AN EVALUATION OF THE PERFORMANCE AND APPLICABILITY OF BATTERY INDUCED POLARIZATION SYSTEMS

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ABSTRACT

The introduction of portable 25 watt Induced Polarization (I.P.) units as a tool for mapping the lateral distribution of subsurface sulphides on a reconnaissance basis has substantially reduced the cost of such surveys but has led to some problems in survey design and evaluation not normally encountered with conventional 2.5 kilowatt equipment.

The electrode geometry and dipole length are variable design parameters that can be used to optimize the effectiveness of a survey. These parameters must be selected with respect to (i) the dimensions and geometry of the target, (ii) overburden thickness, and (iii) electrical properties of the substratum.

The effectiveness of a survey depends in a large measure on the overburden thickness and the intrinsic resistivity contrast between overburden and bedrock. This problem is investigated in the context of the Scintrex IPR-7 25 watt battery powered I.P. system. The applicability of battery I.P. is evaluated for two surveys, one from central British Columbia and the other from the clay belt of Ontario. The evaluation is based on comparisons with two-layer interpretation curves.

Although designed for British Columbia the 25 watt systems have had unexpected success in the Canadian Shield. Within the limitations of the system, areas of the Shield amenable to exploration have been suggested.

ACKNOWLEDGEMENTS

This work has been completed with the financial support of AMAX Exploration Inc. and the case histories presented here are drawn from the AMAX files. The author wishes to thank W.M. Dolan of AMAX for suggesting the topic and G. DePaoli and W. Ryall for supplying the field data contained herein. Thanks are extended to the author's thesis advisor Dr. C.D. Anderson of the University of Manitoba for his helpful suggestions and to Dr. D.H. Hall of the University of Manitoba and Dr. Zoltan Hajnal of the University of Saskatchewan for serving on the author's thesis committee.

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CHAPTER I

INTRODUCTION

Introduction

Battery-powered induced polarization equipment has gained prominence as a tool to perform routine reconnaissance induced polarization (I.P.) surveys and at least three manufacturers have 25 watt portable units available. Although hampered by limitations which may seem serious when compared to conventional 25 kilowatt systems, the performance of the 25 watt system for mapping the lateral distribution of subsurface sulphides in a variety of environments is excellent. Coupled with careful interpretation and operating within the system's capabilities, the information supplied is as revealing as conventional data with the attraction that the surveys can be performed at a cost reduction of approximately 50 percent.

The following discussion pertains to the 25 watt battery I.P. system developed by Newmont Exploration, which is manufactured and distributed by Scintrex Limited. It is tacitly assumed that other equipment available on the market has comparable performance and, further, the arguments presented are not affected by equipment brand

and are equally applicable to measurement of any I.P. parameter.

This thesis will discuss the limitations of the battery system and assess its performance in two areas; interior British Columbia and the clay belt of Ontario. The results show that battery I.P. can be effective with widely different surface, subsurface, and geologic environments.

Although specifically designed for conditions encountered in British Columbia, the system has been applied to exploration in the Canadian Shield and an attempt will be made to assess the applicability of the equipment in this environment.

In view of recent trends which indicate that the newly developed 250 watt portable battery I.P. system is replacing the 25 watt unit in many areas, the relative performance of the 250 watt system and the desirability of this trend will be discussed.

Philosophy of Battery I.P.

Traditionally, I.P. surveys have been relegated to the last phase (prior to drilling) in the sequential development of a mining property, even though the method is definitive over a wide range sulphide percentages up to and including those that are considered massive (largely because most massive deposits have a halo of disseminated mineralization). High survey costs have led to this situation. The battery system, becuase of reduced capitalization and operating costs, allows I.P. to be used at an earlier stage in the exploration program. Also, in porphyry copper environments where most of the targets are susceptible only to detection by the I.P. technique, the portable system allows I.P. to be used on a routine and reconnaissance basis.

The high deployment cost of conventional I.P. surveys stems from the power specifications, which require cumbersome equipment to attain. It is the author's judgement that in many instances where conventional equipment is deployed, battery systems could be used effectively and with reduced expenditures.

The most critical limitation of the portable battery powered I.P. system is the lack of vertical performance i.e. we get limited depth of exploration and little information concerning the vertical continuity of a source body. The most important consideration, however, is the location and lateral extent of the sulphide body which can be rapidly determined with battery units, provided the source is within the vertical capability of the instrument. Cases where the overburden thickness is too great are easily identifiable and other solutions, such as higher powered equipment can be brought to bear on the problem. In other words, it is possible to determine whether a lack of anomalies results from the inability of the system to detect them or from a paucity of causative bodies.

Within the system's limitations, portable battery I.P. systems provide a definitive geophysical system capable of detecting most types of sulphide occurrences on a reconnaissance basis.

CHAPTER II

THEORY AND PRACTICE OF INDUCED POLARIZATION

Introduction

The I.P. method, in recent years, has been used successfully for the detection of a wide variety of sulphide occurrences. Hallof (1972) has compiled a collection of I.P. discoveries which display divergent properties and environments. This chapter will briefly outline the theory and practice of the I.P. method. The reader is referred to works by Madden and Cantwell (1967) and Seigel (1967) for a more complete theoretical and mathematical description of the I.P. phenomenon.

Causes of the Induced Polarization Phenomenon

The induced polarization (or overvoltage) phenomenon occurs at the interface of ionic conducting and electronic conducting media when a current passes across the boundary. Current flow through rock takes place via ionic conduction in fluids contained in interconnected pore spaces in the rock. Where sulphides (electronic conductors) block or border these pore spaces an electrochemical barrier is established and the excess voltage required to drive the current across the interface (overvoltage) generates the polarization effects. The process is called 'electrode polarization'. For a complete discussion of the relationship between the I.P. effect and conduction of electricity in rocks, see Ward and Fraser (1967).

If the source current is terminated, the overvoltage generates secondary currents and potentials which decay in time and can be monitored (time domain measurement). Also since a finite time is required for these voltages to build up, the impedence of the zones decreases with increasing frequency of the impressed current. Frequency domain measurements rely on the latter effect.

The storage of electrochemical energy in this manner accounts for the largest portion of the I.P. effect. However, other causes account for the I.P. response of unmineralized rocks (called intrinsic I.P. response) and some overburdens. The most important are membrane potentials, Mayper (1959), which arise because most minerals present an external negative charge when immersed in an electrolyte. Positive ions are adsorbed in a diffuse cloud impeding the movement of conducting ions and the relaxation of the double layer of ions upon termination of the impressed current produces an I.P. response. The process is termed membrane polarization. Clay particles, arranged in alternating zones which acquire this effect and non-selective zones, produce the largest effects and account for the application of the I.P. method to ground water geophysics.

Electrical energy can also be stored by mechanical processes termed electro-kinetic effects (Mayper, 1959). These include compression of gas bubbles, electro-osmosis, and streaming potentials caused by fluid flow induced by the passage of electric currents.

Fortunately, electrode polarization is the most significant of these effects and the others merely amount to noise in mineral exploration.

The common minerals which enhibit polarization effects are listed in Table I; sphalerite is a conspicuous absentee.

In a comprehensive study, Marshal and Madden (1959) concluded that both electrode polarization and membrane polarization were caused by identical diffusion phenomena and consequently indistinguishable over the practical range of frequencies used for I.P. measurements. However, the amplitude of the I.P. effect for mineralized rocks is usually diagnostic except where the target is at a considerable depth. In this case the significant I.P. response may be lost to background effects.

Measurement of the Induced Polarization Effect

The induced polarization phenomenon can be measured in the time domain (pulse-transient method) or the

TABLE I

Common Minerals with the Induced Polarization Property (after Madden and Cantwell, 1967).

Oxides	Sulphides	Others
magnetite	pyrite	graphite
pyroluscite	pyrrhotite	native copper
cassiterite	marcasite	
	galena	
	chalcopyrite	
	molybdenite	
	pentlandite	
	cobaltite	
	argentite	
	bornite	
	enargite	

frequency domain (variable frequency method).

In the pulse-transient method a square wave direct current with 'on' cycles of opposite polarity and 'off' cycles of equal duration is impressed on the ground (Figure 1A). The shape of the discharge curve during 'off' cycles is analyzed and a parameter called chargeability (M) is determined.

The chargeability can be determined in two ways:

(i) Integrating the surface area beneath the discharge curve with respect to time and normalizing by dividing the result by the primary voltage (V_p). In this case:

$$M = \frac{\int_{t_1}^{t_2} V_S(t)\,dt}{V_p} \quad \frac{\text{sec-millivolts}}{\text{volt}} \quad \text{or} \quad \text{millisec.}$$

where $V_S(t)$ is the time dependent secondary voltage. In practice, finite time intervals are required; for example, the Scintrex IPR-7 receiver has 2 sec. on and off periods and integrates between 0.45 sec. and 1.1 sec. Figure 1 shows the primary wave form of the Scintrex unit, as well as the shape of the transient voltage decay curve.

(ii) Sampling the transient voltage decay curve at discrete intervals (t_i) and normalizing as before, then:

$$M \propto \frac{V_S(t_i)}{V_p} \text{ millivolt/volt}$$

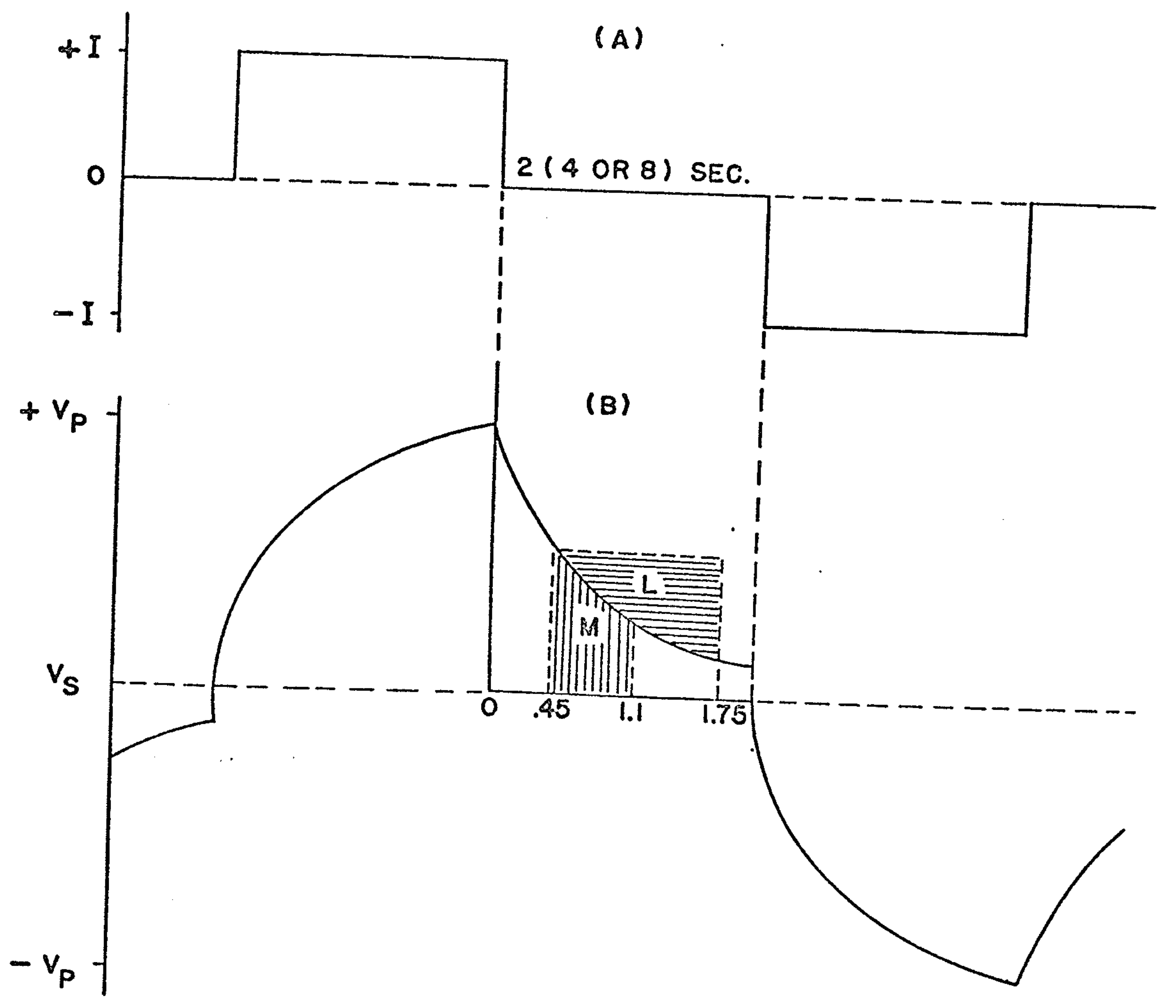

FIGURE 1. OPERATION OF SCINTREX MARK VII (NEWMONT TYPE) I.P. SYSTEM. (A) PRIMARY WAVE FORM. (B) TRANSIENT WAVE FORM. (AFTER SEIGEL, 1970).

The departure in the units for chargeability here from that given in (i) arises because the secondary voltage measured is the average voltage over a relatively narrow time gate, so that the voltage is recorded at discrete time intervals. Huntec equipment has the capability of determining four points on the decay curve.

Theoretically the expression for chargeability is given by

$$M = \frac{\int_0^\infty V_s(t)dt}{V_p}$$

In practice, however, a finite time interval is required to expediate the measurement. The Scintrex IPR-7 receiver has an adjustable pulse width at 2, 4, or 8 sec. but the I.P. measurement is always made between the previously defined limits. The above expression also includes transient electromagnetic and inductive coupling effects. Since these usually have short time constants the integration or amplitude measurement is delayed in order to allow the decay of these transient effects.

Opposite polarities on subsequent current pulses are required to inhibit the build-up of steady state emf's.

Another parameter of significance in time domain measurements is the L-factor, the area above the transient decay curve (Figure 1). Departures from the theoretically acceptable values of the L/M ratio of $0.9 < L/M < 1.1$

indicate an abnormally shaped transient decay curve although field measurements indicate that the normal range of the L/M parameter is from 0.7 to 0.8. The shape of the transient decay curve is influenced by (i) sulphide particle size and geometry (ii) interline electromagnetic coupling and (iii) electromagnetic coupling caused by conductive overburden. Figure 2 shows some of the possibilities. The electromagnetic transients normally have short time constants and are eliminated by delaying the measurement of L and M subsequent to the cessation of the primary field. However in areas of low resistivity, using long dipoles and the higher operating frequencies, the electromagnetic transients may persist into the domain of measurement of L and M. Seigel (1970) and Baird *et al.* (1972) have discussed the significance of the L/M ratio.

It is generally impossible to distinguish between geometric effects (particle size) and electromagnetic eggects. Swift (1973) demonstrated that the L/M ratio was independent of intrinsic chargeability and was related to electromagnetic coupling only.

Dey and Morrison (1973) have shown that the proper choice of electrode array can minimize the effects of electromagnetic transients. For 25 watt battery I.P. surveys electromagnetic effects have little significance because the dipoles are necessarily short and the system has little utility in low resistivity areas.

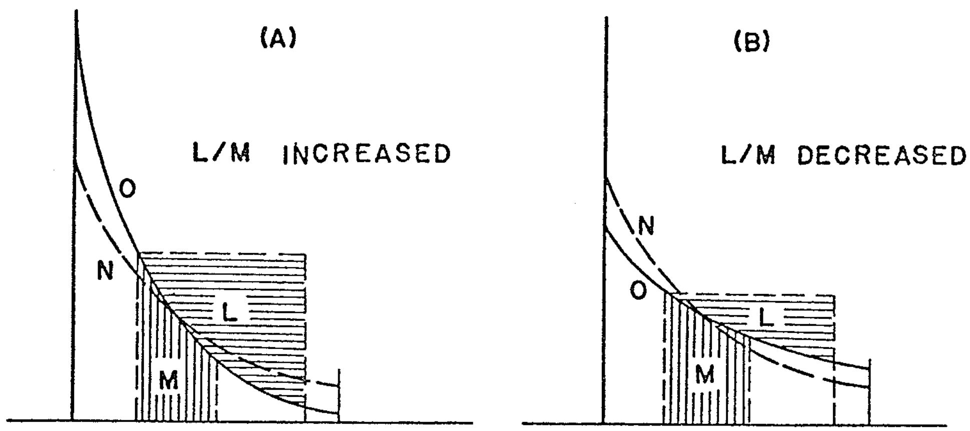

FIGURE 2. SIGNIFICANCE OF THE L/M RATIO. (A) SHORT TIME CONSTANT, SMALL PARTICLE SIZE, OR POSITIVE E.M. EFFECTS. (B) LONG TIME CONSTANT, LARGE PARTICLE SIZE, OR MINOR NEGATIVE E.M. EFFECTS. (AFTER SEIGEL, 1970). N – NORMAL, O – OBSERVED.

Usually, the L-factor is not systematically recorded unless significant electromagnetic coupling is suspected.

In the variable frequency method the resistivity (ρ_a) is measured at two frequencies of impressed current; one frequency being sufficiently low to be considered d.c. for all practical purposes. The induced polarization effect in this case is the percent frequency effect (PFE) and is given by

$$PFE = \frac{\rho_{dc} - \rho_{ac}}{\rho_{ac}} \times 100$$

where ρ_{dc} and ρ_{ac} are the apparent resistivities at the low and high frequencies, respectively.

The proper choice of frequencies has been discussed by Hallof (1965). However, practical frequencies are less than 10 Hz in order to reduce inductive coupling effects and greater than 0.2 to 0.5 Hz, in order that a high pass filter can be incorporated to eliminate low frequency telluric noise.

Another parameter commonly used in the frequency domain is the metal conduction factor (MCF) and is given by

$$MCF = \frac{PFE}{\rho_{dc}} \times 2\pi \times 1000 \quad (\text{ohm-ft})^{-1}$$

The constants used in this equation may vary with individual use.

Comparison of Induced Polarization Systems and Systems Parameters

For a given polarizable medium the maximum (intrinsic) values of frequency effect and chargeability are theoretically equivalent (Hallof, 1964) but practical limitations prevent measurement of the intrinsic values. The two parameters (M and PFE) are derivable from one another by Fourier analysis, however, field measurements are usually too crude to make the transformation.

Empirically, McLaughlin *et al.* (1970) found that

$$_{33}M_1\ ^{*} = 7\ \mathrm{PFE}$$

and Madden and Cantwell (1967) have compiled a matrix for converting frequency effect and chargeability for most practical frequencies and switching times.

Marshall and Madden (1959) and Hallof (1964) have discussed the role of the metal conduction factor (MCF) as the diagnostic I.P. parameter. The usual models representing the configuration of metallic sulphides in rocks include, pore passages that are blocked by sulphides and unblocked passages. In rocks where the resistance of the unblocked paths is low the polarizing effect is shunted whereas tight rocks (high resistivity) with similar

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* $_{33}M_1$ is the notation used for chargeability measured over 1 sec. interval where current 'on' and 'off' periods are 3 sec. each.

sulphide content may give larger I.P. effects because the mineralized passages shunt the current. The metal conduction factor amounts to the measurement of the change in conductivity of unblocked passages, thereby amplifying the effect of well mineralized zones and attenuating zones of sparse mineralization. The equivalent parameter in the time domain measurement is the static capacity (Keller, 1959) given by

$$\text{Static Capacity} = M/\rho_a \quad \text{(in units of capacitance)}$$

where the symbols are as defined previously. As can be seen, the static capacity is a measure of the capacitance of the rocks and Marshall and Madden object to the use of this parameter stating that the I.P. effect is due solely to resistance effects, whereas the dialectric properties of the I.P. phenomenon vary widely with frequency. In practice, however, the static capacity is not normally computed because the chargeability is sufficiently dianostic for anomaly discrimination.

Apparently then, the advantages of one system over the other are purely logistical with respect to equipment design and cost and field performance. Dolan and McLaughlin (1967) have compared the two systems and both appear competitive.

Practice in Induced Polarization

Current, either a.c. for the variable frequency method or square wave with alternating polarity for the pulse-transient method, is impressed into the ground by way of grounded current electrodes. The current electrodes may be either metal rods or aluminum foil. The amount of current transmitted into the ground depends on the subsurface resistivity in the vicinity of the electrode and the power of the transmitter and is maximized within equipment capabilities by reducing ohmic losses near the electrode. This is achieved by increasing the specific surface area of the electrode; directly, by using more stakes or aluminum foil, or indirectly, by addition of a salt-water-detergent soil to the electrode site.

Non-polarizing porous pots charged with a saturated copper sulphate solution are used as potential electrodes. Metallic electrodes, which are susceptible to the generation of spurious potentials are not prohibited but not recommended, especially in battery I.P. surveys because noise may exceed the inherently weaker signal strength.

Various electrode configurations are possible and Figure 3 shows the common ones in use. The choice of electrode geometry will be discussed in a later chapter.

Depth profiling, to test the behaviour of an anomaly with depth and analyze cover thickness and substratum electrical properties, is achieved by an incremental

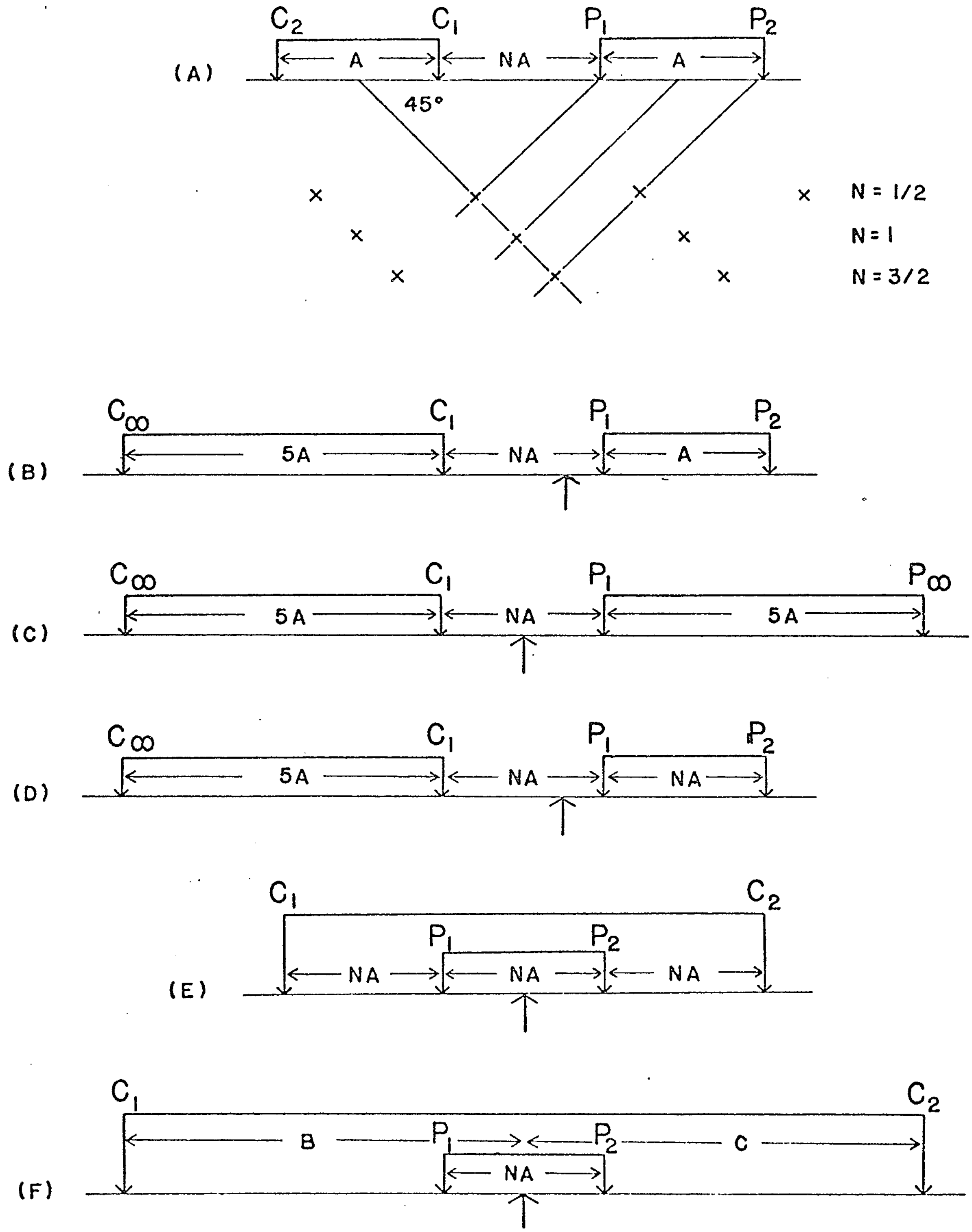

FIGURE 3. I.P. ELECTRODE ARRAYS. (A) DIPOLE – DIPOLE. (B) POLE – DIPOLE. (C) POLE – POLE. (D) THREE ARRAY. (E) WENNER. (F) GRADIENT. ↑ AND × INDICATE DATA PLOTTING POINTS

increase in 'N'; where 'NA' is the separation between the current and potential dipoles and 'A' is the length of current and potential dipole (see Figure 3). Data plotting points depend on the location of the current and potential electrodes and the type of electrode array as shown in Figure 3. The two-dimensional array of data is plotted and contoured. The 'pseudo-sections' generated are not actual profiles of the electrical properties of the substratum but when contoured with logarithmic intervals superficially represent real cross-sections. This approach is typical of dipole-dipole data.

Common practice with the other arrays entails profiling the data for each separation (value of 'N') and superimposing each profile on a single page.

Presentation of the lateral continuity of anomalous values is achieved by contouring the data for a significant value of 'N' or a bar designating the width of the anomaly along each line.

CHAPTER III

FIELD EQUIPMENT AND PROCEDURE

Introduction

The equipment and survey procedure described herein have been adopted by AMAX Exploration Inc. for their reconnaissance I.P. work. It is tacitly assumed that other equipment and procedures have comparable performance and are equally applicable. No bias toward a particular system or manufacturer is intended.

Description of the Scintrex 25-watt Battery Induced Polarization System

The Scintrex battery I.P. system consists of the IPR-7 (Newmont type) receiver, which has been described in detail by Dolan and McLaughlin (1967), in conjunction with the 25 watt transmitter. The transmitter has the following specifications (after Scintrex, 1971).

Output voltage	in 5 steps between 40 and 200v
Maximum output current	0.5 amp.
Dimensions	7"x7"x9" (18 cm x 18 cm x 23 cm)
Weight	11 lb (5 kg) including batteries
Power source	2 sealed lead-acid batteries (24v)
Battery life	approximately 2 days continuous operation approximately 200 charges (nominal)
Charging source	20-30v (d.c.) charger or 115/230v (a.c.) 50/400 Hz charger

The entire package, including ancilliary equipment such as electrodes, wire, etc., weighs less than 200 lb. and the equipment required in the field amounts to about 20 lb. per man for a four-man crew.

Origin of the 25 watt Specification

The 25 watt transmitter specification arises by requiring a minimum 10 mv signal with 200 foot dipoles (dipole-dipole electrode geometry) for an apparent ground resistivity of 100 ohm-m. With this configuration the minimum current allowed at the transmitter is approximately 115 ma. Since 25 watts of power are available, it is apparent that the maximum bulk resistance between the current electrodes, from the relationship $P=I^2R$, must be less than 2000 ohm. This total resistance consists of the cable resistance, the internal resistance of the power source, the electrode-ground contact resistance, and the resistance of the ground in the immediate vicinity of the electrode. The first two relatively insignificant and Taggs (1964) has shown that the electrode-ground contact resistance is also negligibly small. The near electrode ground resistance can be kept below 2000 ohm by the measures outlined previously. From signal strength considerations (see Chapter IV), it is obvious that as ρ_a (the apparent ground resistivity) increases ample power is available to meet the minimum signal requirements and lower currents can be tolerated. For practical reasons, however, the maximum power capabilities cannot be realized or sustained and signal strength may occasionally suffer.

The requirement that the signal remain above 10 mv ensures that the induced signal strength will generally exceed the telluric noise strength. The Scintrex system, because it measures in the time domain, is susceptible short wave length bursts of telluric noise (telluric signals of relatively long duration are compensated for by an automatic self-potential balance). In practice, the amplitude of self potentials caused by telluric currents are much lower than this limit, except in anomalous zones where channelling of natural earth currents and anomalously low resistivities occur. However, it is usually easy to recognize an anomalous reading even in the instance where the signal/noise ratio may be adverse and averaging the I.P. response over several consecutive pulses improves the reading.

Survey Procedure

A brief description of the survey procedure is merited although it is recognized that these logistical aspects depend on the electrode array and personal preferences. However, the procedure outlined here has proven to be functional.

The equipment includes that traditionally used in

I.P. surveys, i.e. transmitter, receiver, dipole wires, electrodes, and support equipment. The current and potential wires are precut but several different lengths may be carried. The potential electrodes used are copper sulphate charged porous pots and four-foot stainless-steel rods are employed for current stakes (the number inserted depended on local ground conditions).

The aim of the entire procedure was to maintain the portability, mobility and flexibility of the system. A four man crew is employed in the following manner: a leading potential electrode man and the receiver operator at the trailing end of the potential dipole, followed by the transmitter operator at the leading end of the current dipole and a trailing current electrode man. The 'train' is advanced, in line, with the potential dipole leading and current dipole trailing.

All communication is verbal and terse and proves adequate with dipole lengths of up to 200 feet.

Details of the exact procedure for taking a reading are unnecessary but in general an attempt is made to (i) transmit over the fewest number of current pulses in order to conserve battery life, (ii) cater to the current operators since that is the limiting phase of the operation, and (iii) maintain production.

Multiple separations are obtained by maintaining the current dipole fixed and advancing or retarding the potential dipole in appropriate dipole-length increments. Normally, only one separation is read consistently. Multiple separation data allows quantitative analysis of the overburden and bedrock electrical properties and is required if (i) overburden masking is suspected, (ii) quantitative information regarding the anomalous zone is desired, or (iii) the overburden thickness is required.

Usually each reading is taken at one dipole length interval, but when an anomalous reading is encountered, the system is 'backed-off' to obtain an intermediate reading. This procedure adds detail and allows definition of the margin of the causative body closer than plus or minus a dipole length. For example, station intervals for a 200 foot dipole length survey are 200 feet except over the anomalous zone and on its margins where 100 foot moves occur.

CHAPTER IV

SURVEY DESIGN AND EVALUATION

Signal Strength Considerations

Signal strength, a function of electrode array, apparent resistivity, and impressed current, is given by the relationship

$$V = I\rho_a/F\pi a$$

where V is the signal strength in mv; ρ_a the apparent resistivity in ohm-m; a the dipole length in meters; I the current in ma; and F a geometric factor which depends on the electrode geometry. This well known relationship is used to compute apparent resistivities in any resistivity survey.

The geometric factor (F) is computed by considering all potential-current electrode pairs in the array with respect to the distribution of potential about a point current source in a homogeneous half-space, i.e.:

$$V_r = I\rho/2\pi r$$

where V_r is the potential measured at a radius r from a point source carrying current I and ρ is the resistivity of the medium. Table II is a comparison of the geometric factors for a spectrum of separation values (n) for the arrays commonly used in I.P. work.

An electrode geometry not shown in Table II is the gradient array. The apparent resistivity for the in-line configuration is given by

$$\rho_a = 1.92 \frac{V}{I} \left(\frac{c^2 b^2}{a(b^2 + c^2)}\right)$$

ρ_a is in ohm-m, all distances are in feet, and b and c > 5a (see Figure 3 for the configuration of this and the other arrays).

Three features are apparent from Table II, namely, (i) geometric factors for fractional separations have been included, (ii) the dipole-dipole array is the poorest selection with respect to signal strength, and (iii) the rate of fall-off of signal strength by increasing 'a' is less than that encountered by increasing 'n'.

Fractional separations have been included because the currents generated by the 25 watt transmitter are insufficient to allow separations greater than n=2. This depends, of course, on dipole length and apparent resistivity but if vertical profiling is required for overburden and bedrock analysis, fractional separations are usually necessary to obtain sufficient interpretational data

TABLE II

Geometric Factors for the Common I.P. Electrode Arrays

	n	F
Dipole-dipole	1/2	1.88
	1	6
	3/2	13
	2	24
	3	60
	4	120
Pole-dipole	1/2	1.5
	1	4
	3/2	7.5
	2	12
	3	24
	4	40
Pole-pole*	1/2	1
	1	2
	3/2	3
	2	4
	3	6
	4	8
3-Array*	1/2	2
	1	4
	3/2	6
	2	8
	3	12
	4	16
Wenner*	1/2	1
	1	2
	3/2	3
	2	4
	3	6
	4	8

* Note that here n is not used in the traditional sense but serves only as a multiplier for comparison purposes.

points. As an example of the last point, there is a two-fold increase in signal strength for the dipole-dipole geometry with n=1 and a=200 feet over the same configuration with n=2 and a=100 feet.

The significance of these considerations will be discussed later in this chapter.

Current strength and apparent resistivity also influence the measurable signal strength. Current strength is unpredictable because of its variability with surface environment. Elaborate electrode preparation should be avoided in order to maintain the battery system's reconnaissance mode and experience indicates that unprepared stake type electrodes suffice and apparent resistivities encountered in Canadian environments are usually high enough to afford adequate signal strength.

Survey Design

The optimum electrode configuration in any I.P. survey is selected with respect to the parameters (i) signal strength, (ii) overburden thickness and electrical properties of the substratum and (iii) geometry of the target. Signal strength is not normally a problem for conventional I.P. work but can be a critical limitation with the 25 watt system. Also, in battery I.P. surveys an additional consideration is the maintenance of the system's mobility and for this reason the dipole-dipole array is preferred.

The logistical problems associated with the other configurations are obvious, although they are not strictly prohibited. The gradient array is untenable because the current densities and hence the signal strength is too low using a 25 watt current source. Where precise quantitative information about the overburden properties is required the Wenner array can be used although possible line coupling of the parallel dipoles, especially with the variable frequency method, in low resistivity areas may occur. The advantage of the array, since the frequencies used in I.P. work are low enough that resistivities are ohmic, is that high resolution d.c. resistivity interpretation curves, such as those of Mooney and Wetzel (1956), may be used.

The dipole length must also be considered with respect to the parameters listed. Along with the advantage in signal strength, the 200 foot dipole (n=1) has improved depth of penetration over the configuration with a=100 and n=2, this is schematically indicated in Figure 4. Although the demonstration in Figure 4 is based on a superficial plotting convention two-layer interpretation curves show that the generalization persists over a wide range of subsurface resistivity contrasts. In general, the source must have an effective width of at least one dipole length to register as a single station anomaly. Overburden thickness, substratum electrical properties, signal strength, and communication problems suggest 200 feet as a maximum compromise dipole length.

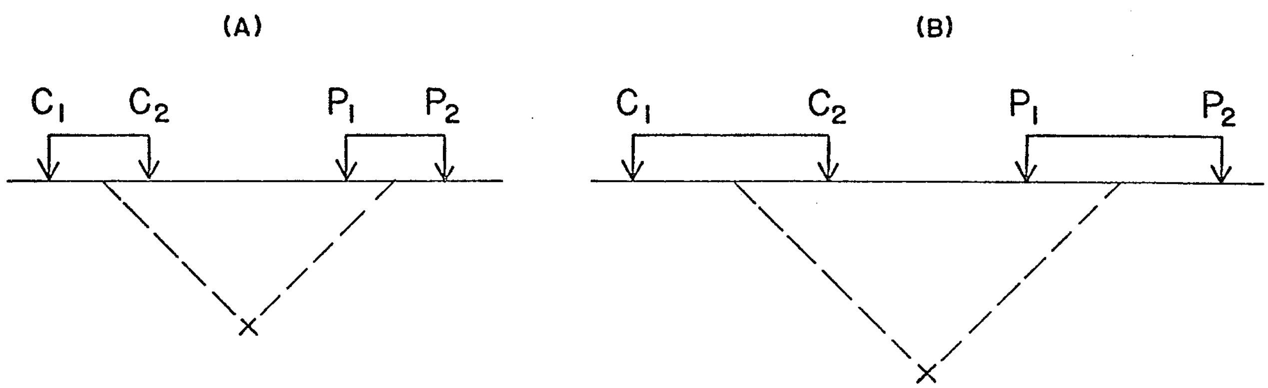

FIGURE 4. COMPARISON OF THE HYPOTHETICAL PENETRATION CHARACTERISTICS OF THE DIPOLE – DIPOLE ARRAY. (A) A=100', N=2. (B) A=200', N=1.

Normally, all these parameters are considered simultaneously and the survey designed by use of interpretation curves. The procedure is equivalent to the reversal of the interpretation procedure outlined in the next section but requires beforehand, a knowledge of the conditions likely to be encountered. However, the critical conditions of overburden/bedrock resistivity contrast and overburden thickness are invariably unavailable for an unexplored area and must be determined and assessed at the beginning of a battery I.P. survey.

It is common practice at the onset of any I.P. survey to assess these parameters, either qualitatively or quantitatively, in any area where the most adverse conditions are expected and select the electrode geometry accordingly.

Survey Evaluation

The mathematical description of the I.P. phenomenon by Seigel (1959) allows the computation of the I.P. response of any polarizable medium. In particular Seigel computed the response of a two-layer model for the Wenner electrode geometry. In a similar treatment Elliot (1967) computed the resistivity and I.P. response of an identical model for the more commonly used electrode geometries.

By simple fitting of the field data to the theoretical curves it is usually possible to define the parameters of the field problem.

Elliot's curves give the apparent resistivity and

I.P. response over a two-layer earth for a spectrum of layer 2/layer 1 resistivity contrasts and layer 1 thicknesses for the dipole-dipole, pole-dipole, 3-array, and pole-pole arrays. The significant set of curves in this study are those for the dipole-dipole geometry.

The I.P. response parameter (B_2) for the two-layer model is given by

$$B_2 = \frac{(IP)_a - (IP)_1}{(IP)_2 - (IP)_1}$$

where the subscripts 1 and 2 indicate the layer and correspond to overburden and bedrock, respectively, (IP) followed by a numerical subscript represents the intrinsic I.P. response of the layer, and $(IP)_a$ represents the apparent (measured) I.P. effect.

Chargeability (M) and percent frequency effect (PFE) are the available I.P. parameters. The metal conduction factor (MCF) cannot be used because it does not conform to the theoretical considerations involved.

Commonly, $(IP)_1$ can be taken as zero, so the expression for the response parameter reduces to

$$B_2 = (IP)_a/(IP)_2$$

Here, the significance of B_2 is readily apparent, i.e. B_2 is the ratio of the measured I.P. response to the intrinsic response of the target medium 2 for a fixed resistivity ratio and with the geometry (n) of the system variable.

The apparent resistivity curves have a similar structure, with the response parameter being the ratio of the apparent (measured) resistivity and the intrinsic resistivity of the first layer, i.e. ρ_a/ρ_1.

Superposition of the field data over the families of B_2 and resistivity curves yields a solution for $(IP)_2$ ρ_1, ρ_2 and D_1 (overburden thickness).

The importance of the theoretical curves is manifest in two ways (i) they allow calculation of sub-surface physical and electrical properties which include the intrinsic I.P. response of an anomalous zone for estimation of sulphide content and the overburden thickness, and (ii) they allow assessment of the 'effectiveness' of the survey; a feature which is critical to the effective deployment of the 25 watt battery system.

By 'effectiveness', it is meant the degree in which the bedrock is being investigated and whether an anomalous zone is, in fact, detectable. Since continuous coverage of an area by multiple separations negates the reconnaissance nature of the 25 watt I.P. system, it is reassuring to note that instances where overburden masking is occurring are readily apparent from the trends of both resistivity and I.P. response collected during the systematic single separation (n=1) survey. In these recognizable circumstances multiple separations ($n = \frac{1}{2}, 1, 3/2$) are read and the degree of masking assessed.

The only constraint required is that there must be some indication of horizontal layering. This arises because the two-layer earth model is adopted for the theoretical calculations, where the first layer represents overburden and the second bedrock. Although this is a gross simplification of most real situations, it has proven to be adequate especially if the data to be interpreted is from a non-anomalous area. Over anomalous zones the anomalous values must be continuous enough to have infinite lateral extent (dimensions 5-10 times the dipole length). Most porphyry copper targets exhibit this property.

The occurrence of horizontal layering in field problems is difficult to assess largely because normally only anomalous responses are reported in the literature. In the authors experience (approximately 50 miles of I.P. work) which included investigation of three areas with porphyry copper potential and two areas where the targets were dyke like, there was usually no difficulty in recognizing horizontal layering in the field data; especially in the I.P. response which is less susceptible than resistivity to lateral inhomogeneities and variations.

Because of invalidity in the assumption that the I.P. response of the first layer (overburden) is zero, it is possible to establish a practical limit in the level of B_2 below which masking is likely to occur. Obviously, where any overburden exists a degree of masking will occur, but below a value of B_2 = 0.1, depending on the intrinsic I.P. response of the bedrock, the apparent response will usually be in the range of geologic and instrument noise.

For example, for an unmineralized bedrock with an intrinsic chargeability of 20 ms, a B_2 of 0.1 yields an apparent chargeability of 2 ms, which is in the noise band because of assumption that M_1 = 0 is invalid. Actually, M_1 is determinable provided the survey is conducted in accordance with good survey procedures.

An additional complication arises when a dyke-like target is included in the two-layer model. In this case unless the dyke's lateral dimensions are geophysical infinite the anomalous response (above a background of 2 ms) will be reduced as the target width decreases and even though the intrinsic response of the dyke would be expected to be an order of magnitude above that of the host rock, the masking problem may result in an anomalous response still below the noise level and, therefore, indiscriminable.

The procedure for evaluation and interpretation of I.P. data is best demonstrated by the examples which will be introduced in Chapter V.

Elliot's curves also show that the dipole-dipole array is the worst selection as far as the level of B_2 is concerned, i.e. the pole-dipole and pole-pole arrays generate larger B_2's under a given ensemble of overburden bedrock properties. This is equivalent to stating that the dipole-dipole array has the poorest effective depth of investigation. Considering only depth of investigation and signal strength, it appears that the dipole-dipole array would be the worst choice. However, this array is used because it is logistically simple and, therefore, preserves the reconnaissance mode of the 25 watt battery system.

System Limitations

By placing a limit of 0.1 on the anomaly detection level (B_2), it is possible to roughly outline the distribution of overburden thicknesses allowable. The region to the left of the curves in Figure 5 demonstrates the overburden thicknesses allowable for the dipole-dipole array for the fixed resistivity contrasts shown.

As M_2 increases, as is the case in porphyry coppers, a lower detection level can be considered and better depth of investigation at the extreme resistivity contrasts can be expected.

The maximum effective depth of penetration for the 25 watt battery system in the reconnaissance mode (a=200 feet, n=1) occurs at a resistivity contrast of 1 and is approximately 180 feet.

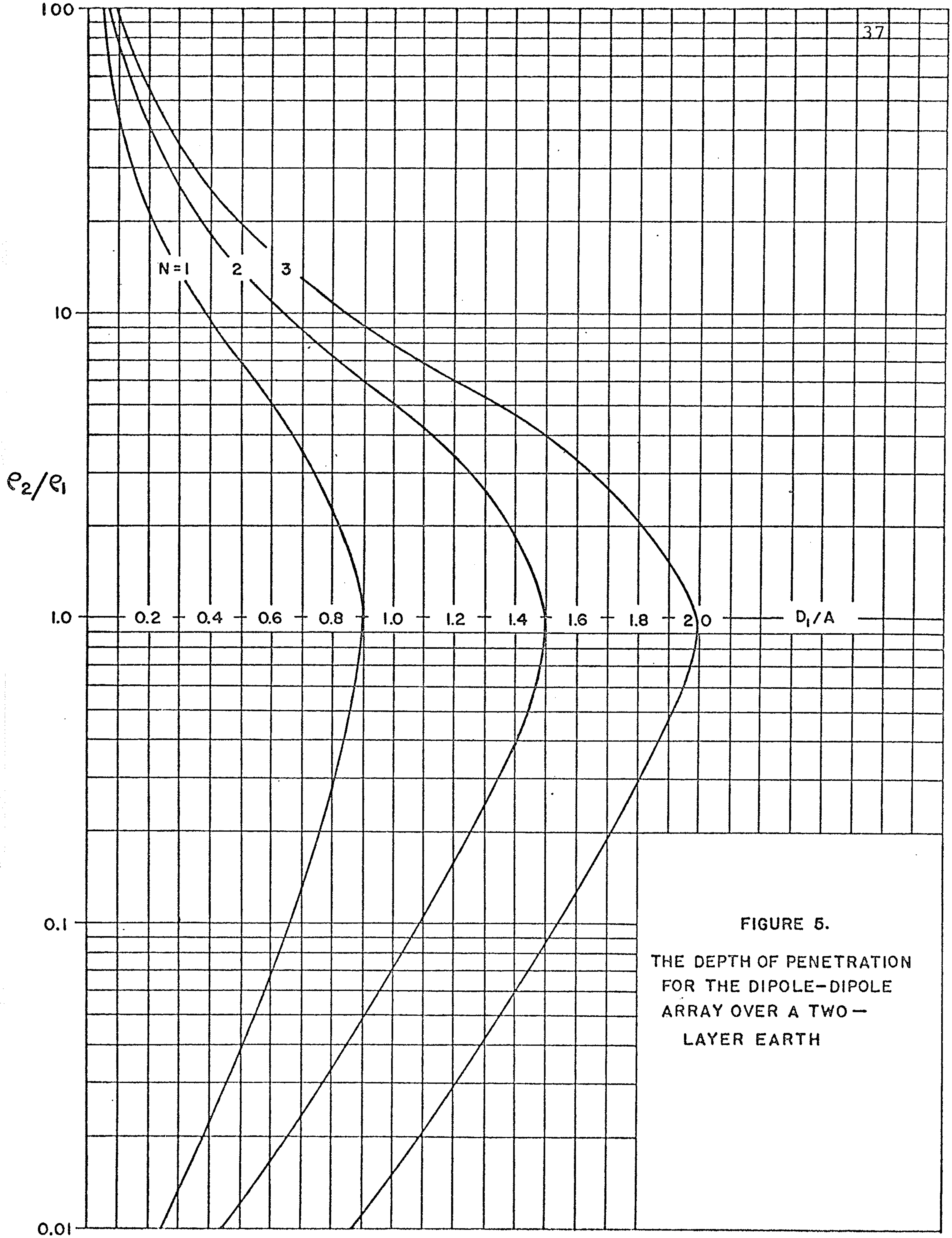

FIGURE 5.

THE DEPTH OF PENETRATION FOR THE DIPOLE–DIPOLE ARRAY OVER A TWO-LAYER EARTH

CHAPTER V

CASE HISTORIES

Introduction

The case histories presented here have been selected from I.P. work performed by the author during the summer of 1971 while in the employ of AMAX Exploration Inc.

The first example is typical of the western Canadian cordillera where overburden resistivities range from 100 to 500 ohm-m and bedrock, typically, has values from 300 to 1000 ohm-m (Dolan, 1971, personal communication). The 25 watt transmitter was, in fact, designed for this sort of environment.

The second case history is from a typical Precambrian greenstone belt where overburden resistivities range from 20 to 200 ohm-m while the range of bedrock resistivities is 10^3 to 10^5 ohm-m with an average of 5×10^3 ohm-m (Dolan, 1971, personal communication). Although the 25 watt system is not specifically adapted to search for sulphides in the greenstone environment, it has encountered some limited success there.

Case History 1: British Columbia

Figures 6 and 7 show the results obtained from a 25 watt battery I.P. survey conducted in mid-central British Columbia.

The property is underlain by a complex of intrusive porphyrys situated within the Jurassic rocks of the Hazelton Group and has potential as a typical porpyry copper deposit.

The area lies in a cirque with two distinct physiographic settings; the vase of the cirque valley contains water-soaked glacio-fluvial deposits whereas the flanks are dry with poorly developed soil and some talus.

A previous I.P. survey indicated that the area would be favorable for investigation by the 25 watt system, but the coverage was somewhat limited and did not include the central portion of the valley where 100 to 150 feet of boulder till intercollated with varved clays was present.

The plan of apparent resistivities shows values typical of British Columbia. It is interesting to note the continuity in chargeability between the creek bottom profile, where erosion to bedrock had occurred, and the bulk of the survey, which was conducted on the overburden surface, where a degree of masking invariably occurred. Resistivities have not been presented for the creek profile because of distortion in the electrode geometry caused by the creek meanders.

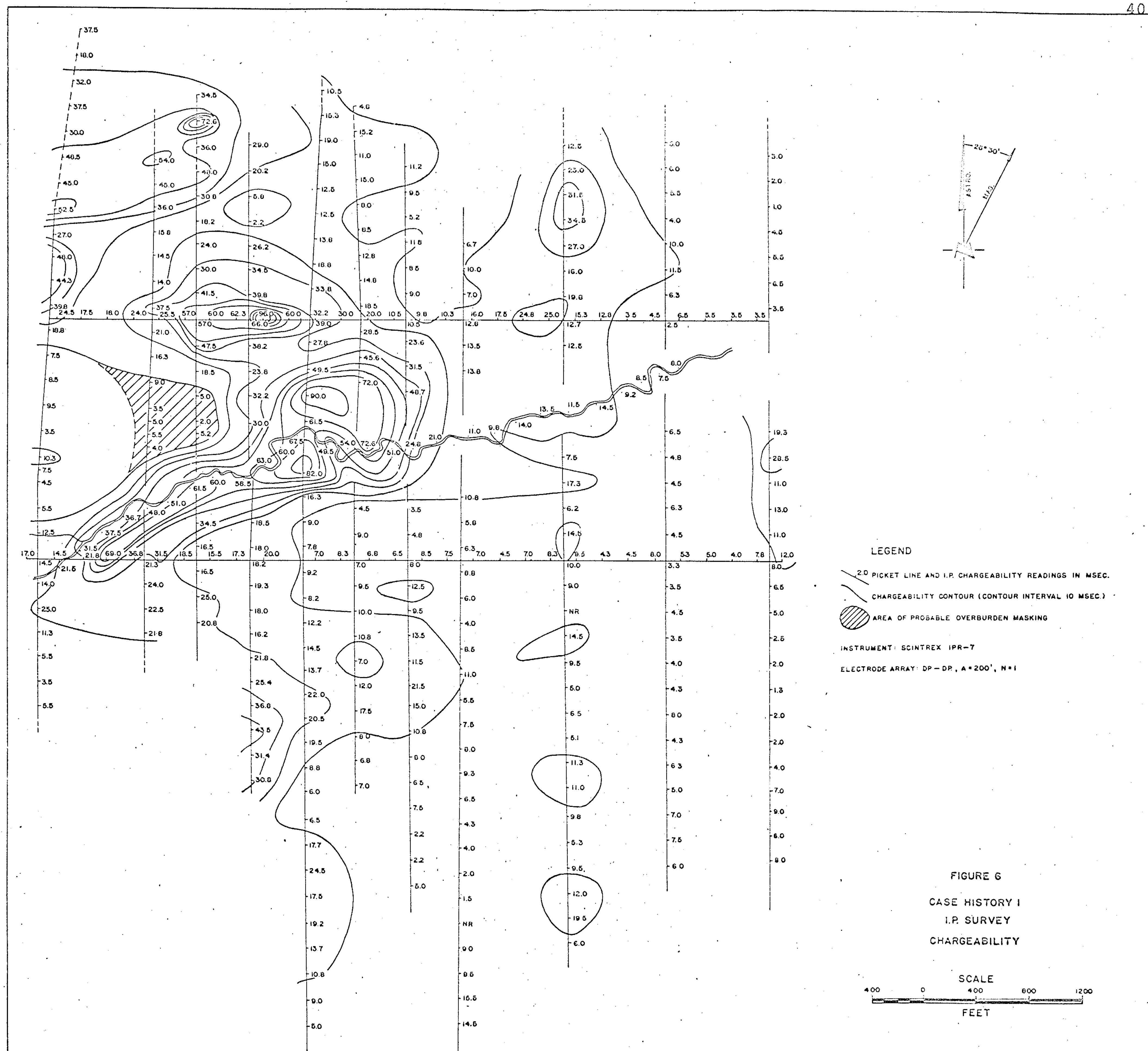

FIGURE 6

CASE HISTORY I

I.P. SURVEY

CHARGEABILITY

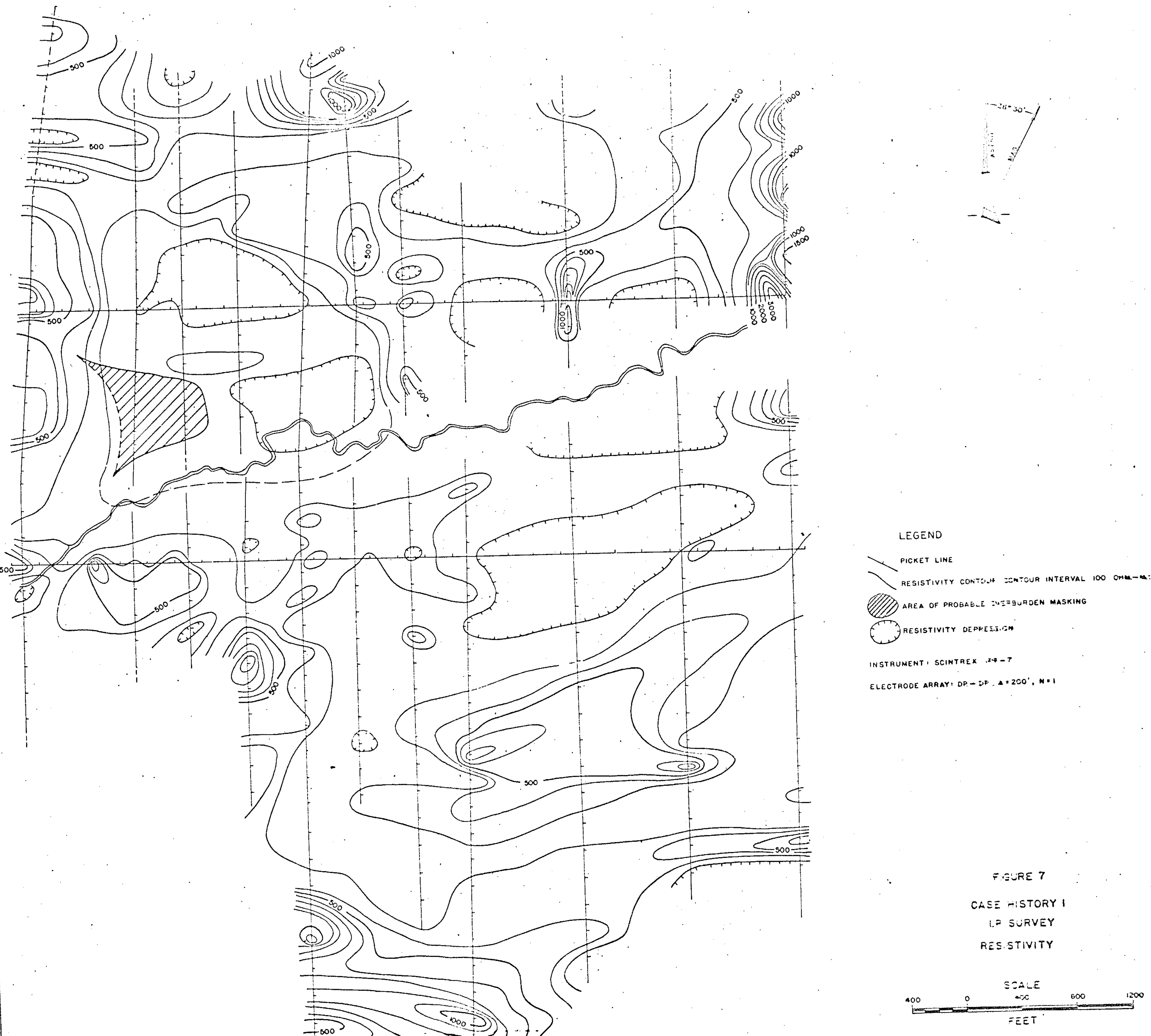

FIGURE 7
CASE HISTORY I
I.P SURVEY
RESISTIVITY

The cross-hatched region in Figures 6 and 7 indicates an area where the chargeabilities decreased from the flanking anomalous zones. Overburden masking was suspected and appropriate multiple separations were read on the two lines intersecting the area. Table III gives the average of the three sets of data taken.

An unusual amount of information was available from the property and some inferences toward the degree of masking were possible. Overburden thickness adjacent to the area was visually estimated, where the creek had incised the glacial till, at 100 feet and the continuation of the survey on outcrop, along the creek bottom nearby, gave apparent bedrock resistivities of approximately 500 ohm-m. This value may be too low because of (i) shunting of current through the low resistivity banks of the creek and (ii) distortions in the colinear electrode geometry and dipole length caused by meanders in the creek, In addition, the data at $n = \frac{1}{2}$ suggested an intrinsic resistivity of overburden of 100 ohm-m, although this value may be excessive because at $n = \frac{1}{2}$ the effective penetration is about 60 feet and bedrock influences would still be in the measurement. Apparently then, a conservative estimate of ρ_2/ρ_1 would be 5.

The parameters available are:

TABLE III

Case History 1

Multiple Separation Data

Spacing	ρ_a (ohm-m)	Ma (msec)
1/2	121	1.3
1	143	5.2
3/2	264	7.8

$$\rho_2/\rho_1 = 5$$

$$A = 200 \text{ feet}$$

$$D_1 = 100 \text{ feet} = 0.5\ A$$

$$M_1 = 0 \text{ msec (assumption)}$$

$$M_a \text{ (at n=1)} = 5.2 \text{ msec}$$

Referring to the appropriate set of interpretation curves for n = 1, D = 0.5 A, and $\rho_2/\rho_1 = 5$ it is apparent that

$$B_2 = M_a/M_2 = 0.14$$

Therefore

$$M_2 = 37 \text{ msec}$$

The interpretation suggests that in the region indicated moderate overburden masking has occurred and the 30 msec chargeability contour can be altered to enclose the area, thereby increasing the acreal extent of the anomaly considerably.

Direct analysis of the data in Table III, although there is no conclusive evidence of horizontal layering, yields a similar result. Figures 8 and 9 show the field data superimposed on the best fit theoretical curves.

Figure 8 yields a chargeability solution of

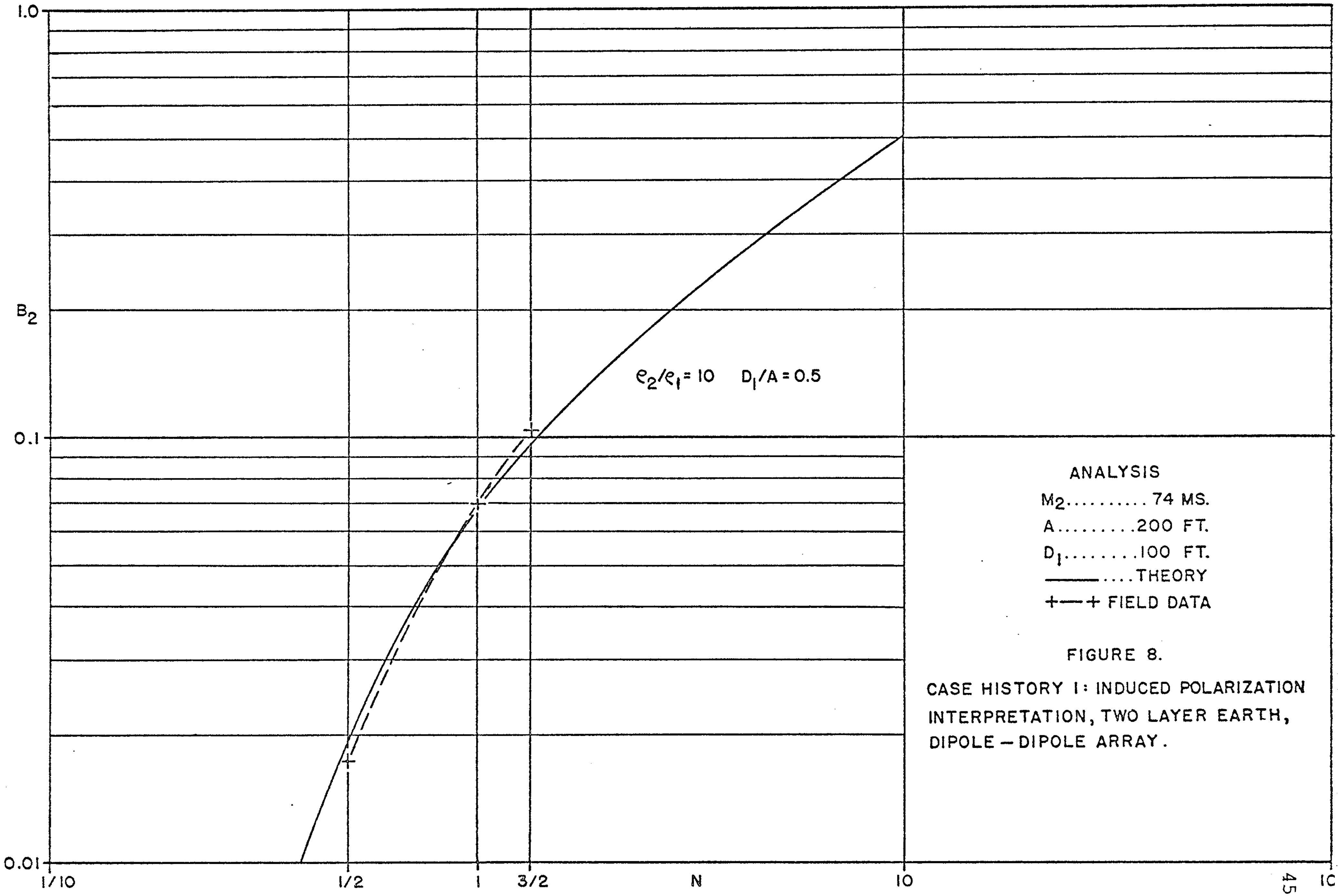

FIGURE 8.

CASE HISTORY I: INDUCED POLARIZATION INTERPRETATION, TWO LAYER EARTH, DIPOLE – DIPOLE ARRAY.

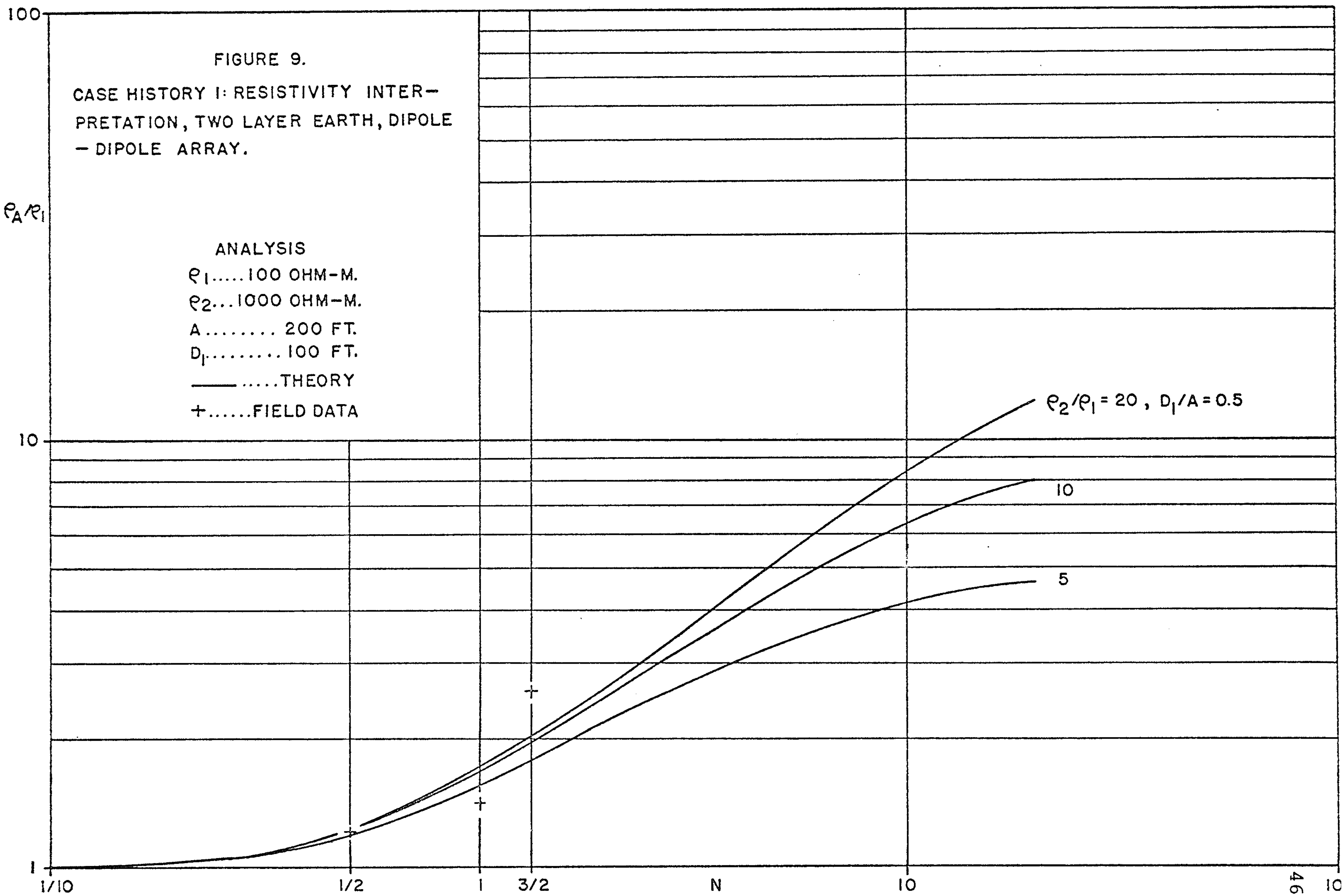

FIGURE 9.

CASE HISTORY I: RESISTIVITY INTERPRETATION, TWO LAYER EARTH, DIPOLE – DIPOLE ARRAY.

$$M_2 = 74 \text{ msec}$$
$$\rho_2/\rho_1 = 10$$
$$D_1 = 100 \text{ feet} = 0.5 \text{ A}$$

The resistivity data of Figure 9 yields an ambiguous resistivity contrast although the best fit family of curves are those for $D_1 = 0.5$ A. The scatter in the data can be attributed to lateral inhomogeneities in resistivity which produce effects comparable to vertical resistivity variations.

In the central portion of the anomaly (Figure 6) the overburden conditions are similar to those previously indicated, but here, the reduction in bedrock resistivity caused by the presence of metallic sulfides improves the ρ_2/ρ_1 ratio, so that, essentially 100 percent of the intrinsic I.P. response of the bedrock is available for measurement at the surface.

The applicability of the 25 watt battery I.P. system to trace the lateral distribution of subsurface sulfides is well demonstrated. Granted, the vertical distribution and continuity of the causative body remains unknown but most deposits of this sort have considerable vertical extent which can be best defined by drilling.

Production rates per working day were 2.5 miles for the system, with a maximum 4.0 miles for a single day. Mobilization costs were also low, making overall costs less than conventional I.P. by a factor of 2.

Case History 2: Ontario

The second case history is drawn from the Abitibi greenstone belt of northeastern Ontario where shield type physiographic, geologic, and target conditions prevail.

Figures 10 and 11 show the resultant chargeabilities and resistivities. The resistivity survey is virtually a map of the outcrop distribution and the extreme variations should be noted. A dichotomy existed in that the poorly developed soil in rocky terrain afforded miniscule currents but signal strength was improved substantially by the high apparent resistivities, whereas, in swampy areas larger currents compensated for the accompanying low resistivities.

Another difficulty encountered was an abundance of noisy signals caused by poor potential electrode contacts in poorly consolidated swamp material and on moss covered outcrops; however, anomalous readings were easily distinguishable.

In terrain with such high resistivity contrasts 'masking' should occur and the apparent closure of the southwestern end of the anomaly was suspected to be superficially caused by overburden masking. Figure 5 indicates that as ρ_2/ρ_1 approaches 100 the allowable overburden thickness is limited to a maximum of 20 feet. A detailed analysis of profile data collected in the region

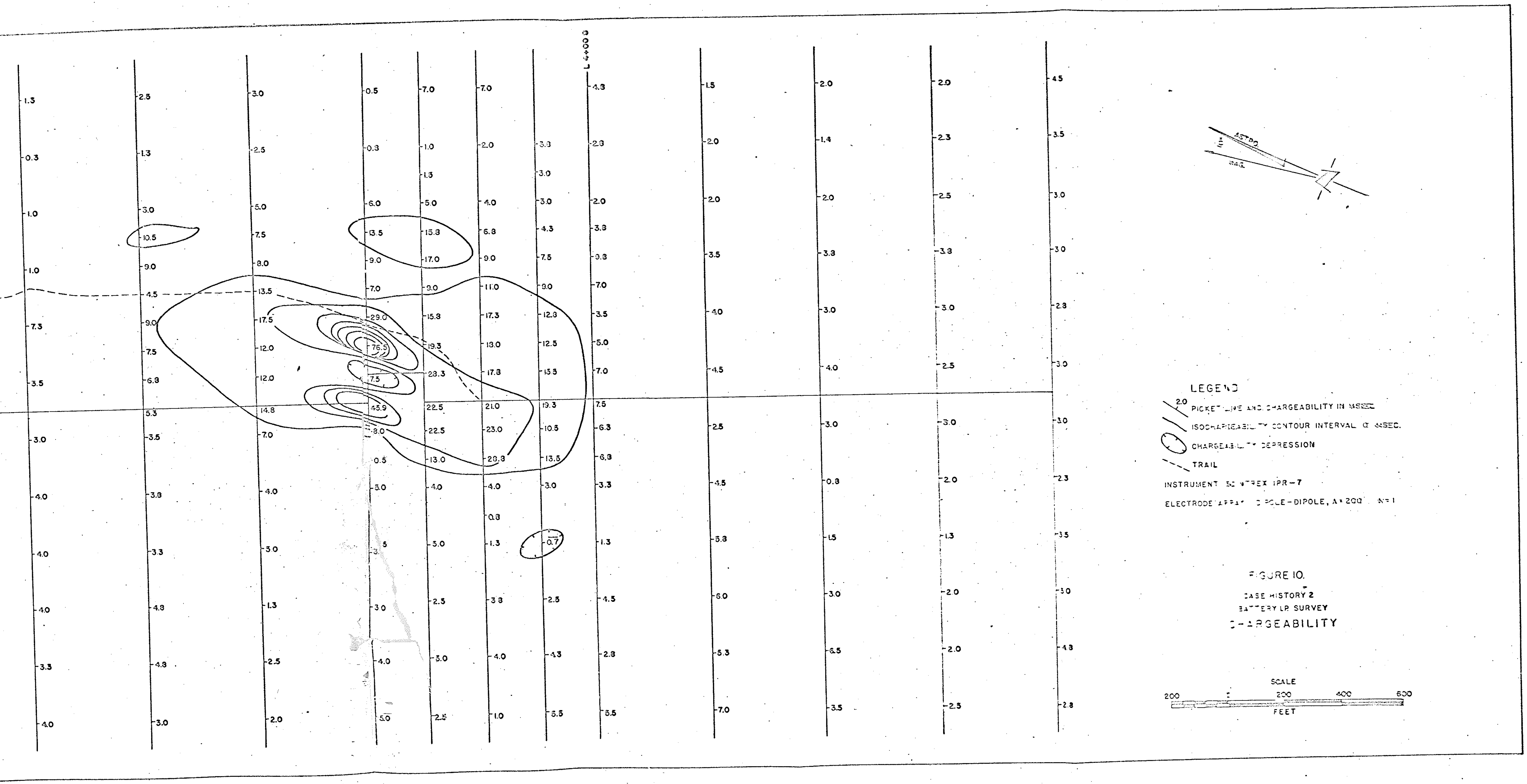

FIGURE 10.
CASE HISTORY 2
BATTERY I.P. SURVEY
CHARGEABILITY

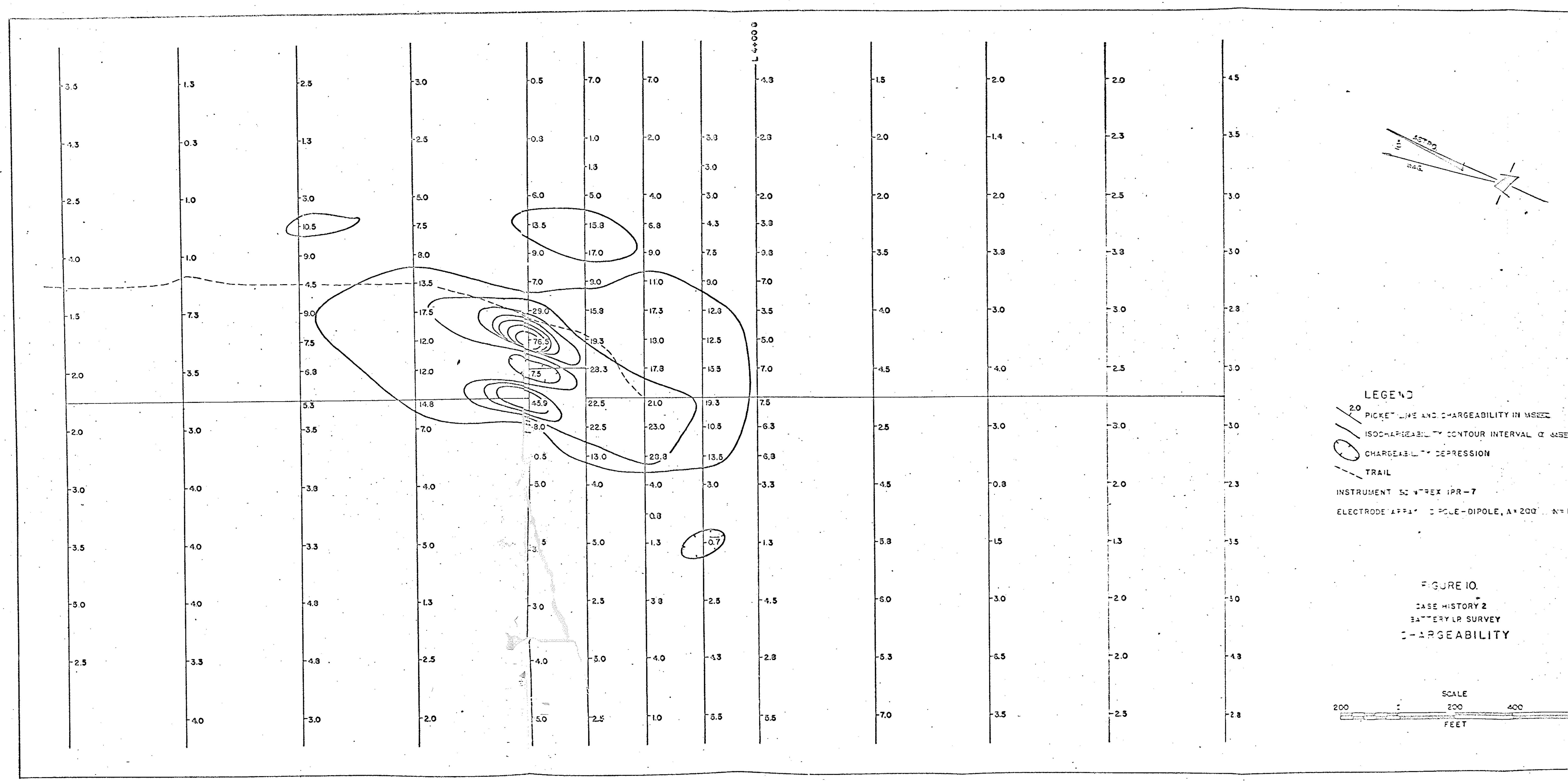

FIGURE 10.
CASE HISTORY 2
BATTERY I.P. SURVEY
CHARGEABILITY

FIGURE 11.
CASE HISTORY 2
BATTERY I.P. SURVEY
RESISTIVITY

FIGURE 11.
CASE HISTORY 2
BATTERY I.P. SURVEY
RESISTIVITY

suggests, however, that masking was not significant and the apparent closure of the anomaly represents a real termination of the causative body.

Figure 12 is a plot in cross-section of the data collected over the southern end of the anomaly. The resistivity appears to depict an expression of a narrow swamp filled bedrock depression. The lack of apparent horizontal layering reduces the quality of any interpretation, but it is possible to bracket the variation in resistivity and overburden thickness and make some inferences as to the conditions most likely. Only two data sets conform to the theoretically required continuous downward increase in resistivity and these are plotted in Figure 13 over the best fit theoretical curves.

The analysis yields the following limits on the properties of interest:

$$\rho_2/\rho_1 = 5 \text{ to } 100$$

$$\rho_1 = 55 \text{ to } 300 \text{ ohm-m}$$

$$\rho_2 = 1{,}500 \text{ to } 30{,}000 \text{ ohm}$$

$$D_1 = 10 \text{ to } 100 \text{ feet}$$

In view of the large variations in apparent resistivity over the property, it is possible to eliminate resistivity contrasts less than 50 and 100 is a likely maximum. Also, swamps are usually highly conductive, so that ρ_1 must be 50 ohm-m or less. The high resistivities

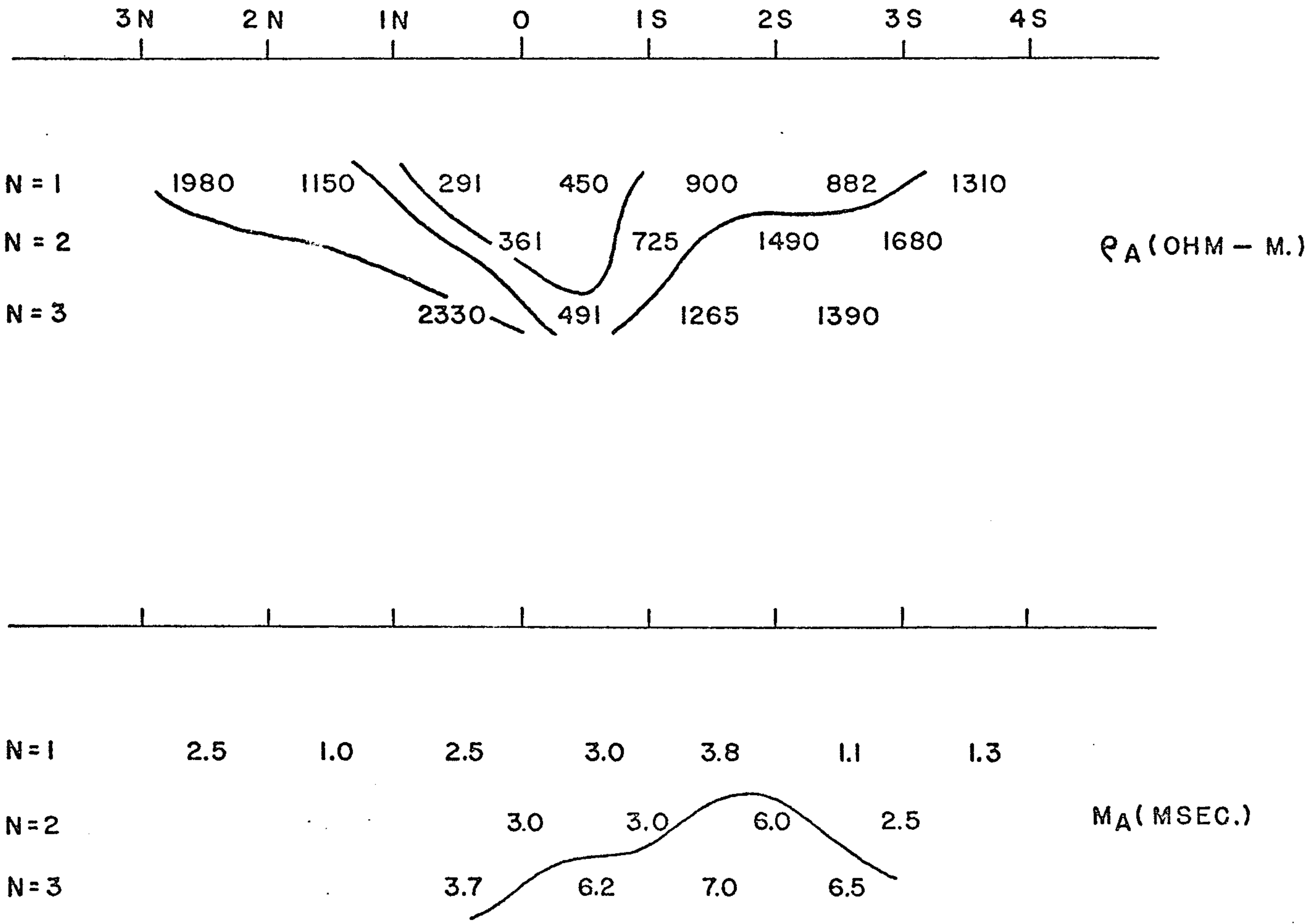

FIGURE 12. CASE HISTORY 2: LINE 4+00 S PSEUDOSECTIONS.
DIPOLE – DIPOLE ARRAY, A = 100' FT.

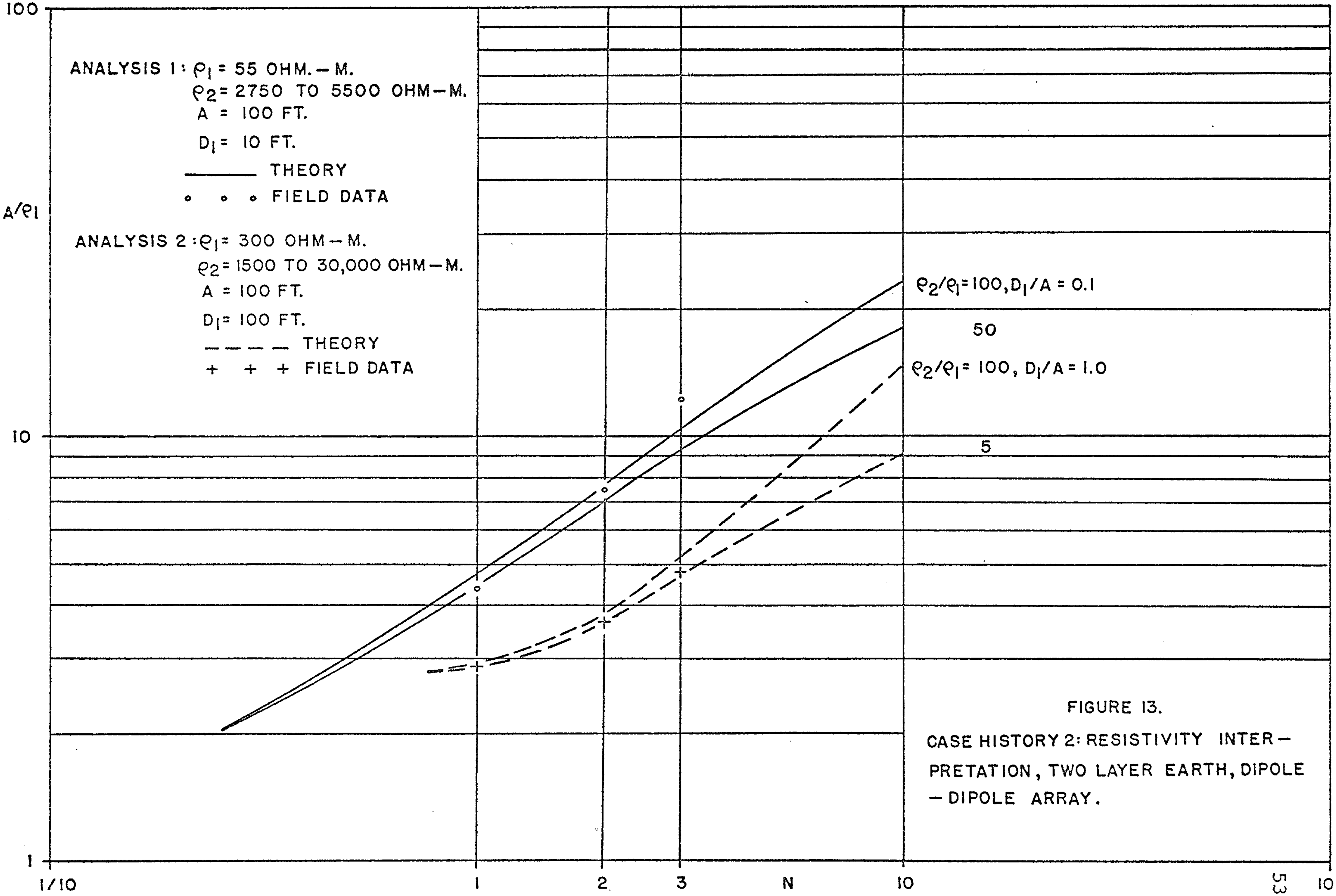

FIGURE 13.

CASE HISTORY 2: RESISTIVITY INTERPRETATION, TWO LAYER EARTH, DIPOLE–DIPOLE ARRAY.

(greater than 10,000 ohm-m) conform to the outcrop distribution of a quartz diorite whereas, the anomaly is confined within an acidic volcanic unit, so that the inferred ρ_2 of 5,000 ohm-m is probably representative.

Owing to the proximity of outcrop, an overburden thickness of 100 feet is extreme. The overburden thickness should encompass a range of 10 to 50 feet, although it should be remembered that a wedge of surface material is present and the inferred depth represents a maximum.

This qualitative filtering generates

$$\rho_2/\rho_1 = 100$$
$$\rho_1 = 50 \text{ ohm-m}$$
$$\rho_2 = 5{,}000 \text{ ohm-m}$$
$$D_1 = 10 \text{ to } 50 \text{ feet}$$

Interpretation of the chargeability yields a somewhat more coherent result because this parameter is less susceptible to lateral variations. The interpretation (Figure 14) yields the results

$$\rho_2/\rho_1 = 100$$
$$M_2 = 60 \text{ msec}$$
$$D_1 = 10 \text{ feet}$$

The area underlying line 4+00 s, apparently then still carries anomalous amounts of sulfides (in the order of 6 percent).

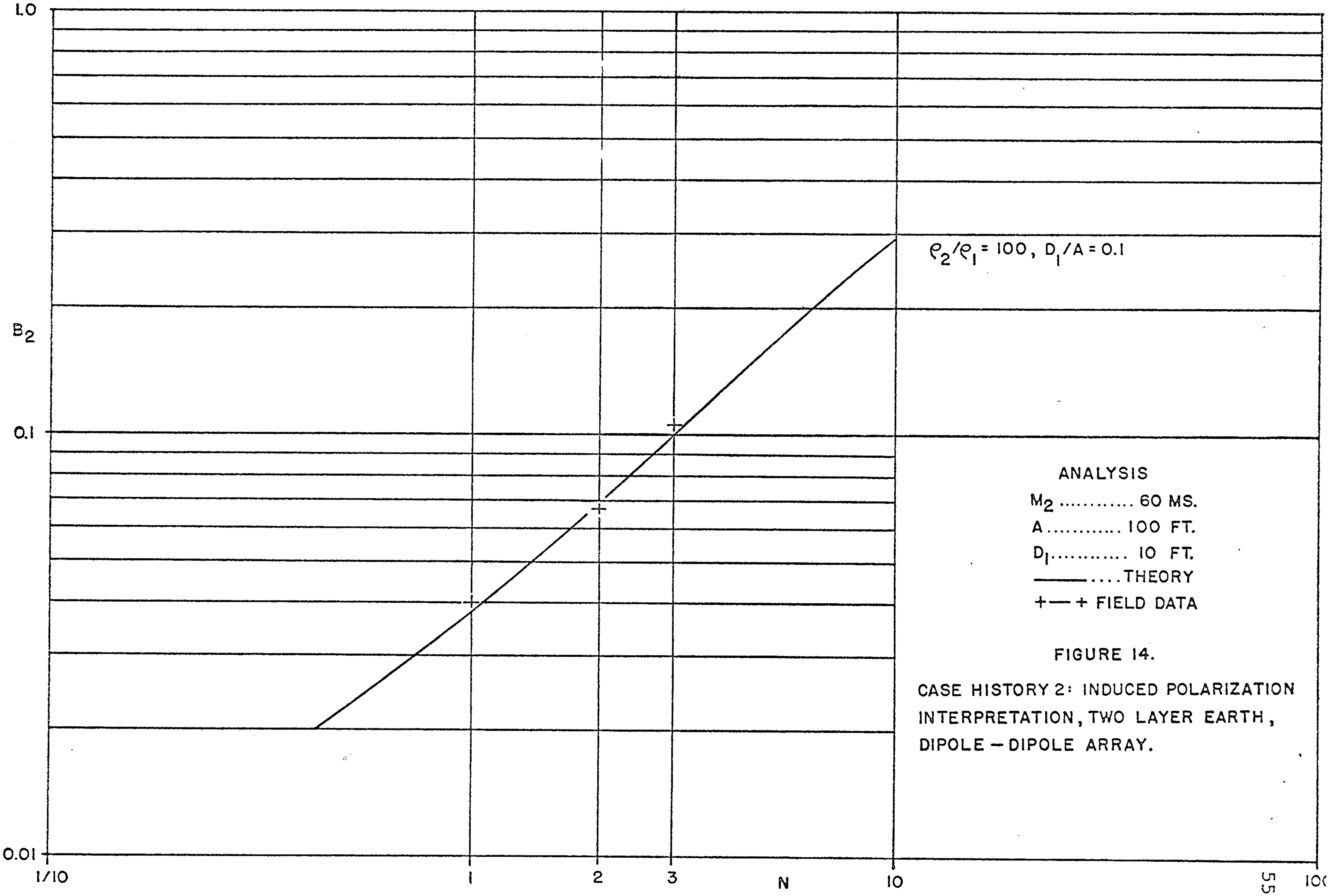

FIGURE 14.

CASE HISTORY 2: INDUCED POLARIZATION INTERPRETATION, TWO LAYER EARTH, DIPOLE – DIPOLE ARRAY.

Application of this information, i.e. $D_1 = 10$, to line 8+00 s and taking 40 msec as the average chargeability for the mid-section of the line, yields an M_2 of 20 msec; a value approaching background for a fissile rock. Since the line was read with a 200 foot dipole length ($D_1/A = 0.05$), it was necessary to extrapolate the theoretical curves to arrive at the value of B_2 (0.20).

The resistivity contrast was at the upper limit for the 25 watt system but the abundance of outcrop and shallow swamp made the survey possible.

Again, it is felt that the system generated an adequately effective survey without the use of cumbersome conventional equipment.

Primary coverage, excluding detail, was 6 miles in three days. Assuming conventional coverage would be one mile per day, a two-fold decrease in survey cost was realized.

CHAPTER VI

THE 250 WATT INDUCED POLARIZATION SYSTEM

Introduction

Recent trends suggest that the 'newly' developed 250 watt I.P. transmitter is being used to perform many battery reconnaissance surveys. Although no field examples can be cited, a comparison will be drawn between the 25 watt and 250 watt portable systems to discuss their relative merits. For continuity the 250 watt transmitter manufactured by the Scintrex organization will be discussed.

Description of the Scintrex IPC-8 250 Watt Transmitter

The Scintrex IPC-8 250 watt I.P. transmitter has the following specifications (after Scintrex, 1972).

Power	250 watt (maximum)
Output voltage	150 v to 850 v (in 5 steps)
Output current	1.5 amp (maximum)
Pulse duration	1, 2, or 4 sec.
Dimensions	5½" x 12" x 18" (14cm x 30cm x 46cm)
Weight	35 lb (15.5 kg)

The weight requirement for the 250 watt transmitter, compared to the 25 watt unit, makes the larger system, what the author prefers to call 'semi-portable'.

Depth of Investigation of the 250 watt System

The depth of investigation of any I.P. system regardless of power available, provided the electrode configuration remains identical, is fixed by the subsurface electrical and physical properties.

In order to improve the penetration characteristics the electrode geometry must be altered by (i) increasing the dipole length, (ii) increasing the separation (na), or (iii) deploying a different array. The first two require an increase in signal strength by way of more current impressed into the ground, which is accomplished by boosting the power of the transmitter.

By employing the same parameters that were used in establishing the power requirements for the 25 watt system, i.e. ρ_a = 100 ohm, minimum signal strength = 10 mv, it follows that the following dipole-dipole configurations are possible with the 250 watt transmitter.

(1) a = 200 feet, n = 1, 2, 3

(2) a = 400 feet, n = 1, 2

(3) a = 500 feet, n = 1

Figure 5 reveals the maximum penetration for effective anomaly detection for each of these configurations. There is at least a two-fold increase in penetration over the 25 watt system for each category and this feature should persist for any given model.

Relative Merits of the 250 watt I.P. System

The 250 watt system, because of the transmitter weight, is only semi-portable and because of its better performance over the 25 watt system is not strictly a reconnaissance tool except in areas where extreme resistivity contrasts exist. This makes it a valuable addition to array of I.P. equipment especially for work in the Canadian Shield.

Its performance characteristics, however, do not indicate that it should replace the 25 watt system for routine syrveys in the Canadian cordillera.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The case histories presented are representative of some 50 miles of I.P. work; 40 miles in British Columbia and 10 miles in northeastern Ontario. Other areas with similar environments presented no difficulty in anomaly detection.

It is felt that the 25 watt battery I.P. system is a versatile reconnaissance tool with reduced cost of the service when tempered simultaneously with careful interpretation and an awareness of the systems limitations. It was found that the occurrence or possible occurrence of overburden masking was easy to recognize during the survey and the degree of masking could be evaluated by the use of interpretation curves.

Subsurface conditions in British Columbia suggest that the 25 watt system can be used to perform all routine I.P. work. Extreme resistivity contrasts over the Canadian Shield render the 25 watt system applicable only where overburden thickness is less than 50 feet; this probably includes less than 25 percent of the land area.

The evaluation of the 250 watt system showed that it more closely approximates the performance and logistical characteristics of conventional units and, therefore, should not be misconstrued as a replacement for the 25 watt unit.

In Ontario the 250 watt system has a definite advantage and it is estimated that the system will be effective over 75 percent of the area.

The 25 watt unit has blanket application in British Columbia provided sufficient current can be applied to the ground. This is a problem with any I.P. survey but may be more serious with higher powered units because longer dipoles are used and readings are expected for several separations.

Areas with one or more adverse physical or electrical properties can be expected but the array of I.P. equipment available allows selection of the best system.

A possible deployment chart is given below:

Survey Status

	Routine	Problem
British Columbia	25 watt	250 watt
Ontario	250 watt	2500 watt

With several choices of I.P. system available it is important to know beforehand, especially if the work is in an inaccessible area, the electrical and physical properties to be encountered but specific information of this sort is generally unavailable through current publications.

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