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PART 2

REPORTS ON NOGAP R & D STUDIES

Real-Time Interpretation of Marine Resistivity

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1.0 Introduction

This paper describes the development of a real-time interpretation capability for the MICRO-WIP marine resistivity system. The program was carried out in 1987 by Hardy BBT Ltd. for Indian and Northern Affairs Canada (INAC). Scientific Authority for the project was Mr. R.J. Gowan of INAC. W.J. Scott of Hardy BBT was the project leader.

The detection of sub-bottom permafrost and granular deposits is very important for the design and construction of off-shore facilities in the Beaufort Sea. Granular deposits will supply valuable borrow material for construction of islands while the presence of permafrost will influence the choice of routes and construction of pipelines.

In 1980, Hardy Associates (1978) Ltd. (now Hardy BBT Ltd.) began the development of the marine resistivity system known as MICRO-WIP, (MICROprocessor controlled Waterborne Induced Polarization). In various stages of development, this system was used for fresh water work in mineral exploration and for salt-water searches for granular materials. Initial results of a survey off-shore Alaska were described by Scott et al., 1983. At that time, design of the system was relatively established and only minor changes were made from then until the commencement of the program described in this paper. The system was used in the Canadian southern Beaufort Sea in 1985 in a successful program to map granular materials for island construction (Scott and Maxwell, 1989). In this survey, it was felt that a major limitation to the 1985 system was the lack of a real-time resistivity interpretation capability.

In 1977, with INAC funding, the existing marine resistivity system hardware and computer software were redesigned to incorporate real-time interpretation of the resistivity data. The system was assembled and bench tested prior to carrying out a field trial. Descriptions of the equipment design, bench tests and field trial results are presented in this report. Since the 1987 INAC program, the MICRO-WIP has been transferred to a PC-based system, which is also briefly described in this paper.

2.0 Background

The use of electrical resistivity measurements has long been accepted on land as a means of mapping the distribution of granular resources and permafrost (Scott et al., 1979). In general, electrical resistivity of soils is a function of grain size, with sands and gravels having a higher resistivity than silts and clays. This relationship holds even when the pore water in the materials is saline. Furthermore, frozen materials have much higher electrical resistivities than the same materials in an unfrozen state.

Figure 1A, after Scott and Maxwell (1989), shows values of electrical resistivity for some typical soils on land as a function of temperature. From this figure, it is clear that freezing the soil generates a drastic increase in its resistivity. Figure 1B shows the range of resistivity values for typical soils on land. The higher the resistivities observed in soils, the more coarse-grained those soils are likely to be, provided that temperature and moisture content conditions are similar. A similar relationship prevails for seabed materials, although the actual resistivity values are smaller. Results of the 1991 survey, as yet unpublished, indicate that increasing gas content in a soil increases resistivity as well.

2.1 Resistivity Measurements

Measurement of resistivity on land or water involves injection of electrical current through two electrodes and measurement of the resulting potentials between other electrodes. A quantity known as apparent resistivity is calculated from these measurements in the following manner:

$$\rho a = (V/I) * f(G)$$

Where: ρa = apparent resistivity.
I = the injected current.
V = the observed voltage.
f(G) = a function of the geometry of the electrodes.

If V is in volts, I is in amperes and the distances in f(G) are in metres, then the units of ρ are ohm-metres (Ω-m).

If the ground under the electrode array is homogeneous to a depth much greater than the size of the array, then the measured apparent resistivity would be equal to the true resistivity of the earth. Such a uniform case rarely occurs in nature, the apparent resistivity usually represents some function of the distribution of values in the earth within the range of the measurement.

The general procedure in making electrical resistivity measurements involves varying the size of the array and thus, the volume of ground affected by the measurement and observing changes in apparent resistivity as a function of this variation. The resulting set of observations is called a sounding.

The array most commonly used in marine resistivity is the multi-dipole array. For this array, an increase in depth of penetration is normally accomplished by increasing the spacing between transmitter and receiver dipoles, while keeping the dipole size constant. The expansion of array sizes is carried out in terms of the dipole multiple "n". The smallest array is with $n = 1$. In this case, the distance between the nearest transmitter and nearest receiver electrode is one dipole length. Increased penetration is achieved by increasing the number of dipole lengths separating transmitter and receiver dipoles. In practical field situations, the largest separation normally achievable is limited by signal strength to $n = 6$. Thus, a multi-dipole sounding consists of six apparent resistivities calculated for $n = 1$ to 6.

2.2 Interpretation of Resistivity Measurements

Once a set of apparent resistivity values has been measured, interpreting the results of electrical surveys to identify granular materials or permafrost is a two-part process. The first part is obtaining a model which fits the observations, the second part is making the correlation between the model parameters and the type of soil to be expected.

Resistivity models are described by layer thicknesses and resistivities. In the case of a multi-dipole sounding, the apparent resistivities for $n = 1$ to 6 can be used to develop simple models involving the water and two sub-bottom layers lying on a half space. The resistivity and thickness of the water can be determined by independent means. Sub-bottom materials can be modelled in terms of two layers lying on a half space. In areas where granular materials are expected to be close to the bottom, variation of resistivity in these upper two layers would be indicative of variation of grain size in the near sub-bottom.

The parameters of the model are obtained from the measured apparent resistivities by an inversion process. A first estimate is made of the model resistivities and thicknesses and the apparent resistivities which would be observed for this model are calculated. These resistivities are compared with those observed in the field and adjustments are made in the model parameters in the direction which minimizes the disagreement between observed and calculated apparent resistivities. Normally, several cycles of calculation and adjustment will bring the calculated and observed apparent resistivities into reasonable agreement, provided that a good initial model is used.

It should be understood that it is frequently possible to obtain more than one model which will satisfactorily match the observed apparent resistivities. Thus, it is important that the starting model be reasonably close to the situation which is being investigated. External control such as drillhole information, sub-bottom profile information and geological inference can thus be used to help sharpen the precision of the geophysical interpretation.

2.3 Measurement Techniques for the MICRO-WIP

Marine resistivity measurements with the MICRO-WIP system are made by means of a streamer towed behind a survey vessel. This arrangement is shown schematically in Figure 2. The multi-dipole array is incorporated into the streamer. The two electrodes nearest the survey vessel are used to transmit electrical current into the water and sub-bottom materials. The other seven electrodes on the streamer are used to measure the resulting voltage distribution as a function of distance from the source and consequently, as a function of penetration into the sub-bottom. These seven electrodes allow the calculation of the six values of apparent resistivities as discussed above. Experience in the Beaufort Sea in 1985, indicates that a current of 15 amperes is adequate to give reliable signal levels for measurements of this sort with a dipole length of 25 m and separations of $n = 1$ to 6.

2.4 1985 MICRO-WIP Survey, Southern Beaufort Sea

During the summer of 1985, the system was operated in the Beaufort Sea to map resistivities in support of evaluation of granular resources (Scott and Maxwell, 1989). This survey was carried out prior to the dredging of material to build an artificial island. Despite very bad ice conditions which allowed only very limited access to the survey area, some 40 km of survey data were obtained during a two day period. After completion of the survey, however, a ten day period elapsed before the first preliminary interpretation was provided to the client. A further period of a month ensued before presentation of the detailed interpretation.

Fortunately for the future of MICRO-WIP, other geotechnical information had already indicated the presence of granular material and the borrow pit was successfully established shortly after the preliminary interpretation was supplied. The final interpretation showed that the borrow pit was indeed in the optimum location.

From the 1985 survey several things emerged. The first was the need for real-time processing in order to avoid delay in providing interpretation. The second was an understanding of the general range of resistivities to be expected in the sub-bottom materials. These resistivities correlated reasonably well with those initially determined by Scott (1975) in resistivity soundings carried out through the sea ice in the same general area. The 1985 survey further provided some observed values of apparent resistivity as a function of dipole spacing which could be used in simulated trials with modified equipment.

It was in light of this experience that the 1987 INAC development program was undertaken. The objective of this program was to develop the capability to carry out interpretation in real-time, in order that reconnaissance surveys could be performed shortly before dredging, with interpretations produced shortly thereafter.

3.0 System Design and Testing

To provide real-time interpretations, two functions had to be developed within the system. The first of these was the averaging of the digitized wave forms and calculation of apparent resistivity values. The second was to invert the apparent resistivity values in terms of a three-layer model. Within the time constraints of real-time processing, it did not appear possible to perform both functions in a single computer. It was, therefore, decided to carry out the first function within a data acquisition system (DAS) and the second in the computer which controlled the DAS.

A Hewlett Packard HP 3852 data acquisition and control system was selected. The system could be configured for a variety of applications. It had built-in intelligence, an internal clock and a programmable pacer which could be used as timing control for remote devices. A controller was built to turn the transmitter on and off in synchronization with the timing supplied by the pacer signal in the HP 3852. A Hewlett-Packard 9816 computer was selected to drive the DAS and to run the inversions.

To test the system in the laboratory, a resistance network was devised to simulate a streamer in the sea. With this network and a very low-powered transmitter, bench tests were conducted to refine the performance of the real-time inversion routines.

Finally, the entire system was installed on a suitable vessel for a field trial on Okanagan Lake, British Columbia. There the real-time resistivity interpretation capability of this system was demonstrated during the field trial.

Two computer programs were developed to run the system. Both of these have now been superseded by the PC-based programming and thus, will not be described in detail here. The first program down-loaded a set of instructions to the DAS to set up the system pacer, scan the amplifier channels, stack the voltages and check the gains. The main program initialized the plotter, started the DAS, read data from the DAS, ran the inversion and plotted the real-time resistivity section.

In the 1991 system, the DAS has been replaced by a set of data acquisition boards installed in the PC, which stack the incoming signals and store the results directly in memory. The PC then uses these values to calculate the apparent resistivity and chargeability values. At present, the system does not have the real-time inversion implemented, but the programming is structured to include inversion and the routines developed in 1987 will be incorporated in the near future.

4.0 Choice of Electrode Array

The 1985 survey was performed with an array of 25 m dipoles and n = l to 6. This array was initially designed for mineral exploration, where arrays with constant dipole size are common. The combination of water depth, water resistivity and sub-bottom conditions in the 1985 Beaufort Sea survey area was such that the 25 m array gave good definition of the surface layers and at the same time, adequate penetration to map relic permafrost at depth.

Subsequent computer modelling supported by an Industrial Research Assistance Program (IRAP) Grant suggested that better resolution of deep features and better definition of near-surface resistivities could be obtained with an array in which the receiver dipole size increased logarithmically with distance from the transmitter dipole. As part of the IRAP program, such a streamer was built. The spacings of this streamer are given in Table 1.

Because the 1985 data were taken with constant dipole lengths, the simulator network was established for this configuration, but the data acquisition system and inversion routines were configured to handle either constant-spacing arrays or logarithmic-spacing arrays.

Table 1 - Logarithmic Streamer

Distance (m)	Identification	Electrode
0	Start of Cable	
		C1
25		
	Current dipole	
50		C2
60		P1
	Potential Channel 1	
70		P2
	Potential Channel 2	
85.75		P3
	Potential Channel 3	
107.75		P4
	Potential Channel 4	
141.25		P5
	Potential Channel 5	
189.25		P6
	Potential Channel 6	
260.50		P7

5.0 Simulation of Beaufort Sea Measurements

Within the time and cost constraints of the 1987 INAC program, it was impossible to collect real data from the Beaufort Sea with the modified system. It was, however, possible to predict, from forward modelling programs already in existence, the apparent resistivities that would be observed with the new system over given geologic conditions and to choose a network of resistors that would provide the appropriate signal levels.

The interpretation carried out on the data from the 1985 survey showed that the resistivity of the sea water in the southern Beaufort Sea was typically about 2.0 Ω-m (interpretations of data from the 1991 survey, over a wider area, show variations of sea water resistivity from 1 to 8 Ω-m). In electrical terms, the sub-bottom materials in the 1985 survey area could be represented by three layers. The uppermost layer appeared to have resistivities ranging from 1.6 to 2.6 Ω-m. From the limited drilling carried out to a establish the borrow pit, it appears that this range of resistivities spanned materials from clayey silts to coarse sands with occasional pebbles. Within the survey area, none of this material appeared to be frozen.

The bottom-most layer interpreted in the 1985 survey had resistivities which ranged from a low of 10 Ω-m to a high of >500 Ω-m. The variation of resistivity generally reflected the depth to the top of the layer, with the highest resistivities occurring where the layer was shallowest. A single drillhole intersected permafrost at the interpreted depth to the top of this layer within the borrow area. From the high interpreted resistivities and from the fortuitous intersection in the borehole, it was concluded that the high resistivity parts of this layer represent the ice-bonded material and that the ice content generally correlated with the interpreted resistivity values.

An unexpected outcome of the interpretation procedure was that between the uppermost layer, (1.6 to 2.6 Ω-m) and the deepest (permafrost) layer, there appeared to be a layer of significantly lower resistivity (0.5 to 1.5 Ω-m). This layer has no apparent direct geological correlation. However, work in the Alaska Beaufort Sea, (Sellmann, P.V., 1985 personal communication) suggests that there is a pronounced increase in salinity of pore waters immediately above the degrading permafrost. Such an increased salinity would result in lowered resistivities and would provide a reasonable explanation for the observations from the 1985 survey.

Table 2 summarizes the likely set of conditions which would be encountered in looking for granular materials in the southern Beaufort Sea. While this is a reasonably comprehensive set of geologic conditions, the innate perversity of nature is such that it is not possible to predict all configurations which are likely to be encountered. Furthermore, it should be realized that even with the logarithmic array, the maximum number of layers that can be resolved is three layers lying on a half space. Forward calculations can be carried for all of the models in Table 2 and a set of observed of apparent resistivities can be derived. However, in cases with more than three layers, the inversion will not necessarily lead back to the starting model. This is an intrinsic limitation of resistivity methods and must be recognized if application of marine resistivity is contemplated.

This problem, known as the problem of equivalence, can be resolved to some extent if acoustically determined boundaries coincide with some of the electrically defined boundaries. For example, it is obviously possible to define the bottom of the water (top of seabed) with a depth sounder and thus to remove the influence of the water from any model by calculation. In the case of Group 5 (Table 2), the top of the granular material under the silts and clay should constitute an acoustic reflector unless the fines are gas-saturated. In such a case, fixing the thickness of the fine-grained layer from the sub-bottom profiler record will aid in resolving such equivalences.

Table 2
Typical Sub-Bottom Geological Configurations*

Model No.	Lateral Material [ρ (Ω-m), t (m)]
1A	Granular (2.2,20)/Saline (1,20)/Permafrost (100,∞)
1B	Granular (2.2,10)/Saline (1,10)/Permafrost (500,∞)
1C	Granular (2.2,20)/Saline (1,20)/Unfrozen (10,∞)
2A	Fines (1.6,20)/Saline (1,20)/Permafrost (100,∞)
2B	Fines (1.6,10)/Saline (1,10)/Permafrost (500,∞)
2C	Fines (1.6,20)/Saline (1,20)/Unfrozen (10,∞)
3A	Permafrost(20,2)/Granular (2.2,20)/Saline (1,20)/Permafrost (100,∞)
3B	Permafrost(20,2)/Granular (2.2,10)/Saline (1,10)/Permafrost (500,∞)
3C	Permafrost(20,2)/Granular (2.2,20)/Saline (1,20)/Unfrozen (10,∞)
4A	Permafrost(15,2)/Fines (1.6,20)/Saline (1,20)/Permafrost (100,∞)
4B	Permafrost(15,2)/Fines (1.6,10)/Saline (1,10)/Permafrost (500,∞)
4C	Permafrost(15,2)/Fines (1.6,20)/Saline (1,20)/Unfrozen (10,∞)
5A	Fines (1.6,5)/Granular (2.2,20)/Saline (1,20)/Permafrost (100,∞)
5B	Fines (1.6,20)/Granular (2.2,10)/Saline (1,20)/Permafrost (100,∞)

Table 2 shows 14 likely geologic configurations, of which only 1A, 1B and 2A, the three most representative of conditions encountered in the 1985 survey were built into the physical simulator.

In order to provide a realistic transition from one of the three models to another, it was necessary to prepare a series of intermediate models so that the variation in measurement could proceed incrementally as would be the case in a field survey. Five or six intermediate steps were chosen between the three models.

A single simulator network requires fourteen resistors. The three models, with the necessary transition resistor arrays as well, represented an array of 154 resistors. Physical simulation of larger numbers of models becomes extremely difficult without a large investment in switching and resistor arrays.

The simulator starts with Model 1B (Table 2). Rotation of the selector switch moves through the transition resistors, arrives at Model 2B and then through more transitions to Model 1A. Thus with the MICRO-WIP receiver connected to the output of the simulator, it was possible, by rotating the selector switch, to simulate a survey starting in granular material on ice-bonded permafrost, passing into an area of silts and clays on ice-bonded permafrost and then on into an area of granular material on low-resistivity permafrost. Turning the switch in the opposite direction would run the simulated survey in the other sense.

Figure 4 shows parts of the survey results for a "two-way run" through the simulator. The apparent resistivities are referred to by their fiducial numbers, shown along the top of the section. Model 1B is represented by the interpreted resistivities at Fiducials 2 and 108. Model 2B is represented by Fiducials 26 and 78 and Model 1A by Fiducial 52.

It is reassuring to note that there is good agreement between the two interpretations for Model 1B,(Fiducials 2 and 106) and for Model 2B (Fiducials 26 and 52). Hence, the inversion has indeed led back to essentially the original model in each case. The interpreted resistivity of the upper layer repeats within about 1.5% and surprisingly, the resistivity of the deepest layer repeats exactly. The most poorly determined layer is the conductive (saline) middle layer, whose resistivity is interpreted to only within about 7%.

Note that the resistivities presented on the simulated data set did not match exactly the model resistivities presented on Table 2. This occurred because the current supplied by the simulation network was incorrect by approximately 10%. Since it is a constant difference, it does not affect the conclusions reached for the simulated trial.

In general, resistivity interpretations provide resistivities to a precision of only a few percent. However, the experience in the Beaufort Sea was that with slowly varying apparent resistivities, the repeatability of estimates of resistivity for near surface materials was within 2 - 5%. The variation in interpreted resistivity values as a function of grain size was in the order of 40% and thus, well beyond the likely error of interpretation.

6.0 Field Trials in Okanagan Lake

Once the system had been proven on the simulator network, it was then taken into the field for an operational trial. Okanagan Lake was chosen because it was the nearest body of water to Calgary which was of sufficient size and which was likely to be navigable during the winter time. The field trials were carried out in mid-February, 1987.

Okanagan Lake is a long lake which runs approximately north-south through the central part of British Columbia. The lake is typically 5 km wide and extends over 100 km from Penticton in the south to Vernon in the north. The test area was situated at Kelowna, B.C. Figure 5 is a location map that shows the approximate area of the lake in which the trials were carried out.

In the deeper parts of Okanagan Lake, the water depth is up to 300 m. The depth sounder operated with the MICRO-WIP system has a useable water depth of 120 m. This depth was exceeded several times during the trials. In the neighbourhood of Kelowna, there are significant areas where water depths ranged from 4 to 8 m and the bottom was relatively smooth. It was felt that the deeper water would allow an assessment of the noise level of the system in a uniform medium and the shallow areas would represent operating conditions which are similar those expected in the Beaufort Sea.

In Okanagan Lake, water resistivities are approximately 30 times greater than those of the Beaufort Sea. By the same token however, sub-bottom resistivities are also 30 times higher; the contrast between water and bottom is therefore reasonably similar to that to be expected in the Beaufort Sea.

Very little is known about the unconsolidated deposits in Okanagan Lake. However, Nasmith (1981) describes the surficial geology of sediments in the neighbourhood of the lake. From Nasmith's description, it appears that the sediments underlying the shallow portions of the test area are deltaic deposits derived from the mixed fine and coarse sediments lying above Kelowna. The shallower areas are predominantly fine grained silts and clays while granular areas are exposed on the slopes on the edges of the shallows.

Rocks exposed on shore in the neighbourhood of this survey showed intense shearing. The rocks under the lake are probably even more strongly sheared and water-saturated as well. They would, therefore, be expected to have resistivities of a few hundred ohm-metres. It is reasonable to assume that the bedrock resistivities would be in the same ratio to the shallow sub-bottom resistivities as would permafrost resistivities in the southern Beaufort Sea to the overlying sediments.

While the geology of Okanagan Lake is obviously different from that to be expected in the Beaufort Sea, resistivity contrasts from water to sub-bottom sediments to deeper sub-bottom materials should be in the same general proportions as those in the Beaufort Sea. Because resistivity interpretations deal primarily with contrasts between resistivities of layers rather than with absolute values, it is reasonable to use this area as a test site for assessing the performance of a system designed for the Beaufort Sea.

The major difference would be that in the Beaufort Sea, to obtain readings at the same level of confidence, much higher transmitter currents would be required. It is probable that currents would have to be approximately 30 times higher to compensate for the approximately 30 times lower general resistivities. The survey on Okanagan Lake was carried out with 0.5 amps while measurements in 1985 in the Beaufort Sea used 15 amps. Thus it appears that the ratio of currents used in the two settings is approximately in proportion to the ratio of the resistivities to be observed.

The primary purpose of the field trials was to establish that the modified data processing system could provide inversion of resistivity data in real-time. The field survey was thus broken into two parts. The first was to establish the noise levels in the system and demonstrate that these are low enough not to interfere with the measurements. The second was to demonstrate that the inversion technique provided answers within the real-time constraints of operating the survey.

Because of budgetary limits, a minimum set of equipment was deployed for the survey. The minimum equipment included the MICRO-WIP and an analogue-recording depth sounder with a digital output. The depth sounder was deployed in order to provide water-depth information as part of the input to the inversion process.

The budget constraints prevented the use of the sub-bottom profiler and magnetometer which normally would be part of this survey system in the field. Furthermore, because no exact geological control was available, it appeared unnecessary to employ the precise navigation system which normally would be part of the survey.

The MICRO-WIP system performed extremely well on trials with only minor modifications necessary to provide smooth functioning. The Huntec Lopo transmitter used in this survey produces an extremely noisy wave form, which was filtered to remove high-frequency components. The filtered wave form was essentially the same in character and frequency content as that which is normally obtained from the high-powered system used in the Beaufort Sea.

In this survey, for the first time, the raw data consisted of the six apparent resistivities associated with the six dipoles, normally stored on disk. Figure 6A shows a plot of the pseudo-sections of apparent resistivity and chargeability derived in the field and plotted in real-time. The beginning of the line is in deep water. This represents essentially the noise level of the system in a homogeneous medium. The end of the line is in water depths of 4 to 8 m. These resistivities and chargeabilities in mineral surveys, constitute the raw data which is recorded with the system in its present configuration. Figure 6B shows the results of real-time inversion of the raw data on a different line, in terms of a layered model.

It should be emphasized that without control, it is difficult to come to an absolute determination of the accuracy of the interpretations. However, the resistivity values and thicknesses determined for the sediments appear to be consistent with those derived from the on-shore geological model. Resistivities range from sixty to several hundred ohm-metres and the resistivity of near surface materials appears somewhat higher in areas where granular material would be expected.

7.0 Discussion and Recommendations for Future Work

The development program described in this paper resulted in a system which operated on a variety of surveys, in freshwater lakes mainly in Ontario and Quebec. The major limitation of the system was that the operator was required constantly to adjust the gain settings to avoid saturation and maintain adequate signal levels. The DAS used in the system was not capable of sufficient calculations to monitor and adjust the gains. Accordingly, in 1991, it was decided to transfer the system to an IBM-PC compatible computer and to incorporate automatic gain control. This work was completed just in time for a survey in August, 1991, funded by Atlantic Geoscience Centre, EMR, through NOGAP. Unfortunately, the real-time inversion programming had not been transferred by the time of the survey, although it is expected to be ready by the summer of 1992. The survey included side scan sonar and two sub-bottom profilers as well as the MICRO-WIP resistivity system. The results are now being compiled.

There is a relationship between lateral resolution and survey speed. One inversion is carried out for every 32 seconds worth of data. At a survey speed of 1 km/h, each sounding represents a lateral translation of approximately 9 m. At a survey speed of one knot, each reading represents a distance of approximately 16 m and at a survey speed of three knots, each sounding represents a distance of 50 m. Thus, the choice of survey speed depends upon the lateral resolution that is required in near surface features. As vessel speed increases, so does the noise level and a practical upper limit for resistivity surveying appears to be about three knots.

Lateral resolution also depends on the array size. The volume of measurement which is represented by each of the apparent resistivities depends upon the spacing between the transmitter and receiver pair which are used for the calculation. Thus, the volume involved in measurement of shallow resistivities is quite small and a movement of 50 m may involve significant lateral variation. However, for permafrost at depths of 50 - 100 m, separation between the transmitter and the farthest spaced dipole is of the order of 200 m and thus, a lateral translation of 50 m does not imply a major replacement of the volume of measurement by new material. The desired depth and resolution of the target, therefore, will have some influence on the selected speed, as it appears feasible to make reliable resistivity measurements at the speeds of up to three knots.

There is some evidence (Olhoeft, 1975) that frozen clays give rise to small induced polarization (IP) effects. The IP effect may be a useful indicator to distinguish between frozen granular materials and frozen clays. The IP effect is more noise-sensitive than the resistivity. A survey in which IP affects are measured would probably have to be conducted at a significantly lower speed than one conducted solely for resistivity measurements. It appears that with the 1987 system, realistic measurements of IP affects can only be made at survey speeds of one knot or less. Much of the present development work is concentrated on improving this noise performance.

Present research is concentrating on electrode design and on improvement of averaging processes in the programming. With improved electrodes, it is felt that reduced noise levels would allow higher survey speeds even when measuring IP effects as well.

The marine resistivity system provides information which is a valuable supplement to, but not a replacement of normal acoustic surveys. The results of the 1991 survey indicate that gaseous sediments are easily penetrated by electrical measurements and structure which is lost in acoustic profiles can be followed with electrical measurements. Incorporation of depths from seismic surveys in post-survey interpretations improves the reliability of the electrical models and thus, of the final interpretation.

There is some evidence in the 1991 survey data that gaseous sediments have elevated resistivity values. The presence of gas in pores of a soil should also give rise to increased IP effects. It is possible that gas contents can be estimated from combined acoustic and electrical surveys.

In its present form the MICRO-WIP is clearly a useful tool for the mapping of grain-size variations in near-bottom sediments in the Beaufort Sea. If geophysical mapping of granular deposits in the Beaufort Sea is to be undertaken, then consideration should be given to the use of the MICRO-WIP system.

8.0 References

Dyck, A.V., Scott, W.J. and Lobach, J., 1983, Waterborne Resistivity/Induced Polarization Survey of Collins Bay, Wollaston Lake, in Uranium Exploration in Athabasca Basin, Saskatchewan, Canada, ed. E.M. Cameron., Geol. Surv. Can., Paper 82-11, p. 281-289.

Lobach, J.L. and Scott, W.J., 1980, A System for Resistivity Surveying in Water: *in* Scott, W.J. and Brown, R.J.E., eds., Nat. Res. Counc. Can., Tech. Mem. 128, p.35-45.

Nasmith, H., 1981, Late Glacial History and Surficial Deposits of the Okanagan Valley, British Columbia. B.C. Ministry of Energy, Mines and Resources, Bull. 46.

Olhoeft, G.R., 1975, The Electrical Properties of Permafrost, Unpublished Ph.D. Thesis, University of Toronto, 172 p.

Scott, W.J., 1975, Preliminary Experiments in Marine Resistivity Near Tuktoyaktuk, District of Mackenzie. Geol. Surv. Can., Paper 75-1, Part A, p. 141-145.

Scott, W.J., Sellmann, P.V. and Hunter, J.A., 1979, Geophysics in the Study of Permafrost: Review Paper, Proc. Third Int. Conf. on Permafrost, **2**, National Research Council of Canada, p. 93-115.

Scott, W.J., Laing, J.S. and Botha, W.J., 1983, Waterborne Resistivity/Induced Polarization Survey in Prudhoe Bay. Proc. Fifteenth Off-Shore Technical Conference, Houston, May, 1983, p. 227-230.

Scott, W.J. and Maxwell, F.K., 1989, Marine Resistivity Survey for Granular Materials, Beaufort Sea: J. Can. Soc. Expl. Geoph. **4**, 4, p. 104-114.

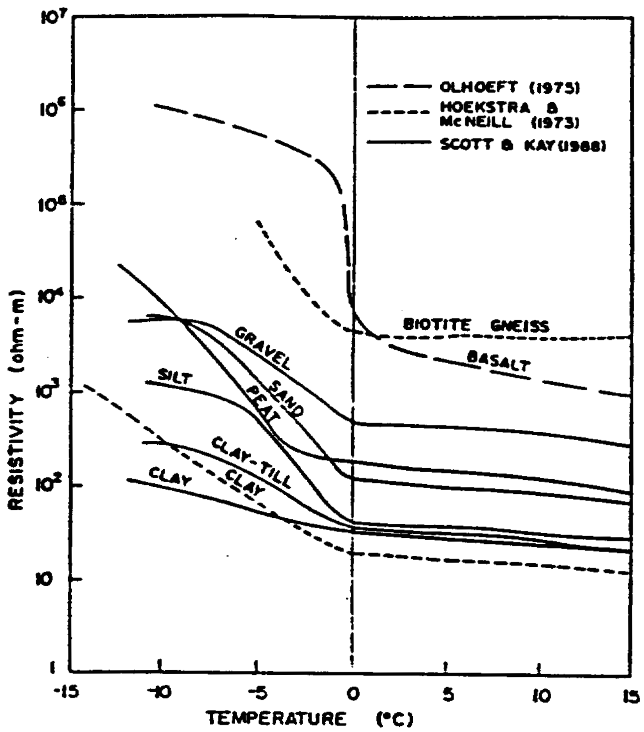

Figure 1: a) Resistivity as a function of temperature.

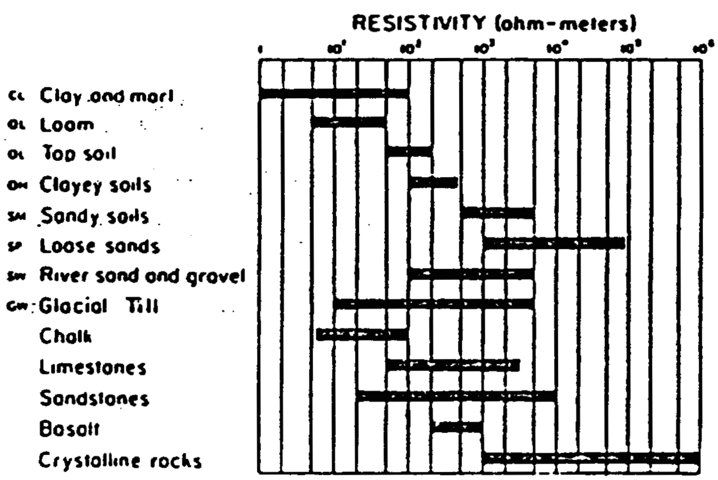

Figure 1: b) Resistivity ranges for typical soils. (Scott and Maxwell, 1989)

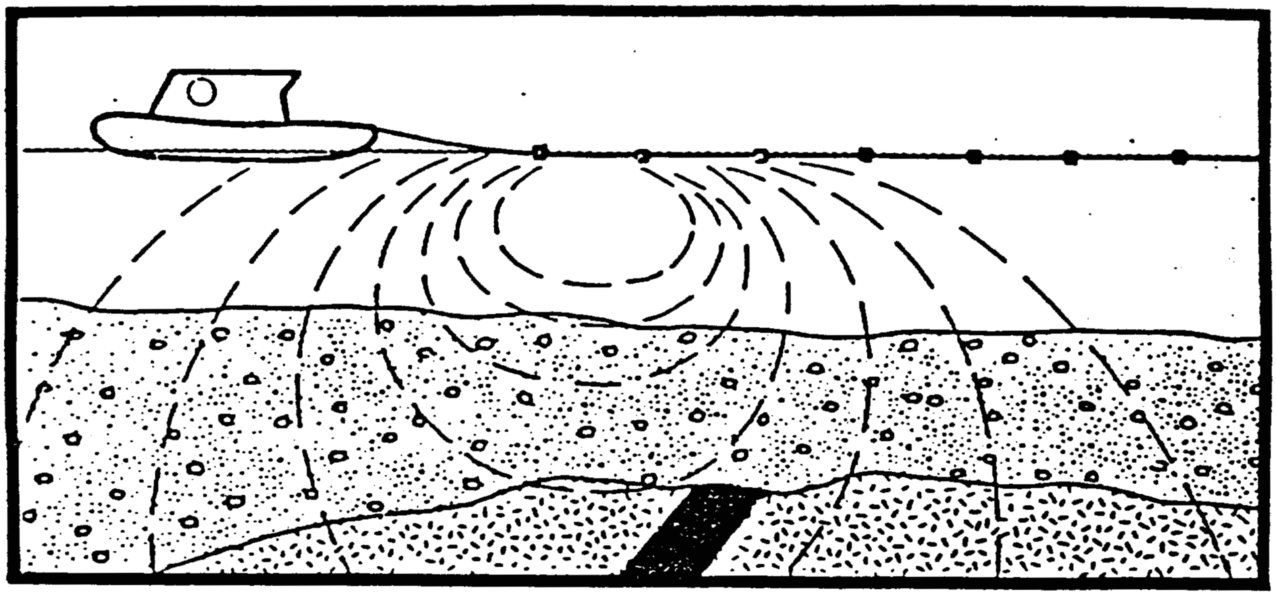

Figure 2: Schematic layout of MICRO-WIP marine resistivity system.

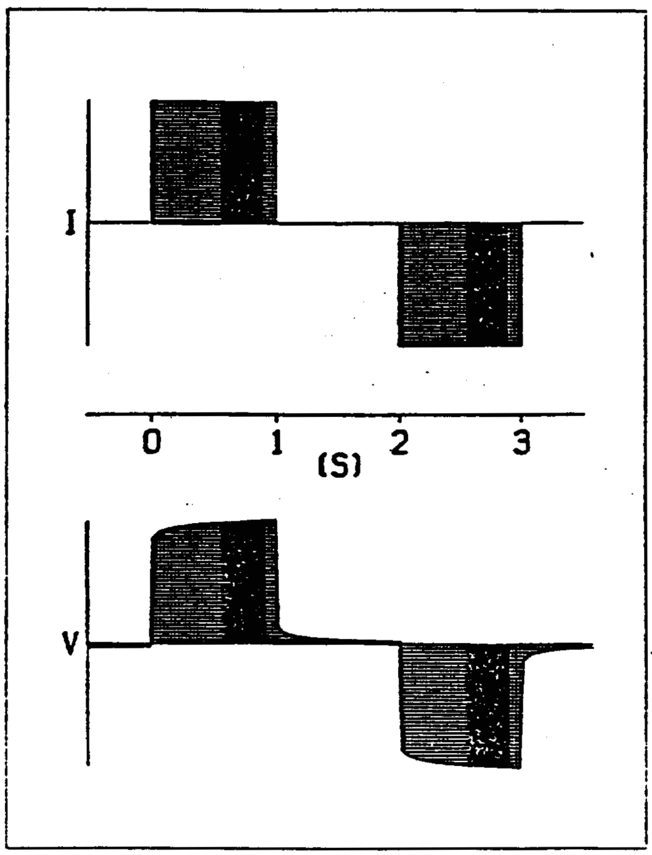

Figure 3: Waveforms of current and voltage, showing measurement windows. (Scott and Maxwell, 1989)

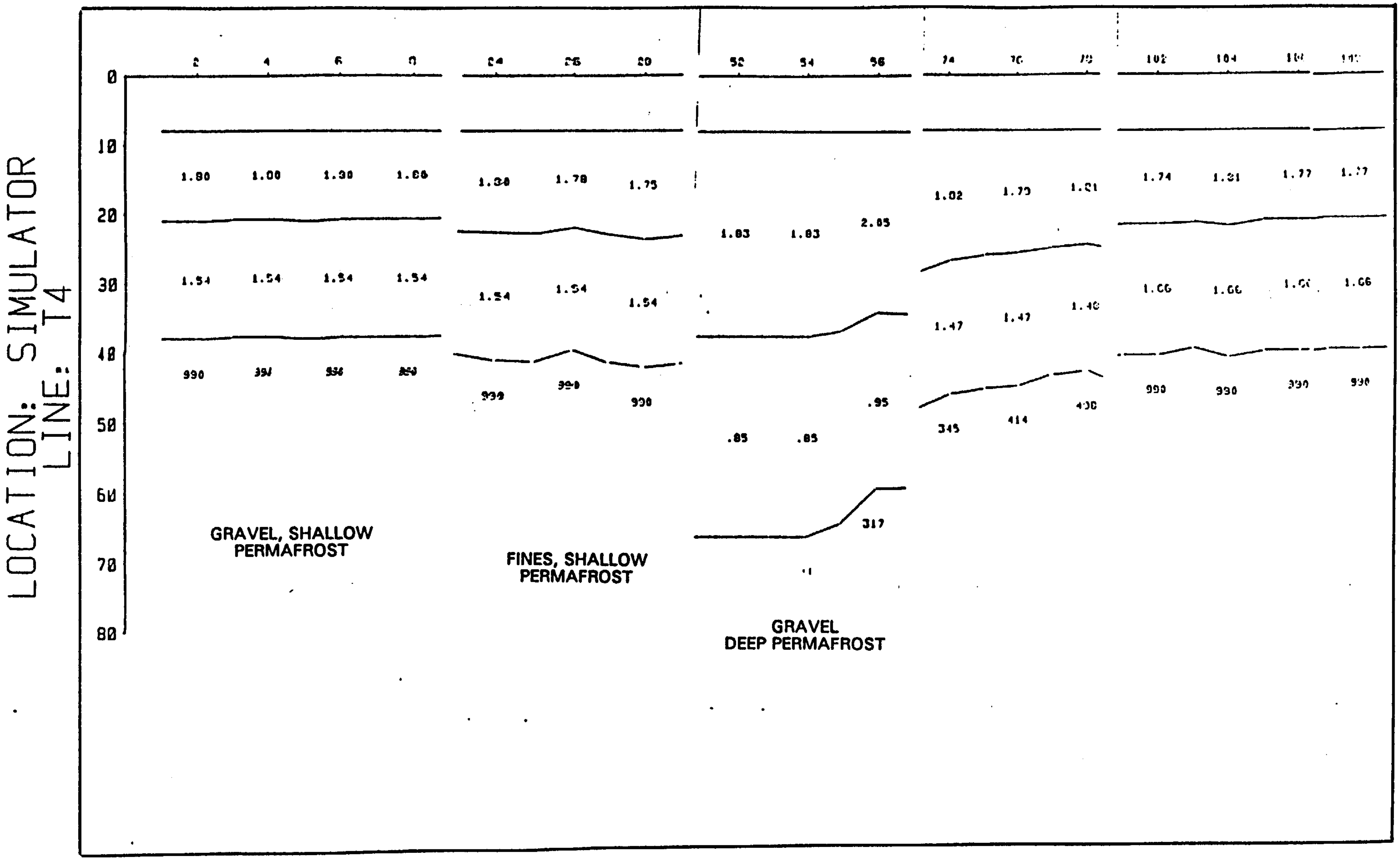

Figure 4: Parts of real-time inversion results from simulator run.

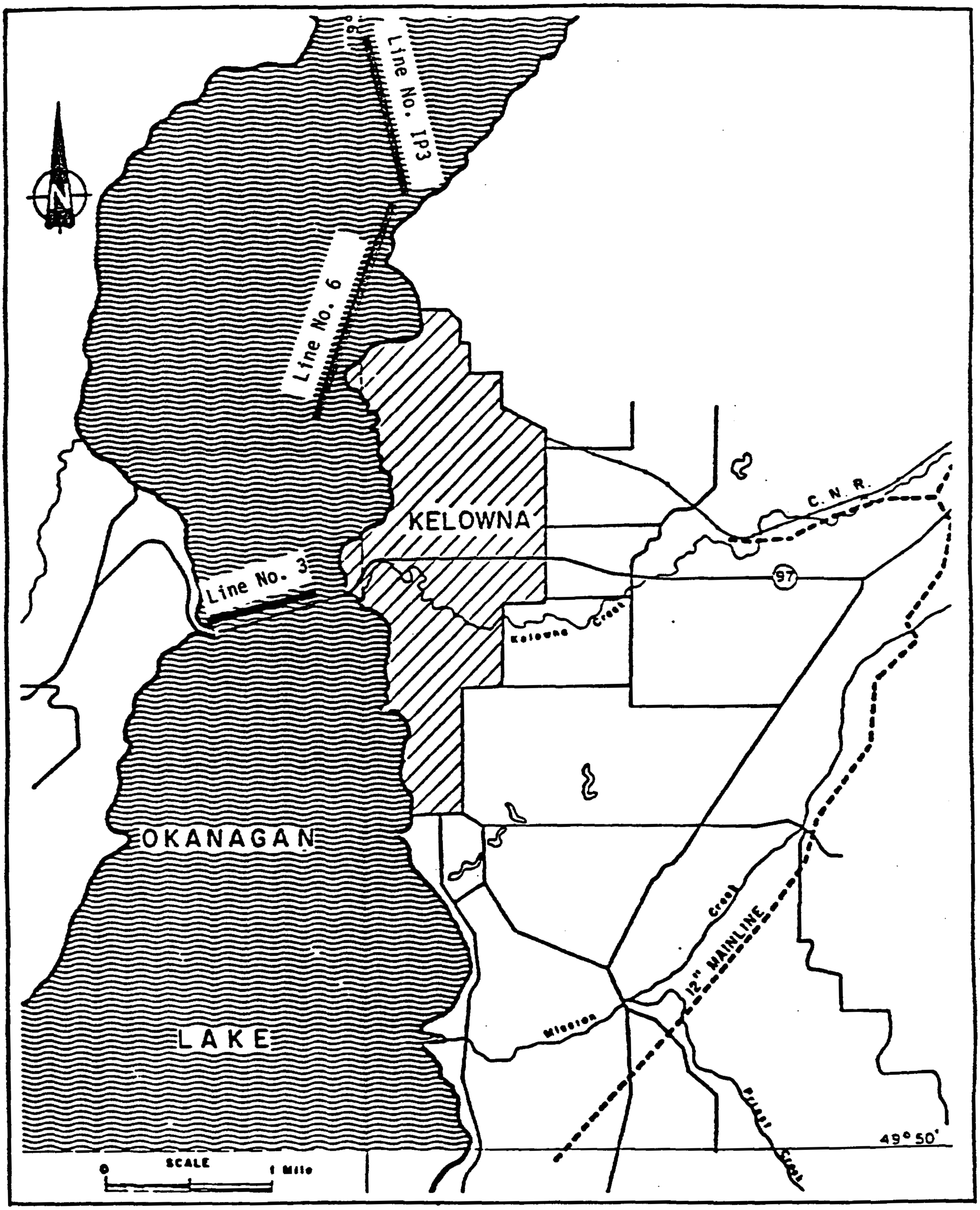

Figure 5: Okanagan Lake, showing survey lines for field trial.

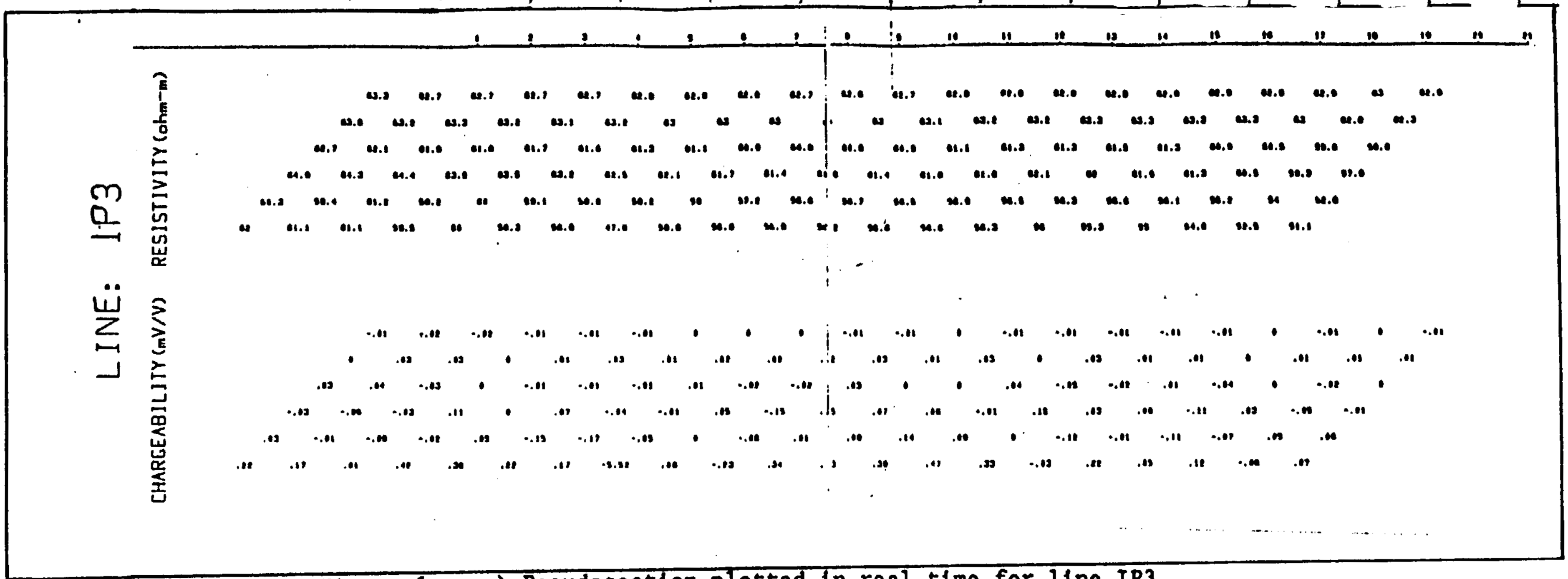

Figure 6: a) Pseudosection plotted in real time for line IP3.

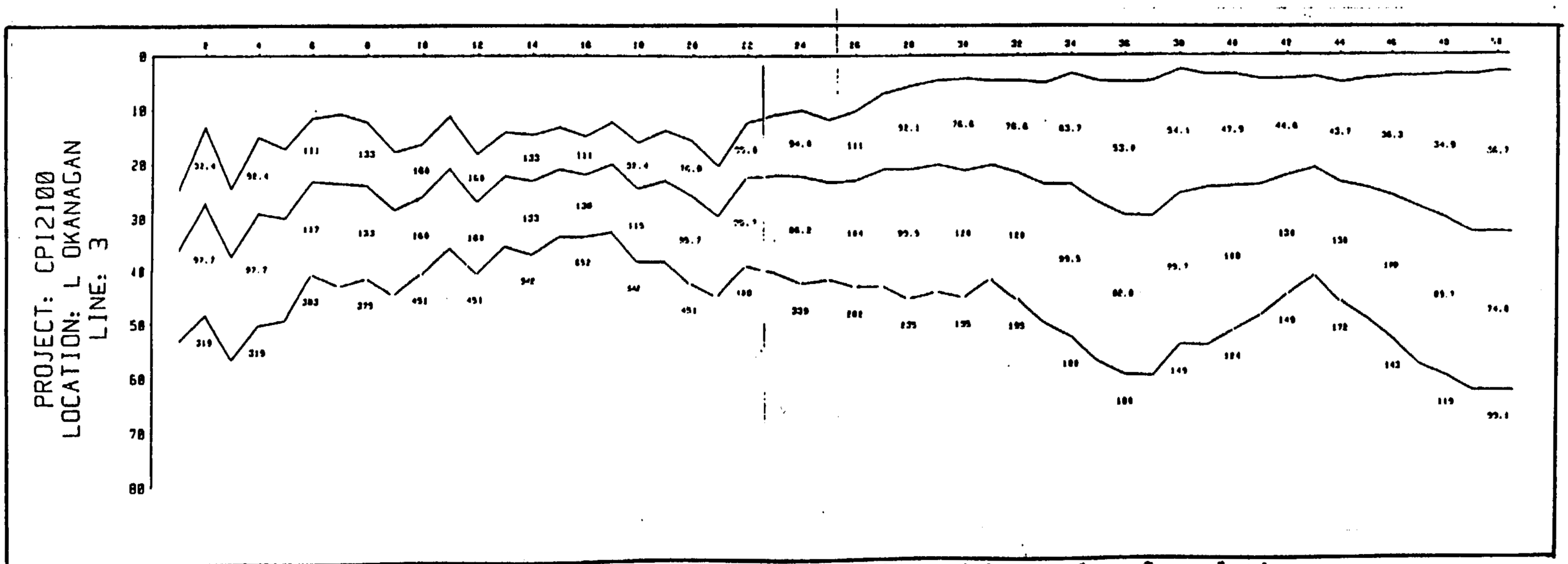

Figure 6: b) Part of Line 3 in Okanagan Lake, with result of real-time inversion of resistivity data.