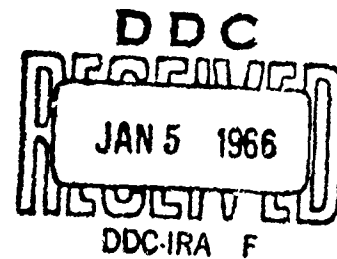


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OMEGA NAVIGATIONAL SYSTEM

CONDUCTIVITY MAP

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ABSTRACT

A conductivity map of North America has been prepared showing effective earth conductivity values for a 10 kc/s propagating wave. This map was prepared as an aid in propagation studies and chart preparations for the Omega Navigational System using a technique referred to as "geologic correlation". Values of conductivity were determined for regions whose boundaries are based upon climatological, pedological, physiographical, and geological information. Regional values were based (whenever possible) on available conductivity data taken within these regions. Additional four-terminal array conductivity measurements (described in Appendix C) were made in the permafrost region of the Canadian Shield and along the Gulf Coast to aid in the determination of conductivities for these regions.

The effective conductivity map is printed on a 17 X 22 inch sheet, and utilizes color hue and saturation to present effective conductivity values in half-decade steps from 1×10^{-5} mho/meter (for the Greenland ice-cap) to 3×10^{-2} mho/meter. Confidence and variability factors are indicated on the map.

OMEGA NAVIGATIONAL SYSTEM CONDUCTIVITY MAP

1. INTRODUCTION

The accuracy of the Omega Navigation System depends on the predictability of the phase velocity of electromagnetic radiation in the very low frequency band. The velocity of propagation at a given frequency is a function of ionospheric height and conductivity gradient, and the effective conductivity of the earth. This report is concerned with the knowledge of the earth and its characteristics and does not consider the ionosphere.

The work of Wait and Spies [1964] has provided reasonably accurate calculations of attenuation coefficients and phase velocities for a smooth earth and ionosphere when their electrical characteristics are known. It was the purpose of this program to provide more accurate information regarding the electrical properties of the North American continent such that theoretical relationships could be more accurately applied.

Conductivity maps have been produced for the continental United States by Fine, [1954], and for Canada, by Ireland, [1961], for use at broadcast frequencies. The much greater penetration of VLF energy renders the broadcast frequency conductivity maps of little use to the Omega program. The 10 kc/s effective conductivity map of North America which has been produced under this program and is included as a part of this final report should help to fill this serious gap in our knowledge of the radio frequency conductivity of the earth's surface. The maps of Fine and Ireland were obtained primarily by determining the groundwave attenuation at broadcast frequencies while this VLF conductivity map of North America has been produced using a technique

referred to as 'geologic correlation'. In other words, using the relationships between various geologic factors and known conductivity values it was possible to produce an effective conductivity map of North America.

Some work relating earth conductivity to geologic structure and age was done by Card, [1940]. Very little work has been done to extend the relationships between conductivity and geologic parameters initiated by Card until the present time. Dostovalov, [1947] indicated that in most cases correlation was lacking or was so indefinite that it could not be used.

This report discusses theoretical aspects of earth conductivity, methods of measuring the conductivity of the earth and the means or methods of interpreting conductivity measurements for propagation applications. In addition, the collection of data which was necessary for the preparation of the North American map is discussed along with other aspects involved in the preparation of the map. The main body of the report is concluded with a discussion of the map and its proper use and application. Several appendices discuss in more detail subjects presented briefly in the main body of the report.

2. CONDUCTIVITY

This section will discuss some aspects of effective conductivity in relation to phase velocity as well as various methods of determining the conductivity of the earth.

2.1 Effective Conductivity

The effective conductivity of a real earth may be defined as that conductivity of a uniform homogeneous conducting earth which would give the same effect to a propagating electromagnetic field as that of a real earth. In the case of a real earth in which the earth material is completely uniform and homogeneous, the effective conductivity is equal to the actual conductivity. In all other cases, however, one finds that the effective conductivity is affected by layering of geologic strata, by vegetation and soils, and also by inhomogeneities and anisotropies of the earth materials. Given complete information of a geoelectric situation, one can compute effective conductivity using principles described in Appendix A. In the literature, effective conductivity is usually computed considering a horizontally layered earth and making certain approximations convenient for calculation. It has been found that these approximations are valid for most situations arising throughout North America.

For the present problem, it is important to note that there is a much greater change in phase velocity when effective conductivity ranges between 1 mmho/m and 10 mmho/m than there is with conductivity varying between 10 mmho/m and 100 mmho/m. Figure 1 graphically illustrates this fact. Recent work by Wait, [1965] extends the relationship illustrated here to conductivities lower than 1 mmho/m.

2.2 Measurements of Conductivity

Conductivity may be measured in many different ways, and one common method is the four-terminal array technique. With this method, the potential between two electrodes resulting from a current driven between

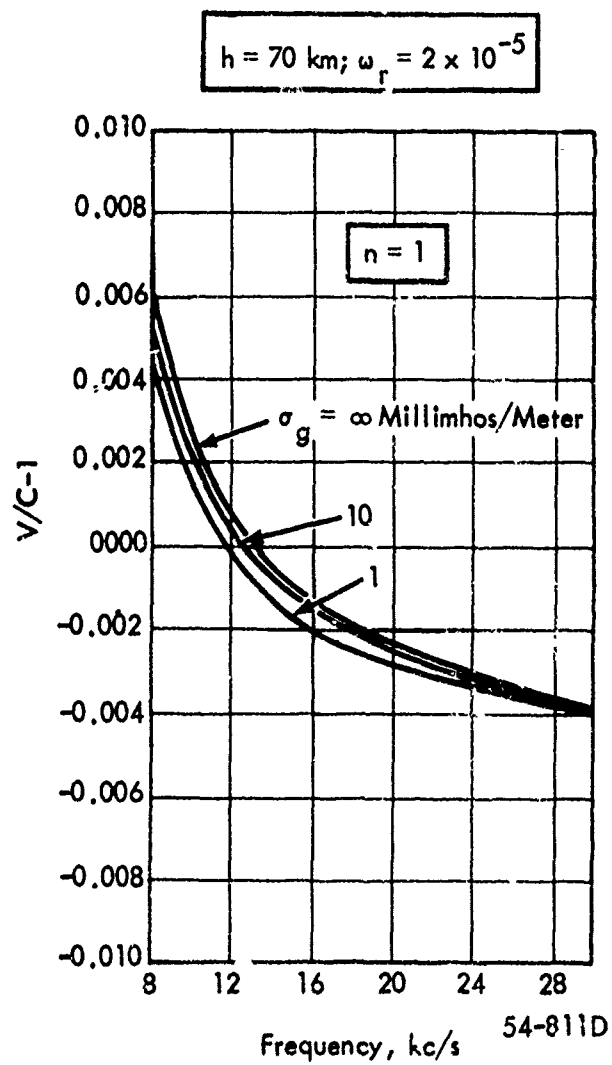


Figure 1 Phase Velocity of the First Mode for an Imperfectly Conducting Earth and an Imperfectly Reflecting Ionosphere, (Wait 1962)

two other electrodes gives the transfer impedance between the two pairs of electrodes. The apparent conductivity of the earth all around the electrodes and to a depth approximating the pair spacing is obtained by multiplying the transfer admittance by an appropriate geometric factor. Figure 2 illustrates some common four-electrode configurations. Geophysical surveys using four-terminal array techniques yield data in the form of spacing factors and apparent conductivity. If the potential drop for a selected current in a selected configuration is substituted in the formula for a uniform geophysical space (i. e., a homogeneous, isotropic geophysical half-space), the computed conductivity is an "apparent conductivity" for this particular configuration. Roman, [1960] considers this problem in detail. Figure 2 also lists formulas used in computations. This measurement technique was used for the present work because of the small amount of development work required to produce suitable equipment, and because the field and interpretation techniques are well known.

It should be stressed that for four-terminal array techniques, careful interpretation is required because of various complications of lateral conductivity contrasts and anisotropic behavior of layered medium, Schlumberger, [1934]. Notes on interpretations are included in Appendix A. The basic theory of the four-terminal array technique has been reported in the literature (see, for example, Maxwell, et. al., [1961]).

Subsurface conductivities can be measured directly with geophysical well logging methods in drilled holes (oil wells, water wells). The electrode configurations used are similar to those encountered in four-terminal array surface measurements, with the exception that contact with the earth is made down the hole by means of electrodes on the logging tool (the sonde). Most of the various electrical logging methods measure parameters controlled by the true conductivity of the rocks, Dakhnov, p. 59 [1959]. Conductivity information comparable to that obtained from surface measurements may be computed as described by Keller, [1964].

Type Array	Apparent Conductivity	Type Array	Apparent Conductivity
Schlumberger	$\sigma_a = \frac{b}{2\pi a_1 a_2} \left(\frac{1}{V} \right) K = \frac{b}{2\pi a_1 a_2}$ $d = \sqrt{a_1 a_2}$ $b \leq 0.4a$	Three-Pole	$\sigma_a = \frac{b}{2\pi a_1 a_2} \left(\frac{1}{V} \right) K = \frac{b}{2\pi a_1 a_2}$ $d = \frac{a_1 a_2}{2\pi \ln \frac{a_2}{a_1}}$ $a_2 > 20 a_1$
Wenner	$\sigma_a = \frac{1}{2\pi a} \left(\frac{1}{V} \right) K = \frac{1}{2\pi a}$ $d = a$	General Dipole	$\sigma_a = \left(\frac{a_1 a_2}{\pi b (b^2 - a^2)} \right) \left(\frac{1}{V} \right) K$ $\left(\cos \theta \cos (\theta - \phi) - \frac{1}{2} \sin \theta \sin (\theta - \phi) \right)$ $d = \frac{b}{1 - \cos \theta}$ $a_1 < \frac{b}{2}, a_2 < \frac{b}{2}$
Elton	$\sigma_a = \frac{1}{2\pi a} \left(\frac{1}{V} \right) K = \frac{1}{2\pi a}$ $d = a$	Where: σ_a is apparent conductivity, (ohm/meter) d is the effective spacing factor, indicating the effective depth of measurement. V denotes the receiver (voltage). I denotes the transmitter (current source). a_1 indicates the transmitter electrode spacing, (meters). a_2 indicates the receiver electrode spacing, (meters). b is the transfer resistance, and is the current (amperes) divided by the potential difference (volts).	
In-line	$\sigma_a = \frac{a_1 a_2}{2\pi b (b^2 - a^2)} \left(\frac{1}{V} \right) K$ $V = \frac{a_1 a_2}{2\pi b (b^2 - a^2)}$ $d = b/2$		
Beckwith	$\sigma_a = \frac{a_1 a_2}{2\pi b (b^2 - a^2)} \left(\frac{1}{V} \right) K$ $K = \frac{a_1 a_2}{2\pi b (b^2 - a^2)}$ $d = b$		

Figure 2 Common Four Terminal Array Electrode Configurations

Oil well logs are readily available from various petroleum information sources for areas of North America, but (unfortunately) these oil well logs stop a few hundred feet or more short of the surface. Since the 10 kc/s skin depth for earth material of 1×10^{-2} mho/m conductivity is only 160 feet, the well log information is not directly applicable in computation of effective conductivities at VLF frequencies.

It is possible to determine effective conductivity directly from measurement of the intrinsic impedance of the earth. This is accomplished by measuring the horizontal E and H fields for a propagating wave and is commonly called Audio-Magneto-Telluric (AMT) measurements. A feasibility study concerning this method of obtaining ground conductivities was reported by Farstad, [1963].

In this study, the horizontal magnetic field strength H was measured with a loop antenna and the horizontal electric field strength E, was measured with a 50 foot length of shielded cable connected to two ground stakes. Values of conductivity may be obtained from the following expressions:

if $\sigma \gg \omega \epsilon$,

$$\eta \approx \left[\frac{j\omega\mu}{\sigma} \right]^{1/2} = E/H \text{ which gives}$$

$$|\sigma| = 7.94 \times 10^{-6} \frac{f}{\eta} \quad (2-1)$$

where

- ϵ = permittivity in farad/m
- η = intrinsic impedance in ohms
- ω = $2 \pi f$ in radians/sec.
- f = frequency, c/s
- μ = permeability, assumed = μ_0
- σ = conductivity, effective, mho/m.

This is discussed in some detail in Appendix A.

There are many advantages in measuring conductivity with the above technique instead of the four-terminal array technique. One of these advantages is rapidity of measurement: only one simple setup is needed to obtain effective conductivity at several frequencies. It is especially valuable when man-made signals are available for measurement, which is generally the case above 10 kc/s. This kind of data was not readily available for this study since it is a relatively new technique. Also, equipment for making these measurements has not been highly developed and is generally more expensive than standard four-terminal array equipment.

Another technique for determining conductivity measurements is that of laboratory sample measurement. This is a very convenient and simple approach but falls short of the desired result in that the material is not in its natural environment and macroscopic effects of the earth are lost. Values of conductivity are often different from those obtained from insitu measurements. It should be noted, however, that laboratory studies are one of the most convenient means of extending our basic knowledge of the "geologic material-conductivity" relationship. It should be stressed that application of laboratory results to propagation studies requires careful interpretation to be sure that misleading values of conductivity are not assumed.

Other techniques of obtaining conductivity by measurement include measurements of field strength values from known transmitters. This method requires careful interpretation, and considerable data is necessary to be sure that misleading results are not obtained owing to ionosphere variations and unknown path effects such as scattering. It is usually necessary to take many values of field strength and interpret a general curve relationship to get valid information. (See Pullen, [1953], FCC Rules and Regulations, [1964], Wait and Howe, [1956], and Norton, [1941]).

Another means of measuring earth conductivity is by use of electromagnetic induction methods. There are many different variations, but basically the method consists of passing an alternating current through a coil or very long wire. The field is then measured at some distance by a receiver connected to another coil (one variation uses a loop to establish the field and a grounded dipole as the receiving element). There are two advantages in the field application of electromagnetic induction methods over four-terminal methods:

- (1) No electrical contact with the earth is required if loops are used. This can be important in areas where permafrost, granite, or ice caps present such a high impedance to a current dipole (of the four-terminal method) that the current (and hence the maximum effective depth of sounding) is limited.
- (2) Vertical soundings are accomplished by simply changing the frequency of the induced field. This requires much less time than changing dipole spacings as required in four-terminal array techniques.

In contradiction of the obvious field advantages of the induction methods there are at present serious limitations which have prevented their widespread application. Basic physical limitations are discussed by Watt, Mathews and Maxwell, [1963]. Another limitation is that some of the methods are not "in the public domain", and patents cover not only the instrumentation but also the method. Another limitation is the general unavailability of interpretation curves outside of certain mining companies. Considerable material has been published in Russia, however, and this latter difficulty may soon be resolved. (See Grant and West, [1965] for a more detailed discussion of electromagnetic methods and theory).

One more important method of measuring conductivity should be mentioned. This is the bridge substitution method used by Watt and Maxwell, [1960] to measure electrical properties of snow and glacial ice. Some of the disadvantages of this method are that it is not generally suited for measuring large volume properties of material and cannot be extended to great depths. In addition, small cracks or voids in the material can cause rather large errors in conductivity values because of the short distances involved in measurements. This method does give precise results, however, when field conditions are within the requirements of the technique.

2.3 Factors Affecting Conductivity; Basis for the Geology-Conductivity Correlation

Many years of experience in measuring and analyzing conductivities have indicated some important correlations between geology and earth conductivity. See Schlichfer and Telkes, [1942], Dakhnov, [1959], Leonardon and Kelley, [1929], Kihlstedt, [1934], Gilchrist, [1931], McCollum and Logan, [1913], and Watt, et. al., [1963]. It is unfortunate that the geological, climatological, pedological (study of the soils), and physiographical disciplines do not record directly some parameter closely related to electrical conductivity. A brief discussion of the major factors affecting conductivity in rocks and soils will aid in understanding the use and limitations of geologic and other information to estimate earth conductivity. There are three major physical and chemical factors affecting conductivity in rocks and soils. They are: porosity and infilling water (water filling the interstices of the material), inter-action of infilling water and earth materials, and electrical properties of dry earth materials.

The first of these properties, porosity and infilling water, is the most important. Electrical conduction in a natural state rock is determined primarily by infilling water. The complex relationship between the water and the rock is as important in determining the rock's conductivity as the amount

and conductivity of the infilling water. The passage of water through a rock or soil may be by means of intergranular pores which provide a path for the charge carriers in the infilling water. In this respect, the fluid permeability, or measure of the capacity of a porous medium to transmit fluids, is helpful in determining electrical conductivity. It is well known that the conductivity of a rock material is directly proportional to an empirical coefficient related to the type of porosity (either inter-granular or joint) and inversely proportional to the porosity of the rock raised to some empirical exponent related to the cementing and granular relationship present in the earth material. There is much information in the literature concerning this relationship, known as Archie's Law, and many different forms have been proposed, Winsauer, et.al., [1952].

Another factor affecting conductivity is the interaction of infilling water and earth material which may cause considerable departure of conductivity from predicted values. Ions contained on the surface of mineral grains can undergo a desorption process and act as conductors in the infilling water. These desorbed ions will exhibit less mobility than similar ions in a free solution. Another interaction process involves oriented adsorbed layers of water molecules on the surface grains of a rock. This surface layer will limit the affect of conducting ions in the infilling water. The adsorbed oriented surface layer charges act to attract a large number of other ions thereby causing a much thicker layer of ions on the surface. This causes an increase in pressure because of the thicker layer, and in this way the viscosity is increased and the mobility of the conducting ions is thereby significantly reduced. These mechanisms are quite common in minerals exhibiting ion exchange capacities, such as kaolinite, hallosite, montmorillonite, illite, and vermiculite. It can be seen then, that the interaction processes can have a limiting control over rock conductivity. It would be reasonable to expect that rocks containing water

with larger numbers of conducting ions will not have a proportional increase in conductivity: this effect is more pronounced in fine grained rocks than in coarse grained rocks.

The final factor that will be considered as affecting the conductivity of rocks is that of the electrical properties of the material itself; that is, the electrical properties of the dry earth materials with no infilling water. The nature of the material usually determines characteristic structures and intergranular relationships. In this sense, and also in the sense that each material has a particular ion exchange capacity, the material parameter is important in determining earth conductivity. The conductivity of the material itself becomes important only for certain minerals which can affect rock conduction in themselves. Such minerals are magnetite, hematite, carbon, graphite, pyrite, and pyrrhotite. Magnetite and hematite can have a characteristic interconnecting type structure which provides continuous conduction paths. In this respect only a small percentage of the mineral needs to be present to cause a drastic change in earth conductivity. This effect is normally insignificant over areas of several tens of square miles because of the characteristic occurrence of the minerals.

Considering the three major factors which determine the conductivity of earth material which are discussed above, it is reasonable to expect that the conductivity of the earth in a particular region can be estimated. However, it is difficult to find any region in which all these factors are well known and, in fact, a region in which these factors are well known usually has undergone extensive electrical surveys as a means of obtaining this type of information. These principles of rock conduction are useful in interpreting and estimating conductivity for any given region in that there is almost always some information available from which one can estimate the grain sizes of the earth material, the salinity of the infilling water, and perhaps ion exchange capacities for some regions in which the lithology is well known.

Table 1 presents some conductivity ranges of rocks as a function of lithology. Interpretations within these conductivity ranges based on the considerations mentioned above can significantly improve the accuracies of estimates. Table 2, taken from the paper by Watt, Mathews and Maxwell, [1963], presents a more complete tabulation of earth materials and their approximate conductivity ranges. At the present time it is necessary to use most of the above relationships in a qualitative manner.

Some comments are in order regarding the validity of conductivity estimates for sedimentary, igneous and metamorphic rocks. Even though there is some scatter in the data, the value of conductivity for a particular sedimentary basin frequently varies over a range of less than one decade (average values). There are frequent exceptions in local areas; for example, changes in thickness of glacial drift or the presence of alluvial fans or similar relatively local features can give anomalous values of conductivity. However, if enough conductivity measurements are taken over a large region, there is an almost monotonous value of surface and near-surface conductivity for a particular sedimentary area. This is pointedly illustrated in the paper on electrical resistivity surveys in Illinois by Buhle and Brueckmann, [1964]. They have tabulated over 1100 separate resistivity surveys and indicate values of the background (regional) resistivity as well as local anomalies. In this list the average of the first 276 conductivity measurements is 2.15×10^{-2} mhos/m. Most of the individual surveys give averages of conductivity which vary much less than one decade from this average, Figure 3 presents in detail an analysis of this data for Illinois. It has been found from the literature that average conductivity values in regions of sedimentary deposits show this same sort of order, and experience has proven that conductivity values within a given geologic environment are quite orderly, Keller, [1964].

Conductivity measurements in igneous and metamorphic rocks frequently exhibit a much greater variability than do measurements in sedimentary rocks. Measurements by DECO Electronics, Inc. in the Idaho batholith region,

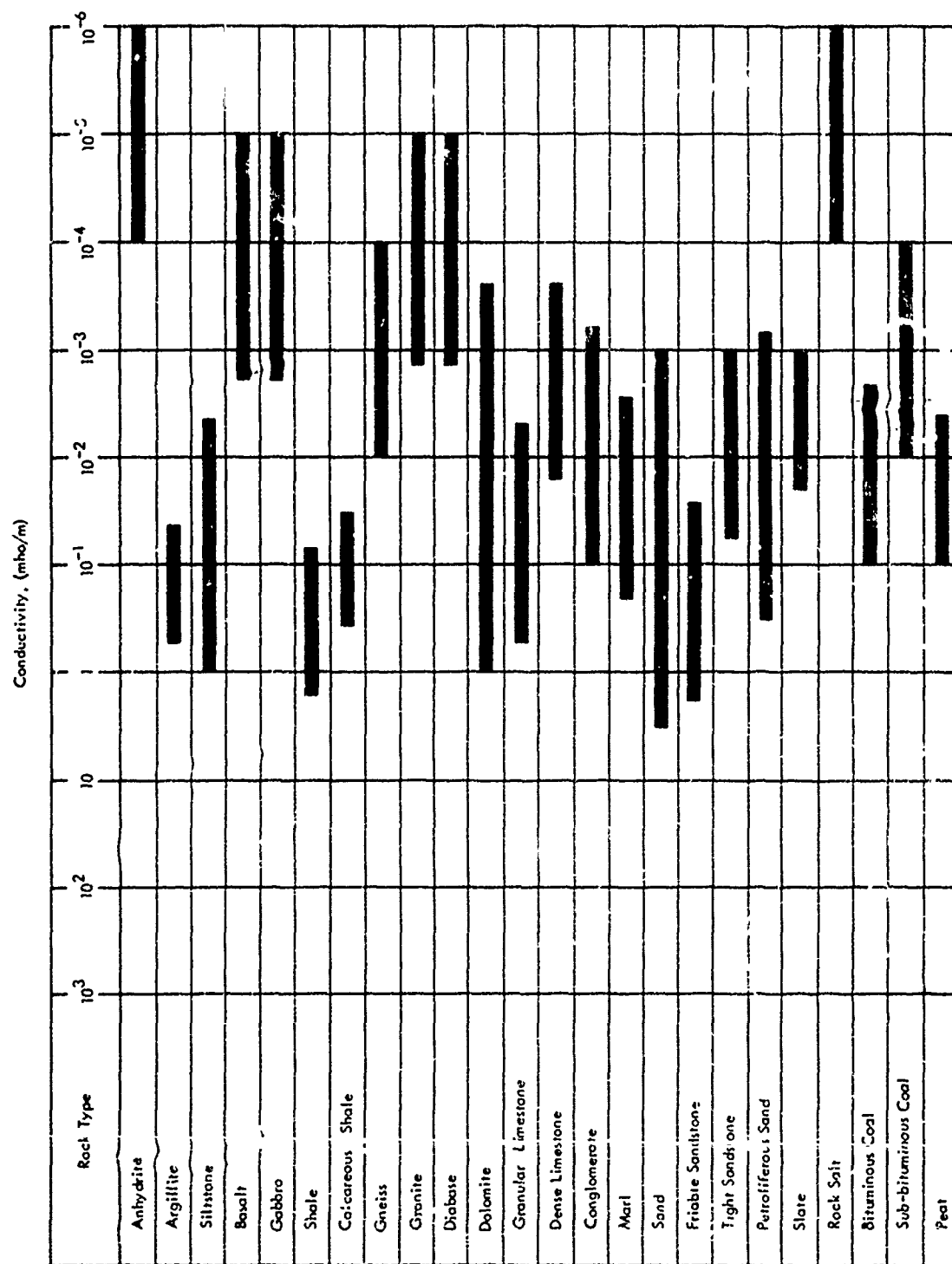


Table 1 Conductivity Ranges for Some Common Rock Types.
(Dokhnov, 1959)

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TABLE 2
APPROXIMATE ELECTRICAL CONDUCTIVITIES OF EARTH'S MATERIALS (AT NORMAL SURFACE TEMPERATURE AND PRESSURE)

Material	Approximate σ (mho/m)	Comments
soils {good average poor}	10^{-2} to 10^{-1} 10^{-3} to 10^{-2} 10^{-4} to 10^{-3}	{relatively nondispersive.
water {sea connate, in rocks* fresh}	$\frac{1}{2}$ to 5 10^{-1} to 1 10^{-4} to 10^{-3}	
snow (drifted, wet)	2×10^{-4} @10 cps to 3×10^{-4} @10 kc	{values very dependent upon temperature, frequency, and impurities.
ice (glacial)	10^{-4} @100 cps to 3×10^{-3} @ 10 kc	
permafrost	10^{-4} to 10^{-2} estimates	likely to have variations similar to glacial ice.
sediments {marine sands and shales marine sandstones clay sandstone (wet) sandstone (dry) limestone rock salt}	10^{-1} to 1 10^{-2} to 1 10^{-2} to 10^{-1} 10^{-4} to 10^{-2} 10^{-7} @100 cps to 10^{-4} @10 kc 10^{-4} to 10^{-3} 10^{-1} to 10^{-2}	relatively frequency independent.
igneous rock {granite basalt gabbro peridotite}	10^{-9} to 10^{-3} 10^{-9} to 10^{-3} 10^{-7} to 10^{-3} 10^{-9} to 10^{-7} @300°C	very dependent on water content
metamorphic {slate marble gneiss serpentine}	10^{-4} to 10^{-3} 10^{-4} to 10^{-3} 10^{-7} to 10^{-3} 10^{-7} to 10^{-3}	
ore bodies {native silver native copper galena (PbS) hematite (Fe ₂ O ₃)}	5×10^7 3×10^8 to 5.7×10^7 20 to 200 10^{-7} to 10^{-4}	

Note: lower conductivities are found for dense, dry, rock samples believed to be of oldest geological age such as the Precambrian. The values quoted are for frequencies in the 10- to 100-cps region. σ for dry rocks generally increases with frequency and in many cases follows a relation $\sigma \approx kf^m$ where m can vary with frequency f , and ranges from 0.1 to 1 in the 10- to 100-cps frequency region. The actual manner in which σ varies with frequency can be quite complex and depends upon the material involved. Wait [7], p. 33, indicates that the conductivity can be approximated by the relation $\sigma \approx k_1 + k_2 \log f$ in the frequency region of 1 to 100 cps.

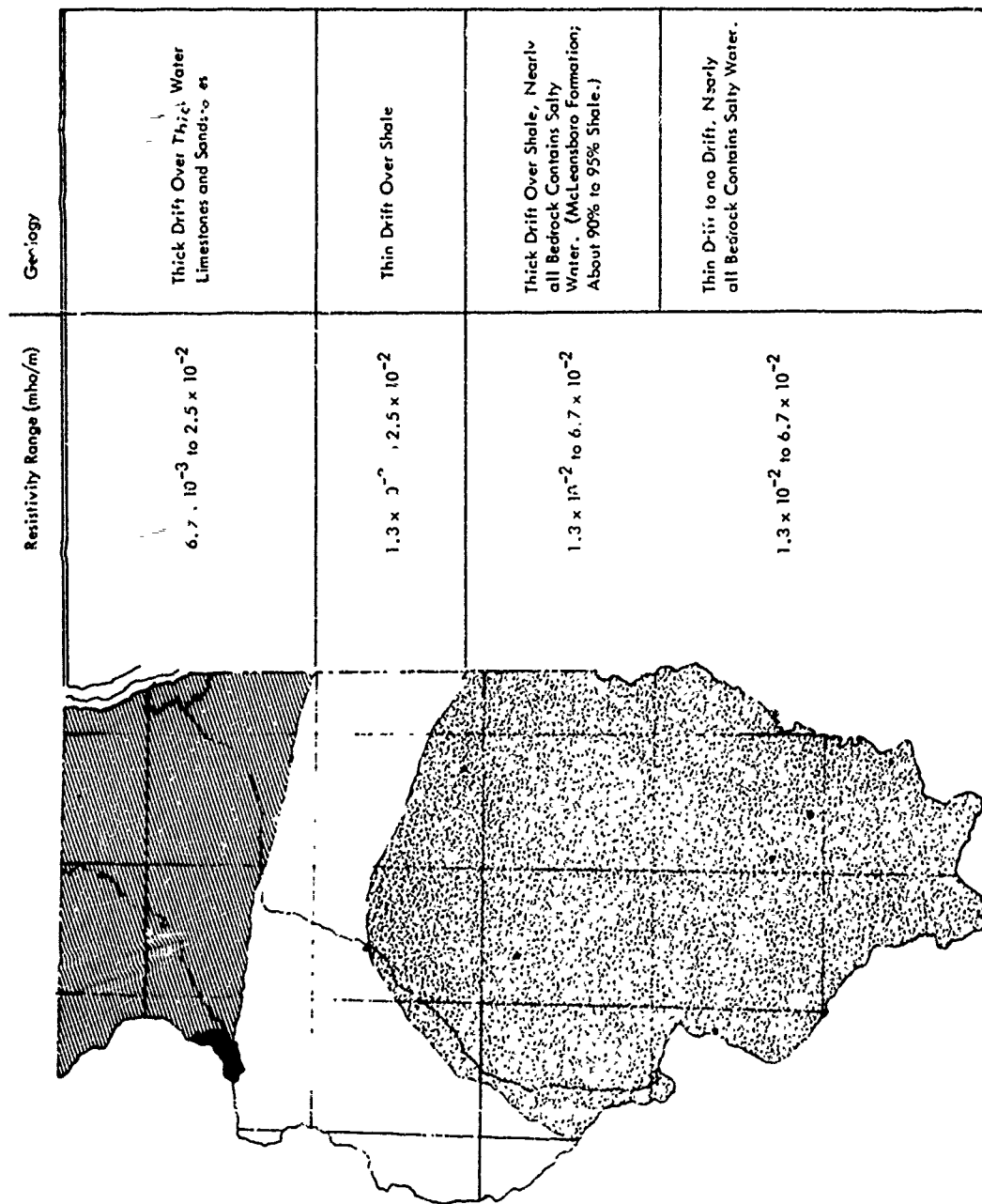
* R. H. Ford, "Earth resistivity and geological structure," *Elec. Engng.*, pp. 1153-1161; November, 1935.

† C. A. Heiland, "Geophysical Exploration," Prentice-Hall, Inc., New York, N. Y.; 1946.

‡ C. V. Keller, private communication.

§ K. Noritomi, "The electrical conductivity of rock and the determination of the electrical conductivity of the earth's interior," *J. Min. Coll. Akita Univ.*, vol. 1A, p. 27; 1961.

§ H. A. Wheeler, *Electronics*, vol. 32, p. 59; September, 1941.



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Figure 3 Detail Map Showing the Conductivity-Geology of Illinois. Note the Relative Narrow Range of Conductivity Values in This Sedimentary Region (Buhle, 1964)

for example, have provided conductivity values with scatter of greater than two decades. There is no reason to expect that estimates of average regional conductivity for areas of this sort are any less valid than average regional conductivities in a sedimentary area.

3.3 Special Regional Problems

In making estimates of conductivity values for North America, there are regions which required special considerations. These are areas of permafrost, desert areas, and jungle areas. Little work has been done outside of Russia regarding the electrical characteristics of permafrost. Careful consideration was given to the area of permafrost in North America because of the importance of this lower conductivity material in phase velocity studies. Details of the results of the permafrost study are presented in Appendix B. It would be expected that conductivity in a desert region would be relatively low because of the lack of infilling water in the surface and near-surface materials. The actual effect is just the opposite, however; the lack of near-surface water is offset by an increase in the salinity of the infilling water. Waters which are drawn to the surface by capillary attraction evaporate and leave salts which become more concentrated in time. This high salinity increases the conductivity to a value limited by the thicker layers of adsorbed polar molecules which then build up surface pressures and decrease ionic mobilities. In jungle areas, where there is heavy rainfall, one finds the reverse paradox of the desert regions. Potentially desorbable ions are leached out by heavy seasonal rain and consequently the infilling waters contain relatively few conducting ions. In tropical and subtropical regions these soils become leached of silica, producing laterite type soils.

3. PRODUCTION OF CONDUCTIVITY MAP

3.1 Collection of Data

A literature search was conducted utilizing the standard bibliographies available, the most useful of which were the U. S. Geological Survey, Geophysical Abstracts. Scientific and technical aerospace reports and technical abstract bulletins were also utilized in this effort. Many data recovered from the literature have been of limited usefulness, in that information on local conditions have not been included. It was also found that much of the data was directed towards delineation of anomalies and other factors which are not representative of background (regional) conductivity values, and in this way do not reflect information useful for phase velocity and propagation studies. An attempt was made, in constructing the map, to evaluate data taken from the literature so that only data representing regional conductivities was used.

Much valuable data was obtained through private communications. In particular, information was obtained from U. S. G. S. personnel regarding unpublished memos and progress reports of the Geophysical branch. Other personal correspondence was with Mr. Buhle of the Ground Water Geology and Geophysical Exploration Section of the Illinois Geological Survey, and also with Dr. Orvidall with World Soils Map Section. Conferences were held with the U. S. Department of Agricultural personnel at Ft. Collins, Colorado and also at the Denver office of the Department of Agriculture in an attempt to obtain information and references regarding soil conductivities. Comments in correspondence with Dr. Coolbaugh (United Nations Technical Assistance Board, Mexico City) were of help in determining conductivities in Northwestern Mexico, and in evaluating the extent of electrical measurements in Mexico.

Early in the project, it was determined that there was little data on the conductivity of the permafrost region of North America and that measurements would be highly desirable on the Canadian Shield permafrost area in Canada. Another region in which conductivity estimates were determined

to be difficult was the Gulf Coast region of North America. Equipment was developed and field trips taken to provide this information which was otherwise not available. The permafrost measurements have provided some of the first measurements of conductivity of permafrost covering this frequency range.

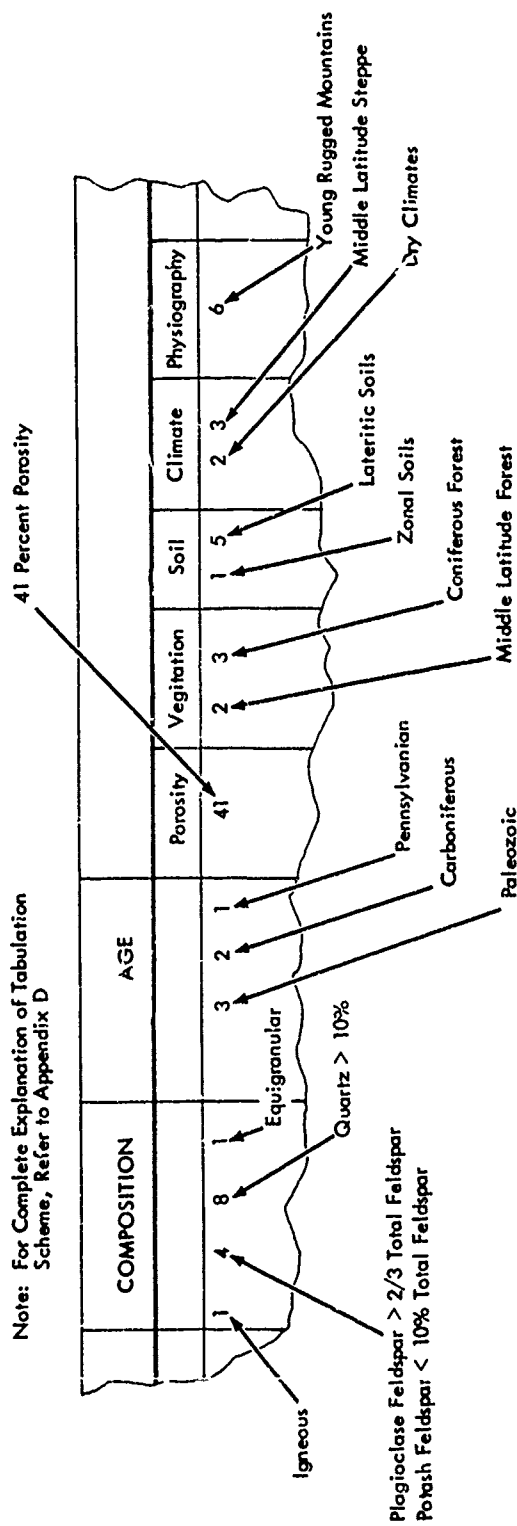
Details of these field trips and presentation of data obtained are given in Appendix C. A description of the portable equipment which was specially designed for this use is also included in this Appendix.

3.2 Data Tabulation Effort

One of the objectives of the present project was to improve the technique of making conductivity estimates for any given area. Consistent with this objective, a system for tabulating and correlating data collected from the literature search was established. It was decided that the long-term objective could be better fulfilled if this system were set up initially so that a computer could later be used to correlate and search the conductivity data. Figure 4 is an example of some of the data tabulation showing some of the number codes used for geologic and geographic descriptions. A sample tabulation is included in Appendix D. Using this system, additional data can be easily added to extend the effort.

3.3 Geologic Study

Early in the project, concurrent with the data collection effort, geologic studies were made. It was found that a more detailed geologic study of several regions was relatively unprofitable. It is, for example, not important to delineate individual faults and structures within the interior basins, (see Figure D-5, in Appendix D). The individual features within these basins are of very minor significance compared to the areal extent of the basins, and on a broader basis, the interior lowlands. It was found from these local studies and also from personal communication with Dr. Keller that information more detailed than that provided, for example, by the Geological Map of



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Figure 4 Data Tabulation Scheme Showing how Number Codes Represent Geologic and Geographic Information

North America on a scale of 1:5,000,000 is of little value in this type of study. This does not mean that some detailed studies are not of value but only that they must be interpreted with the larger regions in mind. Included in Appendix D is information regarding soils, vegetation, climate, geology and other material of value for estimating conductivity values.

In each of the geologic provinces, conductivities were assigned on the basis of measurements in the area and on the basis of lithology, geologic age, climate, and soils information for which there were data indicating a relationship for this particular geologic environment and conductivity. In some instances there were either very few or very unreliable data on actual conductivity measurements. Areas in which there was the least amount of direct information include Mexico, portions of Alaska, and the permafrost areas of Canada. Interpretation techniques for these difficult areas include utilization of the best possible estimates based upon personal experience, consultation with experts in the field, personal correspondence, and data tabulated for similar areas. A system of symbols (described in the next section) was established to indicate confidence levels for these interpretations.

3.4 Description of Conductivity Map

The area of coverage of the effective 10 kc/s conductivity map of North America includes the Canadian Archipelago, Greenland, Alaska and countries of Central America including Honduras, El Salvador, Nicaragua, Costa Rica and Panama. The map has a dipolar oblique conic conformal projection modified near the edges which is described more fully in the Geographical Review, [1941].

The base map was adapted from the following references:

1. Alaska, Northern Canada, and Greenland, Atlas of the Americas Sheet 1D, 1948: compiled and drawn by the American Geographical Society of New York.
2. Iceland, U. S. A. F. Long Range Navigation Chart - Baffan (LR-4) 1954: Army Map Service.
3. United States, Southern Canada, and Newfoundland, Atlas of the Americas Sheet 1E, 1948: compiled and drawn by the American Geographical Society of New York.
4. Mexico, Central America, and the West Indies, ANS1106 Second Edition, 1952: compiled and drawn by the American Geographical Society of New York.
5. South America, Sheet North AMS, 1106, Second Edition, 1952: compiled and drawn by the American Geographical Society of New York.

The geology data used is from a large variety of sources, the main one of which is an advance copy of the geologic map of North America, compiled by the North American Geologic Map Committee of the Geological Society of America and provided by Dr. Edwin N. Goddard.

Color hue and saturation have been used to denote effective conductivity with white designating the conductivity of the oceans and the seas and any other region having a conductivity greater than 10^{-1} mhos/meter. At the other end of the scale light yellow has been used to designate the conductivity of snow and ice covered regions. Although desirable for conductivities less than 10^{-3} mhos/meter it is not possible at the present time to estimate values more accurately than $\pm$ one/half decade. Confidence factor symbols have been added to indicate the reliability of the conductivity values given. This confidence factor involves consideration of the amount of data available, the type of data available, i. e., field methods used, direct measurements or correlations, etc. and the quality of the data available. A further designation

for variability was required since there might be some areas for which regional values are known with great confidence over which considerable local variation might be found. The symbol for variability indicates therefore, the estimated departure of local conductivity data from the average regional values.

Since the map was made for use at VLF frequencies, it is important that the values of conductivity are not used for frequencies outside this general range. Geologic materials which are deeper than 1 or 2 skin depths or shallower than a few tenths of a skin depth at 10 kc were not considered. Therefore, for frequencies appreciably higher or lower than the VLF range one may get misleading values of conductivity. Regions having dimensions of less than 100 miles were generally not considered in the preparation of this map since energy spreading will generally negate any effect they might have upon propagation. Users of this map should be aware of closed lines and similar effects where it is evident that energy spreading and defraction results in less attenuation than would be obtained for a straight line path between receiver and transmitter. Conversely transmission across a very narrow conductivity contrast which the energy may not bypass or circumvent may result in more attenuation than predicted because of energy conversion, reflection and scattering.

Scattering and energy conversion effects due to extremely rough terrain are not shown or indicated on the conductivity map since these effects are not directly relatable to the conductivity of the earthen materials. Areas having extremely rough terrain are indicated, however, on Figure 5. Little is known quantitatively about their effect and it is expected that considerable variation will result from crossing them in different directions. These regions may generally indicate an apparent conductivity up to 1 order of magnitude less than the true effective conductivity of the materials.

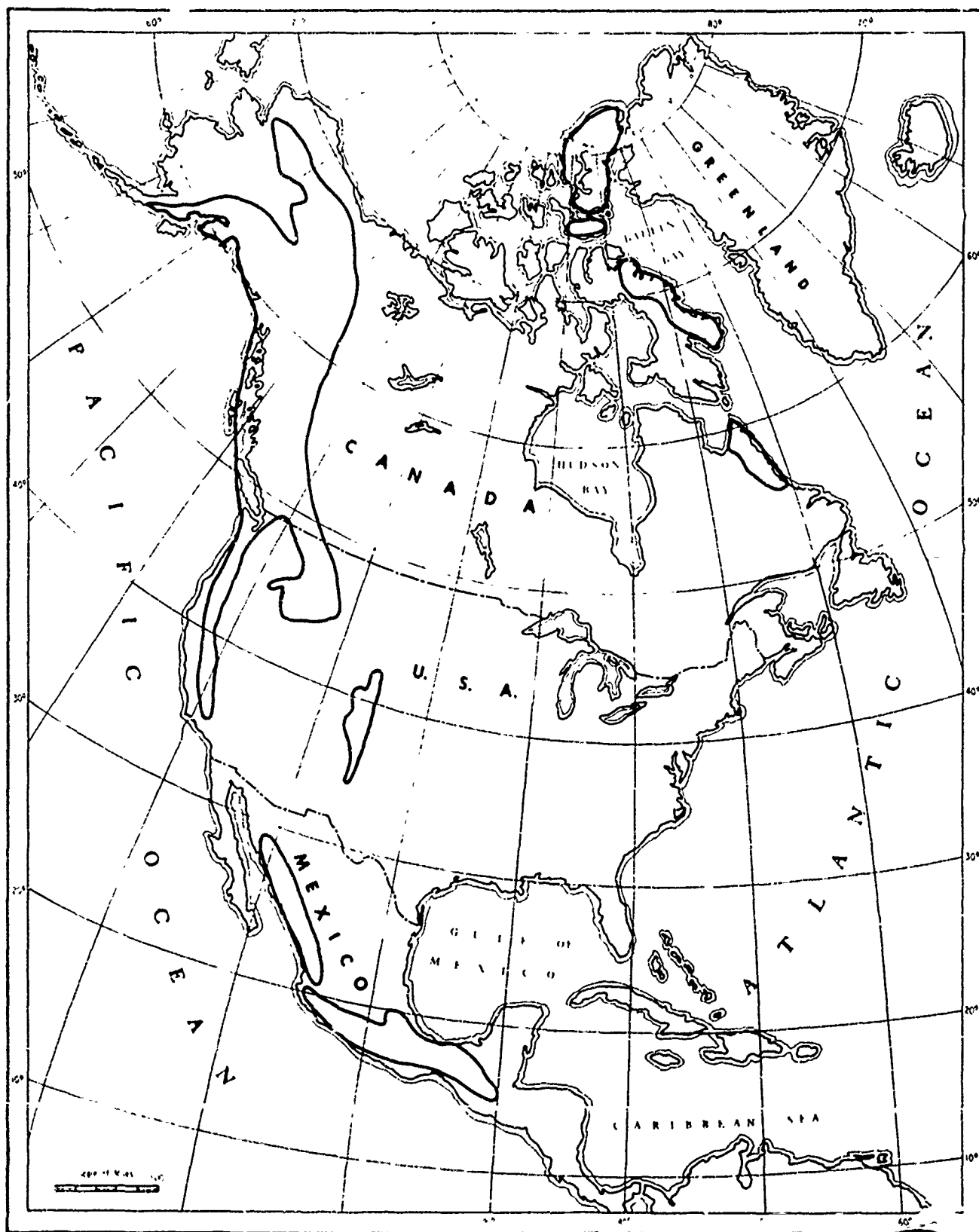


Figure 3 Map Showing Areas of Rough Terrain Where Scattering and Energy Conversion Effects May Cause Abnormally High Attenuation.

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4. CONCLUSIONS AND RECOMMENDATIONS

Some definite conclusions and recommendations can be formed regarding the correlation approach, data tabulation system, and instrumentation used to produce the effective conductivity map of North America. They are as follows:

1. The correlation approach is the best method for producing an effective conductivity map of first-order approximation at VLF.

- (a) It is a rapid and convenient means of assigning approximate conductivity values to large areas of similar geology. Problems of access to politically sensitive areas can therefore be circumvented, and the expense of making continent-wide measurements is considerable reduced.

- (b) At VLF, the skin depths are of such magnitude that the material which determines the effective conductivity is (in most cases) the surface or near-surface geology rather than vegetation and soils. The seasonal variations and the almost complete lack of correlation of conductivity with soil type, Orvedal, [1964] would present a more formidable problem for higher frequencies (shallower skin depths).

2. The data tabulation effort provides a convenient method for handling large volumes of data, and can be easily adapted to use with high-speed computers. Data can be rapidly correlated with respect to any one or several of the parameters:

location, composition, age, porosity, vegetation, soils, climate, physiography, and depth (below surface).

3. On the basis of the conclusions presented in 1 and 2 above, it is suggested that a world-wide map may be obtained using the same techniques. It is expected that more precise correlations can be made when a comprehensive tabulation of data is accomplished. It is also recommended that the development of AMT instrumentation be undertaken, so that rapid economical field data can be obtained to aid in estimating regional conductivity value. It is believed that this is, at present, the most efficient and accurate means of increasing the reliability of effective conductivity maps.

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APPENDIX A

COMPUTATION OF EFFECTIVE CONDUCTIVITY AND ASSOCIATED MEASUREMENT TECHNIQUES

APPENDIX A

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APPENDIX A

COMPUTATION OF EFFECTIVE CONDUCTIVITY, AND ASSOCIATED MEASUREMENT TECHNIQUES

A. 1 INTRODUCTION

The conductivity of the earth can have a large influence on attenuation rates and phase velocity of VLF radio waves propagating across the earth. It is therefore important to know the effective conductivity of the earth along any given propagation path. There are many different ways of obtaining this effective conductivity: one method requires a knowledge of the electrical layering of the earth, another requires a knowledge of the wave impedance at the desired frequency.

This appendix will discuss how the electrical layering of the earth may be determined from four terminal array measurements; and, in turn, how effective conductivity may be computed from this electrical section and from audio-magneto-telluric measurements. The discussion will be directly applicable to VLF propagation work, but the principles are general, and could be extended for application at other frequencies.

A. 2 FOUR TERMINAL ARRAY MEASUREMENTS

There are many different field techniques and arrays (electrode arrangements) which can be used to measure the electrical section of the earth. Some four terminal arrays have been illustrated in the text (Figure 2). Data from each of these different arrays is reduced to a value of apparent conductivity, which is defined as the conductivity that a uniform homogeneous isotropic media would have to have to give the same measured values for a particular array.

Formulas for apparent conductivity for each array can be obtained from basic principles [Dakhnov, 1962 (translation)], and are listed in Figure 2. Each expression contains the ratio I/V , and an additional factor, K , which depends upon the particular electrode configuration. A nomograph such as the one shown in Figure A-1 can be used to facilitate computation of this K factor. Interpretation of the computed apparent conductivity is accomplished by comparing apparent conductivity versus spacing-factor curves with theoretically computed "nondimensional" curves for a layered medium.

Development of the expressions for apparent conductivity of a layered earth is quite involved (see Keller, G. V. and Frischknecht, F., [1966]). Theoretical equations for four of the common arrays are given below:

Eltran Array

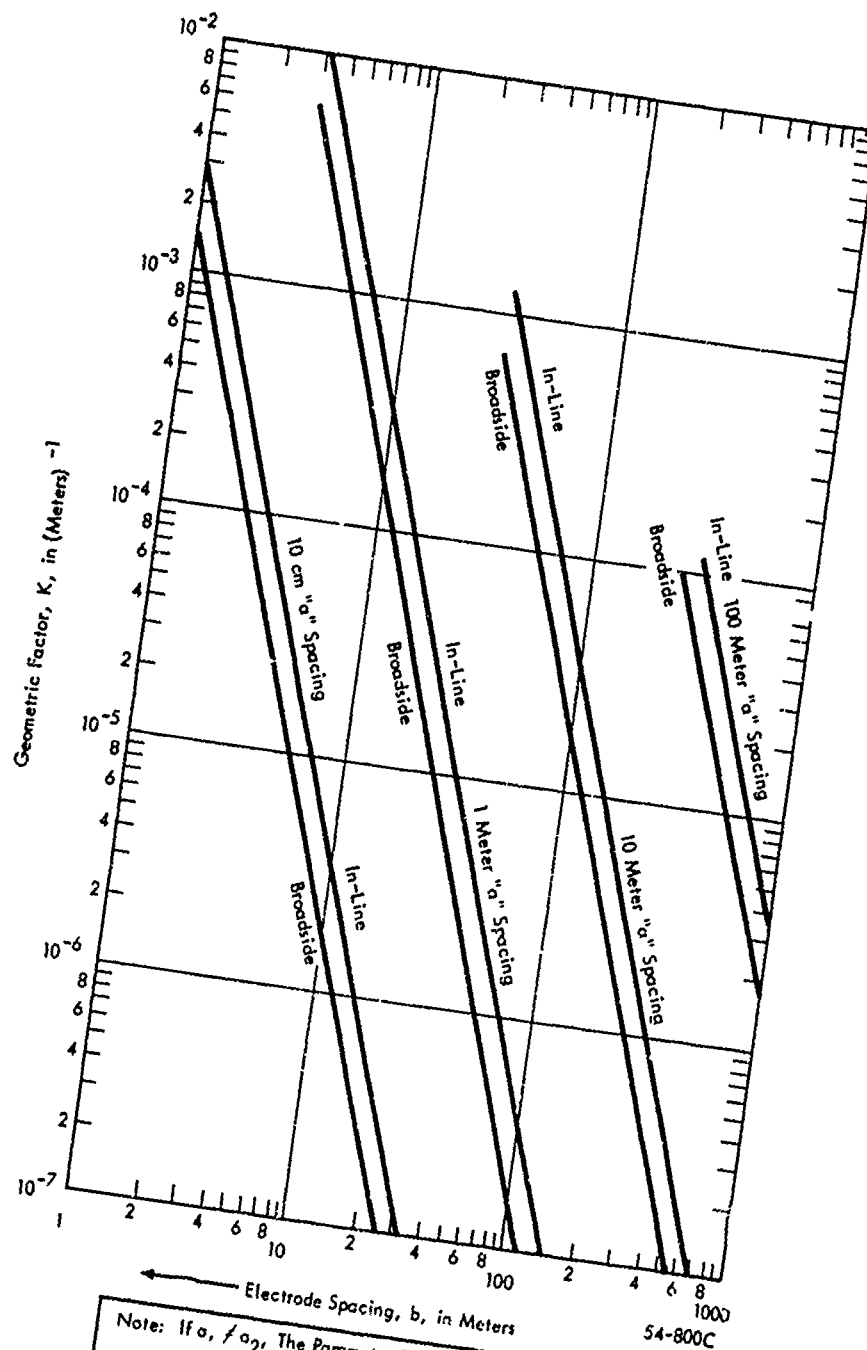
$$\frac{\sigma_a}{\sigma_1} = 1 + 6 \sum_{n=1}^{\infty} k^n \left\{ \left[1 + \left(2n \frac{h}{a} \right)^2 \right]^{-1/2} + \left[9 + 2n \frac{h}{a} \right]^{-1/2} - 2 \left[4 + 2n \frac{h}{a} \right]^{-1/2} \right\}^{-1} \quad (A-1)$$

Schlumberger Array

$$\frac{\sigma_a}{\sigma_1} = \left\{ 1 + 2 \sum_{n=1}^{\infty} k^n \left[1 + \left(2n \frac{h}{a} \right)^2 \right]^{-3/2} \right\}^{-1} \quad (A-2)$$

Polar Dipole Array

$$\frac{\sigma_a}{\sigma_1} = \left\{ 1 - \sum_{n=1}^{\infty} k \left[1 + \left(2n \frac{h}{b} \right)^2 \right]^{-3/2} + 3 \sum_{n=1}^{\infty} k^n \left[1 + \left(2n \frac{h}{b} \right)^2 \right]^{-5/2} \right\}^{-1} \quad (A-3)$$



Note: If $a_1 \neq a_2$, The Parameter "a" as Shown Here $= \sqrt{a_1 a_2}$

$$\text{In-Line Array } K = \frac{a^2}{\pi b (b^2 - a^2)}$$

$$\text{Broadside Array } K = \frac{a^2}{2 \pi b (b^2 - a^2)}$$

Figure A1 Graphical Presentation of the Geometric Factor, K , Used in Computation of Apparent Conductivity. (Broadside and In-Line Arrays)

Equatorial Dipole Array

$$\frac{\sigma_a}{\sigma_1} = \left\{ 1 + 2 \sum_{n=1}^{\infty} k \left[1 + \left(2n \frac{h}{b} \right)^2 \right]^{-3/2} \right\}^{-1} \quad (\text{A-4})$$

where:

- σ_a is apparent conductivity, (mho/m);
 σ_1 is the first layer conductivity, (mho/m);
 k is reflection coefficient $\frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2}$;
 h is the first layer thickness, (m);
 a, b are electrode spacings, (m).

The comparison of apparent conductivity versus spacing-factor curves with theoretical curves (often referred to as curve matching) allows a layered interpretation of the apparent conductivity data. The technique of curve matching has been described [Maxwell, et al., 1961], and will not be repeated here. Results of curve-matching interpretations -- average conductivity of the layers and layer thickness -- are then used to determine effective conductivity.

A.3 EFFECTIVE CONDUCTIVITY DETERMINATION

Effective conductivity is defined in section 2.1 (text), and may be computed for an electrically layered earth. Information about the electrical layering of the earth may be obtained from estimates (made on the basis of regional geology -- or sample logs) or from interpretations of field data (such as those described above). This section will discuss briefly the development of an expression for effective conductivity, and a means of implementing calculations will be presented.

It is convenient to make certain assumptions and approximations in developing an expression for effective conductivity. These are as follows:

- (a) The electrical layers of the earth are in a horizontal attitude.

This is a valid assumption for most of the interior sedimentary basins of North America. It is much more difficult to justify this assumption in areas of igneous and metamorphic rock, but the strictly regional nature of the present application, and the lack of another simple approach is certainly a valid reason for using the assumption.

- (b) $\frac{\sigma}{10} > \omega\epsilon$ for each electrical layer in the earth.

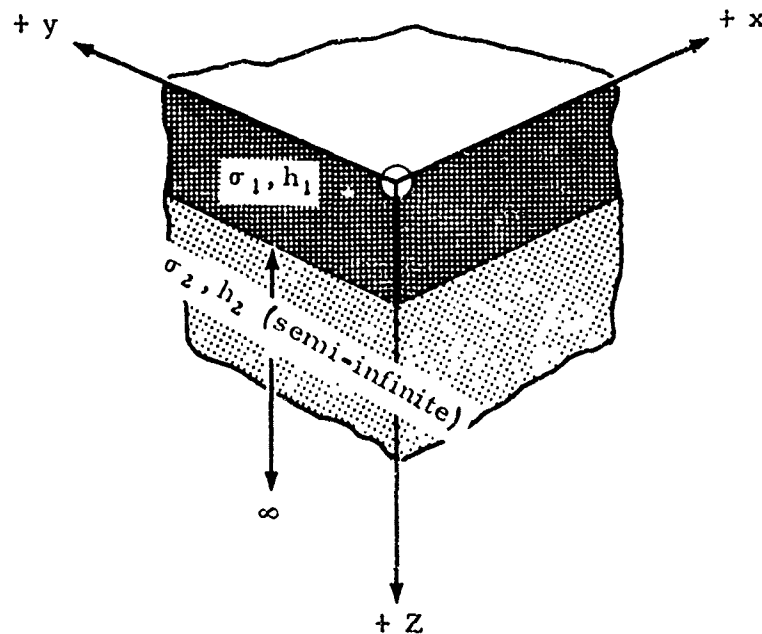
This is a generally accepted approximation for most earth material at VLF -- there could be some question of the validity of this approximation, however, in permafrost regions. Evidence which indicates that this is reasonable in permafrost is presented in Appendix B.

- (c) Impinging electromagnetic waves are propagated normally into the earth.

The development of an expression for the effective conductivity of a horizontally stratified earth is greatly simplified by this assumption. It can be shown that if the approximation in (b) above is true, then the impedance presented to an impinging EM wave with any angle of incidence can be assumed to be the same as that impedance presented to a vertically impinging wave. This assumption of normal propagation is in no way a restriction upon the general application of the resulting expression for effective conductivity, (see Harrington, [1961 p. 60-61]).

A useful expression for the effective conductivity of the earth, for the above assumption, may be developed as follows:

Consider a simple two layer earth, with a plane electromagnetic wave propagating downward into the top layer. The downward direction will be assumed to be the +Z direction. We can determine the magnitude of the horizontal electric field by considering the sum of terms representing the downward propagating field, and the various reflections present in the first layer caused by the two interfaces: the first and second layer interface, and the interface between the air and the first layer.



The above diagram shows the co-ordinate system used in the development of the effective conductivity relationship:

$$E_{y_1} = E_{y_0} (e^{-\gamma z} + R_2 e^{-\gamma(2h-z)} + R_1 R_2 e^{-\gamma(2h+z)} \\ + R_1 R_2^2 e^{-\gamma(4h-z)} + R_1^2 R_2 e^{-\gamma(4h+z)} \\ + R_1^2 R_2^3 e^{-\gamma(6h-z)} + R_1^3 R_2^2 e^{-\gamma(6h+z)} + \dots),$$

Where:

- E_y is the horizontal electric field, (volt/meter).
 E_{y_1} is the horizontal electric field in the first layer.
 E_{y_0} is the horizontal electric field at the surface.
 σ is conductivity, (mho/meter).
 σ_1 is the conductivity of the first layer (note that number subscripts designate the layer).
 h_1 is the thickness of the first layer, (meters).
 ϵ is permittivity, (farad/meter).
 ω is angular frequency = $2\pi f$, (radius/second).
 f is frequency, (cycles/second).
 R_1 is the reflection coefficient of the earth-air boundary:

$$R_1 = \frac{\eta_0 - \eta_1}{\eta_0 + \eta_1} = \frac{\sqrt{\sigma_1} - \sqrt{\sigma_0}}{\sqrt{\sigma_1} + \sqrt{\sigma_0}}$$

$$R_2 = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} = \frac{\sqrt{\sigma_1} - \sqrt{\sigma_2}}{\sqrt{\sigma_1} + \sqrt{\sigma_2}} E_{y_0}$$

 $\eta_0 = \text{intrinsic impedance} = \frac{E_{y_0}}{H_{x_0}}, \text{ (ohm).}$

Note that each term in the above expression, $(E_0 e^{-\gamma f(z)})$, is a solution to the more general wave equation for a plane wave in conducting media, (which is easily obtained from Maxwell's curl equations [Kraus, 1963, p. 394-395]):

$$\frac{1}{\mu} \frac{\partial^2 E_y}{\partial x^2} - \epsilon \frac{\partial^2 E_y}{\partial t^2} - \sigma \frac{\partial E_y}{\partial t} = 0. \quad (A-6)$$

μ is permeability, (henry/meter). $\mu_1 = \mu_2 = \mu_0$ assumed earth materials, where μ_0 is for free space.

To continue our development, we next separate the terms in $e^{-\gamma z}$ from those in $e^{+\gamma z}$ of equation (A-5), and write the n^{th} terms:

$$\begin{aligned} E_y \text{ (in the first layer)} &= E_{y_0} e^{-\gamma z} (1 + R_1 R_2 e^{-2\gamma h} + R_1^2 R_2^2 e^{-4\gamma h} + \dots) \\ &\quad + E_{y_0} e^{+\gamma z} (R_2 e^{-2\gamma h} + R_1^2 R_2 e^{-4\gamma h} \\ &\quad + R_1^2 R_2^3 e^{-6\gamma h} + \dots) \\ &= E_{y_0} (e^{-\gamma z} + R_2 e^{+\gamma(z-2h)}) \left(\sum_{n=1}^{\infty} (R_1 R_2)^n e^{-2n\gamma h} \right) \end{aligned} \quad (\text{A-7})$$

A similar expression may be obtained for the H field:

$$H_x \text{ (in the first layer)} = H_{x_0} (e^{-\gamma h} - R_2 e^{+\gamma(z-2h)}) \left(\sum_{n=0}^{\infty} (R_1 R_2)^n e^{-2n\gamma h} \right) \quad (\text{A-8})$$

The effective wave impedance, η_e , may now be obtained by taking the ratio $\frac{E_y}{H_x}$ and evaluating at the surface of the first layer (at $z = 0$):

$$\eta = \frac{E_y}{H_x} = \frac{E_0 (e^{-\gamma z} + R_2 e^{+\gamma(z-2h)})}{H_0 (e^{-\gamma z} - R_2 e^{+\gamma(z-2h)})} \quad (\text{A-9})$$

$$\eta_e = \frac{E_{y_0} (1 + R_2 e^{-2\gamma h})}{H_{x_0} (1 - R_2 e^{-2\gamma h})} = \eta_1 \left(\frac{1 + R_2 e^{-2\gamma h}}{1 - R_2 e^{-2\gamma h}} \right) \quad (\text{A-10})$$

For the assumed conditions,

$$\eta = \frac{j\omega\mu}{\gamma} \approx \left(\frac{\mu\omega}{\sigma}\right)^{1/2}, \text{ magnitude, therefore,}$$

$$\sigma_c = \sigma_1 \left(\frac{1 + R_2 e^{-2\gamma h}}{1 - R_2 e^{-2\gamma h}} \right)^{-2} \quad (\text{A-11})$$

This expression is identical to that in DECO report No. 30-F-2 and can be shown [Farstad, 1964], to be identical to the expressions of Wait[1962] . where

$$\sigma_c = \frac{\sigma_1}{Q_1^2}, \text{ where } Q_1 = \frac{\gamma_1 + \gamma_2 \tanh \gamma_1 h_1}{\gamma_2 + \gamma_1 \tanh \gamma_1 h_1} = \frac{1 + R_2 e^{-2\gamma h}}{1 - R_2 e^{-2\gamma h}} \quad (\text{A-12})$$

It is quite easy to extend the σ_c computation to more than two layers by evaluating the complex correction factor, Q , for the lowest two layers --- the lower layer being semi-infinite --- and then substituting the resultant Q_n into an expression for Q of the next higher layer:

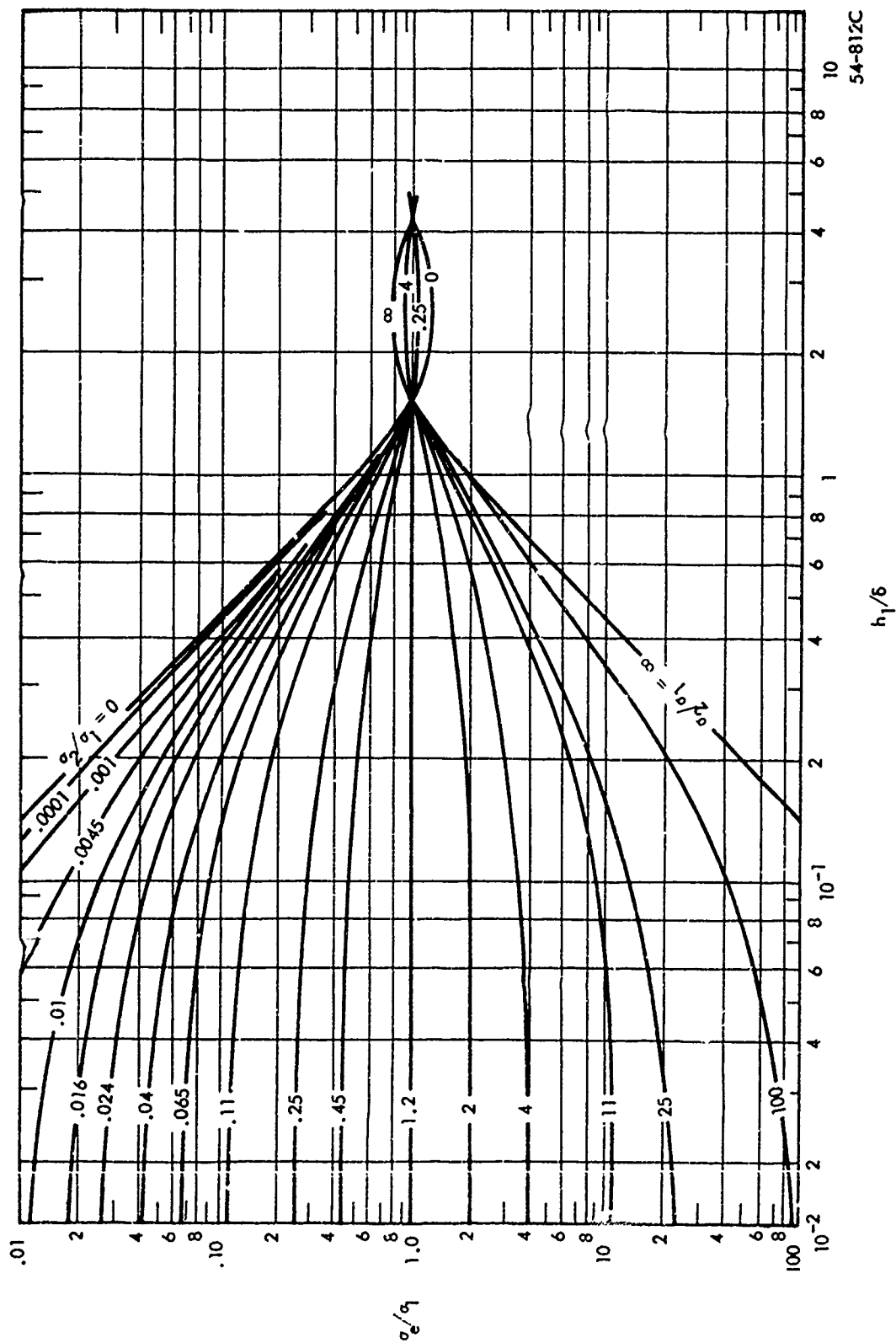
$$Q_{n-1} = \frac{\gamma_{n-1} Q_n + \gamma_n \tanh \gamma_{n-1} h_{n-1}}{\gamma_n + \gamma_{n-1} Q_n \tanh \gamma_{n-1} h_{n-1}}, \quad (\text{A-13})$$

where

$$Q_n = \frac{\gamma_n + \gamma_{n+1} \tanh \gamma_n h_n}{\gamma_{n+1} + \gamma_n \tanh \gamma_n h_n},$$

for an $n + 1$ -- layered earth.

For purposes of quickly evaluating the effective conductivity of a two layer case, some curves normalized with respect to conductivity and first-layer height are presented in Figure A-2. It should be emphasized, here, that these



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Figure A-2 Nomograph for Determining σ_e/σ_1 , Effective Conductivity, for a Horizontally - Stratified, Two-Layer Earth

curves yield magnitude of σ_e , and that in order to apply this procedure to more than two layers, the complex nature of Q_n as indicated above must be regarded.

To find σ_e for a two layer case, the ratio σ_2/σ_1 is first evaluated. This will determine which of the parametric curves in Figure A-2 apply -- and will determine what interpolation between the established curves will be required. The abscissa is h_1/δ , and can be evaluated next from the skin depth chart. Figure A-3, for the particular frequency of interest (10 kc/s). (Note, that $K \cong 1$ for earth materials at VLF.) The ratio σ_e/σ_1 can now be read directly from the chart, and the actual σ_e is obtained by multiplying the determined σ_e/σ_1 ratio by the first-layer conductivity.

Effective conductivity may be determined not only from the electrical layering of the earth as described above, but also from two other well-known approaches: (1) from field strength measurements of known transmitters, and (2) from measurements of either natural or man-made E_{y_o} and H_{x_o} fields (horizontal fields). The latter method is commonly referred to as audio-magneto-telluric measurements; the former method is relatively unimportant to the present consideration since no measurements of this type were made, and the method is not as desirable as either the four-terminal array or AMT measurements [see Pullen, 1953; and Norton, 1941].

A.4 EFFECTIVE CONDUCTIVITY FROM AUDIO-MAGNETO-TELLURIC, (E_{y_o} and H_{x_o}) MEASUREMENTS

In computing σ_e from measurements of the E and H fields, it is helpful to recognize that an electromagnetic field propagating along the earth's surface experiences a wave-tilt because of losses associated with the electrical properties of the earth material.

This wave-tilt, or "loss," results in a downward propagating wave and the ratio of the electric field to the magnetic field of this downward traveling wave is a measure of the effective intrinsic impedance, η_e , of the earth material. This intrinsic impedance is a function of the total electrical environment at any given location.

$$\delta = \left(\frac{2}{\omega_{\mu_0 \sigma}} \right)^{1/2} \left\{ \left(\frac{\omega_{\epsilon}^2}{\sigma^2} + 1 \right) - \frac{\omega_{\epsilon}}{\sigma} \right\}^{-1/2} \text{ or}$$

$$\delta = \frac{1}{\alpha} = \frac{1}{\omega} \left[\frac{\mu_0 \epsilon}{2} \left[\left(1 + \frac{v^2}{\omega^2 \epsilon^2} \right)^{1/2} - 1 \right] \right]^{-1/2}$$

Y-axis: Skin Depth, δ , in Meters (log scale, 10^1 to 10^7)

X-axis: Frequency, in cps (log scale, 1 to 10^5)

Curves shown for conductivity σ (mhos/meter):

- $\sigma = 10^{-8}$
- $\sigma = 10^{-7}$
- $\sigma = 10^{-6}$
- $\sigma = 10^{-5}$
- $\sigma = 10^{-4}$
- $\sigma = 10^{-3}$
- $\sigma = 10^{-2}$
- $\sigma = 10^{-1}$
- $\sigma = 1$

Curves shown for permeability K :

- $K = 10$
- $K = 1$
- $K \leq 10^3$
- $K \leq 10^2$

A dashed line with diagonal hatching is also plotted, intersecting the curves.

Figure A3 Skin Depths as Function of the Frequency of Electromagnetic Waves for Various Conductivities and Permittivities, Where $k = \epsilon/\epsilon^0$

To compute the effective conductivity from the measured horizontal components of the electromagnetic field, consider the following:

$$\frac{E_{y_0}}{H_{x_0}} = \eta_c = \sqrt{\frac{j\omega\mu}{\sigma_c + j\omega\epsilon}} \approx \sqrt{\frac{j\omega\mu}{\sigma_e}} \quad (A-14)$$

therefore

$$\sigma_c = \frac{\omega\mu}{\eta^2} = 7.94 \times 10^{-6} f/\eta^2. \quad (A-15)$$

It is quite simple to determine directly from the measured fields, a value of effective conductivity which is not dependent upon the validity of an earth-layering interpretation such as is made from four-terminal array measurements. The source of the propagating electromagnetic field can be natural atmospheric noise (for conditions in which the source lightning activity is "distant"), or from known VLF transmitters, [Farstad, 1963].

APPENDIX B

PERMAFROST: Occurrence, Characteristics, and Electrical Properties

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APPENDIX B

PERMAFROST: Occurrence, Characteristics, and Electrical Properties

B.1 INTRODUCTION

Permafrost, or perennially frozen ground, is found in over half the land area of Alaska and Canada. About one-fifth of the land area of the world is subject to permafrost [Brown and Johnston, 1964]. Since the electrical conductivity of permafrost can be 1×10^{-3} mho/m and lower, it is important that its extent, thickness, and electrical properties of permafrost be determined to aid in world-wide radio propagation studies.

The fact that there is a marked decrease in rock conductivity at temperatures below 0°C was recognized by Professor M. I. Evokimov-Rokotovskiy in 1928. One of the later classical works on electrical conductivity in frozen rocks was done by M. A. Nesterova and L. Ya. Nesterov in the Geological Survey Institute (Russia), [1939]. Other work includes papers by Higgs [1930], Smith-Rose [1934], and Dumas [1962]. Some of the characteristics and electrical properties of permafrost and frozen rocks will be summarized in this appendix.

B.2 OCCURRENCE AND CHARACTERISTICS OF PERMAFROST

There is a delicate thermal balance which controls the occurrence of permafrost. Slight changes in vegetation or temperature will upset this balance and cause major changes in the thickness (or extent) of permafrost. For example, if one assumes a geothermal gradient of $1^{\circ}\text{F}/100\text{ ft.}$ then a surface temperature change of one degree can cause a corresponding 100 ft. change in permafrost thickness.

In addition to the geothermal gradient, the thermal properties of the rock material that are important in controlling the occurrence of permafrost

are diffusivity and specific heat. One finds a perplexing change in these properties with water content and freezing for some materials. Table B-1 presents some thermal conductivities of peat for various conditions.

Condition of Peat	Thermal Conductivity [(Calories)/(cm - ° C. - sec.)]
Dry bog	0.00017
Unsaturated	0.0007
Saturated	0.0011
Saturated and Frozen	0.0056

Table B-1. Thermal conductivity of peat for different condition of water content and freezing. [Data taken from Geology of the Arctic, 1961].

Some definite criteria for the occurrence of permafrost can be established based on the fact that the mean annual ground temperature in northern regions is on the average of 4 to 8 degrees (F) higher than the mean annual air temperature. This immediately determines that a mean annual air temperature sufficiently low to support permafrost is approximately 26° F.

Slight changes in mean annual air temperature can cause considerable change in permafrost thickness, as illustrated in Table B-2 [adapted from Johnston, et al., 1963]. A difference of 2-1/2° F between Thompson (or Hay River) and Yellowknife corresponds to a difference of over 200 ft. in permafrost thickness.

Freezing and thawing indices are a measure of heat added to or extracted from the ground. Maps of freezing and thawing indices, mean annual air temperature, and distribution of permafrost in Canada are presented in Figures B-1, B-2, B-3, and B-4. Note the similarity in the character of the air temperature and freezing and thawing indices to the permafrost distribution.

STATION (Canada)	LOCATION Longitude North Latitude West		MEAN ANNUAL Air Temp. (°F)	FREEZING Index (Degree days)	THAWING Index (Degree days)	PERMAFROST Distribution (Approximations)
Aishihik, Y. T.	61° 39'	137° 28'	25.5			Widespread, max. thickness - 90 ft.
Fort Simpson, N.W.T.	61° 52'	121° 21'	25.0			Patchy, variable thickness to 40 ft.
Fort Providence, N.W.T.	61° 20'	117° 40'	24.8			Patchy
Hay River, N.W.T.	60° 51'	115° 46'	24.7	5548	3171	Patchy, variable thickness to 40 ft.
Yellowknife, N.W.T.	62° 28'	114° 27'	22.5	6623	3079	Widespread, max. thickness - 250 ft.
Fort Resolution, N.W.T.	61° 10'	113° 41'	23.7	5776	3176	Patchy, variable thickness to 40 ft.
Fort Smith, N.W.T.	60° 01'	111° 58'	25.6	5613	3365	None Reported
Thompson, Man.	55° 36'	98° 42'	24.9	5535	3149	Patchy, variable thickness to 40 ft.
Fort George, P.Q.	53° 50'	79° 05'	25.2			None Reported
Nitchequon, P.Q.	53° 12'	70° 35'	24.4			None Reported
Cape Hopes Advance, P.Q.	61° 05'	69° 33'	19.2	5443	974	Continuous, several hundred feet.

Table B-2 Some permafrost distributions for Canadian stations indicating freezing and thawing indices and mean annual air temperatures.

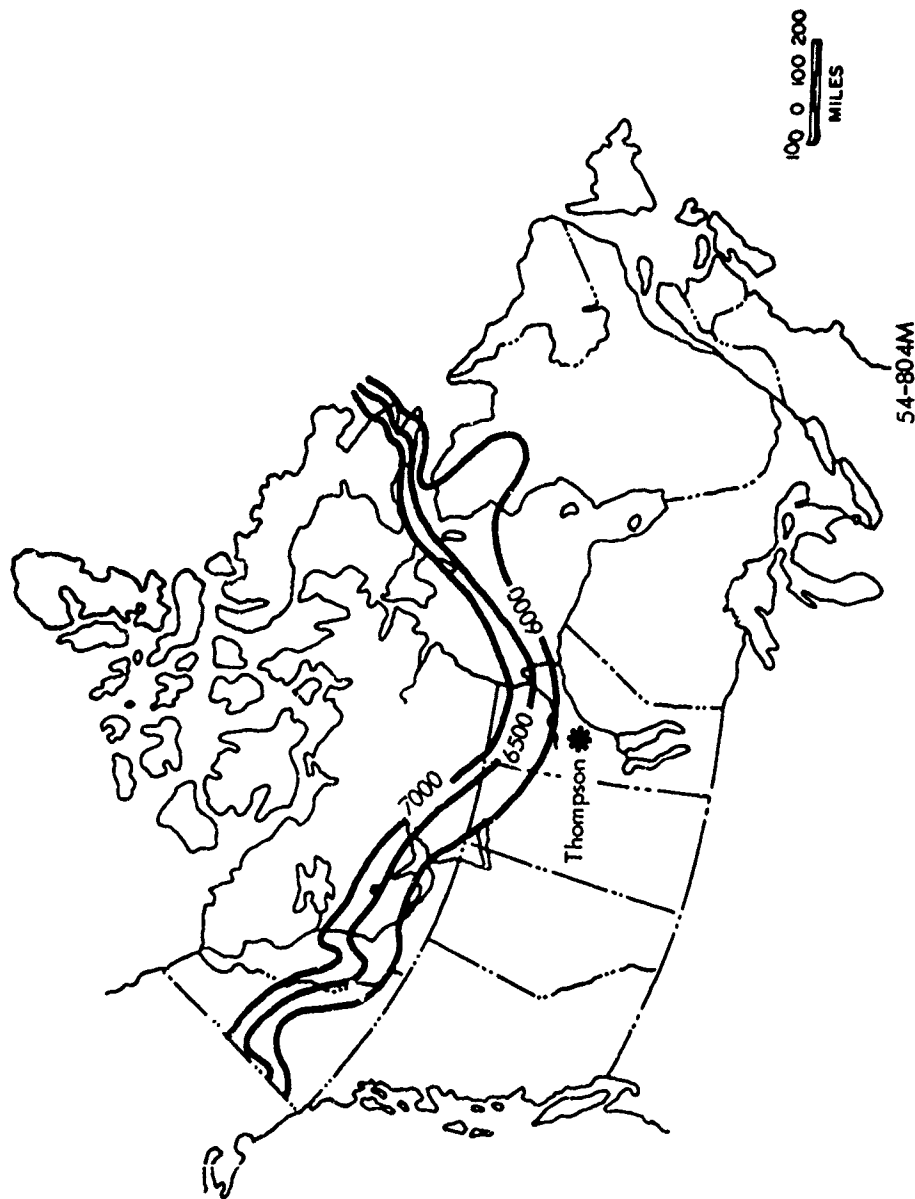


Figure B-1 Some Freezing Indices for Canada
(Fahrenheit Degree Days)

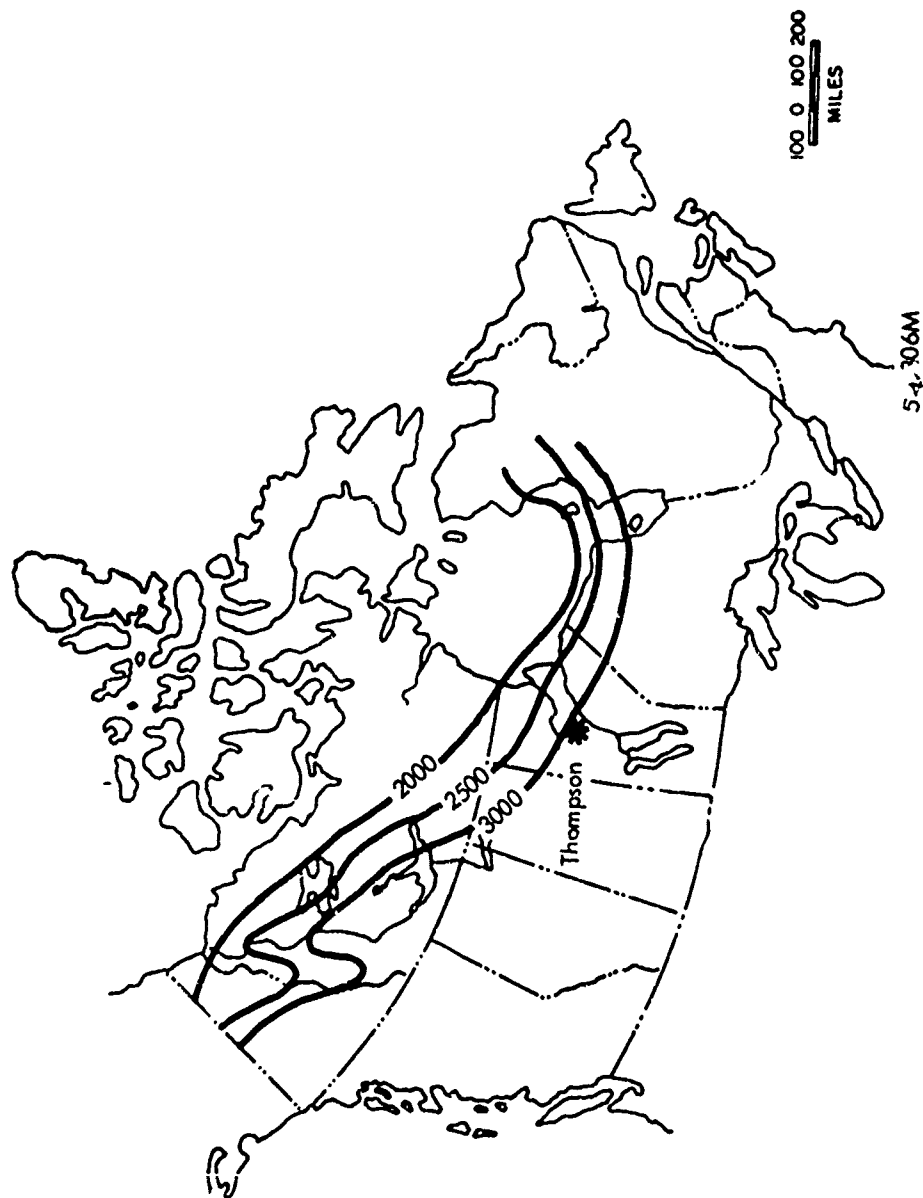


Figure B-2 Some Thawing Indices for Canada
(Fahrenheit Degree Days)

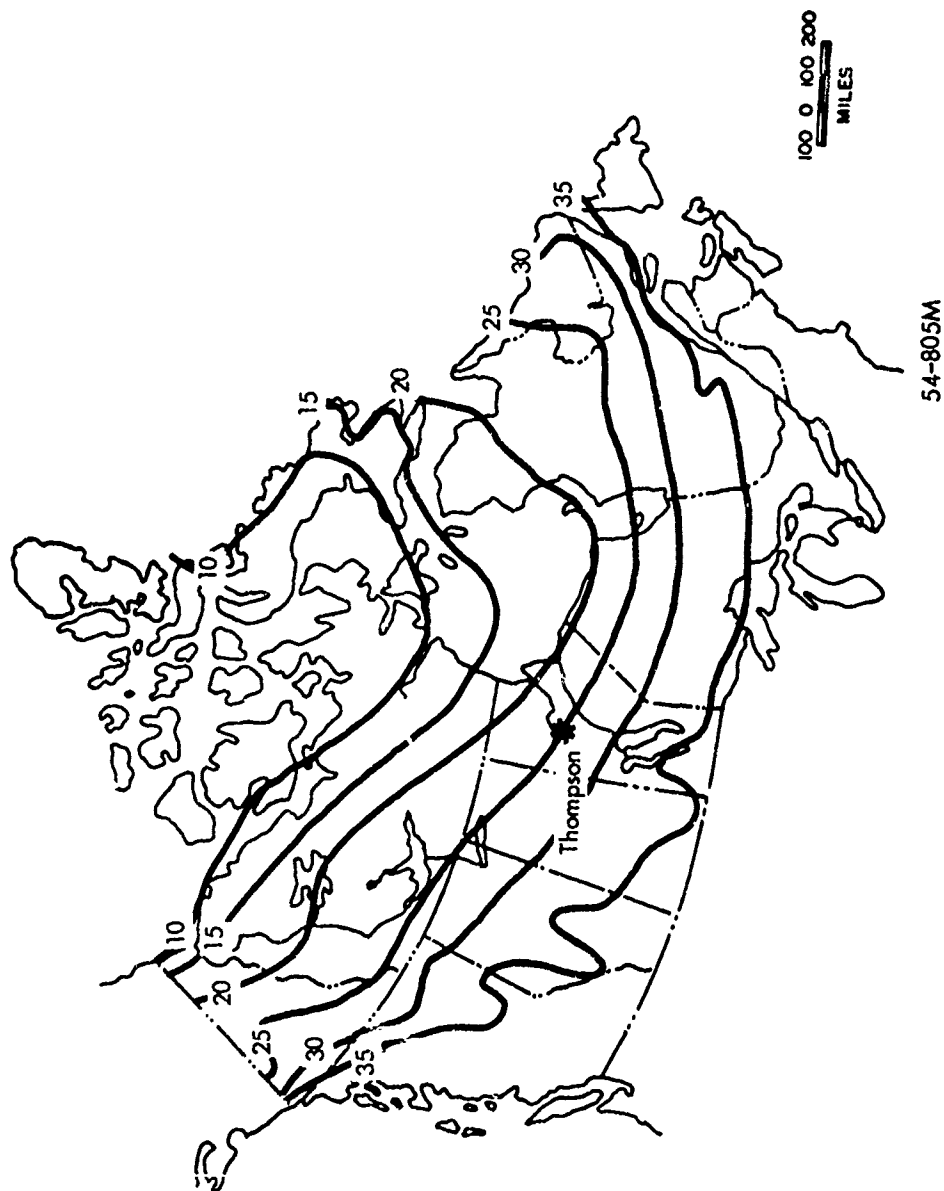


Figure B-3 Mean Annual Air Temperature for
Canada (Degrees Fahrenheit)

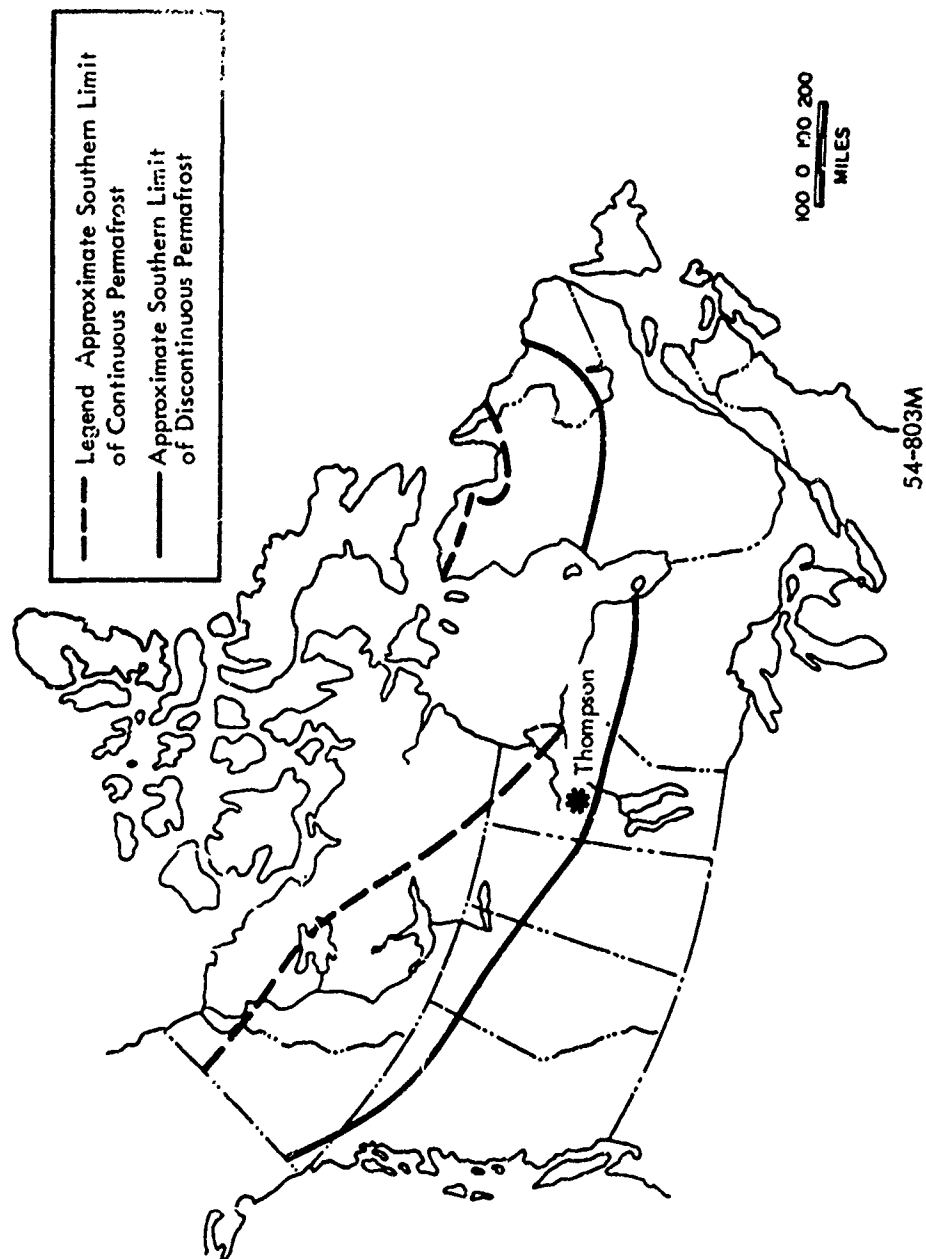


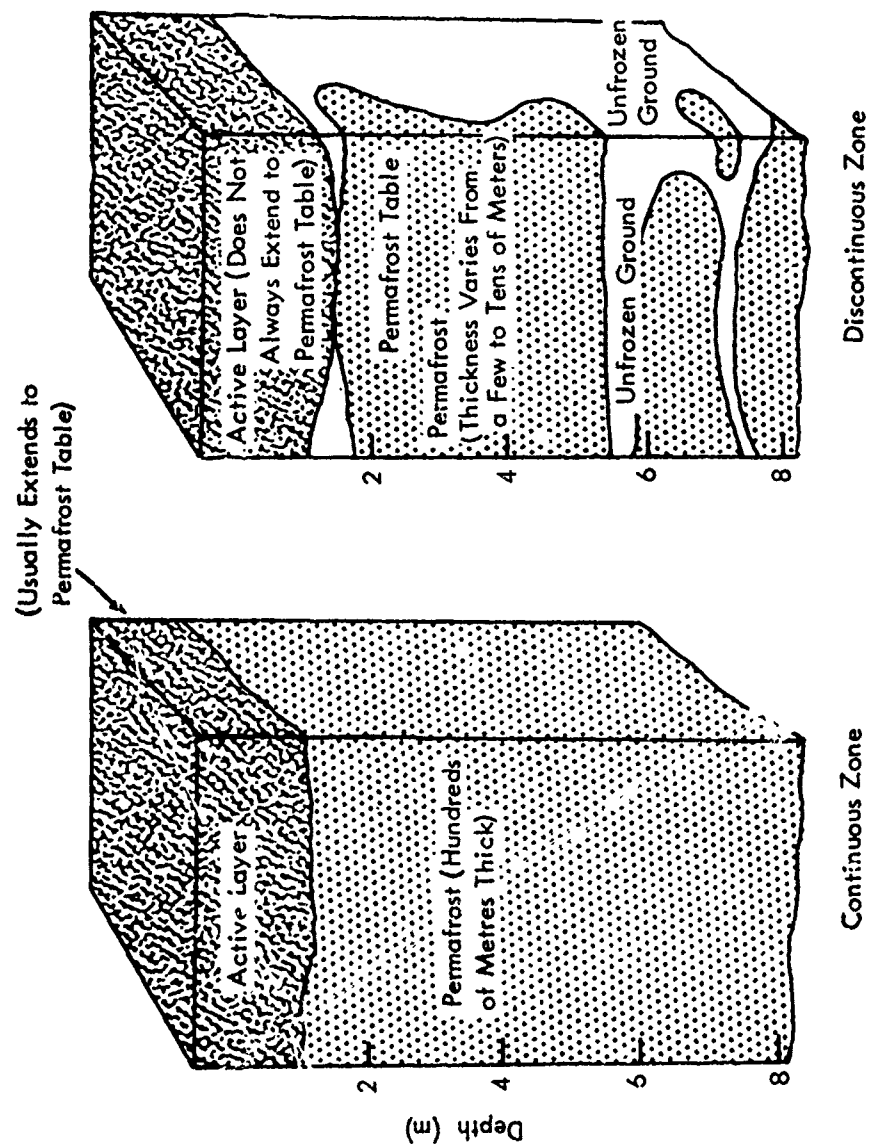
Figure B-4 Distribution of Permafrost in Canada
June 1962 DBR/NRC

Of particular interest in radio propagation studies are inhomogeneities, or departures from the typical models presented in Figures B-5 and B-6, which could produce changes in electrical conductivity of an area. Two of the important inhomogeneities are: ice and brine inclusions and taliks (unfrozen layers between the active layer and the permafrost). At the present time, the effects of these inhomogeneities cannot be quantitatively determined; however, it is important to recognize that there are such effects. Brewer has indicated from work in Alaska that taliks can be expected beneath lakes which do not freeze to the bottom during winter: lakes deeper than seven feet are in this category for the North American Arctic. Ice can occur in permafrost as coating on particles or as layers or lenses (often in fine grain deposits). The amount of included ice varies with the material. Some rough estimates for various earth materials are presented in Table B-3.

<u>Material</u>	<u>Amount of Included Ice</u>
"Solid" rock	Much
Gravel	Much
Sand	Much
Peat	Little
Organic Material	Little
Silty Soil	Little

Table B-3. Amount of included ice for some common earth material in an arctic region.

Inclusions of brine are very common, and it is well known that earth material is never completely "frozen" but rather pockets of brine are nearly always found in permafrost. There is no way at present to determine the amount and character of included ice and brine in a frozen earth except by drilling - a very difficult thing in itself.



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Figure B-5 Typical Vertical Distribution and Thickness of Permafrost

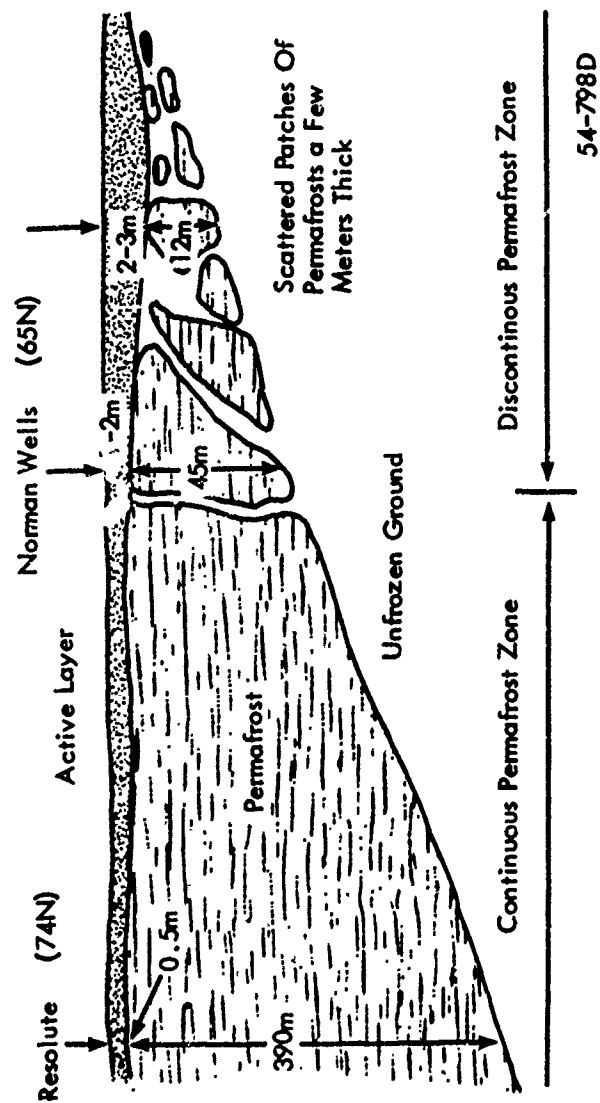


Figure B-6 Typical Profiles in Permafrost Region

B.3 THE ELECTRICAL PROPERTIES OF PERMAFROST AND FROZEN ROCKS

Before discussing some of the particular electrical properties of frozen rocks, it will be instructive to consider the freezing process itself. 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. At this time the freezing rate is greatly reduced for a further decrease in temperature. *

The pressure exerted on the unfrozen solution may be 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. Pressure on the unfrozen solution may also be caused by adsorption at the solid-liquid interface. Investigators have reported pressures as high as 25,000 kg/cm² for methyl alcohol in Fuller's earth. Even higher pressures may be associated with water [Winterkorn, 1943]. A complicating factor involved in these considerations is that water adsorbed on a clay particle has different characteristics from liquid water. The surface adsorption effect will be less for rocks of larger grain size (because of the smaller total surface area).

Conductivity in rocks decreases by a factor of 10 to 100 with a temperature change from 0° C to a few degrees below, after which there is a more gradual decrease in conductivity with temperature. (There are, as expected, some exceptions to this in cases of extremely pure infilling water, or with very dense crystalline rocks [see Dostovalov, 1947, p. 26]).

Table B-4 presents data showing the decrease in conductivity by a factor of 10 to 50 from + 14°C to -5°C [Dostovalov, 1947]. Measurements made by Dumas show similar trends - Table B-5 presents some data from laboratory samples at 10 kc/s [Dumas, 1962]. Some values of resistivity are listed along with moisture content information in Table B-6 [Dostovalov, 1947].

*Pertinent references dealing with infilling liquid and the freezing process are: [Parker, 1921], [Bodman and Day, 1943], [Cannel and Walter, 1959], and [Low, 1958].

Table B-4. Changes in soil conductivity with freezing.

TYPE SOIL	σ , (mhos/m) $t = + 14^{\circ}\text{C}$	σ , (mhos/m) $t = - 5^{\circ}\text{C}$
1. gray clay with layers of ice	1.4×10^{-1}	1.6×10^{-2}
2. clay, gray, gravelly	5×10^{-2}	6×10^{-3}
3. clay, heavy, dark gray	2×10^{-2}	8.7×10^{-4}
4. clay, dark gray with gravel to 1 cm in diameter	1.2×10^{-1}	1.3×10^{-3}
5. clay, gray, gravelly with layers of ice	5.7×10^{-2}	2.0×10^{-3}
6. clay, light, with fine gravel	1.2×10^{-1}	4.5×10^{-3}
7. quartz, fine grained sand, with slate particles	6.8×10^{-2}	2.4×10^{-3}
8. clay sand, with quartz admixture	2.3×10^{-2}	9.1×10^{-4}
9. limestone, fine grain with admixture of quartz and slate particles	5.6×10^{-2}	1.8×10^{-3}
10. clayey fine grain sand with admixture of quartz particles	1.7×10^{-1}	5.9×10^{-3}

Sample No.	Porosity of Sample	Molarity of Solution	Temperature = 0°C			Temperature = 5°C			Temperature = -11°C			Temperature = -20°C		
			ϵ/ϵ_0	@ 10kc/s	σ	ϵ/ϵ_0	@ 10kc/s	σ	ϵ/ϵ_0	@ 10kc/s	σ	ϵ/ϵ_0	@ 10kc/s	σ
1	3.5	0.10	138	7.6×10^{-5}	4.5×10^{-3}	72	4.0×10^{-5}	8.2×10^{-4}	72	4.0×10^{-5}	3.5×10^{-4}	53.7	3.0×10^{-5}	1.3×10^{-4}
2	6.5	0.10	239	1.3×10^{-4}	1.2×10^{-2}	95	5.3×10^{-5}	1.1×10^{-3}	103	5.7×10^{-5}	4.6×10^{-4}	69	3.8×10^{-5}	1.6×10^{-4}
3	17.5	0.020	393	2.2×10^{-4}	1.3×10^{-2}	130	7.2×10^{-5}	2.1×10^{-3}	134	7.5×10^{-5}	7.6×10^{-4}	103	5.7×10^{-5}	2.7×10^{-4}
4	17.5	0.1	640	3.5×10^{-4}	3.2×10^{-2}	166	9.2×10^{-5}	6.5×10^{-3}	170	9.5×10^{-5}	2.3×10^{-3}	122	6.8×10^{-5}	7.8×10^{-4}
5	17.5	0.2	800	4.4×10^{-4}	5.4×10^{-2}	228	1.3×10^{-4}	1.1×10^{-2}	189	1.0×10^{-4}	5.1×10^{-3}	141	8.3×10^{-5}	1.8×10^{-3}
6	17.5	0.5	1030	5.7×10^{-4}	1.1×10^{-1}	1150	6.4×10^{-4}	8.7×10^{-2}	222	1.2×10^{-4}	2.3×10^{-2}	157	8.7×10^{-5}	8.2×10^{-3}

Table B-5. Values of σ and $\omega\epsilon$ (measured values) for sandstone samples at 10 kc/s. Note that $\omega\epsilon$ is small compared to σ in every case from 0°C, down to -11°C. (Data adapted from Dumas [1962].)

Sample Number	Rock Type	3	4	5	6	7	8	9	10	11	12	13	14
		Porosity (%)	Moisture Content (% of volume)	Resistivity at +18 to +20°C (Ω - cm)	Resistivity at T _C (Ω - cm)	Temperature T _C (°C)	Resistivity at T _B (Ω - cm)	Temperature T _B (°C)	Resistivity at T _A (Ω - cm)	Temperature T _A (°C)	Sodium Chloride in Solution (%)	Moisture Content After Freezing (%)	Resistivity of Water Left in the Pores (Calculated) (Ω - cm)
1													
351	Marioplyte	0.75	0.1	1.0 · 10 ⁴	2.51 · 10 ⁴	+1°	2.51 · 10 ⁷	-7°	1.0 · 10 ⁸	-18°	0.001	--	3.3 · 10 ²
188	Pyroxenite	0	0.1	1.4 · 10 ⁵	6.31 · 10 ⁵	-7°	3.96 · 10 ⁴	-11°	1.58 · 10 ⁷	-20°	0.01	--	4.7 · 10 ²
253	Paleobasalt	6.4	0.15	1.1 · 10 ⁴	2.51 · 10 ⁵	+5°	2.0 · 10 ⁴	-9°	3.16 · 10 ⁴	-20°	0.01	--	3.7 · 10 ²
239	Biotite Granite	3.4	0.15	3.0 · 10 ⁵	5.0 · 10 ⁵	0°	1.0 · 10 ⁴	-11°	3.98 · 10 ⁴	-20°	0.001	0.10	1.5 · 10 ²
299	Nepheline Syenite	0.75	0.17	5.5 · 10 ⁵	1.0 · 10 ⁴	-3°	2.0 · 10 ⁷	-11°	5.0 · 10 ⁷	-19°	0.01	0.02	3.1 · 10 ²
16	Finagrained Limestone	2.2	0.40	8.0 · 10 ⁴	2.5 · 10 ⁵	-3°	7.94 · 10 ⁵	-10°	1.26 · 10 ⁶	-19°	0.01	--	1.1 · 10 ²
304	Limestone	1.1	0.40	3.0 · 10 ⁴	3.98 · 10 ⁵	+1°	1.0 · 10 ⁴	-3°	1.26 · 10 ⁶	-19°	1.0	0.4	4.0 · 10 ²
16	Finagrained Limestone	2.2	0.50	5.8 · 10 ⁴	1.0 · 10 ⁴	0°	1.0 · 10 ⁷	-15°	--	--	0.1	--	9.7 · 10 ²
304	Limestone	1.1	0.50	4.0 · 10 ⁴	1.78 · 10 ⁴	0°	2.5 · 10 ⁷	-8°	1.0 · 10 ⁸	-13°	1.0	--	6.6 · 10 ²
219	Quartzitic Sandstone	4.14	0.50	4.0 · 10 ⁴	1.78 · 10 ⁴	0°	1.6 · 10 ⁷	-7°	1.0 · 10 ⁸	-14°	0.001	0.2	6.6 · 10 ²
246	Limestone	7.3	0.60	4.5 · 10 ⁴	6.31 · 10 ⁵	+4°	2.0 · 10 ⁷	-3°	7.94 · 10 ⁷	-11°	0.005	0.5	9.0 · 10 ²
353	Syenite	4.92	0.60	6.0 · 10 ⁴	3.16 · 10 ⁵	-2°	1.46 · 10 ⁶	-10°	2.0 · 10 ⁶	-19°	0.005	0.3	1.2 · 10 ²
298	Conglomerate	1.8	0.76	5.2 · 10 ⁵	5.60 · 10 ⁵	+7°	3.16 · 10 ⁷	-4°	1.0 · 10 ⁸	-9.5°	0.205	0.5	1.3 · 10 ³
298	Conglomerate	1.8	0.80	6.8 · 10 ⁴	2.0 · 10 ⁴	+2°	2.0 · 10 ⁷	-6°	6.3 · 10 ⁷	-13°	0.1	0.4	1.8 · 10 ³
353	Syenite	4.92	0.80	4.0 · 10 ⁴	1.26 · 10 ⁵	-2°	3.98 · 10 ⁵	-8°	5.62 · 10 ⁵	-13°	1.04	0.75	1.1 · 10 ²
214	Quartzitic Sandstone	3.8	1.00	8.5 · 10 ⁴	7.94 · 10 ⁴	-4°	5.0 · 10 ⁴	-8°	6.3 · 10 ⁴	-12°	1.01	0.73	2.8 · 10 ²
252	Quartzitic Sandstone	8.7	1.30	2.4 · 10 ⁴	7.94 · 10 ⁴	-4°	7.94 · 10 ⁴	-10°	1.0 · 10 ⁷	-13°	1.0	0.9	1.0 · 10 ²
247	Sandstone	11.9	1.40	1.5 · 10 ⁴	2.82 · 10 ⁵	+5°	5.0 · 10 ⁴	-5°	7.08 · 10 ⁷	-15°	0.001	0.6	7.0 · 10 ²
289	Red Porphyry	10.0	1.62	1.0 · 10 ⁴	--	--	--	--	--	--	0.01	1.2	5.4 · 10 ²
247	Sandstone	11.9	1.68	2.4 · 10 ⁴	1.0 · 10 ⁵	-1°	1.0 · 10 ⁴	-12°	5.0 · 10 ⁷	-16°	1.0	--	1.3 · 10 ²
248	Quartzitic Sandstone	9.8	1.80	1.1 · 10 ⁴	2.51 · 10 ⁴	-4°	1.0 · 10 ⁵	-12°	2.0 · 10 ⁵	-19°	5.0	--	6.6 · 10 ¹
268	Quartzitic Sandstone	7.1	1.90	3.5 · 10 ⁴	3.6 · 10 ⁵	-4°	1.0 · 10 ⁵	-12°	2.0 · 10 ⁵	-19°	0.1	--	2.2 · 10 ²
267	A Red Porphyry	12.2	2.71	1.0 · 10 ⁴	2.82 · 10 ⁵	+2°	1.58 · 10 ⁷	-10°	6.31 · 10 ⁷	-19°	0.1	1.0	7.2 · 10 ²
213	A Light-colored Conglomerate	21.0	3.30	1.6 · 10 ⁴	8.91 · 10 ⁴	+1.7°	3.98 · 10 ⁵	-5°	5.0 · 10 ⁵	-16°	0.1	--	1.8 · 10 ²
213	A Light-colored Conglomerate	21.0	3.30	5.5 · 10 ⁴	5.5 · 10 ⁴	+8°	1.0 · 10 ⁴	-5°	1.58 · 10 ⁴	-12°	0.005	--	6.0 · 10 ¹
251	Sandstone	6.8	4.70	5.0 · 10 ⁴	1.0 · 10 ⁵	+4°	2.0 · 10 ⁵	+1°	1.0 · 10 ⁶	-5°	0.001	--	7.8 · 10 ¹
349	Dolomite	20.0	5.80	6.0 · 10 ³	1.0 · 10 ⁴	--	--	--	--	-15°	0.01	5.10	1.2 · 10 ²
389	Dolomite	20.4	6.72	4.0 · 10 ³	1.0 · 10 ⁴	+5°	5.0 · 10 ⁵	-9°	1.26 · 10 ⁶	-15°	0.01	2.67	9.0 · 10 ¹
202	Shale	13.6	10.1	4.7 · 10 ³	--	--	--	--	--	--	0.005	8.79	1.6 · 10 ¹
49	Mass of Chalcopyrite	?	0.1	5.0 · 10 ⁻²	5.62 · 10 ⁵	+2°	3.72 · 10 ⁴	-0.5°	--	-11°	0.001	--	--
--	Dibase	?	0.1	4.5 · 10 ⁵	--	--	--	--	--	--	--	--	--
163	Mass of Chalcopyrite	--	--	1.8 · 10 ⁻³	--	--	--	-7°	3.6 · 10 ⁷	--	--	--	--

Table B-6 Resistivity values at various temperatures for some common rock types. [Dostovalov, 1947 (in Russian)].

It is possible to calculate the conductivity of a frozen rock using an empirical relationship:

$$\sigma_r = \frac{W}{300 \sigma_I} \quad (B-3-1)$$

where σ_r = Conductivity of frozen rock.
 σ_I = Conductivity of the ice in the rock.
 W = Remaining moisture after freezing.

This relationship is valid at only one temperature, and the remaining moisture, as well as the conductivity of the ice are 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 this is quite 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 (i. e., the grain size, interconnections, the ion desorption capability, and other factors which might effect the freezing point of the infilling water).

Each of the three factors must be considered in relation to temperature. Semenov [1937] has made some experimental studies evaluating some of the above factors. See Table B-7 and Figures B-7 and B-8.

Figure B-6 indicates that rock conductivity for high purity water in a medium-grain sand decreases by as much as 1000 times with a temperature depression to -8° or -12° C. This effect is reduced to a decrease of no more than a factor of 10 to 20 for a strongly-mineralized, high-salinity infilling water. Note that here again the most rapid change in conductivity occurs within the first two degrees below freezing. This data is for a completely saturated quartz sand

Sample Number	Rock Type	Volume of Sample (cm ³)	Porosity (% of Sample Volume)	Water Content (% of Available Pore Space)	Volume of Water in Sample (cm ³)	Temperature of Measurement (°C)	Absolute Expansion (mm ³)	Theoretical Expansion (mm ³)	Quantity of Frozen Water (% of Total Water Present)
1	Argillaceous material	6	46.20	100	2.76	-3.4	121	248	49.0
2		6	34.65	75	2.07	-3.5	98	186	53.0
3		6	23.10	50	1.38	-4.1	60	124	48.5
4		6	11.55	25	0.69	-4.8	15	62	24.2
5		6	4.62	10	0.27	-6.5	1.6	24	7.0
6	Sand, Grain size from 1/2 to 1 mm.	6	29.10	100	1.74	-4.0	95	159	60.0
7		6	21.84	75	1.30	-3.0	62	117	53.0
8		6	14.56	50	0.87	-4.1	44	78	56.4
9		6	7.28	25	0.43	-3.4	10	38	26.2
10		6	37.60	100	2.15	-3.7	102	193	52.8
11	Sand, Grain size less than 1/2 mm.	6	28.20	75	1.62	-3.2	76	145	52.4
12		6	18.80	50	1.08	-3.7	46	97	47.8
13		6	9.40	25	0.54	-3.7	24	48	50.0

Sample Number	Temperature (°C)	Volume of Sample (mm ³)	Volume of Water in Sample (mm ³)	Quantity of Frozen Water (mm ³)	Quantity of Unfrozen Water (mm ³)
Measurements on Peat Samples					
1	-3.0	5786	2660	1767	893
2		5483	2500	1700	800
3		4712	1665	700	965
4		4783	1665	600	1065
Measurements on Argillaceous Samples					
5	-3.0	5434	2280	1288	922
6		5423	2280	1389	891
7		4388	1439	622	817
8		5516	2133	1822	1313
9		5542	3035	1611	1424

Table B-7 Water saturations and percent of frozen water for various rock and soil samples at freezing temperatures. Note that 50 percent or more of the water remains unfrozen in many of the samples for freezing temperatures [Semenov, 1937].

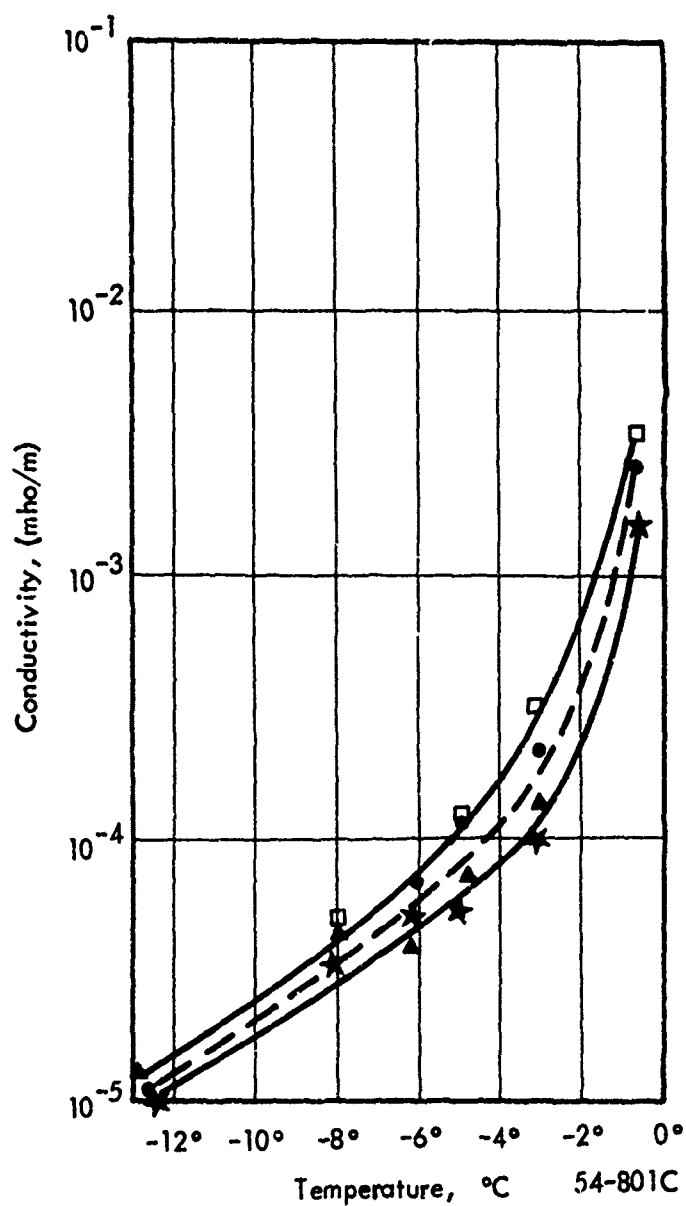


Figure B-7 Conductivities of Sand vs Temperature With Different Saturations of Distilled Water.

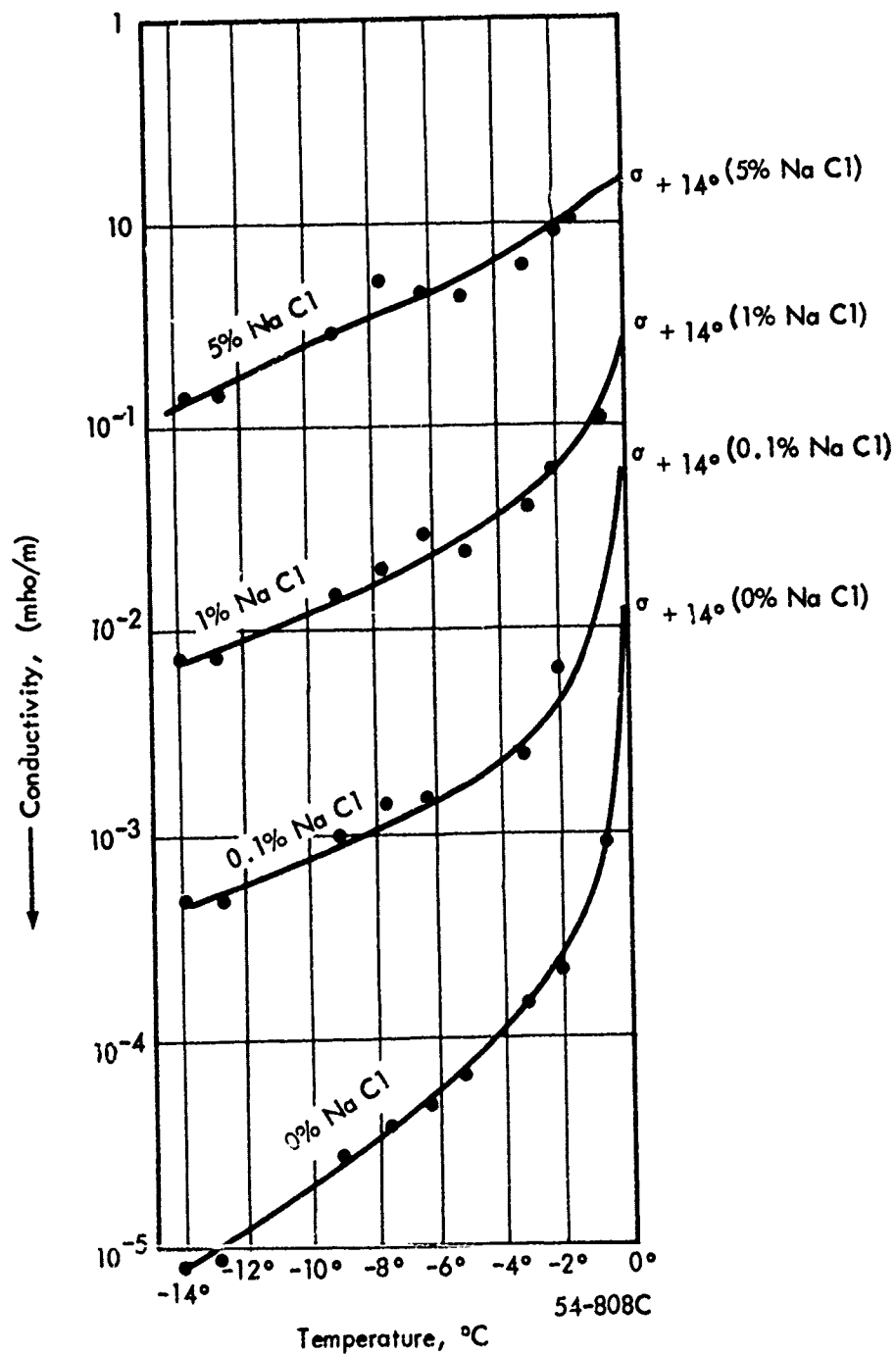


Figure B-8 Conductivity as a Function of Temperature for a Medium Grained Sand for Various Concentrations of Infilling Na Cl Solution

(with presumably little or no "clay effect"; desorption of conducting ions and freezing point depression due to an oriented surface layer.)

Results of a similar study for conductivities of sand with different saturations of distilled water are presented in Figure B-8. The sands had a diameter of 1 to 1/2 millimeters, and water saturations are expressed as percent of the available pore space. See, also, Table B-8.

It is important to note that Semenov found that the curves do not fall near each other for other conditions: sands of other grain sizes, higher salinity waters, and for shale and peat. The conclusion is, again, that the character and structure as well as grain size determines the conductivity of rock material at sub-zero temperatures. These other factors have a subordinate effect, however, compared to the salinity of the water.

The value of the dielectric constant, ϵ/ϵ_0 , for frozen rocks is of considerable importance to the present study, because of the approximations involving the $\omega\epsilon$ product. Calculations are conveniently simplified if $\omega\epsilon < \sigma/10$, and the calculation of effective conductivity from an electrically layered earth is valid for all angles of incidence of electromagnetic energy if this approximation holds (see Appendix A). Figure B-9 gives the minimum values of conductivity as a function of ϵ/ϵ_0 in order for the approximation $\omega\epsilon < \sigma/10$ to be true. Measurements on sandstone samples show the $\omega\epsilon$ product to be small compared to σ at temperatures above -11°C . The behavior of ϵ/ϵ_0 with frequency and temperature further support indications that the approximation may be valid in permafrost regions in North America.

The dielectric constant of rock material changes with frequency and temperature. Table B-8 presents some experimental data showing average decreases in ϵ/ϵ_0 for decade frequency increments. This decrease in dielectric constant is most pronounced at room temperatures, and becomes smaller at lower temperatures.

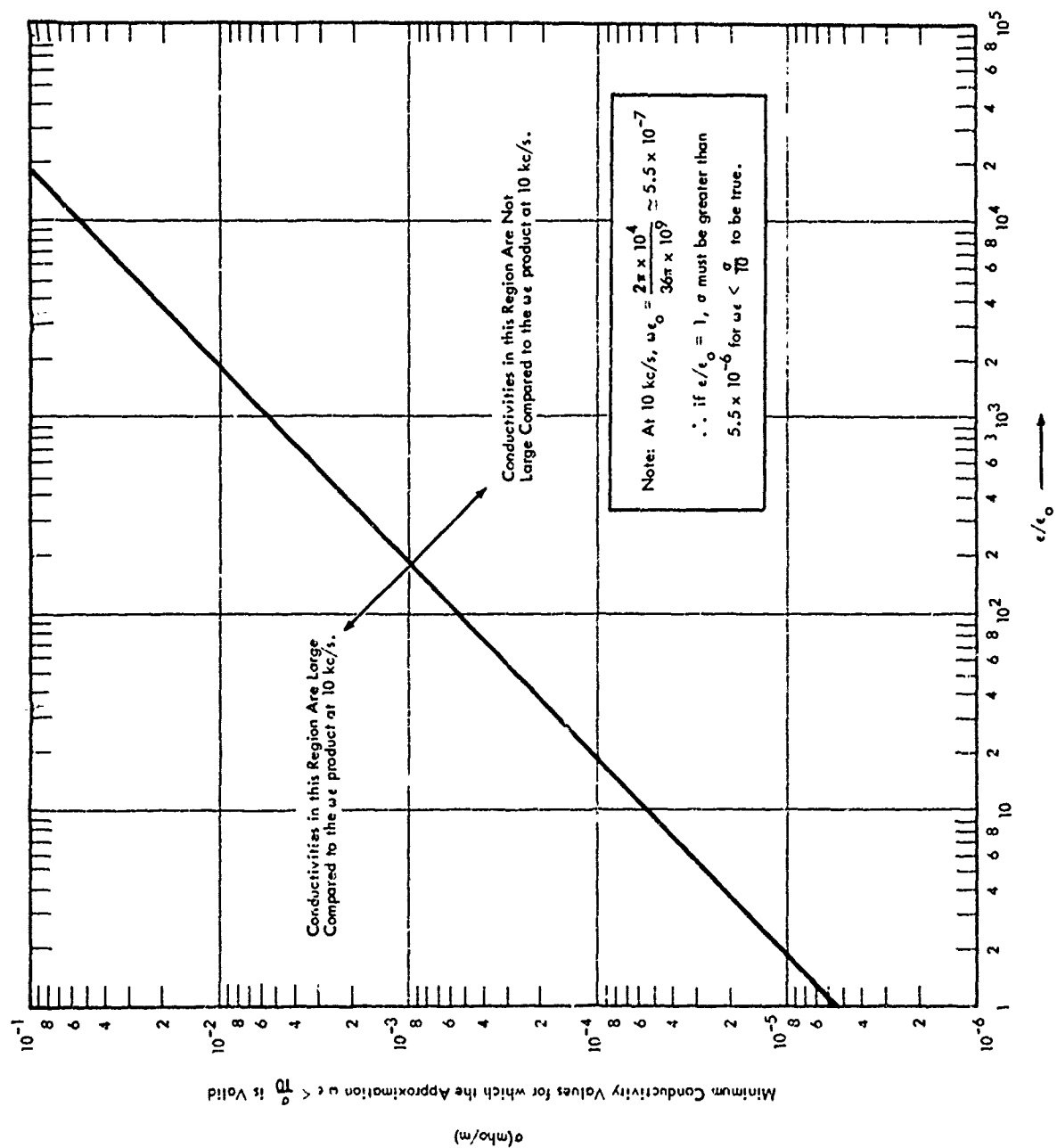


Figure B-9 Minimum Values of Conductivity as a Function of ϵ/ϵ_0 for $\omega\epsilon < \frac{10}{\epsilon}$ at 10 kc/s.

Table B-8. Average decrease in ϵ/ϵ_0 for decade increase of frequency (various temperatures).

Temperature (°C)	Average Decreases in ϵ/ϵ_0 (6 sandstone samples, Dumás, 1961) Frequency Increments, (c/s)		
	10^2 to 10^3	10^3 to 10^4	10^4 to 10^5
+ 3	10*	9.1	6.3
0		8.1	6.4
- 5	4.8*	4.7	3.1
-11		3.4	2.4
-20		2.9	2.3
*These values are extrapolations, and are not as reliable as the other data (200 c/s is the lowest frequency for which ϵ/ϵ_0 was measured).			

The value of the dielectric constant at frequencies below 100 c/s is expected to increase at a much faster rate as frequency decreases (from 0°C). There are several reasons for expecting such a behavior: (1) dielectric constants at temperatures above freezing show this behavior (Keller, [1959], has measured constants as high as 2×10^5 at a few hundred cycles/second); (2) the dielectric constant of ice increases very rapidly as frequency is lowered [Watt and Maxwell, 1960]. If the change in this constant is as expected, then a change of several hundred would occur with each decade of frequency below a few hundred cycles/second.

B.4 SUMMARY AND CONCLUSIONS

The following are some conclusions and summarizations of the material on the occurrence, characteristics and electrical properties of permafrost and frozen rocks:

1. Permafrost occurs in 1/5 of the total land area of the world. A mean annual air temperature of 26°F is sufficiently low for permafrost occurrence, but other factors such as thermal conductivity of the earth, freezing and thawing indices, and lakes (depth) are extremely important to the delicate thermal balance existing in the Arctic regions.

2. Data indicates that the decrease in rock conductivity depends first upon the purity of the infilling water (the greater the salinity, the less the effect of freezing upon the conductivity), and second upon the grain size, degree of saturation, and the rock material. Details of conduction mechanisms in frozen earth are not well known at the present time, but the usual effect in freezing is to decrease the conductivity by a factor of 30 to 100.

3. Indications from laboratory measurements on samples are that the approximation $\omega\epsilon < \sigma/10$ is valid for permafrost regions at VLF. The behavior of the dielectric constant with temperature and frequency indicates that at frequencies below a few hundred cycles/second, this approximation may not be valid in permafrost, but that it is quite reasonable at VLF.

APPENDIX C

EQUIPMENT SPECIFICATIONS AND CONDUCTIVITY MEASUREMENTS

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APPENDIX C

EQUIPMENT SPECIFICATIONS AND CONDUCTIVITY MEASUREMENTS

1.0 Introduction

Early in the program it was determined that there was a definite lack of information on the electrical properties of permafrost regions, and regions of lateritic type soils with humid and subhumid climates. The lower conductivities expected in both of these types of regions make these areas particularly important in phase velocity studies.

This Appendix will discuss conductivity soundings which were taken in the permafrost region of the Canadian Shield, and in the Gulf Coast region, near Houston, Texas and Pensacola, Florida to aid in making conductivity estimates for these areas. Specifications for the equipment which was designed, developed, and fabricated by DECO to accomplish these measurements are also included.

2.0 Equipment Specifications

1. General features

- (a) Battery operated, hand portable, all solid-state circuitry.
- (b) Usable with any four-probe method of conductivity measurement.
- (c) Frequencies available are: 9 c/s, 90 c/s, and 900 c/s. Provision is made for 9 kc/s frequency if such modification is required.

2. Transmitter

- (a) Frequency stability: ± 0.02 percent
- (b) Voltage ranges: 50, 60, or 120.
- (c) Maximum current capacity: 1 ampere,
- (d) Solid-state current commutation.
- (e) Current control and regulation (1 %) can be selected if desired, and is usable over the entire current and voltage range.
- (f) External power source connection is provided.
- (g) Micrologic elements used in frequency divider for maximum efficiency.
- (h) All batteries can be checked while unit is in operation (using built in circuits).
- (i) Current meter ranges (full scale) are 100 ma, 300 ma, and 1 ampere.

3. Receiver

- (a) Narrow-band, (constant-Q) tuning provides a bandwidth of 0.7 c/s at 9 c/s.
- (b) Noise at 9 c/s is 10 μ v rms or less referred to the input. Noise at all other frequencies is 10 db or more below 10 μ v.
- (c) Attenuation is calibrated directly to read full-scale meter ranges, and is encapsulated for reliability for ruggedness.
- (d) Stability with temperature is excellent: 1 db or less change in amplitude calibration from room temperature values to 15° F and to +140° F, (environmental chamber tests).

3.0 Canadian Conductivity Measurements

Four-terminal array conductivity measurements were made in the permafrost region of the Canadian Shield using electric and dipole arrays (see

Appendix A for array descriptions). Transportation in Northern Canada was provided by a Canadian Beaver aircraft equipped with floats, and locations for measurements were selected so as to provide as much as possible a representative sampling of the region. Because of limitations in funding and time, it was possible to make only a limited survey at each location.

Figure C-1 shows the locations at which measurements were made. Table C-1, which presents "skin-depth" interpretations of the measurements, includes accurate latitude and longitude data for the locations. Figure C-2 shows the apparent conductivity versus depth for some locations.

Some comments are in order regarding the field data and the interpretations. It was not possible to interpret the apparent conductivity curves by assuming a horizontal layering, and using the curve matching technique as described in Appendix A. There are two reasons for this:

- 1) The extreme contrast in conductivity between the surface unfrozen layer, (the active layer), and the second permafrost layer (described in more detail in Appendix B) makes it impossible to determine the ratio of the two conductivities using the standard non-dimensional $\frac{\sigma_1}{\sigma_2}$ curves.
- 2) Equipment limitations did not allow soundings to depths enough greater than the lower limit of the permafrost to allow interpretation on the basis of this second-third layer contrast.

An alternate method of interpretation, which may be applied in instances in which the first layer skin-depth is negligible compared to the dominating second layer, is to interpret the effective conductivity as the apparent conductivity at a depth corresponding to one skin-depth at the frequency of interest.

Scatter in the apparent conductivity data is expected as indicated in the discussion on permafrost characteristics and occurrence. A more extensive survey at each of the locations would have been desirable since detailed geologic maps are not generally available for the Canadian Shield region. The region, in general, is covered by recent glacial deposits which not only contribute to the scatter of the deeper electrical soundings, but also complicate attempts at mapping the underlying geology.

Table C-1 Effective conductivity values for the Canadian Shield area.

Location (See Figure C-)		(Near Surface) Conductivity (mho/m)		Effective 10 kc/s Conductivity (mho/m)
		N. Lat.	W. Lon.	
C-1	Near Downer Lake	60° 33'	96° 55'	1×10^{-3}
C-2	Culliton Lake	61° 19'	98° 29'	1.5×10^{-3}
C-3	Ferguson Lake	62°	96° 58'	4.0×10^{-4}
C-4	Baker Lake	64°	96° 5'	1.7×10^{-2}
C-5	Near Pelley Lake	66°	101° 21'	4.3×10^{-4}
C-6	Near Bathurst Inlet	66°	108° 51'	5.0×10^{-3}
C-7		64°	108° 41'	2.1×10^{-4}
C-8	Near Eileen Lake	62°	107° 32'	1.6×10^{-3}
C-9	Near Ennadai Lake	60°	100° 3'	5.0×10^{-4}
C-10	Near Lynn Lake			8.0×10^{-3}
Average values			3.6×10^{-3}	$3.7 \times 10^{-4} *$

* Special note: A weighted average which de-emphasizes the measurements near Downer and Culliton Lakes places this value near 1×10^{-4} mho/m.

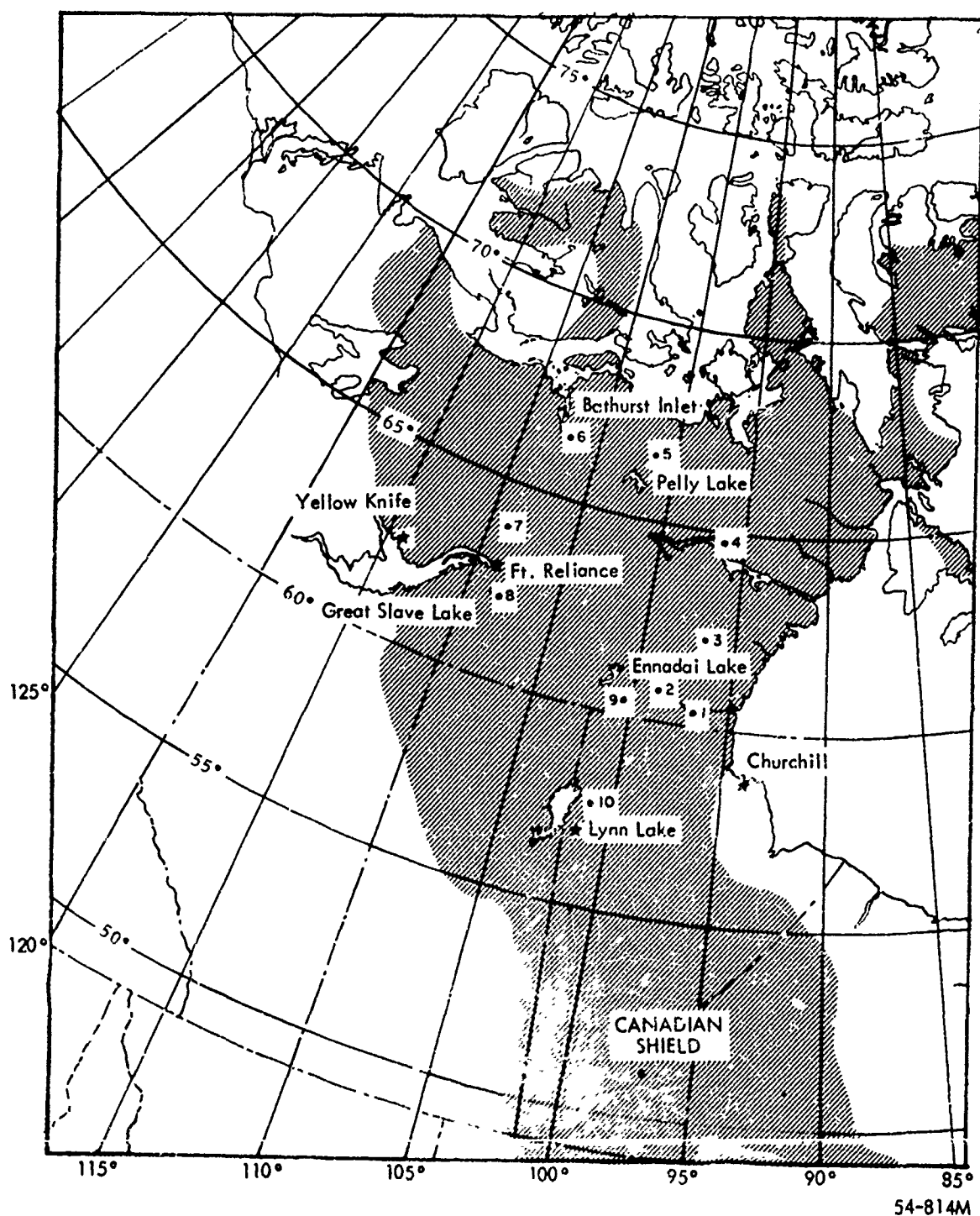


Figure C-1 Measurement Locations on the Canadian Shield

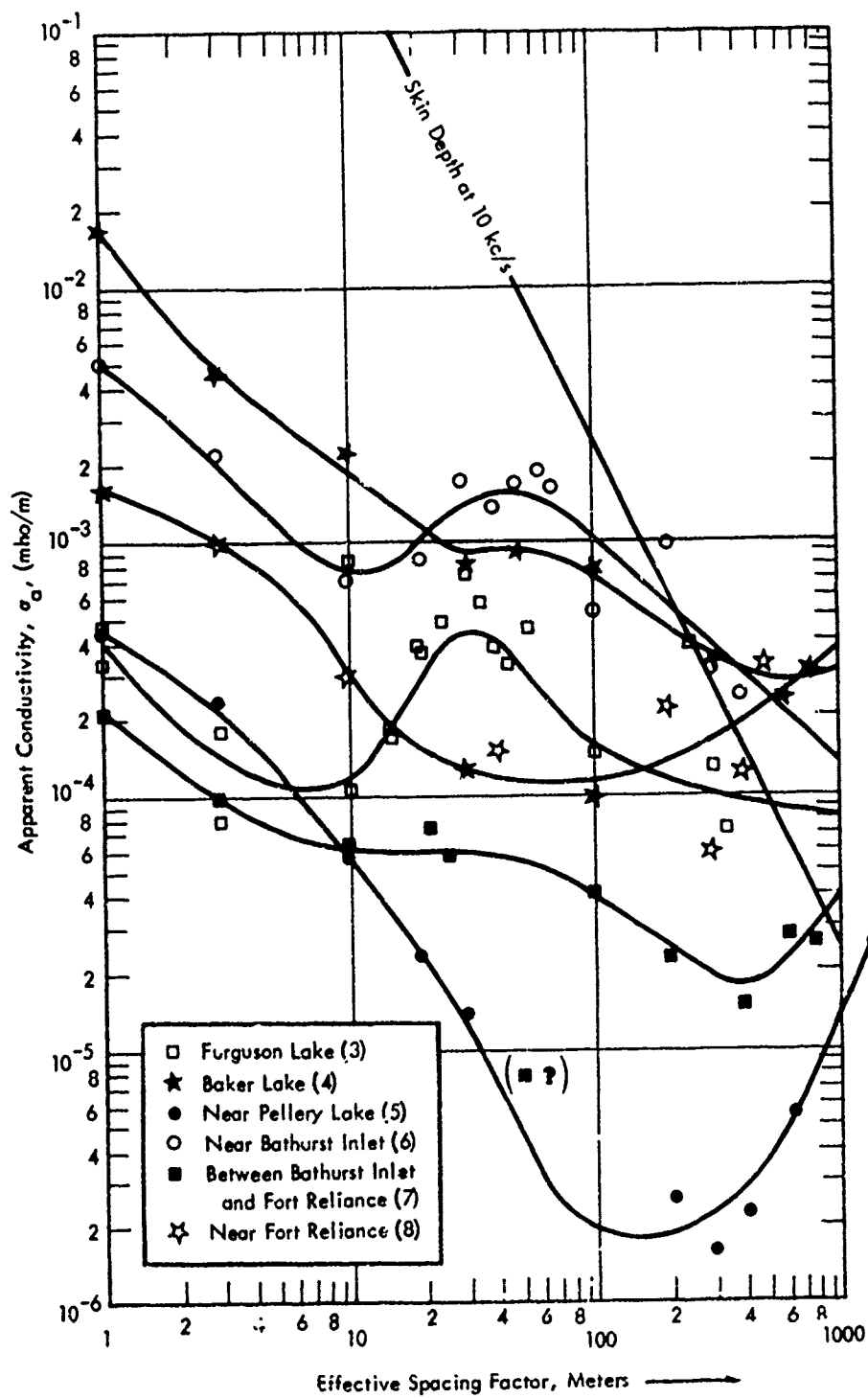


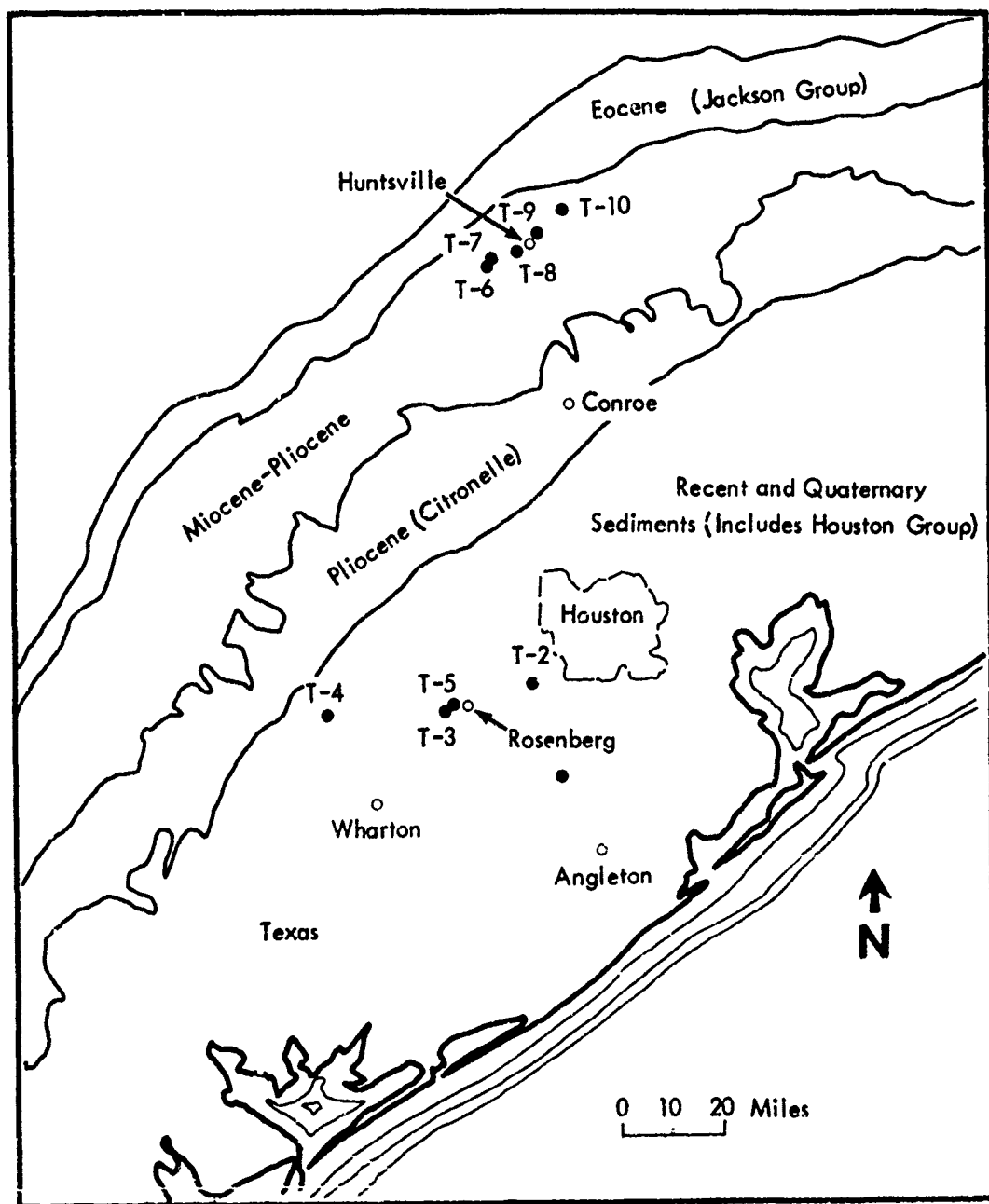
Figure C-2 Apparent Conductivity vs. Effective Spacing Factor for Canadian Shield Area (Representative Sampling)

Interpretations of the Canadian Shield permafrost conductivities on a regional basis indicate that the 10 kc/s effective conductivity ranges from a low of 8.5×10^{-6} mho/m to a high of 1.5×10^{-3} mho/m. The value chosen on the basis of measurements alone would be approximately 1×10^{-4} mho/m. Estimates based on the correlation of conductivity with lithology, and on regional permafrost conditions are likewise 1×10^{-4} mho/m for the shield region south of the Arctic Circle. It would be difficult to place confidence in this value if it were not for the mass of supporting evidence in Appendix B. An extensive measurement program would, of course, be highly desirable to provide additional experimental data for this geologically complex region.

4.0 Gulf-Coast Conductivity Measurements

Measurements in the Gulf-Coast region were made near Houston, Texas and near Pensacola, Florida. Eltran and in-line dipole arrays were used at locations indicated in Figures C-3 and C-5. Some of the apparent conductivity curves are presented for each in Figures C-4 and C-6. The effective conductivity interpretations for 10 kc/s frequency are summarized in Table C-2.

Measurements in Texas show two distinctly different electrical sections. One area, 35 to 80 miles from the coast (locations 1-T, 3-T, 4-T, and 5-T) has a surface conductivity of 2×10^{-2} mho/m to 8×10^{-1} mho/m. The apparent conductivity curves for this area are similar in shape, and increase to maximum values of between 7×10^{-2} mho/m and slightly over 1×10^{-1} mho/m at two to three meter effective spacings. These curves all show a definite decrease in conductivity beyond this spacing until the effective conductivities at a 10 kc/s skin depth range from 6.8×10^{-3} mho/m to 4×10^{-2} mho/m. A second area which is farther inland (about 110 miles) has a much greater variation in surface conductivity values ranging from 4.5×10^{-4} mho/m to 6.8×10^{-3} mho/m (locations 7-T, 8-T, 9-T, and 10-T). The apparent conductivity values in this area show a very steep positive slope which continues beyond the 10 kc/s skin depth. The 10 kc/s apparent conductivities range from 2.7×10^{-2} mho/m to 1.4×10^{-1} mho/m.



54-816M

Figure C-3 Locations of Four-Terminal Array Conductivity Soundings Taken Near Houston, Texas

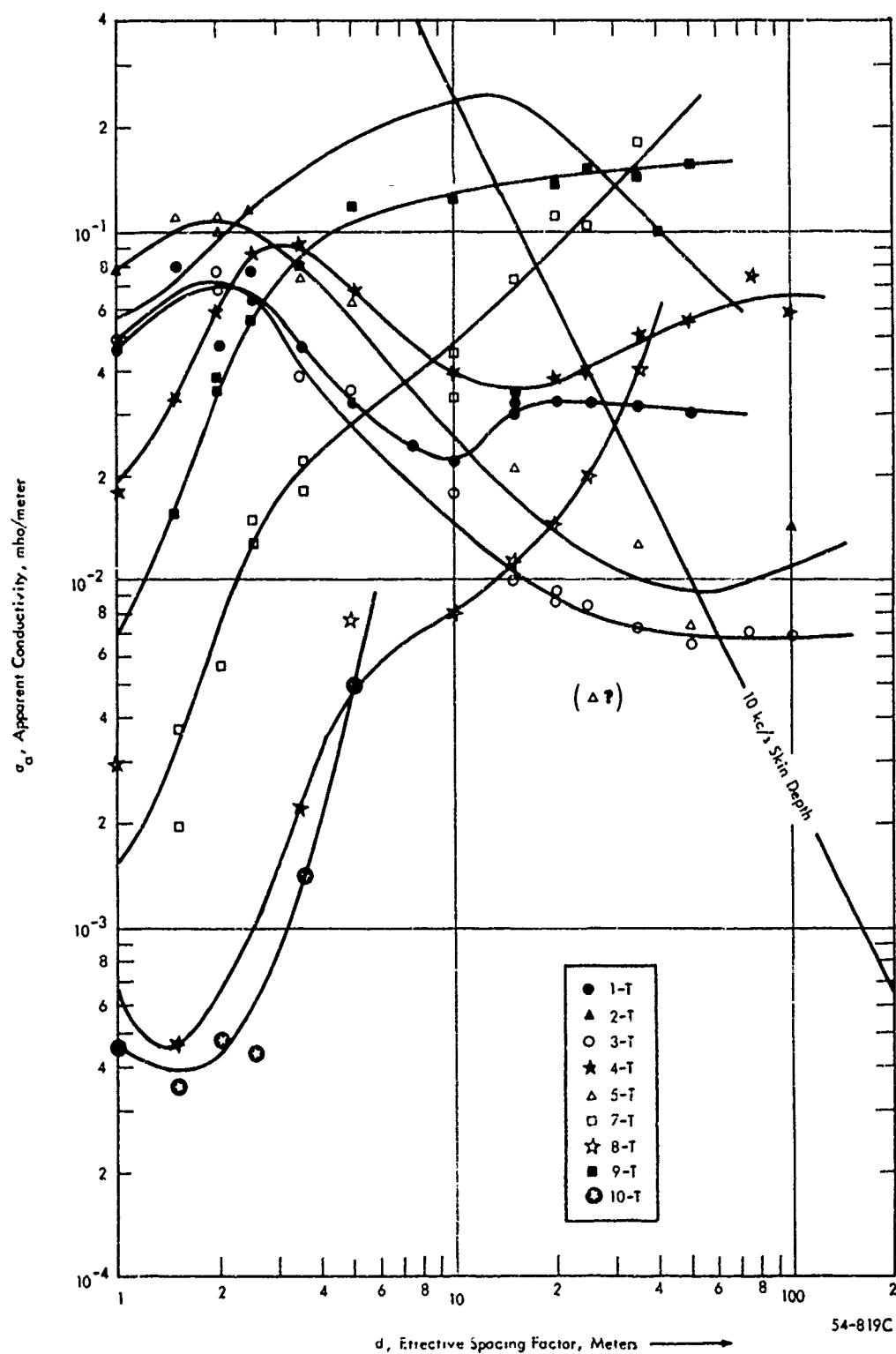


Figure C-4 Apparent Conductivity vs. Effective Spacing Factor Curves For Houston, Texas Area.

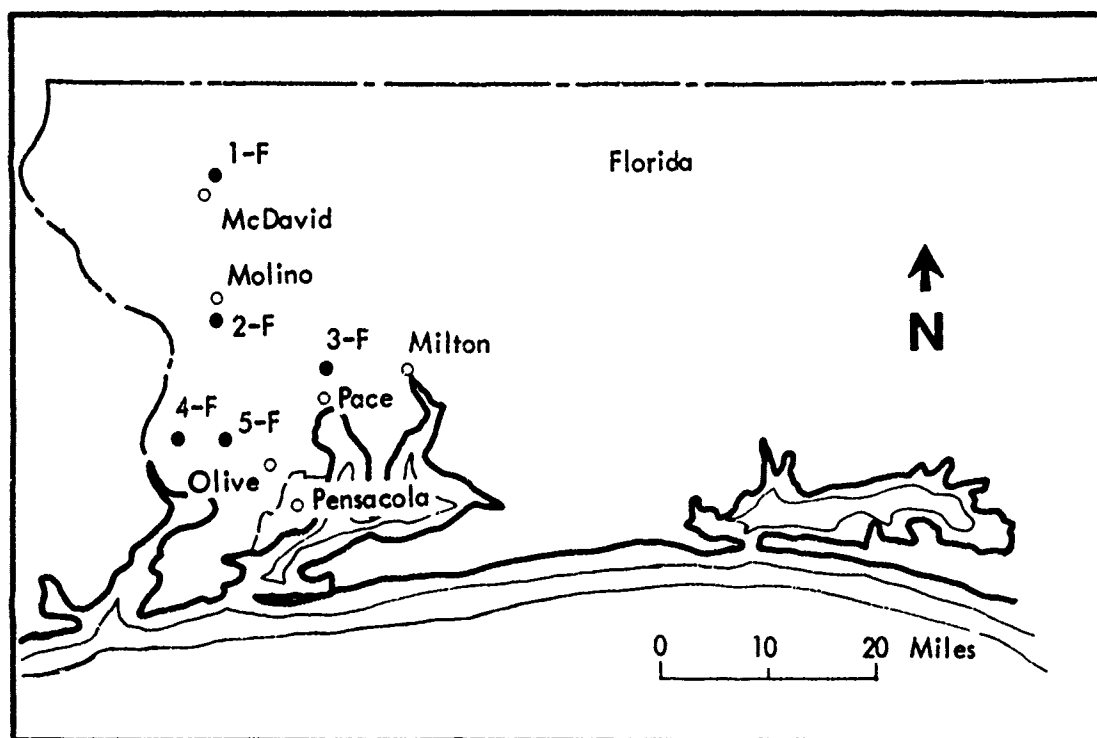


Figure C-5 Locations of Four-Terminal Array Soundings
Taken Near Pensacola, Florida.

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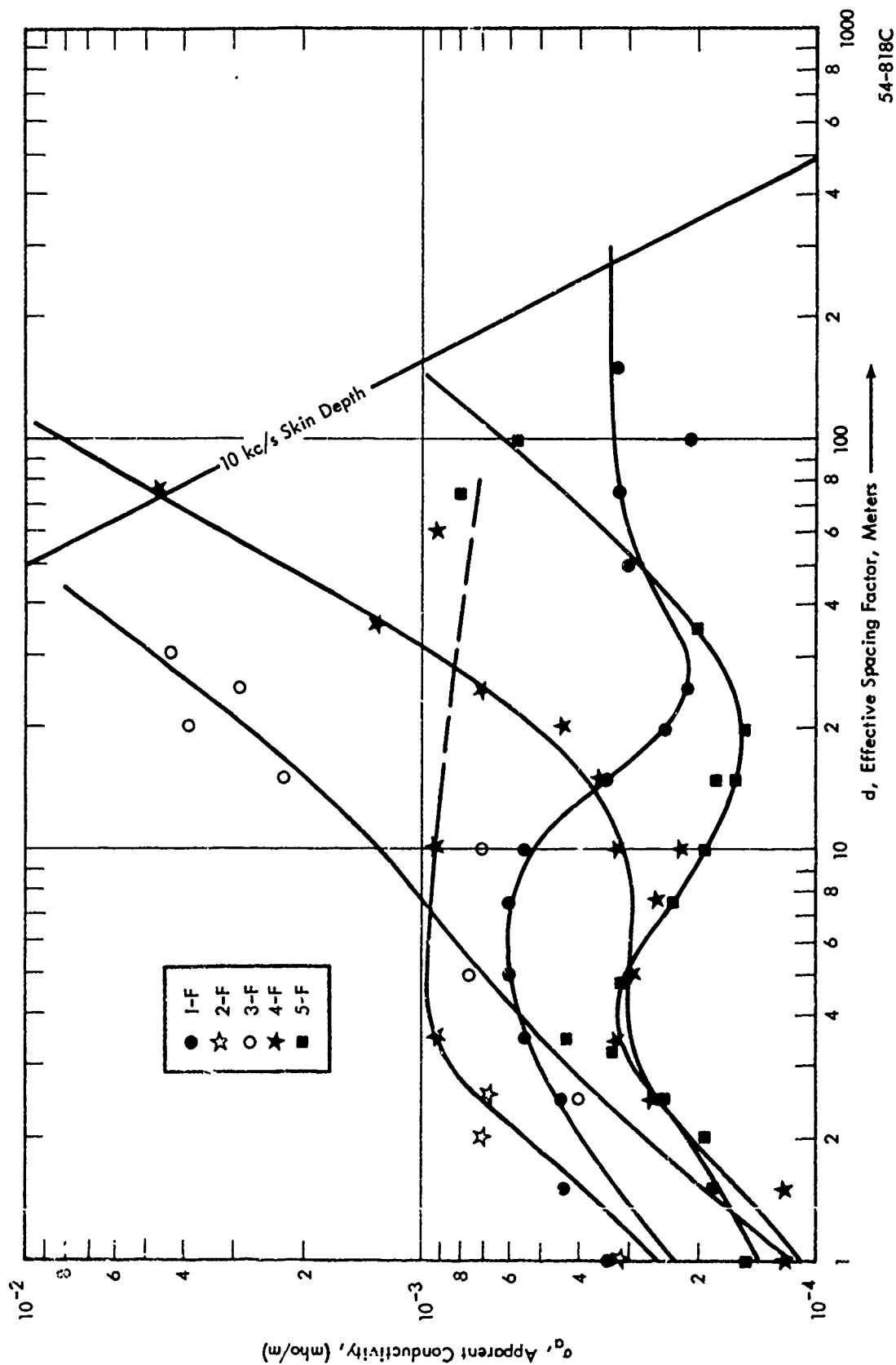


Figure C-6 Apparent Conductivity vs. Effective Spacing Factor
Curves for Pensacola, Florida Area.

Table C-2 (a) Effective 10 kc/s conductivities for the Houston, Texas area.

<u>Location</u> (refer to Figure C-3)	<u>Surface Conductivity</u> (mho/m)	<u>Effective (area)</u> 10 kc/s conductivity (mho/m)
1-T	4.6×10^{-2}	} 2×10^{-2} (measurement at 2-T not included, $\sigma_e \cong 2 \times 10^{-1}$ at 2-T).
2-T	5.6×10^{-2}	
3-T	4.8×10^{-2}	
4-T	1.8×10^{-2}	
5-T	7.7×10^{-2}	
6-T	Unable to obtain sufficient "source current", surface σ very high.	
7-T	approx. 1.5×10^{-3}	} 7×10^{-2}
8-T	approx. 7×10^{-4}	
9-T	6.7×10^{-3}	
10-T	4.5×10^{-4}	

Table C-2 (b) Effective 10 kc/s conductivities for the Pensacola, Florida area.

<u>Location</u> (refer to Figure C-6)	<u>Surface Conductivity</u> (mho/m)	<u>Effective (area)</u> 10 kc/s conductivity (mho/m)
1-F	2.3×10^{-4}	$\left. \begin{array}{l} 5 \times 10^{-4} \\ \\ \\ 3 \times 10^{-3} \end{array} \right\}$
2-F	2.4×10^{-4}	
3-F	1.2×10^{-4}	
4-F	1.1×10^{-4}	
5-F	1.4×10^{-4}	

The two types of electrical sections described above indicate that there has not been an extensive leaching of conducting ions in either area. The region further inland, on the earlier sediments, shows leaching in the first few meters of surface material. The shape of the apparent conductivity curves indicates that the surface conducting ions may have been transferred to the earth material immediately underlying this shallow surface layer. A regional evaluation of these data indicates that the "leaching effect" (described more fully in the text) is not a significant factor, and that the average effective conductivity at 10 kc/s is 2×10^{-2} mho/m, with local variations in this effective value of $\pm$ less than one decade.

The apparent conductivity curves for the Pensacola, Florida area show a low near surface conductivity of 1×10^{-4} to 3×10^{-4} . This surprisingly low conductivity layer is underlain by higher conductivity material as indicated by the steep positive slopes of the σ_a curves at effective spacings to depths of four or five meters (Figure C-6).

The data is scattered at greater depths, but there is a marked similarity between the conditions at locations 3-F, 4-F, and 5-F in that there appears to be an intermediate layer of low conductivity of varying thickness which causes a "dip" in the curves: this is most pronounced at 5-F, and almost of negligible significance at the 3-F location. These three locations are located within about 15 miles of the coast, as shown on Figure C-4. The effective conductivities for 10 kc/s frequency in this area range between 10^{-3} mho/m and 10^{-2} mho/m. The two locations farther inland have apparent conductivities of 3×10^{-4} mho/m for location 1-F, and 7×10^{-4} mho/m (estimated) at 2-F for a 10 kc/s skin depth. The flat portions of the apparent conductivity curves at the larger effective spacings indicate an electrically uniform condition at the 10 kc/s skin depth (for location 1-F, Figure C-6).

Soils of this region are lateritic type, and the unusually low surface conductivities (of less than 10^{-3} mho/m) are caused by considerable leaching of the conducting ions by downward percolating meteoric waters. This is

characteristic of areas which have had a humid tropical and subtropical type climate.

Regional interpretations reflect the fact that considerable leaching has taken place in the surface and near surface materials particularly at more than 15 miles from the coast. (The region very near the salt water may be "seeded" by salt spray, and so the leaching action may not be indicated by conductivity values.) Although more measurements are needed to confirm the results, the regional value of effective conductivity is interpreted to be on the order of 3×10^{-3} mho/m at 10 kc/s. Variability is estimated at $\pm$ less than one decade; more data may show that this is too low, however.

There are two unconfirmed reasons why the leaching in the Western region of the Gulf-Coast may be of negligible consequence compared to that in the Eastern region. One may be a difference in rainfall over a considerable time (thousands of years), and the other a difference in lithology because of the depositional environment, source areas, and climate, which may make the recent sediments in the Eastern region more susceptible to leaching than those of the Western Gulf-Coast.

APPENDIX D

TABULATION OF DATA: CORRELATION WITH GEOLOGICAL
CLIMATOLOGICAL, PEDOLOGICAL, AND PHYSIOGRAPHICAL INFORMATION

APPENDIX D

TABULATION OF DATA: CORRELATION WITH GEOLOGICAL, CLIMATOLOGICAL, PEDOLOGICAL, AND PHYSIOGRAPHICAL INFORMATION

This appendix will discuss the system which has been devised for tabulating and correlating conductivity data with other related information. For convenience in tabulation and to facilitate the possible extension of the tabulation effort (including the use of a computer to search and correlate the information), a number code has been used to present the following information: rock classification, geologic age of rocks, vegetation, soils, climate, physiography, and conductivity measurement techniques. The inclusion of this additional information in the data tabulation has made it desirable to collect some of this material in the form of maps for convenient reference. Maps for North America showing vegetation, soils, climate, physiography, sedimentary basins, and major structural features (tectonic map) are included in Figures 1 through 6. Tables 1 through 8 present a series of charts used to reduce the geological, climatological, pedological, and physiographical information to a number code. A brief description of this number code follows.

A system to classify rocks based on the method of Travis [1955] was used to reduce any lithologic descriptions (provided in references, or from other sources) to a series of numbers. The system divided rocks into three groups: (1) Igneous rocks, (2) Sedimentary rocks, and (3) Metamorphic rocks. The first digit in the numbering sequence will be 1, 2, or 3, depending upon the rock type.

Igneous rocks are further classified as follows: The second digit appearing in the numbering sequence defines the rock by the kind and amount

of feldspar it contains. The third digit indicates the amount of quartz or other material. The fourth digit indicates the crystalline structure.

Sedimentary rocks are classified as follows: The second digit indicates the composition of the major fraction. The third digit indicates the minor fraction and the fourth digit indicates the texture.

Metamorphic rocks are classified as follows: The second digit indicates the chief minerals, the third digit indicates the texture, and the fourth digit indicates the color.

Refer to Tables 1, 2 and 3 for appropriate rock charts. A similar numbering system (Table 4) is used to identify the geological age of rocks. The first digit denotes the Era, the second digit denotes the Period, and the third digit denotes the Epoch.

Porosity values for various samples were not obtained in the same manner. For an explanation of how any specific porosity value was obtained refer to the applicable reference number.

The two numbers in the Vegetation column refer to the vegetation chart in Table 5. Table 5 gives the vegetation for any particular area and also identifies the area on an accompanying map.

Table 6 provides a numbering system to identify the soils of an area. Two numbers in the soils column of the correlation chart represent the first and second digits on the soils chart.

Table 7 describes the climate of any area found on the correlation chart. The two digits in the climate column identify the climate of the area from the climate chart. The table also gives map designations for an accompanying climatological map.

Physiographic provinces are defined by only one number in Table 8.

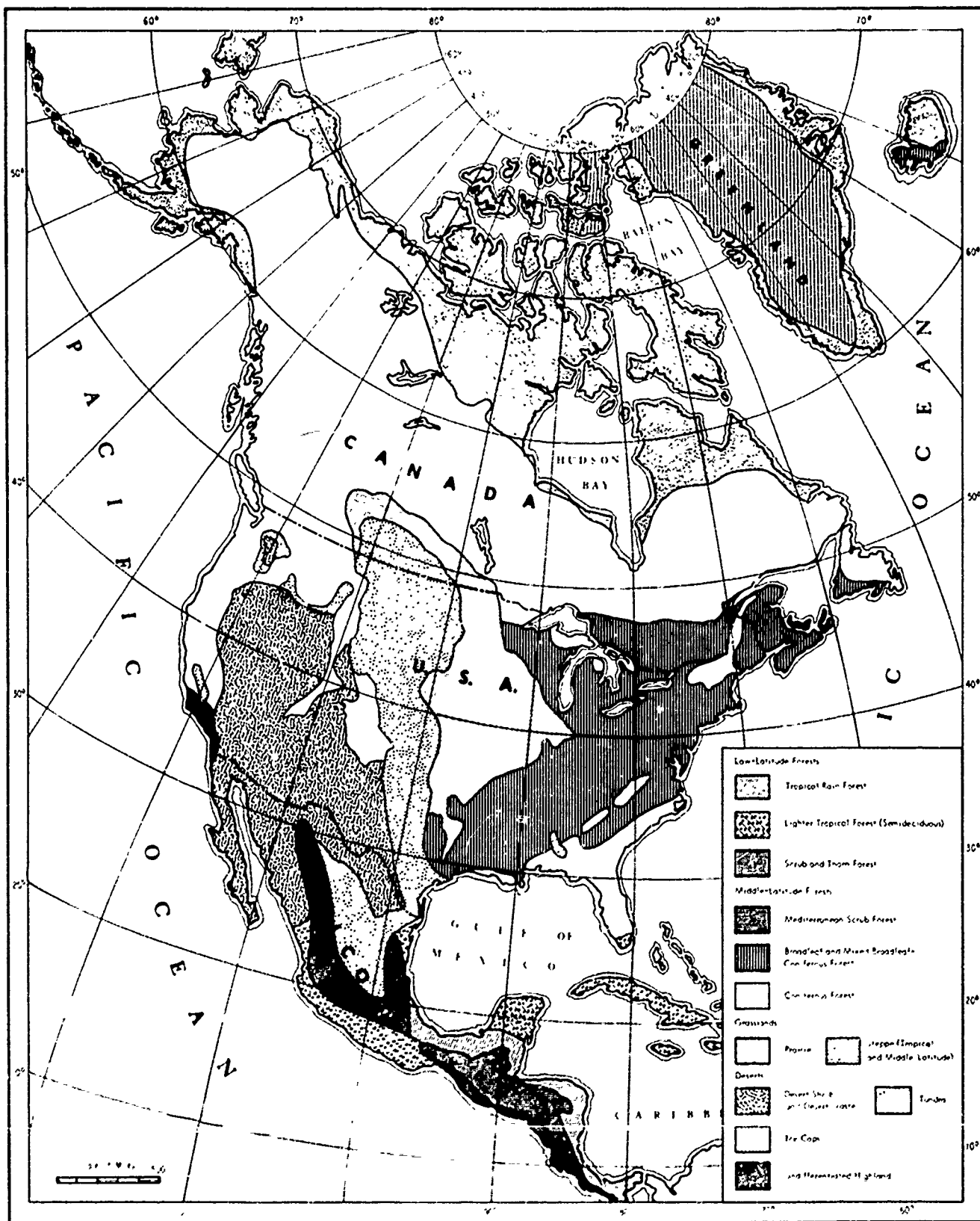


Figure 1. Major Vegetation Types

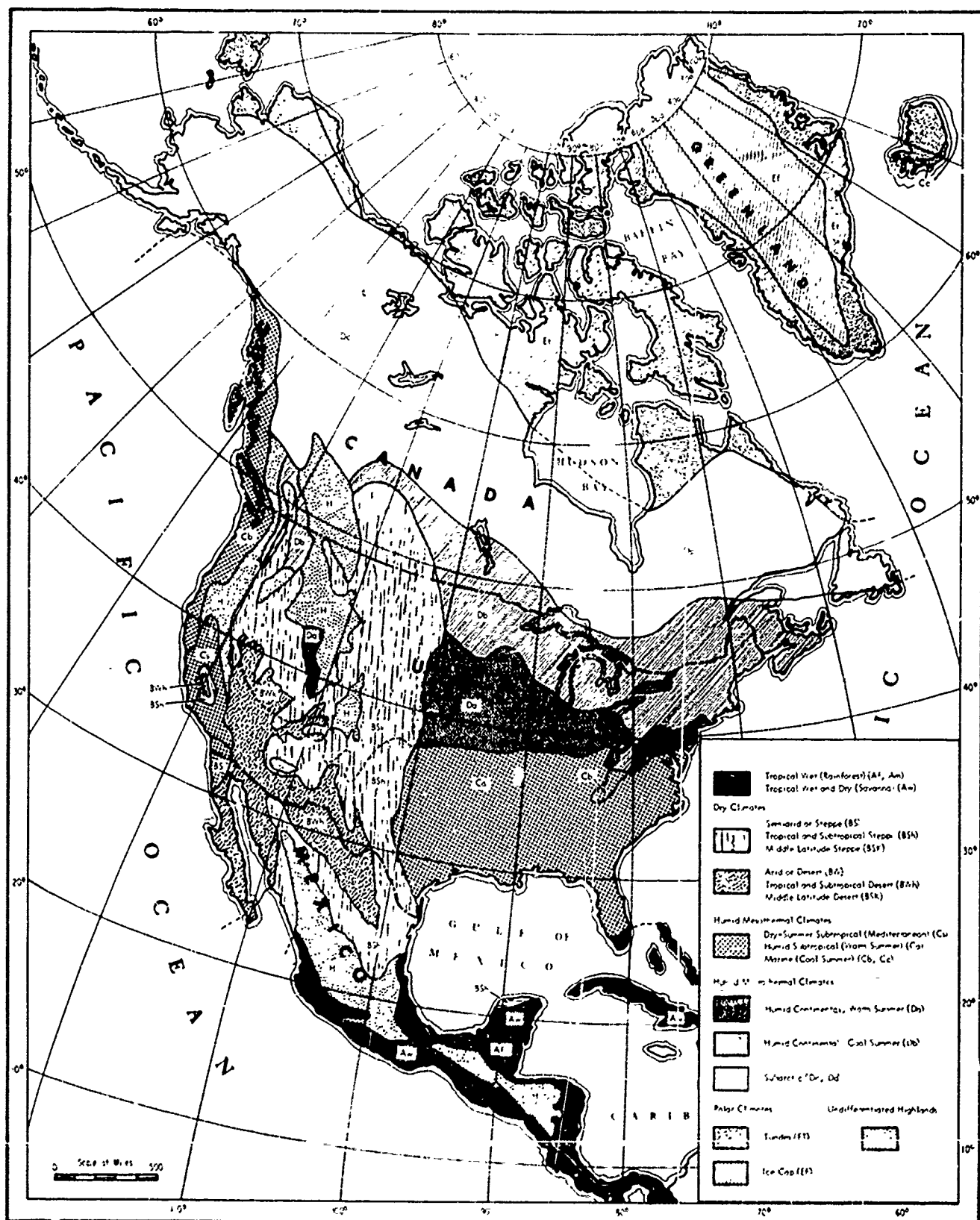
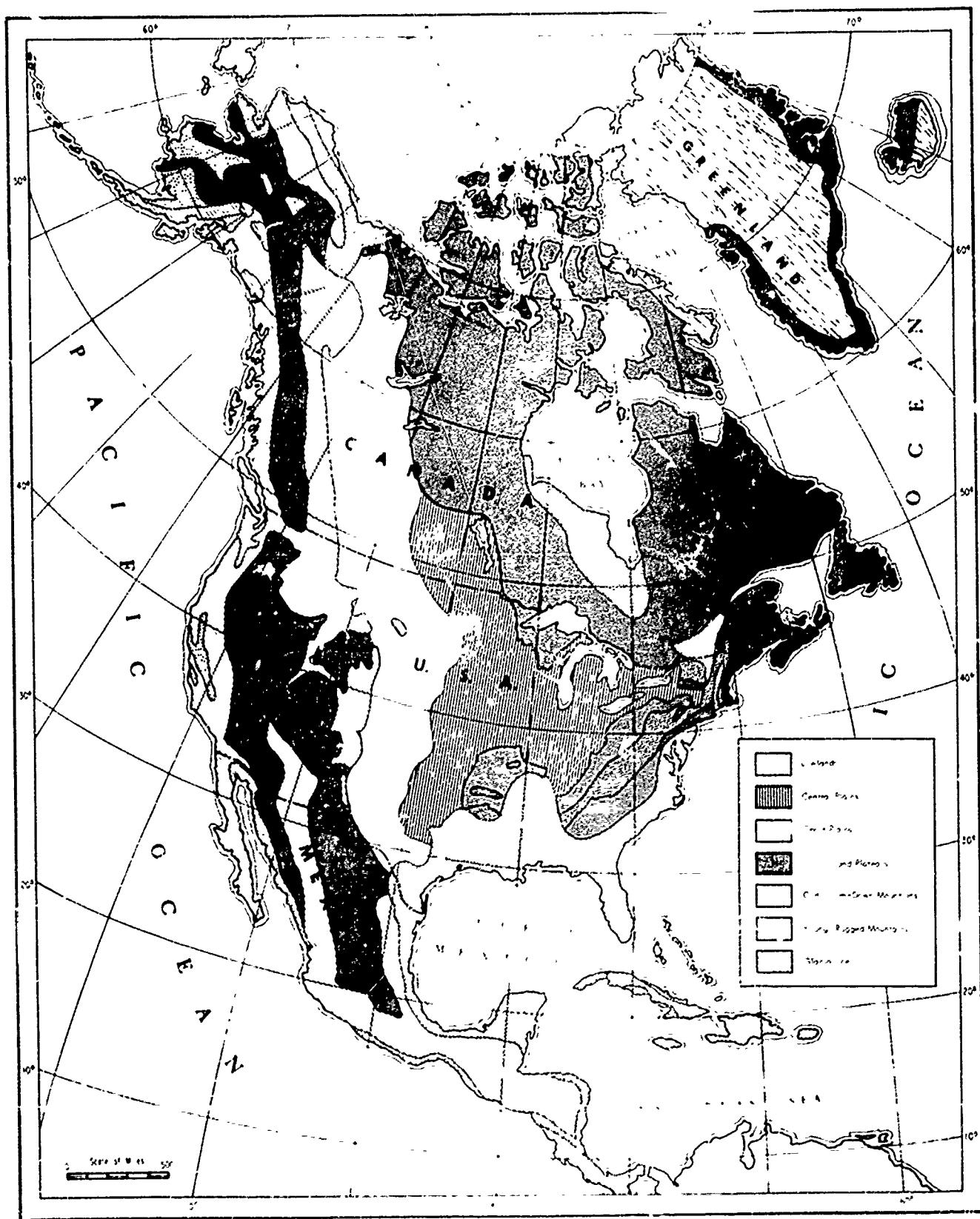
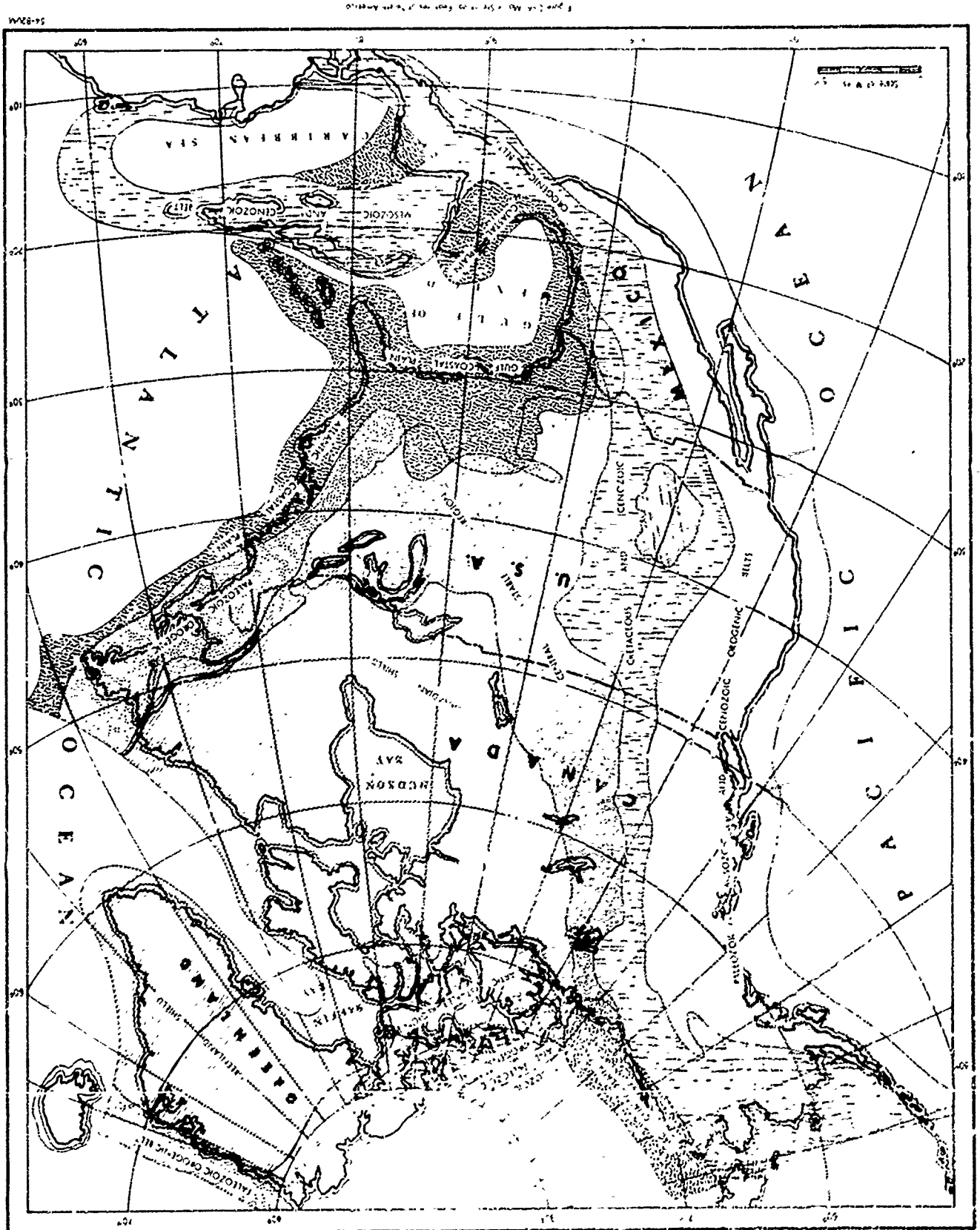
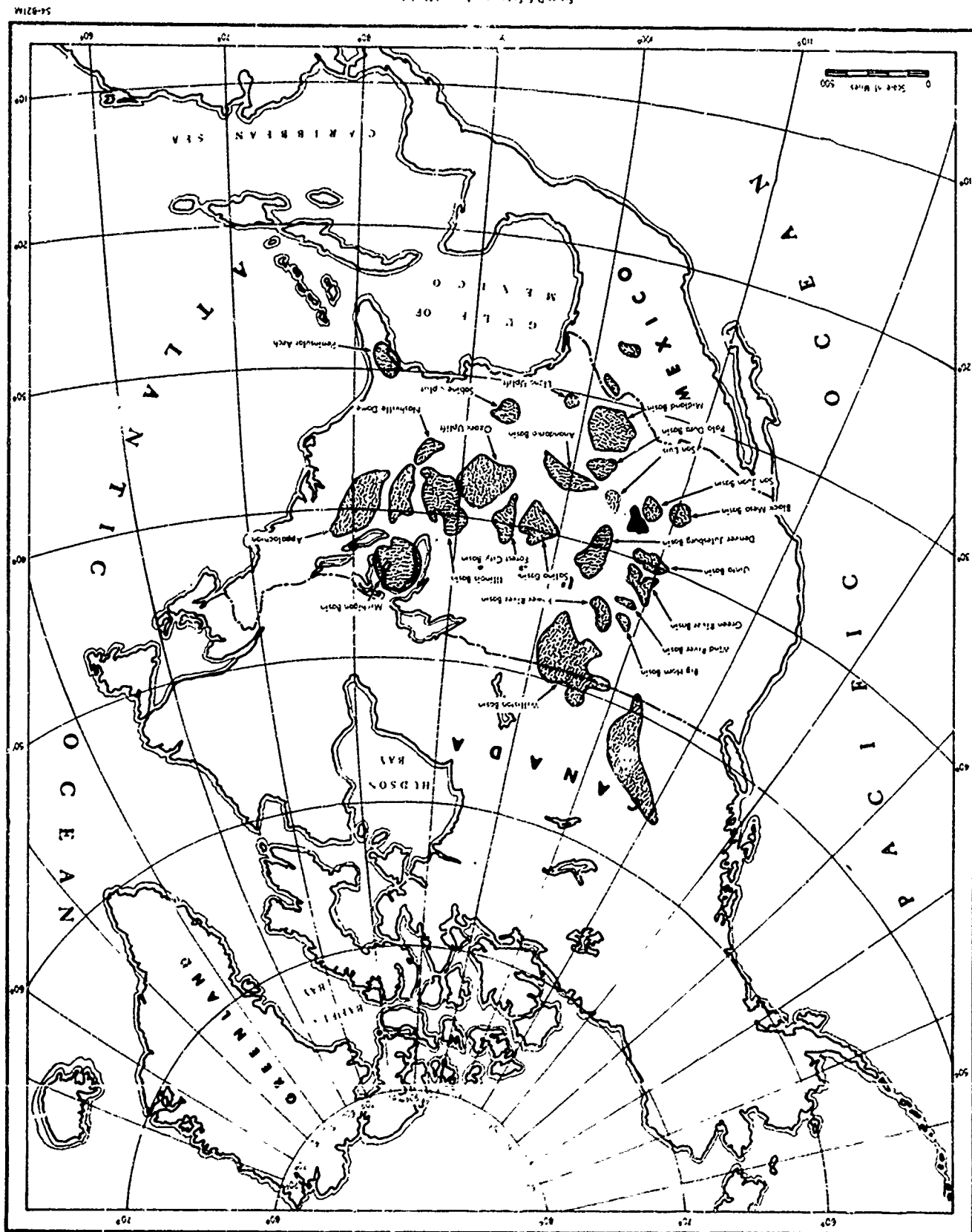


Fig. 10. Climate of North America.

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COMPOSITION CHART
Number System Based on Rock Charts
1st Digit [1] IGNEOUS ROCK

Table 1

2nd Digit		3rd Digit	4th Digit
1	Potash Feldspar > 2/3 Total Feldspar	1 Quartz 2 Quartz 3 Feldspathoid 4 Quartz 5 Quartz 6 Feldspathoid 7 Potash Feldspar 8 Quartz 9 Quartz 10 Quartz 11 Feldspathoid 12 Pyroxene 13 Chiefly Pyroxene and/or Olivine 14 Chiefly Ferro-Magnesian Minerals and Feldspathoids	1 Equigranular 2 Phaneritic Groundmass 3 Aphanitic Groundmass 4 Microcrystalline 5 Glassy
2	Potash Feldspar 1/3-2/3 Total Feldspar		
3	Plagioclase Feldspar > 2/3 Total Feldspar		
4	Plagioclase Feldspar > 2/3 Total Feldspar Potash Feldspar < 10% Total Feldspar (Sodic Plagioclase)		
5	Plagioclase Feldspar > 2/3 Total Feldspar Potash Feldspar < 10% Total Feldspar (Calcic Plagioclase)		
6	Little or no Feldspar		
7	Special Types		

COMPOSITION CHART

Number System Based on Rock Charts

1st Digit [2] SEDIMENTARY ROCK

Table 2

2nd Digit	3rd Digit	4th Digit
0 Soil	1 <10% Minor Fraction	1 Crystalline, Clastic, or Amorphous
1 Composition as indicated in 3rd digit column.	2 Clay Minerals or Clay-Size Materials	2 Crystalline, Clastic, Bioclastic, Oolitic, etc.
2 Clay Minerals or Clay-Size Material	3 Silica-Opal, Chalcedony, Quartz	3 Clastic-unconsolidated-silt, sand
3 Composition as indicated in 3rd digit column.	4 Calcite or Dolomite	23 Silt 1/256-1/16 mm.
4 Chiefly Calcite or Dolomite	5 Iron Minerals - Chiefly: Limonite, Goethite, Hematite, Siderite, Chamosite	24 Very fine sand 1/16-1/8 mm.
5 Chiefly Quartz >90% Quartz	6 Carbon-Humus-Yields carbonaceous derivatives	25 Fine sand 1/8-1/4 mm.
6 Chiefly Quartz Feldspar 10-25%	Sapropel-Yields bituminous derivatives	26 Medium sand 1/4-1/2 mm.
7 Chiefly Quartz Rock Chips >10%	7 Miscellaneous-Phosphate (Cellophane) Evaporites: Halite and Sylvite	27 Coarse sand 1/2-1 mm.
8 Quartz and >25% Feldspar	Anhydrite, Gypsum	28 Very coarse sand 1-2 mm
9 Quartz, Feldspar, Rock Chips, Pelitic Matrix, Angular grains, Tough		4 Clastic-consolidated-siltstone, sandstone
10 Volcanic Ejecta		29 Siltstone
		30 Very fine sandstone
		31 Fine sandstone
		32 Medium sandstone
		33 Coarse sandstone
		34 Very coarse sandstone
11 Chiefly One Constituent-Especially Quartz, Chert, Orgartzite. Also shale or limestone. Homogeneous conglomerates and breccias		5 Clastic-unconsolidated-gravel(rounded)
12 Several Constituents-Usually including unstable constituents. Mixed conglomerates and breccias		35 Granule gravel 2-4 mm.
		36 Pebble gravel 4-64 mm.
		37 Cobble gravel 64-256 mm.
		38 Boulder gravel >256 mm.
		39 Gravel rubble
		40 Pebble rubble
		41 Cobble rubble
		42 Boulder rubble
		6 Clastic-consolidated-conglomerate(rounded) breccia(angular)

COMPOSITION CHART
Number System Based on Rock Charts
1st Digit [3] METAMORPHIC ROCK

Table 3

2nd Digit	3rd Digit	4th Digit
1 Chief Minerals 2 Characterizing Accessory Minerals 3 Nondirectional Structure Massive or Granulose 4 Directional Structure (Lineate or Foliate) Mechanical Metamorphism 5 Directional Structure (Lineate or Foliate) Regional Metamorphism 6 Directional Structure (Lineate or Foliate) Plutonic Metamorphism	1* 2* 3 Fine Grained (Aphanitic) 4 Medium or Coarse Grained (Phaneritic) 5 Cataclastic 6 Slaty 7 Phyllitic 8 Schistose 9 Gneissose 10 Migmatic	1 Light color 2 Intermediate color (includes red or brown) 3 Dark color (includes green)
1* Chief Minerals: 1. Quartz 2. Feldspar 3. Calcite 4. Dolomite 5. Talc 6. Muscovite 7. Sericite	2* Characterizing Accessory Minerals: 1. Anorthite 2. Sericite 3. Sillimanite 4. Kyanite 5. Cordierite 6. Tremolite 7. Wollastonite 8. Albite 9. Andalusite 10. Garnet 11. Phlogopite 12. Diopside 13. Enstatite 14. Staurolite 15. Glaucophane 16. Anthophyllite 17. Pyrophyllite 18. Chloritoid 19. Actinolite 20. Tourmaline 21. Epidote 22. Chiasolite 23. Olivine 24. Serpentine 25. Chlorite 26. Biotite 27. Graphite 28. Chondrodite 29. Scapolite	

AGE CHART
Number System Based on Age Chart

Table 4

1st Digit	2nd Digit	3rd Digit
1 Cenozoic	1 Quaternary	1 Recent
	2 Tertiary	2 Pleistocene
		1 Pliocene
		2 Miocene
		3 Oligocene
		4 Eocene
		5 Paleocene
2 Mesozoic	1 Cretaceous	
	2 Jurassic	
	3 Triassic	
3 Paleozoic	1 Permian	
	2 Carboniferous	
		1 Pennsylvanian
		2 Mississippian
	3 Devonian	
	4 Silurian	1 Silurian
		2 Ordovician
	5 Cambrian	
4 Precambrian	1 (Algonkian) Proterozoic	1 Keewonawan
	2 Archean	2 Huronian

VEGETATION CHART
Number System Based on Vegetation Chart

Table 5

1st Digit		2nd Digit	Map Designation
1	Low Latitude Forests	1 Tropical Rain Forest 2 Lighter Tropical Forest (Semideciduous) 3 Scrub and Thorn Forest	A1 A2 A3
2	Middle Latitude Forest	1 Mediterranean Scrub Forest 2 Broadleaf and Mixed Broadleaf Forest 3 Coniferous Forest	B1 B2 B3
3	Grasslands	1 Savannah 2 Prairie 3 Steppe (Tropical and Middle Latitude)	C1 C2 C3
4	Deserts	1 Desert Shrub and Desert Waste 2 "undra 3 Ice Caps	D1 D2 D3
5	Undifferentiated Highlands		E1

SOILS CHART
Number System Based on Soil Char*

Table 6

1st Digit		2nd Digit
1	Zonal soils	1 Tundra
		2 Podzols (with much bog)
		3 Gray-Brown Polyzolic soils
		4 Prairie soils and Degraded Chernozems
		5 Lateritic soils (Laterites, Terra Rossa, Reddish-Brown-Lateritic, Red Polyzolic soils, etc.)
		6 Chernozems and Reddish-Chestnut soils
		7 Chestnut, Brown, and Reddish-Brown soils
		8 Sierozems, Desert and Red Desert soils
		1 Brown Forest soils (Braunerde)
		1 Alluvial soils
2	Intrazonal soils	2 Soils of the Mountains and Mountain Valleys (Complex)
3	Azonal soils	

CLIMATE CHART
Number System Based on Climate Chart

Table 7

	1st Digit	2nd Digit	Map Designation
1	Tropical Rainy Climates	1 Tropical Wet (Rainforest)	Af, Am
2	Dry Climates	2 Tropical Wet and Dry (Savannah)	Aw
		1 Semi-arid or Steppe	Bs
		2 Tropical and Subtropical Steppe	Bsh
		3 Middle Latitude Steppe	Bsk
		4 Arid or Desert	BW
		5 Tropical and Subtropical Desert	BWh
		6 Middle Latitude Desert	BWk
3	Humid Mesothermal Climates	1 Dry Summer Subtropical (Mediterranean)	Cs
		2 Humid Subtropical (Warm Summer)	Ca
		3 Marine (Cool Summer)	Cb, Cc
4	Humid Microthermal Climates	1 Humid Continental, Warm Summer	Da
		2 Humid Continental, Cool Summer	Db
5	Polar Climates	3 Subarctic	Dc, Dd
		1 Tundra	Et
6	Undifferentiated Highlands	2 Ice Cap	Ef

PHYSIOGRAPHY CHART
Number System Based on Physiography Chart

Table 8

Digit	Physiographic Provinces
1	Lowlands
2	Central Plains
3	Great Plains
4	Uplands and Plateaus
5	Old, Worn-Down Mountains
6	Young, Rugged Mountains
7	Glacial Ice

MISCELLANEOUS CHART

Number System Based on Measurement Technique

Table 9

Digit	Measurement Technique
100	Four Terminal Array (General)
101	Schlumberger (Regular or Modified)
102	Schlumberger (Single-ended), Keller's Modification
110	Wenner Array
115	Magneto-Telluric
120	Dipole (General: polar, equatorial, eltran)
121	In-line Dipole (Polar)
122	Broadside Dipole
125	Dipole-Interpreted for σ_e , (Effective Conductivity from Layered Case)
126	Wave-Tilt Method
130	Soil Sampling
135	Lecher Wire
136	Well Log

				LOCATION			COMPOSITION		AGE						Phys grap
Sample	Section	T.S.	Range	Lat.	Long.	Name				Porosity	Vegetation	Soil	Climate		
1	26, 27	+1	-6	+40	-91	Adams, Ill.	2	13	2	3	2	1	3	1	2
2	26	+1	-6	+40	-91	Adams, Ill.	2	13	2	3	2	1	3	1	2
3	34	+1	-6	+40	-91	Adams, Ill.	2	12	2	3	2	1	3	1	2
4	34	+1	-6	+40	-91	Adams, Ill.	2	13	2	3	2	1	3	1	2
5	26, 27...	+1	-6	+40	-91	Adams, Ill.				3	2	1	3	1	2
6	31	+2	-5	+40	-91	Adams, Ill.	2	12	2	3	2	1	3	1	2
7	21	+2	-7	+40	-92	Adams, Ill.				3	2	2	3	1	2
8	11	+1	-8	+40	-92	Adams, Ill.	2	12	2	3	2	2	3	1	2
9	10, 11...	+5	-3	+39	-89	Bond	2	13	2	3	2	1	3	1	2
10	10, 11...	+5	-3	+39	-89	Bond	2	13	2	3	2	1	3	1	2
11	10, 11...	+5	-3	+39	-89	Bond	2	13		3	2	1	3	1	2
12	22, 23	+5	-3	+39	-89	Bond	2	13	2	3	2	1	3	1	2
13	36	+6	-2	+39	-89	Bond	2	13		3	2	1	3	1	2
14	0	+5	-1	+39	-89	Bond	2	13		3	2	1	3	1	2
15	3, 4	+4	-4	+39	-90	Bond	2	13	2	3	2	1	3	1	2
16	8	+5	-2	+39	-89	Bond	2	12	2	3	2	1	3	1	2
17	31	+7	-4	+39	-90	Bond	2	13		3	2	1	3	1	2
18	8, 17	-1	-3	+40	-91	Brown	2	12	2				3	1	2
19	17, 18	-2	-2	+40	-91	Brown	2	12	2				3	1	2
20	17	-2	-2	+40	-91	Brown	2	12	2				3	1	2
21	33, 34	+16	+7	+41	-90	Bureau	2	12	2	3	2	1	3	1	2
22	27	+17	+11	+41	-89	Bureau	2	12	2	3	2	1	3	1	2
23	27	+17	+11	+41	-89	Bureau	2	13	2	3	2	1	3	1	2
24	24	+16	+11	+41	-89	Bureau	2	13	2	3	2	1	3	1	2
25	24	+16	+11	+41	-89	Bureau	2	13	2	3	2	1	3	1	2
26	10, 15	+13	+6	+41	-90	Bureau	2	12	2	3	2	1	3	1	2
27	36	+16	+11	+41	-89	Bureau				3	2	1	3	1	2
28	19	+16	+7	+41	-90	Bureau				3	2	1	3	1	2
29	34, 35	+16	+11	+41	-89	Bureau	2	13	2	3	2	1	3	1	2
30	34	+16	+11	+41	-89	Bureau	2	13	2	3	2	1	3	1	2
31	34	+16	+11	+41	-89	Bureau	2	13	2	3	2	1	3	1	2
32	8	-12	-2	+39	-91	Calhoun				3	4	2	3	1	2
33	1	13	-2	+39	-91	Calhoun				3			3	1	2
34	6, 7	-13	-1	+39	-91	Calhoun	2	13		3			3	1	2
35	2	-9	-2	+39	-91	Calhoun	2	13		3	2	2	3	1	2
36	11	-9	-2	+39	-91	Calhoun	2	13		3	2	2	3	1	2
37	27, 34	-9	+2	+39	-91	Calhoun	2	13		3			3	1	2
38	6, 7	+25	+5	+42	-90	Carroll	2	13		3	4	2	3	1	2
39				+40	-96	Auburn, Neb.				3	2	1	3	1	2
40				+38	-121	Tracy, Calif.	3						2	3	6
41				+38	-121	Tracy, Calif.	3						2	3	6
42				+38	-121	Tracy, Calif.	2	12	2				2	3	6
43				+38	-121	Tracy, Calif.	2	12	2	1	2	2	2	3	6
44				+38	-121	Tracy, Calif.	2		24/28	1			2	3	6
45				+38	-121	Tracy, Calif.	2		24/28	1		12/21	2	3	6

Sample Page of Conductivity Correlation Chart

Vegetation	Soil	Climate	Physio- graphy	DEPTH		CONDUCTIVITY				MEASUREMENT		
				Top	Bottom	High	Low	Average	Technique	No.	Frequency	Ref.
1	1 6	4 1	2		100			3.3 10^{-2}	100	475+		1
1	1 6	4 1	2		40			3.3 10^{-2}	100	50+		
1	1 6	4 1	2		50			3.3 10^{-2}	100	5		
1	1 6	4 1	2		25			3.3 10^{-2}	100	32		
1	1 6	4 1	2		60			1.0 10^{-1}	100	245		
1	1 6	4 1	2		60			3.3 10^{-2}	100	145+		
1	1 6	4 1	2		40			2.0 10^{-2}	100	15		
1	1 6	4 1	2		100			2.0 10^{-2}	100	108+		
1	1 3	4 1	2		160			2.0 10^{-2}	100	128		
1	1 3	4 1	2		160			2.0 10^{-2}	100			
1	1 3	4 1	2		160			2.0 10^{-2}	100	100		
1	1 3	4 1	2		120			2.0 10^{-2}	100	13		
1	1 3	4 1	2		100			2.0 10^{-2}	100	55		
1	1 3	4 1	2		50			1.4 10^{-2}	100	43		
1	1 4	4 1	2		100			3.3 10^{-2}	100	103		
1	1 4	4 1	2		60			3.3 10^{-2}	100	29		
1	1 4	4 1	2		50			2.0 10^{-2}	100	104		
1	1 6	4 1	2		60			2.0 10^{-2}	100	24		
1	1 6	4 1	2		100			3.3 10^{-2}	100	54		
1	1 6	4 1	2		50			2.0 10^{-2}	100	27		
1	1 6	4 1	2		300			1.4 10^{-2}	100	25		
1	1 4	4 1	2		175			2.0 10^{-2}	100	202		
1	1 4	4 1	2		120			1.4 10^{-2}	100	40		
1	1 4	4 1	2		100			1.2 10^{-2}	100	29		
1	1 4	4 1	2		25			1.4 10^{-2}	100	31		
1	1 6	4 1	2		120			2 10^{-2}	100	253		
1	1 4	4 1	2		100			3.3 10^{-2}	100	40		
1	1 6	4 1	2		200			2.0 10^{-2}	100	26		
1	1 4	4 1	2		70			3.3 10^{-2}	100	178		
1	1 4	4 1	2		100			1.4 10^{-2}	100	83		
1	1 4	4 1	2		30			2.0 10^{-2}	100	295		
1	1 4	4 1	2					1.0 10^{-1}	100	7		
1	1 4	4 1	2					3.3 10^{-2}	100	42		
1	1 4	4 1	2					3.3 10^{-2}	100			
1	1 4	4 1	2					1.2 10^{-2}	100	17		
1	1 4	4 1	2					3.3 10^{-2}	100	15		
1	1 4	4 1	2					3.3 10^{-2}	100	9		
1	1 4	4 1	2		200			3.3 10^{-2}	100	69		
1	1 4	4 1	2		500			5.7 10^{-2}				2
3	3 2	3 1	6		54			4.1 10^{-3}		1		3
3	3 2	3 1	6		121			8.0 10^{-3}		1		3
3	3 2	3 1	6		1050			5.5 10^{-2}		1		3
3	3 2	3 1	6		128	1.6 10^{-1}	3.0 10^{-2}	4.0 10^{-2}		1		3
3	3 2	3 1	6					5.0 10^{-2}		7		3
3	3 2	3 1	6		103			1.4 10^{-1}		1		3

Sample	Section	T.S. Range	LOCATION		COMPOSITION	AGE	Porosity	Vegetation	Soil	Climate	Physio- graphy	T
			Lat.	Long.								
46			+38	-121	Tracy, Calif. 2 0/12 2	1 2 4		2 3	3 2	1 6	6	0
47			+39	-78	Royal Martinsburg, Washington	1 2 1		2 2	1 3	4 1	1	0
48			+19	-78	Royal Martinsburg, 1/3 Washington			2 2	1 3	4 1	1	30
49			+31	-99	Llano, Texas 1 1 1	4		3 2	3 2	3 2	3	1
50			44/45/46	-115	Idaho Batholith 1 1 1	2 1		2 2	1 8	6	6	0
51			+33	-116/117	S. California 1 1 1	2 1		4 1	1 8	2 1	6	0
52			+46	-69	Sour Dnahunh Springs, Maine 2	3 3		2 2	1 2	4 2	4	0
53			+46	-69	Kakadjo Post Office, Maine 1 1 1 1 1	3 4/5		2 2	1 2	4 2	4	0
54			+44	-72/73	North Woodstock, New Hampshire 1 1 1 1 1	3 3/42		2 3	1 2	4 2	5	1
55			+44	-73/74	Barre, Vermont			2 3	1 2	4 2	5	1
56			+44/45	-73/74	Elizabethtown, N. Y. 1	4		2 3	1 2	4 2	5	1
57			+42	-77	Watkins Glen, N. Y. 2	3 3		2 2	1 3	4 2	4	1
58			+41	-78	Philipburg, Pa. 2			2 2	1 3	4 2	5	1
59			+41	-96	Omaha, Nebr. 2			3 1	1 4	4 1	2	1
60			+41	-96	Neb. City, Nebr. 2			3 1	1 4	4 1	2	32
61			+39	-106	S. Park, Como, Hartsel, Colo. 2			2 3	3 2	2 3	4	1
62			+37	-108	Oxford, Colo. 2	1 2		4 1	1 8	2 3	4	1
63			+37	-109	Aneth, Utah 2			4 1	1 8	2 5	4	1
64			+37	-110	Kayenta, Arizona 2	3 1		4 1	1 8	2 5	4	1
65			+36	-111/112	Cameron, Ariz. 2	2 3		4 1	3 2	2 5	4	1
66			+37	-112/113	Kanab, Utah 2			4 1	1 8	2 3	4	1
67			+36	-115	Boulder City, Nev. 2	4		4 1	1 8	2 6	4	1
68			+35	-117	Barstow, Calif. 2			4 1	1 8	2 6	4	1
69			+32	-111	Demetrie Wash, Arizona 1 9 4 1			4 1	1 8	2 5	4	1
70			+33	-110	Safford, Arizona 1 4 9 4 1			1 1	1 8	2 5	4	1
71			+47/48	-122	Gilbreath, Wash. 1 4 8 1 1	1 2 2		2 3	3 2	3 3	6	1
72			+40	-112	Tintic, Utah 2 11/125			4 1	1 8	2 3	4	1
73			+44	-75	Balmat, N. Y. 3 2 4 6			2 2	1 3	4 2	5	1
74			+44	-75	St. Lawrence City Balmat, N. Y. 2 4 4 2 1			2 2	1 3	4 2	5	12
75			+44	-75	St. Lawrence City Balmat, N. Y. 2 4 3 2 1		1	2 2	1 3	4 2	5	25
76			+44	-75	St. Lawrence City Balmat, N. Y. 2 4 4 2 2			2 2	1 3	4 2	5	37
77			+44	-75	St. Lawrence City Balmat, N. Y. 2		1	2 2	1 3	4 2	5	1

Sample Page of Conductivity Correlation Chart

							DEPTH		CONDUCTIVITY				MEASUREMENT		
Vegetation	Soil	Climate	Physio-graphy	Top	Bottom				High	Low	Average	Technique	No.	Frequency	Ref.
2 3	3 2	1 6	6	0	69						5.0 10^{-2}		1		3
2 2	1 3	4 1	1	0	30?						1.0 10^{-2}				4
2 2	1 3	4 1	1	30	23,000				1.0 10^{-4}	1.0 10^{-6}	1.0 10^{-5}				4*
3 2	3 2	3 2	3	0	50K +						1.0 10^{-3}	121	5		5
2 3	1 8	6	6	0	2,800						1.0 10^{-3}	125	9		6
4 1	1 8	2 1	6	0	100K						1.7 10^{-4}	125			7
2 2	1 2	4 2	4	0	1214				1.0 10^{-3}	5.89 10^{-4}	7.41 10^{-4}	100	17		8
2 2	1 2	4 2	4	0	262						1.0 10^{-3}	100	24		8
2 3	1 2	4 2	5	0	164						7.7 10^{-4}	100	20		8
2 3	1 2	4 2	5	0	98						1.43 10^{-3}	101			8
2 3	1 2	4 2	5	0	11,480						2.0 10^{-4}	100			8
2 2	1 3	4 2	4	0	7,876						1.25 10^{-3}	100			8
2 2	1 3	4 2	5	0	22,966				1.18 10^{-2}	1.18 10^{-3}	2.14 10^{-3}	100			8
1 1	1 4	4 1	2	0	492						6.25 10^{-2}	100			8
1 1	1 4	4 1	2	20	4110				1.25 10^{-1}	7.15 10^{-2}	9.1 10^{-2}	100			8
2 3	3 2	2 3	6	0	17,000						1.0 10^{-1}	100			8
4 1	1 8	2 3	4	0	89						3.12 10^{-2}	101			8
4 1	1 8	2 5	4	0	5700						8.0 10^{-2}	100			8
4 1	1 8	2 5	4	0	3100						1.06 10^{-3}	101			8
4 1	3 2	2 5	4	0	984						2.5 10^{-1}	101			8
4 1	1 8	2 3	4	0	1640						5.0 10^{-3}	101			8
4 1	1 8	2 6	4	0	3773						6.06 10^{-2}	101			8
4 1	1 8	2 6	4	0	590						3.0 10^{-1}	101			8
4 1	1 8	2 5	4						1.97 10^{-2}	1.48 10^{-2}	1.70 10^{-2}	115	4		9
4 1	1 8	2 5	4						1.82 10^{-2}	1.61 10^{-2}	1.70 10^{-2}	115	2		9
2 3	3 2	3 3	6						9.53 10^{-4}	8.9 10^{-4}	8.7 10^{-4}	115	5		9
4 1	1 8	2 3	4						7.7 10^{-1}	8.75 10^{-3}	3.89 10^{-3}	115	12		9
2 2	1 3	4 2	5	0	125						1.22 10^{-5}		1		10
2 2	1 3	4 2	5	125	250						0.45 10^{-4}		1		10
2 2	1 3	4 2	5	250	375						0.09 10^{-5}		1		10
2 2	1 3	4 2	5	375	500						1.04 10^{-4}		1		10
2 2	1 3	4 2	5	0	175						2.55 10^{-3}		1		10

			LOCATION		COMPOSITION		AGE					
Sample	Section	T. S. Range	Lat	Long.	Name			Porosity	Vegetation	Soil	Climate	Physio- graphy
91			+ 32	-111	Twin Buttes, Ariz.	1	4	9	4			
104			+ 37	-116	Nye Co., Nevada	1	3	7	1			4
111			+ 30/31	- 87	Elgin AFB, Florida	2		27				4
132			+ 40	-102	Yuma Co., Colo.				1	2		1
140			+ 53	-118	Athabasca Glacier			3/12				3
					Glacial Ice							7
					Alberta, Canada							
172			+ 51	0	Rugby, England	2	0					
228			+ 51	-3	Devon, England	1	1	1	1			
293			+ 30	-104	Alpine, Texas	1	4/5	9/10	4			
42			+ 68	+60	Amderminsk	2	0	5	1/1			4
					Region, USSR							
491			+ 38	-109	Colo. Plateau	2	1	2	1/4			
					Morrison Formation							
496			+ 37	-117	Nev. Test Site	2	12	2	6			
					Nye Co., Nev.							
552			+ 48	+14	Linz, Austria	2		2	3			
565			+ 35	-117	Harper Dry	1	2	4	1			
					Lake, Calif.							
566			+ 40	-122	Red Bluff, Calif.	2		5				
600			+ 36	-110	Northern Arizona	2		4	1			6
623			+ 18	-67	Mayaguez, Puerto Rico	1	6	12	1			4
627			+ 37	16	Nev. Test Site	2	12	2	6			6
					Sedan Site				41			4
638			+ 38	109	Morrison Formation	2/2	1	2	1/3			
					Egnar, Colorado							
641			+ 36	183/84	Jefferson Co.	2	4	1	2			
					Jefferson City, Tenn.							5
647			+ 37	-91	Southeast Missouri	2	4	1	2			
659			+ 37	-116	Oak Spring For.	2	10					4
					mation, Nev. Test Site							
669			+ 35	-117	San Bernardino Co.,	3/2	3/4	3/3	2/2			
					Cal.							4
672			+ 50	-120	Craigmont Mine,	3/1	2/4	2/9	1			
					South Central Brit. Col.							4
675			+ 50	-120	Craigmont Mine	2	9	1	4			
677			+ 50	-120	Craigmont Mine	2	1	2	1			4
684			+ 50	-120	Craigmont Mine	3/1	1/4	1/9	3/1			4
688			+ 47/48	-91/92	Lake Superior Region	1	5	10	1			4
					Minnesota							2
689			+ 47/48	-91/92	Lake Superior Region	2	12	2	6			2
692			+ 47/48	-91/92	Lake Superior Region	2	0	5				2

Representative Page of Conductivity Correlation Chart

					DEPTH		CONDUCTIVITY				MEASUREMENTS		
Vegetation	Soil	Climate	Physio-graphy		Top	Bottom	High	Low	Average	Technique	No.	Frequency	Ref.
4	1	1 8	2 5	4	0	148			2.8 10^{-2}		1		10
4	1	1 8	2 6	4	0	277			1.64 10^{-6}				11
2	3	1 5	3 2	1	164	328			2.5 10^{-4}		15		12
3	2	1 7	2 3	3	0	6,000			4.97 10^{-2}				13
2	3	3 2	6	7	0	30			3.9 10^{-7}	100		10 Kc	15
2	2	1 3	3 3		Surface				3.78 10^{-2}	130		100 Kc	16
2	2	1 3	3 3			>1			2.88 10^{-6}	130		100 Kc	16
4	1	1 8	2 5	4	0	115			2.0 10^{-2}	100	15	10 Kc	17
4	2	1 2							5.0 10^{-2}	130			21
4	1	1 8	2 3	4			2.5 10^{-5}	1.11 10^{-5}	1.58 10^{-5}	130	13	10 Kc	22
4	1	1 6	2 5	4	100	410			1.84 10^{-2}	136			23
2	2	1 3					2.0 10^{-2}	2.0 10^{-3}	1.10 10^{-2}				24
4	1	1 8	2 6	4	Basement				8.33 10^{-4}	101			27
2	3	1 9	3 1	6	0	26			3.12 10^{-2}	102			
4	1	1 7	2 2	4					1.72 10^{-3}	130			
1	3	1 5	1 1	6		400			9.09 10^{-4}	130			
4	1	1 8	2 6	4	58	113			2.63 10^{-3}	130			31
4	1	1 8	2 3	4	12	210	9.25 10^{-3}	2.47 10^{-3}	4.35 10^{-3}	136	24	21cps	33
2	2	1 5	3 2	5	30	1,050			1.32 10^{-4}	136			34
2	2	1 5	3 2	4					1.61 10^{-4}	136			35
4	1	1 8	2 6	4			9.61 10^{-1}	4.70 10^{-1}	6.25 10^{-1}	136			36
4	1	1 8	2 6	4			[Normality of Saturating Electrolyte]		4.0 10^{-4}	136			8
2	3	3 2	2 3	4		1,500		[10^{-3} N NaCl]	4.0 10^{-4}	130		1 Kc	39
2	3	3 2	2 3	4		1,500		[10^{-3} N NaCl]	1.7 10^{-3}	130		1 Kc	39
2	3	3 2	2 3	4		1,500		[10^{-3} N NaCl]	1.2 10^{-3}	130		1 Kc	39
2	3	3 2	2 3	1		1,500		[10^{-5} N NaCl]	2.2 10^{-4}	130		1 Kc	39
2	3	1 2	4 2	2			1.1 10^{-3}	2.0 10^{-4}	6.55 10^{-4}	136			40
2	3	1 2	4 2	2			5.0 10^{-4}	1.67 10^{-4}	3.34 10^{-4}	136			40
2	3	1 2	4 2	2			2.86 10^{-2}	1.43 10^{-2}	2.15 10^{-2}	136			40

REFERENCES FOR APPENDIX D

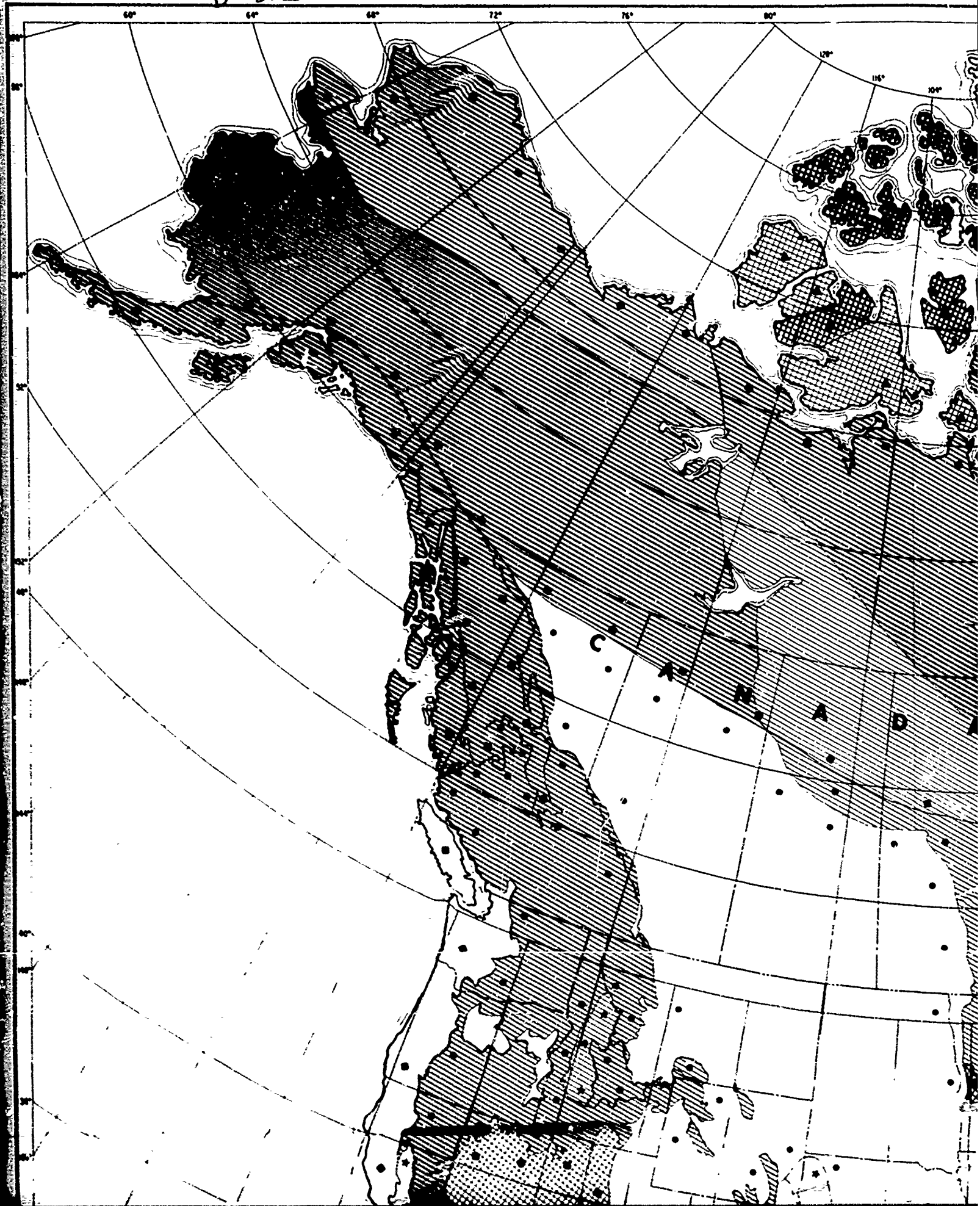
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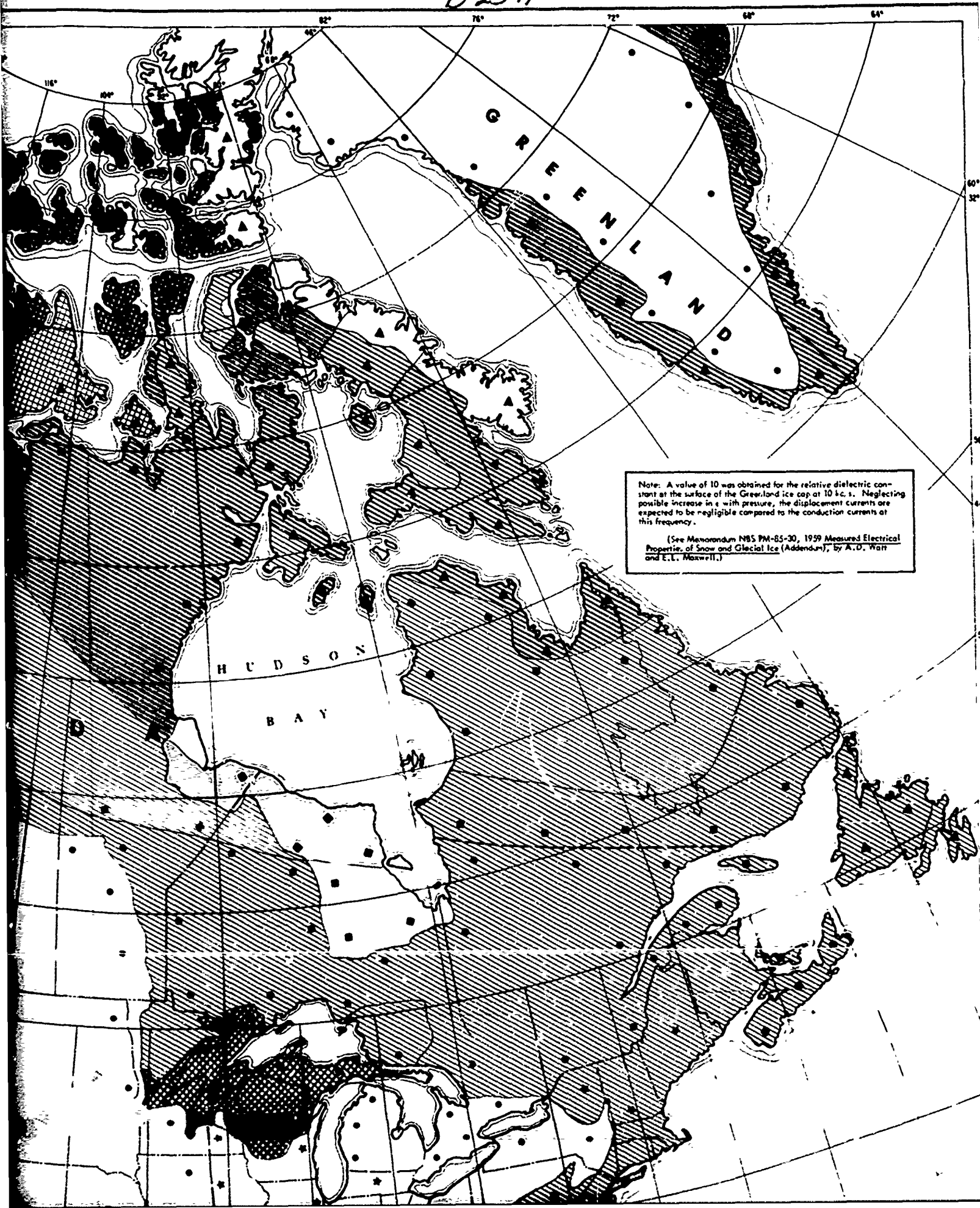
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D-25-A



Refer to DECO Report 54F-1
For Information Relating to the Fabrication and Use of This Map

Key for Conductivity Map

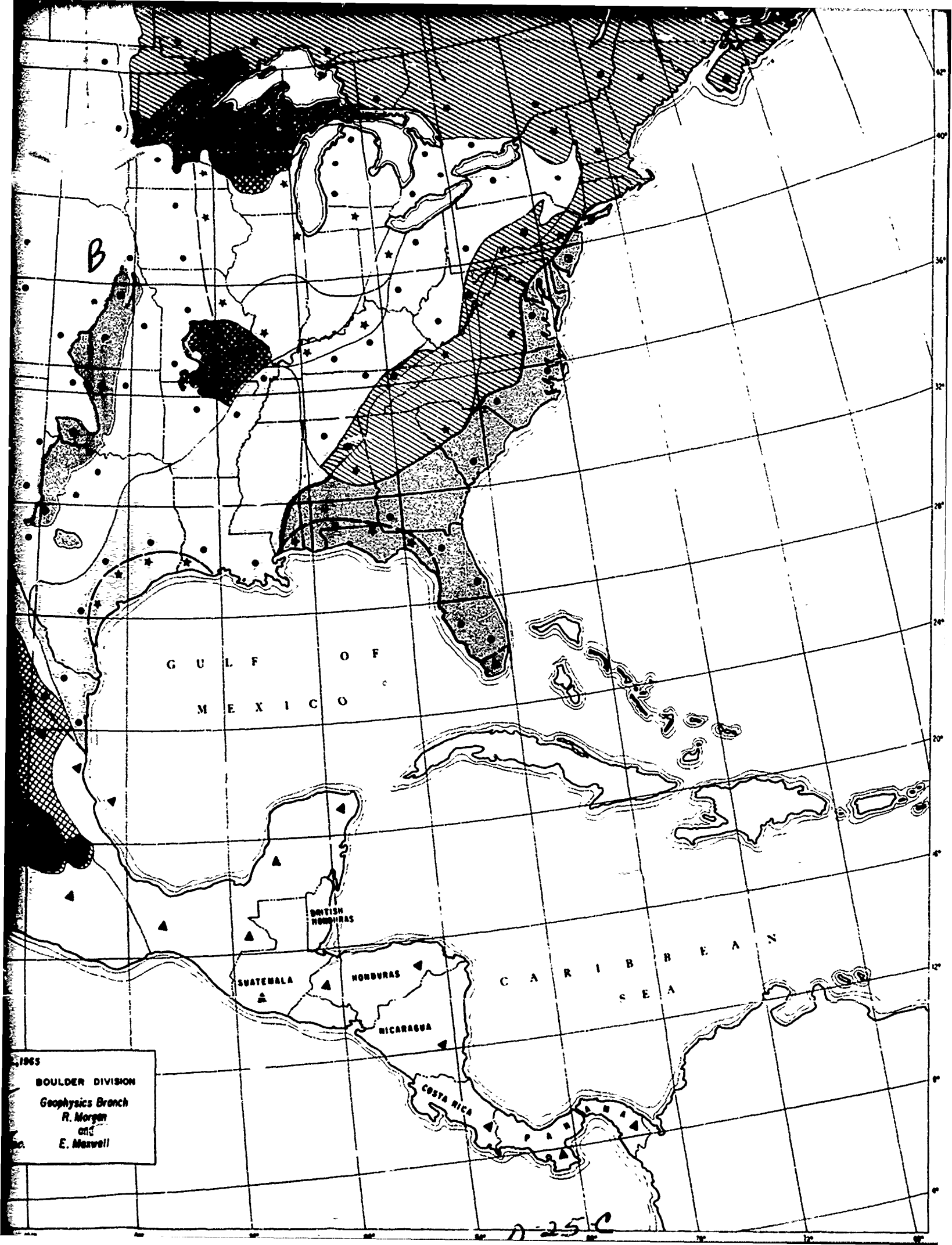
Effective 10 kc/s Conductivity σ_e (mho/m)	Confidence Factor	Variability Factor
1×10^{-5}	Highest Confidence. Correlation based on sound geologic and conductivity data.	Highly Variable : One Decade or More
3×10^{-5}		
1×10^{-4}		
3×10^{-4}	Moderate Confidence. Some data available. Geology-Conductivity correlation believed to be reliable.	Moderately Variable : Less Than One Decade
1×10^{-3}		
3×10^{-3}	Limited Confidence. Geology - Conductivity correlation not well defined. Limited Data	Slightly Variable : Less Than Half Decade
1×10^{-2}		
3×10^{-2}		
4 mho/m	Estimates Only. Estimates based on extrapolations of known relationships.	

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