

---

Masters Theses

Student Theses and Dissertations

---

1949

## Application of electrical prospecting methods to two types of sulphide ore deposits

Robert Van Nostrand

Follow this and additional works at: [https://scholarsmine.mst.edu/masters\\_theses](https://scholarsmine.mst.edu/masters_theses)



Part of the [Physics Commons](#)

Department:

---

### Recommended Citation

Van Nostrand, Robert, "Application of electrical prospecting methods to two types of sulphide ore deposits" (1949). *Masters Theses*. 4793.

[https://scholarsmine.mst.edu/masters\\_theses/4793](https://scholarsmine.mst.edu/masters_theses/4793)

This thesis is brought to you by Scholars' Mine, a service of the Missouri S&T Library and Learning Resources. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact [scholarsmine@mst.edu](mailto:scholarsmine@mst.edu).

APPLICATION OF ELECTRICAL PROSPECTING METHODS

TO

TWO TYPES OF SULPHIDE ORE DEPOSITS

BY

ROBERT G. VAN NOSTRAND

-----

A

THESIS

submitted to the faculty of the  
SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI  
in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE, PHYSICS MAJOR

Rolla, Missouri

1949

Approved by Harold B. Fuller  
Professor of Physics

ACKNOWLEDGEMENTS

I express my gratitude to the United States Geological Survey for its permission to use data from an official project as the basis for this thesis. Special thanks are extended to Mr. F. C. Farnham, of that organization, for his guidance of the investigations, and for his help in reviewing the material after it had been assembled.

I thank Mr. Ed Carlson of the Virginia Iron, Coal, and Coke Company, Mr. Harold Ewoldt of the Calumet and Hecla Consolidated Copper Company, and Mr. O.E. DeWitt of the Vinegar Hill Zinc Company for permission to use their properties, and for their aid in locating suitable sites for the various phases of the project.

I am grateful to Dr. Harold Q Fuller, Chairman of the Department of Physics, Missouri School of Mines, for his aid and suggestions in reviewing this paper before it was put in its final form.

TABLE OF CONTENTS

|  | Page |
|--|------|
| Acknowledgments .....                                | ii   |
| List of Illustrations .....                          | iv   |
| Introduction .....                                   | 1    |
| Geological Background .....                          | 2    |
| Virginia .....                                       | 2    |
| Wisconsin .....                                      | 5    |
| Equipment and Standard Procedures .....              | 8    |
| Resistivity Data .....                               | 13   |
| Virginia .....                                       | 14   |
| Wisconsin .....                                      | 19   |
| Self-Potential Data .....                            | 24   |
| Virginia .....                                       | 25   |
| Apparent Resistivity versus Current<br>Density ..... | 27   |
| Potential Decay Phenomena .....                      | 30   |
| An "In-Hole" Technique .....                         | 39   |
| Summary .....  | 50   |
| Bibliography .....                                   | 51   |
| Curriculum Vitae .....                               | 53   |

LIST OF ILLUSTRATIONS

|  | Page |
|--|------|
| 1. Sketch of Wenner Configuration .....  | 9    |
| 2. Chestnut Creek Segment - Sketch of Gossan<br>Outcrop and Vertical Resistivity Profile ..... | 15   |
| 3. Betty Baker Segment - Vertical Profile .....  | 16   |
| 4. Cranberry Segment - Horizontal Traverse .....   | 16   |
| 5. Vertical Profile over Typical Wisconsin<br>Ore Body .....                                   | 20   |
| 6. Horizontal Traverse over a Typical Wisconsin<br>Section .....                               | 22   |
| 7. Cranberry Segment - Vertical Section and Self-<br>Potential Profile .....                   | 26   |
| 8. Resistivity versus Current Density .....  | 28   |
| 9. Resistivity versus Current Density .....  | 29   |
| 10. Anomalous Potential Decay .....  | 33   |
| 11. Rectification of Potential Decay Curves .....  | 35   |
| 12. Potential Decay versus Current Duration .....  | 36   |
| 13. Action of a Buried Chemical Cell .....   | 38   |
| 14. Block Diagram of "In-Hole" Technique .....   | 40   |
| 15. Results in Ore Hole Number One .....   | 42   |
| 16. Results in Ore Hole Number Two .....   | 43   |
| 17. Results in Ore Hole Number Two .....   | 44   |
| 18. Results in Ore Hole Number Three with inter-<br>ference from Drill Rig .....               | 44   |
| 19. Results in Ore Hole Number Three .....   | 46   |
| 20. Results in a Barren Hole .....   | 46   |

## INTRODUCTION

Although certain types of sulphide ores, especially those near the surface of the earth, lend themselves very well to electrical prospecting methods, quite the opposite is true of the extensive deposits of the type found in the Mississippi River Valley. The purpose of this investigation was to discover additional facts concerning two distinct types of sulphide ores, and therefrom to develop a new technique which would be applicable to prospecting for the lead and zinc deposits found in the Mississippi Valley.

The development of this paper follows approximately the lines along which the investigation was made. First will be given the geology of the areas in which the work was done. Most of the information on the geology was obtained from data which had been collected during previous investigations by other investigators. Following the section on geology is a discussion of the standard methods employed, together with the type of equipment which was used.

The actual work will first be discussed in a treatment of the ordinary electrical properties of the rocks involved. The results of this author will be compared to the data found in the literature on the same types of rocks and formations. Finally, there will be presented two procedures which yielded outstanding positive results, one at each of the two locations investigated. Unfortunately, due to circumstances impressed by the size of the equipment, the

great distance between the two locations, and a lack of sufficient time, the results are by no means to be considered complete. Rather, they are presented here as the statement of problems which are well worth further consideration. In addition, a third procedure yielding a negative result will be described.

### GEOLOGICAL BACKGROUND

Virginia. The Gossan Lead runs in a northeasterly direction for about 17 miles through Carroll County, Virginia, some 15 miles northwest of the crest of the Blue Ridge. The region is a high plateau which drains through numerous meandering streams northwest into the New River. There is an average elevation of about 2500 feet with a maximum relief of 700 feet. The topography is characterized by fairly steep, rounded hills without the prominent ridges which are found in most of the Blue Ridge region. The countryside is about evenly divided between forests and farmlands.

The mineralized zone, which is one of the largest sulphide ore bodies known, is enclosed in the Pre-Cambrian Lynchburg gneiss which may be equivalent to the widespread Carolina gneiss found farther south.<sup>1</sup> Long thought to be

---

1. Wright, R.J. and Raman, N.D. The Gossan Lead, Carroll County, Virginia. U.S. Department of the Interior. Information Service Release. 19 February 1948. p. 3.

---

a series of lenses, the apparent pockets of gossan have been shown, through recent work, to be the surface expression of a continuous vein of sulphides consisting principally of pyrrhotite. Because of the idea of lenses, parts of the gossan lead have been named the Chestnut Creek Segment, the Cranberry Segment, the Betty Baker Segment, etc.

The Lynchburg gneiss, in the region of the gossan, is predominately light gray, quartz-mica schist in which there are minor occurrences of sericite schist, mica-garnet schist, amphibole gneiss and schist, and granitic zones.<sup>2</sup>

---

2. Ibid.

---

The foliation of the schist trends generally northeast with an average dip of 60 degrees to the southeast at the surface of the earth. Due to the great amount of folding of the rock, the dip varies considerably below the surface. At one place near the Betty Baker Segment, at a depth of a few hundred feet, the layers are known to be horizontal.<sup>3</sup>

---

3. Mr. Ed Carlson, Virginia Iron, Coal, and Coke Company. Private correspondence.

---

As a general rule, the ore vein cuts slightly across the schistosity.

The primary ore mineral is pyrrhotite while pyrite, chalcopyrite, sphalerite, and galena are also commonly



found in small quantities.<sup>4</sup> Gangue minerals include quartz,

---

4. Wright and Raman. op.cit. p 4-5

---

feldspar, amphibole, chlorite, biotite, dolomite, and spess-  
arite. The per centage of sulphides varies considerably  
along and across the strike of the vein; there is a complete  
gradation from nearly massive sulphides to sulphides sparsely  
disseminated in gangue materials. These sulphides often in-  
clude rounded and slickensided pieces of the country rock,  
in places so abundant that it is apparent that the sulphides  
were deposited in a brecciated or fracture zone. In de-  
scribing several stages of mineralization, Ross indicates  
that the mineralization occurred concurrently with various  
periods of movement.<sup>5</sup> The sulphides were deposited after

---

5. Ross, Clarence S. Origin of the Copper Deposits of the  
Ducktown Type in the Southern Appalachian Region. U.S. Geo-  
logical Survey. Professional Paper 179. 1935. p 77-85.

---

the period of greatest disturbance, but before the movement  
had ceased.

Gossan is the name applied to the weathering product  
of the sulphide ore. In this region, the weathering pro-  
duct of the ore body varies from the pure gossan, which is  
a porous brown material consisting of nearly pure limonite,  
a schistose gossan, limonitic schist, and iron stained  
schist which are named in the order of descending iron con-

tent.<sup>6</sup> Other minerals, mostly carbonates and sulphates,

---

6. Wright and Raman. op.cit. p 6.

---

were formed during the weathering process but they have been carried away in solution by the ground water.

Wisconsin. The upper Mississippi lead and zinc district lies amidst the pastures and cornfields of northwestern Illinois, southwestern Wisconsin, and a small adjoining portion of Iowa. The bulk of the district is in Wisconsin. The region is one of gently rolling hills dissected by a few deep valleys and spotted with an occasional steep sided hill which is locally known as a "mound." The elevation of the Mississippi River in this area is 600 feet and the average elevation of the countryside is about 900 feet; the maximum relief is a little more than 800 feet.

Besides the small outliers of Lower Silurian limestone which form the mounds, the only outcropping rocks in the region are Ordovician.<sup>7</sup> These sedimentary rocks include,

---

7. Willman, H.B., Reynolds, R.R., and Herbert, Paul, Jr. Geological Aspects of Prospecting and Areas for Prospecting in the Zinc-Lead District of Northwestern Illinois. Illinois State Geological Survey. Bulletin 116. 1946. p 12-14.

---

in ascending order: the St. Peter formation, from 40 to over 100 feet of almost pure, poorly cemented, quartz sand; the Platteville formation, 60 to 65 feet of limestone and dolomite; the Decorah formation, 35 to 40 feet of non-

cherty dolomite and a brown limestone interbedded with reddish brown shale; the Galena formation, 220 to 225 feet of massive rock grading from a cherty dolomite with some shale partings to a buff colored dolomitic limestone containing thin yellow dolomitic shales; and the Maquoketa formation which represented by 105 to 160 feet of shale. The main horizon of ore occurrence is in the dolomite beds of the lower Galena and upper Decorah, and in the limestone of the upper Platteville.

It can be generally said that the ore deposits show consistent orientation and grouping which are related to local structural features superimposed upon a slight regional dip to the southwest. Many of the ore bodies appear to be grouped in curved, or arcuate, patterns one half to one mile wide, following broad, shallow synclines. Ore zones are more prevalent along the lower slopes of the synclines than along the bottoms. There are also some long, straight ore bodies which are associated with narrow structures, probably shear zones, oriented in a northwestern direction. Although, in the non-ore bearing ground the strata are little disturbed, the rocks within the ore bodies present both vertical and inclined crevices and shear zones, and are commonly faulted on a small scale. The local structures, with which the ores are associated, are thought to be the result of slumping caused by differential solution of the limestone beds by the same mineralizing waters which brought the ore minerals.

Ore deposits are found in five general forms.<sup>8</sup> "Ver-

---

8. Behre, Charles H. Paragenesis of the Wisconsin-Illinois-Iowa Lead-Zinc District. Geological Society of America. Special Paper 24. 30 December 1939. p 116.

---

ticals" are joint fillings, essentially vertical; "pitches" are deposits in inclined joints or fractures along which there usually has been some movement; "flats" are deposits along planes of parting between beds; "breccia fillings" are localized in areas where the rock has been heavily shattered; and, "disseminated ore bodies" are of vague outline, the ore occurring chiefly in shale, separate crystals having grown by crowding the laminae apart. Named because of their position in the ore bearing strata, "lower run" deposits, which contain both lead and zinc, involve all of the above mentioned types of deposits, generally all in one ore body.<sup>9</sup> The "top run" deposits generally contain only

---

9. Willman, Reynolds, and Wilson. op.cit. p 13-18.

---

lead, and occur in vertical crevices.

The principal ore minerals are sphalerite and galena. Two other sulphides commonly present are the two of iron, pyrite and marcasite.<sup>10</sup> Calcite, barite, and the secondary

---

10. Behre. op.cit. p 114-115.

---

minerals, cerussite, anglesite, calamine, and smithsonite are also present to varying degrees. Most of the deposits

are presumed to have been formed by crystallization from solutions in open channels, but some replacement is always in evidence.

The grade of the ore is highly variable.<sup>11</sup> Ten per

---

11. Willman, Reynolds, and Wilson. op.cit. p 15-16.

---

cent zinc is considered to be minable. Lead usually averages one per cent, but rich pockets of pure galena are occasionally found. Iron varies from five to ten per cent. In many cases, mineralized zones may run high in the sulphide of any one of these metals, almost to the exclusion of the others.

In this district, work was done over three known ore bodies and one area which had been proven to be barren of ore. All were in the vicinity of Shullsburg, Wisconsin. In all cases, the ore occurred in the lower run deposits which were discussed previously.

#### EQUIPMENT AND STANDARD PROCEDURES

There are two standard methods which were used in this project to determine resistivity. The first, which was the earlier to be developed, employs the Wenner configuration of electrodes.<sup>12</sup> Four electrodes are arranged as shown in

---

12. Gish, H. and Rooney, W.J. Measurement of the Resistivity of Large Volumes of Undisturbed Earth. Terrestrial Magnetism. Volume 30. 1925. pp 161-188.

---

figure 1 with a separation of "a" meters. A direct current of "I" amperes is supplied to the ground through two steel stakes at  $C_1$  and  $C_2$ . By means of a potentiometer, the potential differences of "V" volts between the two points  $P_1$

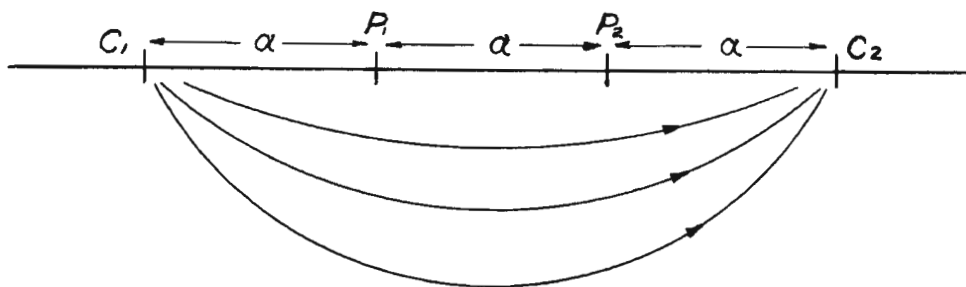


Figure 1 - A Sketch of the Wenner Configuration.

and  $P_2$  is measured. The resistivity in meter-ohms is then given by:  $\rho = 2\pi a V/I$ . The derivation of this expression is based upon the assumption of an isotropic, homogeneous earth. In actual practice, the earth being investigated is neither homogeneous nor isotropic. Therefore, the measured quantity represents an average effect; and, as such, it is called the "apparent resistivity."

It has been determined, both theoretically and experimentally, that when this configuration is used the measured value of the resistivity is affected only by the material within a distance "a" of the line of electrodes.<sup>13</sup> Under

---

13. Ibid.

---

normal conditions, the earth is essentially a series of

roughly horizontal layers; and, therefore the electrode separation "a" is often referred to as the effective depth of investigation. For the same reason, a series of measurements, in which "a" is varied systematically, is referred to as a "depth determination," "electrical drilling," or "depth profiling." At the same time, a survey conducted by moving the configuration, with "a" constant, from station to station along a line is known as a "horizontal traverse."

The second method, and the one employed most during this project, employs the Lee Partitioning Configuration.<sup>14</sup>

---

14. Lee, F.W. U.S. Patent 1,951,760. 20 March 1934.

---

The Lee configuration is much the same as the Wenner configuration with the exception that a third potential electrode,  $P_0$ , is placed midway between  $P_1$  and  $P_2$ . The potentials at  $P_1$  and  $P_2$  are then measured with respect to  $P_0$ . In this case, the apparent resistivity is given by:  $\rho = 4\pi a V/I$ , where  $V$  is the potential difference in one or the other of the potential segments. By this technique, it is possible to learn something about the symmetry of the potential distribution.

In general, there is always at least a small potential difference between two points picked at random on the surface of the earth. Moreover, contaminations on the bottoms of the porous pot electrodes cause slight potential differences. To eliminate the effect of these possible errors, at least two readings are taken at every setting - one with

the current flowing in one direction and the second with the current flowing in the opposite direction. These readings are referred to as "direct" and "reverse" readings.

When it is desired to map the natural potentials at points on the surface of the earth, only two porous pot electrodes and a potentiometer circuit are used. One electrode is fixed for a reference, while the second is moved about in a regular fashion so that the potentials at all of the desired points are measured with respect to the same fixed point.

In order to obtain high voltage direct current which could be maintained for extended periods of time, a generator system was used. During the project, two complete sets of equipment were used; but, since the first differed from the second primarily in age, a description of only the new set will be included. It was used only on the Wisconsin part of the project.

Sixty cycle alternating current was supplied from a 7.5 kilowatt, gasoline driven, 3 phase generator. The ordinary shunt connection for the field coils of the generator exciter was replaced by a connection to a bank of 45 volt "B" batteries which then supplied the necessary current to the field coils. The output voltage, which would have normally been constant at 115 volts, was varied manually by using a variable rheostat to regulate the current which flowed from the "B" batteries through the coils.



The desired direct current was obtained from a closed unit which housed both a step-up transformer and a set of six mercury vapor, full wave, rectifier tubes. The filaments of the tubes were heated by a 110 volt, 60 cycle, alternating current from a second gasoline driven generator rated at 2.5 kilowatts. The system developed up to 5000 volts, but its maximum voltage output was seldom used. All of the above power equipment was permanently mounted in a one and one-half ton truck with dual rear wheels.

The current, applied to the ground through two sets of one or more steel stakes, was passed through a standard one ohm resistance. The magnitude of the current was determined by using a potentiometer to measure the potential drop across the standard resistance. The potentiometer was calibrated to read directly in milliamperes and readings could be estimated to tenths of milliamperes. However, the actual accuracy of the current determinations was limited to about  $1 \frac{1}{2} \%$  by fluctuation of the generator and by the lack of linearity, or uniformity in the cross-section area, of the slide wire of the potentiometer.

Using non-polarizing porous pot electrodes as contacts with the ground, the potential difference between various points was measured directly with a second potentiometer calibrated to suit the particular needs of the situation. For example, in the expression given above for the resistivity in the case of the Wenner configuration, it would be

useful to calibrate the potentiometer to read " $2\pi kV$ " where  $k$  is the conversion factor from feet to meters, instead of " $V$ ". Then, if  $I$  in milliamperes is made equal to " $a$ " in feet, the reading of the potentiometer will actually give the resistivity in meter-ohms. The accuracy of this potentiometer is also limited to a maximum possible error of about  $1\frac{1}{2}\%$  by the lack of linearity of its slide wire.

In the case of both potentiometers mentioned, the accuracy could be increased through the use of a calibration curve to correct each reading. In this paper, the data have not been adjusted in this manner because it was felt that the values determined could not be repeated with any more accuracy than is allowed by the potentiometers as they stand.

#### RESISTIVITY DATA

Two classical conceptions of the electrical properties of sulphide ores present themselves. The first concerns the low resistivities of most of the sulphides. Of these minerals, only sphalerite has a fairly high resistivity.

The following values for the resistivities of various rocks and minerals, encountered during this project, have been taken from extensive information which Heiland<sup>15</sup> has

---

15. Heiland, C.A. Geophysical Exploration. New York. Prentice-Hall, Inc. 1940. pp 659-664.

---

tabulated from many sources:

| <u>Material</u>          | <u>Resistivity</u>                      |
|--------------------------|---|
| Galena                   | .05 meter-ohms                          |
| Pyrite                   | .001                                    |
| Marcasite                | .01 to .1                               |
| Sphalerite               | 100,000                                 |
| Hematite                 | $4 \times 10^4$ to $10^7$               |
| Limonite                 | 100,000                                 |
| Mica                     | $1.5 \times 10^8$ to $9 \times 10^{13}$ |
| Mica schist <sup>a</sup> | 1300                                    |
| Garnet gneiss            | 200,000                                 |
| Shale <sup>a</sup>       | 20 to 1400                              |
| Sandstone <sup>a</sup>   | 35 to 1000                              |
| Limestone <sup>a</sup>   | 120 to 1500.                            |

<sup>a</sup> Resistivities determined for materials in situ. All other determinations made on laboratory samples.

There is one fact which must be remembered in reviewing the above resistivities. In the ground, the principal current carrying agent is the ground water which contains various ions. Thus, the materials which yield such high values when tests are made on dry samples in the laboratory would, in general, display much lower values when measurements are made in situ, even if the material is only moistened by the ground water. On the other hand, the minerals showing such low values as are shown in the table would have those low values moderated upward when the minerals are disseminated in other materials as they are in the earth.

Virginia. On the Virginia project, the low resistivities of the sulphides were accented by the extremely high values found in the surrounding country rocks. The great variation in resistivity can readily be seen in figures 2 and 3, on the following page, which represent

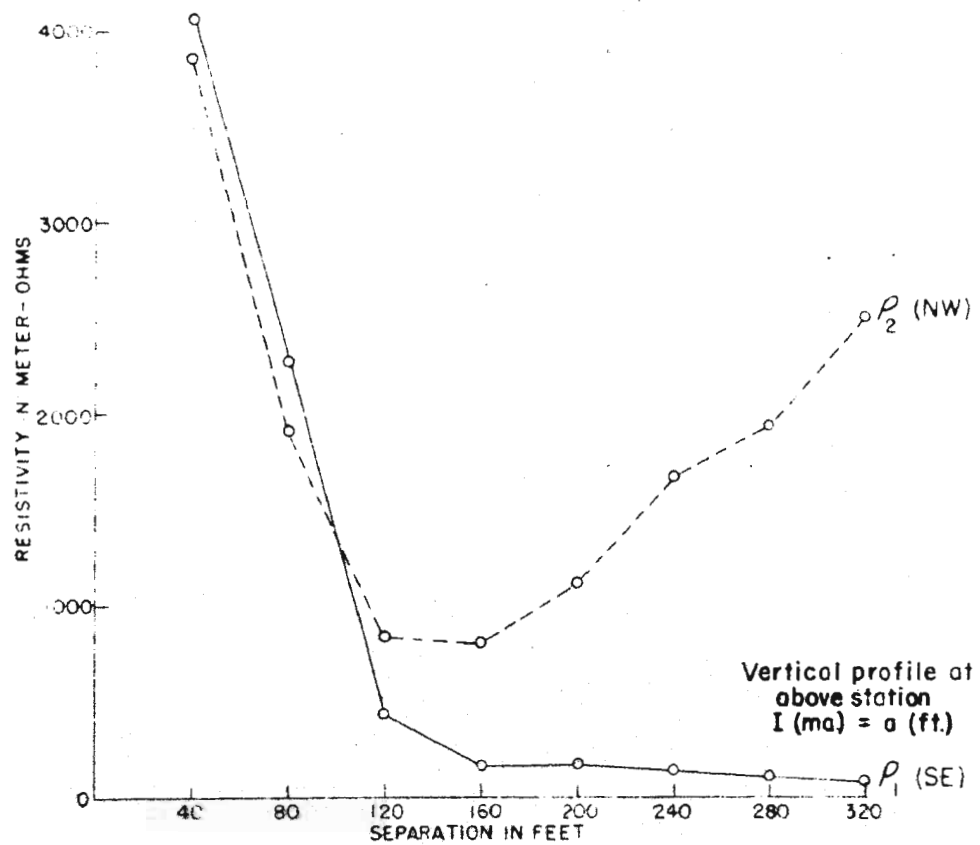
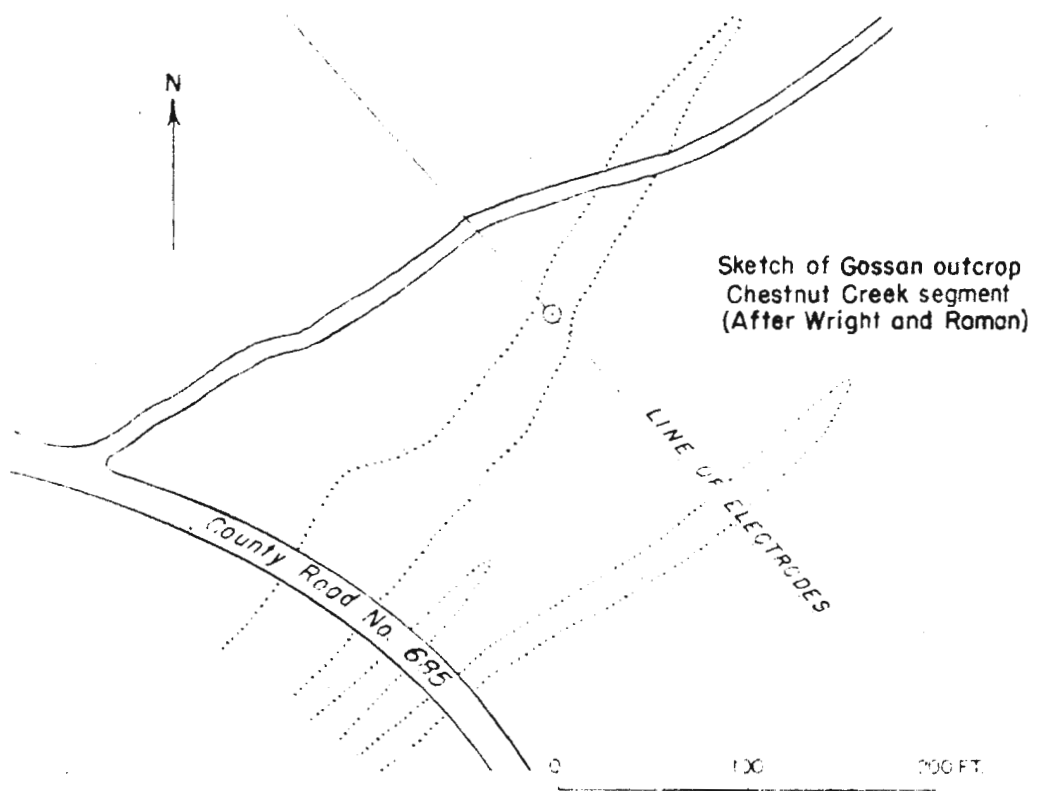


Figure 2

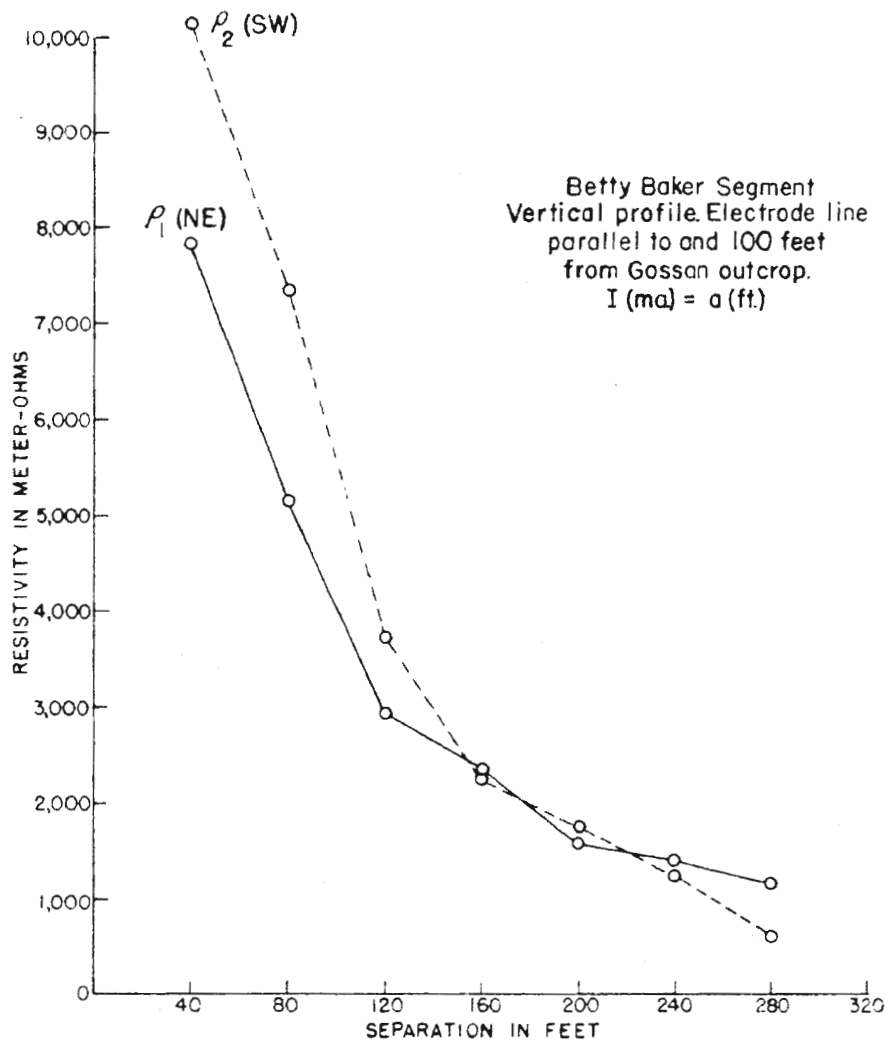


Figure 3

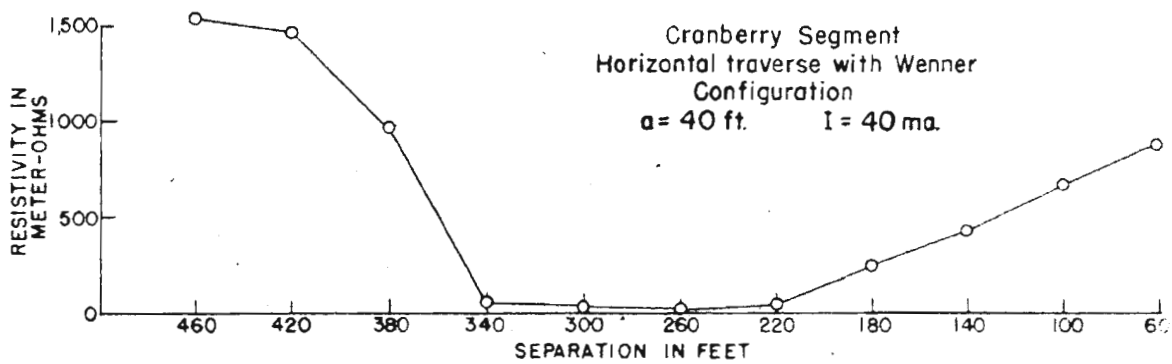


Figure 4

typical curves obtained in depth profiling in the vicinity of the gossan lead. The first shows data taken on an electrode line perpendicular to the gossan zone, and centered over the gossan near its northwest boundary. The initial value of the resistivity, obtained with an electrode separation of 40 feet, indicates a value for the near surface material which is probably not too high in iron content. The resistivity in both  $\rho_1$  and  $\rho_2$  curves drops rapidly as the separation is increased to 120 feet. At that point the curves separate abruptly.  $\rho_1$  continues to decrease to a constant value a little below 100 meter-ohms which is the approximate value for the ore deposit at that place. On the other hand,  $\rho_2$  breaks sharply upward and continues to increase. In this case, the breaking point indicates the place where the northwest potential electrode,  $P_2$ , moves from the influence of the gossan. The continued low values for  $\rho_1$  indicate that the many fingers of the gossan outcrop, outlined by geologists<sup>16</sup> as shown in figure 2, are joined

---

16. Wright and Raman. op.cit. Figure 6.

---

below the surface in a single body of ore.

The curves of the second graph decrease together because the line runs parallel to the gossan so that  $\rho_1$  and  $\rho_2$  are equally affected. This line is incomplete because physical conditions kept it from being extended.

The second graph gives a value for the resistivity of

the enclosing rocks which is more consistent with other measurements made during this project. In the direction parallel to the schistosity, the resistivity was found to be in excess of 10,000 meter-ohms when determined by the Lee method. In the direction perpendicular to the schistosity, the resistivity was found to be slightly less than 10,000 meter-ohms, perhaps as low as 8000 in certain places.

Comparatively, the resistivity of the gossan is extremely small. The lowest value, which was of the order of 10 meter-ohms, was found where a road cut has exposed the gossan of the Cranberry Segment four miles northwest of Hillsville. Other values for the gossan were found to be somewhat higher, presumably because of a lower iron content than occurred in the vicinity of the road cut. The very low resistivity associated with the gossan has been attributed by Farnham<sup>17</sup> to the presence of sulphuric acid pro-

---

17. Mr. F.C. Farnham, U.S. Geological Survey. Private correspondence.

---

duced in the oxidation of the sulphides.

An example of a horizontal traverse may be seen in the graph in figure 4. The data was taken by running the Wenner configuration, with constant electrode spacing of 40 feet, across the exposed gossan at the Cranberry Segment. The resistivity of the surrounding materials is relatively low in this area due to the erosion of the gossan and its consequent spreading into the overburden. However, there

is a distinct anomaly over the gossan outcrop where the resistivity is found to be as low as 15 meter-ohms. It is suggested that this anomaly be compared with the self-potential curve and the vertical section shown in figure 7.

In upland areas, although the resistivity over the gossan is found to be higher at the same electrode spacing, the resistivity of the enclosing materials is great enough to produce an even greater contrast than is found at the Cranberry Segment. Thus, the outline of the gossan outcrop could be mapped quite readily by this method. To this date, such a method has not been attempted although surface geology methods have failed to trace the line of the gossan throughout its length.

Wisconsin. The resistivity situation in the Wisconsin lead and zinc district is entirely different from that found in connection with the gossan lead of Virginia. The ores lie at moderate depths so that their effect on the measured resistivity is nil; and, the resistivity of the country rock is comparatively low - running from about 50 meter-ohms for soils and shales to a maximum of about 1000 meter-ohms for the limestone and dolomite.

The sort of resistivities to be expected in the Wisconsin area is well illustrated in figure 5. The electrode line runs north-south with the center a short distance inside the boundary of the Makoqueta shale. The shale, and a thick overburden derived from the shale, are the factors



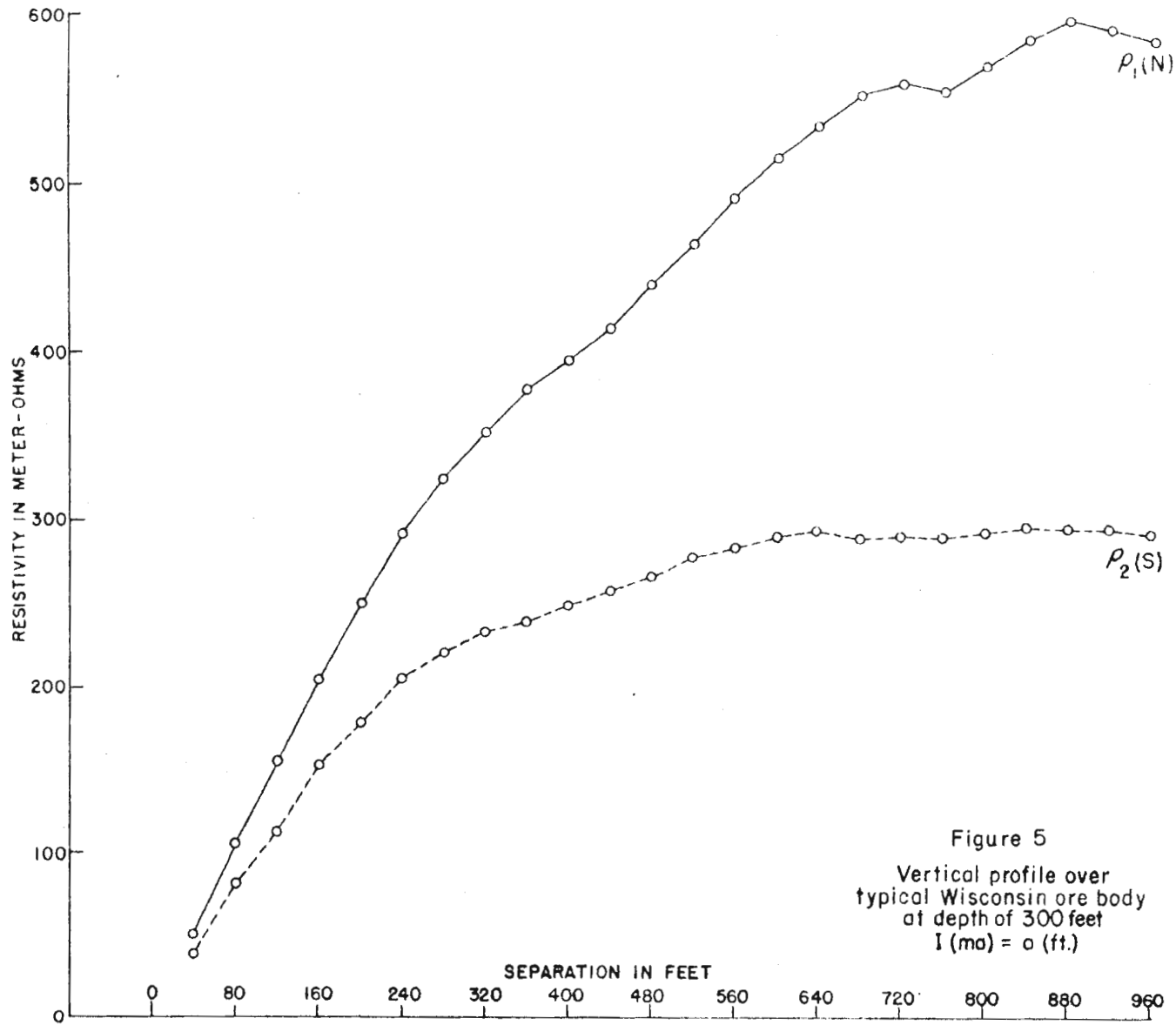


Figure 5  
 Vertical profile over  
 typical Wisconsin ore body  
 at depth of 300 feet  
 $I (ma) = 0 (ft.)$

which make the low resistivity found for the low values of the electrode separation. As the separation is increased, the higher resistivity of the underlying limestone causes the curves to rise rapidly. In this case, the north current and potential electrodes moved beyond the shale-limestone contact as the separation was increased, while the south electrodes moved in the direction of the thickening shale. Consequently,  $\rho_2$  (north) continues to increase until it reaches a value representative of the limestone.  $\rho_1$  levels off at a much lower value due to the continued influence of the shale. As long as the shale continues to thicken to the south, the apparent resistivity will remain about the same for all greater electrode separations. The "kinks" at the end of the  $\rho_2$  curve are due to fractures being crossed by the north current electrode. These fractures, as well as being indicated by the curve, could be observed on the ground.

It can readily be seen from these curves that, although the electrode separation was carried to 960 feet, there is nothing which would indicate the presence of the mineralization which was known to exist in quantity at a depth of about 275 feet.

One useful purpose of resistivity measurements in this area is in the mapping of fracture zones which occur near the surface of the earth. In many cases, there is mineralization associated with such zones. Figure 6 contains a

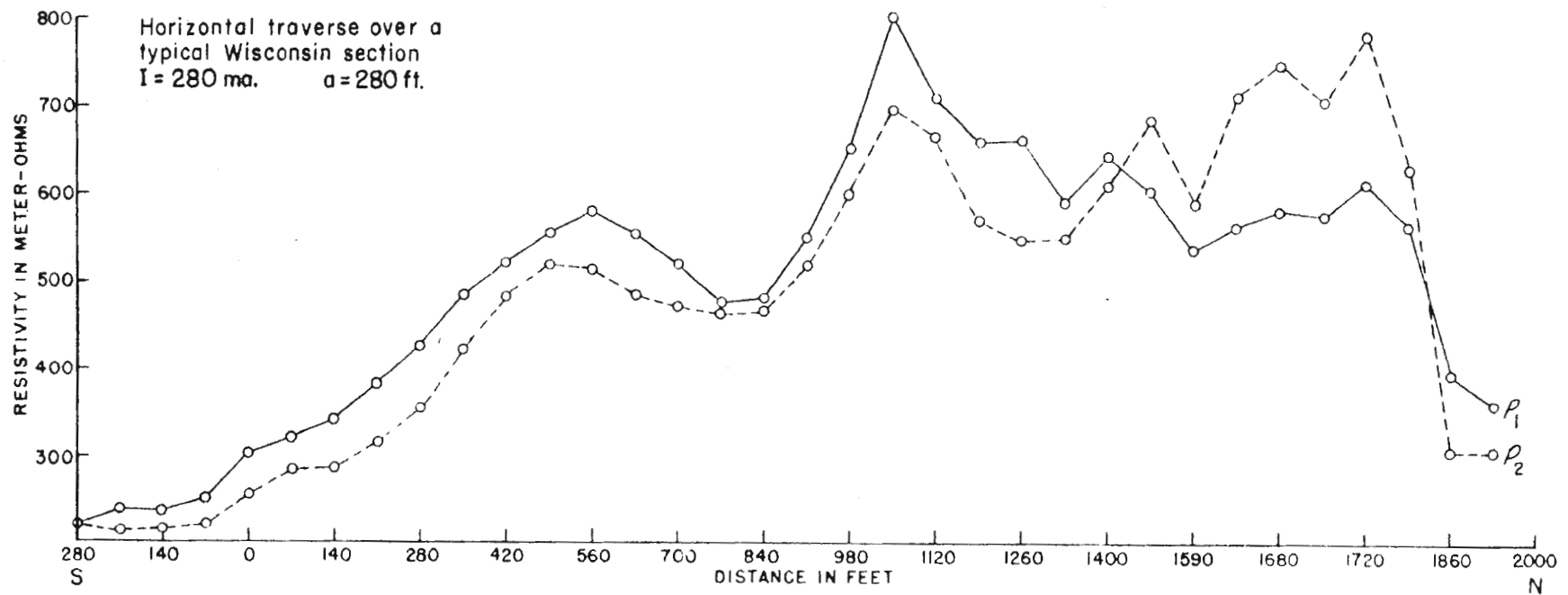


Figure 6

graph which typifies the manner in which the fractures may be discovered and mapped. The data was taken in a horizontal traverse along a north-south line extending over 1000 feet north of the known ore body. The Lee configuration was used with an electrode separation of 280 feet; and, the values for  $\rho_1$  and  $\rho_2$  are plotted in each case against the position of the midpoint of the corresponding potential segment.

As the configuration was moved north, the leading current electrode ( $C_1$ ) crossed the first fracture in the neighborhood of 850 feet, giving rise to the minor maximum in the  $\rho_1$  curve shown on the graph at 560 feet. The maximum is also experienced by  $\rho_2$  to a lesser degree. As the current electrode moved beyond the fracture and the north potential electrode approached, a minimum was obtained for  $\rho_1$ .  $\rho_2$  is almost unaffected during this stage. As the center of the configuration, the common potential electrode  $P_0$ , approaches the fracture, both  $\rho_1$  and  $\rho_2$  rise to a sharp maximum. Under ideal conditions, the two curves would cross during this stage and a symmetrical set of curves would be obtained. However, in this case, beyond the first fracture there was a series of other faults and fractures which make further interpretation of the graph difficult, if not impossible. Better definition and interpretation could be had by using a smaller electrode separation.

This particular fracture, which occurs in the middle

of a level field, was predicted on the basis of the above data. Verification was later given by local geologists who had the necessary drill records and geological data.

#### SELF-POTENTIAL DATA

The second of the classical features of a sulphide ore body, especially one which is only partly submerged below the water table, concerns the associated spontaneous potentials. Near the surface of the earth, the zone of percolating ground water is rich in oxygen.<sup>18</sup> Normally, the

---

18. Jakosky, J.J. Exploration Geophysics. Los Angeles. Times-Mirror Press. 1940. pp 256-266.

---

lower portions of the ore body lie in a zone where there is little oxygen, or even the presence of reducing agents. Thus, the conditions which prevail foster a potential difference and the ore body becomes a battery such that current flows down through the ore and returns upward through the surrounding rocks. A study of the potential distribution at the surface of the earth in the vicinity of such an ore body reveals that there is a potential minimum directly over the ore. Previous investigators, since about 1900, have found potential differences as high as one volt, and have used such data in the location and mapping of various geologic situations.

Virginia. The high self-potentials found associated with the gossan lead in Virginia are typically represented

in the graph of figure 7. The graph is drawn in connection with the vertical section at the road cut in the Cranberry Segment where the data was taken. It is to be noted that the potential is a minimum at a point which is a short distance from the gossan outcrop on the downdip side. This would indicate that the present zone of oxidation is not at the surface of the ground where the sulphides were freshly exposed only a few years ago, but at some point within the vein a small distance below the surface. The hump in the middle of the curve probably represents a neutral zone, and the second minor minimum is a reflection, on the up-dip side, of the same oxidation zone which produces the first minimum.

Wisconsin. In the Wisconsin area, several attempts were made to find some self-potentials which could be linked with known ore bodies, but without success. This lack of useful self-potentials is attributable to one or both of two facts. The mineralization is found from 100 to 300 feet below the surface of the ground, well below the water table, so that there is little or no differential chemical action taking place. Secondly, the depth of the ore would itself make it difficult to detect any natural potentials originating at the mineralized horizons, even if such natural potentials do exist. This fact would be especially true in a region of comparatively low resistivity such as is found in Wisconsin.

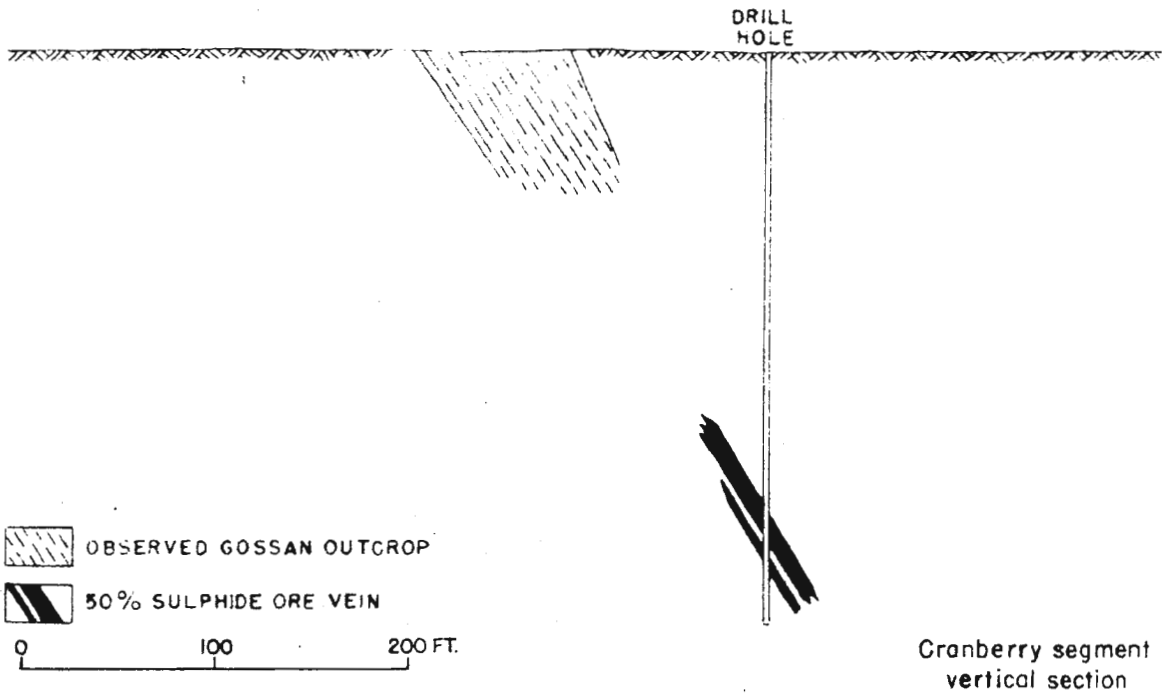
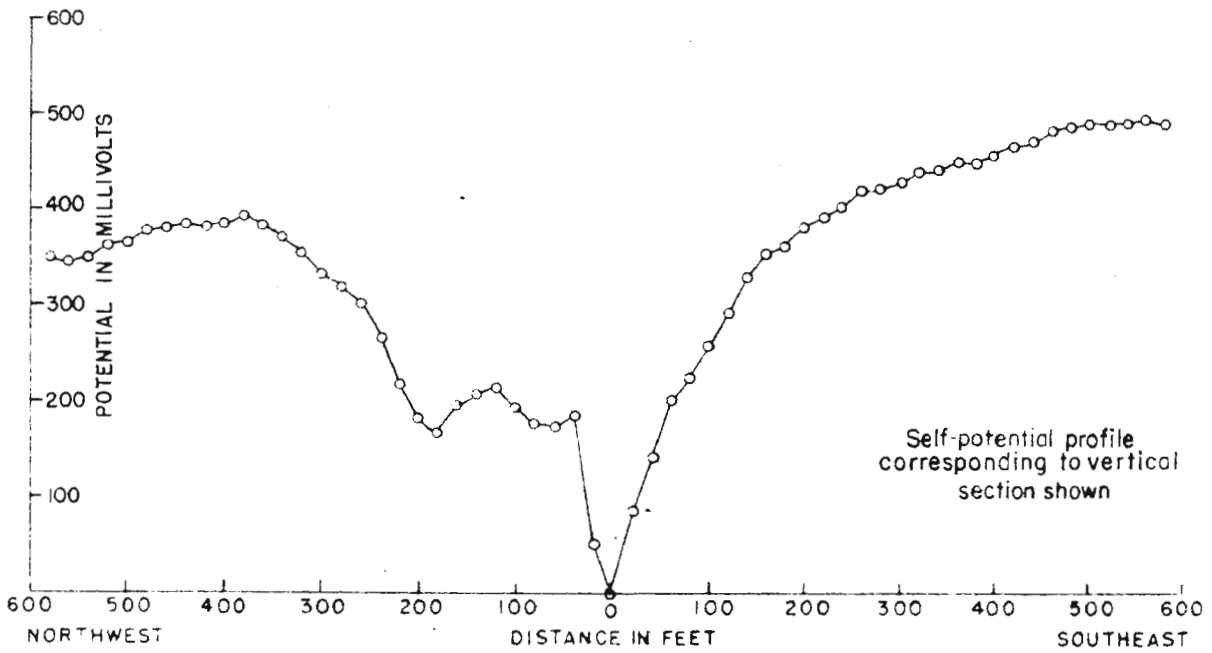


Figure 7

### APPARENT RESISTIVITY VERSUS CURRENT DENSITY

During this project, there were three new effects which were studied. For the first of these, only negative results were obtained.

It is a well known fact that, when current is passed through an electrolytic cell, the cell becomes polarized. Current will not flow through the cell at all until the applied potential is raised above the polarization potential. As the applied potential is raised, the current which flows is proportional to the difference between the applied potential and the polarization potential. Then, if the resistance of the cell, computed by Ohm's Law from the current and the applied potential, is plotted against the current, the curve would start from infinity for low values of the current and would fall asymptotically to the true value of the resistance for high values of the current. The reason is that, for high values of the current, the applied potential is very high compared to the polarization potential.

By the same reasoning, it was anticipated that similar polarization potentials should be created in the same manner in the vicinity of the sulphides. Consequently, the apparent resistivity should be affected in the same way as the resistance in the above example.

Figures 8 and 9 contain data showing the variation found in experiments in both Virginia and Wisconsin. In figure 8, the data are too regular to be the change being



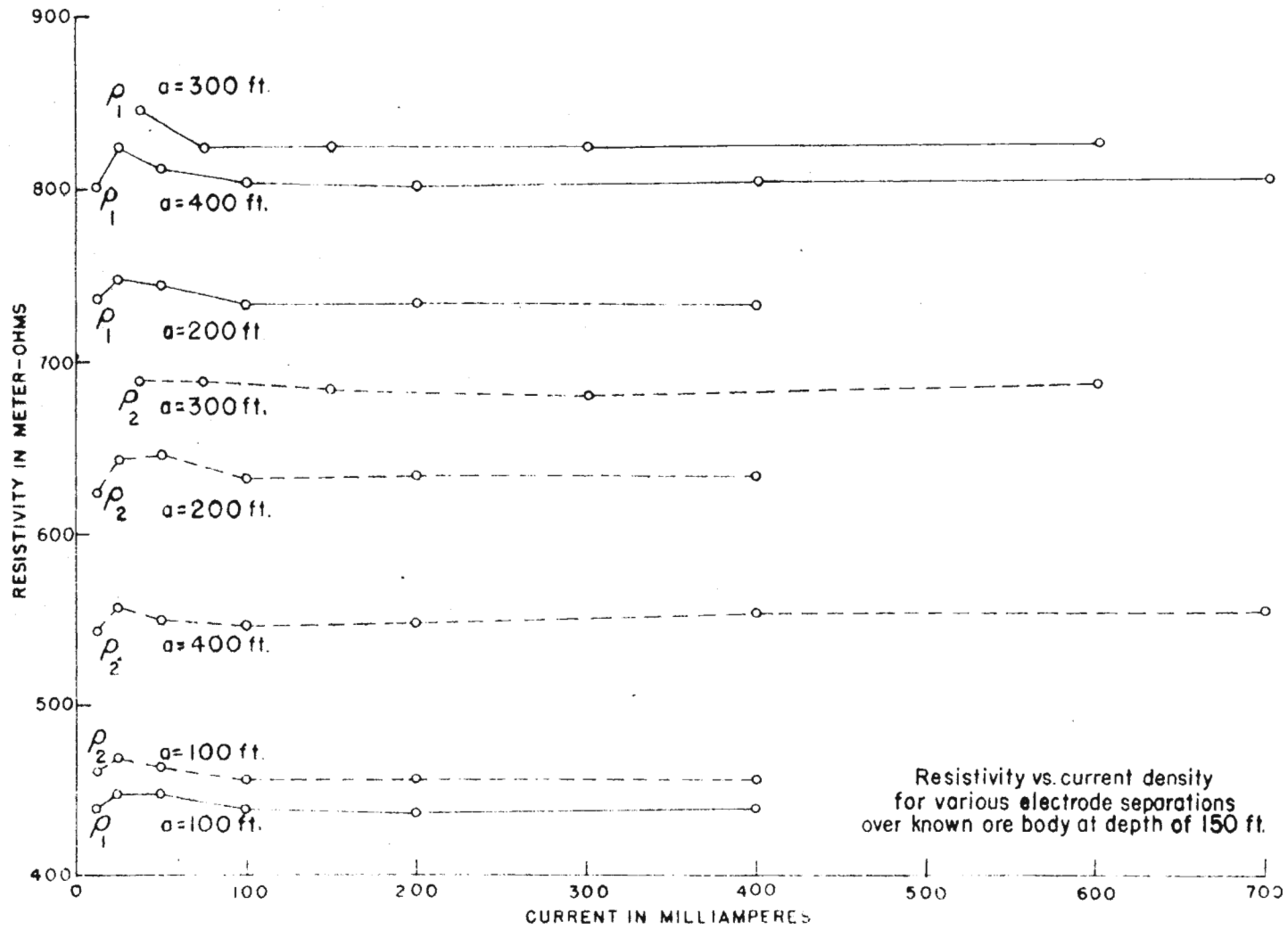


Figure 8

Resistivity vs. current density  
for various electrode separations  
over known ore body at depth of 150 ft.

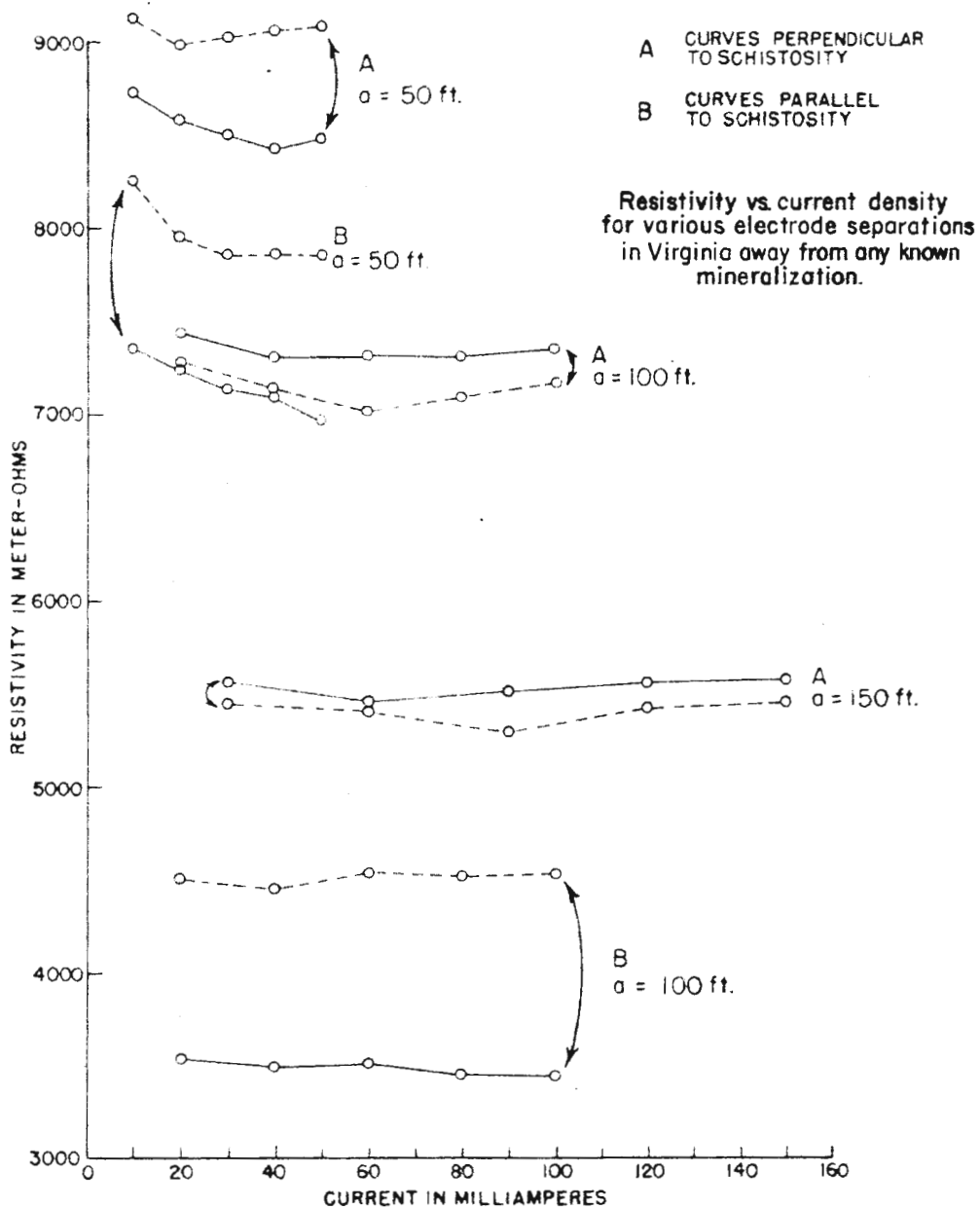


Figure 9

hunted. The sharp rise in all of the curves for a current of 25 milliamperes, and the gradual rise in all of the curves, for the larger values of the current, can only be due to a systematic error in the instruments. If these characteristics of the curves were due to polarization, they would appear for corresponding ratios of electrode separation to current rather than for the same values of the current.

In figure 9, it is readily apparent that any variation of the resistivity with the current is random. Therefore, from the data represented in these two graphs, it must be concluded that, within the limits of accuracy of the equipment used, there is no variation of apparent resistivity with the current density.

#### POTENTIAL DECAY PHENOMENA

Of the two investigations which lead to positive results, the first was in connection with the gossan lead of Virginia. Although it has not yet indicated a direct use in locating economic deposits, it is of prime importance in planning the technique to be used in conducting a survey.

The normal procedure in determining resistivities by direct current methods is to balance the instruments and to read them as rapidly as possible; the transients in the current are of such duration that they are of no significance. When the same technique was used in Virginia, it was found that determinations of the resistivity at a given place, and seemingly under constant conditions, could seldom be repeated with as consistent results as should have been

attained. By balancing the instruments, and then waiting a few minutes to read them, it was soon learned that considerable time elapsed from the time that the current circuit was closed until the reading for the potential circuit rose to its maximum value.

This phenomenon explains the technique which had to be adopted for use in determining the resistivities in the area which contained the gossan lead. Instead of applying the current and taking readings in a random fashion, the following procedure was used. The current was applied to the ground for exactly 90 seconds during which time the potential circuit was kept balanced against the potential drop from  $P_1$  to  $P_0$ . At the end of the 90 seconds, the reading was taken and the current immediately reversed. The procedure was repeated four times, once for a direct and reverse reading for both  $P_1-P_0$  and  $P_2-P_0$ , taking a total of six minutes.

The same procedure was found to be unnecessary in the Wisconsin area because no such decay effect could be detected.

At the high voltages used in the current circuit, the current fluctuated too much to permit adequate measurement of this upward drift of the measured potential. However, it was reasoned that, if there was an upward drift when the current was closed, there should be a similar decay when the current circuit was opened. Such a decay was found;

and, since there was no current to be regulated, a good quantitative picture of the decay could easily be obtained.

In the decay experiments, a current is applied to the ground for a fixed length of time, usually 60 seconds. Using the Lee configuration, the potential of  $P_1$  with respect to  $P_0$  is measured at regular intervals from the time when the current circuit is broken. Readings are generally taken for a period of 2 or 2 1/2 minutes, after which time the current circuit is reversed and closed, and the procedure is repeated. Four sets of readings are taken to correspond to the four normal readings taken in resistivity determinations. The current used in the decay experiments was 2 1/2 to 4 times the current used in resistivity measurements.

Figure 10 shows a typical set of data taken in this manner at a station in the vicinity of the gossan lead. The direct and reverse readings in the case of each potential segment have been averaged so as to eliminate the effect of any natural potentials. Therefore, there is only a single curve to represent  $P_1$  and another for  $P_2$ .

The curves appear to have the shape of normal decay curves; and, consequently, it is to be expected that an equation of the form:  $y = Ax^{-kt}$  would be a true expression of the data. However, plotting potential against time on both logarithm and semi-logarithm paper fails to rectify the curves. It is possible that the failure is due

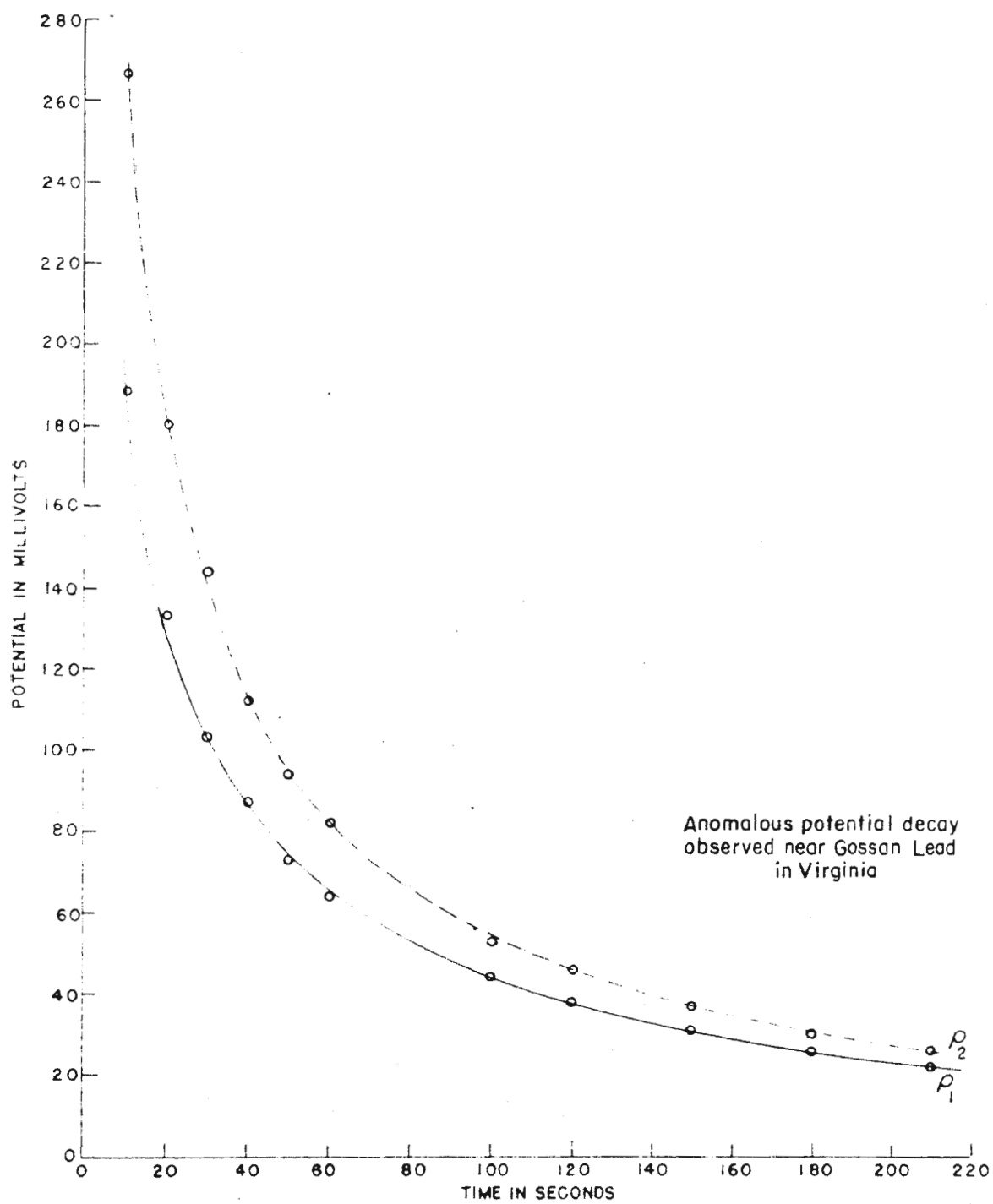


Figure 10

to the fact that the potential is a sum of two or more exponentials arising from different sources. It is felt that additional study will reveal such a function.

It has been found that plotting the potential, plus a constant, against the time on logarithm paper satisfactorily rectifies the curves. In this fashion, the following equations for the curves have been obtained from figure 11:

$$P_1 = 684 t^{-.488} - 28.$$

$$P_2 = 981 t^{-.507} - 40.$$

In this case, the constant which has been added to the potential is 0.15 times the value of the potential at the end of 10 seconds from the time the current circuit was opened. Actually, this constant may be varied as much as 15% without varying the results more than about 1%. As the equations stand, they fit the data very well over the whole period recorded, except for a single point on the  $P_2$  curve where  $t = 30$  seconds. Since the equation fits this point only within about 9%, and since this is the only point which it does not fit, it is possible that the original data may be in error.

A further clue as to the character of the anomalous decay is found in figure 12. The data indicates a dependency of the potential decay upon the duration of the current before the decay is measured. The first set of curves shows the actual potential decay curves for various values

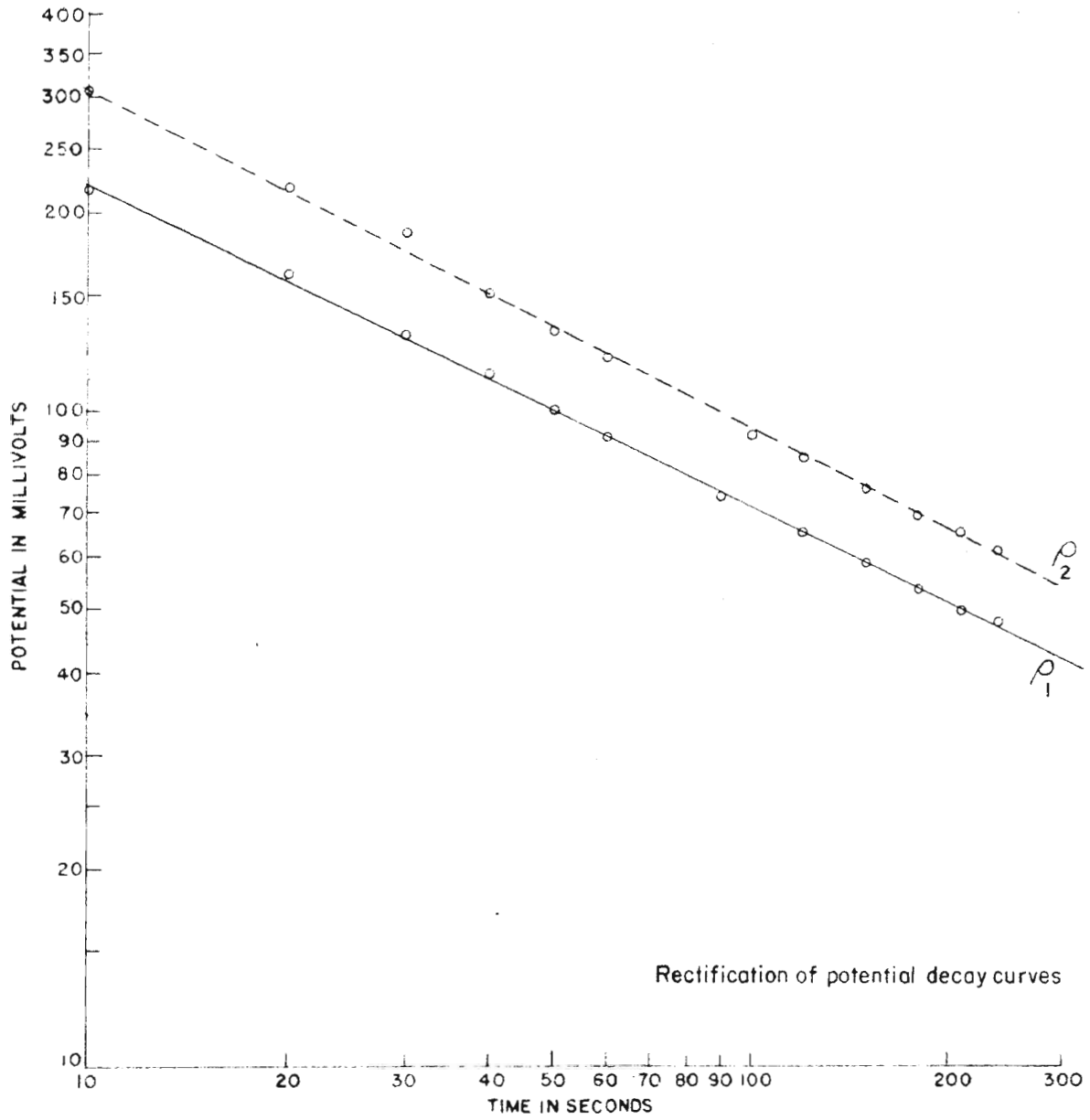


Figure II



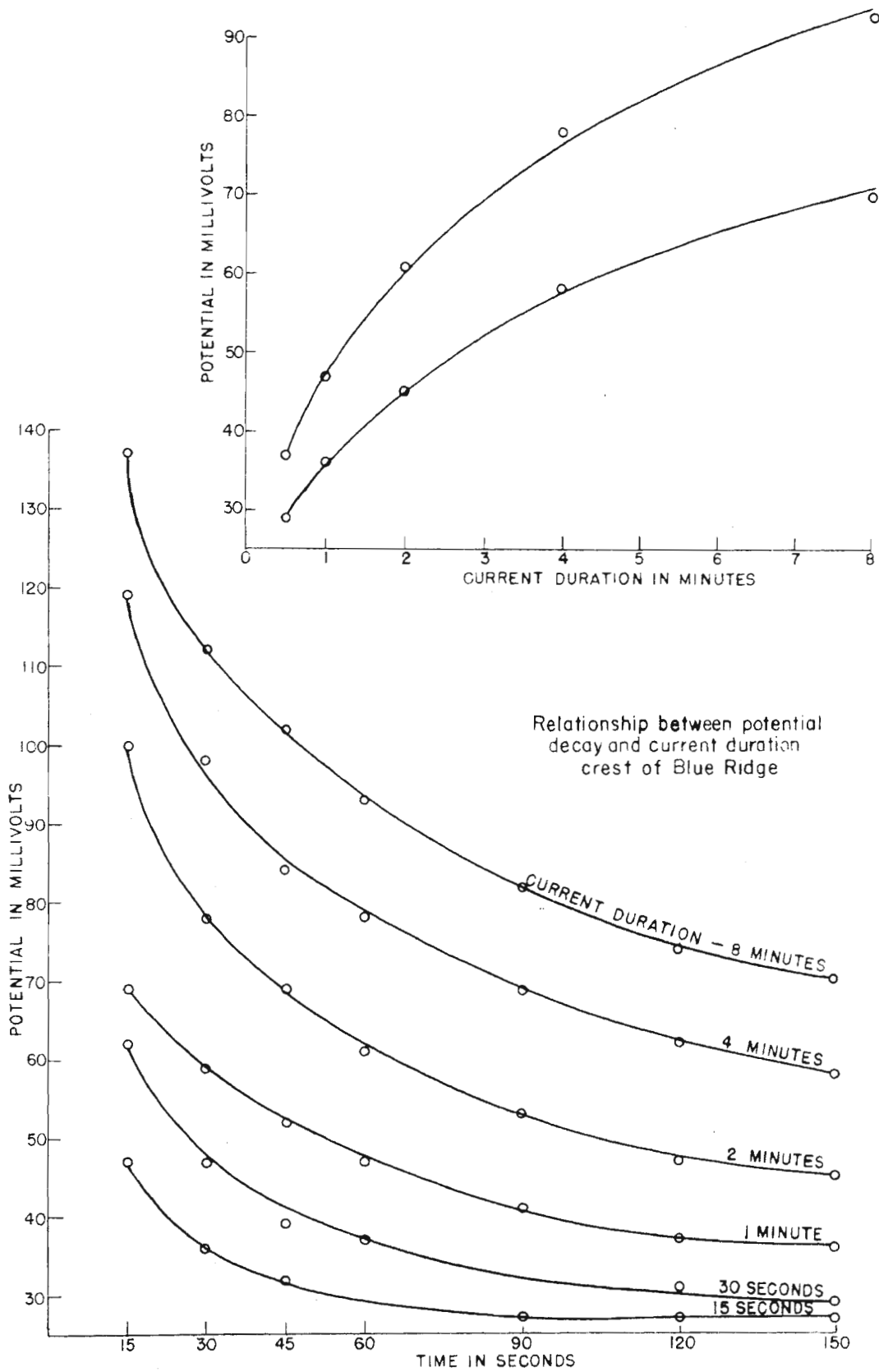


Figure 12

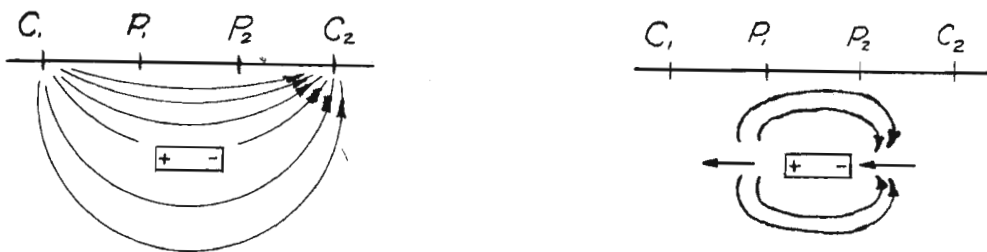
of current duration. The second set indicates, for various values of current duration, the potential at given times after the current circuit was opened. The picture for this one station appears to show that the residual potential after a given time, in addition to being a function of the current duration, tends to approach a saturation value.

A thorough study of potential decay data taken over the metamorphic rocks of Virginia, at stations in the vicinity of the gossan and at stations many miles from the gossan, permits one to draw certain qualitative conclusions. The residual potential at any given time is roughly proportional to the apparent resistivity, not only for the two potential segments at a given station but also at widely separated stations; the coefficient and the exponent of  $t$ , in the above equations are characteristic of the place at which the measurements are made; and, within the limits of this investigation, the constant which must be added to the potential, in order to rectify any given curve, is a fixed fraction of the potential at the end of a fixed time. It is felt that the ultimate constant to be added will be found to be a function of the potential at the time the current circuit is opened. In these experiments, the initial potential was above the range of the instruments, and thus was not measured.

No quantitative conclusions may be drawn from this work concerning the anomalous potential decay. It is hoped

that a further, more systematic investigation will reveal the cause and character of this phenomenon.

A possible explanation of the anomalous decay effect is related to chemical polarization within the earth between the current electrodes. To simplify the explanation, consider a single cell as illustrated in figure 13.



(a) Applied current flowing. (b) Current circuit open.

Figure 13 - Action of a buried chemical cell.

As the current flows in the earth from  $C_1$  to  $C_2$ , and thus through the cell, the cell becomes polarized in such a direction that it opposes the current through the cell. When the applied current is discontinued, the cell causes current to flow in the earth until it has become depolarized. As long as this current is flowing, the natural potential of  $P_1$  with respect to  $P_2$  appears to be larger than normal.

This explanation need not contradict the previous negative conclusions pertaining to the variation of resistivity with current density. Only rarely, did the residual potential at the end of 15 seconds amount to more

than 2% of the maximum value of the potential. As a first approximation, if this value is considered to be the polarization effect while the applied current is flowing, its effect on the measured value of the potential would still not be great enough to vary the resistivity within the accuracy limits of the equipment used.

A parallel explanation of this phenomenon could be found in the formation of elementary capacitors in the earth instead of polarized cells. In figure 13, consider the cell to be replaced by a capacitor consisting of a single crystal of mica. The explanation follows very much that given above for the polarized cells. The capacitor becomes charged when the current is applied and becomes discharged after the current circuit has been broken. It is more difficult to visualize the mechanism in the case of a capacitor, and it is reasonably certain that the process would not occur at all unless the resistivity of the earth were very high.

#### AN "IN-HOLE" TECHNIQUE

In order to accentuate any slight differences in resistivity which may exist in the types of ore bodies found in Wisconsin, a technique was developed in which the positive current electrode was placed at the top of a hole while the negative current electrode was moved up and down the hole through the mineralized horizon. The potential was then measured, with respect to infinity, at several points along

the circumference of a circle drawn with the hole as its center. The configuration is illustrated in figure 14, in which the block represents the section of the earth in one quadrant from the hole.

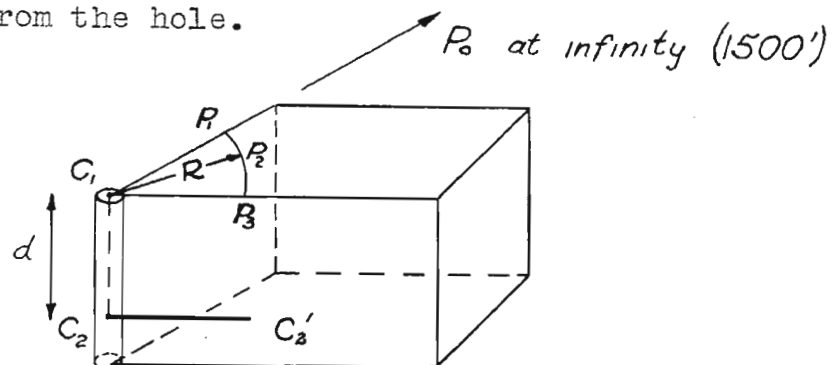


Figure 14 - Block diagram of "in-hole" technique.

Four drill holes were used in these preliminary experiments, three in which there was extensive mineralization including ore, and one in which there was found practically no mineralization. It was anticipated that, as the negative electrode was drawn up through the mineralized zone, the changes in the potential at points in the direction of the trend of the mineralized zone would be less than the changes in the potential at other points.

Also, theory indicates that the potential in the direction of the trend of the mineralization should be lower than in other directions. The author has substantiated this fact by considering, as a first approximation, that the mineralized zone could be considered to be a line of infinitely conducting material as shown by the line  $C_2C_2'$  in figure 14. However, in practice, this effect, if it does

exist, is completely obscured by near surface resistivity differences, and does not make a dependable criterion from which to work.

Figures 15 through 20 are graphs in which the potential has been plotted against direction from the hole for various values of  $d$  and  $R$ .

Figure 15 shows the data taken at a hole from which the mineralization, at a depth of about 290 feet, extends to the west-southwest. For  $R$  equal to 400 feet, it can be seen that the potential changed appreciably, when  $d$  was changed from 285 to 265 feet, at all points except those to the west and the southwest. On this basis, it was predicted that the ore body terminated near the hole. Shortly after the prediction was made, company geologists came to the same conclusion based upon their knowledge of the local geology and on one more drill hole east of this one.

Figures 16 and 17 represent data taken at a hole at the western end of an east-west line of holes, all of which had cut through a mineralized horizon at a depth of about 270 feet. In figure 16, for which  $R$  equals 300 feet, it is difficult to see any marked effect such as is illustrated in figure 15. However, when  $R$  was made 400 feet, as in figure 17, the potential at the northern point changed very little as  $d$  was changed from 260 to 240 feet. Although one point in data of this kind is insufficient to justify any conclusions, it may be used to add to the picture which we

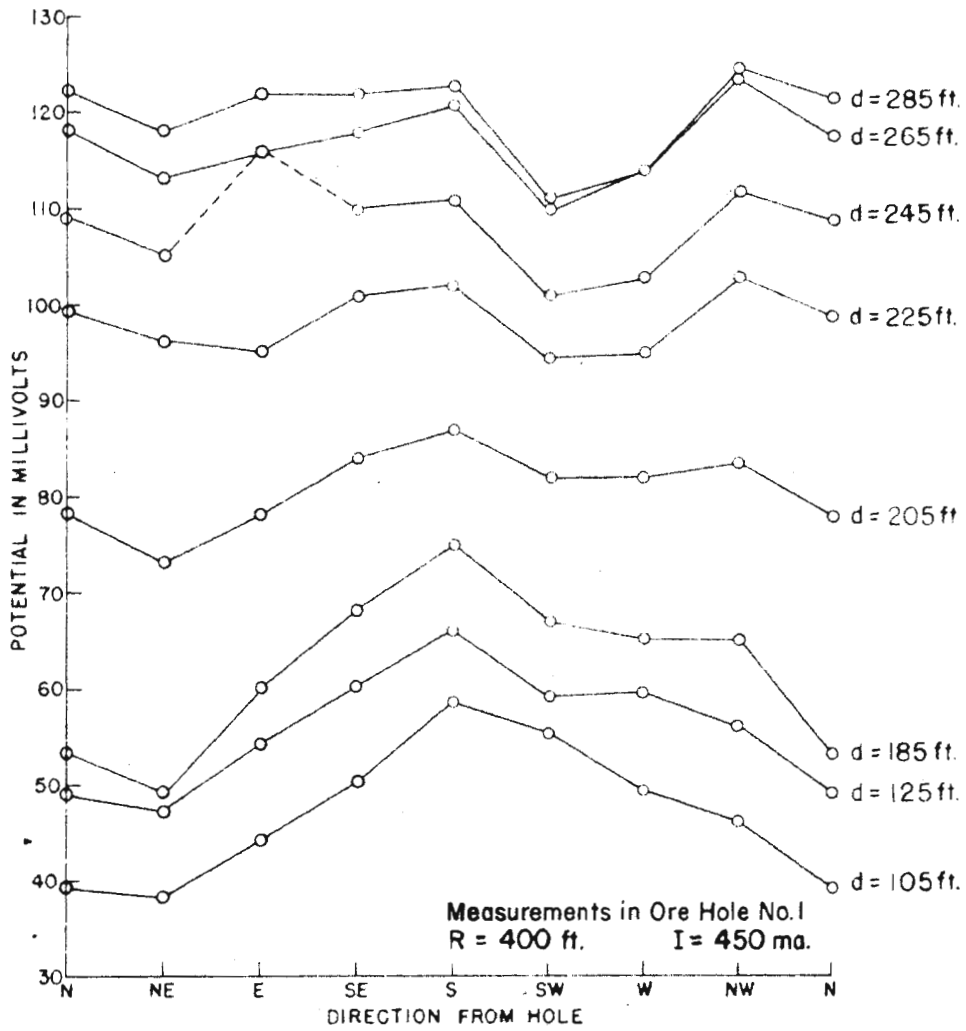


Figure 15

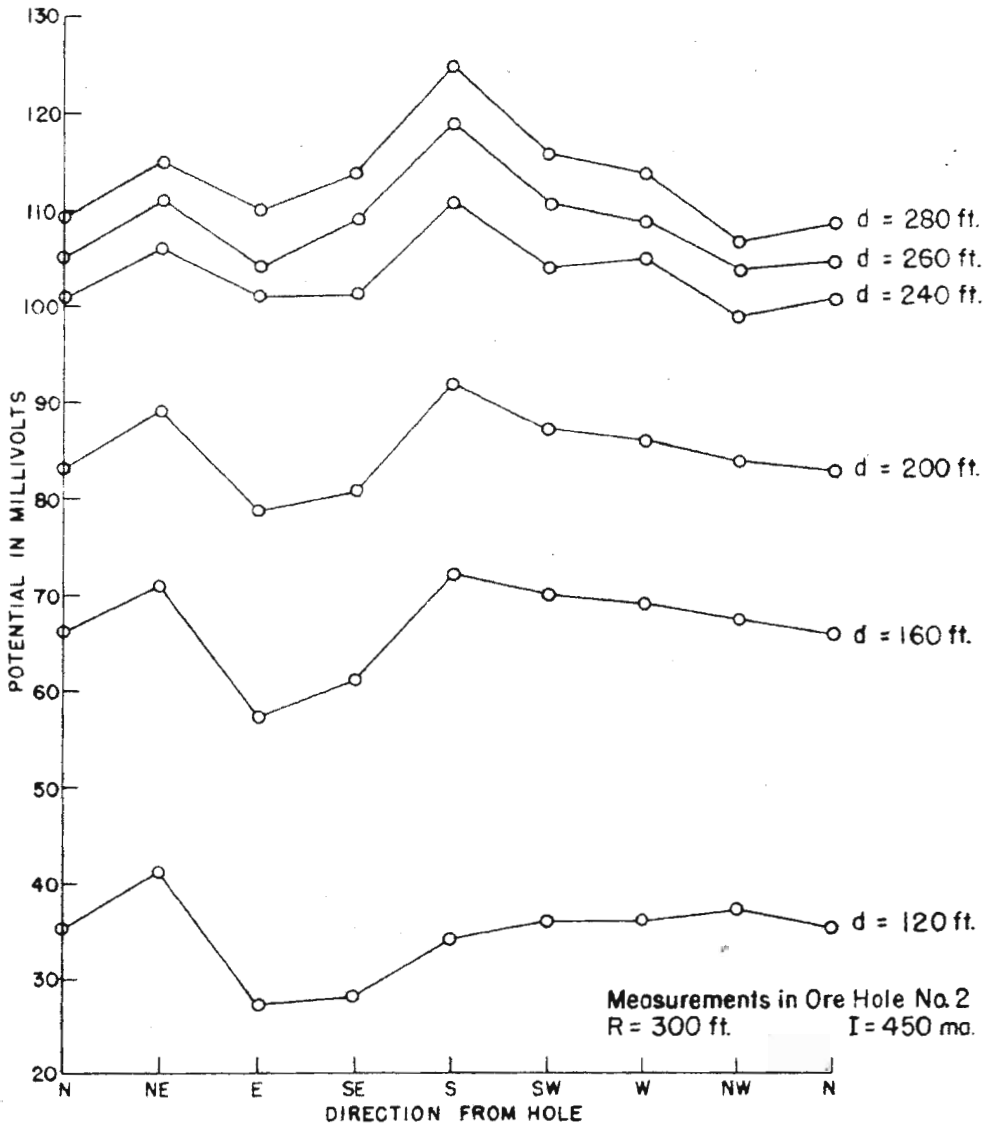


Figure 16



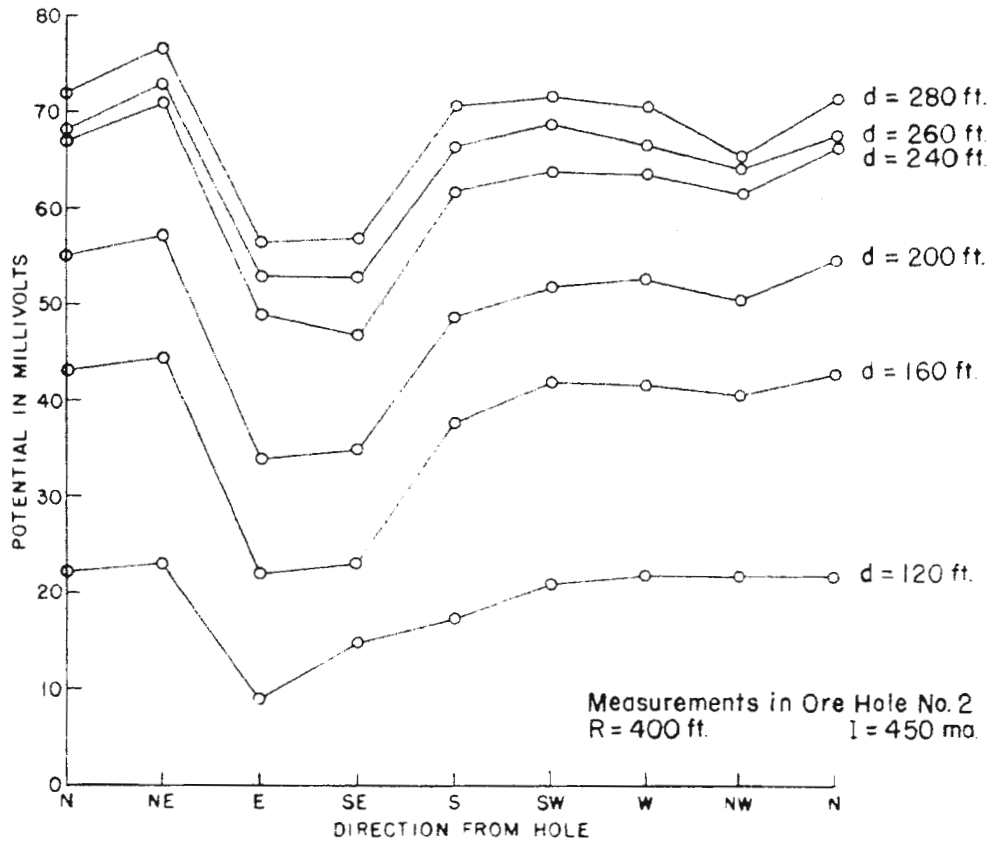


Figure 17

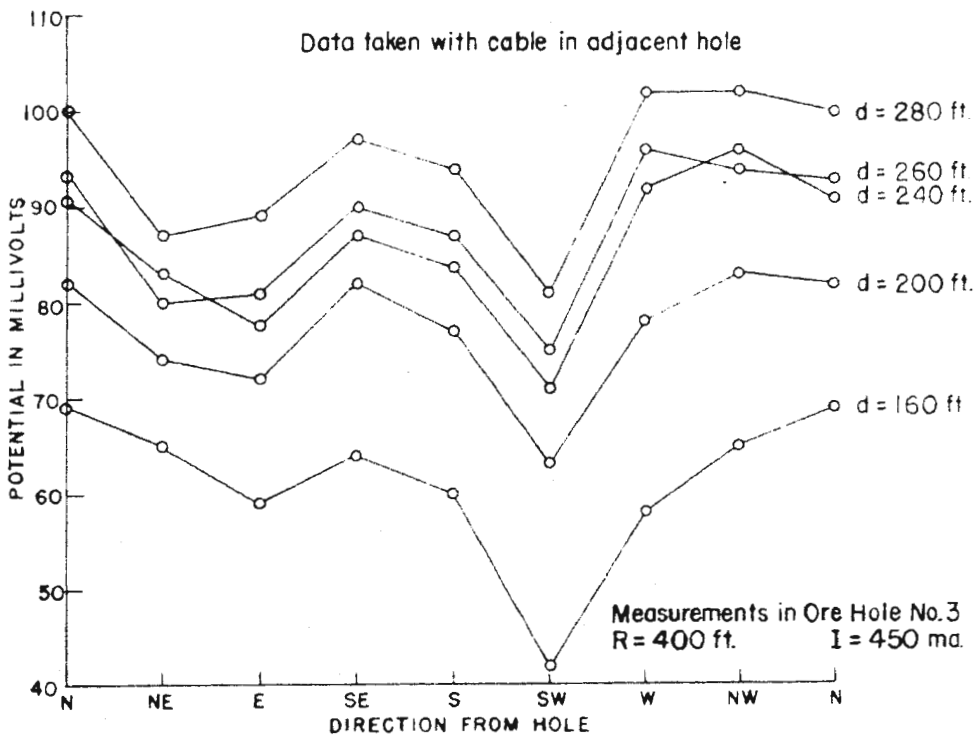


Figure 18

have from other sources.

The marked differences in the potential, for a given value of  $d$ , in the various directions in figures 16 and 17 can be traced directly to differences in the resistivities of the surface materials. About 330 feet southeast of this hole, the land was lower and there existed a semi-marshy condition.

Figures 18 and 19 give data taken at a hole 400 feet east of the above mentioned hole. For  $R$  equal to 400 feet, in figure 19, there is definitely less change in potential in the northeast and in the northwest than in other directions, when  $d$  changes from 260 to 240 feet. On the basis of this information, together with the scrap of evidence from figure 17, it was predicted that the ore body was arcuate in form, curved toward the north, and that the line of drill holes only locate its southern edge. As yet the necessary drill information is not available to prove or to disprove this theory.

While taking data at this hole, there was an opportunity to determine the effect of drill rig working in the area. Fifty feet east of the hole, there was another hole in which the steel cable extended from the surface of the earth to the mineralized zone during the entire time when the data for the curves in figure 18 were being taken. The data for the set of curves in figure 19 were taken when the cable was not in the adjacent hole. The only effect

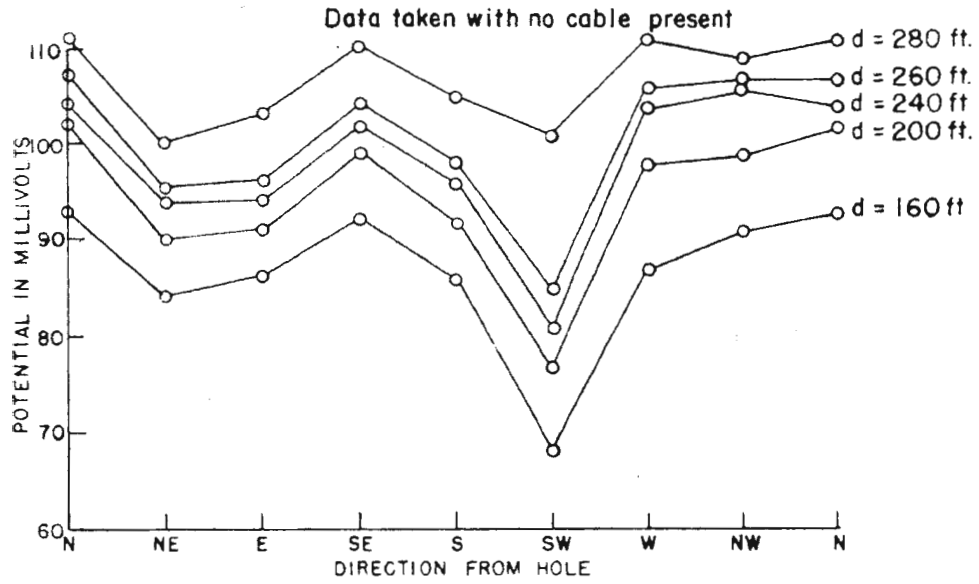


Figure 19

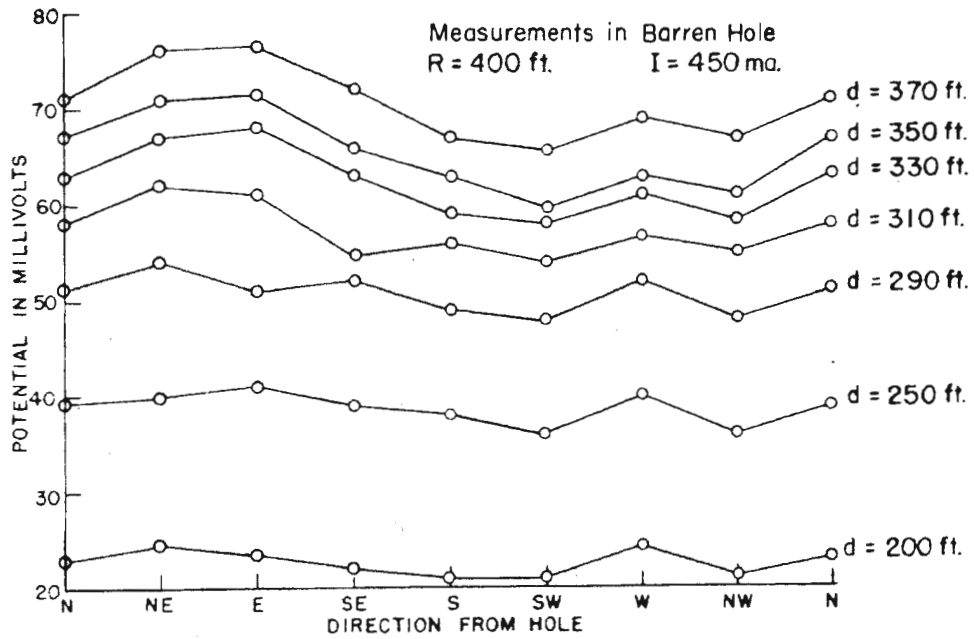


Figure 20

which the cable seems to have had was to reduce the potential readings all about the same. There seems to have been no more effect in one direction than in another.

Figure 20 shows data taken at a hole in which there was no appreciable mineralization, although the bottom of the hole is in the same horizon as the bottoms of the other holes discussed. It can readily be appreciated that there is no such pronounced effect in this case as there are in the other examples. The reason that the potentials here were smaller than in the other areas is that this area is overlain by thick layers of low resistivity shales while the others were not.

In all of the above measurements, it will be noted that the positive current electrode was fixed at the top of the drill hole. Therefore, the effect of this electrode on the potentials was constant throughout an experiment. As the negative electrode was raised up the hole, its effect on the potentials continually changed. References here to positive and negative electrodes are only figurative; the same as in previous experiments, direct and reverse readings were taken to eliminate an error due to natural potentials.

Further experience in this technique will make possible better evaluation of the changes which appear in this type of data. This fact pertains not only to the rate of change of potential at the various points as  $d$  is varied, but also to the change in shape of the curves which are obtained.

To extend the work on this technique, and to test its value to lead and zinc prospecting, there should be tests made in as many holes as possible; several runs should be made in each hole to see whether dependable repeat readings can be obtained; various values of R should be tried to see which is the optimum; and, in addition, there should be a further attempt to set the problem up theoretically.

#### SUMMARY

It has been seen that the two types of ore deposits differ as widely electrically as they do geologically. The pyrrhotite and gossan in Virginia may be mapped quickly and easily by either resistivity or self-potential methods, although the resistivity technique will give the most dependable results. However, except for mapping fracture zones, ordinary electrical methods fail to give any satisfactory results in searching for lead and zinc in the Wisconsin area; novel and more appropriate techniques must be developed.

A thorough search for a change in apparent resistivity with a change in current density indicated that there was none within the limit of accuracy of our equipment.

This investigation has opened the door to two results which are in themselves two new problems. The first is an anomalous potential decay of several minutes duration which

is associated with the metamorphic rocks of Virginia. The second is an "in-hole" technique for extending ore bodies already cut by at least one drill hole. In both cases, a need for further study is indicated.

BIBLIOGRAPHY

Agnew, Allen F. and Heyl, Allen V. Recent Developments in the Wisconsin-Illinois-Iowa Lead-Zinc District. Iowa Academy of Science. Proceedings. Volume 53. 1946.

Bain, H. Foster. Zinc and Lead Deposits of Northwestern Illinois. U.S. Geological Survey. Bulletin 246. 1905 56 pp.

Behre, Charles H. Paragenesis of the Wisconsin-Illinois-Iowa Lead-Zinc District. Geological Society of America. Special Paper 24. 30 December 1939. pp 114-119.

Gish, H. and Rooney, W.J. Measurement of the Resistivity of Large Volumes of Undisturbed Earth. Terrestrial Magnetism. Volume 30. 1925. pp 161-188.

Heiland, C.A. Geophysical Exploration. New York. Prentice-Hall, Inc. 1940. pp 619-824.

Jakosky, J.J. Exploration Geophysics. Los Angeles. Times-Mirror Press. 1940. 800 pp.

Jakosky, J.J., Dreyer, R.M., and Wilson, C.H. Geophysical Investigations in the Tri-State Zinc and Lead Mining District. Geological Survey of Kansas. Bulletin 44. December 1942. 151 pp.

Karcher, J. C. and McDermott, Eugene. Deep Electrical Prospecting. American Association of Petroleum Geologists. Bulletin. Volume 19. pp 64-77.

Kay, G. Marchall. Stratigraphic Setting of Wisconsin-Illinois District. Geological Society of America. Special Paper 24. 30 December 1939. pp 25-28.

Lee, F.W. Method of Conducting Geological Survey. U.S. Patent 1,951, 760. 20 March 1934.

Ross, Clarence S. Origin of the Copper Deposits of the Ducktown Type in the Southern Appalachian Region. U.S. Geological Survey. Professional Paper 179. 1935. 165 pp.

Wenner, Frank. A Method of Measuring Earth Resistivity. U.S. Bureau of Standards. Bulletin. Volume 12. 25 May 1916. pp 469-478.

Willman, H.B. and Reynolds, R.R. Geological Structure of the Zinc-Lead District of Northwestern Illinois. Illinois State Geological Survey. Bulletin 124. 1947. 15 pp.

Willman, H.B., Reynolds, R.R., and Herbert, Paul, Jr. Geological Aspect of Prospecting and Areas for Prospecting in the Zinc-Lead District of Northwestern Illinois. Illinois State Geological Survey. Bulletin 116. 1946. 48 pp.

Wright, R.J. and Raman, N.D. The Gossan Lead, Carroll County, Virginia. U.S. Department of the Interior. Information Service Release. 19 February 1948.



CURRICULUM VITAE

Robert G. VanNostrand was born at Oneida, New York on 28 November 1918. He graduated from Sherrill High School, Sherrill, New York in June, 1937. After working for a year in the Oneida, Ltd., silverware factory, he entered Missouri School of Mines in September, 1938. On 1 May 1942, he received the degree of Bachelor of Science, Physics Major, together with a Second Lieutenant's commission in the U.S. Army Signal Corps. He was immediately called to active duty and was in the army a total of 5 years, three years of which were spent in Europe. On 2 April 1946, while still in the army, he was married to Janine Lachelin of Paris, France. He returned to the United States and civilian life in the spring of 1947. He re-entered the Missouri School of Mines in September, 1947 where he has served as an instructor in physics while carrying on graduate studies. In the summer of 1948, he was granted a "when actually employed" appointment in the Geophysical Section of the U. S. Geological Survey. He still holds that appointment.