II.2. SEISMIC REFRACTION AND ELECTRICAL RESISTIVITY MEASUREMENTS OVER FROZEN GROUND

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During the summer of 1963 a geophysical test programme was conducted near Kettle Rapids on the lower Nelson River in northeastern Manitoba to determine the feasibility of using refraction seismic and electrical resistivity methods for predicting depth to rock through frozen ground in connection with hydroelectric site studies for the Manitoba Hydro. Subsequent refraction seismic surveys were made from mid-summer through early fall of 1963 and 1964 along the Nelson River at Gillam Island, Limestone, Long Spruce, Kettle, Gull, Bladder and Warren's Landing sites. The principal objectives of these investigations were to provide reconnaissance subsurface information pertaining to depth of bedrock and delineation of overburden strata for preliminary engineering planning and to assist in selecting locations for test drilling.

Most of the sites explored lie within the discontinuous permafrost zone and, although the principal objective of the investigations was not to delineate the limits of frozen overburden, some knowledge of the applicability of the electrical resistivity and refraction seismic methods for this purpose was gained as a byproduct of these studies. This paper will be confined to those features of the geophysical investigation which are directly concerned with detecting lateral and vertical limits of frozen ground and determining depths to rock beneath frozen overburden.

ELECTRICAL RESISTIVITY METHOD

The electrical resistivity measurements were limited to six locations at Kettle Rapids during the initial test program in early July of 1963. The equipment employed for this investigation was a DC-type electrical resistivity meter. These measurements were carried out to a maximum electrode separation of 200 feet using the Wenner 4 electrode configuration and voltages of 22.5 to 180 volts DC.

The most striking feature of the resistivity data is the extremely wide variation in resistivity values calculated for the overburden in adjacent areas in spite of the fact that the overburden materials are of a similar nature. In all cases the resistivity measurements were made at the location of existing test borings in order to furnish correlation for these data. At one location, Resistivity Test #4 at Drill Hole 37, a methyl blue frost indicator was installed which has furnished further information for correlating the resistivity data.

Figure 1 gives a graphical comparison of the results obtained from the six resistivity tests. For this comparison the field curves are shown in the left hand column, the values having been determined by the formula

$$R_a = \frac{E}{I} A$$

where R_a is apparent resistivity, E is volts, I is current and A is electrode separation in feet. The centre column shows reduced values of resistivity, in ohm feet, as determined by the Barnes Layer Method. It would have been desirable to interpret the field curves by one of the several curve matching methods but the resistivity contrast is too great for the type curves that are presently available. The right hand column shows a generalized log of the boring at each of the resistivity locations.

The pertinent feature of the field curves is the abrupt deflection of the graph at electrode separations between 0 and 40 feet. Extreme deflections of the graph such as seen here are uncommon in our experience. It may be noted that the Barnes Layer graphs tend to exaggerate the inflection points on the field curves. Some of the Barnes values, as shown on tests #4, #5 and #6,approach infinity and although it is theoretically impossible for the current to penetrate zones of infinite resistance, abrupt reductions in resistivity values are observed beneath these zones of infinite or very high resistance.

In comparing the resistivity results to the generalized logs of the test borings it can be seen on the Barnes graphs that extremely wide resistivity variations generally occur at locations where frozen overburden was indicated on the logs of test borings. One exception occurs at Resistivity Test #6 where the overburden was more granular than at the other locations; it is doubtful if the granular material could have been sampled in a frozen condition.

The resistivity curves suggest that there are resistivity variations between unfrozen and frozen ground. It is somewhat difficult to compare the apparent depth of current penetration (or electrode separation) with the indicated depths of frozen ground shown on the drill logs. It should be pointed out, however, that frozen overburden samples were obtained with great difficulty and that zones of frozen material may therefore exist that are not indicated on the bore logs.

In conclusion, the very high resistivity values of frozen overburden precludes, in many cases, the use of the resistivity method for determining depths to rock. The exceptionally high values should however, be readily detected in areas of discontinuous permafrost thus enabling one to define the lateral limits of frozen zones and to determine their approximate thickness. In our opinion the results obtained in this limited experiment are encouraging and further study of the applicability of this method to the detection of vertical and lateral limits of frozen ground is warranted.

SEISMIC REFRACTION METHOD

Approximately 200,000 feet of refraction seismic traverse was completed in connection with the Nelson River investigation, a large percentage of which was conducted in areas of frozen ground within the discontinuous permafrost zone.

Portable 12-channel seismic recording equipment with 7.5 cycle per second geophones was used for this work. Seismic energy was obtained by detonating small charges of explosives at depths from one to three feet below the ground surface or by using air shots. Geologically the area in which these investigations were made is similar to that previously described in connection with the electrical resistivity studies.

In general, the seismic velocity of water saturated sand and gravel, dense till and compact clay ranged between 6,000 and 7,000 feet per second where these materials were unfrozen. In areas where thin lenses of frozen material were suspected, velocities of 7,500 feet per second were recorded increasing up to 14,000 feet per second as the suspected thickness of frozen zones increased.

The effect of thin zones of frozen material in the overburden upon the seismic data is relatively minor and reasonably accurate interpretation of depth to rock can be made without difficulty but thicker frozen zones cause confused seismic recordings such that accurate interpretation becomes difficult, if not nearly impossible. Such confusion is the result of a large percentage of the seismic energy being diffracted, diffused and reflected between high velocity zones in the overburden with the net result that the energy is rapidly attenuated. Under a condition where thick discontinuous lenses of high velocity frozen overburden overlies low velocity unfrozen overburden, the path over which seismic energy travels in a reserved seismic refraction profile may be diverse rather than identical. Generally speaking, refraction arrivals from frozen ground are of higher frequency than those from bedrock. In our experience frequencies in excess of 30 cycles per second are usually recorded from thick frozen zones and frequencies less than 20 cycles per second recorded from bedrock or unfrozen overburden.

Frozen ground is suspected when high-frequency, high-velocity early arrivals, observed near the shot point, attenuate rapidly into lower-frequency, lower-velocity energy, and when total times from reversed refraction profiles are not the same, indicating that the shock waves travel along different paths depending upon the direction travelled. Sample recordings displaying these conditions is shown in Figure 2 along with a recording which has been made over unfrozen ground.

We have concluded from these studies in discontinuous permafrost zones that thin lenses of frozen overburden do not seriously affect seismic recording but thick lenses of frozen material cause considerable confusion.

It has been possible to outline generally the lateral limits of areas of moderate to thick lenses of frozen overburden by seismic methods but not to accurately determine the thickness of the frozen layers. Depth to rock calculations through frozen overburden have been found to be reasonably accurate but generally less accurate than those made where data was obtained over unfrozen overburden.

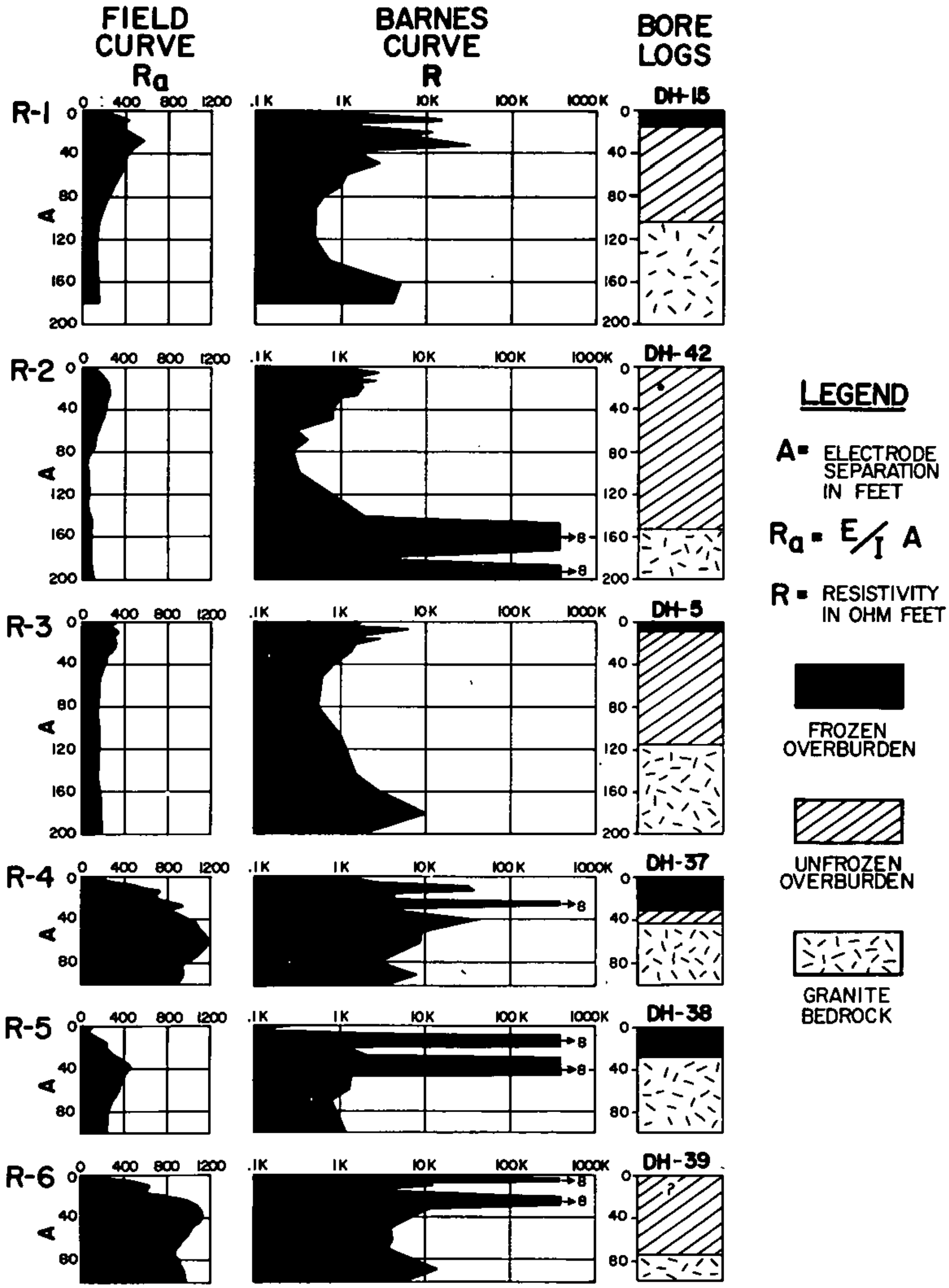

FIGURE 1 ELECTRICAL DATA IN FROZEN GROUND

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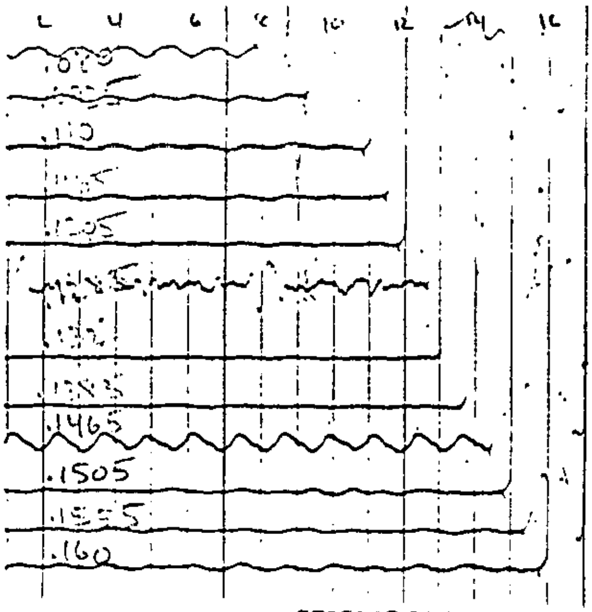
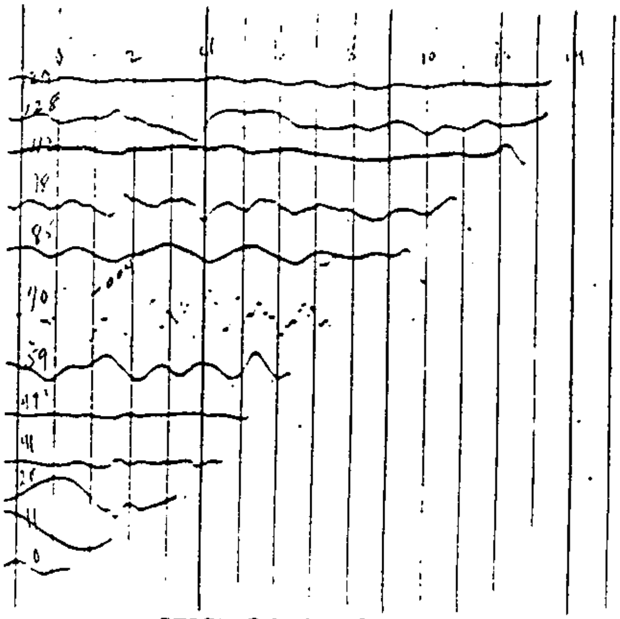
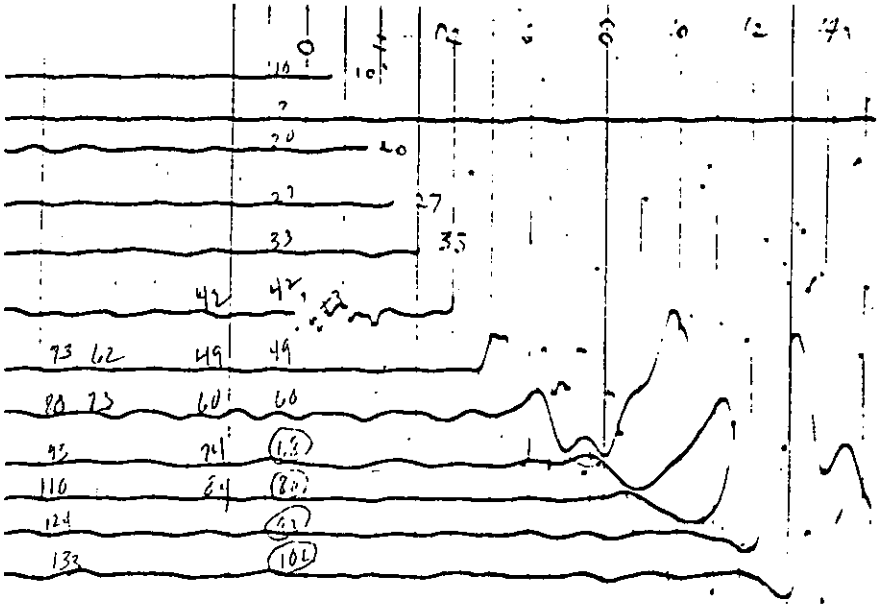


SEISMOGRAM 1
A normal seismogram made over unfrozen ground.



SEISMOGRAM 2
A recording made over frozen ground containing thin lenses of frozen material. Note high frequency early arrivals.



SEISMOGRAM 3
A recording made over thick lenses of frozen ground. Note high frequency, high velocity early arrivals followed by low velocity, low frequency arrivals from underlying, unfrozen overburden.

FIGURE 2 TYPICAL SEISMOGRAMS

Discussion

R.J.E. Brown asked J.G. Fyles to describe the geophysical investigations carried out by the Geological Survey of Canada in the Yukon Territory. Fyles replied that a seismic programme was established in the Klondike area to determine whether the depth to bedrock could be determined beneath frozen overburden. Results were compared with boreholes drilled by the Yukon Consolidated Gold Corporation. Many of the seismic readings were within 2 per cent of the observations obtained in the boreholes but a considerable number did not compare favourably. It was assumed that irregularly shaped thawed areas occurred in the permafrost which distorted the seismic propagations. A paper describing this project will be published in the near future in the Bulletin of the Canadian Institute of Mining and Metallurgy.

S.R.L. Harding asked what type of rock was encountered by the authors in their geophysical prospecting programme. The authors were not present at the Conference but a written discussion was submitted by J.R. Rettie. In his opinion the authors have been too modest in discussing the results of their work. It is a fact that the resistivity tests performed at the Kettle Rapids site in 1963 were unsuccessful. On the other hand, seismic surveys conducted at various sites along the Nelson River by Geo-Recon Ltd. were quite effective in determining bedrock and overburden profiles. These checked out quite well with subsequent diamond drilling. The quality of work performed by this company for G.E. Crippen and Associates and Manitoba Hydro in 1963 was an important factor in its being selected to perform the larger 1964 programme. It is obvious that ability to properly interpret seismic results is essential. This function was performed in the field by either Mr. Schwartz or Mr. Bush and Manitoba Hydro is grateful for their personal attention to this aspect of the work.

With reference to the question regarding geology of the area, Rettie advised that upstream from Limestone Rapids Precambrian rock, mainly granite gneiss and schist, are overlain with plastic and varved clays. Downstream from Limestone Rapids, limestone overlies the Precambrian rock in increasing thickness, with a thin layer of sandstone between the contact. Overburden in this area consists of pervious granular deposits, dense tills and plastic clays in an irregular fashion. Discontinuous permafrost is present at Bladder Rapids and becomes more prevalent as the mouth of the river is approached.

Results of the 1964 seismic surveys are not yet available in final form but it is anticipated that they will afford reduction in the diamond drilling programme to be performed during the winter of 1964-65 and the summer of 1965. It is unfortunate that one of the authors is not present because an interesting question period would have taken place. Mr. Miles, previously associated with Geo-Recon Ltd., made an excellent presentation under difficult conditions since he had not been involved in this project. T.A. Harwood remarked that seismic velocities in Precambrian rock may be as high as 14000 feet per second resulting in possible confusion with frozen ground in interpretation.

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