATION of PERMAFROST - growth of permafrost under the present climate due to natural or artificial causes; opposite to degradation.

ANCHOR ICE (Bottom ice) - ice formed on the bottoms of rivers and lakes

annually thawed layer (Active layer) - a layer in the ground above the permanently frozen ground which is alternately frozen and thawed each year.

APPARENT SPECIFIC GRAVITY - volumetric weight

AQUIFER - a geologic formation or structure that transmits water in sufficient quantity to supply pumping wells or springs

aufeis - German term for ICING - (Flood-ice, "Glaciers," "Glaciering"?)

BERM - a bench or a horizontal ledge partway up a slope

bodeneis - German for ground-ice

boolgoonyakh - frost mount (pingo, "hydrolaccolith") - a mound, usually of a considerable size and of many years duration - not a seasonal frost mound

BOTTOM ICE (Anchor ice) - ice formed during the winter on the bottom of rivers and lakes

CAPILLARITY - the property of tubes with hairlike openings, when immersed in a fluid, to raise (or depress) the fluid in the tubes above (or below) the surface of the fluid in which they are immersed

CAPILLARY FRINGE - the zone immediately above the water table in which water is held above the ground-water level by capillarity

CAPILLARY INTERSTICES - openings small enough to produce appreciable capillary rise

CAPILLARY WATER - water that is retained in the capillary interstices of the ground and is capable of movement through capillary action; it may remain unfrozen at temperatures between -4° to -78° C

CAVE-IN LAKE (Kettle lake, kettle-hole lake) - a lake formed in a caved in depression produced by the thawing of ground-ice (ice lens or ice pipe).

CLOSED SYSTEM - a condition of freezing of the ground when no additional supply of ground-water is available.

COMBINED WATER - water of solid solution and water of hydration which does not freeze even at the temperature of -78°C.

COMPACT CRYSTALLINE ICE - ice formed by quiet freezing of water in large basins.

CONFINED GROUND WATER - a body of ground-water overlain by material sufficiently impervious to hydraulic connection with overlying ground-water except at the intake. Confined water moves in conduits under the pressure due to difference in head between intake and discharge areas of the confined water body

congelating stress - adfreezing strength

constant soil congelation - permafrost

constantly frozen ground - permafrost

CRITICAL MOISTURE CONTENT - maximum amount of interstitial water which, when converted into ice, will fill all the available pore space of the ground

crystocrene (Icing) - surface masses of ice formed each winter by the overflow of springs

crystosphene (Ground-ice) - mass or sheet of ice developed by a wedging growth between beds of other material

DEEP-SEATED SWELLING - swelling of ground cased by the freezing of freely percolating ground water

DEGRADATION OF PERMAFROST - disappearance of the permafrost due to natural or artificial causes

deposited ice - bottom-ice

depth of seasonal change - level of zero annual amplitude

DILATION, WATER OF - water in excess of water of saturation held by the ground in an inflated state (water of supersaturation)

DITCH WATER - is water of air temperature from streams or reservoirs used in the gold mining in Alaska to thaw the frozen ground during the warm season of the year

DRY FROZEN GROUND - ground with temperature below 0°C but containing no ice

DRY PERMAFROST (Dry permanently frozen ground) - permanently frozen ground with temperature below 0°C but containing no ice

DUFF - the vegetable matter which covers the ground in the forest, as leaves, twigs, dead logs, etc.

earth-mound - frost-mound

eisboden - German for frozen ground

eis als felsart - German for ground-ice

eis im boden - German for ground-ice

eruption of soil - frost-mound ?

eternal frigidness - permafrost

eternally frozen ground - permafrost

ever frozen soil, subsoil, or ground - permafrost

FIBROUS ICE - acicular ice

FINE AGGREGATE ICE - ice formed by freezing of stirred water

FIRN ICE - formed by freezing of snow into separate spherical granules of dull appearance

FISSURE-POLYGONS (Mud-polygon) - gently convex polygonal areas of ground separated from each other by grooves or fissures; includes TUNDRA POLYGONS and MUD-FLAT POLYGONS

FIXED GROUND WATER - water held in saturated material with interstices so small that it is permanently attached to the pore walls, or moves so slowly that it is usually not available as a source of water for pumping

FIXED MOISTURE - moisture held in the soil below the hygroscopic limit

flood ice - icing

fossil ice - ground-ice

FRAZIL ICE - ice formed by freezing of turbulent water; it is a mush of ice spicules and water resembling slush

FREE WATER - interstitial gravity water which will freeze at normal temperature ($0^{\circ}C$); according to Bouyoucos it freezes for the first time at the supercooling of $-1.5^{\circ}C$.

FRESH-WATER ICE - ice formed by the freezing of fresh water in lakes, streams, or in ground

FROST-BELT - a ditch that causes an early and rapid freezing of superficial ground forming an obstruction to percolating shallow ground-water

FROST-BLISTER (Soil blister, gravel-mound) - a mound or an upwarp of superficial ground caused chiefly by the hydrostatic pressure of ground-water

FROST-BOIL - accumulation of excess of water at a place of accelerated spring thawing of ground-ice; it usually weakens the surface and may break through causing a quagmire

FROST-DAM - artificially induced freezing of ground to intercept subsurface seepages which cause icings; equivalent to frost-belt

FROST-HEAVING - an upward force usually manifested by a more or less marked upwarp due to the swelling of frozen ground

FROST-MOUND Ground-ice-mound, ice-mound, earth-mound, gravel-mound (in part); pals, pingo (in part); peat-mound, suffosion conves or suffosion complex, or suffosion knob, hydrolaccolith (in part); a seasonal upwarp of land surface caused by the combined action of 1) expansion due to the freezing of water, 2) hydrostatic pressure of ground-water, and 3) force of crystallization of ice

FROST TABLE - a more or less irregular surface that represents the penetration of spring and summer thawing of the seasonal frozen ground (active layer); (Not to be confused with permafrost table)

FROZEN GROUND - ground that has a temperature $0^{\circ}C$ or lower and generally contains a variable amount of water in the form of ice

frozen zone - permafrost

gefronis - permafrost

GLACIER - a body of ice descending along a mountain valley, commonly commencing as a congealed (recrystallized) mass of snow (firn)

glacier - this term unfortunately is widely used in Alaska to denote ground-ice or sheets of surface ice formed by successive freezing of ground or river seepages which in this report are designated as icings

GLACIER ICE (Ice of glacial origin) - may be used for ice found under old moraines or cutwash deposits

gravel-mound (Frost blister) - a low mound of earth or sand and gravel formed by hydrostatic pressure and occurring in areas of frozen ground

GRAVITY WATER (Vadose water) - water in excess of pellicular water and which can, therefore, be drawn away by the force of gravity

GROUND-ICE (Subsoil-ice, underground-ice, fossil-ice, subterranean-ice, stone-ice, bodeneis, ureis, jordbundsis; term "glacier" used by miners in Alaska) - bodies of more or less clear ice in frozen ground; excludes ice of glacial origin

GROUND-ICE WEDGE - ice wedge

HYDROLACCOLITH - usually a large frost-mound or an upwarp of ground produced by the freezing of water into a large lenticular body of ice; in a general way resembling a laccolith (Pingo)

hydraulics - that part of hydrodynamics which treats of fluids in motion

hydrodynamic - pertaining to fluids in motion

hydrostatic - pertaining to fluids at rest

HYGROSCOPIC MOISTURE - the thin film of water on the surface of the ground particles which is not capable of movement through gravitational or capillary forces

ice-field - icing

ice-heap - icing-mound

ice-hillock - icing-mound

ice-mound - frost-mound

ICE-PIPE - ice wedge of cylindrical shape

ICE-WEDGE - a narrow crack or fissure of the ground filled with ice which may extend below the permafrost table

ICING - a mass of surface ice formed during the winter by successive freezing of sheets of water that may seep from the ground, from a river, or from a spring. When the ice is thick and localized it is called icing-mound, and when it survives the summer it is called "taryn".

ICING-MOUND - a localized icing of substantial thickness but of more or less limited areal extent. May also form entirely or in part by the upwarp of a layer of ice (as in a river) by the hydrostatic pressure of water

INTRAPERMAFROST WATER - ground-water in unfrozen layers, lenses, or veins within the permafrost

ISLAND OF TALIK - unfrozen ground beneath the seasonally frozen ground (active layer) surrounded on the sides by the permafrost and extending vertically to the bottom of the permafrost

ISOPIESTIC LINE - a contour of the pressure surface of an aquifer

JUVENILE WATER - water which is derived from the interior of the earth and which has not previously existed as atmospheric or surface water

KARST - uneven topography with short ravines, sink-holes, and caverns, which are produced in a limestone terrain by the solvent action of water

lamellar ever frozen ground - layered permafrost

LAYERED PERMAFROST (Layered permanently frozen ground) - ground consisting of permanently frozen layers alternating with unfrozen layers or taliks

LAYERED PERMANENTLY FROZEN GROUND - layered permafrost

LEVEL OF ZERO AMPLITUDE - abbreviation of "level of zero annual amplitude"

LEVEL OF ZERO ANNUAL AMPLITUDE - the level to which seasonal change of temperature extends into permafrost; below this level the temperature gradient of permafrost is more or less stable the year around

METEORIC WATER - water derived from the atmosphere

MUCK - mixture of decayed vegetable matter and silt-like material forming the surface layer of the ground in areas of permafrost: locally, in river valleys, muck may be as much as 100 feet thick

MUD-POLYGON - polygonal soil, fissure polygon, mud-flat polygon

NEVE - snow ice

niggerhead tundra - local name for hummocky tundra in northern Alaska

OPEN SYSTEM - a condition of freezing of ground when additional supply of water is available either through free percolation or through **capillary** movement

PALS - Finnish term for frost-mound or peat-mound (German plural "Palsen"; Swedish plural "Palsar")

PASSIVE METHOD (of construction) - method of construction in which the regime of the frozen ground at and near the structure is not disturbed or altered

PASSIVE PERMAFROST (Passive permanently frozen ground) - permafrost that was formed during earlier colder climates; once destroyed does not appear again

PEAT-MOUND - frost-mound

PELLICULAR WATER - water adhering as films to the rock surfaces or to the surfaces of grains that compose the rock; pellicular water is stored water above the capillary fringe

PERCOLATION - a type of laminar flow of water in interconnected openings of saturated granular material under hydraulic gradient

PERELETOK - a frozen layer at the base of active layer which remains unthawed for one or two summers (Russian term meaning "survives over the summer"); pereletok may easily be mistaken for permafrost

perennially frozen ground - permafrost

PERMAFROST (Permanently frozen ground) - a thickness of soil or other surficial deposit or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for a long time (from two to tens of thousands of years)

PERMAFROST TABLE (Permanently frozen ground table) - a more or less irregular surface which represents the upper limit of permafrost

PERMANENT TALIK - a layer of unfrozen ground between the active layer (seasonal frozen ground) and the permafrost (permanently frozen ground) or within the permafrost whose unfrozen state is of many years' duration

PERMANENTLY FROZEN GROUND - permafrost

PERMEABILITY - the capacity of water-bearing material to transmit water, (measured by the quantity of water passing through a unit cross section in a unit time under 100 per cent hydraulic gradient)

PERMEABILITY COEFFICIENT - as defined by Meinzer, the rate of flow in gallons a day through a square foot of the cross section of material, under 100 per cent hydraulic gradient, at a temperature of 60°F : in field terms it is expressed as the number of gallons of water per day at 60°F that is conducted laterally through each mile of the water-bearing bed under investigation (measured at right angles to the direction of percolation) for each foot of thickness of the bed and for each foot per mile of hydraulic gradient

perpetually frozen soil, subsoil, or ground - permafrost

PINGO - Eskimo name for "conical hill"; has been used in the past as a local name for a frost-mound; it is suggested that the name pingo should be restricted to frost-mounds that are of longer than seasonal duration and that are, as a rule, of relatively large dimensions

pingorssarajuk - Eskimo name for a frost-mound "the one that is growing"

pluvoon - (slud, paste) Russian term

POLYGONAL MARKINGS [Stone-polygons, soil-polygons, mud-polygons, mud-flat-polygons, fissure-polygons (primary **and secondary**), tundra-polygons, drought-polygons, rudemarks ("rutmarken"), Strukturboden, Polygonboden, Zellenboden, Steinringe, Karreboden, Steinnetz, Spaltennetz, Schuttinseln] - general term for polygonal surface markings of the ground found in the areas that are affected by frost action

POLYGONAL SOIL - polygonal pattern of the surface of the ground produced by a more or less marked segregation of textural constituents of the ground and also indicated by a slight relief

POLN'YA (Russian term) - an unfrozen portion or a window in the river ice which remains unfrozen during all or a part of the winter owing to a local inflow of warm water either from a subaqueous spring or from a tributary

POROSITY - the property of a rock or soil determined by the presence of interstices of any size or shape, and of any manner of interconnection or arrangement of openings. It is expressed as percentage of total volume occupied by interstices

PRESSURE SURFACE - the surface to which confined water will rise in non-pumping wells that pierce a common aquifer whose water levels are not affected by a pumping well (It is a graphic representation of the pressure exerted by confined water on the conduit walls)

PRESSURE-SURFACE MAP - a map showing the contours (isopiestic lines) of the pressure surface of a confined-water system

PSEUDOISLAND OF TALIK - unfrozen ground beneath the seasonally frozen ground (active layer) surrounded and underlain by continuous permafrost

RESIDUAL SWELLING - the difference between the original pre-freezing level of the ground and the level reached by the settling after the ground is completely thawed

SALT WATER ICE - ice formed by the freezing of salt water

SATIN ICE - acicular ice

SATURATION, WATER OF - the total water that can be absorbed by water-bearing materials without dilation of the sediments

SEASONALLY FROZEN GROUND - ground frozen by low seasonal temperatures and remaining frozen only through the winter

SEEPAGE - the percolation of water through the surface of the earth or through the walls of large openings in it, such as caves or artificial excavations; may be influent seepage (seepage into the ground) and effluent seepage (seepage out of the ground)

SLUD - (Provincial English word for soft, wet mud or mire) ground that behaves as a more or less viscous fluid: it may occur as a surficial deposit or as a layer or lens beneath the surface and may at times be under a considerable hydrostatic pressure. It is "Soliflunctional ground" but it is not restricted to the surficial or soil material and its movement is not limited to gravitational flow.

SOIL - the layer or mantle of mixed mineral and organic material penetrated by roots: it includes the surface soil (horizon A), the subsoil (horizon B), and the substratum (horizon C) which is the basal horizon and is limited in depth by root penetration. In engineering practice, are included under the term soil practically every type of surficial earthen material including artifical fill, soft shales, and partly cemented sandstones

soil blister - frost blister

SOLIFLUCTION - a process of subaerial denudation consisting of the slow gravitational flowing of masses of superficial materials saturated with water

SPORADIC PERMAFROST - permanently frozen ground occurring as scattered islands in the area of dominantly unfrozen ground

stable frozen ground - permafrost

STAMP - a device for determining the strength (or ability) of the ground to support or to withstand a load

steineis - German for ground-ice

stone ice - ground-ice

STONE POLYGON - polygonal areas of fine-texture ground delimited by borders of large stones

SUBPERMAFROST WATER (subwater) - ground-water in the unfrozen ground beneath the permafrost

subsoil ice - ground-ice

subterranean ice - ground-ice

subwater - subpermafrost water

suffosion complex - frost-mound

suffosion convex - frost-mound

suffosion knobs - frost-mounds

superwater (suprapermafrost water) - water in the ground above the permafrost

SUPRAPERMAFROST LAYER - thickness of ground above permafrost consisting of active layer, talik and also the pereletok, wherever present

SUPRAPERMAFROST WATER - ground-water above the impervious permafrost table

suprazone - thickness of ground above permafrost consisting of active layer, talik and also the pereletok, wherever present

SURFICIAL SWELLING - swelling of ground, usually of small magnitude (5 to 10 cm), caused by the freezing of meteoric waters which penetrate to a small depth below the surface

SWELLING OF GROUND - increase in volume of surficial deposits due to frost action

symboitic method (of construction) - passive method of construction

taele (Tjäle) - Swedish term for frozen ground

TALIK - a Russian term for a layer of unfrozen ground between the seasonal frozen ground (active layer) and the permafrost; also applies to an unfrozen layer within the permafrost as well as to the unfrozen ground beneath the permafrost

TANGENTIAL ADFREEZING STRENGTH - resistance to the force that is required to shear off an object which is frozen to the ground and to overcome the friction along the plane of contact between the ground and the object

TARYN - a Siberian term for icings or "ice-fields" which do not melt (thaw) completely during the summer

TEMPORARY TALIK - a layer of unfrozen ground between the active layer (seasonally frozen ground) and permafrost, whose unfrozen state is due to an occasional warm winter or unusually early snowfall; it usually disappears with the return of the normal winter regime

THERMOKARST - karst-like topographic features produced by the melting of ground-ice and the subsequent settling or caving of ground

torfheugel - peat mound

TRANSITORY FROZEN GROUND - ground frozen by a sudden drop of temperature and remaining frozen but a short time, usually a matter of hours or days

UNDERFLOW - movement of ground-water in an underflow conduit

UNDERFLOW CONDUIT - permeable deposit that underlies a surface streamway and contains ground-water that percolates generally downstream

underground-ice - ground-ice

underwater ice - bottom-ice

ureis - German for ground-ice

VADOSE WATER - gravity-water

VOLUME WEIGHT (or VOLUMETRIC WEIGHT) - the ratio of the weight of a unit volume of dry ground to that of an equal volume of water under standard conditions

WATER TABLE - In pervious granular material the water-table is the upper surface of the body of free water which completely fills all openings in material sufficiently pervious to permit percolation. In fractured impervious rocks and in solution openings it is the surface at the contact between the water body in the openings and the overlying ground air.

Table 1. Classification of classic aggregates
(Granulometric classification of grounds)
(based on Russian sources)

Name	% of grain-sizes*			Remarks
	<0.005 mm	0.005-0.05 mm	0.05-2 mm	
"Fat" clay	>60	-	<3	Physical properties wholly dependent on amount of ice
Clay	60-30	Less than half of remaining 40-70	More than half of remaining 40-70	Physical properties wholly dependent on amount of ice
Silty clay	>30	More than each of the other two sizes	-	When saturated or oversaturated with water turns to slud (=sludge)
Silty-sandy clay	30-10	More than half of remaining 70-90	Less than half of remaining 70-90	When saturated or oversaturated with water turns to slud (=sludge)
Sandy clay	30-10	Less than half of remaining 70-90	More than half of remaining 70-90	
Silt	<3	>50	-	When saturated or oversaturated with water turns to slud (=sludge)
Clayey sand	10-3	-	>50	Permeable; settles quickly, time element not important
Silty-clayey sand	10-3	More than half of remaining 90-97	Less than half of remaining 90-97	When saturated or oversaturated with water turns to slud(=sludge)
Silty sand	<3	20-50	-	When saturated or oversaturated with water turns to slud (=sludge)
Sand	<3	<20	-	Permeable; settles very little if at all

When thawed are little permeable; settle (compact) very slowly, several years or decades; If oversaturated upon melting will ooze out beneath the foundation.

Grounds containing 10 or more percent of gravel are designated as "gravelly."

Table 2.

Limits of bending strength of ice in kg/cm^2						
Temp. of ice in C$^\circ$	-18.7	-9 to -11	-3 to -5	-4	-0.2	about 0
Load under which bent ice breaks in kg/cm^2	32 to 34	33	18	34	14	10 to 14

Table 3. Mean values of compressive strength of water-saturated frozen grounds.

Ultimate compressive strength in kg/cm^2			
Ground type	At temperatures not lower than -0.5°C	At temperatures from -0.5° to -1.5°C	At temperatures from -1.5° to -2.0°C
Sands	22	27	30
Clayey sands	11	22	-
Sandy clays	-	20	26
Clays	6	17	-
Silts	5	15	23

Table 4. Shearing strength of ice-saturated frozen grounds (From Tsytovich and Sumgin)

Name and composition of ground	Temperature (°C)	Moisture (ice) content by weight (%)	Ultimate shearing strength (kg/cm^2)
Clay (grains<0.005 mm=45%)	-2.1	35	6.6
Clay (grains<0.005 mm=41%)	-1.8	33	8.0
Clay (grains>1 mm=6%;<0.005 mm=31%)	-1.9	29	9.0
Sandy clay (grains<0.005 mm=27%)	-1.9	28	8.9
Sandy-silty clay (grains<0.05 mm=25%)	-2.0	36	8.0
Sand clay (grains<0.005 mm=22%)	-1.9	34	9.0
Sandy clay (grains<0.005 mm=17%; >1 mm=13%)	-2.1	31	8.5
Sandy clay (grains<0.005 mm=17%; >1 mm=16%)	-1.8	27	8.0
Sandy clay (grains<0.005 mm=15%)	-1.9	23	10.0
Sandy clay (grains<0.005 mm=15%)	-1.6	29	7.0
Sandy-silty clay (grains<0.005 mm=15%)	-1.3	23	6.0
Sandy-silty clay (grains<0.005 mm=15%)	-2.8	23	14.0
Sandy clay (grains<0.005 mm=14%)	-1.7	24	8.0
Sandy-silty clay (grains<0.005 mm=14%)	-1.5	34	7.4
Sandy clay/slud/ (grains<0.005 mm =14%;>1 mm=12%)	-1.7	17	10.3
Sandy clay with rubble (grains>1 mm =25%;<0.005 mm=13%)	-1.6	19	10.8
Sandy clay (grains<0.005 mm=11%)	-1.7	34	8.9
Sandy clay (grains<0.005 mm=10%)	-2.0	39	9.5
Silty-clayey sand (grains<0.005 mm=4%)	-1.6	26	10.0
Rubble (weathered granite) (grains>1 mm =44%)	-1.8	23	11.0
Silt (grains 0.01-0.005 mm=68%; <0.005 mm=14%)	-0.6	55	7.8
Sandy clay (grains>0.25 mm=13.6%; <0.005 mm=12%)	-0.9	37	8.9
Sandy clay with rubble (grains>0.25 mm =33%;<0.005 mm=9%)	-1.1	49	15.0
Sand (grains>0.25 mm=51%)	-0.7	18	10.9
Sand (grains>0.25 mm=34%;<0.005 mm=3%)	-0.8	36	12.2

Table 5. Effect of temperature on the shearing strength of frozen grounds (From Tsytovich and Sumgin)

Name of ground and its granulometric composition	Temperature (C°)	Moisture (ice) content by weight (%)	Ultimate shearing strength (kg/cm²)
Clay (grains 0.01-0.005 mm=50%; <0.005 mm=36%)	-0.4	45.5	3.7
	-1.8	50.6	17.2
	-3.0	49.8	20.9
	-4.9	44.0	24.3
	-6.3	42.0	28.5
	-8.8	45.9	33.5
Clayey sand (grains 1.0-0.05 mm=68%; <0.005=8%)	-0.4	18.4	4.9
	-0.9	17.8	10.6
	-3.1	19.1	21.8
	-3.9	16.9	24.8
	-6.7	19.0	44.2
	-8.5	16.2	47.5
	-9.3	19.0	48.5
Clean artifical ice	0.0	-	9.9
	-0.4	-	11.0
	-2.9	-	27.4
	-4.4	-	32.5
	-6.1	-	38.5
	-10.1	-	56.2

Table 6. Thermal conductivity of materials (from Bykov and Kapterev).

Materials	Volumetric weight	Moisture (% of volume)	Mean temperature (C°)	Coeff. of heat cond. (cal/m/h/°C)
Concrete (Portland cement, sand, and gravel (1:2:2)	2.18	Dry (dried ½-2 years	20-30	0.65-0.66
Concrete	1.6	Dry	0	0.72
Concrete (1:5 mixture)	1.9	8.6	0	1.17
Concrete	2.27	10.2	0	1.10
Concrete (mixture 1:12)	2.25	Dried 2 weeks	20-40	0.76
Concrete tamped (cement, sand, stone aggr.)	2.00	Normal	0	1.10
Concrete with brick aggregates	1.90	Normal	0	1.00
Lightweight concrete (1 part cement to 9 parts porous slag	0.55	-	20-90	0.19
Reinforced concrete	2.20	Normal	0	1.33
Brick wall (1 brick thick), plastering 28 cm on each side, right after construction	1.96	25	10	1.20
Same after 4.5 months drying in air	1.76	3.4	10	0.84
Same after 6.5 months drying in air	1.75	1.9	10	0.74
Same after 9 months drying in air	1.74	1.0	10	0.64
Same after12.5 months drying in air	1.72	0.5	10	0.60
Brick wall, new	1.57-1.63	-	20-40	0.82-0.45
Brick wall, dry	1.42-1.46	-	20-40	0.82-0.45
Old brick masonry	1.85	-	20-40	0.35
Stone masonry	-	-	20-40	1.3-2.1
Masonry with stones of sp. gr. 1.6+	1.20	-	0	0.71
Masonry of light stones	1.00	-	0	0.60
Masonry of granite, basalt, marble	2.50	-	0	2.5
Masonry of limestone, sandstone, etc.	2.20	-	0	1.2
Masonry of light rocks	1.60	-	0	0.71
Masonry of light rocks	1.20	-	0	0.60
Water	1.00	-	78-72.4	0.47-0.58
Water	1.00	-	20-40	0.52
Water	1.00	-	0	0.50
Ice	-	-	-	2.05
Ice	0.88-0.92	-	20-40	0.52
Ice	0.90	-	0	2.00
Ice	-	-	-	1.50
Ice	0.92	-	-	1.80-1.86
Air	-	-	.20	0.02-0.022
Air	-	-	100	0.026
Felt (dark grey wool)	0.15	-	40-70	0.056-0.063

Table 6, Contd. Thermal conductivity of materials (from Bykov and Kapterev).

Materials *	Volumetric weight	Moisture % of volume	Mean temperature (C°)	Coeff. of heat cond. cal/m/h/°C)
Felt (common)	0.30	-	0	0.04
Felt soaked in asphalt	0.88	-	30	0.086
Felt treated with asphalt	0.88	-	0	1.05
Granite	-	-	-	3.00
Granite	2.51-3.05	-	20-40	2.7-3.5
Hard graphite	1.58	-	50	38.0
Hard graphite	1.9-2.3	-	20-40	4.2
Gravel, washed, pebbles 3-8 cm	1.85	0	0-20	0.29-0.32
Fine clayey want	2.02	14 (by wt)	20-40	2.0
Fine river sand	1.52	0	0.20	0.26-0.28
Fine river sand	1.64	6.3% (by wt)	20-50	0.97-0.99
Fine quartz sand	-	3% (by wt)	20-40	0.05
Soil (sand, sandy clay, gravel) in the open air	1.90	-	0	2.0
Same, beneath building	1.80	-	0	1.0
Fill of dry sand	1.6	-	0	0.75
Dry dirt	-	-	-	0.12
Moist dirt	-	-	-	0.58
Dirt with coarse gravel	2.04	-	0-70	0.43-0.50
Sandstone, not case-hardened	2.26	Normal		1.33-1.53
Same after drying for 6 months	2.25	Normal	10-40	1.08-1.14
Limestone	2.56	-	100-300	1.08-1.14
Limestone	2.00	-	0	1.00
Limestone, fine-grained	1.66	-	20-40	0.58
Limestone, coarse-grained	1.99	-	20-40	0.80
Quartz, parallel to long axis	-	-	0	11.52
Quartz, at right angles to long axis	-	-	0	6.12
Quartz, fused	-	-	100	0.12
Oak boards, at right angle to layers	0.83	Dry	0-15	0.17-0.18
Oak boards, parallel with layers	0.82	Dry	12-50	0.30-0.37
Oak, air-dried	0.7-1.0	-	20-40	0.18-0.31
Oak, green	0.9-1.3	-	20-40	0.18-0.31
Pine boards, at right angle to layers	0.55	Dry	0-50	0.12-0.14
Pine boards, parallel to layers	0.55	Dry	20-25	0.30-0.32
Pine, air dried	0.3-0.8	-	20-40	0.14-0.31
Pine, green	0.4-1.1	-	20-40	0.14-0.31
Sawdust	0.22-0.25	-	0-20	0.06-0.08
Wood ashes	-	-	-	0.06
Slag, from boilers, coal	0.7-0.8	0	0-20	0.12-0.14
Slag from open hearth furnaces	0.785	-	0	0.14
Peat	0.13	-	0-50	0.03-0.04

* Other materials with a very low coefficient of heat conduction are: Diatomite, pumice, pumiceous tuff, and scoriaceous and vesicular lava

Table 7. Changes in soil conductivity with freezing.

Type soil	σ, (mhos/m) t = +14°C	σ, (mhos/m) t = -5°C
Clay, gray, with layers of ice	1.4×10^{-1}	1.6×10^{-2}
Clay, gray, gravelly	5×10^{-2}	6×10^{-3}
Clay, heavy, dark gray	2×10^{-2}	8.7×10^{-4}
Clay, dark gray with gravel to 1 cm in diameter	1.2×10^{-1}	1.3×10^{-3}
Clay, gray, gravelly with layers of ice	5.7×10^{-2}	2.0×10^{-3}
Clay, light, with fine gravel	1.2×10^{-1}	4.5×10^{-3}
Quartzy, fine grained sand, with slate particles	6.8×10^{-2}	2.4×10^{-3}
Clay sand, with quartz admixture	2.3×10^{-2}	9.1×10^{-4}
Limestone, fine grain with admixture of quartz and slate particles	5.6×10^{-2}	1.8×10^{-3}
Clayey fine grain sand with admixture of quartz particles	1.7×10^{-1}	5.9×10^{-3}

Table 8. Resistivity values at various temperatures for some common rock types. (Dostovalov, 1947, in Russian)

Sample number	Rock type	Porosity (%)	Moisture content (% of volume)	Resistivity at +18 to +20°C (Ω - cm)	Resistivity at temperature "C" (Ω - cm)	Temperature "C" (°C)	Resistivity at temperature "B" (Ω - cm)	Temperature "B" (°C)	Resistivity at temperature "A" (Ω - cm)	Temperature "A" (°C)	Sodium chloride in solution (%)	Moisture content after freezing (%)	Resistivity of water left in the pores (calculated) (Ω - cm)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
351	Mariopolyte	0.75	0.1	$1.0 \cdot 10^6$	$2.51 \cdot 10^6$	+1°	$2.51 \cdot 10^7$	- 7°	$1.0 \cdot 10^8$	-18°	0.001	--	$3.3 \cdot 10^2$
188	Pyroxenite	0.0	0.1	$1.4 \cdot 10^5$	$6.31 \cdot 10^5$	-7°	$3.98 \cdot 10^6$	-11°	$1.58 \cdot 10^7$	-20°	0.01	--	$4.7 \cdot 10^2$
253	Paleobasalt	6.4	0.1	$1.1 \cdot 10^5$	$2.51 \cdot 10^5$	+5°	$2.0 \cdot 10^6$	- 9°	$3.16 \cdot 10^6$	-20°	0.01	--	$3.7 \cdot 10^2$
239	Biotite Granite	3.4	0.15	$3.0 \cdot 10^5$	$5.0 \cdot 10^5$	0	$1.0 \cdot 10^8$	-11°	$3.98 \cdot 10^8$	-20°	0.001	0.10	$1.5 \cdot 10^2$
299	Nepheline Syenite	0.75	0.17	$5.5 \cdot 10^5$	$1.0 \cdot 10^6$	-3°	$3.0 \cdot 10^7$	-11°	$5.0 \cdot 10^7$	-19°	0.01	0.02	$3.1 \cdot 10^2$
16	Finegrained Limestone	2.2	0.40	$8.0 \cdot 10^4$	$2.5 \cdot 10^5$	-3°	$7.94 \cdot 10^5$	-10°	$1.26 \cdot 10^6$	-19°	0.01	--	$1.1 \cdot 10^2$
304	Limestone	1.1	0.40	$3.0 \cdot 10^5$	$3.98 \cdot 10^5$	+1°	$1.0 \cdot 10^6$	- 3°	$1.26 \cdot 10^6$	-19°	1.0	0.4	$4.0 \cdot 10^2$
16	Finegrained Limestone	2.2	0.50	$5.8 \cdot 10^5$	$1.0 \cdot 10^6$	0	$1.0 \cdot 10^7$	-15°	--	--	0.1	--	$9.7 \cdot 10^2$
304	Limestone	1.1	0.50	$4.0 \cdot 10^5$	$1.78 \cdot 10^6$	0	$2.5 \cdot 10^7$	- 8°	$1.0 \cdot 10^8$	-13°	1.0	--	$6.6 \cdot 10^2$
219	Quartzitic Sandstone	4.14	0.50	$4.0 \cdot 10^5$	$1.78 \cdot 10^6$	0	$1.6 \cdot 10^7$	- 7°	$1.0 \cdot 10^8$	-14°	0.001	0.2	$6.6 \cdot 10^2$
246	Limestone	7.3	0.60	$4.5 \cdot 10^5$	$6.31 \cdot 10^5$	+4°	$2.0 \cdot 10^7$	- 3°	$7.94 \cdot 10^7$	-11°	0.005	0.5	$9.0 \cdot 10^2$
353	Syenite	4.92	0.60	$6.0 \cdot 10^4$	$3.16 \cdot 10^5$	-2°	$1.48 \cdot 10^6$	-10°	$2.0 \cdot 10^6$	-19°	0.005	0.3	$1.2 \cdot 10^2$
298	Conglomerate	1.8	0.76	$5.2 \cdot 10^5$	$5.60 \cdot 10^5$	+7°	$3.16 \cdot 10^7$	- 4°	$1.0 \cdot 10^8$	- 9.5°	0.005	0.5	$1.3 \cdot 10^3$
298	Conglomerate	1.8	0.80	$6.8 \cdot 10^5$	$2.0 \cdot 10^6$	+2°	$2.0 \cdot 10^7$	- 6°	$6.3 \cdot 10^7$	-13°	0.1	0.4	$1.8 \cdot 10^3$
353	Syenite	4.92	0.80	$4.0 \cdot 10^4$	$1.26 \cdot 10^5$	-2°	$3.98 \cdot 10^5$	- 8°	$5.62 \cdot 10^5$	-13°	1.04	0.75	$1.1 \cdot 10^2$
214	Quartzitic Sandstone	3.8	1.0	$8.5 \cdot 10^4$	$1.26 \cdot 10^6$	-4°	$5.0 \cdot 10^6$	- 8°	$6.3 \cdot 10^6$	-12°	1.01	0.73	$2.8 \cdot 10^2$
252	Quartzitic Sandstone	8.7	1.30	$2.4 \cdot 10^4$	$7.94 \cdot 10^4$	-4°	$7.94 \cdot 10^6$	-10°	$1.0 \cdot 10^7$	-13°	1.0	0.9	$1.0 \cdot 10^2$
247	Sandstone	11.9	1.40	$1.5 \cdot 10^5$	$2.82 \cdot 10^5$	+5°	$5.0 \cdot 10^6$	- 5°	$7.08 \cdot 10^7$	-15°	0.001	0.6	$7.0 \cdot 10^2$
289	Red Porphyry	10.0	1.62	$1.0 \cdot 10^5$	--	--	--	--	--	--	0.01	1.2	$5.4 \cdot 10^2$
247	Sandstone	11.9	1.68	$2.4 \cdot 10^4$	$1.0 \cdot 10^5$	-1°	$1.0 \cdot 10^6$	-12°	$5.0 \cdot 10^7$	-16°	1.0	--	$1.3 \cdot 10^2$
248	Quartzitic Sandstone	9.8	1.80	$1.1 \cdot 10^4$	$2.51 \cdot 10^4$	-4°	$1.0 \cdot 10^5$	-12°	$2.0 \cdot 10^5$	-19°	5.0	--	$6.6 \cdot 10^1$
268	Quartzitic Sandstone	7.1	1.90	$3.5 \cdot 10^4$	$3.6 \cdot 10^5$	-4°	$1.26 \cdot 10^6$	-12°	--	--	0.1	--	$2.2 \cdot 10^2$
267	A Red Porphyry	12.2	2.71	$1.0 \cdot 10^4$	$2.82 \cdot 10^5$	+2°	$1.58 \cdot 10^7$	-10°	$6.31 \cdot 10^7$	-19°	0.1	1.0	$7.2 \cdot 10^2$
213	A Light-colored Conglomerate	21.0	3.30	$1.6 \cdot 10^4$	$8.91 \cdot 10^4$	+1.7°	$3.98 \cdot 10^5$	- 5°	$5.0 \cdot 10^5$	-16°	0.1	--	$1.8 \cdot 10^2$
213	A Light-colored Conglomerate	21.0	3.30	$5.5 \cdot 10^3$	$5.5 \cdot 10^3$	+8°	$1.0 \cdot 10^6$	- 5°	$1.58 \cdot 10^6$	-12°	0.005	--	$6.0 \cdot 10^1$
251	Sandstone	6.8	4.70	$5.0 \cdot 10^4$	$1.0 \cdot 10^5$	+4°	$2.0 \cdot 10^5$	+ 1°	$1.0 \cdot 10^6$	- 5°	0.001	--	$7.8 \cdot 10^2$
389	Dolomite	20.0	5.80	$6.0 \cdot 10^3$	--	--	--	--	--	-15°	0.01	5.10	$1.2 \cdot 10^2$
389	Dolomite	20.4	6.72	$4.0 \cdot 10^3$	$1.0 \cdot 10^4$	+5°	$5.0 \cdot 10^5$	- 9°	$1.26 \cdot 10^6$	-15°	0.01	2.67	$9.0 \cdot 10^1$
202	Shale	13.6	10.1	$4.7 \cdot 10^3$	--	--	--	--	--	--	0.005	8.79	$1.6 \cdot 10^2$
49	Mass of Chalcopyrite	?	0.1	$5.0 \cdot 10^{-2}$	--	--	--	--	--	--	--	--	--
--	Diabase	?	0.1	$4.5 \cdot 10^5$	$5.62 \cdot 10^5$	+2°	$3.72 \cdot 10^6$	- 0.5°	$3.6 \cdot 10^7$	-11°	0.001	--	--
163	Mass of Chalcopyrite	--	--	$1.8 \cdot 10^{-3}$	--	--	--	--	--	--	--	--	--

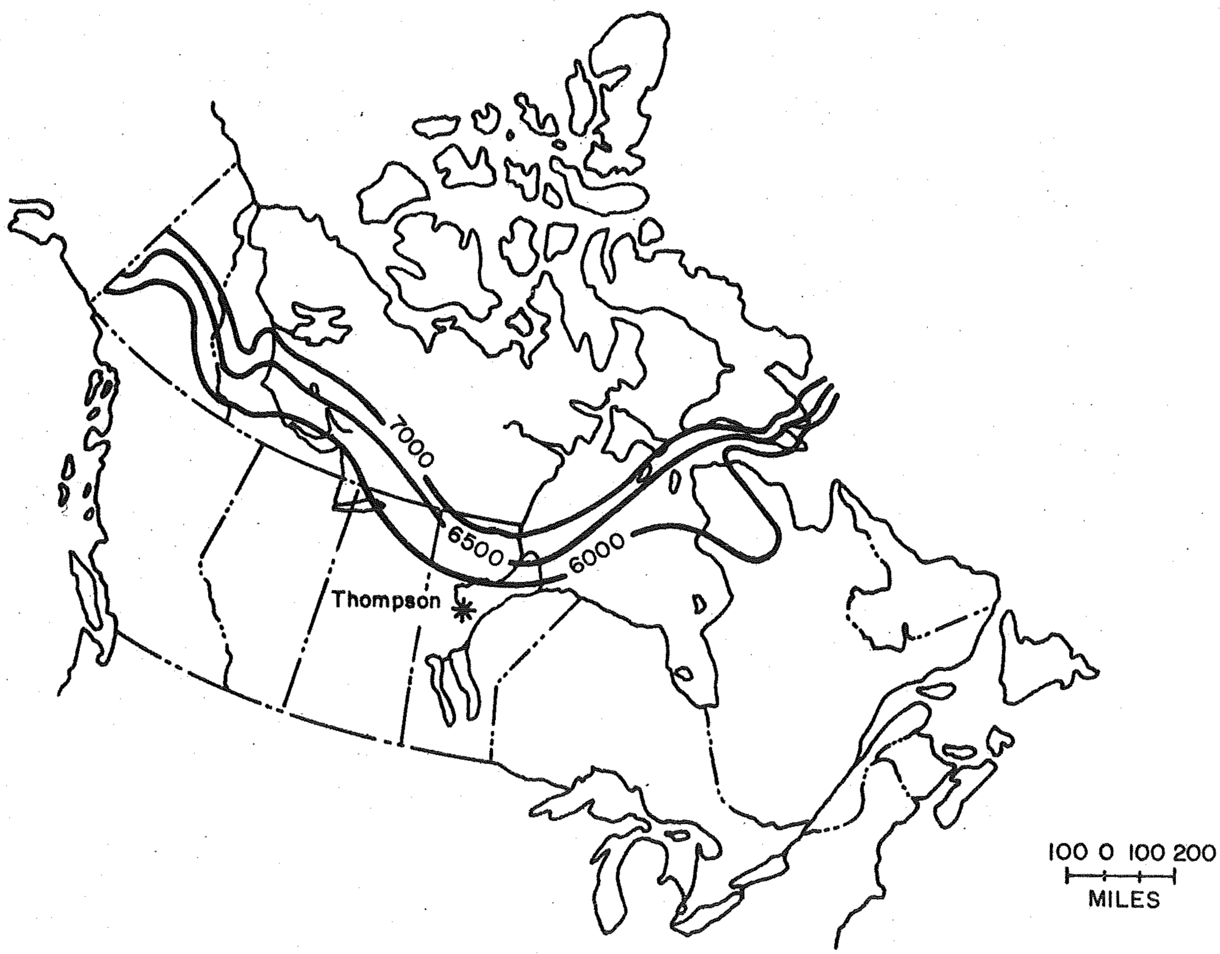


Fig. 1. Some freezing indices for Canada (Fahrenheit degree days).

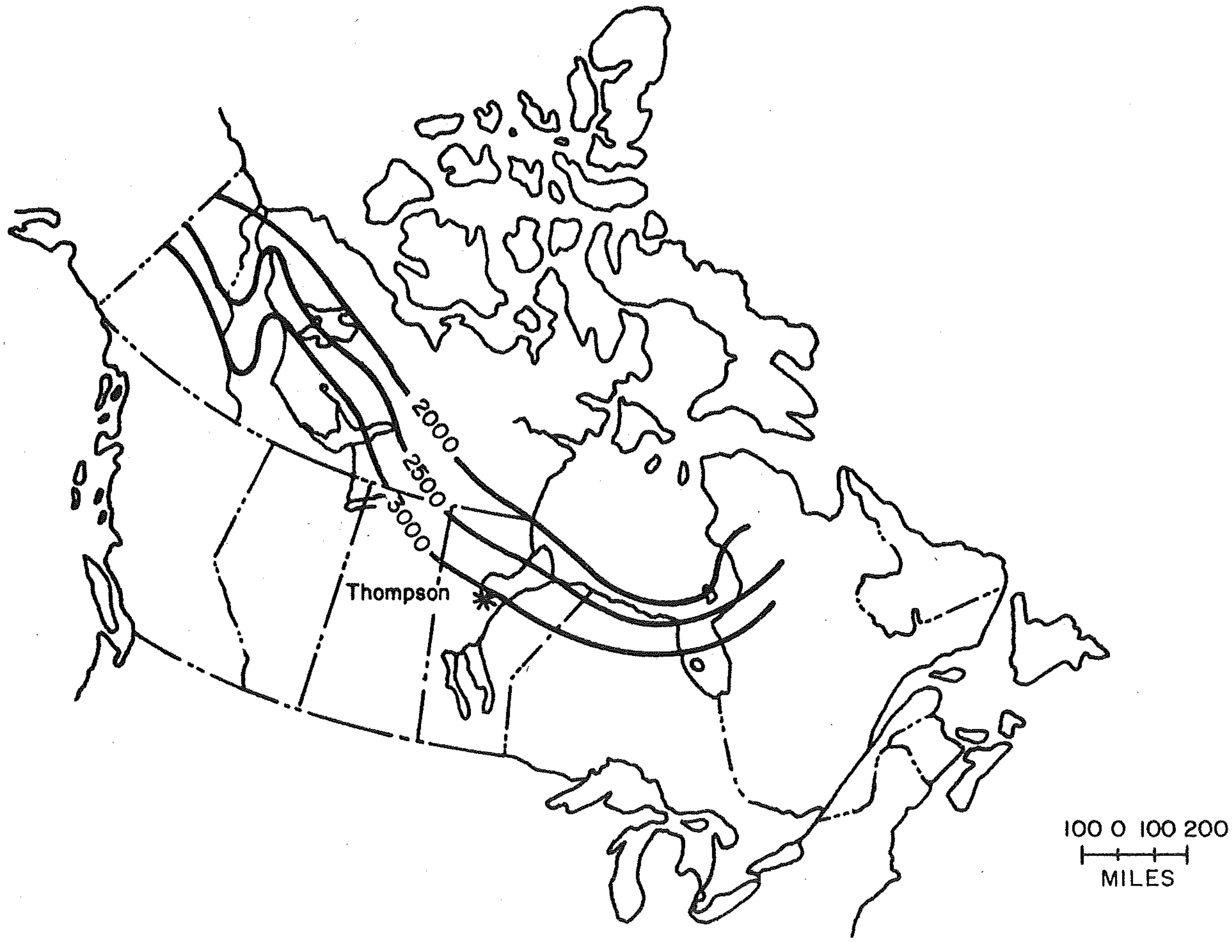


Fig. 2. Some thawing indices for Canada (Fahrenheit degree days).

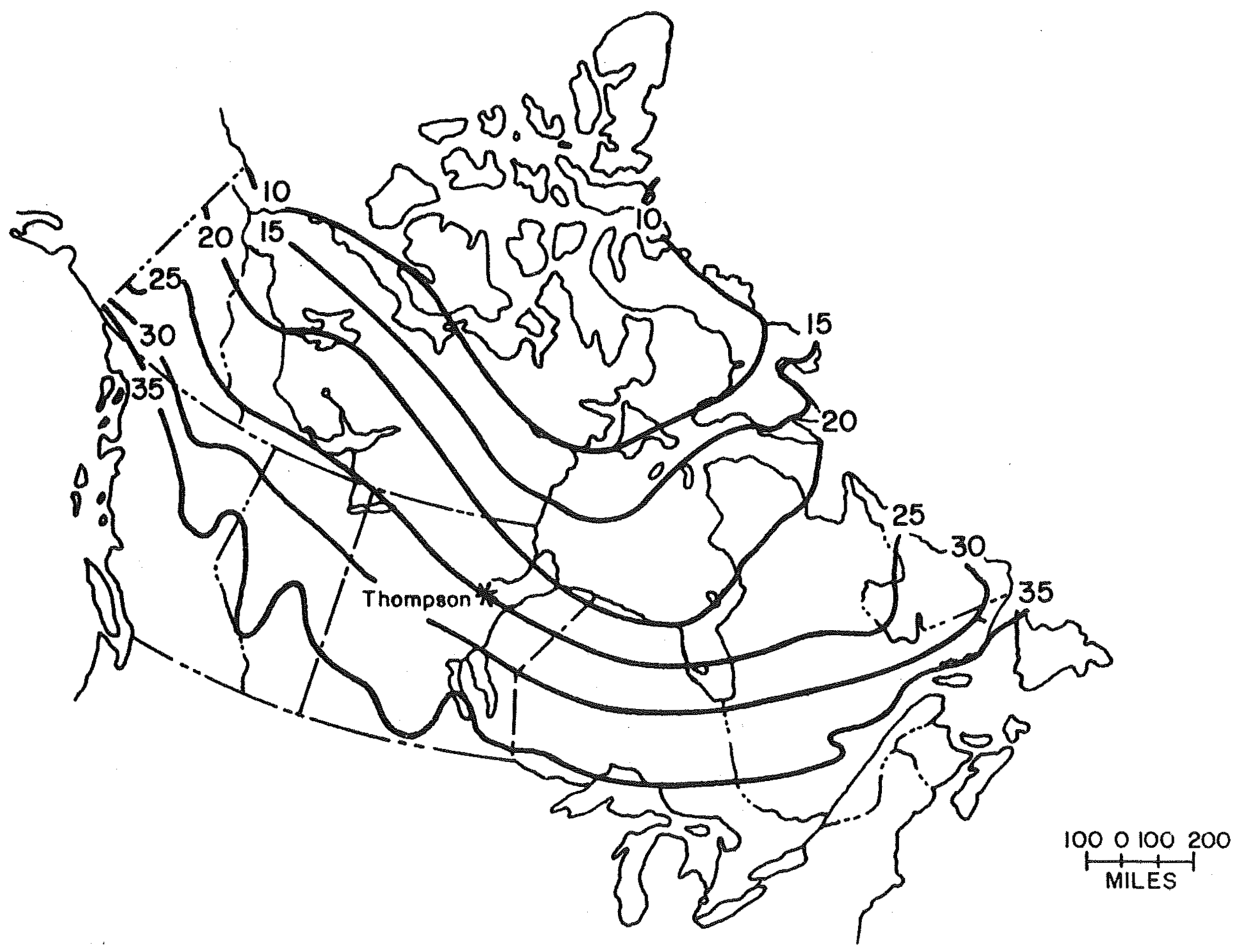


Fig. 3. Mean annual air temperature for Canada.

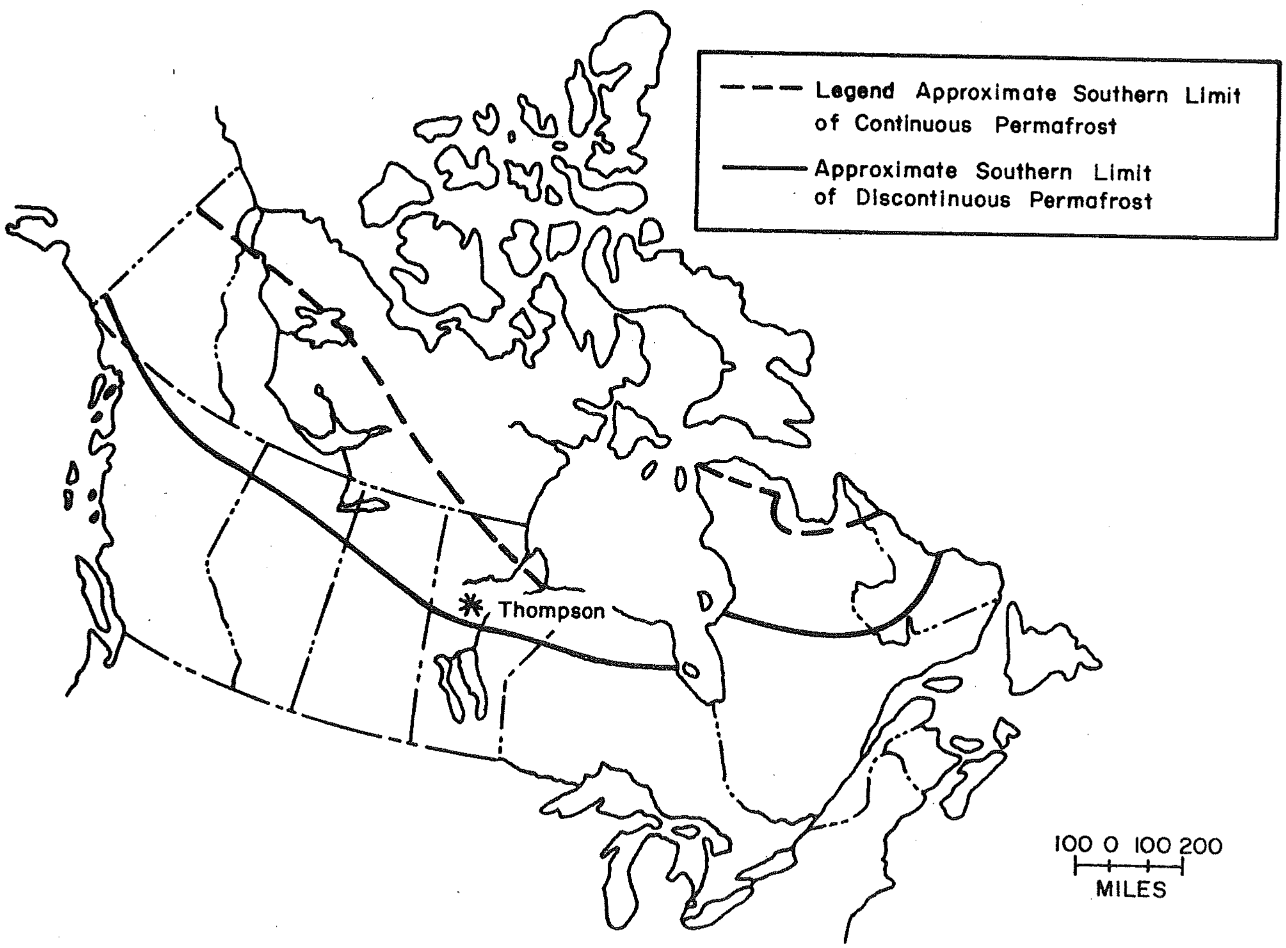


Fig. 4. Distribution of permafrost in Canada, June 1962 DRB/NRC.

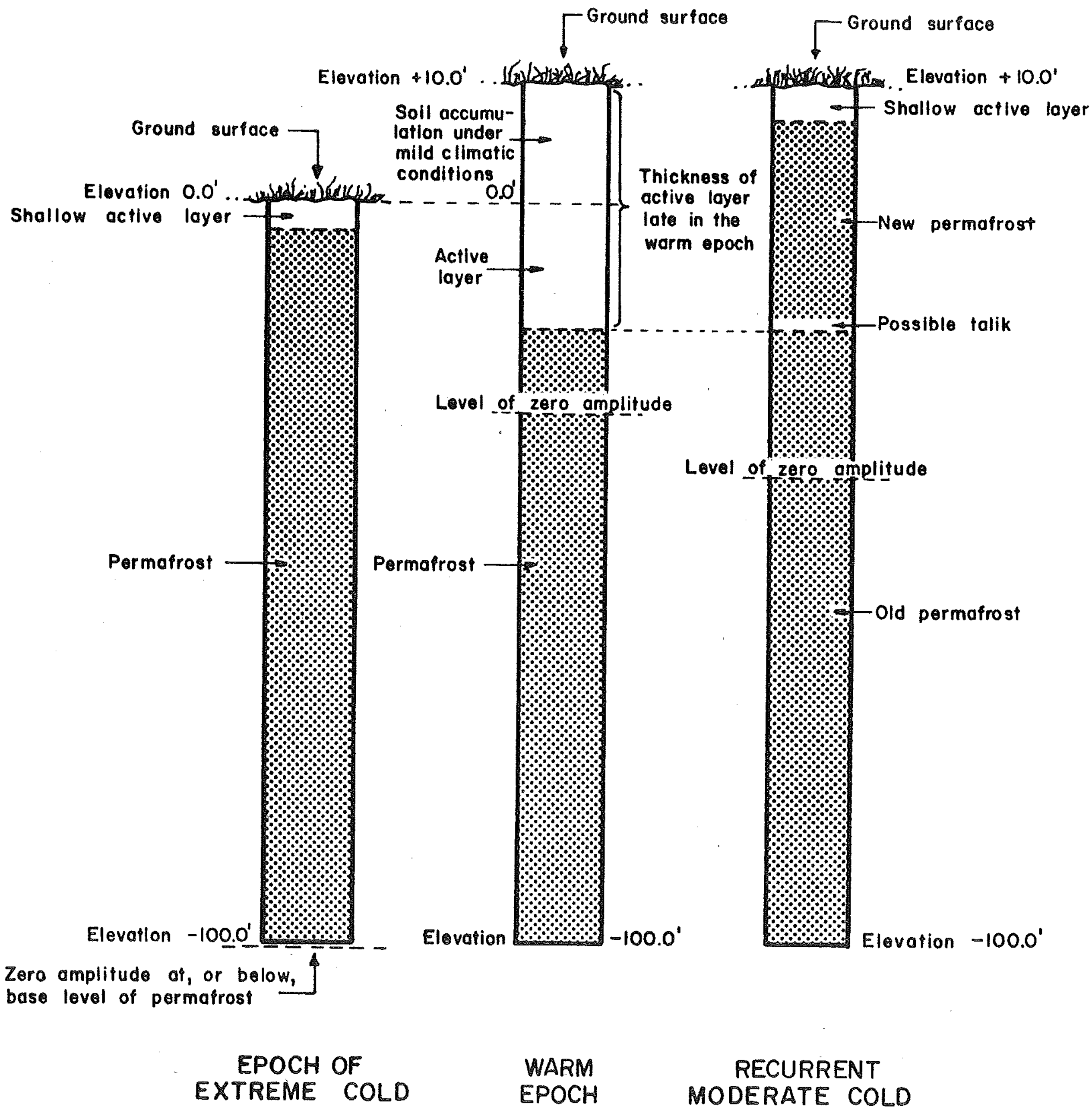


Fig. 5. Diagrammatic illustration of the origin and subsequent growth of very deep permafrost.

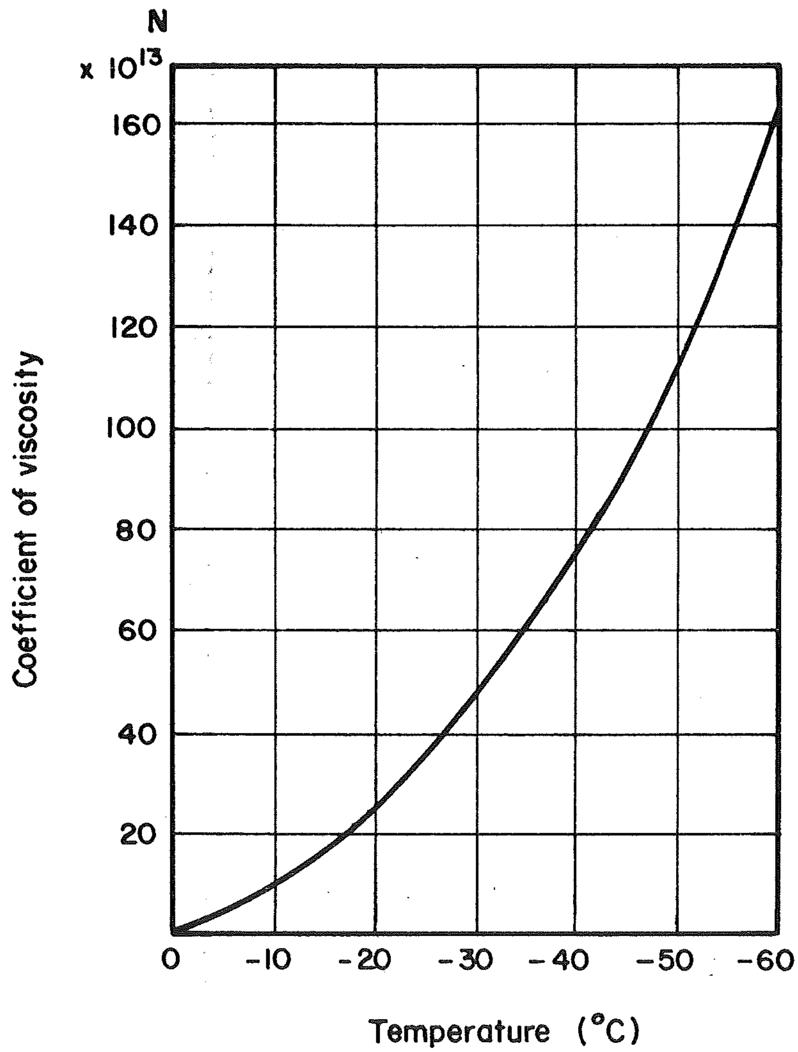


Fig. 6. Coefficient of viscosity of ice in relation to temperature (From Tsytovich and Sumgin).

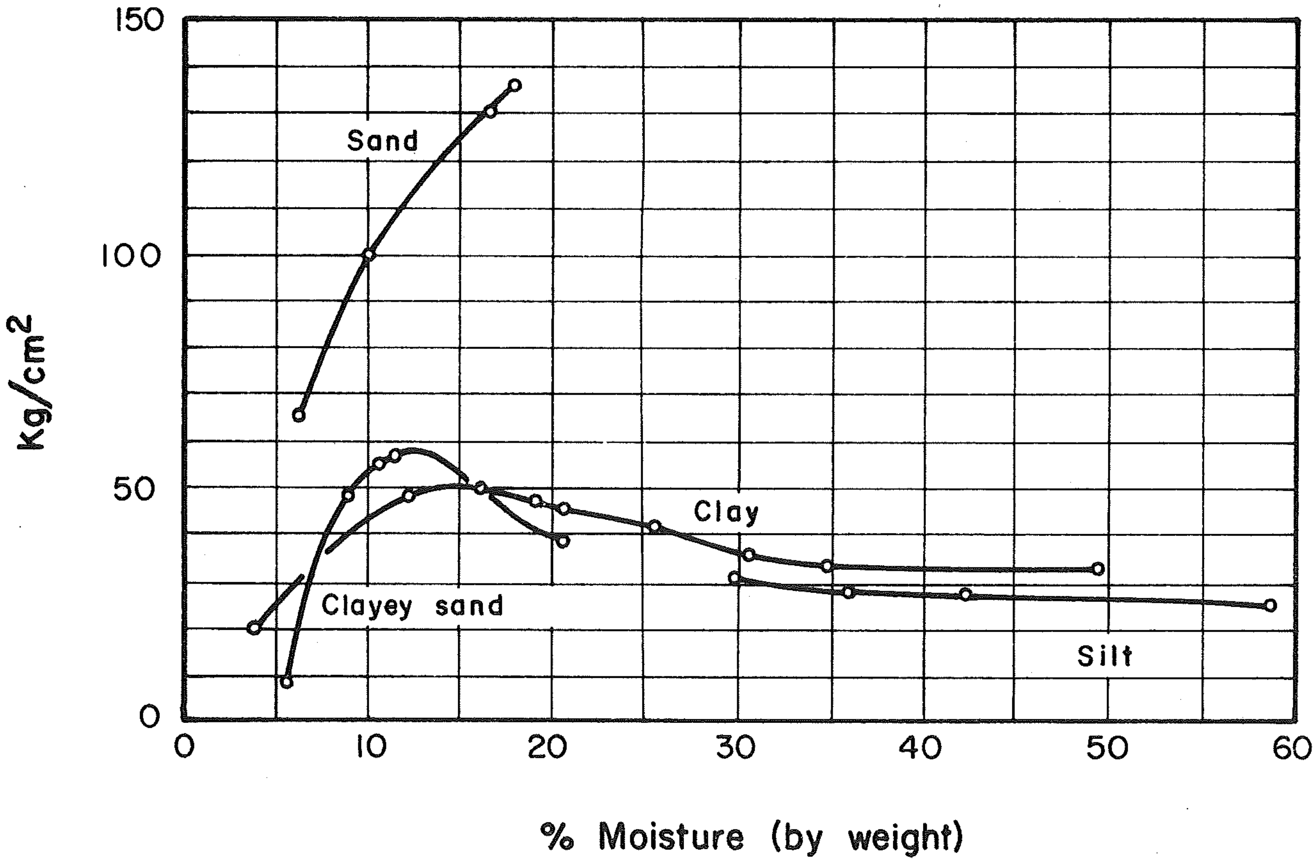


Fig. 7. Compressive strength of frozen grounds in relation to amount of moisture (After Tsytovich and Sumgin).

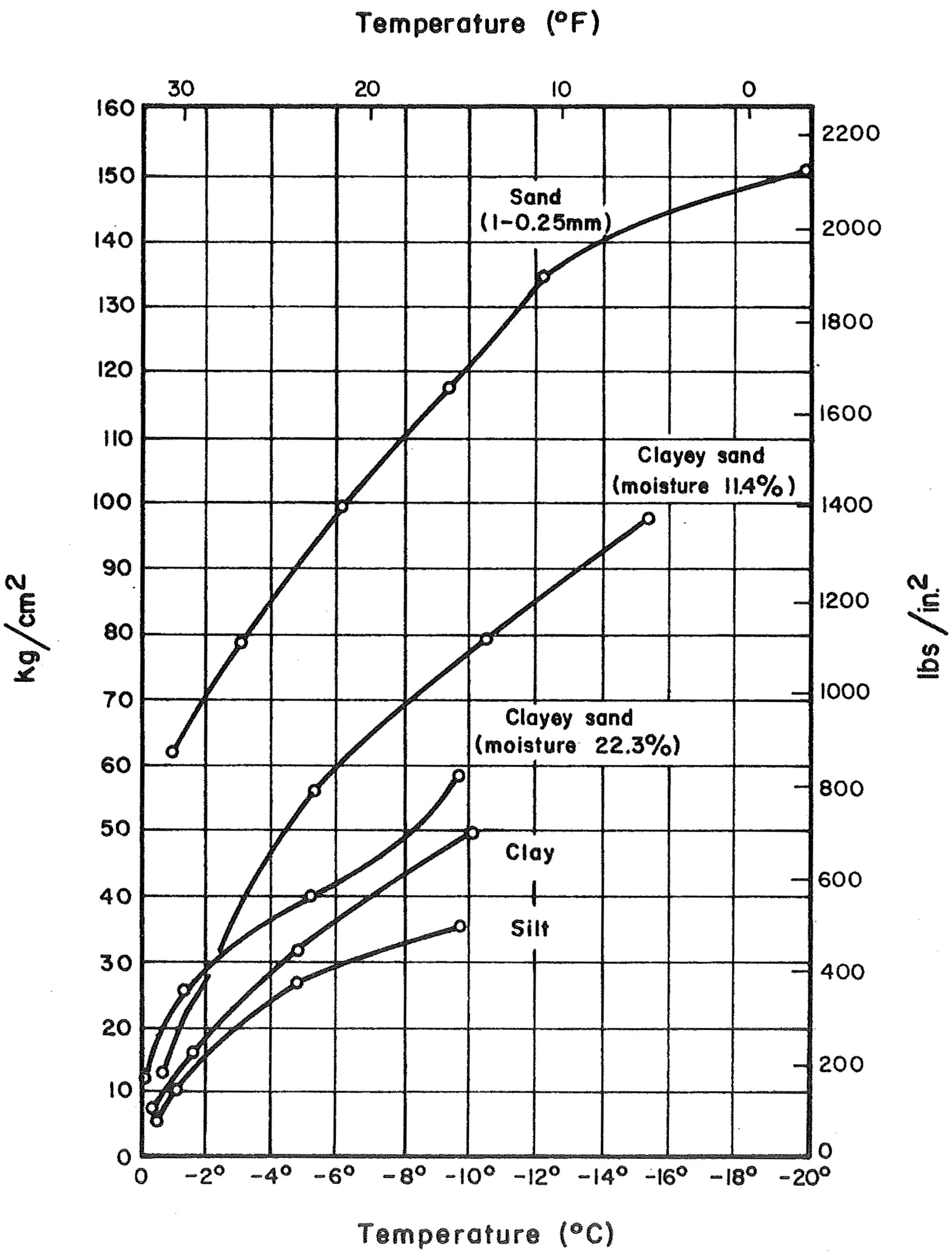


Fig. 8. Ultimate compressive strength of frozen grounds in relation to temperature.

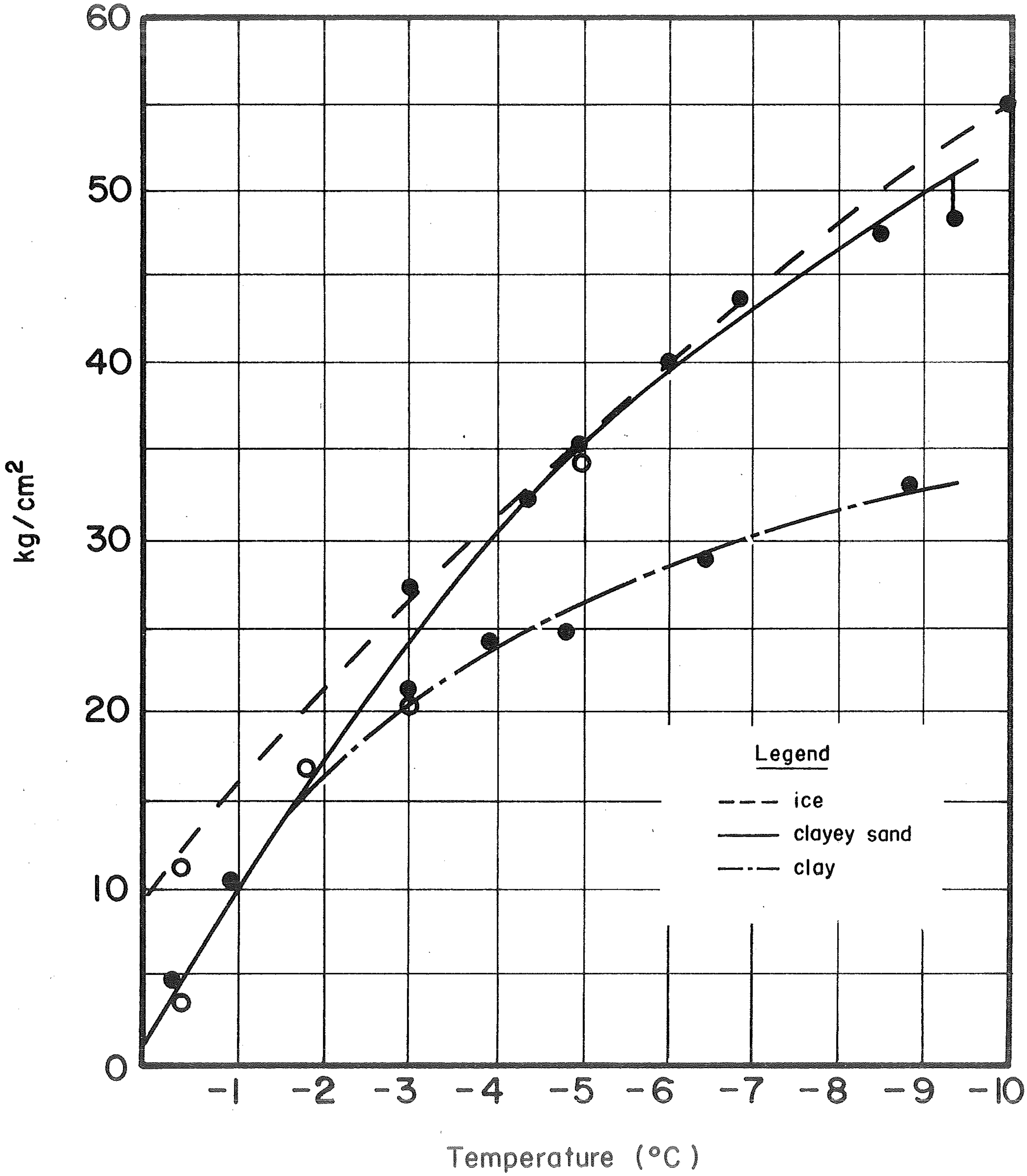


Fig. 9. Shearing strength in relation to temperature.

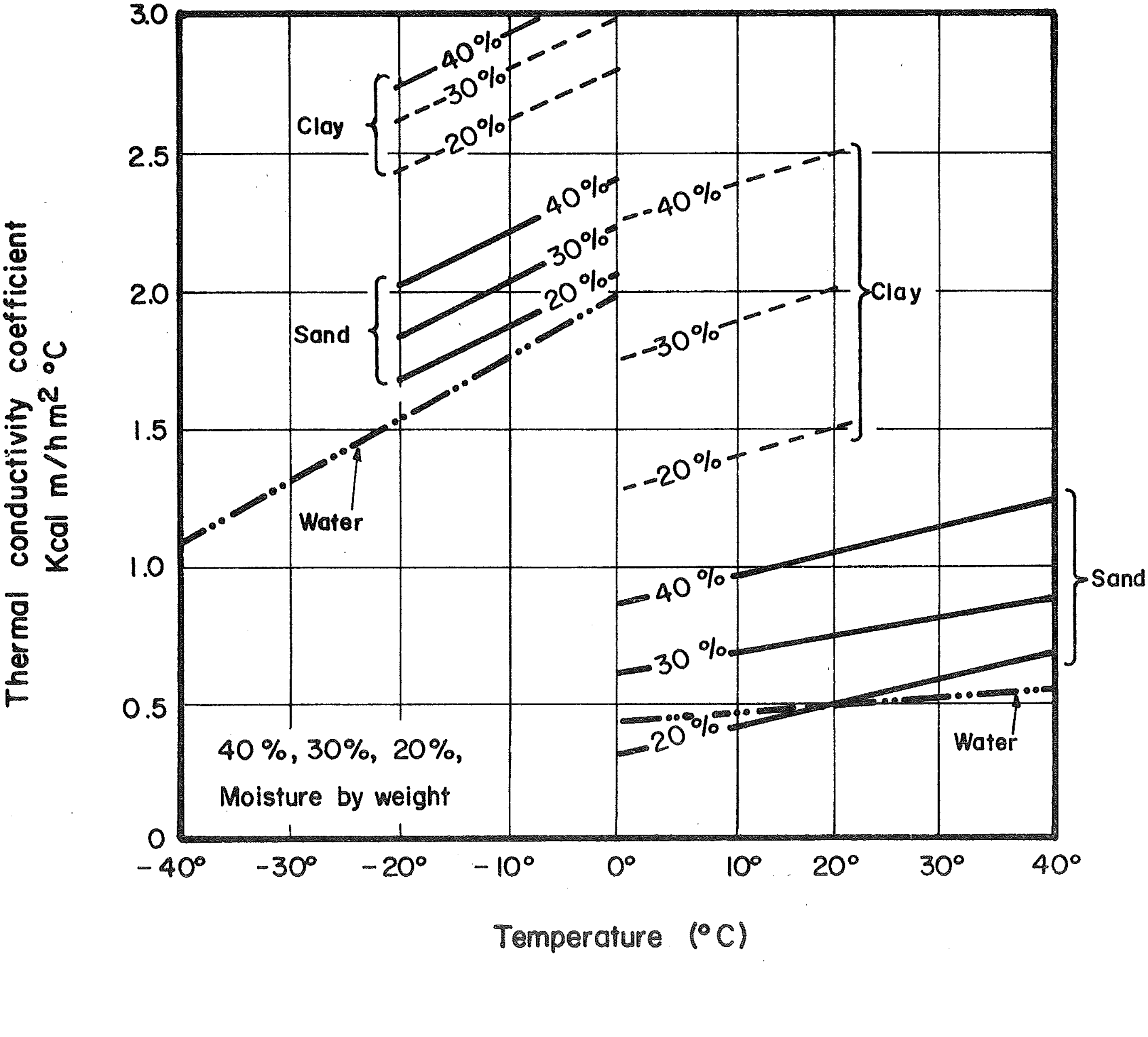
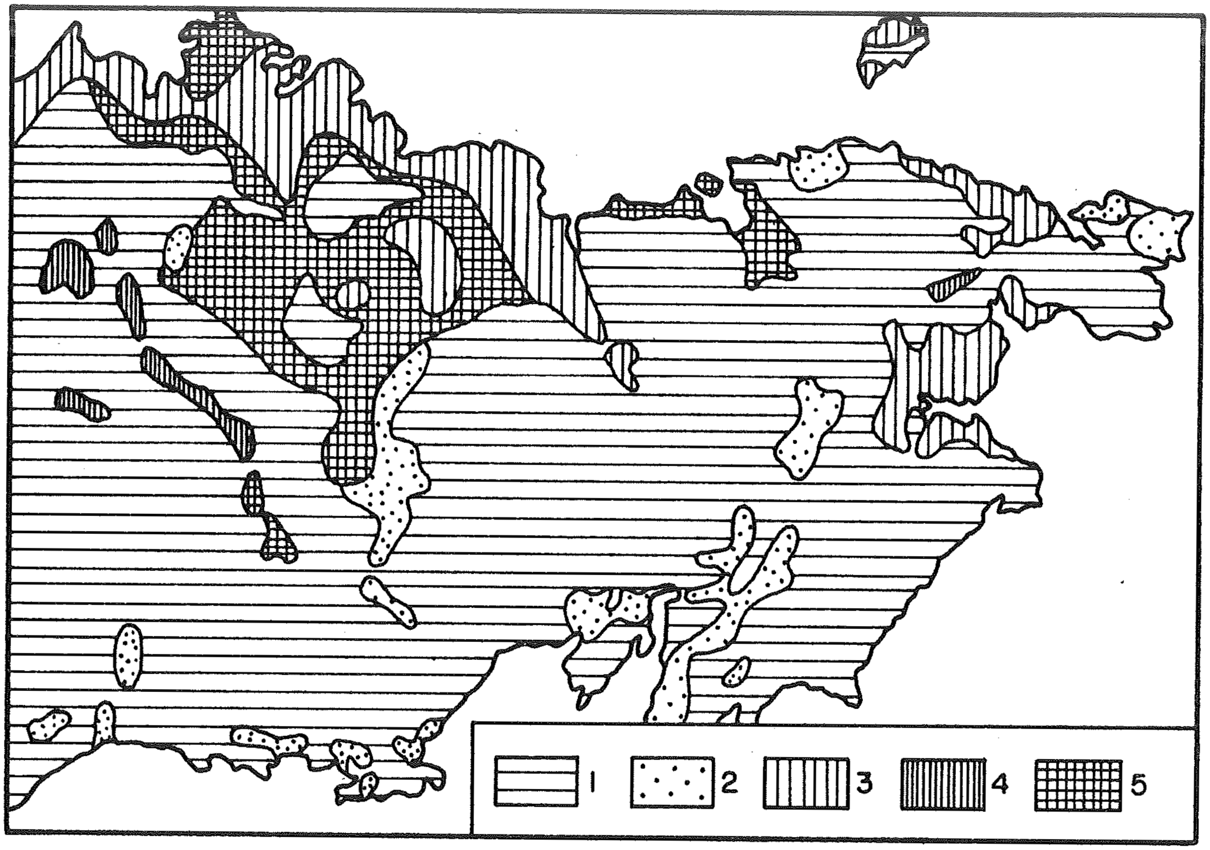


Fig. 10. Thermal conductivity of clay, sand, and water at different temperatures.



1) frozen rocks with an electric conductivity greater than $1.67 \cdot 10^{-4}$ mho/m; 2) frozen rocks with an electric conductivity ranging from $1.67 \cdot 10^{-4}$ to $4 \cdot 10^{-5}$ mho/m; 3) frozen rocks with an electric conductivity ranging from $4 \cdot 10^{-5}$ to 10^{-5} mho/m; 4) frozen rocks with an electric conductivity ranging from 10^{-5} to $2.5 \cdot 10^{-6}$ mho/m; 5) frozen rocks with an electric conductivity of less than $2.5 \cdot 10^{-6}$ mho/m.

Fig. 11. Schematic map of the electric conductivity of the frozen rocks in the northeastern USSR.

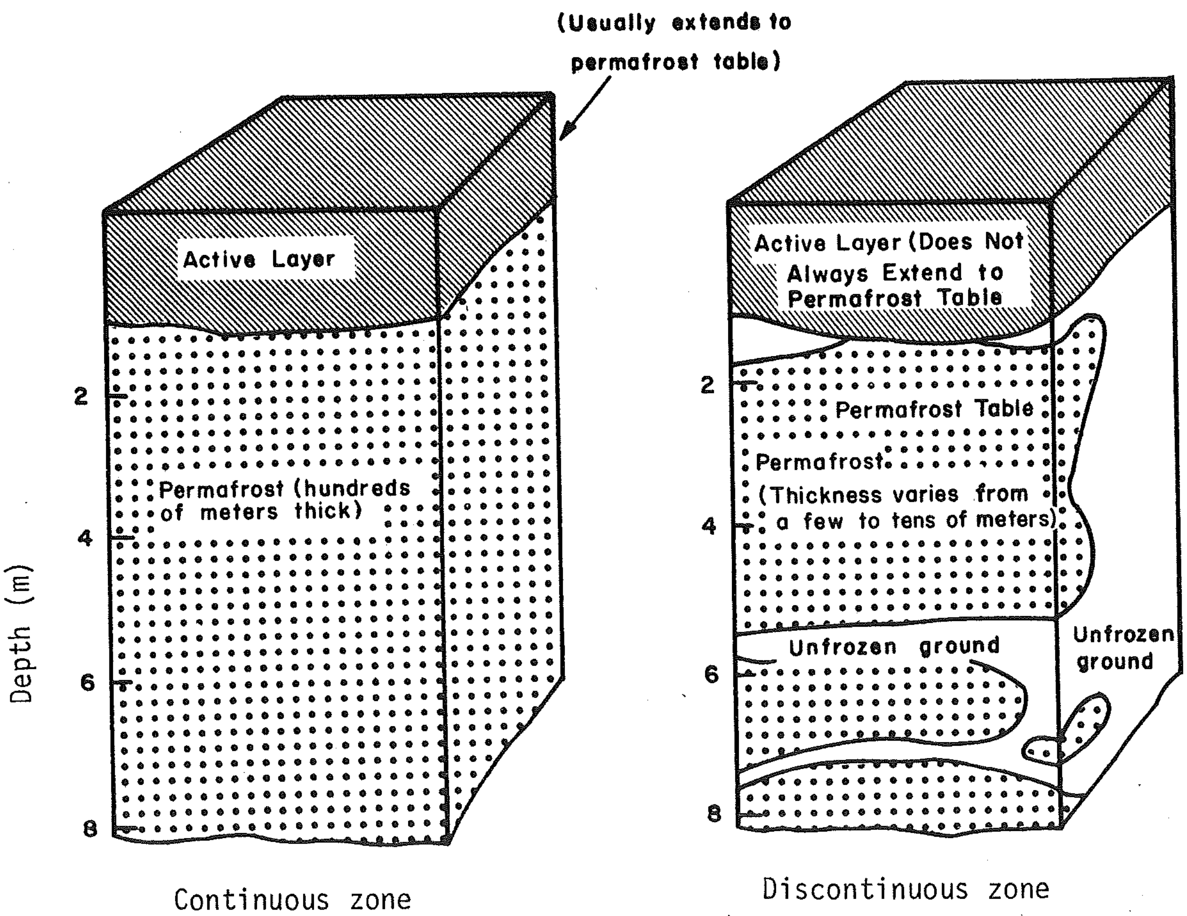


Fig. 12. Typical vertical distribution and thickness of permafrost.

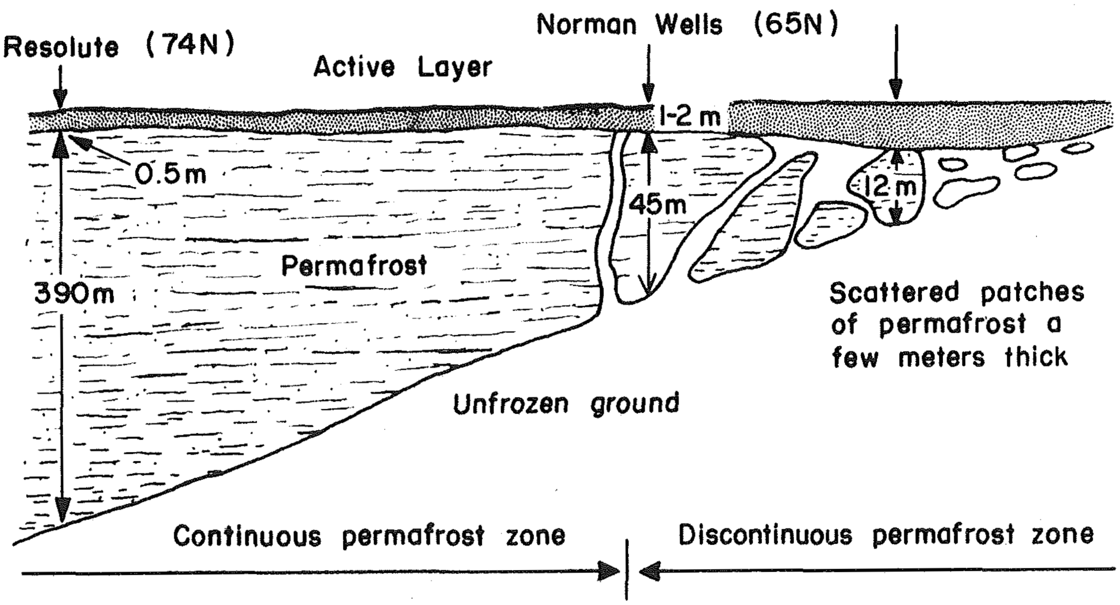


Fig. 13. Typical profiles in permafrost region.

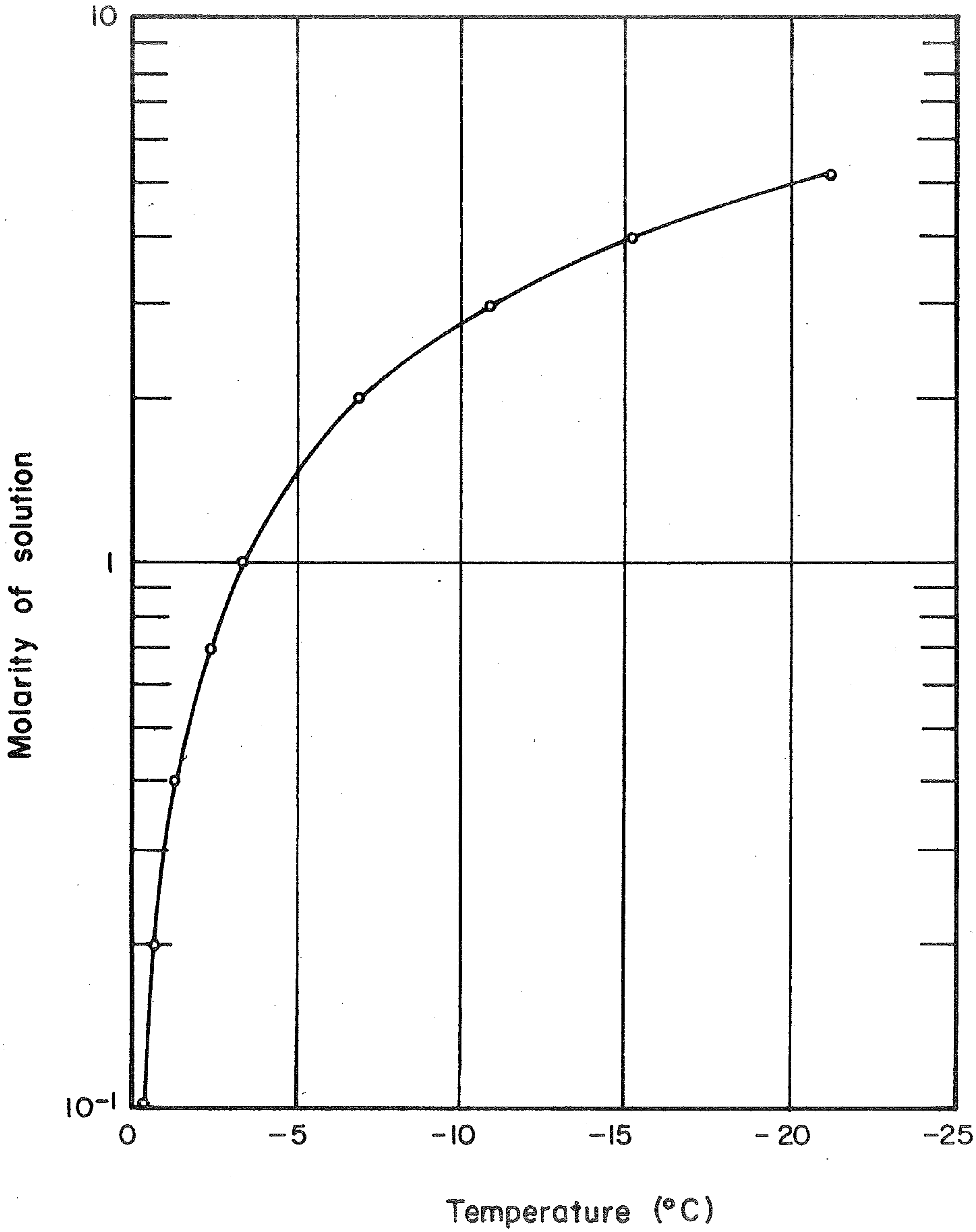


Fig. 14. Freezing point of a sodium chloride solution (Hall and Sherrill, 1928).

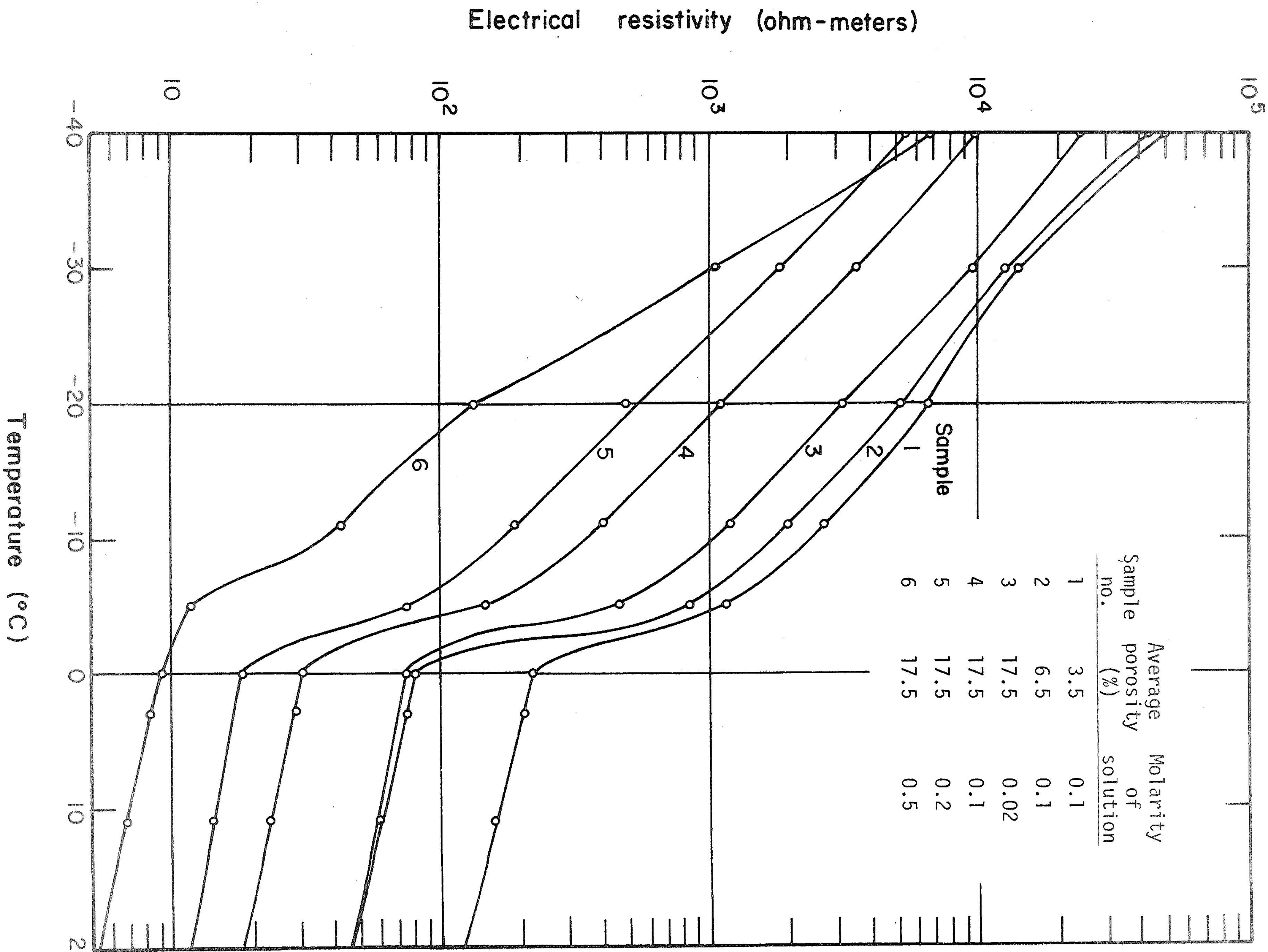


Fig. 15. Electrical resistivity as a function of temperature at a frequency of 50,000 Hz.

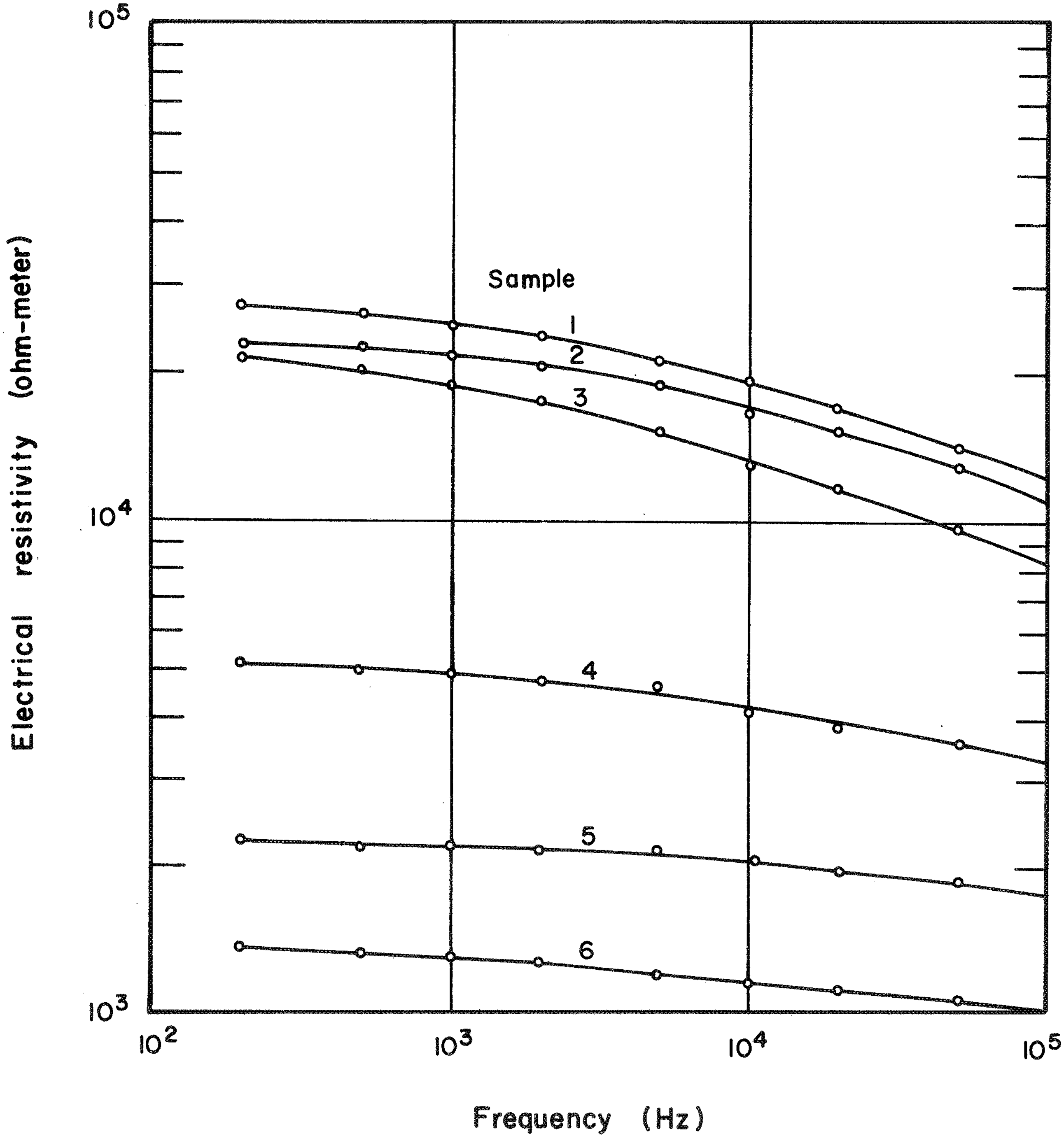


Fig. 16. Electrical resistivity as a function of frequency at -30° C'.

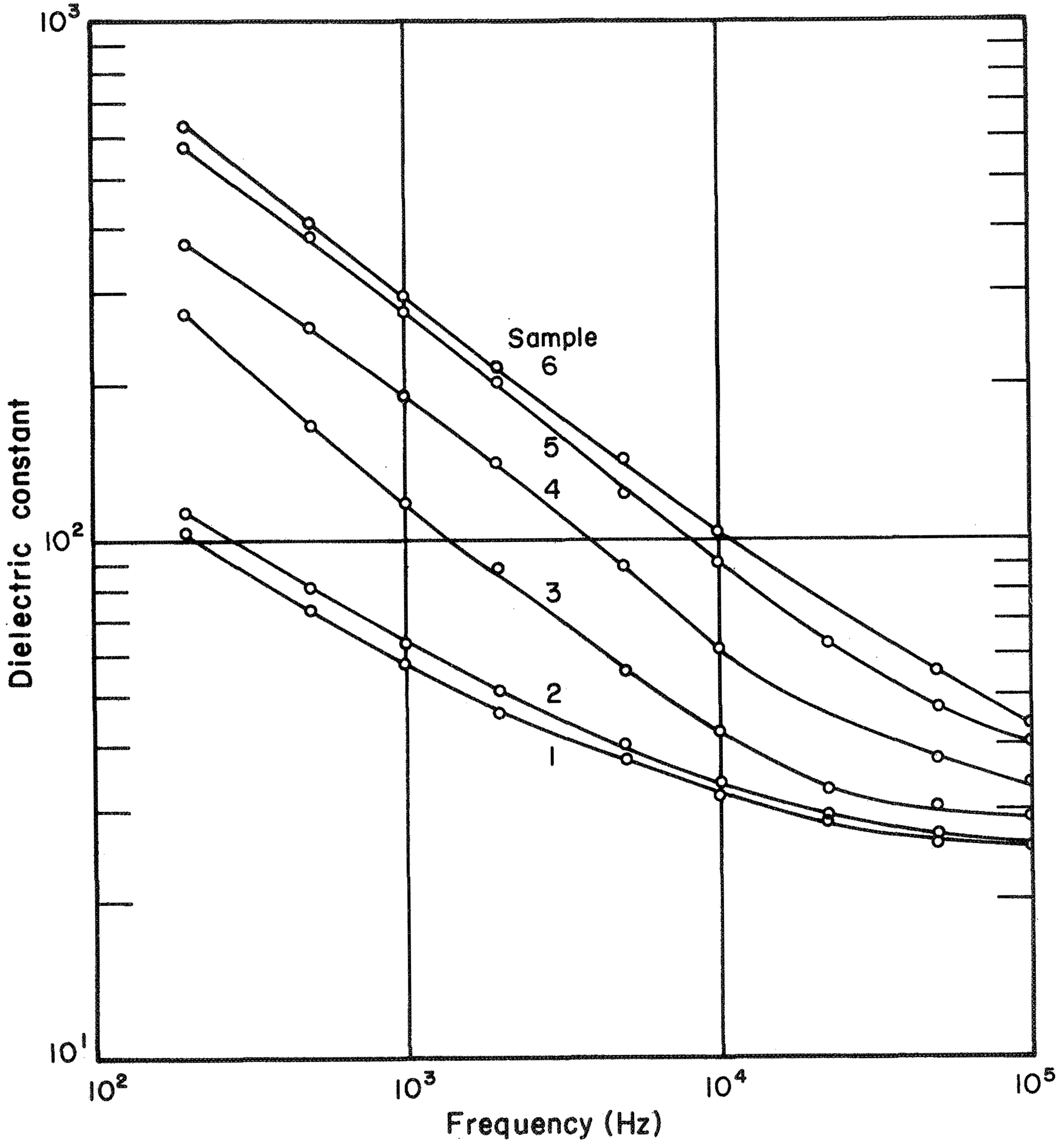


Fig. 17. Dielectric constant as a function of frequency at -40°C'.

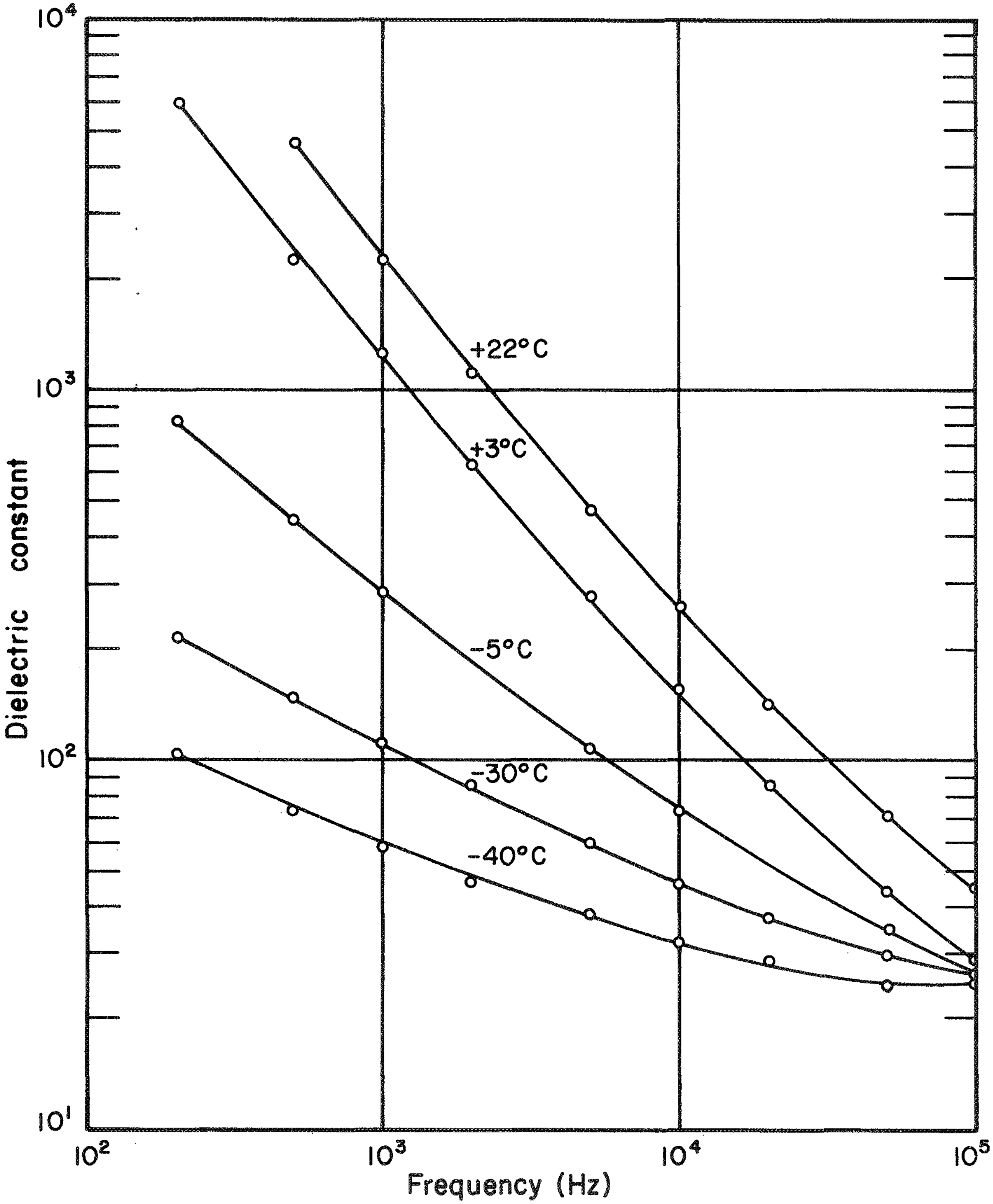


Fig. 18. Dielectric constant of sample 1 as a function of temperature and frequency.

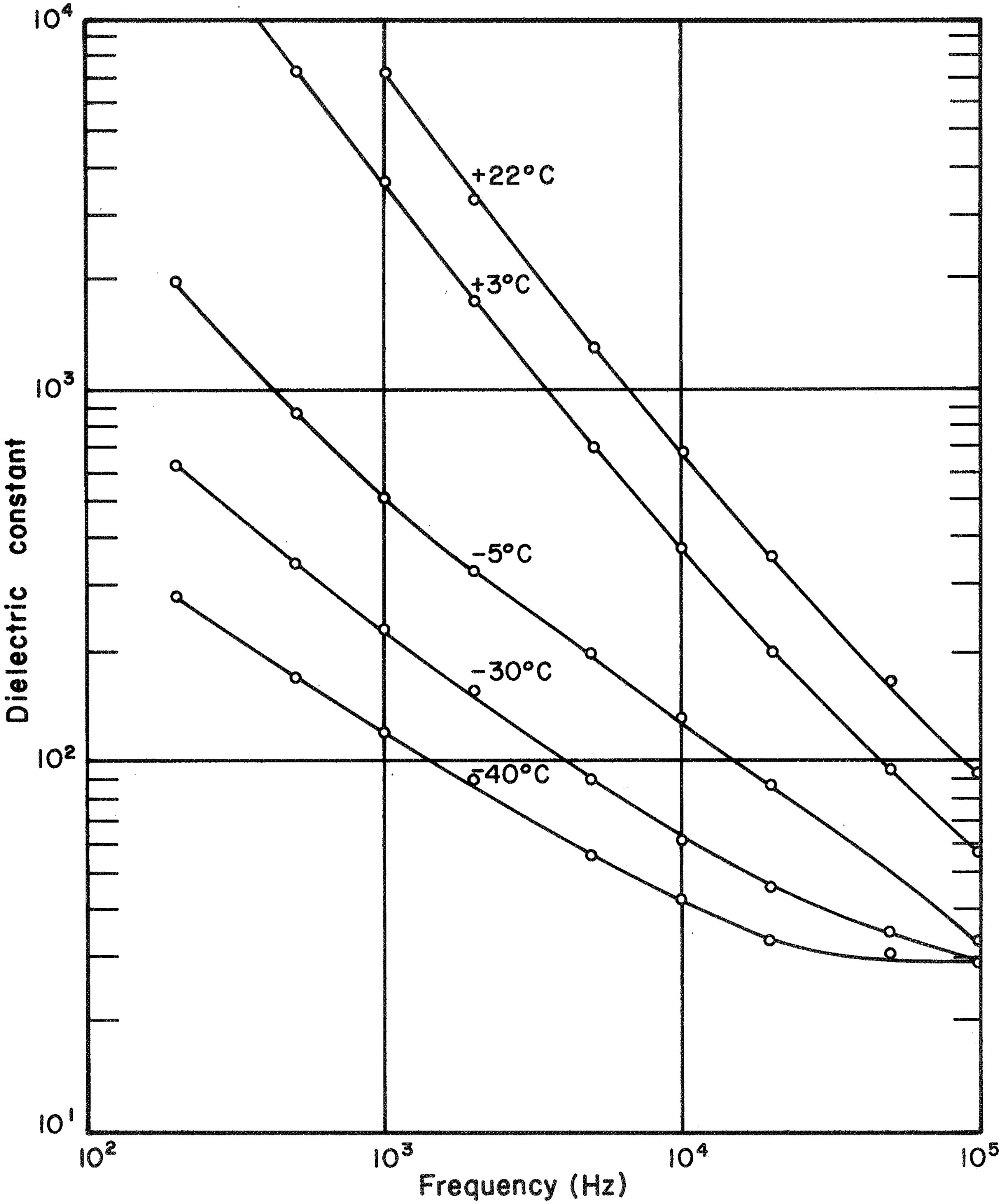


Fig. 19. Dielectric constant of sample 3 as a function of temperature and frequency.

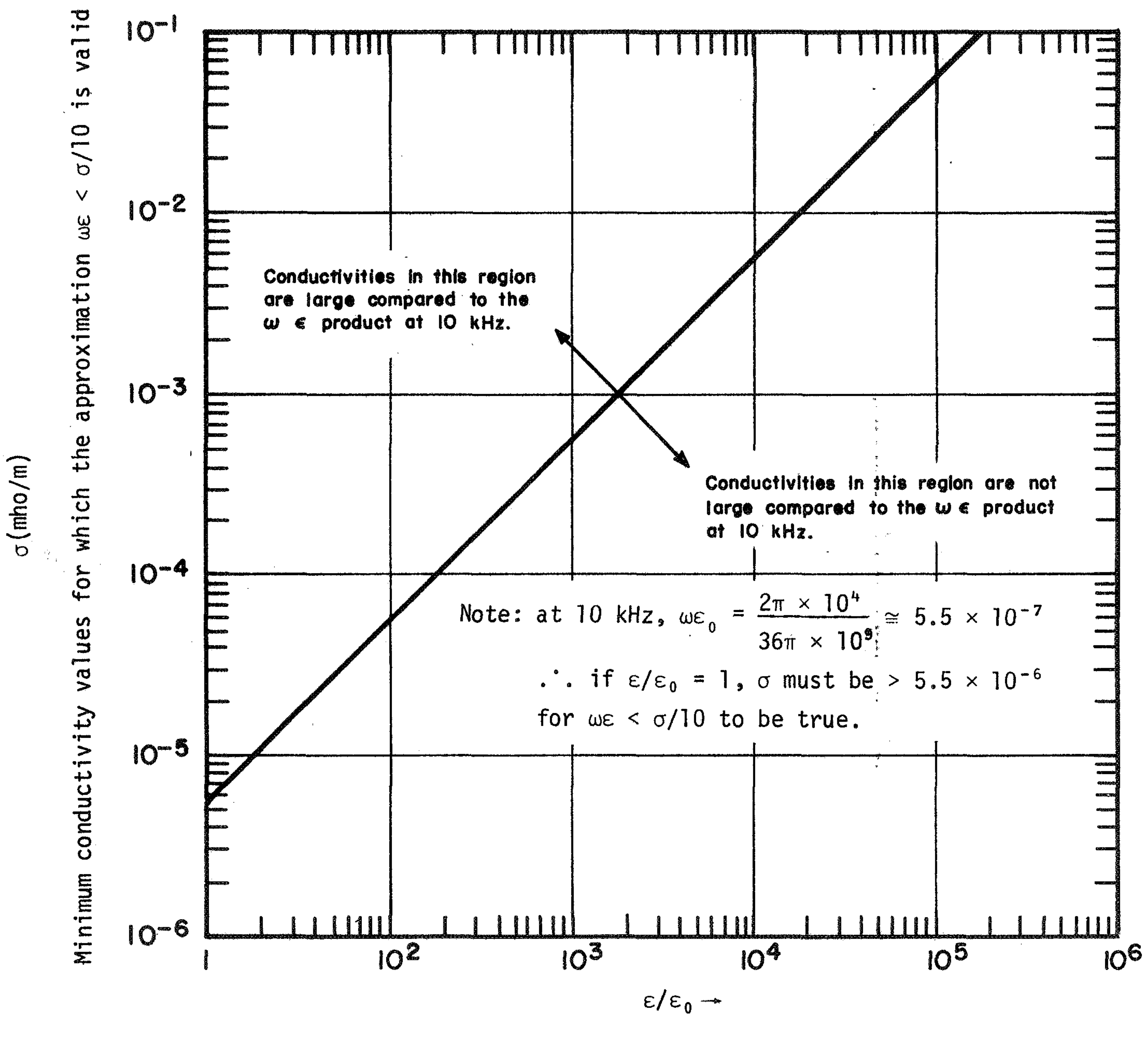


Fig. 20. Minimum values of conductivity as a function of $\varepsilon/\varepsilon_0$ for $\omega\varepsilon < \sigma/10$ at 10 kHz.