244

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

PRELIMINARY REPORT ON TESTS OF THE APPLICATION OF GEOPHYSICAL METHODS TO ARCTIC GROUND-WATER PROBLEMS

By

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This report is preliminary and has not
been edited or reviewed for conformity
with Geological Survey standards

PREFACE

In April 1951 the U.S. Geological Survey was asked to study Arctic ground-water development by the U.S. Army Engineer Research and Development Laboratories at Fort Belvoir, Va. The resulting research covered many problems associated with this development. The studies of permafrost geology (Hopkins and Karlstrom, 1955) and of ground-water geology and drilling (Cederstrom, Johnston, and Subitzky, 1953) have already been published. The geophysical studies included a review of applicable geophysical methods which was followed by field tests during the summer of 1952. The results of these field tests were summarized by this preliminary report, which was written in 1954 for the Engineer Research and Development Laboratories. The report has not been revised to include the results of more recent geophysical developments. It is being released at this time because of requests occasioned by references to it in other publications.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLE

ABSTRACT

Seismic refraction and electrical resistivity surveys were made during the summer and fall of 1952 in the Tanana Valley near Fairbanks, Alaska, as part of the studies of the application of geophysical techniques to ground-water problems in Alaska instigated in 1951 by the U.S. Army Engineer Research and Development Laboratories. Work centered around the highway junctions at Fairbanks, Big Delta, and Tok. It was found that both survey methods defined the horizontal extent of the frozen ground and both were capable of determining the depth to the top of the permafrost but neither regularly yielded reliable information on the material beneath the top of the permafrost. The greatest need at present is for a thorough examination of data obtained in the field seasons of 1948 and 1952. Two fundamental theoretical investigations are desirable: (1) examination of the attenuation of longitudinal waves traveling through a thin layer, and (2) further development of the theoretical multilayer resistivity interpretation of problems in which the second layer has a very high resistivity. Further field work should include: (1) tests of the U.S. Geological Survey's new shallow-reflection seismograph; (2) a brief test of electromagnetic equipment; (3) additional resistivity measurements with commutated current; and (4) both seismic and resistivity measurements in areas where the bedrock possesses different physical properties from the schist usually found in interior Alaska. It is doubtful that geophysical techniques are sufficiently developed to be valuable for use by Army personnel in prospecting for ground water in areas of thick permafrost.

INTRODUCTION

In April 1951 the U.S. Geological Survey was asked to study problems involved in the development of Arctic ground-water resources. The research was initiated and financed by the U.S. Army Engineer Research and Development Laboratories at Fort Belvoir, Va., and included both geological and geophysical investigations.

The Army's interest in ground-water problems resulted from the increasing number of military installations which must obtain water from underground sources. Even in temperate climates, the location of these sources frequently requires the application of geologic and geophysical techniques, but in Arctic areas the problem is further complicated by the presence of large bodies of permanently frozen ground. As techniques for locating water-bearing strata in unfrozen ground are already well established, the Arctic ground-water problem is largely one of delineating permafrost.

The geophysical portion of the Geological Survey's investigation began with a review of the principles and application of electrical resistivity, seismic and electromagnetic methods, and some earlier field investigations in Alaska. This review resulted in the organization during the late spring of 1952 of a field party to make further tests in interior Alaska.

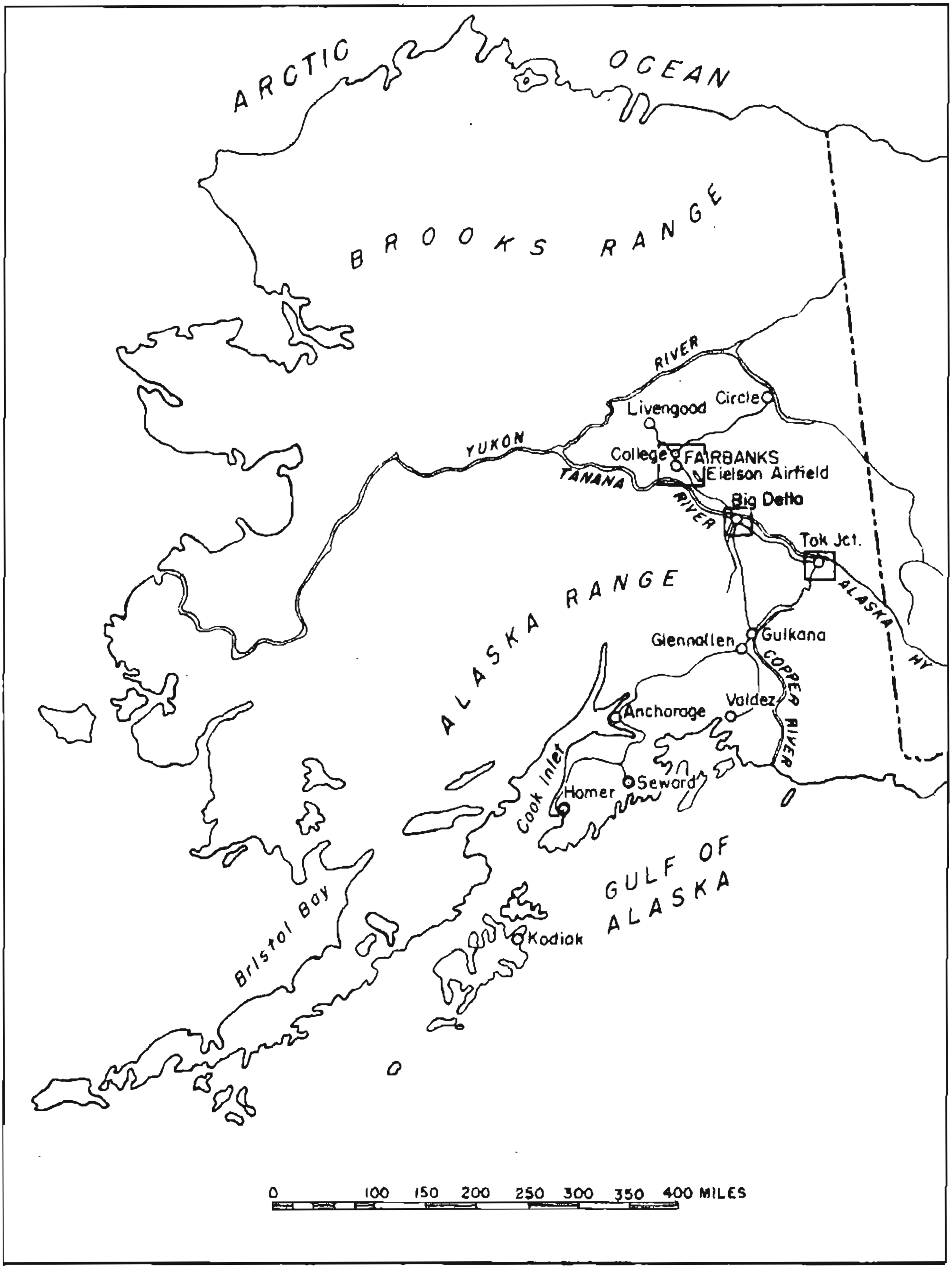
A party of three to five men, including Gerald R. MacCarthy, Chief, David F. Barnes, Milton Genes, and two assistants hired locally, was in the field from early July until early November.

When MacCarthy left in late August, Barnes became party chief.

Because of its late organization, the group relied heavily on the assistance of P. M. Johnston and Maurice Mundorf, of the Ground Water Branch; T. L. Péwé and H. E. Wright, of the Alaskan Terrain and Permafrost Section of the Military Geology Branch; R. M. Chapman, of the Alaskan Geology Branch office at Fairbanks; the Fairbanks Exploration Company; and the personnel of the U.S. Army at Ladd Field, Eielson Field, and Big Delta.

The work was confined to the Tanana Valley in interior Alaska and centered around the three main highway junctions at Fairbanks, Big Delta, and Tok (fig. 1). In general, both electrical resistivity and seismic refraction measurements were made in each area. Most of the resistivity work consisted of making depth stations, but much time was also devoted to constant depth profiling. Permafrost conditions in each of the three areas have been investigated by the Alaskan Terrain and Permafrost Section, and the ground-water geology has been studied by the Ground Water Branch.

This report summarizes the results obtained during the 1952 field season and presents a preliminary evaluation of the geophysical methods that were employed. It has been written primarily as a basis for planning future tests and no attempt has been made to describe the details of the procedures involved nor to present all the data that were obtained.



LOCATIONS OF 1952 GEOPHYSICAL WORK IN ALASKA

Figure 1

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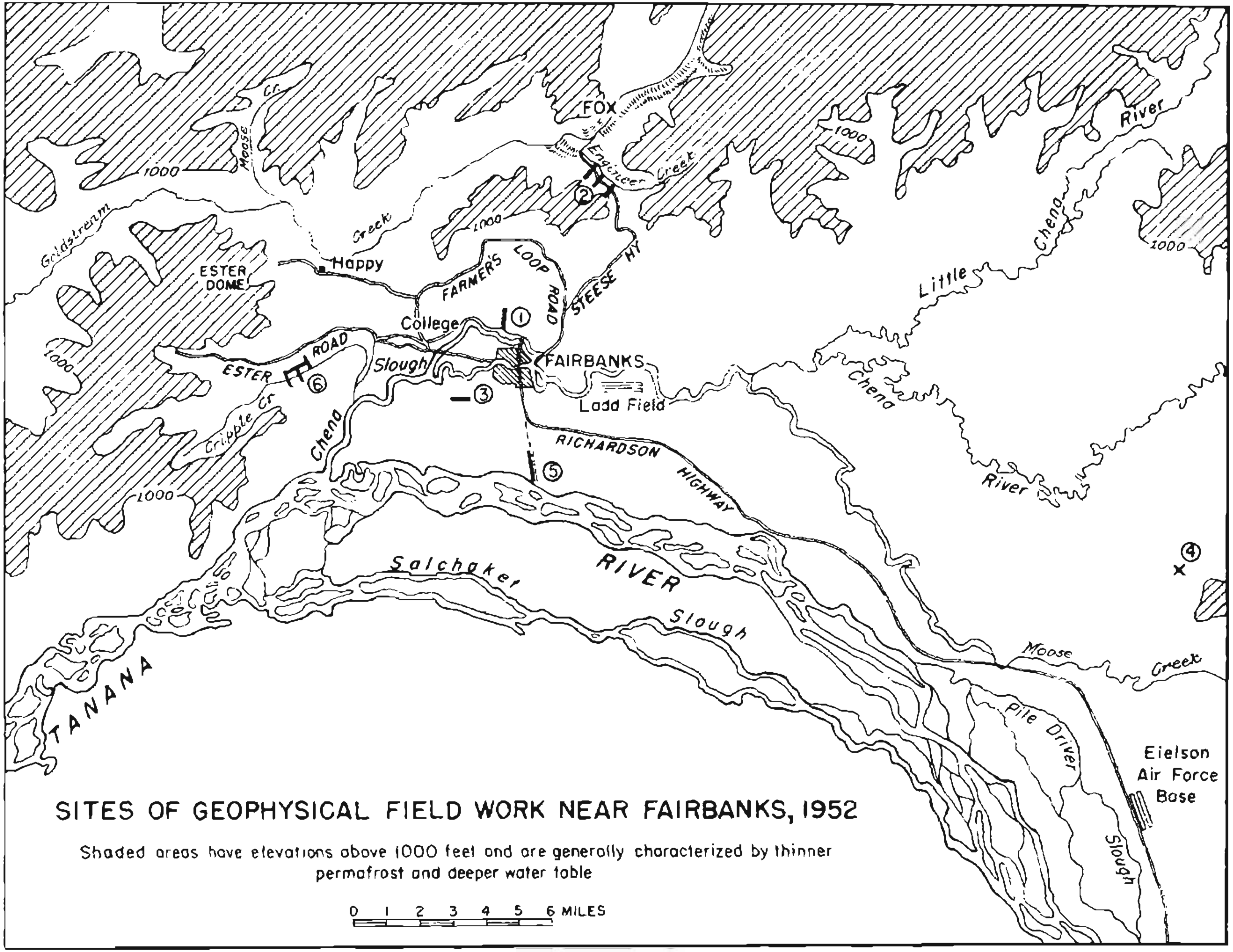
GEOLOGIC SETTING

The Tanana River occupies a broad flood plain developed during Pleistocene times by melt water from the large glaciers in the Alaska Range. During the melting of the Pleistocene ice, large fans were built outward from the mountains across the valley floor; today these fans occupy much of the southern side of the valley, forcing the Tanana River against the northern side. The hills to the north and most of the bedrock in the valley are composed of the thoroughly metamorphosed Birch Creek Schist, of Precambrian age. Fine-grained silts, often high in organic content and known as "muck," mantle the slopes and terraces of these schist hills. The river flood plain consists mostly of alluvial sands and gravels with some clayey silts.

Fairbanks was the main operating base for the field party and most of the field work was done in that vicinity (fig. 2). The large number of water wells in the area, plus the test holes drilled by the Fairbanks Exploration Co., provided information for checking the geophysical results. Péwé (1948) has divided the Fairbanks area into three geologic units. The first unit is the Tanana flood plain, characterized by permeable gravels overlain by a thin layer of silt. Permafrost in the flood plain varies from 0 to 180 feet in thickness and is found at depths of from 2 to more than 40 feet. Ground water is abundant both above and below the permafrost. The second geologic unit is the depositional slope on the flanks of the hills. These sediments consist of large thicknesses of fine silt and muck, which in places overlie gravel



SITES OF GEOPHYSICAL FIELD WORK NEAR FAIRBANKS, 1952

Shaded areas have elevations above 1000 feet and are generally characterized by thinner permafrost and deeper water table

Figure 2

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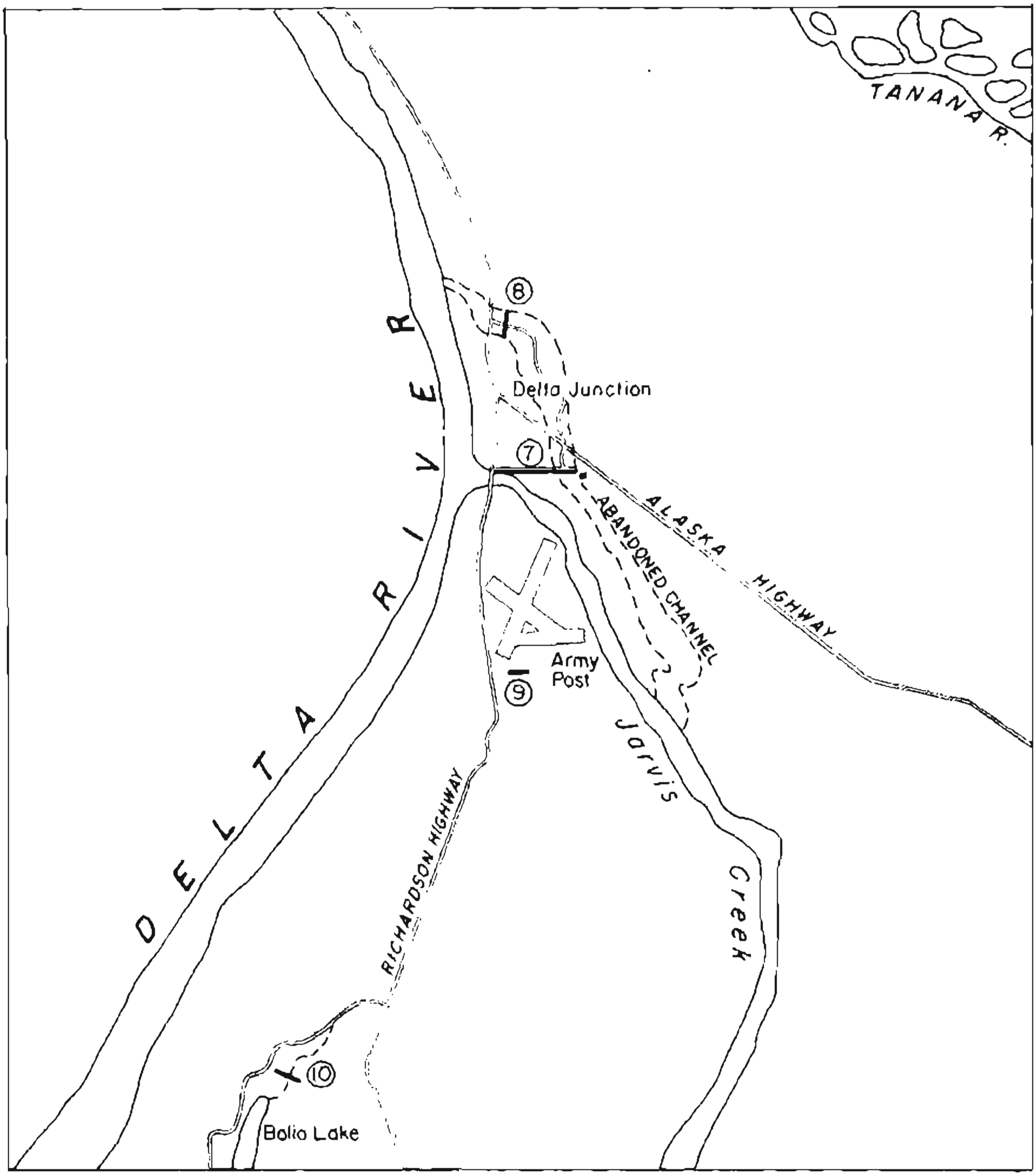
in former stream channels. Permafrost here is practically continuous, is close to the surface, has variable thicknesses, up to at least 175 feet, and contains frequent ice wedges. Water is found only in the permeable layers beneath the permafrost. The third and highest unit, "the hills," is composed mainly of the Birch Creek Schist overlain by a mantle of well-drained silt, but no geophysical work was done in this unit.

Big Delta is on the south side of the Tanana Valley at its junction with the Delta River Valley, from which Pleistocene mountain glaciers extended into the Tanana Valley (fig. 3). Glacial moraines are found a short distance south of Big Delta Army Post, and the Bolio Lake traverse was made across a small valley in this morainal area. The rest of the work at Big Delta was done on the outwash fan to the north of the moraine. Here the ground consists of permeable sands and gravels with only sporadic permafrost. According to Ground Water Branch geologists, the depth to the water table decreases from 185 feet at the Army Post to 80 feet at Delta Junction, a distance of roughly 3 miles. Jarvis Creek (fig. 3) is about 100 feet above the water table and is a perched stream, whose channel probably has been made impermeable by the large amount of glacial flour derived from the Jarvis Creek Glacier.

Tok is on an outwash fan at the mouth of the Tok River (fig. 4). The Pleistocene glaciers do not appear to have extended far down this valley, and no glacial moraines are evident north of the junction of the Tok and Little Tok Rivers. Like



FIELD SITES IN THE BIG DELTA AREA, 1952

0 1 2 3 4 5 MILES

Figure 3

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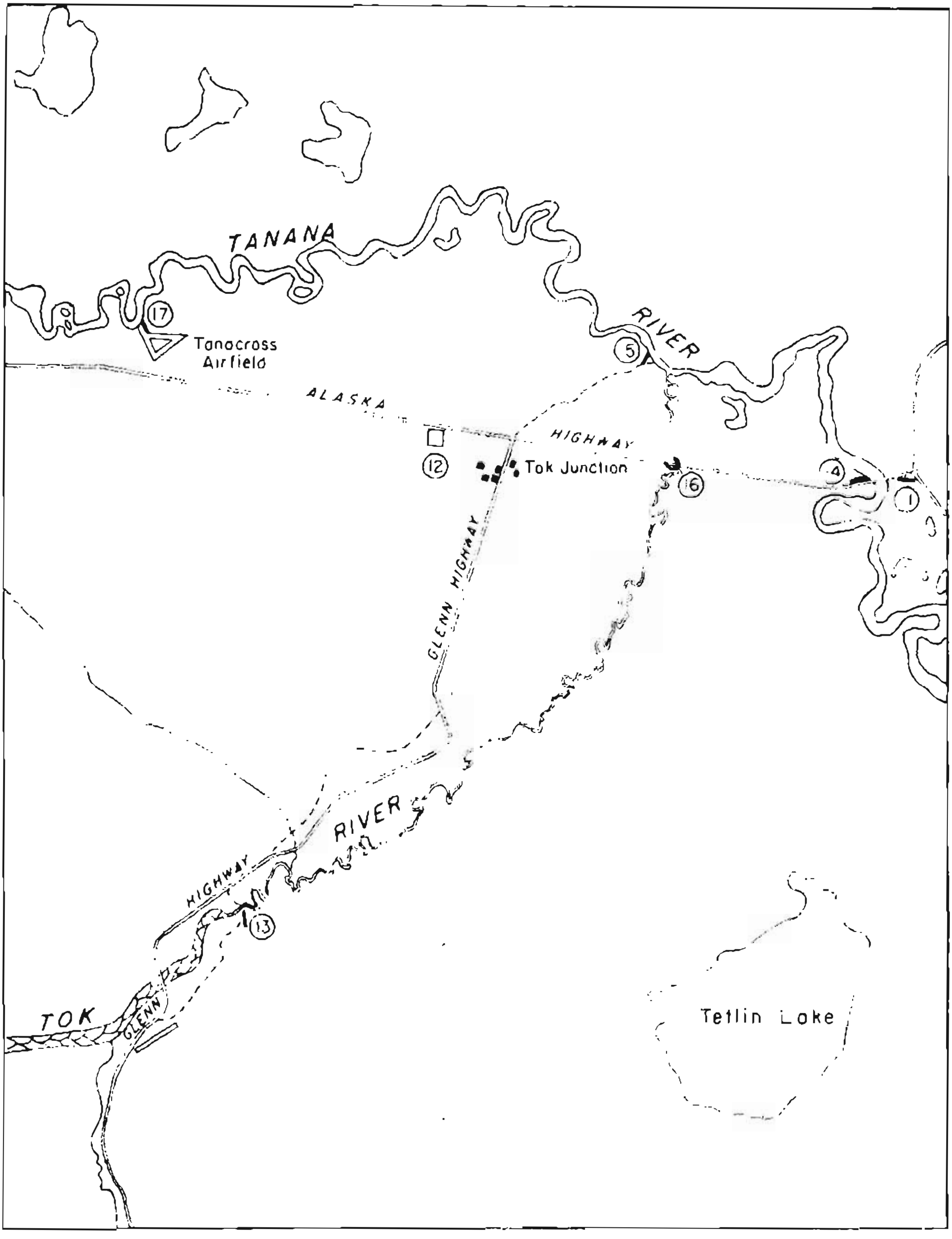

FIELD WORK SITES NEAR TOK

0 1 2 3 4 5 6 MILES

Figure 4

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Jarvis Creek, the Tok River is a perched stream, and the water-table depth is controlled by the Tanana River. Frozen ground in the outwash fan is sporadic and well above water table. Most of the work at Tok was done on the outwash fan, but measurements were made in the valley of the Tok River and on some sand dunes mantling the slopes north of the Tanana at 40-Mile Junction.

Table 1 lists all the sites where work was done and summarizes the observations and geologic conditions at each one.

TABLE 1.–*Geophysical work at 1952 sites*

Area	Site name	Site Number on Figures 2,3,4	Shots	Number of resistivity depth stations	Feet of resistivity profile	Feet of ground potential profile	Kind and date of correlating data	Thickness of permafrost (feet)	Permafrost depth (feet)	Depth to ground-water (feet)	Depth to bedrock (feet)	Kind of sediment	Kind of bedrock
Fairbanks	Creamer's Dairy----	1	10	0	0	0	60-ft well (1936)------------	40	1-40	12	?	Alluvial gravel	Schist
	Engineer Creek-----	2	42	14	0	0	12 F.E. drill holes (1922-33)	30-60	2	60?	40-85	Muck and gravel	Do.
	Cross Well---------	3	0	2	0	0	130-ft well (1951)-----------	22	65	7	?	Alluvial gravel	Do.
	Eielson Field------	4	20	8	2,400	2,400	300-ft well (1951)-----------	80	3-15	70	300	Alluvial silts	Do.
	Bonnifield Trail---	5	50	3	6,125	0	5 wells (1945)---------------	0-50	4	6	400-700	Alluvial gravel	Do.
	Gold Hill----------	6	22	7	0	700	13 F.E. drill holes (1926-52)	0-80	4-50	40-80	50-100	Muck and gravel	Do.
Big Delta	Jarvis Creek-------	7	20	3	6,000	0	-----------------------------	0	----	120	?	Outwash gravel	Do.
	Richardson Highway-	8	8	3	1,325	0	-----------------------------	0?	----	50	?	------do-------	Do.
	Big Delta Army Post	9	0	1	0	0	4 distant wells (1942-48)----	0-65	25	175	?	------do-------	Do.
	Bolio Lake---------	10	6	2	900	0	-----------------------------	100	2-10	?	?	Moraine	Do.
Tok Junction	Tetling Junction---	11	4	1	680	0	250-ft well (1951)-----------	0-25	7	140	?	Outwash gravel	Rhyolite?
	Alderton's Well----	12	8	3	0	0	75-ft well (1950)------------	28	5	55	?	------do-------	Schist?
	Tok River Valley---	13	12	1	0	0	-----------------------------	100?	5	?	?	------do-------	Schist
	Tanana Bridge------	14	4	0	0	0	-----------------------------	0	----	10	?	------do-------	Granite?
	Tanana Ferry-------	15	2	0	0	0	-----------------------------	0	----	10	?	------do-------	Do.
	Tok River Bridge---	16	6	0	0	0	-----------------------------	0	----	50	?	------do-------	?
	Tanacross Airfield-	17	8	1	0	0	2 wells (1941)---------------	0	----	10	?	------do-------	?

FIELD PROCEDURES AND RESULTS

Seismic Refraction Methods

All the seismic measurements were made with a 12-trace portable refraction seismograph. This instrument was light, easy to operate, and performed satisfactorily throughout the entire field season.

The most satisfactory detector spacing for determining the presence and depth of permafrost proved to be about 20 to 30 feet. A 262½-foot spread was usually used with detectors at 6¼, 18-3/4, 37½, and 62½ feet and at 25-foot intervals thereafter. Permafrost is a good energy carrier and charges of one-fourth pound or less proved quite satisfactory. A few bedrock depth determinations were made using detector separations of as much as 100 feet and total spreads as large as 4,000 feet. Very large charges, up to 100 pounds, were necessary for these spreads.

Seismic operations in the subarctic do not differ appreciably from those in warmer areas. When frozen ground is close to the surface, charges cannot be buried deeply without expensive drilling, but the high sound transmission of frozen ground makes deep burial unnecessary unless buildings are close enough to be damaged by the air wave. The ability of frozen ground to carry sound long distances proved extremely annoying, however, when observations were made close to sources of disturbing energy. It was frequently necessary to suspend operations until bulldozers, which are used almost everywhere in Alaska, moved more than half a mile away from the seismic operations.

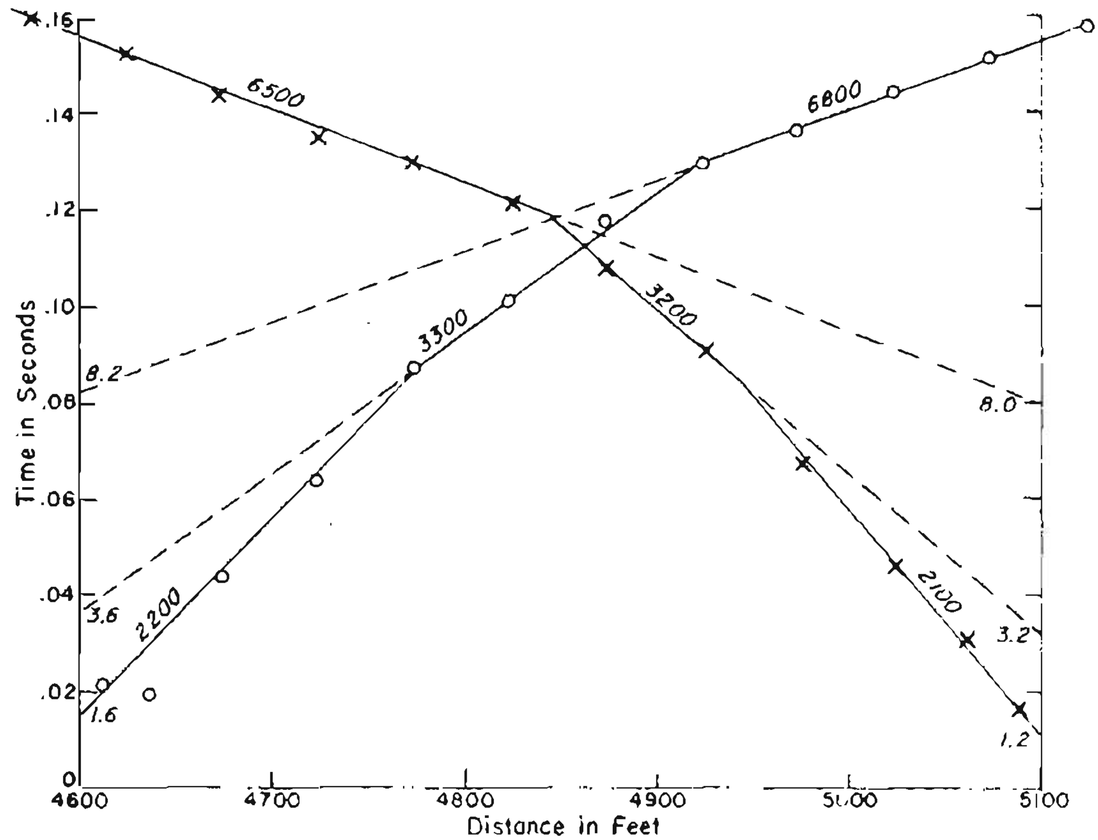
The cold weather produced only minor problems, as the temperatures did not fall below 0°F in the fall of 1952. Modern dynamites do not freeze and are quite safe to handle at very low temperatures. The main difficulty was in keeping the developing solutions warm enough to process the oscillograph paper. There are many methods of accomplishing this, and the choice of a particular one depends on the locality of work and on the equipment available. In the fall of 1952 most of the seismic lines could be reached by a four-wheel-drive Army jeep, which was used as an instrument truck. The blast of hot air from the military model personnel heater in this vehicle was used to warm the developing cans, especially before filling them with solutions. This heater was also used to defrost the mirrors and lenses of the optical system when they became clouded on very cold mornings.

Seismic Results

Seismic refraction methods are capable of detecting any underlying strata with a higher velocity than the overlying layers. Accordingly, in temperate climates they are used primarily for the determination of bedrock depths. In the Arctic, however, the high-velocity, frozen ground is the only layer that is usually recorded. The upper part of figure 5 clearly shows the seismic contrast between frozen and thawed ground. The profile is over a mile long and was made along the old Bonnifield Trail across the Tanana Valley flood plain south of Fairbanks, where the underlying material is alluvial gravel. From 0 to 3,700 feet the slopes of the travel-time curves indicate a low seismic velocity (5,500 to 7,000 feet per second) which is within the normal range for water saturated sands and gravels. Much of this land is owned by the City of Fairbanks Water Department, which has done some successful test drilling on its property. At 3,700 feet the slopes of the seismic travel-time curves decrease, indicating a higher velocity, typical of frozen ground, of approximately 10,000 to 13,000 fps. The only surface evidence of this change is the appearance of corduroy road, indicating a softer roadbed. At the far end of the profile, the velocity again decreases because of the thawing influence of the Tanana River.

Only in rare cases does the refraction seismograph record waves which have traveled through the material underlying the permafrost. In those parts of Alaska where there is no frozen ground, however, the refraction seismograph is quite capable of recording the depth to water table or the depth to bedrock. Figure 6 shows a travel-time curve obtained on the outwash fan at Big Delta. The upper 125 feet at this site is well-drained gravel, and if there is any permafrost, it is dry and possesses the same mechanical properties as unfrozen ground. This well-drained material has a velocity that ranges from 900 to 3,500 fps, but the velocity increases to more than 6,000 fps at the water table. The water-table depth of 122 feet obtained with the seismograph checks reasonably well with the value of 110 feet obtained by interpolating between the nearest water wells at Delta Junction and Delta Airfield.

Figures 7 and 8 are two stations at Eielson Field showing frozen ground fairly close the surface. Ground water could not be obtained in such an area without drilling through a considerable thickness of frozen ground. Figure 9, however, is a travel-time



SEISMIC PROFILE NEAR JARVIS CREEK

Feet	
0-6	Surface layer, velocity 900 feet per second
6-35	Subsurface layer, velocity 2150 feet per sec.
35-122	Subsurface layer, velocity 3250 feet per sec.
122- ?	Water saturated, velocity 6650 feet per sec

Figure 6

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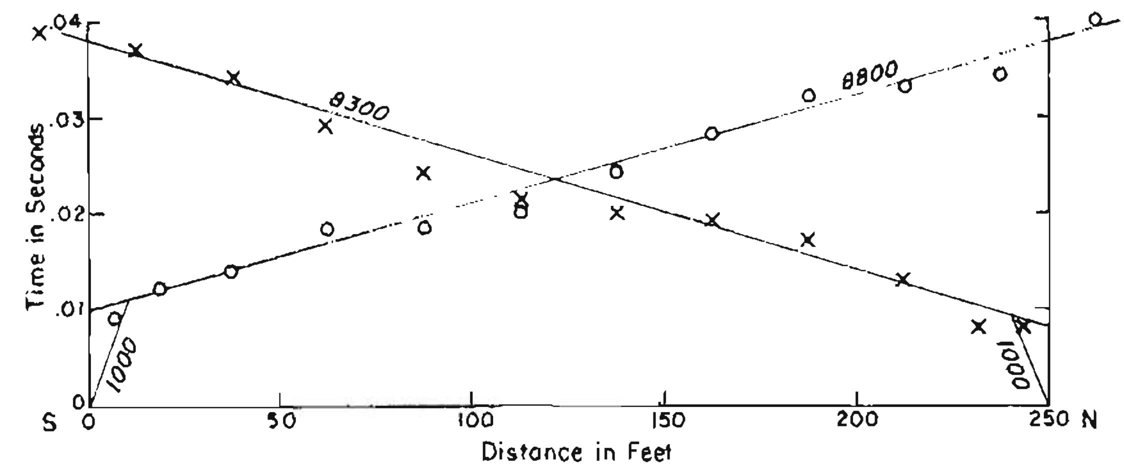
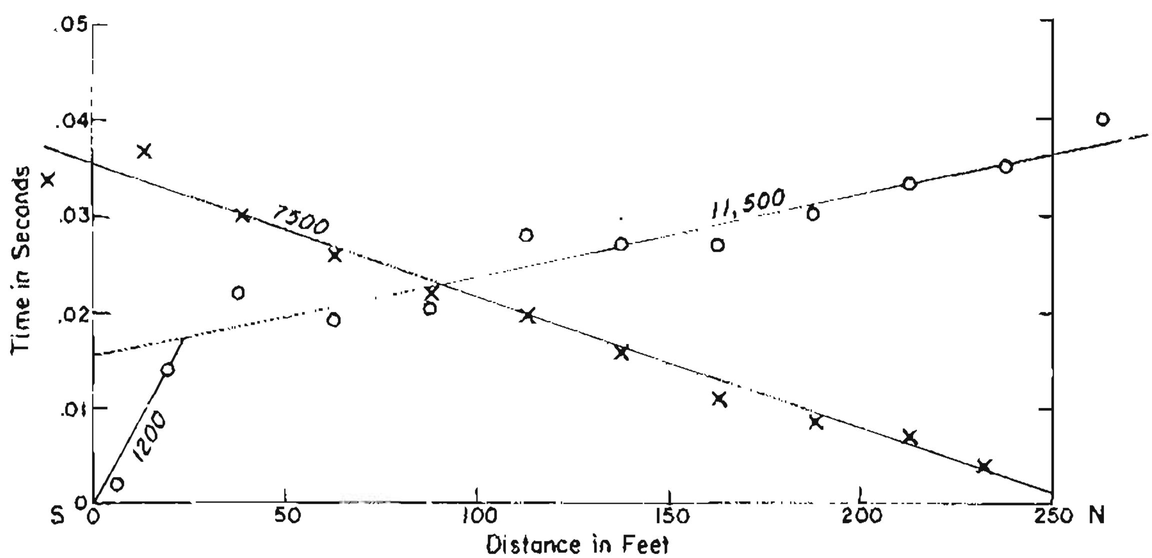


SEISMIC STATION 600 FEET EAST OF EIELSON WELL

Depth of 5 feet to permafrost with a velocity of 8500 feet per second

Figure 7



SEISMIC STATION 600 FEET WEST OF EIELSON WELL

Depth to permafrost increases from one foot on north end to nine feet on south end

Figure 8

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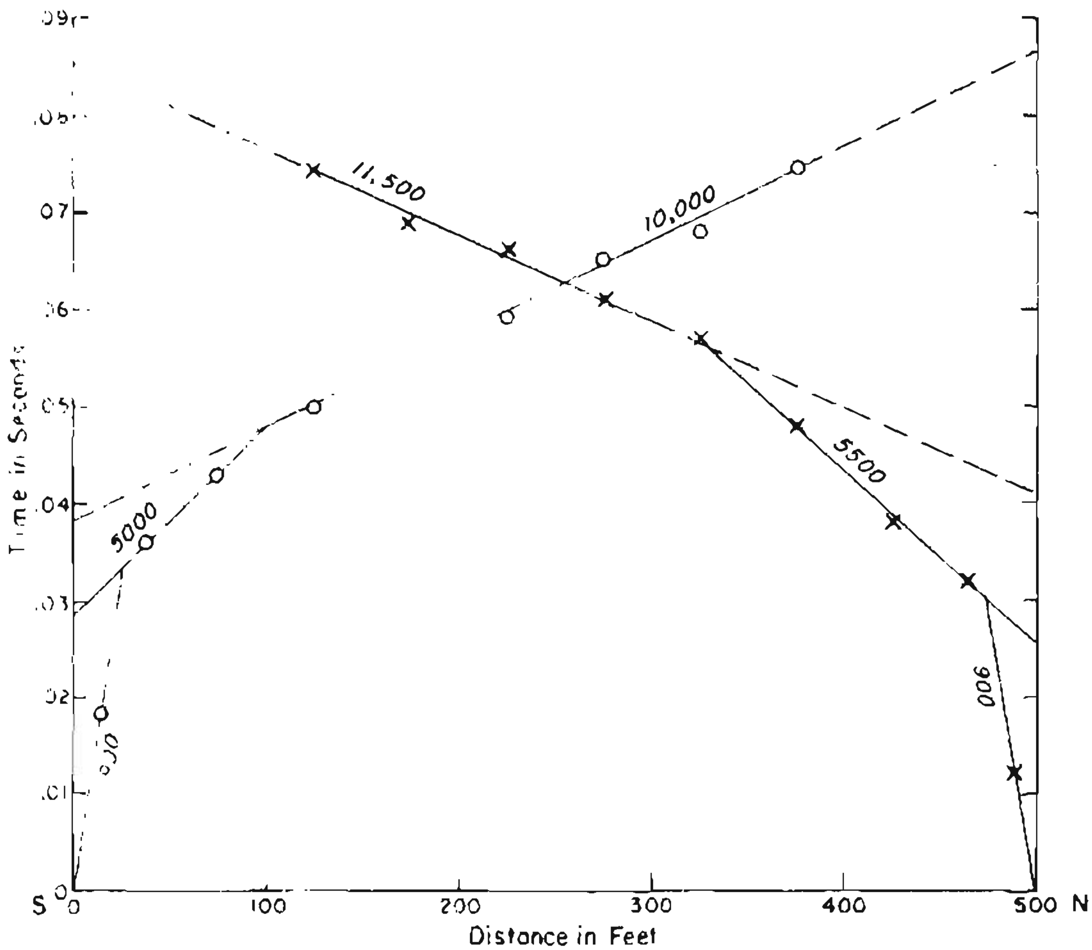


SEISMIC PROFILE NEAR CREAMER'S DAIRY

Feet	
0 - 12	Surface layer, velocity 900 feet per second
12 - 48	Water saturated layer, vel. 5250 feet per sec.
48 - ?	Permafrost, velocity 10,700 feet per second

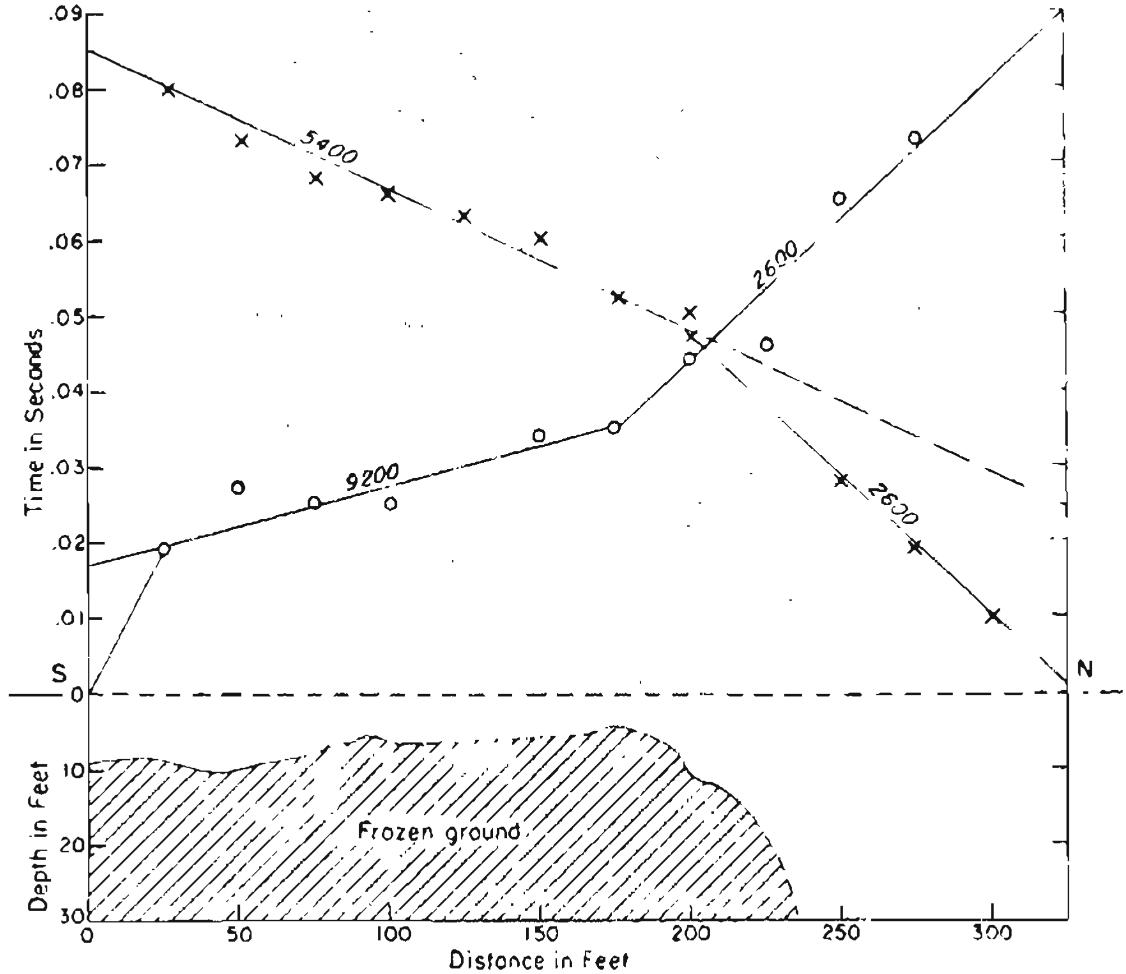
Frost is 40 feet deep on south end and 57 feet deep on north end

Figure 9

curve showing a much greater depth to the frozen ground and revealing an overlying layer of unfrozen, water-saturated sediments. A nearby farmhouse well obtains a reasonable supply of suprapermafrost water at a depth of 40 feet.

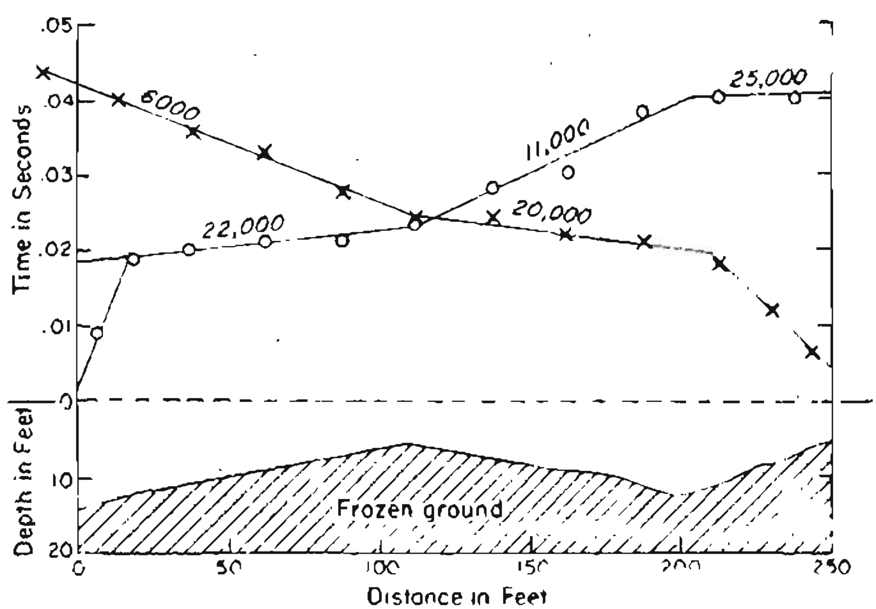
The irregular depth and extent of permafrost is one of the factors that make geophysical prospecting in the subarctic extremely difficult. Horizontal variations in both the depth and the velocity of frozen ground produce time-distance graphs showing such a large scatter in travel times that a true estimate of velocity is difficult to obtain. The use of large detector spacings and long spreads tends to average these erraticisms and yields a mean velocity; the use of small detector spacings and short spreads enables the interpreter to determine the horizontal variations in the depth of the permafrost. Figure 10 shows an unusual travel-time curve that can be explained by assuming a permafrost body similar to that shown in the cross section. The 2,600-fps velocity at the north end indicates that there is little or no permafrost along the northern 100 feet of the profile. Figure 11 shows a travel-time curve that can be explained by a continuous layer of frozen ground whose depth varies as shown in the section. The ability of the refraction seismograph to detail the depth of frozen ground is valuable from a ground-water standpoint only where suprapermafrost water is available, but it could prove very useful for engineering problems.

In general, seismic refraction techniques can determine only the depth of the upper surface of the frozen material; they are probably never capable of measuring the thickness of the frozen layer and only rarely able to indicate the depth to underlying



SEISMIC STATION 150 FEET WEST OF ALDERTON'S WELL
SHOWING ABRUPT END OF FROZEN GROUND

Figure 10



SEISMIC STATION AT EIELSON FIELD SHOWING
IRREGULAR TOP OF PERMAFROST

Figure 11

bedrock. Recently, however, two seismic methods have been developed which may offer a small chance of measuring the thickness of permafrost. Measurements of the frequency dispersion of flexural waves have been used to measure the thickness of sea ice (Press and others, 1950) and have been tried in permafrost by the U.S. Air Force Cambridge Research Laboratories. This technique, however, requires very long spreads, a mile or more, and probably lacks the resolution required for ground-water prospecting. Secondly, the Geological Survey has recently made very successful tests of shallow-reflection equipment, which appears to be promising.

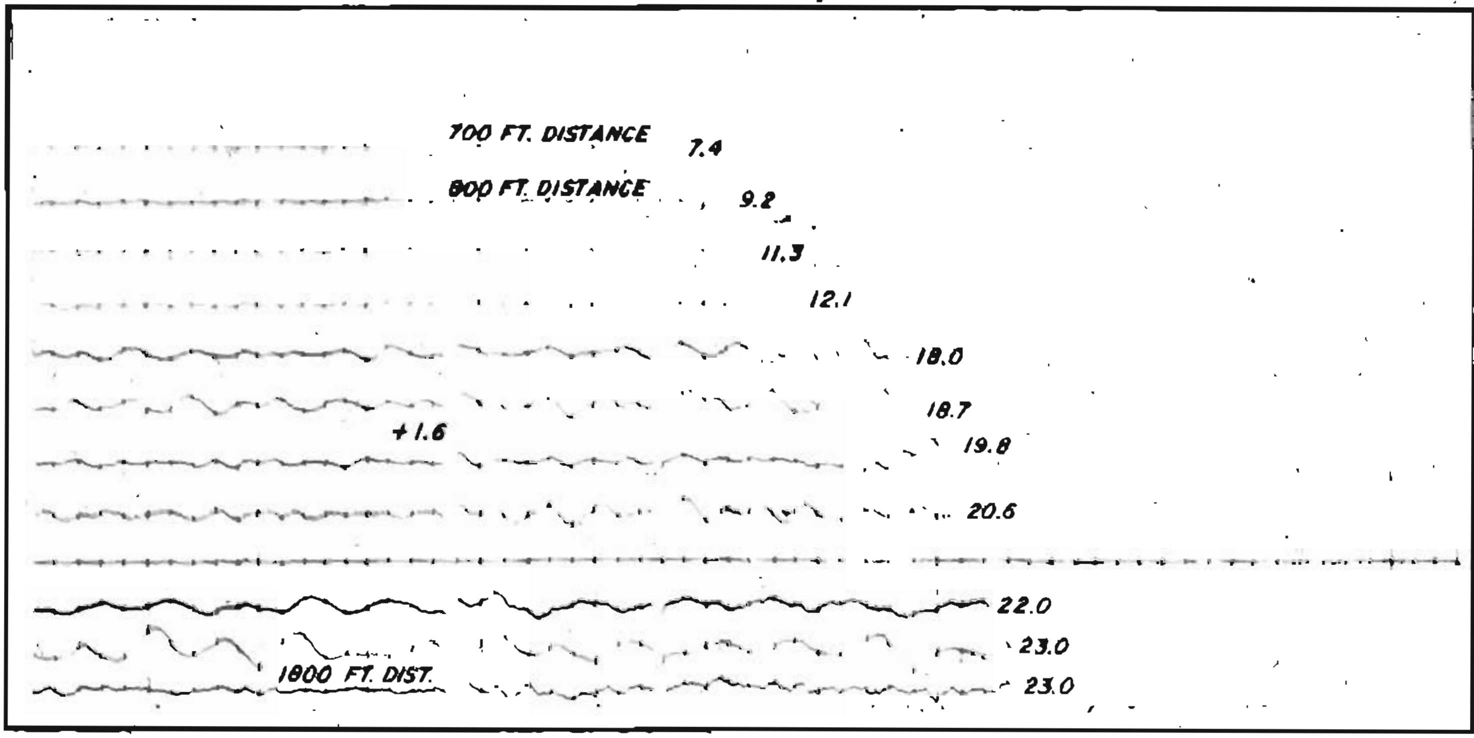
When the bedrock velocity is considerably greater than the frozen-ground velocity, a rough determination of the bedrock depth may be possible. Unfortunately, almost all of the summer's fieldwork was carried out above a bedrock of schist, which has a relatively low velocity, approximately equal to that of frozen ground. Distinguishing between bedrock and permafrost velocities on these records is therefore almost impossible. Furthermore, the very common fluctuations in dip of the top of the permafrost may produce apparent velocities that are even greater than those associated with bedrock; and even in those cases where the bedrock arrivals can be distinguished, there is considerable difficulty in deciding how great a vertical velocity one should use in the depth computation. Any thawed layers within or beneath the permafrost will reduce its vertical velocity considerably below the horizontal velocity shown by the travel-time curve.

In some cases the arrival of sound traveling through the bedrock can be distinguished despite an earlier arrival of energy traveling through the frozen layer. This is possible when the energy traveling through the frozen layer is attenuated sufficiently to allow the interpreter to pick the bedrock-wave arrival. Sound traveling through thin, high-velocity layers may be attenuated quite rapidly, and therefore the seasonal frozen layer found in temperate climates does not interfere seriously with refraction methods. At Eielson Field similar attenuation was found where a well log reported 80 feet of permafrost. Two of the oscillograph records and the travel-time curve obtained there are shown in figures 12 and 13. The horizontal velocity of the frozen layer varies between 7,200 and 10,000 fps, but a vertical velocity of 5,300 fps gives the best value for the depth to bedrock. The suggested vertical velocity is about average for water-saturated sediments, so here the frozen layer does not appear to increase the vertical velocity significantly. In drilling the well a considerable amount of methane was encountered beneath the permafrost. It is possible that, in this example, the high velocity of the frozen material may be partly compensated for by an underlying low-velocity layer of dry sediments. Nevertheless, there appears to be some evidence that, for prospecting purposes, the velocity of frozen ground is quite anisotropic, as its effective horizontal velocity exceeds its vertical velocity.

Very little is known about the attenuation of energy traveling through thin layers. When there is seasonal frost close to the surface, this phenomenon frequently causes considerable difficulty in the interpretation of the early parts of refraction records, but where permafrost is moderately thick, attenuation may greatly facilitate refraction work in the subarctic. If some frequencies are attenuated more rapidly than others, it might be possible to increase the effect of the attenuation by the use of a filter and to pick bedrock arrivals on a greater number of records. The technique would

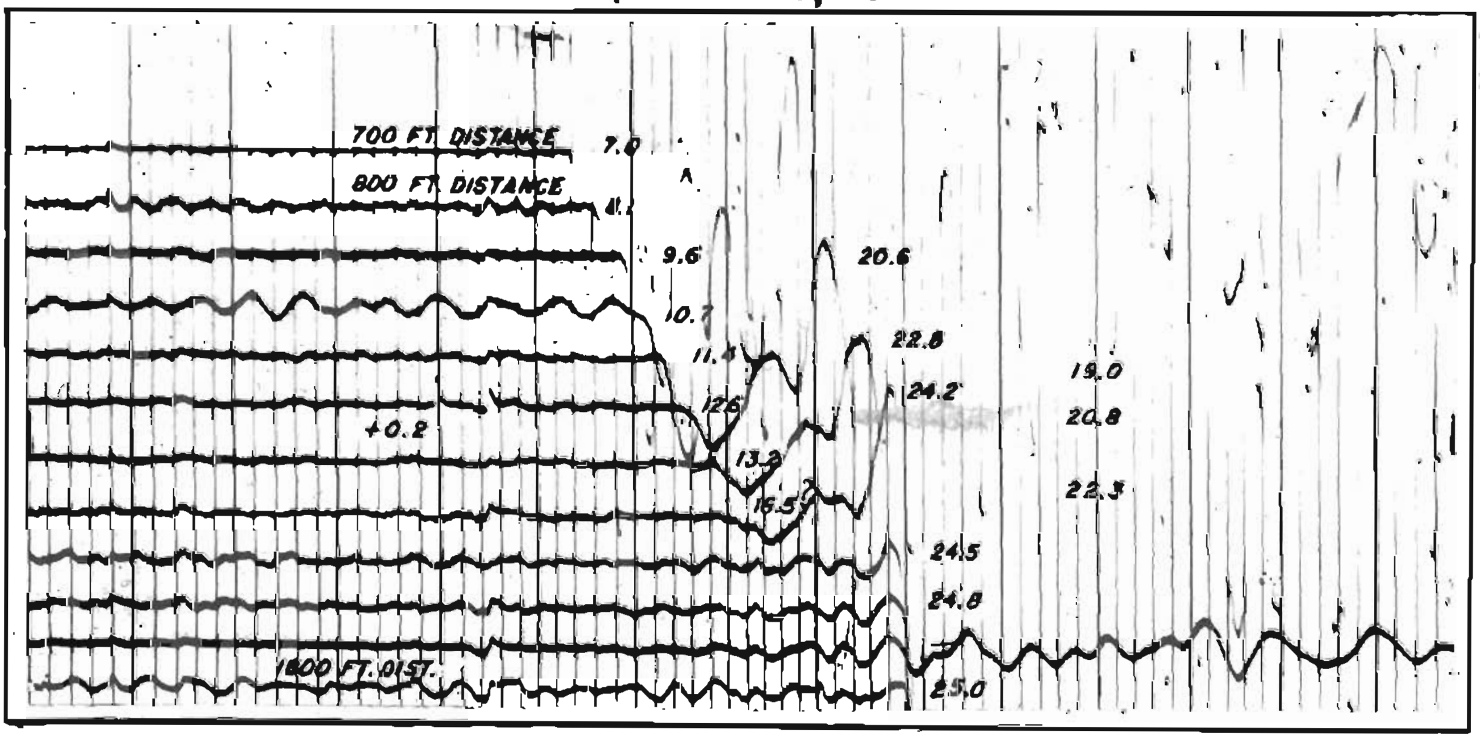
EIELSON FIELD – SHOT NO. 3 AT 600 FEET SOUTH

September 27, 1952



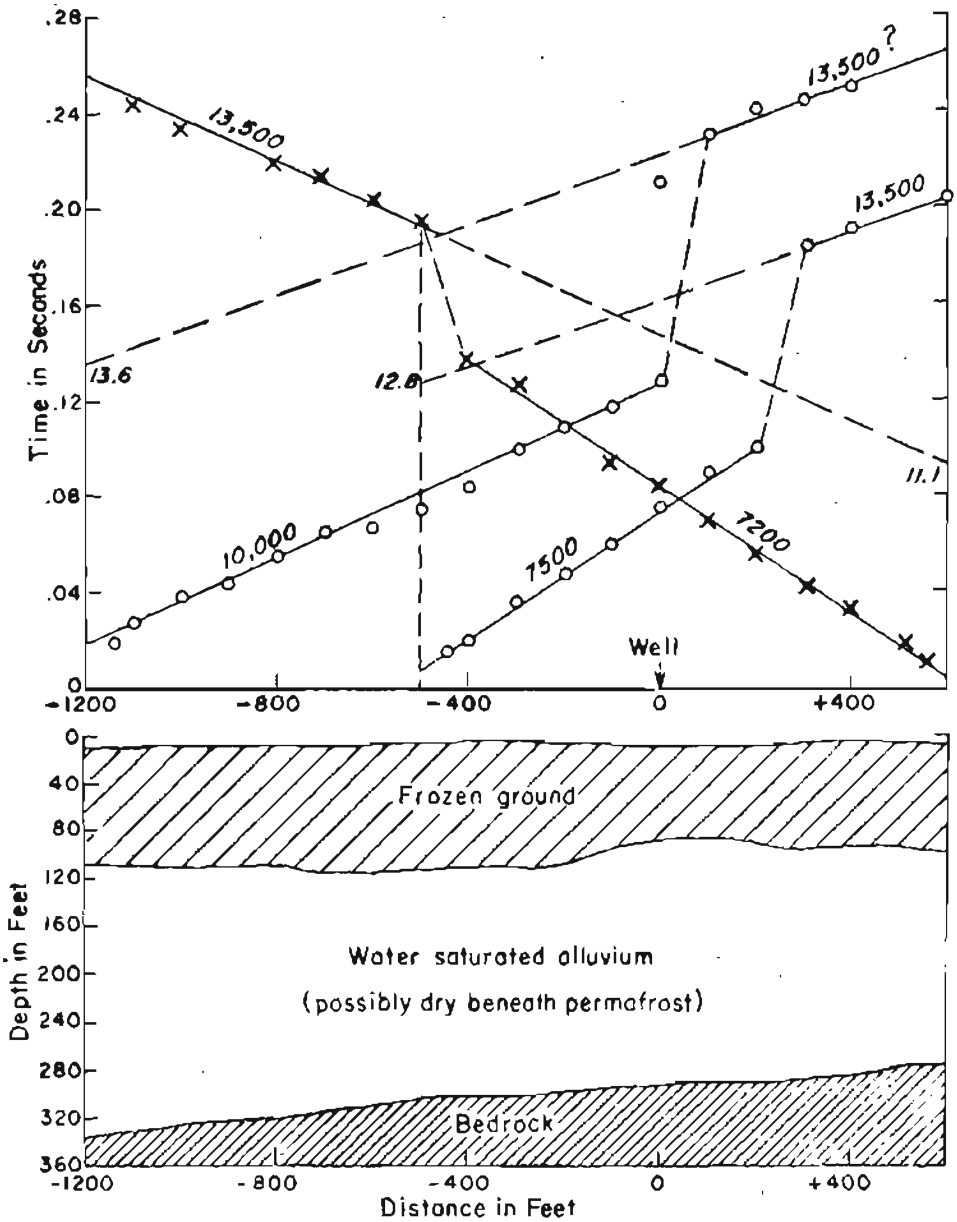
EIELSON FIELD – SHOT NO. 10, 1200 FEET N. OF WELL

September 26, 1952



RECORDS SHOWING ATTENUATION OF PERMAFROST WAVE AND LATER ARRIVAL OF BEDROCK WAVE

Figure 12



SEISMIC STATION AT EIELSON FIELD

Figure 13

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probably work only in those cases where the frost is underlain by a considerable thickness of thawed sediments, but investigation of the method seems highly desirable. Preliminary theoretical analysis of the problem and the use of a reflection seismograph for the next field tests are recommended.

Electrical methods

All resistivity measurements were made with a direct-current "geoscope" built by the U.S. Geological Survey. This equipment has separately boxed current and potential-measuring circuits and uses porous pots containing a saturated solution of copper sulfate as potential electrodes. The Lee modification of the Wenner electrode arrangement was used for all measurements. In general, the equipment operated satisfactorily, although a few changes are recommended for future operations in Alaska.

The potential geoscope has a special circuit which extends its range to 2000 millivolts instead of the usual 1000 millivolts. Even this range is barely great enough for the very high resistivities sometimes encountered in permafrost areas and the measurement of these high values requires a great deal of knob twisting. More rapid work would be possible by using a second scale having a lower sensitivity factor. The high ground resistivities require the use of rather small currents, and the accuracy of the results could be improved by increasing the sensitivity of the measuring circuit in the current geoscope.

Operations during moderately cold weather present only a few minor problems for resistivity work in the Arctic but any work in extreme cold is very difficult. A saturated solution of $CuSO_4$ freezes at about -2°C, but work can be done at somewhat lower temperatures if the pots are occasionally thawed. Prolonged cold-weather work requires the addition of an antifreeze solution such as alcohol or pure ethylene glycol. The addition of these solutions changes the amount of dissolved $CuSO_4$; therefore, the antifreeze concentration must be equal in all pots. During the 1952 field operations described in this report, a number of attempts were made to use alcohol as an antifreeze solution, but on each attempt the self potential of individual pots varied by more than 5 millivolts. This was satisfactory for resistivity operations but made the measurements of natural potentials difficult. However, the alcohol used may not have been pure, because previous investigators have reported no difficulties with pure antifreeze solutions. At temperatures below 0°F instrument shelters are required for efficient resistivity operations.

There was considerable difficulty in getting a sufficiently large amount of current into ground, even with a partly frozen surface. Part of this difficulty may have resulted from the decreased efficiency of batteries at low temperatures. Even at temperatures of 40°F the capacity of dry cells decreases to 70 percent of their capacity at 70°F, and at -20°F their capacity is only 6 percent of that at 70° (U.S. Bureau of Standards, 1949). Overnight storage of batteries in a warm room and the use of insulated battery boxes is recommended for cold-weather operations. However, much of the difficulty encountered in getting current into the ground probably resulted from the high resistance at the current electrodes. Reasonably good electrode contacts can be obtained in frozen clay and muck, especially if the stakes are watered and allowed to freeze in, but only a very small current can be put into frozen gravel. Use of water or water-alcohol wetting solutions greatly improves the performance of both current and potential electrodes. The pot potentials, however, are greatly altered by wetting the holes with a water-alcohol solution.

All readings were usually repeated at each electode setting, and the second set of readings was usually found to be within half a percent of the first. Occasionally, however changes were much greater and field tests could not determine any error in the measuring technique that would account for these discrepancies. Such difficulties occured in a number of localities but usually ceased after a few hours. They may be caused by the large fluctuations in earth currents which occur in high latitudes at times of magnetic storms (Rooney, 1949, p. 293). The use of cummutated current might eliminate some of the difficulties caused by fluctuations in telluric currents.

Resistivity profiling

A large amount of time was devoted to constant depth profiling, which records horizontal changes in resistivity. In this method of surveying, the electrodes are kept a constant distance apart, and the whole configuration is moved along the ground in the direction of the electrode spread. An electrode separation of 50 feet was usually used, and configuration was moved 25 feet between each set of readings. Thus when using the Lee configuration, the center electrode is shifted each time to the previous position of the P_1 electrode. In plotting the results the ρ_1 resistivity is recorded 12½ feet ahead and the ρ_2 resistivity 12½ feet behind the position of the center electrode, so that the two curves approximately coinside. The lower part of figure 5 gives an excellent example of the marked change in resistivity when the configuration is moved from thawed to frozen ground. From 0 to 3,800 feet, where the ground is unfrozen and where successful test wells have been drilled, the resistivity is low, with a value of 20,000 to 60,000 ohm-cm. The frozen ground at 3,800 feet causes an increase in resistivity to between 100,000 and 600,000 ohm-cm, but the resistivity again decreases at the thawed zone near the Tanana River. The contrast is sharp enough to determine quite accurately the boundary between the thawed and frozen material. Considerable care should be used, however, in interpreting resistivity profiles, for changes in type of sediment can produce equally large variations. Figure 14 shows two short profiles plotted to the same scale as figure 5. The upper profile was made on alluvial and lacustrine silts at Eielson Field and represents continuously frozen ground despite the low resistivities recorded. These low resistivities were caused by a 5- to 12-foot surface layer with low resistivity. The rapid increase at 875 feet merely represents a decrease in the depth of the permafrost from 12 to 5 feet. The lower profile was made on the outwash fan at Big Delta and probably represents completely unfrozen gravels, although the resistivity values are considerably higher than those in the upper profile.

As a rule, resistivity profiles give an excellent indication of the location of changes in permafrost, but they should not be interpreted without some type of vertical control in a few places along the profile. The resistivity recorded is a function of both the surface and the deep layers. Accordingly, a few drill holes, seismic stations, or resistivity depth stations should be located along the profile as a guide to interpreting the data.

Resistivity depth stations

The commonest use of resistivity techniques is the determination of the variation of resistivity with depth by changing the horizontal separation of the electrodes. This use of resistivity is the most promising of the electrical prospecting techniques, but it is also the technique which needs the greatest amount of additonal development. Theoretically, resistivity depth measurements are ideally suited to the study of Arctic ground-water problems. The large contrast between the resistivities of frozen and thawed ground, the possibility of distinguishing permeable from impermeable material, and the difference in resistivity between sediments and bedrock all indicate that resistivity should be a very effective prospecting tool. Field tests have shown that the theoretical advantages are quite correct and that in many cases the depth measurements yield excellent results. Nevertheless, two problems still have to be solved before the technique has wide application in the Arctic. The first and greatest of these problems is that of interpretation. The second is that of eliminating the effect of the horizontal variations in surface resistivity.

Methods of interpreting resistivity may be divided into two broad groups differing widely in application and theory. The first group might be called empirical methods which have incomplete theoretical support. The most common of these empirical methods is to assume that the electrode separation equals the depth of penetration and that changes in trend or inflection points appear in the resistivity curve at each depth interface. This technique has been employed in interpreting most of the previous resistivity work in Alaska (Joesting, 1941). Accordingly, most of the field observations were made with this method of interpretation in mind.

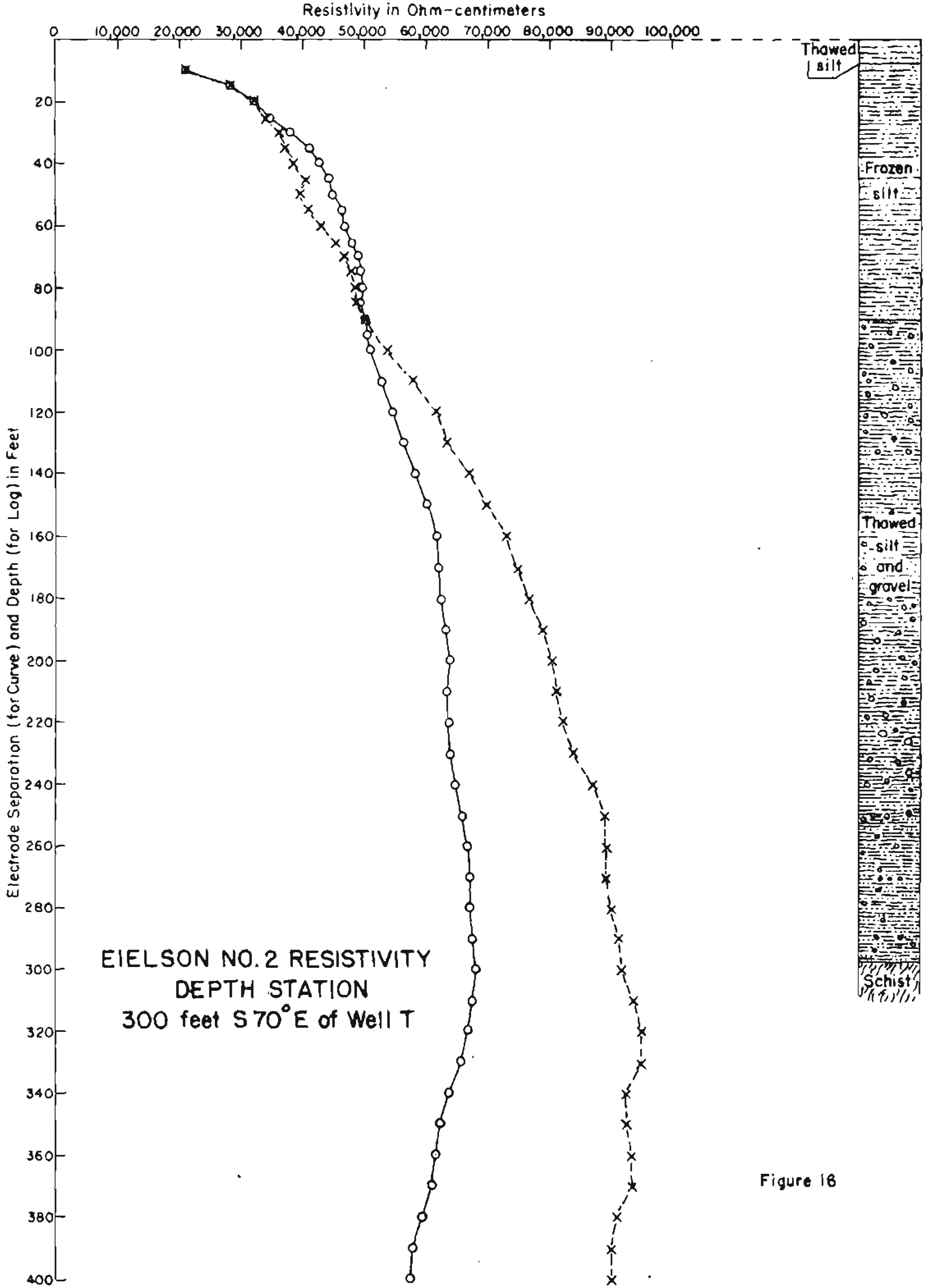
Figure 15 shows seven depth stations and four drill logs made along a 600-foot line at Engineer Creek. The general geologic section consists of four layers, and the shape of many of the curves (stations 2, 3, 4, 4½) indicates a four-layer case. The correlation of sharp breaks with the depth of an interface is, however, somewhat difficult. The first pronounced breaks in the curves of stations 2 and of ρ_2 at station 4 correspond approximately with the bottom of the muck. However, in stations 2½, 3, and 3½ and ρ_1 of station 4, the break corresponds more closely with the top of the bedrock. Finally, station 4 shows two breaks that occur within the frozen muck. The correspondence is good in places, but it is not consistent. Nevertheless, every curve, except those for station 5, which was probably located on ground thawed since drilling of the test hole, shows a pronounced break at some electrode spacing within 25 feet of the depth to the bottom of the permafrost. Thus the simple technique of picking sharp breaks may be useable in very roughly approximating the depths involved.

None of the curves in figure 15 show a pair of breaks that check with both the bottom of the muck and the top of the bedrock. Perhaps theoretical analysis would reveal a layer of coarse sediments too thin to be recorded or masked by horizontal variations in the surface layers. The importance of the last effect is emphasized by the fact that the curves show different trends at wide electrode spacings; either the bedrock is very variable or its effect is masked by surface conditions. A series of resistivity stations made where there is a somewhat thicker, thawed layer between the frozen ground and the bedrock would give a better idea of how well the thickness and resistivity of the thawed layer may be determined. However, most of the data obtained during the summer of 1952 came from localities where the thawed zone was either very thin or else was so thick that the bedrock was not reached.

Figure 16 shows a resistivity curve obtained at Eielson Field with no evidence of a frozen layer, although the drill log indicates 90 feet of frozen silt and the seismic records show a somewhat higher velocity than is found in thawed ground. The most pronounced bend in the curve corresponds rather closely to the depth of bedrock. Theoretical analysis does not raise the depth of the boundary indicated by this break as far as the bottom of the permafrost.

Unfortunately, there is very little difference between the resistivity of dry gravel and that of frozen gravel. Figure 17 shows two stations made on outwash gravel where the water table is more than 60 feet deep. The curves have a similar shape and, at moderate depths, a high resistivity decreasing to lower values at greater depths. Seismic records indicate that the peak in the lower curve represents frozen ground, whereas that in the upper curve represents very dry, unfrozen gravel. The dry gravel probably is dry permafrost that possesses the temperature and electrical properties but not the mechanical properties of frozen ground..

None of these curves show a break that corresponds to the top of the permafrost. The failure of the curves to show this break may be ascribed in some localities to the lack of a sufficient number of measurements at very small electrode spacings; no readings at electrode spacings less than 5 feet were made in the group of curves shown in figure 15, where the depth to permafrost is about 2 to 4 feet. In many other localities, however, readings were made at electrode separations considerably smaller than the permafrost depth; but none of the curves show a pronounced minimum at small electrode spacings, In fact, the only curves that show this minimum are those



Resistivity in Ohm-centimeters
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Electrode Separation (for Curve) and Depth (for Log) in Feet
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
Thawed silt
Frozen silt
Thawed silt and gravel
Schist
EIELSON NO. 2 RESISTIVITY DEPTH STATION
300 feet S 70° E of Well T
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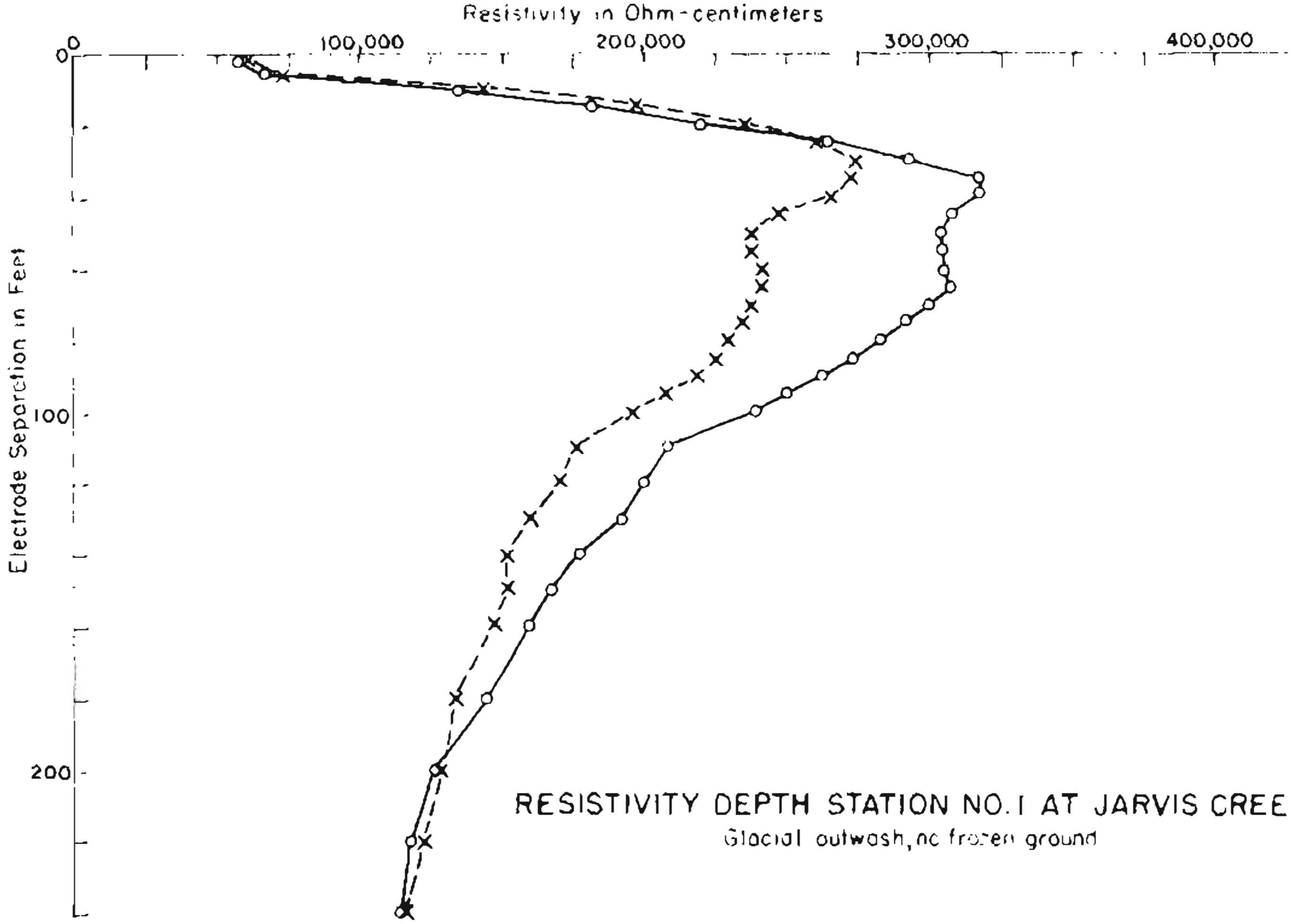
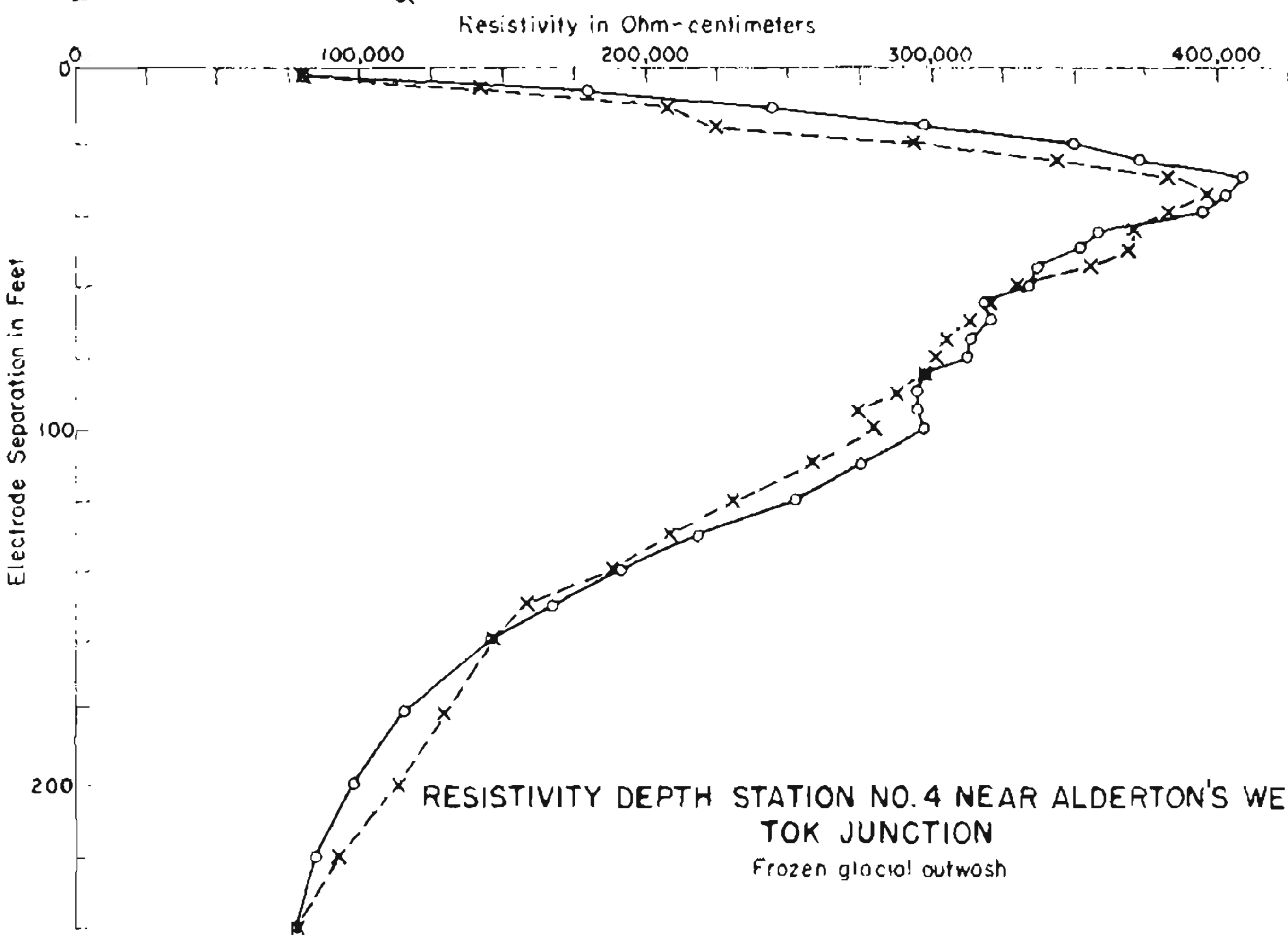
Figure 16



RESISTIVITY DEPTH STATION NO. 1 AT JARVIS CREEK

Glacial outwash, no frozen ground



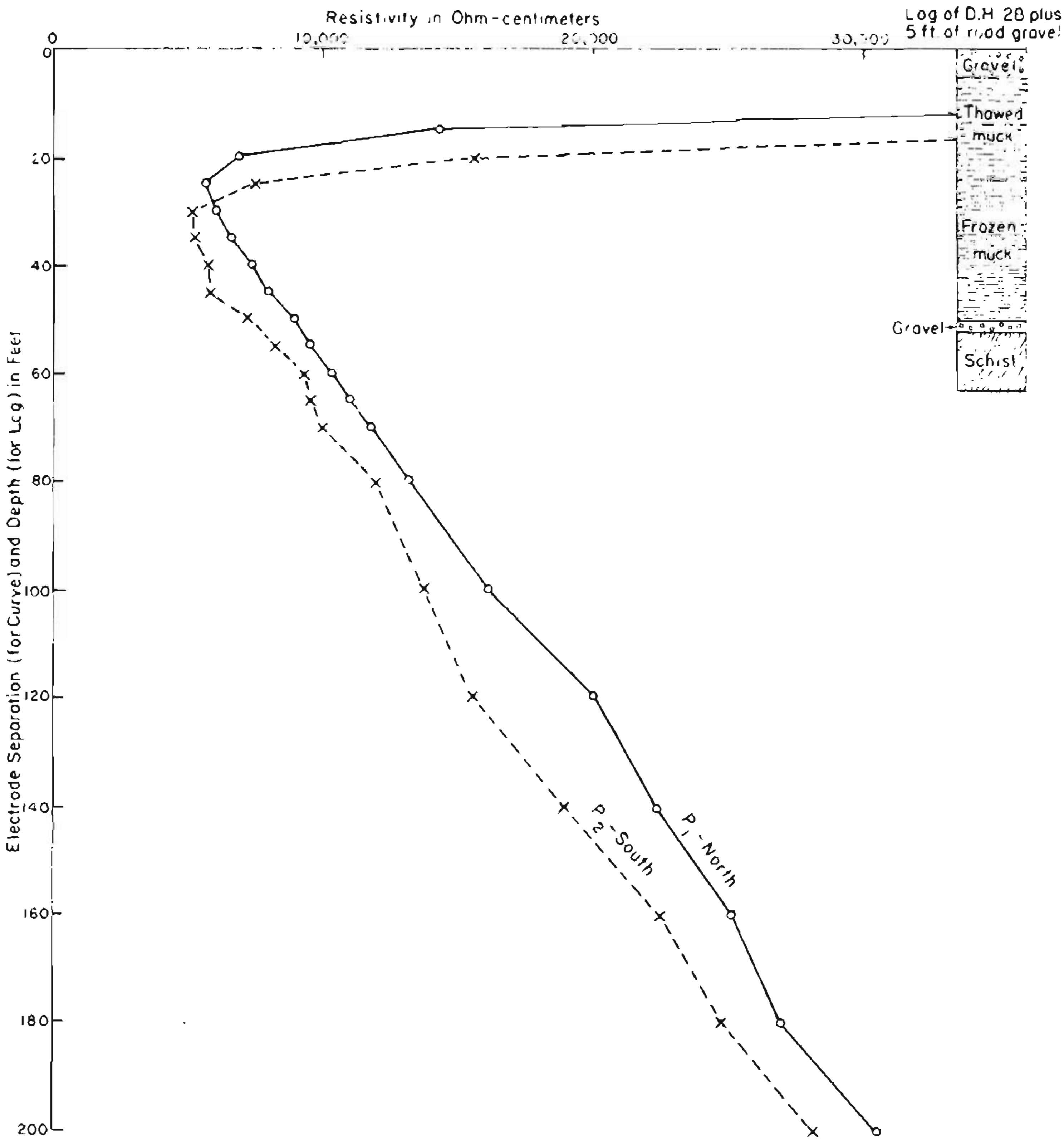
RESISTIVITY DEPTH STATION NO. 4 NEAR ALDERTON'S WELL, TOK JUNCTION

Frozen glacial outwash

Figure 17

plotted from measurements made in the late fall when the ground surface was dry; one of these October curves is shown on figure 18. A test hole was drilled at this location in 1929 but the spot has since been covered with about 5 feet of gravel to form a roadbed. The minimum in the resistivity curve corresponds very closely with the depth to the top of the frozen muck, as shown by the drill log corrected for the additional 5 feet of gravel. The ρ_2 curve on this figure indicates somewhat deeper permafrost, a conclusion that is supported by another drill hole 150 feet in that direction. The presence of a sharp minimum in the resistivity curve corresponding to the depth of permafrost thus seems to depend on a dry, highly resistive surface layer overlying a more conductive layer above the permafrost. The failure of the 1952 fieldwork to record this minimum may be ascribed to an excessive amount of rain, which kept the ground surface moist and conductive. In the more normal dry summers, the surface is probably resistive enough to cause an initial decrease and a resultant minimum in the curves.

The use of sharp breaks and a one-to-one correspondence between depth and electrode spacing is only one of a number of empirical methods of interpreting resistivity data. Moore's method, in which cumulative curves are plotted, is very common, but attempts to apply this technique to the 1952 summer data have not produced useful results. MacCarthy has suggested plotting the function $\frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$, obtained from the resistivities on each side of the Lee configuration, against electrode separation as a guide to picking the depth to interfaces, a method which seems to work rather well in some situations. Attempts to use this technique in permafrost areas fail to give consistent results.



RESISTIVITY CURVES AT LINE 30, HOLE 28, GOLD HILL

Figure 18

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Theoretical analysis and model experiments have shown that there is seldom a one-to-one correspondence between depth and electrode separation. A few resistivity cases have been solved theoretically, however, and these solutions can be used in the analysis of field data.

Most Arctic ground-water problems involve at least four layers: a thawed surface, a permanently frozen layer, a layer of thawed sediments, and bedrock, Unfortunately, there have been almost no theoretical solutions of the four-layer case. The three-layer case has been solved where the first-layer thickness is 1/4, 1/2, or 3/4 of the depth to the third layer and the resistivity ratios have a fairly large variety of values (Wetzel and McMurry, 1937). The active layer in permafrost is, however, usually 1/10 or less the thickness of the frozen layer, so these three-layer curves are not directly applicable. The two-layer case is completely solved and may sometimes be extended to three or more layers.

Figure 10 shows a log-log plot of a very simple resistivity curve obtained at a spot near Engineer Creek where a layer of frozen muck, thawed for about 2 feet at the surface, directly overlies bedrock. The curve's only deficiency is a lack of sufficient points at small electrode separations to give a reliable indication of the surface layer. With a reasonable number of readings (three to six) within the first 10 feet, Roman's two-layer superposition curves (1934) could easily be used to determine the resistivity and the depth of the first layer. The solid line on the left hand side of the figure is obtained from these curves. It was chosen with a knowledge of the depth of the permafrost as predicted by probe tests. There would be little difficulty, however, in choosing it if readings had

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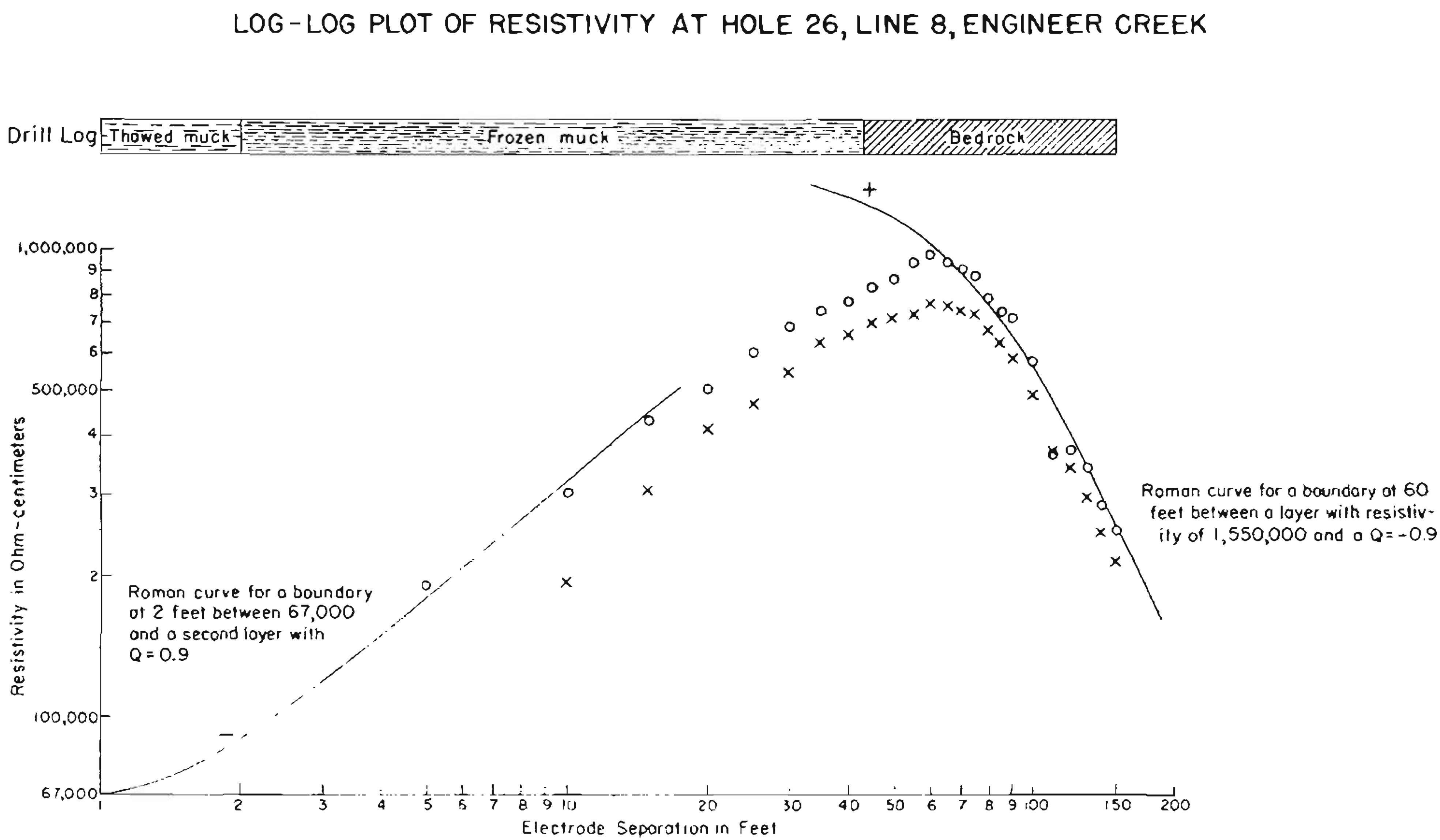


Figure 19

been made at 1- and 2-foot separations. At other stations made during the summer, where readings were made at small separations or where the depth to permafrost was large, Roman's curves gave quite satisfactory indications of the permafrost depth. Furthermore, the determination of the depth of the first layer works equally well whether the surface is wet or dry. When the ground surface is dry, of course, the determination of permafrost depth is a three-layer problem, but it is one that can be solved by the extension of two-layer solutions. Application of theoretical analysis to the latter case shows that for many of the resistivity relationships common in Alaska, the minimum inflection point in the resistivity curve occurs at an electrode separation that is between 100 and 125 percent of the interface depth. This confirms the empirical rule of Swartz and Shepard.

The two-layer curves can be extended to three-layer cases when the first two layers can be combined to form one fictitious layer. The commonest method for combining two layers is to use Hummel's assumption (1931) that the thickness of the combined layer equals the sum of the thicknesses of the component layers ($H_h = h_1 + h_2$) and that the resistivity of the combined layer equals the average longitudinal resistivity of the two constituent layers in parallel:

$$\frac{H_h}{\rho_h} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2}$$

This method is widely used and seems to be fairly accurate for sedimentary conditions in which the highest resistivity is encountered at bedrock depths. Many investigators (Wetzel and McMurry, 1937; Watson and Johnson, 1938), however, have shown that it is very inaccurate in cases where the highest resistivity is in the second layer--those curves that show a pronounced maximum. Unfortunately, this is the condition that prevails in the subarctic, where the highest resistivities are in the permafrost layer. The line drawn from Roman's curves to approximate the right hand side of figure 19 represents an interface at a depth of 60 feet, which is considerably greater than the drill log's 43-foot depth to bedrock.

Maillet (1947) has proposed another method for combining two layers which seems to work much better than Hummel's for resistivity curves that show a pronounced maximum. He proposes that the fictitious layer have a thickness and conductivity such that both its longitudinal and transverse resistivities equal the sum of those of the component layers. In other words, the thickness and sum of the fictitious layer is determined by solving two simultaneous equations:

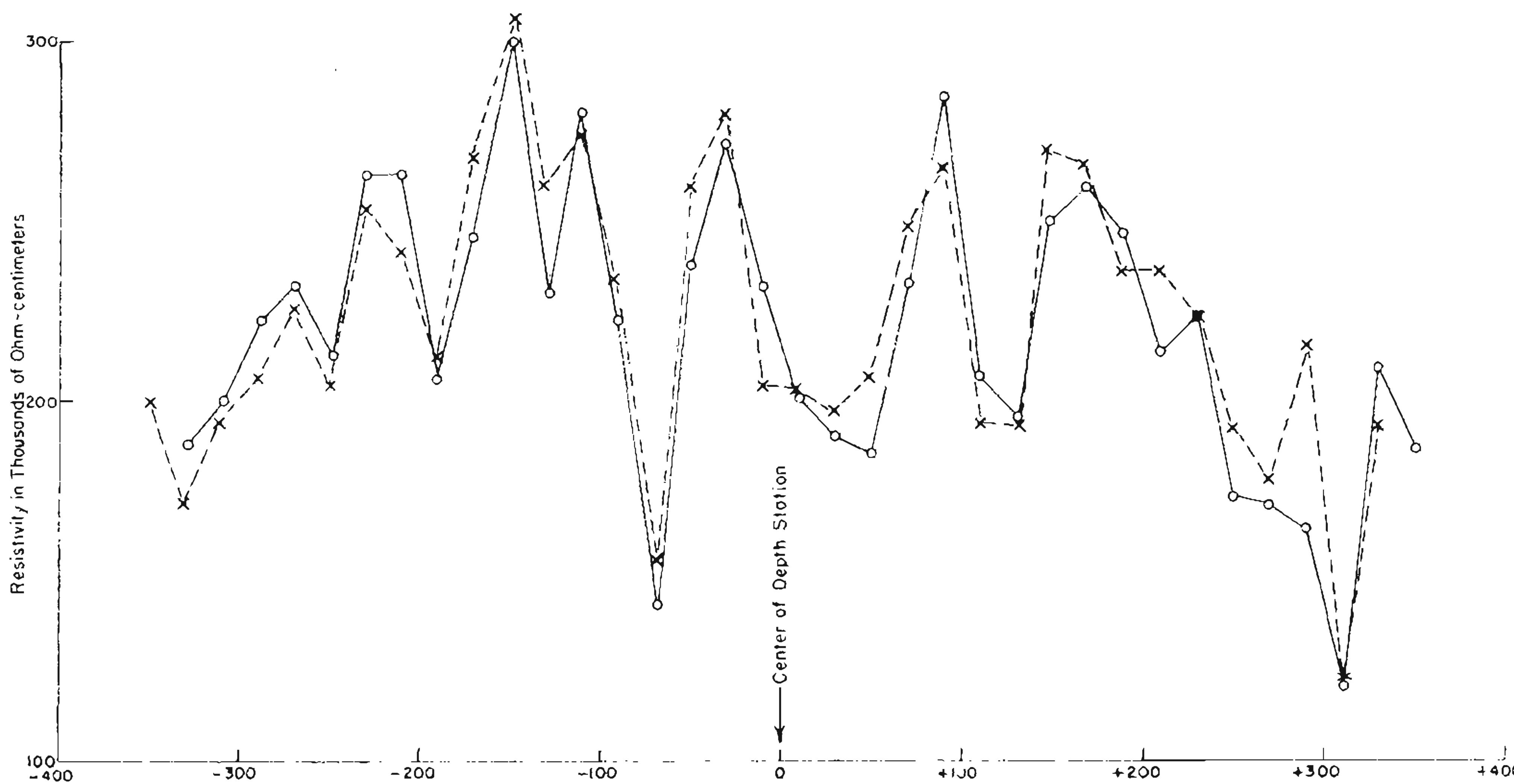
$$Hm \; Pm = h_1 \rho_1 + h_2 \rho_2$$

$$\frac{Hm}{\rho_m} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2}$$

Application of this rule to the interpretation of the curve shown in figure 19 gives a bedrock depth of 39 feet, although the value varies between 35 and 50 feet depending on the choice of first-layer thickness and resistivity, which are not accurately determined because of a lack of points on the curve. In general, application of Maillet's principle to the interpretation of permafrost problems shows considerable promise, but many more curves will have to be analyzed before a reliable evaluation of the method can be made.

Actually, very little theoretical analysis has been done on the resistivity data taken in interior Alaska. Both Roman's method (1934) and Tagg's (1937) should be tried on a number of typical curves. The chances for success with most of the data are not great, because these data were taken for empirical analysis and are not ideally adaptable to theoretical analysis. Observations made for theoretical analysis should include more readings at small electrode separations and should be carried out to electrode spacings several times as large as the desired depth of penetration. Indeed, one of the greatest limitations of resistivity depth measurements is the extremely large spreads required to get a curve suitable for theoretical analysis; with large thicknesses of permafrost, the spreads would probably be so large that the method would be impractical. In general, curves made in 1952 are more suitable for theoretical analysis, although there is less correlating drill data available for this group.

Almost all resistivity curves taken in Alaska show an extreme irregularity that makes matching them to smooth theoretical curves very difficult if not completely impossible. This extreme irregularity can almost definitely be attributed to variations in the surface layer encountered by the electrodes as the spread is increased. As the contrast between the resistivity of thawed and frozen material is extremely large, slight variations in the depth of this interface have a marked effect on the shape of a depth curve. Figure 20A shows the most irregular curve obtained during the summer, and figure 21 shows a resistivity profile made along the same line after the interpreter had given up trying to draw any conclusions from the depth curve. Figures 20B and 20C show four resistivity profiles plotted on a vertical scale proportional to the movements of the stakes and pots in making the depth stations. An approximate



RESISTIVITY PROFILE AT 40 MILE JUNCTION

Figure 21

correlation between the highs on the resistivity profile and the lows on the depth curve is obvious for the C_1 electrode, and similar correlations can be made for the other electrodes.

When the contrast between deep layers is small, these surface irregularities can completely mask the effects of vertical layering. The failure of the curves in figure 15 to show any consistent bedrock trend is attributed to the masking effect of surface variations. Actually, the bedrock resistivity probably does not differ greatly from that of the overlying sediments and its effect is easily obscured.

The influence of these lateral variations could perhaps be reduced by two techniques that have not yet been thoroughly tested in Alaska. The use of commutated current makes possible the elimination of porous pots and allows the use of four identical metal stakes, which may be so balanced as to handle equal currents at each stake setting. This system is reported to have reduced lateral effects in other areas. It might also be possible to estimate the influence of lateral effects from a constant depth profile made along the measurement line. Considerable study would be required before the practicability of this method could be established.

Natural Potential Tests

A few natural potential observations were made to determine whether any distinct changes in potential accompanied permafrost boundaries, as it was thought that the decrease in chemical activity accompanying freezing might have a marked effect on the electrical potentials. A number of horizontal traverses across abrupt changes in permafrost depth produced no significant natural potentials, and even a horizontal traverse along a placer cut exposing alternate areas of thawed muck, frozen muck, and clear ice failed to show any consistent changes. Figure 22 shows the variation in potential found on a vertical profile over a placer cliff that exposed frozen muck overlying thawed muck. The thawed muck shows a somewhat higher potential, but the effect is not marked.

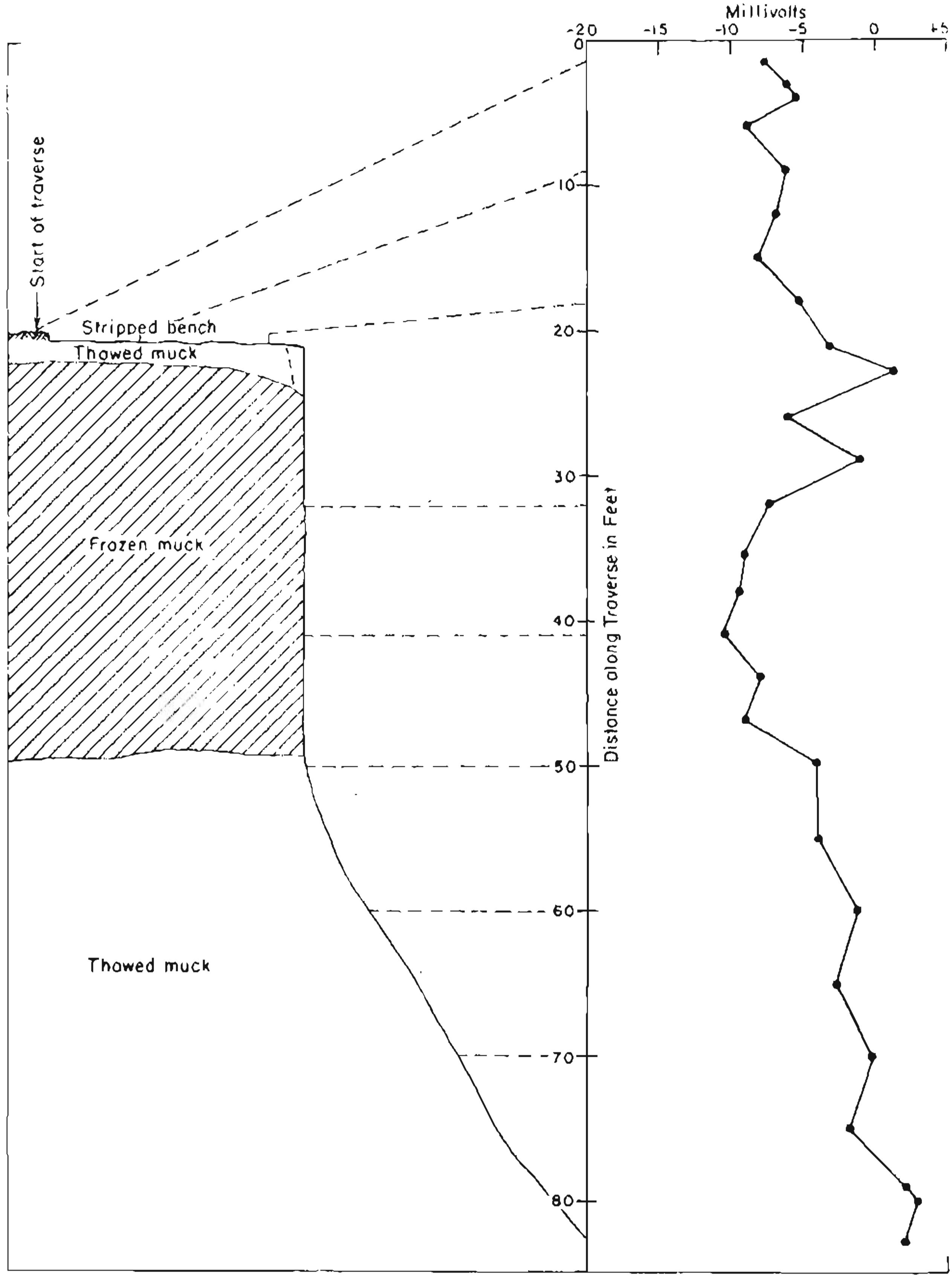
SUMMARY AND RECOMMENDATIONS

Comparison between Seismic and Resistivity Methods

The applications of both the refraction seismograph and electrical resistivity geoscope to Arctic ground-water problems have been discussed individually. A comparison of the effectiveness of these techniques follows.

When there is no frozen ground, seismic refraction can determine the depth to water table and the depth to bedrock. Resistivity, however, can usually distinguish between aquifers and impermeable sediments as well as determine bedrock and water-table depths. Thus in temperate climates resistivity methods have a somewhat broader application to ground-water problems than seismic methods.

In the Arctic both methods are capable of defining the horizontal extent of frozen ground. A high seismic velocity is an almost sure indication of its presence and can only be misinterpreted as bedrock. Resistivity profiling gives a very clear indication of the boundaries between frozen and unfrozen ground, but reliable interpretation requires additional data, because the resistivity changes can also be caused by variations in the type of sediment or in the depth of the frozen ground. The additional data can frequently be supplied by resistivity depth stations. Dry gravel or thick coverings of clay, however, can cause incorrect interpretation of depth stations.



NATURAL POTENTIAL OVER PLACER CLIFF AT GOLD HILL

Figure 22

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Both methods are also capable of determining the depth to the top of the permafrost, and neither method is greatly influenced by the thin layers of seasonal frost which sometimes destroy the accuracy of probing tests. Although skill is required in determining the proper surface velocity for seismic computation, the method is capable of considerable precision in contouring the depth of the permafrost table. If the ground surface is dry, empirical analysis of resistivity gives a rapid determination of the depth of the permafrost, but theoretical analysis is required for measurement of a homogeneous thawed layer.

Neither method regularly yields reliable information regarding the material beneath the top of the permafrost. Seismic methods occasionally show the depth to bedrock when the latter's velocity is sufficiently high or when the initial arrival is attenuated. Resistivity methods should theoretically reveal the thickness of the permafrost, the depth to bedrock, and the character of the intervening sediments; but in practice their present development permits only an approximate determination of permafrost thickness. Very careful theoretical analysis of resistivity curves may yield somewhat greater information, but very long spreads and highly skilled interpretation are required.

Seismic methods cannot be used in the vicinity of construction work or other sources of noise, and electrical methods cannot be employed near buried metallic conductors. Seismic observations can be made by crews as small as three men, only one of whom needs to be well trained. Resistivity methods require at least four men, and six men are needed for efficient and economical operations, but only two of these need much training. The operator of the seismic instrument needs more training than the operator of the resistivity apparatus, but the interpretation of seismic data requires much less skill.

In general, seismic methods are at present the most adaptable to military use, but the resistivity methods have the greatest future potentialities.

Recommendations

The program begun in 1952 is far from complete, and the need for further work is obvious. The greatest need at present is for a thorough examination of the data already obtained, including the results obtained in 1952. In addition, two more fundamental theoretical investigations are desirable. One is a theoretical examination of the attenuation of longitudinal waves traveling through a thin layer. The other is the development of theoretical multilayer-resistivity interpretation of problems in which the second layer has a very high resistivity.

A certain amount of further field work is desirable and should include:
(1) tests of the Geological Survey's new shallow reflection seismograph, (2) a brief test of electromagnetic equipment, (3) additional resistivity measurements with commutated current, and (4) both seismic and resistivity measurements in areas where the bedrock possesses different physical properties from the schist usually found in interior Alaska.

In general, it seems doubtful whether geophysical techniques are sufficiently developed at present to be valuable for use by Army personnel in prospecting for ground water in areas of thick permafrost. In some areas where the permafrost is thin and sporadic, a seismograph might be useful for both ground-water and engineering applications, and recently a number of small, portable, and fairly suitable seismographs have been developed by commercial companies.

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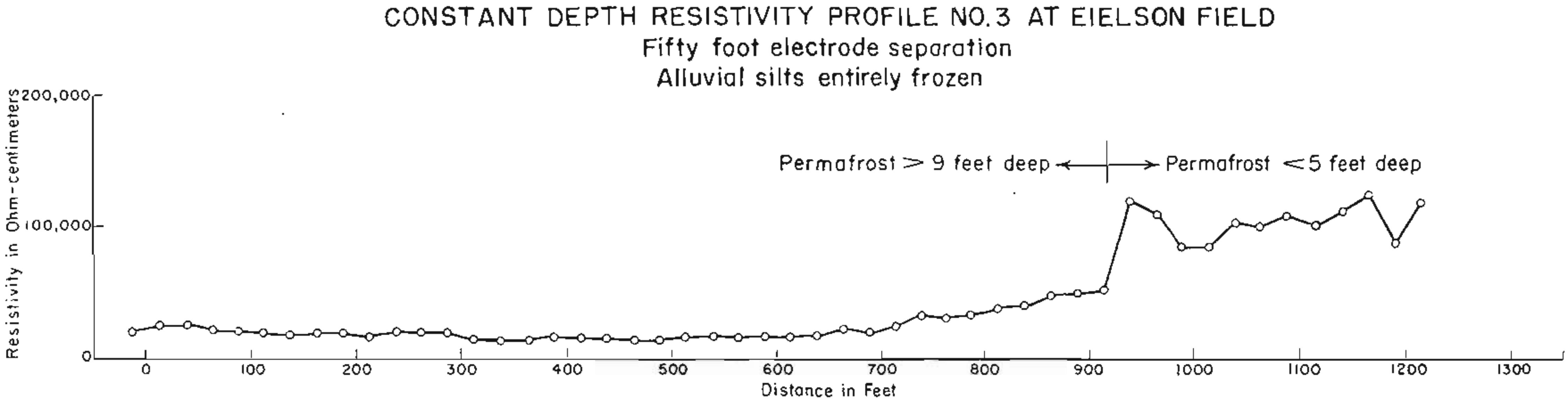

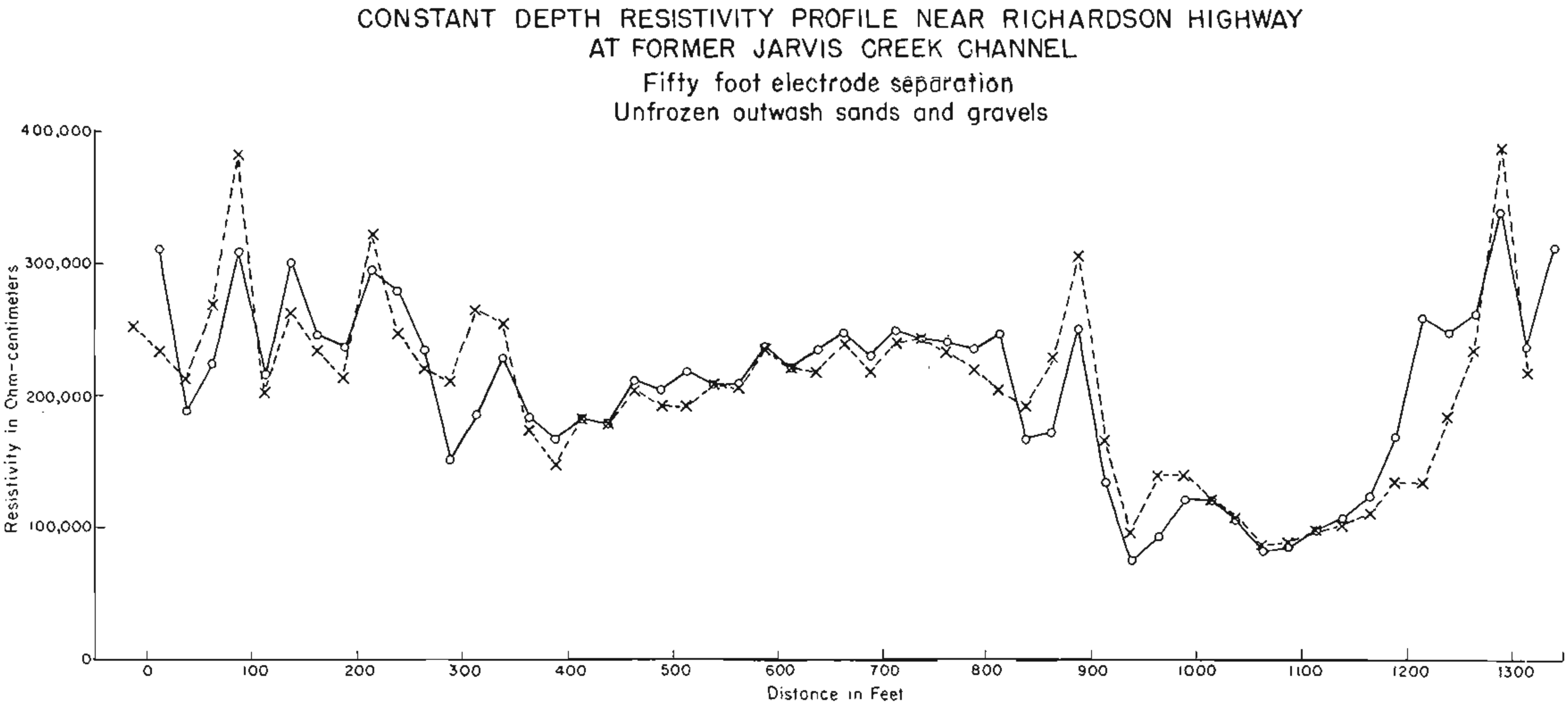

Figure 14

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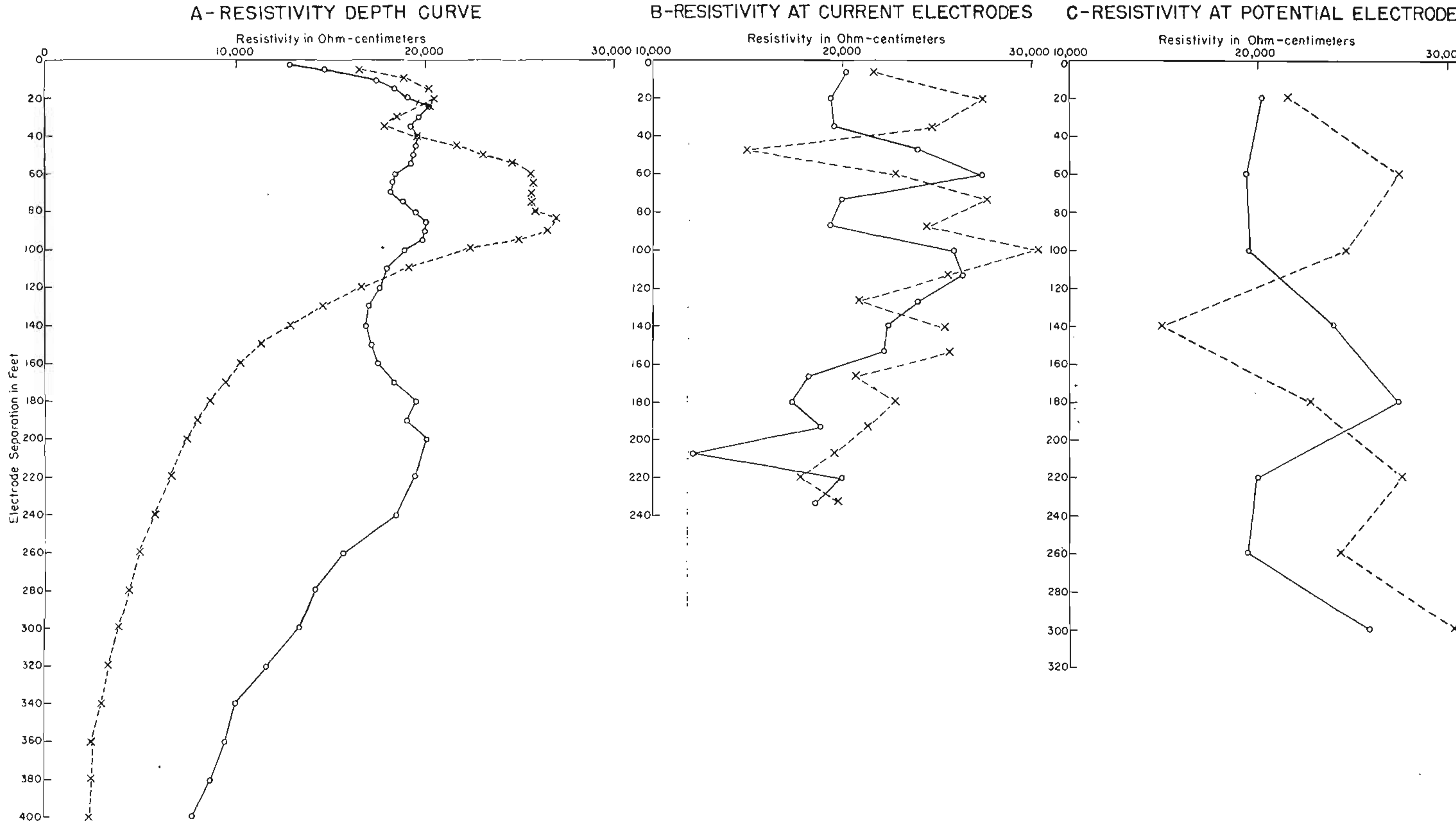

INFLUENCE OF HORIZONTAL VARIATIONS IN RESISTIVITY ON DEPTH CURVE AT 40-MILE JUNCTION

Figure 20

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