GEOPHYSICS, VOL. 35, NO. 5 (OCTOBER 1970), P. 901–915, 25 FIGS.

EVALUATION OF THE MEASUREMENT OF INDUCED ELECTRICAL POLARIZATION WITH AN INDUCTIVE SYSTEM†

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The induced polarization (IP) technique is based on the observation that variations of earth conductivity with frequency may be indicative of buried metallic mineralization. Conventional IP involves the use of grounded electrodes, the installation of which can be quite time consuming. However, the electromagnetic fields about an oscillating magnetic dipole also depend on ground conductivity. Thus, it is conceivable that we might be able to detect IP anomalies with an inductive system, thereby eliminating the need for grounded electrodes. An airborne induced polarization method is a theoretical possibility.

Theoretical calculations based on a conductivity model determined experimentally at frequencies less than 30 hz suggest that the effect of polarizable material on electromagnetic response is quite small.

In order to check the theory and to determine experimentally whether inductive IP is feasible, field tests were conducted in two areas in Nevada which exhibit strong conventional IP anomalies. The field tests consisted of measurements of the amplitudes of the electric and magnetic fields about a horizontal loop of wire carrying current at frequencies ranging from 15 hz to 1500 hz. The presence of the polarizable material is not evident in the inductive data; in fact, the observations can be fitted to theoretical curves for non-polarizable models.

Hence, on the basis of both theory and field tests, it is concluded that inductive IP based on amplitude measurements is not a practical exploration tool for environments such as that of the southwestern United States.

INTRODUCTION

Induced polarization (IP) surveys are routinely used in exploring for buried metallic mineralization in the earth. In the conventional IP method, current is introduced into the ground through two current electrodes, and a potential difference is measured between two potential electrodes located at some distance from the current electrodes. With the frequency domain technique, measurements are made at two or more frequencies. If the potential difference changes with frequency and provided the frequencies are low enough that inductive and capacitive effects are negligible, the change in potential difference is due to the fact that the ground conductivity varies with frequency. Frequency-dependent conductivity can be indicative of metallic mineralization.

However, the electromagnetic fields about an inductive source, e.g., an oscillating magnetic dipole, also depend on the ground conductivity. Thus, it is conceivable that we might be able to detect IP response with an inductive system, thereby eliminating the need for grounded electrodes. Inductive IP surveys presumably would be less expensive than the conventional type, and

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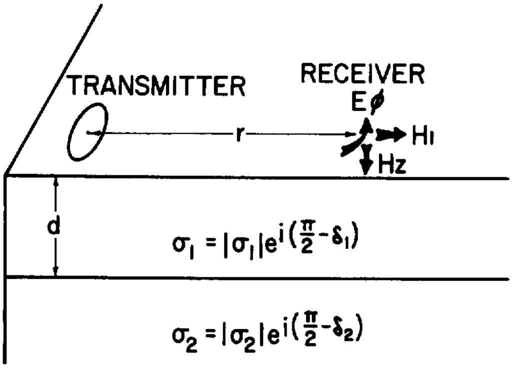

FIG. 1. Field configuration.

airborne IP might be possible. Dias (1968) considered the problem and indicated that inductive IP is theoretically feasible.

The purpose of the research described herein was to determine by field tests whether the method is feasible in practice. Some theoretical considerations are presented first, followed by the results of the field tests.

THEORY

Figure 1 illustrates the field configuration used. The transmitter is a horizontal, multiturn loop of wire at the surface of the earth. The distance r between transmitter and receiver is greater than 10 loop radii, so that the transmitter may be considered to be a vertical magnetic dipole. The resultant electric field is in the ϕ direction, while the magnetic field has vertical and radial components.

In Figure 1 the earth is assumed to consist of two layers having different conductivities. It is possible to show by causality arguments (Fuller and Ward, 1969) that a frequency-dependent conductivity must be complex. Thus, in each medium we represent the conductivity as a complex function; the modulus and phase angle are both functions of frequency. The permeability of each layer is assumed to be unity.

Electromagnetic response is determined by the propagation constant,

$$\gamma = [i\omega\mu_0(\sigma^*(\omega) + i\omega\epsilon^*(\omega))]^{1/2}, \tag{1}$$

where we have assumed $e^{i\omega t}$ time dependency and where

$$\sigma^*(\omega) = \sigma'(\omega) + i\sigma''(\omega), \tag{2}$$

$$\epsilon^*(\omega) = \epsilon'(\omega) + i\epsilon''(\omega). \tag{3}$$

In our formulation, we have lumped together conductivity and permittivity by defining a new parameter

$$\begin{aligned}\sigma &= \sigma_r + i\sigma_i \\ &= (\sigma' - \omega\epsilon'') + i(\sigma'' + \omega\epsilon'),\end{aligned} \tag{4}$$

which we shall call, simply, conductivity.

The loss angle δ is given by

$$\delta = \tan^{-1}\left(\frac{\sigma_r}{\sigma_i}\right). \tag{5}$$

The electromagnetic fields for the configuration of Figure 1 are given by the following improper integrals (Keller and Frischknecht, 1966, p. 339):

$$\frac{H_z}{H_z^p} = 1 + B^3 \int_0^\infty R\left(\frac{d}{r}, K, g\right) \cdot J_0(gB) g^2 dg, \tag{6}$$

$$\frac{H_r}{H_z^p} = B^3 \int_0^\infty R\left(\frac{d}{r}, K, g\right) \cdot J_1(gB) g^2 dg, \tag{7}$$

$$\frac{E_\varphi}{E_\varphi^p} = 1 - B^2 \int_0^\infty R\left(\frac{d}{r}, K, g\right) \cdot J_1(gB) g dg, \tag{8}$$

where

$$H_z^p = -\frac{m}{4\pi r^3}$$

and

$$E_\varphi^p = -\frac{i\omega\mu_0 m}{4\pi r^2}$$

are the primary magnetic and electric fields and where

$$R\left(\frac{d}{r}, K, g\right) = 1 - 2g \frac{u + v + (u - v)e^{-2(d/r)uB}}{(u + g)(u + v) - (u - g)(u - v)e^{-2(d/r)uB}} \cdot$$

$$u = (g^2 + 2i)^{1/2}.$$

$$v = (g^2 + 2iK)^{1/2}.$$

The fields are functions of the three parameters:

$$B = \left(\frac{\omega\mu_0\sigma_1}{2}\right)^{1/2} r, \tag{9}$$

$$\frac{d}{r}, \tag{10}$$

and

$$K = \frac{\sigma_2}{\sigma_1} \cdot \tag{11}$$

In the case of a homogeneous half-space, the electromagnetic response is determined only by the induction number B.

For the present study, integrals (6), (7), and (8) were evaluated numerically using a procedure similar to that described by Frischknecht (1967). However, in order to compute the fields, it is necessary to describe mathematically the real and imaginary parts of conductivity as functions of frequency.

A large number of laboratory and field measurements of resistivity spectra of rocks containing disseminated mineralization have been made by the Exploration Services Department of Kennecott Exploration, Inc. These rocks pertain to the southwestern USA. Measurements were made in the frequency range 0.01 hz to 30 hz. In each case, the resistivity could be described to an accuracy of 0.2 percent by the following formula:

$$\rho = |\rho_1| (1 - c \log f) e^{-i(c/2)} \tag{12}$$

where $|\rho_1|$ is the amplitude of the resistivity at 1 hz, and f is frequency. The parameter c is approximately constant over the frequency range of interest; its magnitude increases with increasing polarizability. Note that the frequency dependence and phase of resistivity are both determined by c, so that we can describe polarizability solely in terms of c. Conductivity is given by

$$\sigma = \frac{1}{\rho} = \frac{|\sigma_1|}{1 - c \log f} e^{i(c/2)} = \sigma_r + i\sigma_i. \tag{13}$$

Degree of polarizability is commonly expressed in the frequency domain as percent frequency effect (PFE) per decade, defined as

$$\text{PFE/decade} = \frac{(|\rho_1| - |\rho_{10}|)}{|\rho_1|} \times 100, \tag{14}$$

where $|\rho_1|$ and $|\rho_{10}|$ are the amplitudes of the resistivity at 1 hz and 10 hz, respectively. From (12) and (14), we see that

$$\text{PFE/decade} = 100c. \tag{15}$$

Normally the phase angle $c/2$ is small, so that $\tan c/2$ can be set equal to $c/2$. But the loss tangent is equal to the reciprocal of $\tan c/2$, so that we can write

$$\tan \delta = \frac{\sigma_r}{\sigma_i} = \frac{2}{c} \cdot \tag{16}$$

It suffices, therefore, to compute the response of the ground to an inductive system as a function of loss tangent if we wish to study the effect of polarizability. From (16), note that large $\tan \delta$ corresponds to small polarizability.

Extrapolating (13) to our frequency range of interest (10 hz to 1500 hz), we can evaluate (6), (7), and (8) for various earth models to get some idea of what effect polarizability might have on inductive response. Figures 2, 3, and 4 illustrate the theoretical inductive response of a homogeneous earth having different degrees of polarizability, under the assumption that (13) holds true. A loss tangent of ∞ represents a nonpolarizable medium; a value of 10 corresponds to 20 PFE/decade; and a value of 5 corresponds to 40 PFE/decade. The differences between the curves are quite small, even for these strong IP effects, considering the fact that in practice the earth resistivity, and hence the horizontal position of the curves, is unknown.

Figures 5 and 6 show the amplitude and phase, respectively, of the magnetic field response for a nonpolarizable layer overlying polarizable material on the one hand and nonpolarizable material on the other hand. The substratum is ten times as conductive as the overburden at $B=1$. Even though the conductivity contrast is favorable and the transmitter-receiver separation is 10 times the thickness of the upper layer, the IP response is almost completely masked by the overburden.

Thus, if the conductivity model is valid, calculations show that even highly polarizable material would be difficult to detect inductively.

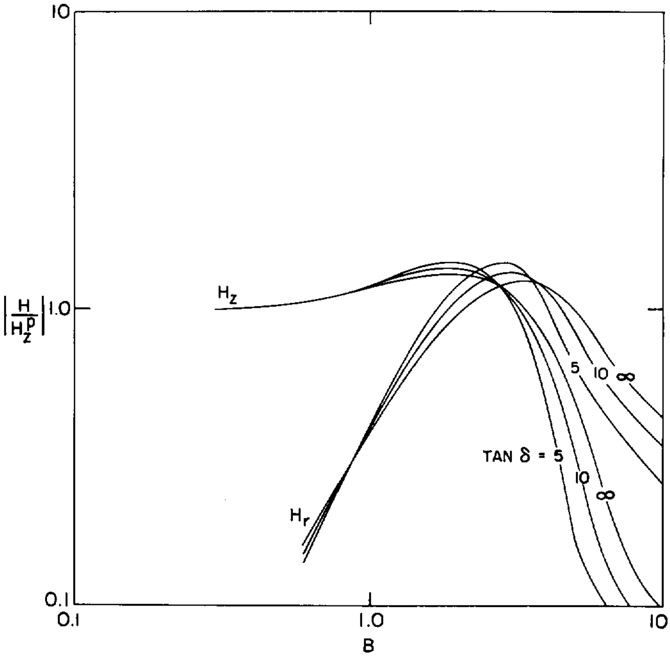

FIG. 2. Theoretical magnetic field amplitude for homogeneous earth.

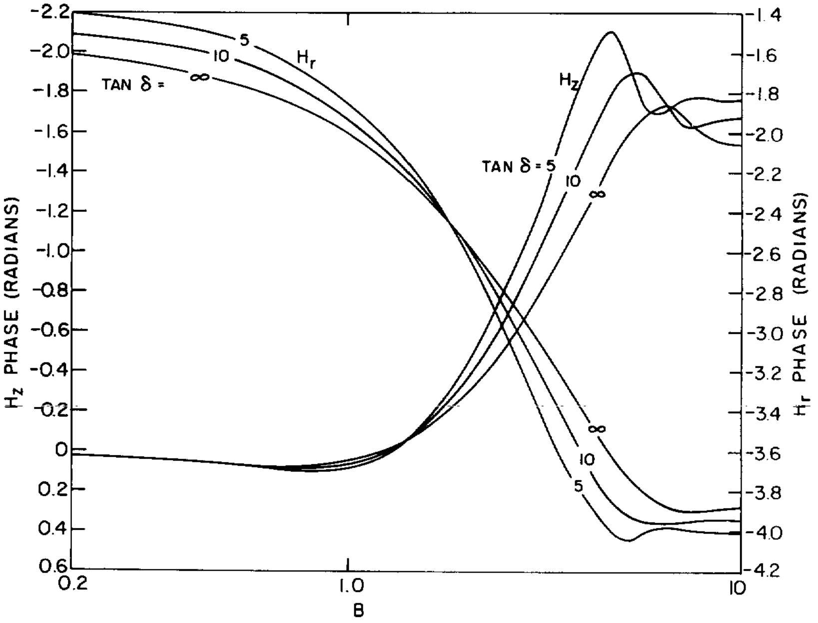

FIG. 3. Theoretical magnetic field phase for homogeneous earth.

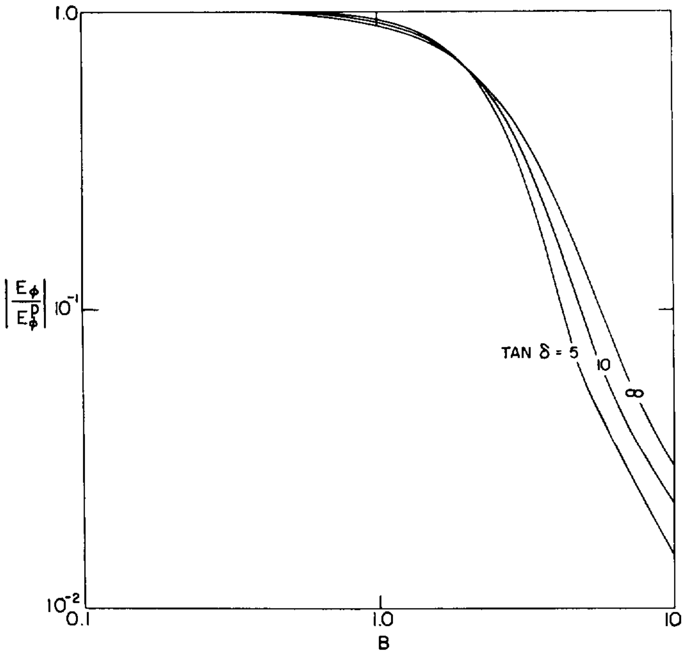

FIG. 4. Theoretical electric field amplitude for homogeneous earth.

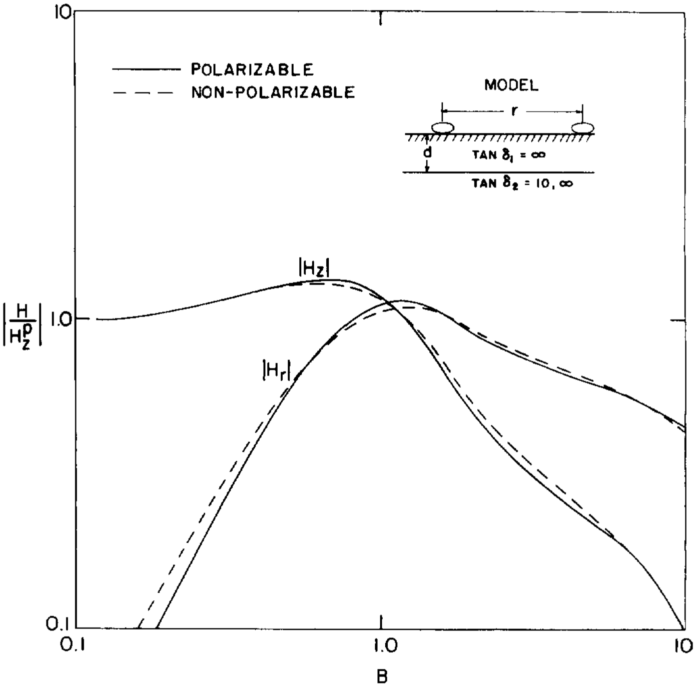

FIG. 5. Theoretical magnetic field amplitude for two-layer earth ($\sigma_2/\sigma_1=10$).

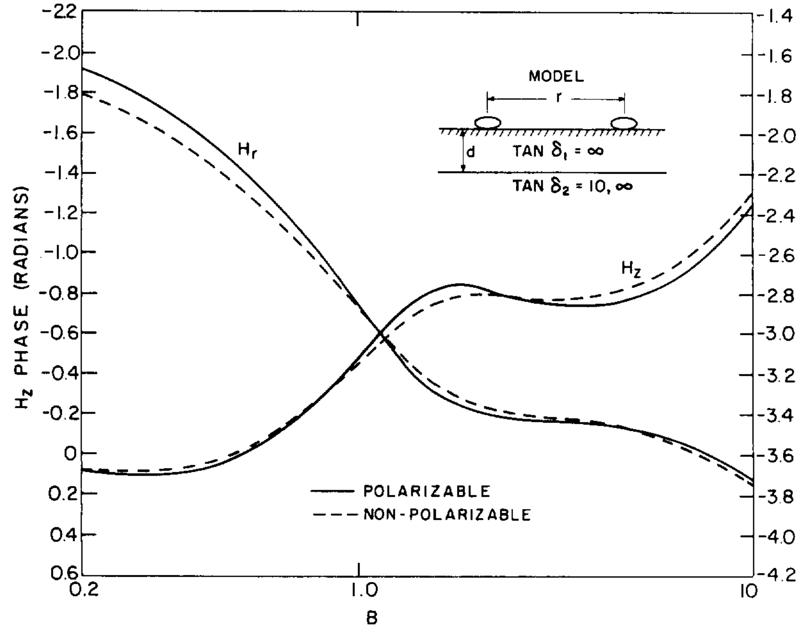

FIG. 6. Theoretical magnetic field phase for two-layer earth ($\sigma_2/\sigma_1 = 10$).

FIELD TESTS

Theoretical calculations for inductive IP are interesting and informative, but the final analysis of the technique must take the form of actual field tests in areas of known conventional IP response. Therefore field tests were conducted in the three areas shown in Figure 7.

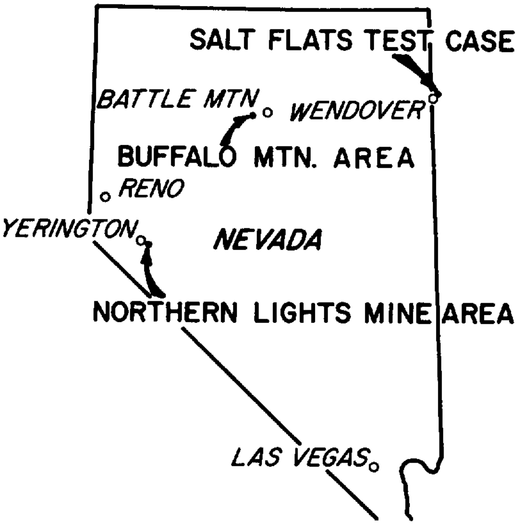

FIG. 7. Field test sites.

The source was a tuned, multiturn loop driven by the Sinclair Oil and Gas Company electromagnetic transmitter, which has been described by Kintzinger (1968). Basically, the transmitter consists of a silicon-controlled rectifier bridge which switches current to provide a square wave at frequencies ranging, for this study, from 15 hz to 1500 hz. The rms amplitude at the fundamental frequency varied from one amp at the higher frequencies to 20 amp at the lower frequencies.

The receiving equipment consisted of a calibrated 12,000-turn coil followed by a Princeton Applied Research Model CR4 preamplifier, a Krohn-Hite Model 3322 variable bandpass amplifier-filter, a Ballantine Model 302C vacuum tube voltmeter, and a Tectronics Model 321A oscilloscope, all of which were battery operated.

Transmitter current was measured with a digital voltmeter and frequency with a digital frequency counter, in order that accurate calibrations could be made.

SALT FLATS CALIBRATION AREA

This area was selected as a test site because the subsurface is highly conductive, nonpolarizable,

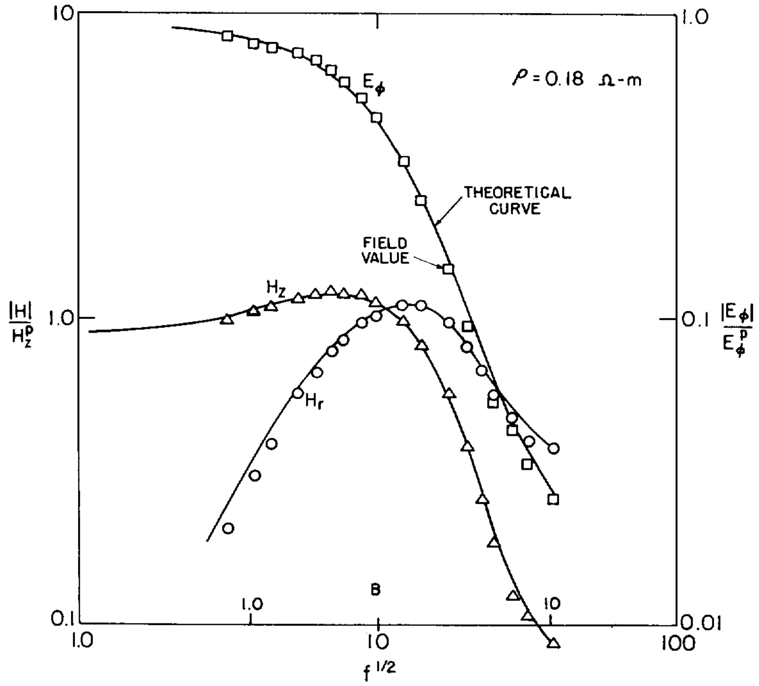

FIG. 8. Salt Flats data (r=57m).

and approximately homogeneous. Therefore, it is an ideal location for testing both equipment and theoretical solutions.

Figure 8 shows that the field data, plotted versus the square root of frequency, correspond almost exactly to the values predicted by theory for a nonpolarizable case. The resistivity is inferred to be 0.18 ohm-m by noting the frequency corresponding to a particular "B" value when the field data are matched with the theoretical curve, and substituting into (9). Standard dc resistivity measurements yielded a value of 0.20 ohm-m. We concluded that the equipment was operating satisfactorily and that our theoretical solutions were correct.

NORTHERN LIGHTS MINE AREA

At this location, a plan map of which is shown in Figure 9, a carbonaceous, pyritic limestone formation is present at the surface. The material has been described by Van Voorhis (1967).

The location of a conventional dipole-dipole IP line run with 300 ft dipoles is shown in Figure 9; the data appear in Figure 10. The resistivity data indicate that a thin, high-resistivity layer of variable thickness overlies a lower layer having a resistivity of about 5 ohm-m. The IP data suggest that the subsurface has a fairly uniform IP effect of about 20 PFE/decade, corresponding to a loss tangent of 10, according to the resistivity model of (12).

The electromagnetic transmitter was set up at the location marked "T" in Figure 9, and measurements were made at five receiver stations marked "X". Although lateral inhomogeneities and rough terrain influence the results to a certain extent, particularly the lower-frequency H_r values, the data from the first four stations compare rather well with theoretical curves for layered models having *no polarizability*, as shown in Figures 11 through 14. The thickness of the upper layer is on the order of 20–40 m. The upper-layer resistivity is about 150 ohm-m; that of the lower layer, about 15 ohm-m. Thus the resistivity of the substratum derived from EM measurements is about three times that determined by dc resistivity measurements. The discrepancy is probably due to the presence of a gradational rather than a sharp boundary. Note that the vertical scale for the field measurements is not

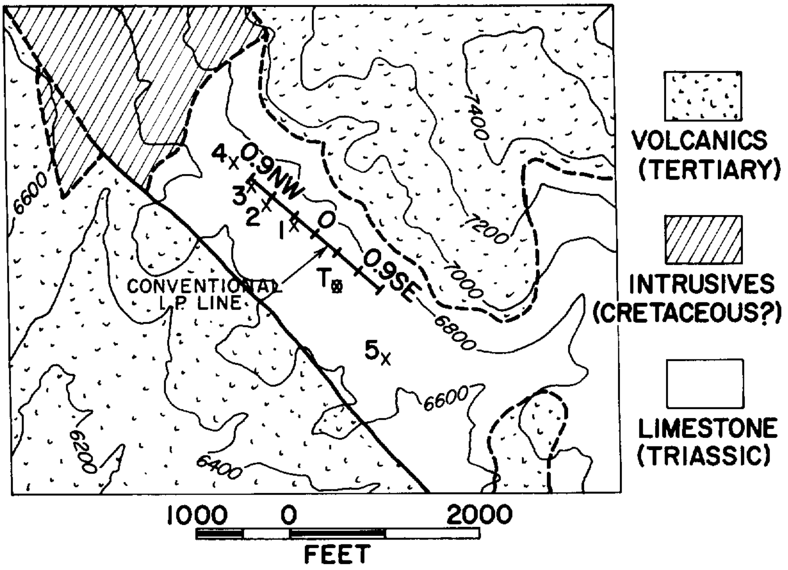

Fig. 9. Northern Lights Mine area.

absolute, because the dipole moment of the transmitter could not be determined accurately.

The EM data from station 5, where a large hill was situated between transmitter and receiver, are shown in Figure 15. Due to the effect of the hill and possibly other inhomogeneities, the data do not fit very well with theoretical curves for a layered model. The departure of the field values from the theoretical curves, however, is in the opposite direction from what we would expect with a conductivity that increases with frequency.

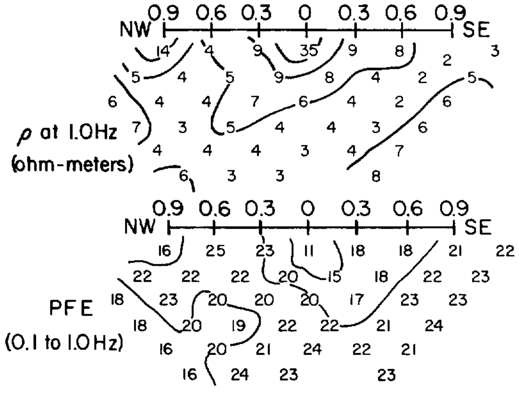

Fig. 10. Northern Lights conventional dipole, dipole IP data (courtesy Kennecott Exploration-Inc.).

BUFFALO MOUNTAIN AREA

In this largely gravel covered area, buried polarizable material produces the IP anomaly outlined in Figure 16. Also shown on the plan map are the locations of two conventional IP lines, a drill hole, and outcrops of Havallah formation (Paleozoic sediments). The topography of the area is relatively flat, except for the small outcrops.

The electrical and geological logs of the drill hole are shown in Figure 17. The IP response is due to carbonaceous limestone and shale with disseminated pyrite at a depth of 430 ft. The intrinsic response of the unit is about 30 PFE/decade, while the resistivity is on the order of 10 ohm-m. Overlying the responsive unit are 130 ft of Paleozoic sediments and 300 ft of alluvium.

The data from lines 7 and 9 of the conventional IP survey, run with 1000 ft dipoles, are shown in Figures 18 and 19, respectively. Resistivities in the area where the inductive tests were made are on the order of 50 to 200 ohm-m. The presence of polarizable material at depth is readily apparent in the conventional IP survey.

The inductive transmitter, a 20-turn loop with a radius of 100 ft, was set up at the location marked "*T*" in Figure 16. Electric and magnetic fields were measured at ten stations marked "*X*",

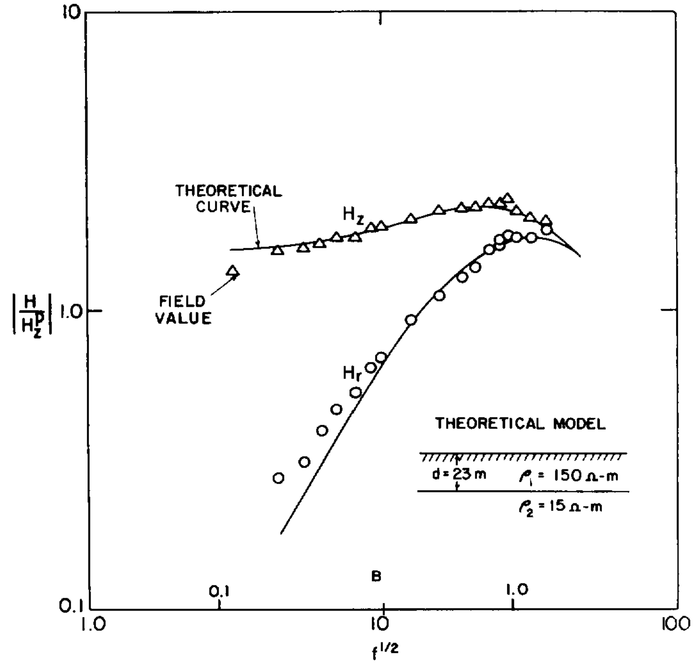

FIG. 11. Northern Lights data, station 1.

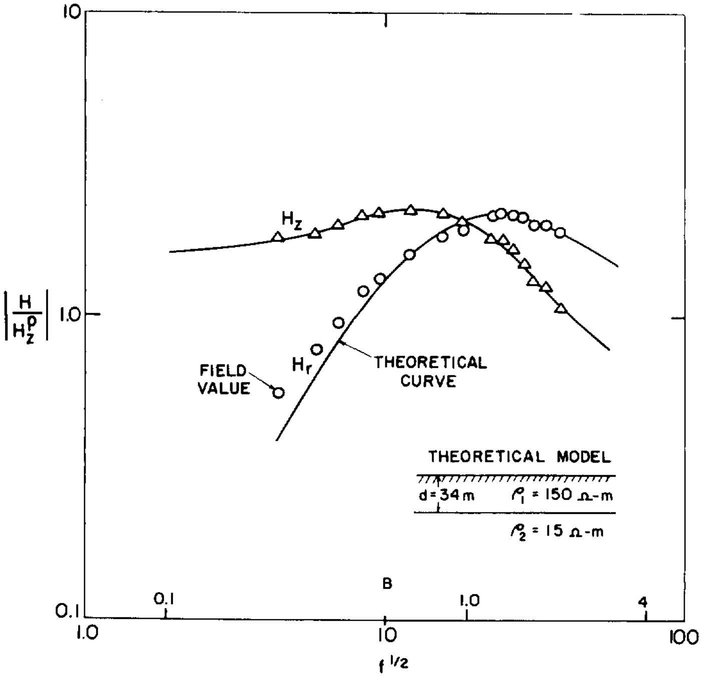

FIG. 12. Northern Lights data, station 2.

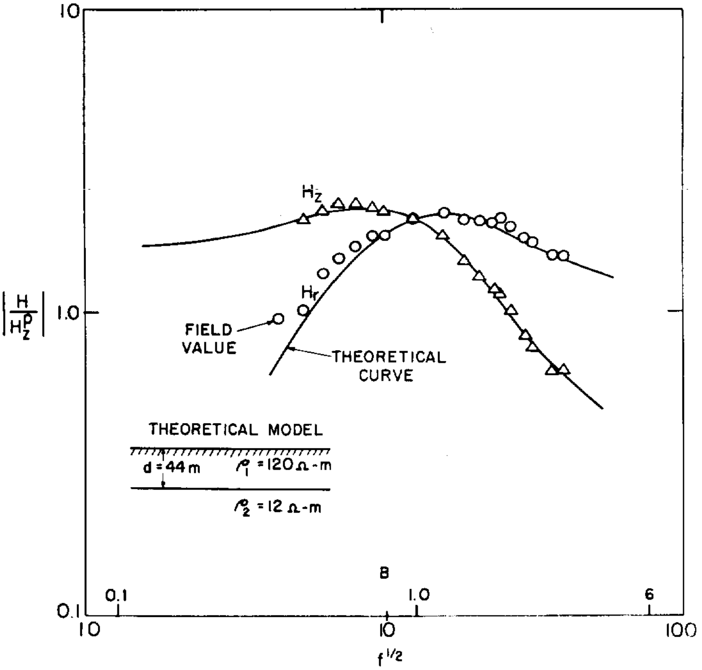

FIG. 13. Northern Lights data, station 3.

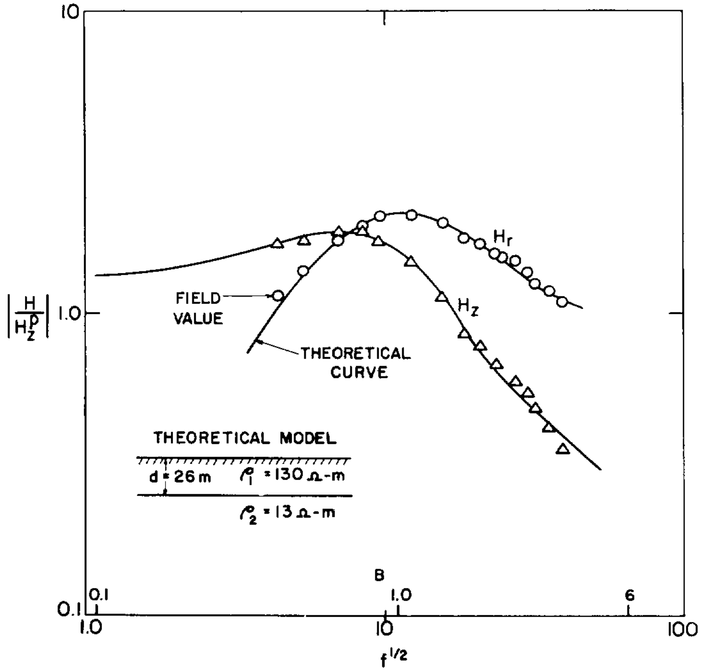

FIG. 14. Northern Lights data, station 4.

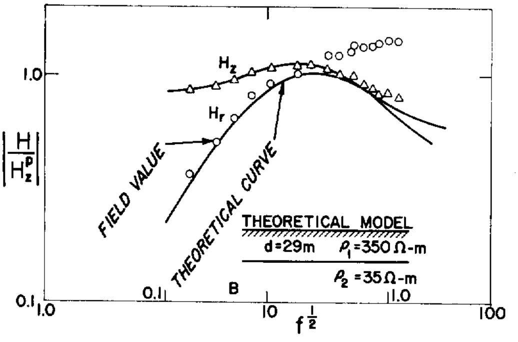

FIG. 15. Northern Lights data, station 5.

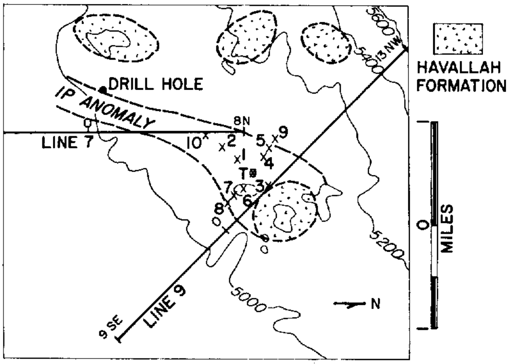

FIG. 16. Buffalo Mountain Area.

at frequencies between 15 hz and 1500 hz and transmitter-receiver separations ranging from 1000 ft to 3000 ft.

Figures 20 through 24 show typical electromagnetic data for the area, along with matching theoretical curves for a *nonpolarizable*, homogeneous earth. The field data closely agree with the theoretical values. Hence, the presence of the buried polarizable material does not significantly affect the inductive response. Resistivities determined inductively are between 50 and 100 ohm-m, corresponding very well with those of the conventional resistivity survey.

Figure 25 shows the data from station 8, which was located near a high-resistivity outcrop. The effects of the inhomogeneity are evident in the data, which can be fitted only roughly to theoretical curves for a laterally homogeneous earth.

CONCLUSIONS

The feasibility of inductive IP was tested in two field areas in Nevada where highly responsive material is easily detected with conventional IP surveys. Except for cases where lateral resistivity changes affect the results, the data correspond quite well with theoretical curves for nonpolariz-

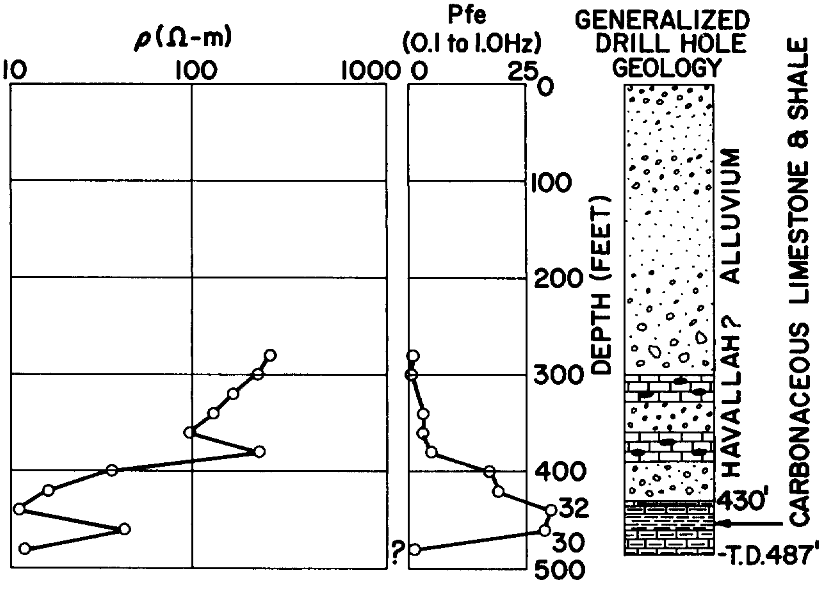

FIG. 17. Buffalo Mountain drill hole logs (courtesy Kennecott Exploration, Inc.).

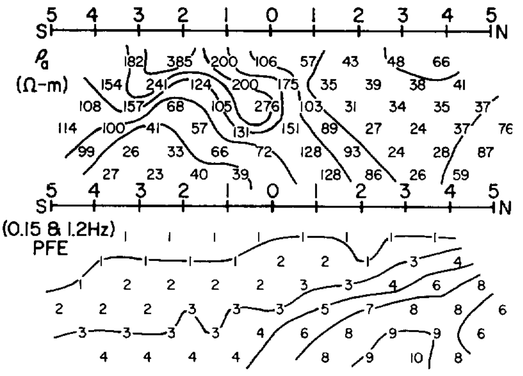

FIG. 18. Buffalo Mountain conventional dipole-dipole IP data, line 7 (courtesy Kennecott Exploration, Inc.).

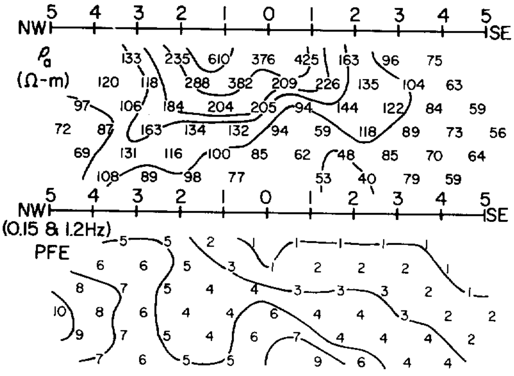

FIG. 19. Buffalo Mountain conventional dipole-dipole IP data, line 9 (courtesy Kennecott Exploration, Inc.).

able models. Hence, for all practical purposes the presence of the polarizable material is not evident in the inductive data. Results of tests on the Salt Flats show that the equipment was functioning properly.

IP response in most mineralized areas is less than that of the localities studied in this research, and usually rough terrain and lateral resistivity changes cause greater geologic noise. Since even these large responses could not be detected under the best of geologic conditions, it appears that inductive IP based on amplitude measurements is not a practical exploration tool for the disseminated sulfide environment of the south-

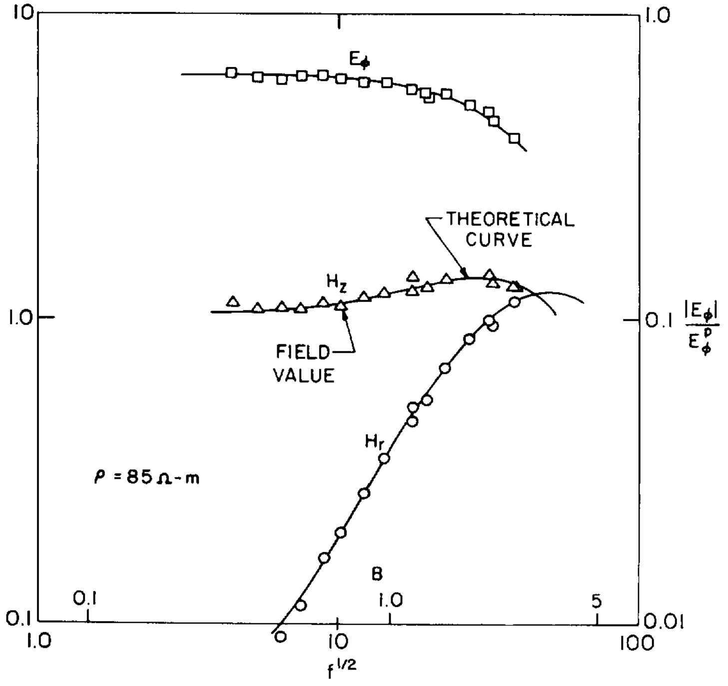

FIG. 20. Buffalo Mountain data, Station 1.

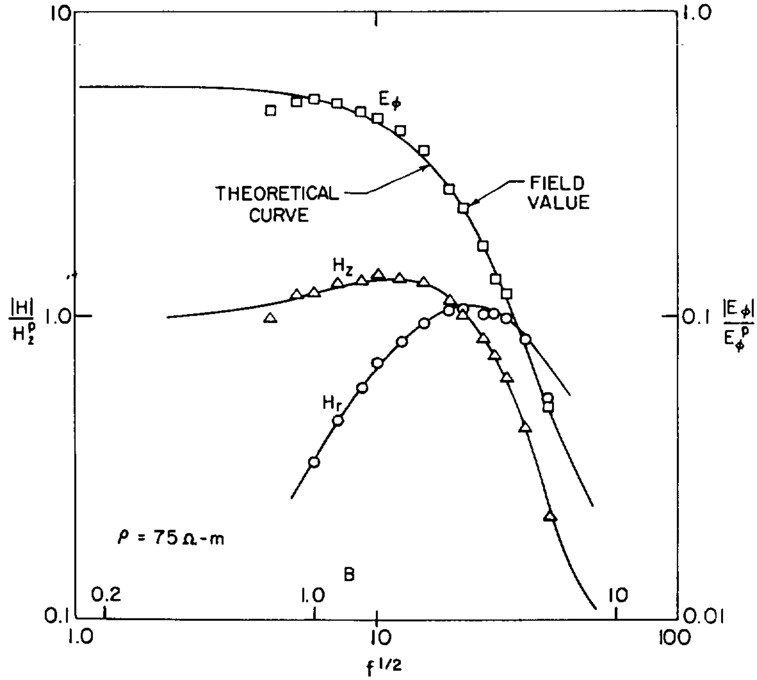

FIG. 21. Buffalo Mountain data, station 2.

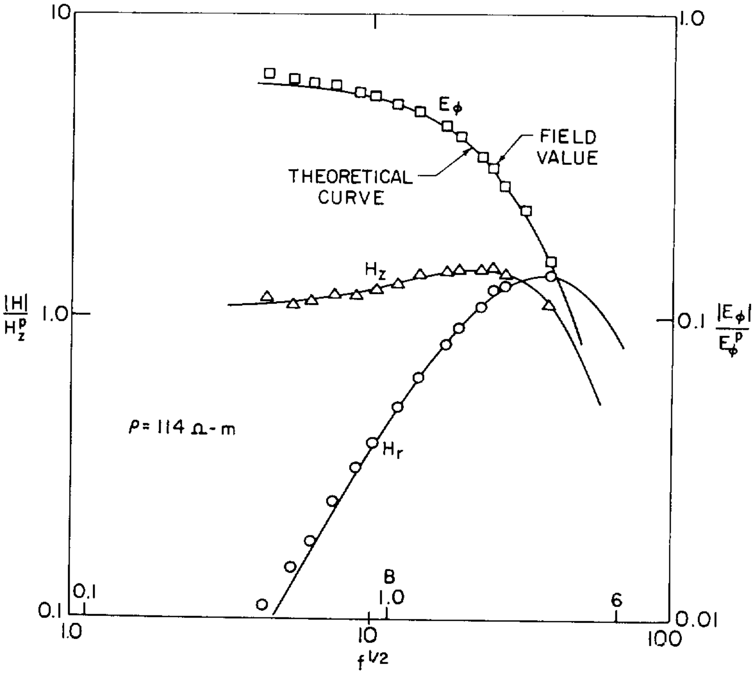

FIG. 22. Buffalo Mountain data, station 5.

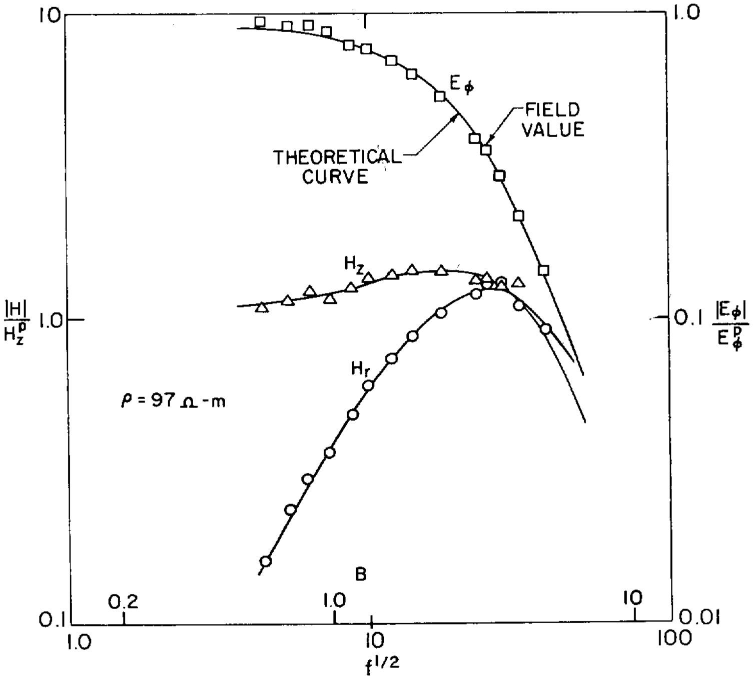

FIG. 23. Buffalo Mountain data, station 9.

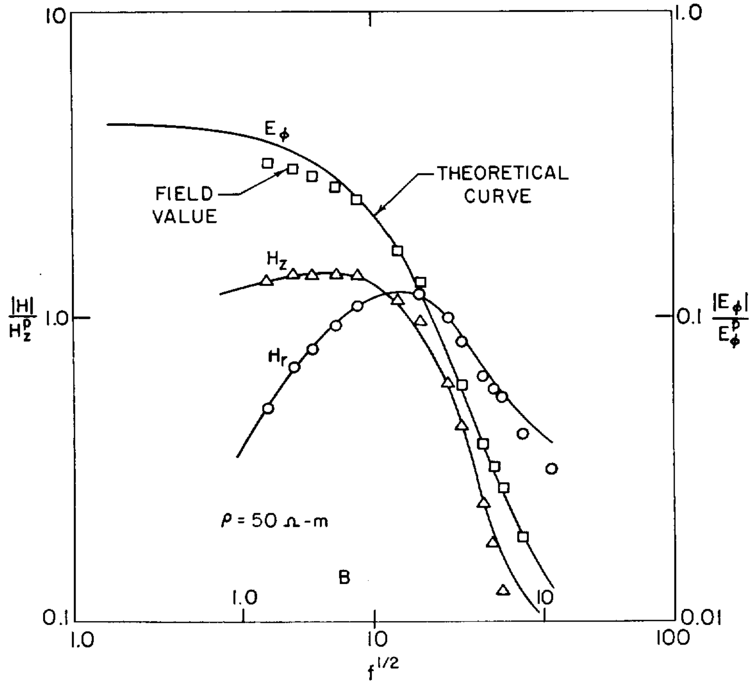

FIG. 24. Buffalo Mountain data, station 10.

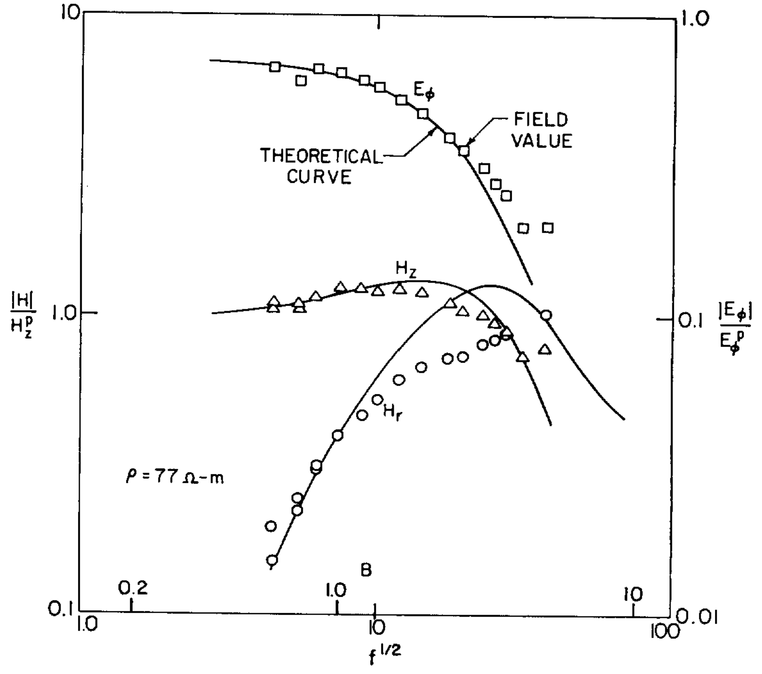

FIG. 25. Buffalo Mountain data, station 8.

western United States. Further field tests are required to determine whether the method is amenable to high-resistivity environments such as that of the Canadian Shield, and to evaluate the utility of phase measurements.

ACKNOWLEDGMENTS

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