NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

A MAGNETOMETRIC SURVEY OF THE IRON HORSE MAGNETITE DEPOSI
SOCORRO COUNTY, NEW MEXICO

BY

DEAN JOHNSON

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ABSTRACT

A detailed vertical-intensity magnetic survey of the Iron Horse magnetite mine was made, and the data taken were analyzed quantitatively in an attempt to ascertain the probable extent in depth of the ore and to obtain an estimate of the tonnage of ore remaining in the deposit. The results of the survey indicate probable values of about sixty feet for the average extent of the ore body down dip, and approximately fifteen thousand tons for the amount of ore in reserve.

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A MAGNETOMETRIC SURVEY OF THE IRON HORSE MAGNETITE DEPOSIT, SOCORRO COUNTY, NEW MEXICO

SECTION I

INTRODUCTION

Although magnetic prospecting for iron deposits has been very extensively used since 1640, when this type of exploration was introduced, most of the work done has been merely qualitative. The relative scarcity of instances in which quantitative interpretation has been undertaken is due largely to several inherent limitations of the magnetic method. Foremost among them is the fact that a potential field problem has no unique solution. Nevertheless, under certain rather special conditions it is possible to analyze magnetic information to obtain worthwhile estimates of the dimensions of an iron-ore body.

This paper describes one attempt to derive quantitative results from magnetic data. A careful survey of a suitable ore body was made with accurate instruments, and the resulting information was analyzed to determine the extent of the deposit.

The ore body that was selected for the experiment is that of the Iron Horse mine of Socorro County, New Mexico. The deposit is at the southern end of Chupadera Mesa, 26 miles west of Carrizozo, N.M., and 46 miles east of San Antonio, N.M., on U.S. Highway 380, in S $\frac{1}{2}$, sec. 9, T. 6 S., R. 7 E.

The writer wishes to express his thanks to Dr. Marvin Wilkening, Head, Department of Physics and Geophysics, New Mexico Institute of Mining and Technology, and to Mr. Hartmut Winkler, Research and Development Division, of the same institution, for their advice and assistance. Thanks are due also to Mr. Richard Anderson and Mr. Lucien Catanzaro for their aid in surveying the area.

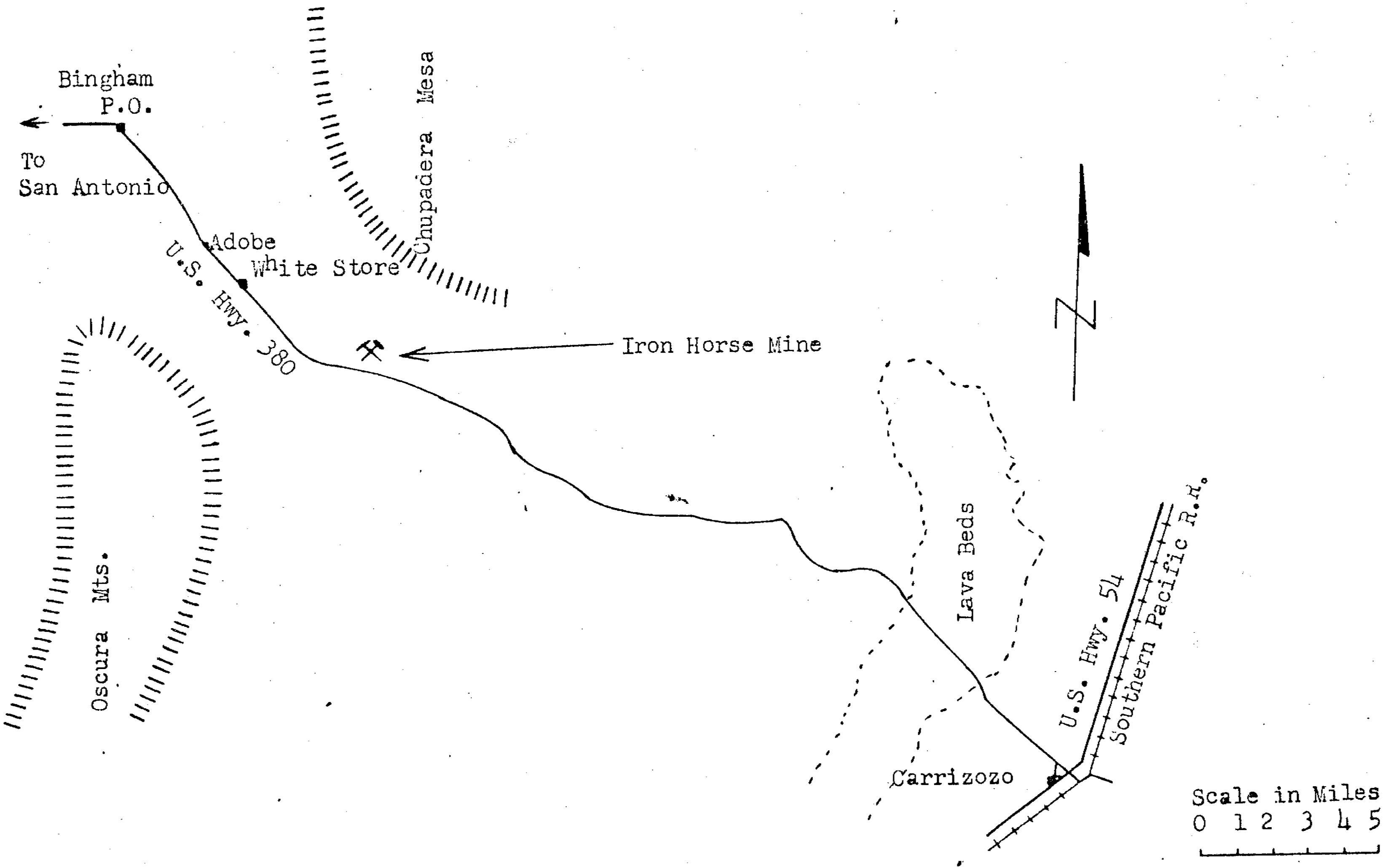

Fig. 1. Index Map of Iron Horse Mine, Socorro County, New Mexico.

SECTION II

GEOLOGIC STRUCTURE

The geology of the Iron Horse deposit has been described by Kelley.[1] The ore is a pyrometasomatic body of magnetite formed along the north side of a monzonite dike of early Tertiary age that has intruded limestone and gypsum of the Yeso formation (Permian). The dike trends N. 75° W. for several thousand feet. Its width at the deposi ranges from 110 feet to 215 feet.

The ore body, which is 5 to 10 feet thick and dips 35° - 70° N., lies between a footwall of monzonite and a narrow hanging wall of gypsum. In the west pit a small anticline in the gypsum and ore is exposed where flat-lying ore at the crest of the fold was mined from a wide cut. The hanging wall between ore and gypsum is faulted in some of the exposures.

To the north of the deposit is a tight anticlinal fold in the limestone.

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[1] V.C. Kelley, *Geology and Economics of New Mexico Iron-Ore Deposits*, pp. 223-225, University of New Mexico Press, 1949

SECTION III

METHOD OF ANALYSIS

Although it is quite true that the interpretation of an anomaly in any of the potential fields is funadamentally incapable of a unique solution, where geologic control is adequate it may be possible to derive quantitative results which will merit some confidence.

In all potential methods of geophysical exploration, two general approaches are very commonly used to obtain a quantitative interpretation of field measurements in terms of geologic structure. In the first of these methods, the field response curve is compared with a set of theoretical curves to determine the best fit. The second method is a cut-and-try process in which the size, shape, and other pertinent physical characteristics of a structure are assumed, and the resultant response curve is calculated and compared with the field curve. In the present survey both of these procedures were used. First, the field curve for each suitable magnetic profile was matched with theoretical type-curves to provide a general idea of the attitude and dimensions of the ore body; then by trial and error a solution was derived that would give the best possible agreement with the field results.

Throughout this paper the method of analysis used is that described by Cook[1] for the interpretation of magnetic anomalies over tabular ore bodies. These bodies may be in the form of vertical or inclined dikes, fissure veins, or replacement veins or pods. Although several other authorities have heretofore derived formulas for the vertical magnetic anomaly over such bodies, each of these authors has given equations that are applicable only in certain special cases. Cook, using ordinary magnetic induction theory, has developed a more general expression for the magnetic intensity over an inclined tabular body. This formula and the curves based on it were used rather extensively and with a considerable degree of success by the U.S. Bureau of Mines in a program of exploration for magnetite ore bodies in the Iron Springs district of Utah.

Cook lists seven assumptions made in developing this formula:

(1) The body is assumed to be uniformly magnetized, and effects of flux concentrations on edges

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[1] Kenneth L.Cook, "Quantitative Interpretation of Vertical Magnetic Anomalies Over Veins," Geophysics, vol.XV, 1950, pp. 585-686

and corners of the body are disregarded.

(2) The theory does not include the demagnetizati
effects produced by the existence of the body
in the magnetic field of the earth.

(3) The formulas considered apply to two dimensio
bodies, that is, to bodies whose length in th
direction of strike is infinite. When referen
is made to a "finite vein" the vein is consid
infinite in length, but finite in depth exten

(4) In computing the magnetic susceptibility of a
ore body whose accompanying anomaly is caused
wholly by magnetite in the ore, it is assumed
that the susceptibility is proportional to
the amount of magnetite by volume contained i
the ore.

(5) The statements and conclusions apply to resul
obtained in the northern hemisphere at intermediate latitudes.

(6) It is assumed that no anomalous polarization
effects are produced by the ore bodies.

(7) Unless stated to the contrary, all directions
of strike and dip to which reference is made
are magnetic directions.

In order that a single set of theoretical curves ma be used repeatedly, it is desirable that the magnetic intensity over all the theoretical bodies be plotted in the same units. This procedure permits a comparison of th true relative magnitudes of the intensity caused by bodie of different dimensions and dispositions. The parameter "p," defined as $p = 2kZ_o$, is used as a standard unit of intensity for all theoretical curves in this paper.

To obtain his formula Cook begins with the expressio given by Heiland[1] for the vertical magnetic intensity ove a slope infinitely long in the direction of strike. (See Fig. 3). One geologic interpretation of the geometric situation would be that of an idealized normal fault. At any point, P, the vertical intensity is

$$\Delta Z = 2k \sin\delta \left\{ H_o \sin\alpha \left[\sin\delta \log_e r_2/r_1 + \cos\delta (\phi_2 - \phi_1) \right] - Z_o \left[\sin\delta (\phi_2 - \phi_1) - \cos\delta \log_e r_2/r_1 \right] \right\}$$

where the following notations are used. H_o and Z_o are, respectively, the horizontal and vertical components of the magnetic field of the earth in the area. The excess of the magnetic susceptibility of the vein over the

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[1] C.A. Heiland, Geophysical Exploration, Prentice-Hall, New York, 1946, p. 397

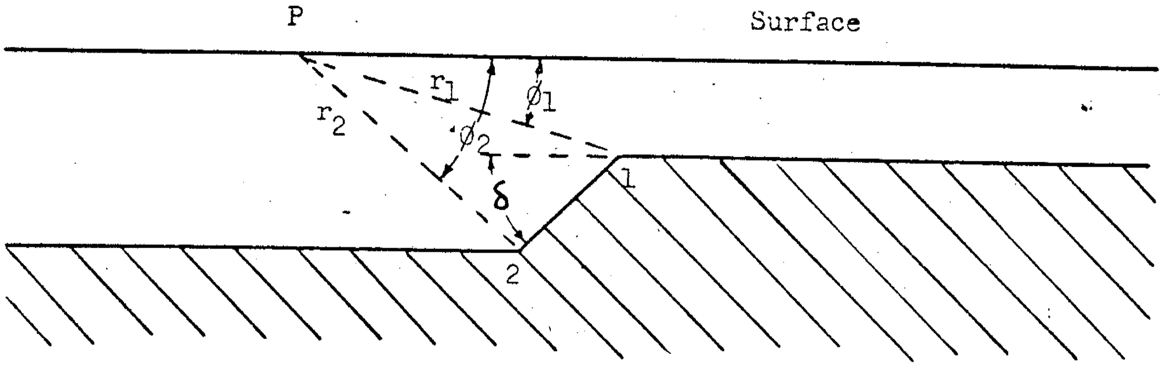


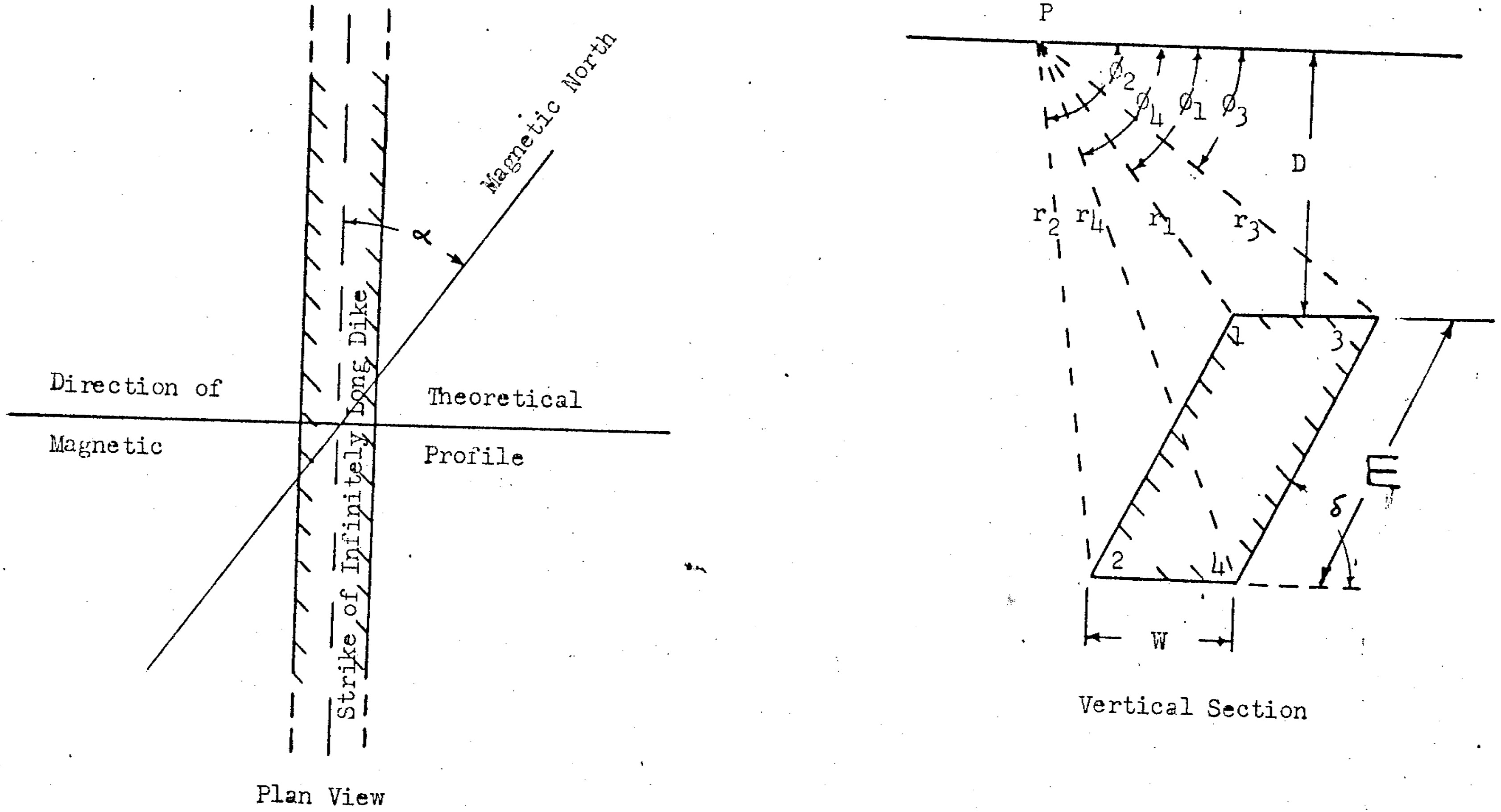
Fig. 3. Vertical Section Through Slope Infinitely Long in Direction of Strike, Showing Angles and Distance.

adjacent rock is denoted by k. The azimuth of the direction of strike of the fault is represented by the symbol, α, and this angle is measured counterclockwise from magnetic north. The other symbols are explained in Fig. 3. Cook applies Heiland's formula for the vertical magnetic intensity over such a slope twice, obtaining the difference between the magnetic effects of two slopes. This is effectively the field caused by an infinitely long tabular body with a parallelogram-shaped cross section. The result is the following:

$$\Delta Z = 2k \sin\delta \Big[(H_o \sin\alpha \sin\delta + Z_o \cos\delta) \log_e r_2 r_3 / r_1 r_4 - (H_o \sin\alpha \cos\delta - Z_o \sin\delta)(\phi_1 - \phi_2 - \phi_3 + \phi_4) \Big]$$

The geometrical situation is illustrated in Fig. 4.

Several special cases of the general formula will now be considered. As the ore body at the Iron Horse mine strikes almost exactly due magnetic east and dips north throughout its extent, all the special equations and theoretical curves presented in this paper are for bodies having this attitude. In order to clarify the physical meaning of the mathematical expressions for vertical intensity, three sets of curves are given to illustrate the effect of changes in value of different variables of the equations. The type-curves are similar to those in Cook's article, but are calculated in accordance with the values of H_o and Z_o



Plan View

Vertical Section

Fig. 4. Plan View and Vertical Section Through Infinitely Long Dike, Showing Angles and Distances.

in the Bingham district.

Case I. Infinite veins striking east: in this case the general equation becomes

$$\Delta Z = 2k \sin\delta \Big[(H_o \sin\delta + Z_o \cos\delta)\log_e r_3/r_1 - (H_o \cos\delta - Z_o \sin\delta)(\phi_1 - \phi_3)\Big]$$

Curves B, C, and D, Fig. 5 are the intensity curves for infinite veins of various northerly dips. Where the dip is 90° the general equation reduces to

$$\Delta Z = 2k\, Z_o \Big[(H_o/Z_o \log_e (r_3/r_1) + (\phi_1 - \phi_3)\Big]$$

Curve A, Fig. 5 is the intensity curve for a vertical vein. The asymmetrical nature of this curve is due solely to the transverse horizontal magnetiztion effect, which is expressed in the term $H_o/Z_o \log_e r_3/r_1$.

Case II. Finite veins striking east. In this case the intensity curve is given by

$$\Delta Z = 2k \sin\delta\ (H_o \sin\delta + Z_o \cos\delta)\log_e r_2 r_3/r_1 r_4 - (H_o \cos\delta - Z_o \sin\delta)(\phi_1 - \phi_2 - \phi_3 + \phi_4)\Big]$$

Where the dip is 90° the general equation reduces to

$$\Delta Z = 2kZ_o \left[H_o/Z_o \log_e r_2 r_3/r_1 r_4 + (\emptyset_1 - \emptyset_2 - \emptyset_3 + \emptyset_4) \right]$$

A special mathematical case arises where a finite vein dips north at an angle equal to the angle of magnetic inclination. Under this condition the expression for the intensity over a vein is

$$Z = 2kZ_o \, (\emptyset_1 - \emptyset_2 - \emptyset_3 + \emptyset_4)$$

As is shown in Fig. 7, the intensity curve is slightly asymmetrical, and both sides of the curve cross the x-axis. This case is of particular interest in the survey considered in this paper, because the almost symmetrical shape of several of the field curves indicates that the dip of the ore body at the location where these profiles were taken must be very close to the angle of inclination of the magnetic field of the earth.

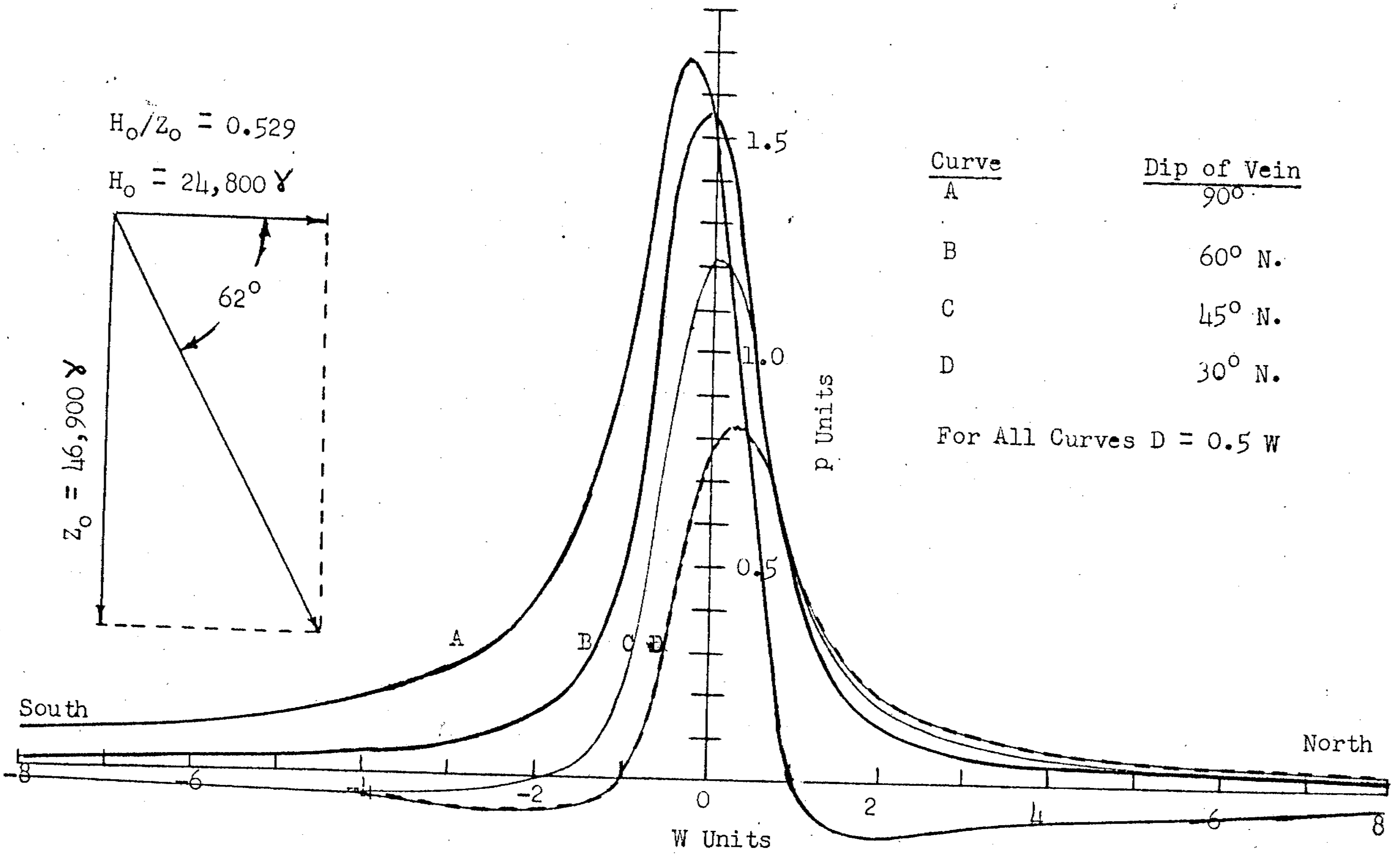


Fig. 5. Vertical Magnetic Intensity Over Infinite Inclined Veins Striking East and Dipping 30° N., 45° N., 60°N., and 90°.

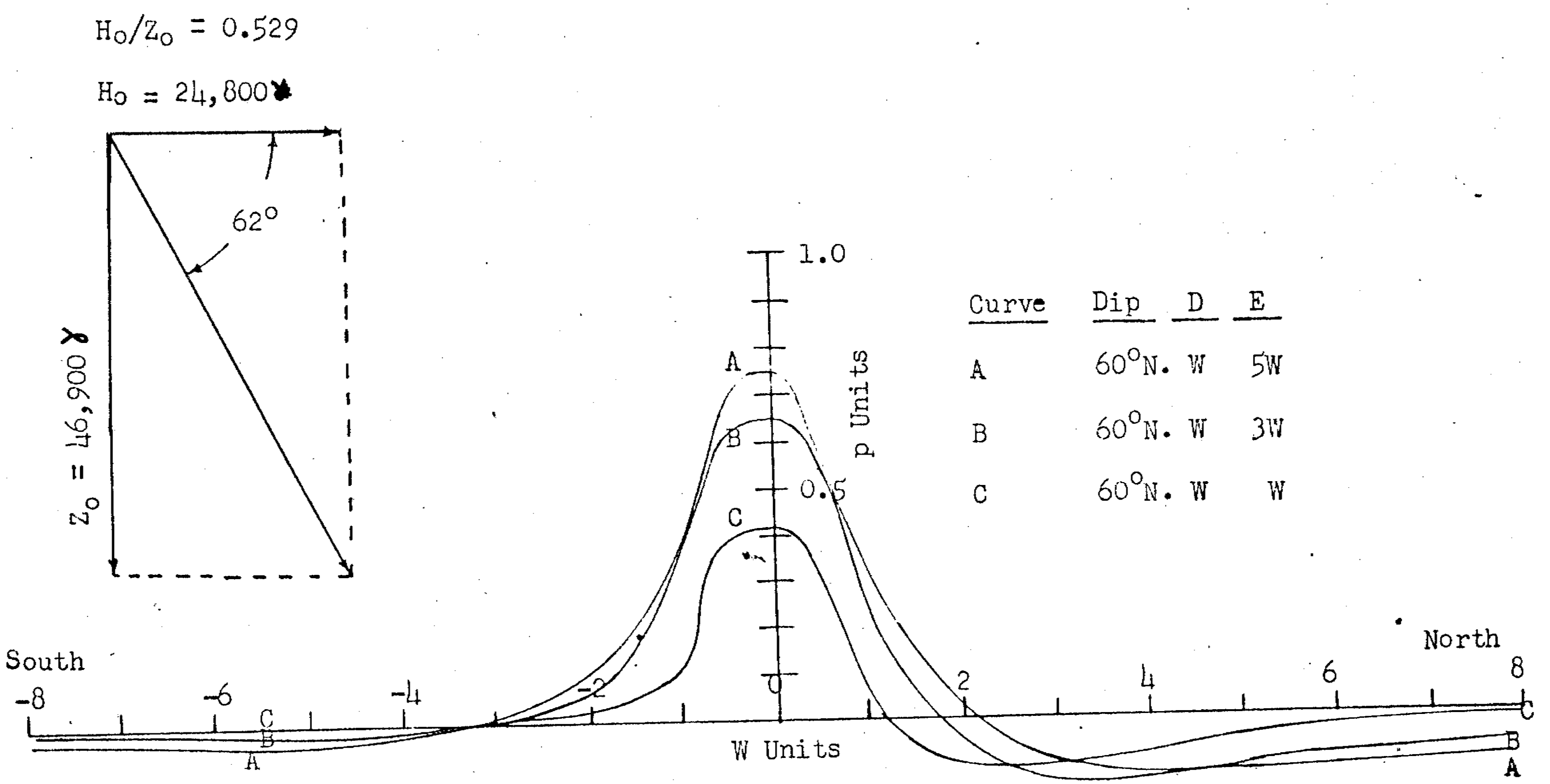
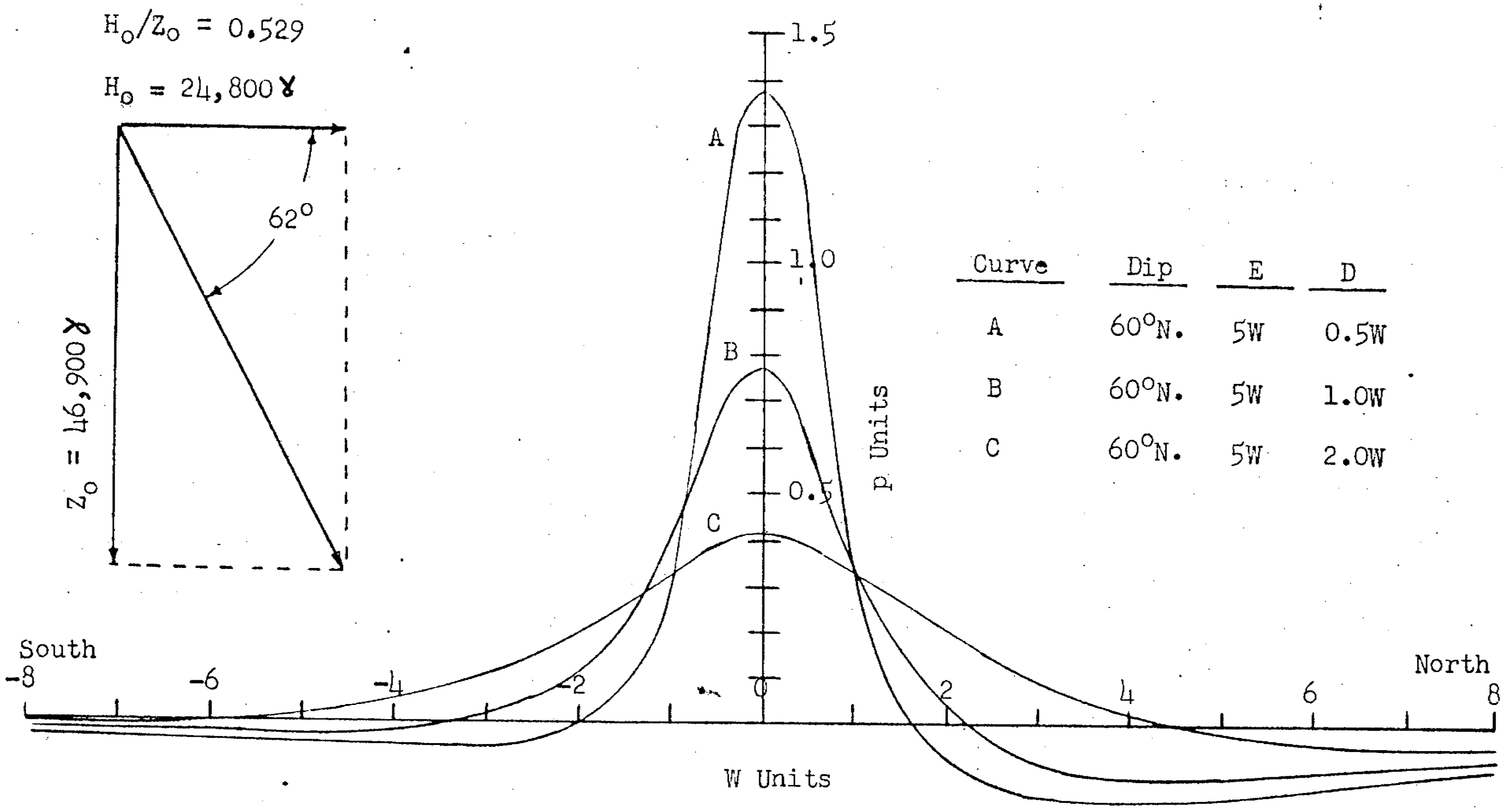


Fig. 6. Vertical Magnetic Intensity Over Finite Inclined Veins Striking East, Showing Effect of Depth Extent.



Curve	Dip	E	D
A	60°N.	5W	0.5W
B	60°N.	5W	1.0W
C	60°N.	5W	2.0W

Fig. 7. Vertical Magnetic Intensity Over Finite Inclined Veins Striking East, Showing Effect of Depth of Cover.

SECTION IV

MAGNETIC SURVEY OF DEPOSIT

The presence of four large cuts and several test pits prevented the establishment of stations in many parts of the area and, consequently, made impractical a regularly spaced grid. Therefore, a base line was laid out along the strike of the ore body, very nearly in coincidence with the apex of the ore. At favorable locations traverse lines were run at right angles to the base line. Stations were set ten feet apart along these traverses.

All surveying preliminary to the magnetic work was done with transit and steel tape. Magnetic field strengths were measured with two vertical intensity magnetometers: one a Schmidt balance type manufactured by the Sprengnether Instrument Co. of St. Louis, Mo.; and the other a null-reading type made by the Levanto Co. of Helsinki, Finland. The latter instrument is known commercially as the Arvela Model 52. The Sprengnether instrument was adjusted to a sensitivity of 138 gammas per scale division; the Arvela for a sensitivity of 10.8 gammas per scale division. Both magnetometers were calibrated with Helmholz coils. Although the anomaly is so large that all the usual corrections applied in magnetic work including that for the normal diurnal variation could be neglected, readings were taken at a base station several times daily to avoid erratic results that might have been caused by a magnetic storm.

As is shown in Fig. 8, a pronounced positive magnetic anomaly exists over the ore body. In plan view the general shape of the outline of the anomaly is very similar to that of the exposed ore. Two positive magnetic centers are associated with the deposit: one, in the vicinity of the westernmost pit, and the other in profile 5 + 72 E. The anomalous magnetic field diminishes in strength at the ends of the ore body, although it can be detected as much as 200 feet to the west of the wide pit. Near the southern end of profile 8 + 70 E is a small localized anomaly. Evidently it is due to a small magnetite segregation that is exposed in a shallow test pit a few feet west of profile 8 + 70 E.

Figs. 10 through 18 illustrate the magnetic profiles and corresponding geologic cross sections.

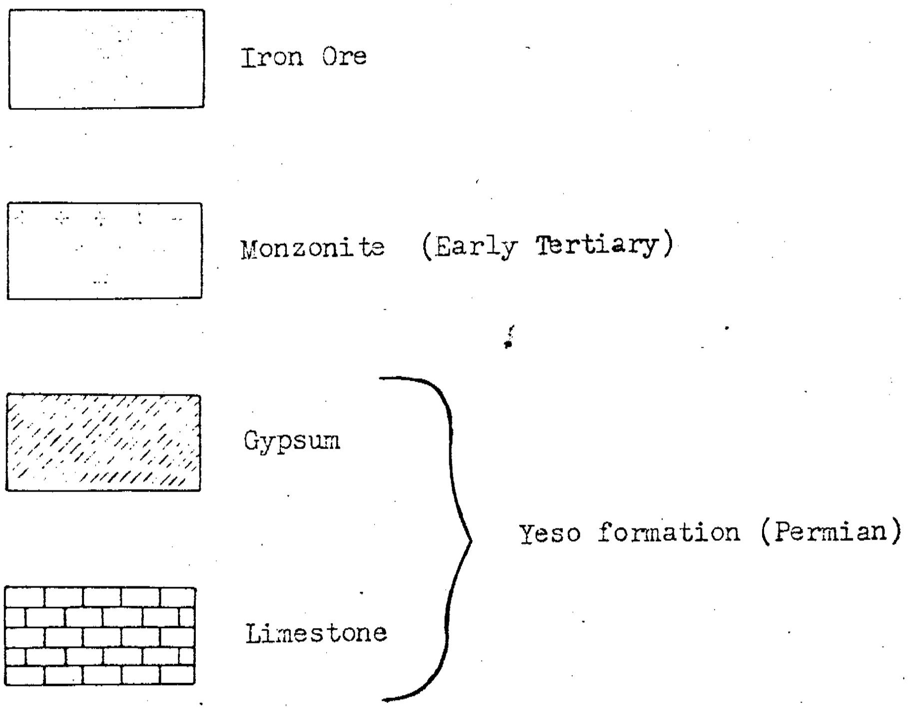


Fig. 9. Symbols Used in Geologic Cross Sections.

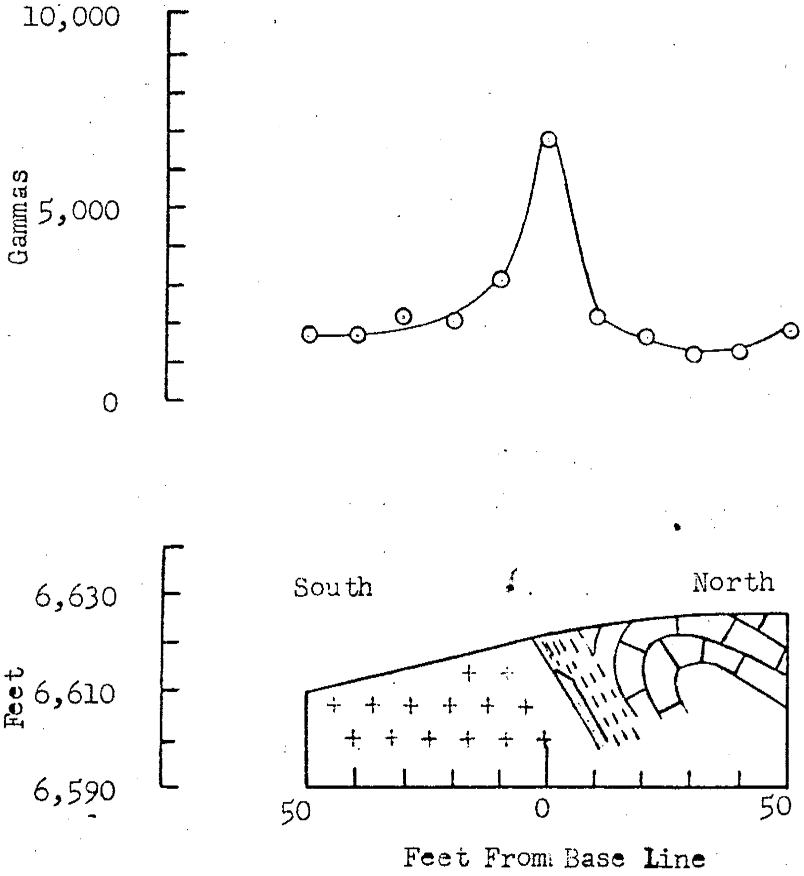


Fig. 10. Magnetic Profile and Geologic Cross Section Along Traverse 0 +93W.

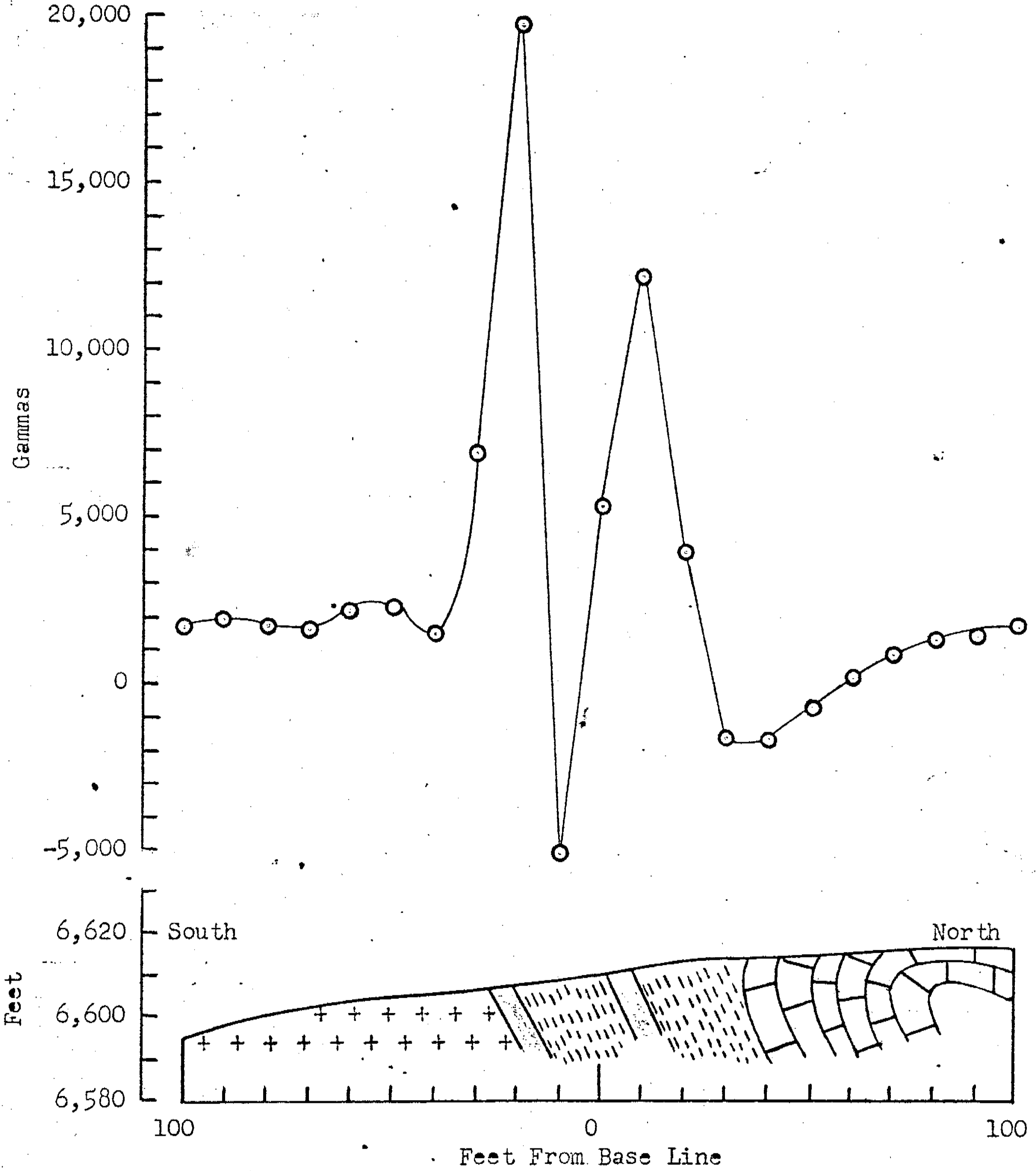


Fig. 11. Magnetic Profile and Geologic Cross Section Along Traverse 0+00.

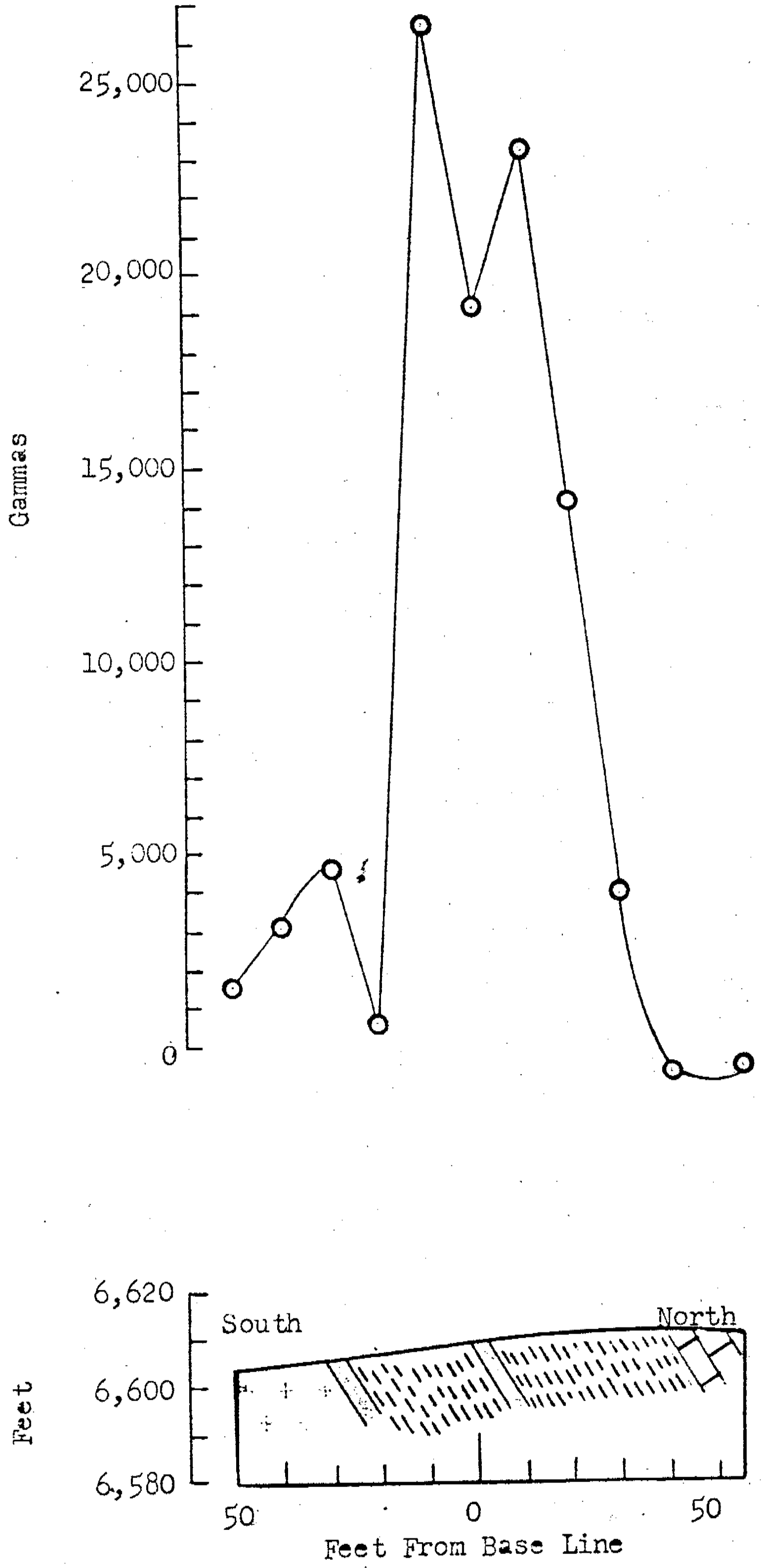


Fig. 12. Magnetic Profile and Geologic Cross Section Along Traverse 0+19E.

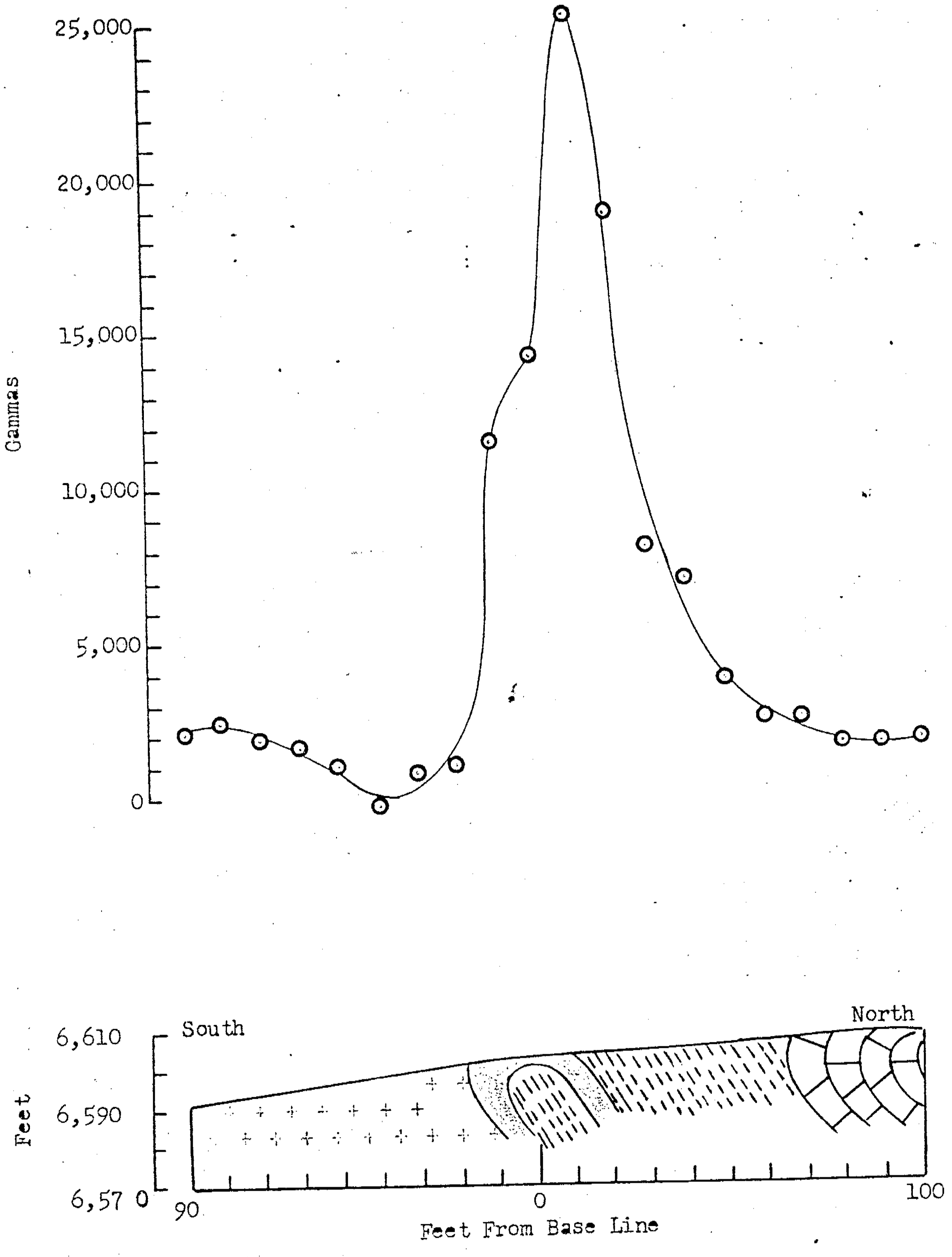


Fig. 13. Magnetic Profile and Geologic Cross Section Along Traverse 1+40E.

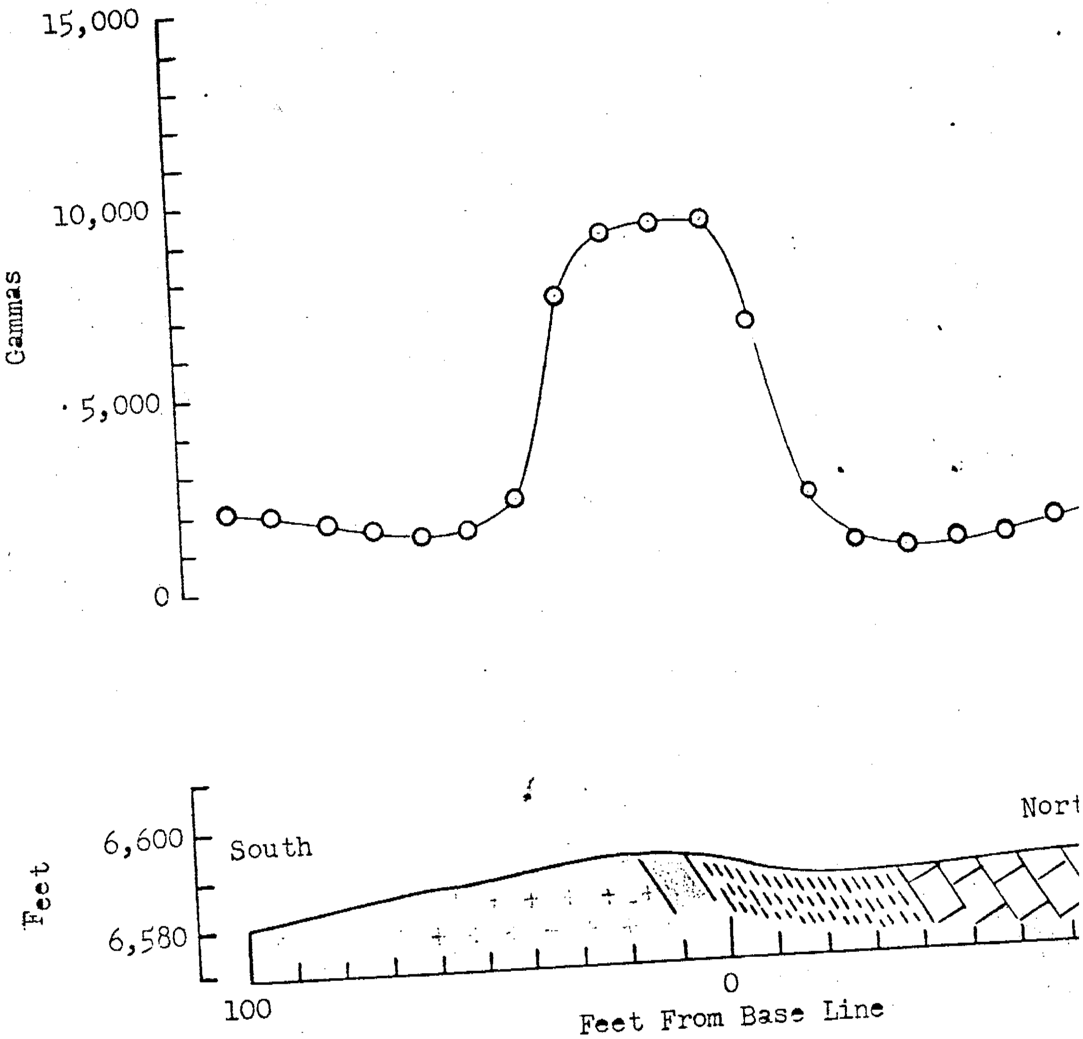


Fig. 14. Magnetic Profile and Geologic Cross Section Along Traverse 3+76E.

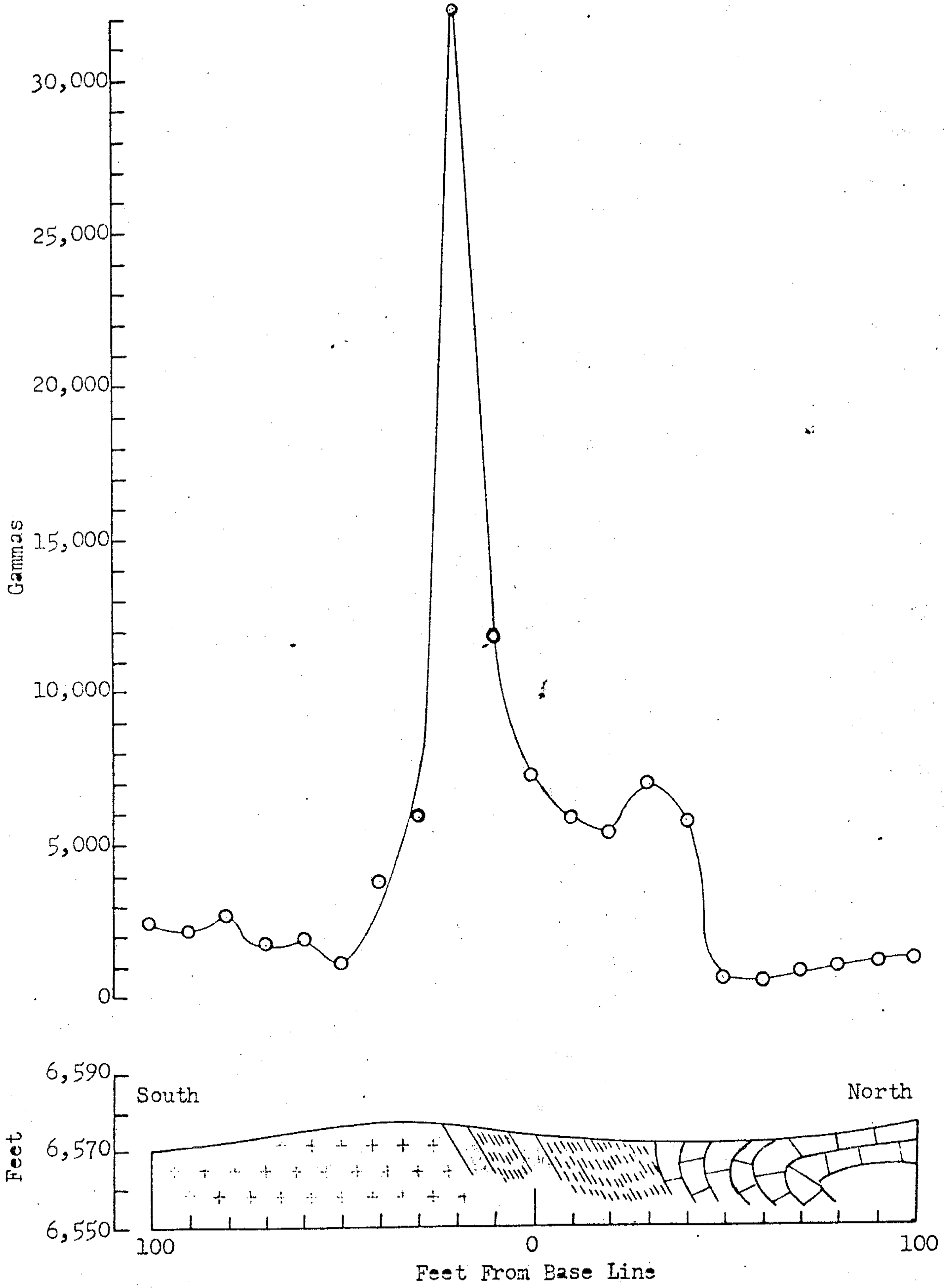


Fig. 15. Magnetic Profile and Geologic Cross Section Along Traverse 5+72E.

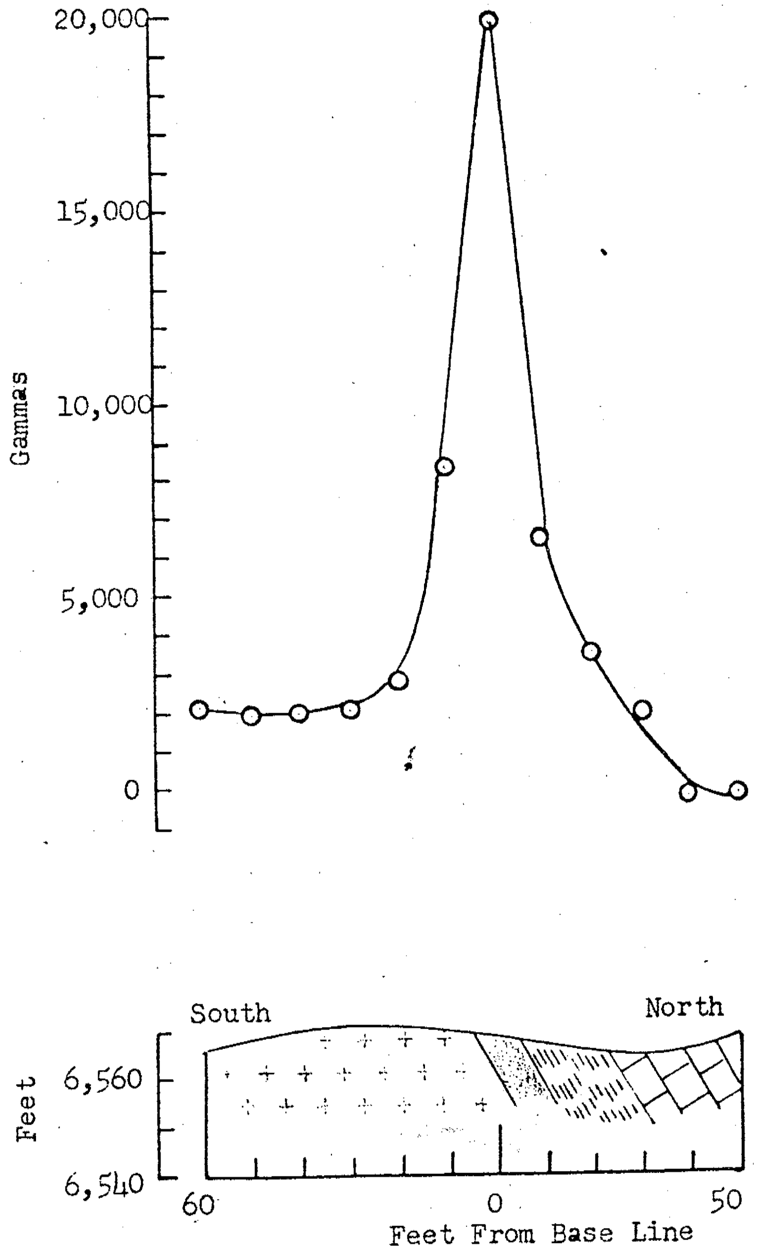


Fig. 16. Magnetic Profile and Geologic Cross Section Along Traverse 6+57E.

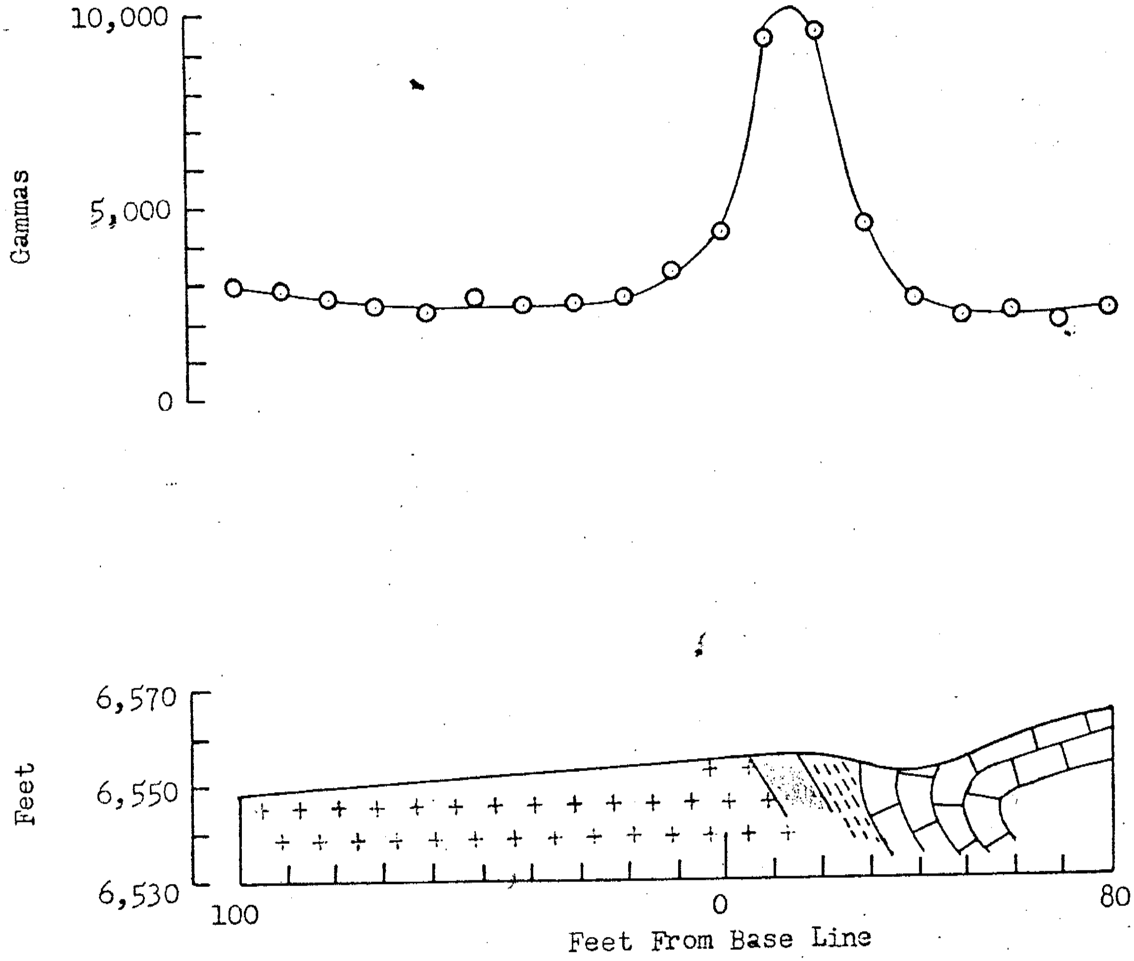


Fig. 17. Magnetic Profile and Geologic Cross Section Along Traverse 8+27E.

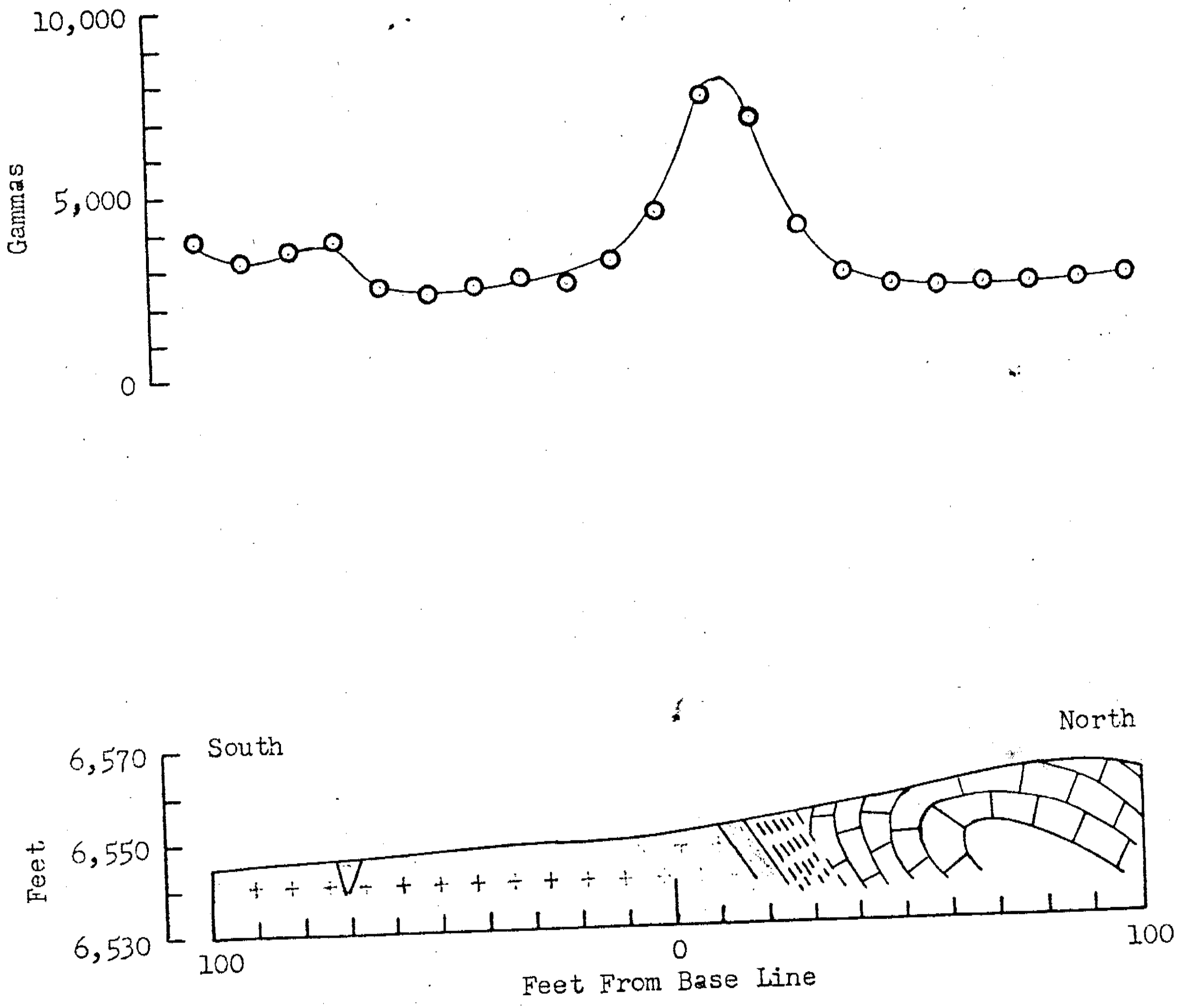


Fig. 18. Magnetic Profile and Geologic Cross Section Along Traverse 8 +70E.

SECTION V

QUANTITATIVE ANALYSIS OF SURVEY

Although the geologic occurrence of the Iron Horse deposit would make it almost ideally suited for the type of analysis undertaken, in practice some very serious handicaps are encountered in attempting to apply the method. Unfortunately, the cuts made during mining operations severely restrict the locations at which stations may be set. The only recourse is to run profiles between the pits and at the ends of the ore body. It must be admitted that this procedure yields rather sketchy information on which to base a prediction of ore tonnage, but there is no practical alternative.

An examination of the geologic map will make evident the unsuitability of several of the profiles for purposes of quantitative analysis. For example, profile 8 + 70 E lies at the extreme eastern tip of the ore body and, hence, does not even approximate the condition of "an infinitely long dike" assumed in the mathematical treatment. No attempt was made to analyze the data obtained from any of the profiles that pass over two masses of ore. Although by the process of superimposing two type-curves it would be possible to derive several possible solutions, these would be so ambiguous that it was not thought worthwhile to attempt them. The following four profiles were considered suitable for interpretation: 0 + 93 W, 3 + 76 E, 6 + 57 E, and 8 + 27 E.

Before any quantitative work is undertaken the values of the constants H_o, Z_o, and k must be known. The United States Coast and Geodetic Survey[1] gave interpolated values of 24,800 and 46,900 gammas for H_o, and Z_o, respectively. Although a laboratory determination of the magnetic susceptibility of the ore might appear to be a simple problem, an examination of the literature of geophysical prospecting will show that such a determination is actually a rather difficult undertaking. The major objection to laboratory measurements is that the susceptibility as measured in a strong field is lower than that determined in a weak field - say one of about 0.5 oersteds, the value of the field of the earth. Accordingly, susceptibilities for prospecting calculations are usually determined by

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[1] Communication with Tucson Magnetic Observatory, Tucson, Arizona

means of an indirect method proposed by Slichter.[1] Assuming that the magnetism of the body under consideration is due entirely to its magnetite content, the susceptibility of the rock is determined by multiplying the volume percentage of the magnetite in the rock by the susceptibility of magnetite (considered to be 0.3 c.g.s. units). Although it would be desirable to determine the magnetite percentage of the ore experimentally, it was decided that an extensive sampling program would be necessary to derive a representative value. Instead, Kelley's[2] value of 55% for the iron content of the ore was used as a starting point in the susceptibility calculations. Although the ore contains subordinate amounts of limonite and hematite, it is preponderantly magnetite. Moreover, it is likely that even smaller amounts of limonite and hematite will be present at depth than at the surface. Consequently, calculations were made assuming that all the iron was contained in magnetite. Using specific gravities of 5.1 for magnetite and 2.5 for the gangue, a value of 59.4% is obtained for the volume percentage of magnetite. This figure gives values

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[1] L.B. Slichter, "Certain Aspects of Magnetic Surveying", _Transactions of the American Institute of Mining and Metallurgical Engineers_, vol. LXXXI, 1929, pp. 238-260

[2] Kelley, _op. cit._, p. 224

of 0.178 c.g.s. units for k, and 16,700 gammas for the p unit.

Once the constants have been determined, the field curves are replotted in terms of the p and W units, and are then compared with the type-curves. The match made to magnetic profile 0 + 93 W is shown in Fig. 19. The field curve was plotted, using a value of 3 feet for W. For the theoretical curve, D = 2.5 W, E = 10 W, and the dip = 60° N. This is equivalent to a depth of cover of 7.5 feet and a down dip extent of 30 feet. It must be remembered that for ore bodies of such small dimensions as those dealt with here, the distance D is not the actual depth of overburden because D includes the height of the magnetometer system above the surface of the ground. Thus in this case the true depth of overburden is about 4 feet. The down dip extent is about 30 feet.

Although a casual examination of profile 3 + 76 E indicates that it is suitable for analysis, a more careful inspection proves that it is not. A comparison of the field curve with the various type-curves shows that the peak of the field curve is much too wide and flat for any feasible match. Several explanations might be devised to explain this situation, but the most likely solution for the broad anomaly seems to be the existence of two or more bodies of magnetite lying so close together that the resolving power of the magnetic observations cannot separate the effects of the different bodies.

Magnetic profile 6 + 57 E was plotted using W = 12 feet, and was matched to a theoretical curve having the following constants: E = 5 W, D = 0.5 W, and dip = 45° N. It is unfortunate that field conditions made it impossible to take readings farther to the north in this particular profile. The ore crops out at the surface; hence the calculated value of 6 feet for D is largely the height of the magnetometer above the ground, plus about 2 feet of overburden. The calculated down dip extent is 60 feet. At a dip of 45° this would mean a vertical extent of 42.5 feet.

Magnetic profile 8 + 27 E was plotted using a value of 7.5 feet for W. As is shown in Fig. 21, it was matched with a theoretical curve in which D = 1.5 W, E = 3 W, and the dip = 60° N. This is equivalent to a true depth of overburden of about 7.5 feet and a down dip extent of 22.5 feet.

If a magnetic survey had been made before the deposit was mined, it should have been possible, by using closely spaced traverses, to determine the width and depth extent of the ore body at many locations along its length. Then the

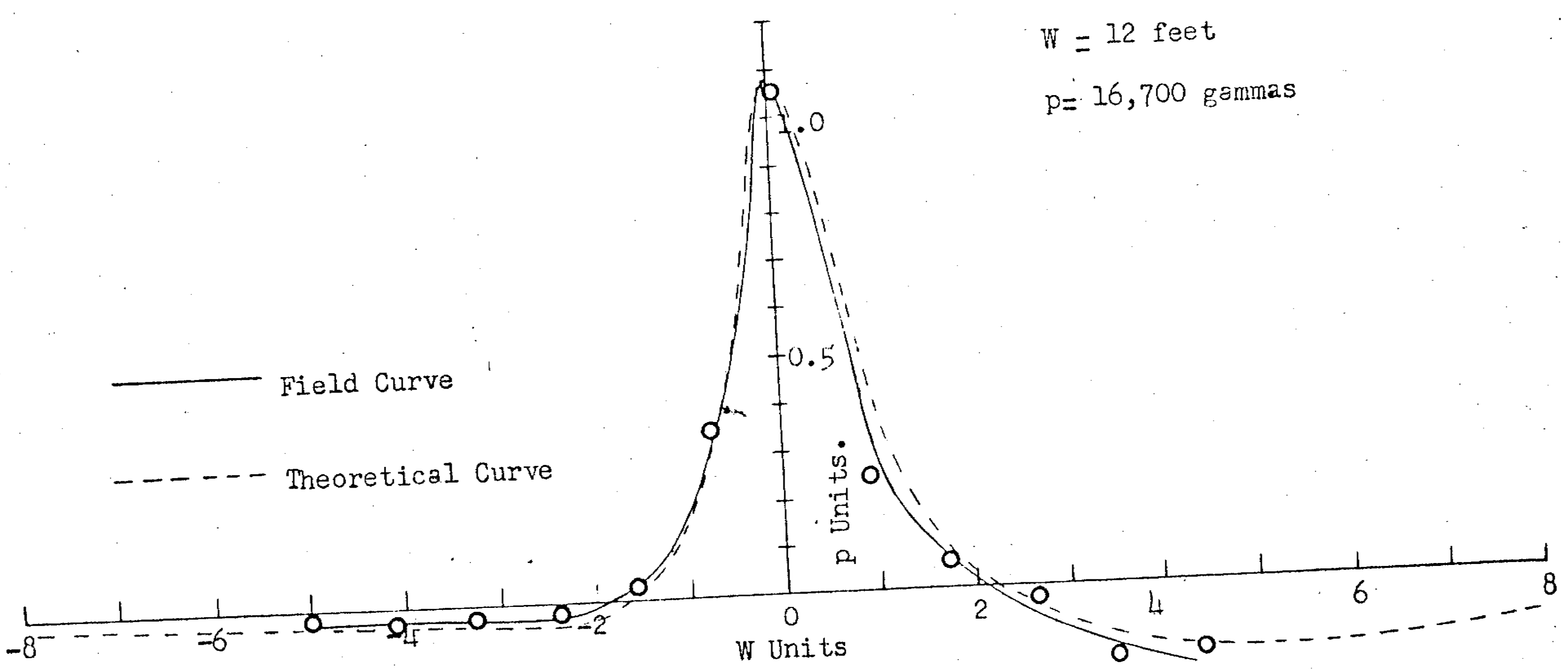

Fig. 20. Comparison of Field Magnetic Response Curve Obtained on Traverse 6+57E With Theoretical Curve.

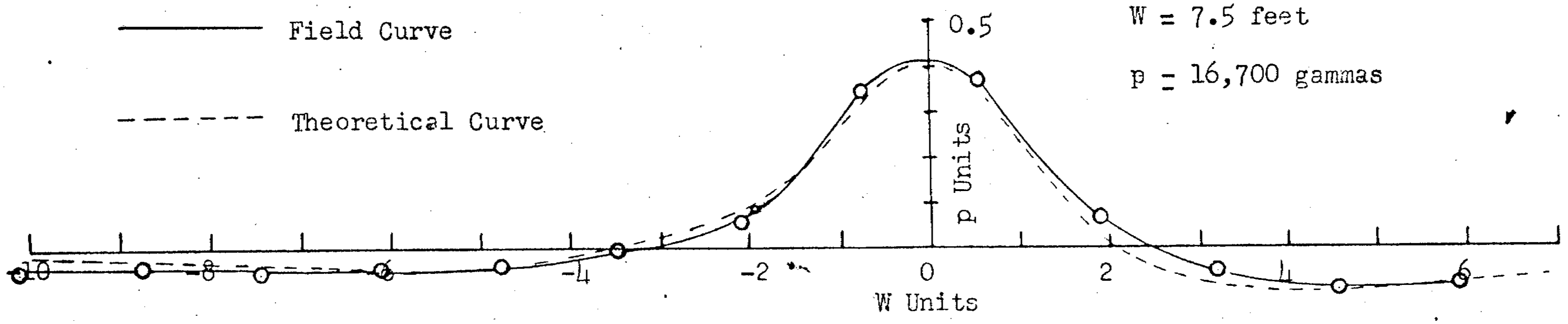

Fig. 21.Comparison of Field Magnetic Response Curve Obtained on Traverse 8+27E With Theoretical Curve.

tonnage could have been determined on the basis of the volume of a number of blocks of computed average cross-sectional area and length. It is obvious that the data obtained in the survey discussed in this paper are insufficient for any such procedure. Any computation of tonnage based on the information available must lean heavily on the judgment of the person making the estimate.

Of the three profiles considered analytically, both 0 + 93 W and 8 + 27 E are near an end of the deposit. It is likely that the depth extent at each of these two locations is considerably less than the overall average depth of the ore. It is probable that the down dip extent of 60 feet, which was determined for profile 6 + 57 E, is nearer the average than either of the other two values. If the average dip is assumed to be 45° N., a reasonable estimate of the average vertical extent of the ore body is 40 feet. Using this figure and Kelley's[1] value of 500 tons of ore per foot of depth, an estimate of 20,000 tons is obtained for the amount of ore originally present in the deposit. As 5,000 tons have been mined[2], the reserves should be about 15,000 tons.

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[1] Kelley, op. cit., p. 225

[2] Ibid., p. 224

although it was clearly recognized that such information was not sufficient to provide more than a general idea of the dimensions of the deposit.

SECTION VI

CONCLUSIONS

A vertical-intensity magnetic survey was made of the Iron Horse magnetite deposit of Socorro County, New Mexico. The survey delineated a very sharp, narrow, elongated magnetic anomaly associated with the tabular contact-metamorphic deposit of magnetite. The anomaly extends for a horizontal distance of more than 1,000 feet, and reaches a peak value in excess of 32,000 gammas.

Of several traverses that were run transverse to the strike of the ore body, three were considered suitable for quantitative analysis. The curves obtained from these three profiles were compared with theoretical curves based on magnetic induction theory. The results of the analysis indicate a probable down dip extent of 60 feet, and ore reserves of about 15,000 tons.

It cannot be overemphasized that these estimates are subject to large errors. An attempt was made to derive the best solution possible from the information available, although it was clearly recognized that such information was not sufficient to provide more than a general idea of the dimensions of the deposit.

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