UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Preliminary results of spectral induced polarixation measurements, Wadi Bidah district, Kingdom of Saudi Arabia

by

Bruce D. Smith 1/ and Charles L. Tippens 1/, Vincent J. Flanigan 1/,

and Handy Sadek

Open-File Report 83-612

Prepared for the Ministry of Petroleum and Mineral Resources
Deputy Ministry for Mineral Resources
Jiddah, Kingdom of Saudi Arabia

1/ U.S. Geological Survey, Denver, CO

1983

CONTENTS

ILLUSTRATIONS

Page

PRELIMINARY RESULTS OF SPECTRAL INDUCED POLARIZATION MEASUREMENTS, WADI BIDAH DISTRICT, KINGDOM OF SAUDI ARABIA

by

Bruce D. Smith[1], Charles L. Tippens[1], Vincent J. Flanigan[1], and Hamdy Sadek

ABSTRACT

Laboratory spectral induced polarization (SIP) measurements on 29 carbonaceous schist samples from the Wadi Bidah district show that most are associated with very long polarization decays or, equivalently, large time constants. In contrast, measurements on two massive sulfide samples indicate shorter polarization decays or smaller time constants. This difference in time constants for the polarization process results in two differences in the phase spectra in the frequency range of from 0.06 to 1 Hz. First, phase values of carbonaceous rocks generally decrease as a function of increasing frequency. Second, phase values of massive sulfide-bearing rocks increase as a function of increasing frequency. These results from laboratory measurements agree well with those from other reported SIP measurements on graphites and massive sulfides from the Canadian Shield.

Four SIP lines, measured by using a 50-m dipole-dipole array, were surveyed at the Rabathan 4 prospect to test how well the results of laboratory sample measurements can be applied to larger scale field measurements. Along one line, located entirely over carbonaceous schists, the phase values decreased as a function of increasing frequency. Along a second line, located over both massive sulfides and carbonaceous schists as defined by drilling, the phase values measured over carbonaceous schists decreased as a function of increasing frequency, whereas those measured over massive sulfides increased. In addition, parts of two lines were surveyed down the axes of the massive sulfide and carbonaceous units. The phase values along these lines showed similar differences between the carbonaceous schists and massive sulfides.

To date, the SIP survey and the SIP laboratory measurements have produced the only geophysical data that indicate an electrical difference between the massive sulfide-bearing rocks and the surrounding carbonaceous rocks in the Wadi Bidah district. However, additional sample and field measurements in areas of known mineralization would fully evaluate

[1]/U.S. Geological Survey, Denver, CO

the SIP method as applied to various geologic environments and styles of massive sulfide mineralization. Additionally, the efficiency of SIP surveys in delineating areas of sulfide mineralization might be improved by surveying lines down the axes of known electrical conductors. An evaluation of the applied research done on the SIP method to date suggests that this technique offers significant exploration applications to massive sulfide exploration in the Kingdom of Saudi Arabia.

INTRODUCTION

The discrimination between massive sulfide-bearing and graphitic rocks (carbonaceous) using geophysical methods has been a problem for exploration geophysicists for many years. Unfortunately, many massive sulfide bodies are located in geologic settings where graphitic rocks are common. The Wadi Bidah district, Kingdom of Saudi Arabia, is typical of such a geologic setting (fig. 1; Kiilsgaard and others, 1978). Previous electrical geophysical surveys in the district (Flanigan and others, 1982) demonstrated that the carbonaceous rocks are at best difficult to discriminate from massive sulfide-bearing rocks because both are good conductors of electrical current. Consequently, the Wadi Bidah district is a good area in which to evaluate the ability of a new technique, spectral induced polarization (SIP), to discriminate between massive sulfide-bearing and carbonaceous rocks. The study was divided into two parts:

1. Laboratory measurements of the electrical properties of massive sulfide rocks and their metavolcanic and metasedimentary host rocks

2. Field measurements over known sulfide deposits, to test the extrapolation from the results of laboratory measurements to those obtained in field surveys

This report briefly describes the SIP method and presents preliminary results of laboratory and field measurements. A more comprehensive report is planned at the completion of the project.

Induced polarization (IP) techniques utilize the characteristic of some rocks to store and release electrical energy through a variety of mechanisms that will not be explained here. Sumner (1976) presented a detailed account of some of the mechanisms that lead to the IP effect.

About 10 years ago various workers realized that the IP effect could be characterized much better if measurements were made over a broad range of frequencies. Additionally, highly accurate measurements of the current waveform transmitted into the ground were monitored and subtracted from the received voltage waveform.

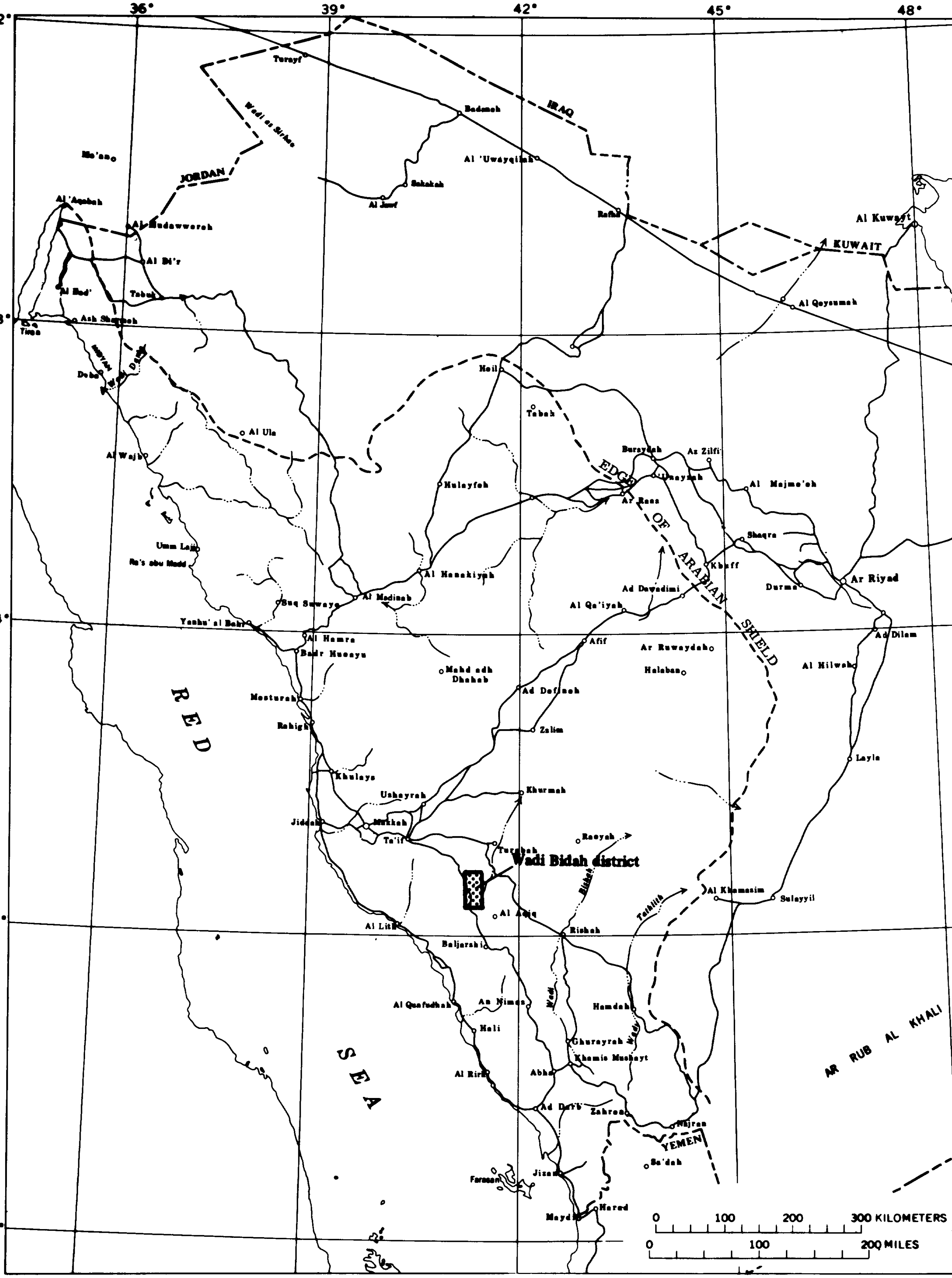


Figure 1.--Index map of western Saudi Arabia showing the location of the Wadi Bidah district.

The various groups making the measurements developed the terminology used for these advanced IP measurements. The group responsible for much of the early work, Zonge Engineering, used the term "complex resistivity (CR)" because both amplitude and phase measurements are made (Zonge and Wynn, 1975). We chose to use the term "spectral induced polarization (SIP)" because it describes the broad frequency range of the measurements and because most interpretation is done by using spectral plots.

Before discussing the various aspects of the SIP measurements, it may be useful to review a few basic concepts about IP spectra. The two fundamental parameters measured are the amplitude and phase of the received voltage relative to the current waveform transmitted into the ground. Observed changes in amplitude and phase as a function of frequency result from conduction and polarization processes that produce the IP effect in rocks. These changes in amplitude and phase are commonly plotted on logarithmic scales.

The interpretation of SIP measurements is based on a mathematical formula or model having parameters that characterize the amplitude and phase spectra. These parameters (chargeability, frequency dependence, and time constant) each affect the shape of the spectra. Figure 2 illustrates how the peak of the phase response changes as only the time constant is changed. Pelton (1977) and Washburne (1982) discussed in more detail the relationship between the model parameters and the shape of IP spectra. For the purpose of this report, it is sufficient to observe from figure 2 that the time constant is approximately the reciprocal of the frequency at which a phase maximum occurs. Although constants estimated in this fashion will be less than the true value, these estimates are sufficient for preliminary interpretation. A final quantitative interpretation can be made by using a computer to provide more accurate estimates of all the model parameters.

SIP measurements can be used to discriminate between graphites and massive sulfides because each typically is associated with a drastically different time constant (Pelton, 1977). For graphites in the geologic setting of the Canadian Shield, the peak in the phase spectra commonly is at much less than 1 Hz, or equivalently, the time constant is greater than 10 sec. In contrast, the peak in the phase spectra of many massive sulfides is at about 2 Hz and the time constant is less than 1 sec. In general, experimental studies (Pelton and others, 1978) show that as the grain size of polarizable particles increases the time constant of the polarization process also increases. In very simplistic terms, graphites tend to have much larger polarizable grains than do many massive sulfide-bearing rocks. It is important

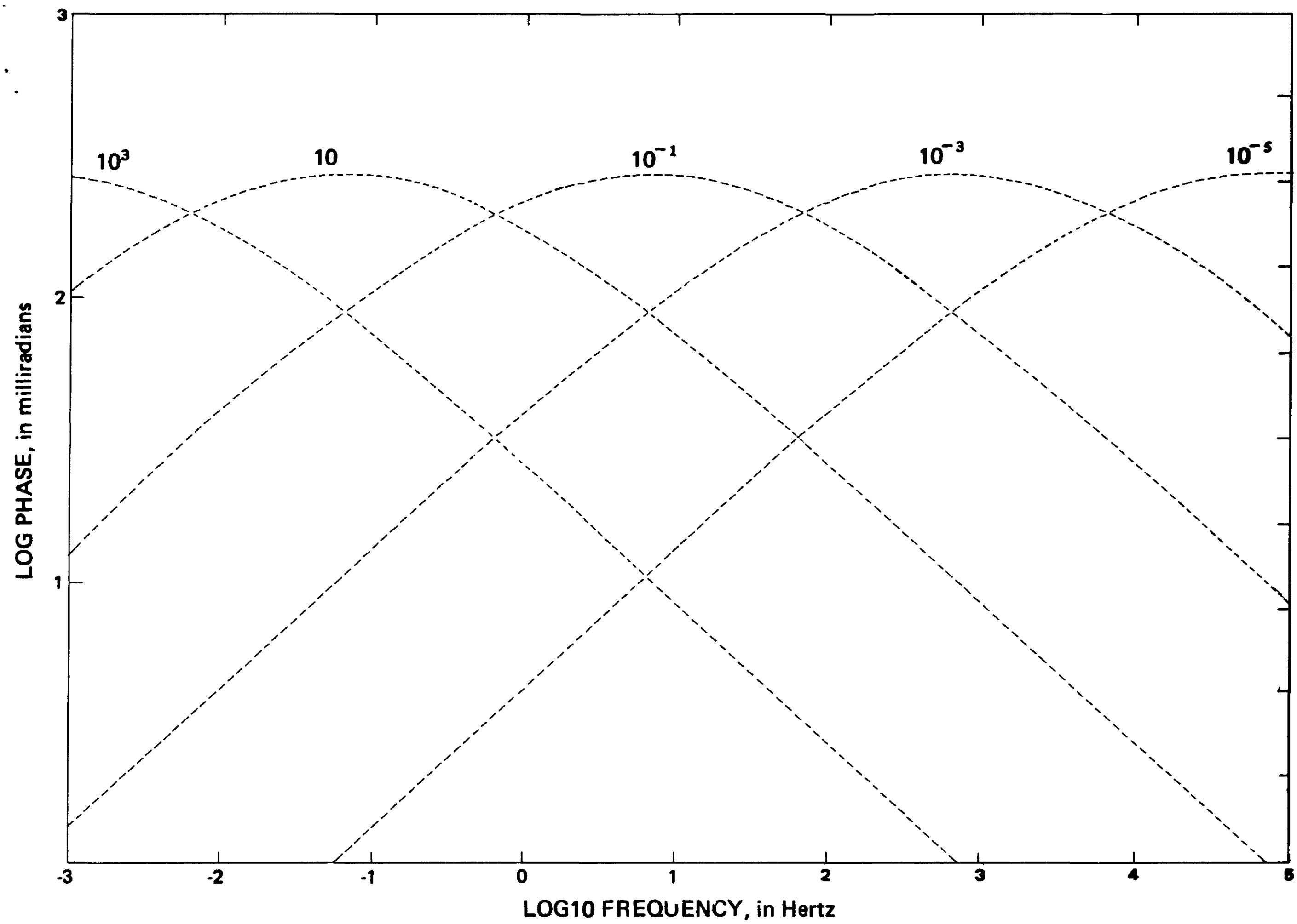


Figure 2.--Graph showing differences in character of phase spectra as a function of frequency for different values of the time constant (in seconds).

to understand that mineral discrimination between graphites and sulfide-bearing rocks is not based on a unique electrical signature of either rock type because in most geologic settings neither will be a homogeneous mass.

A more detailed discussion of results from SIP measurements in the Canadian Shield was presented by Hallof and others (1979). However, because significant differences (such as metamorphism and age) between the geologic history of the Canadian and the Arabian Shields could be reflected in the different electrical characteristics of massive sulfides and their host rocks, laboratory and field SIP measurements of massive sulfide deposits in the Arabian Shield are needed to evaluate similarities and differences between those deposits and reported measurements made in the Canadian Shield.

LABORATORY SAMPLE MEASUREMENTS

A suite of samples, mostly from the Wadi Bidah district (fig. 1), were obtained from a collection made by Flanigan. The choice of samples was dictated by availability. These samples can be broadly grouped as follows:

1. Carbonaceous schists (29 samples), composed of varying amounts of calcite, chlorite, quartz, and disseminated sulfides (from trace amounts to 5 percent)

2. Greenstone and limonitic sandstone (1 sample each), in which no sulfides were detected by use of binocular microscope

3. Massive sulfide-bearing rocks (2 samples), at least 60 percent of which are composed of sulfide minerals

The samples were in the form of cores ranging from 4 to 6 cm in diameter and from 3 to 6 cm in length. Sample measurements were made by means of a Zonge Engineering GDP-12 receiver and following procedures described by Olhoeft (1979) and Washburne (1982). General results of sample measurements are described below.

The resistivities of the carbonaceous schists, as measured at the lowest frequency of the GDP-12 system (0.0625 Hz), ranged from 17 ohm-m to more than 100,000 ohm-m and the average for all samples was about 300 ohm-m. The four samples having resistivities of more than 4,000 ohm-m have a calcareous or silica latticework, which breaks up the conduction path of the carbonaceous material. With the exception of the highly resistive samples, the phase spectra of the carbonaceous samples had peaks at a frequency of less than 0.06 Hz or had time constants of more than 16 sec.

Two representative phase spectra of carbonaceous samples are shown in figure 3. The more conductive carbonaceous samples (curve A, 25 samples) had time constants of more than 16 sec. In contrast, the anomalously resistive graphite samples (curve B, 4 samples) had much shorter time constants.

The apparent resistivities of the two massive sulfide samples were 41 and 42 ohm-m at 0.0625 Hz. The phase peaks of the two samples were at higher frequencies (fig. 3, curves C and D) than those of the conductive carbonaceous samples. The two samples were from drill holes RB-10 and RB-11 at the Rabathan 4 prospect (fig. 5; Kiilsgaard and others, 1978; MODS 02701).

Phase spectra of the two remaining samples, a greenstone and a limonitic sandstone, are shown in figure 4. The greenstone phase spectrum had a phase peak at about 6 Hz or an approximate time constant of 0.1 sec. A second polarization mechanism in this sample caused the phase to increase at very high frequencies (between 200 and 2000 Hz). The time constant for this mechanism was less than 0.0005 sec. The resistivity of the sample at 0.06 Hz was 4,570 ohm-m.

The phase spectrum for the limonitic sample (fig. 4) also has two phase peaks, the first at less than 0.06 Hz and the second at about 6 Hz. Thus the phase spectrum of this sample has characteristics similar to the phase spectra of both the massive sulfide and carbonaceous samples. However, this phase spectrum is not likely to be confused with that of the massive sulfide sample because the magnitude of the phase of the former is small and two phase peaks are present.

Although the number and types of samples measured are very limited, a few general conclusions can be made. The carbonaceous samples having low resistivities (less than 1,000 ohm-m) generally have long time constants (greater than 10 sec), whereas the massive sulfide samples have much shorter time constants (less than 2 sec). This difference in time constants generally leads to phase spectra peaks of from 0.06 to 1 Hz that have decreasing values for carbonaceous samples and increasing values for massive sulfide samples. These observations agree well with those made from measurements of graphites and massive sulfides in the Canadian Shield.

The only phase spectra that have time constants of less than 10 sec are those of either the anomalously resistive carbonaceous samples or the resistive greenstone sample. Consequently, the laboratory measurements suggest that massive sulfide-bearing rocks of the Wadi Bidah district can be identified by using their short time constants and low resistivities. This conclusion would be strengthened by a

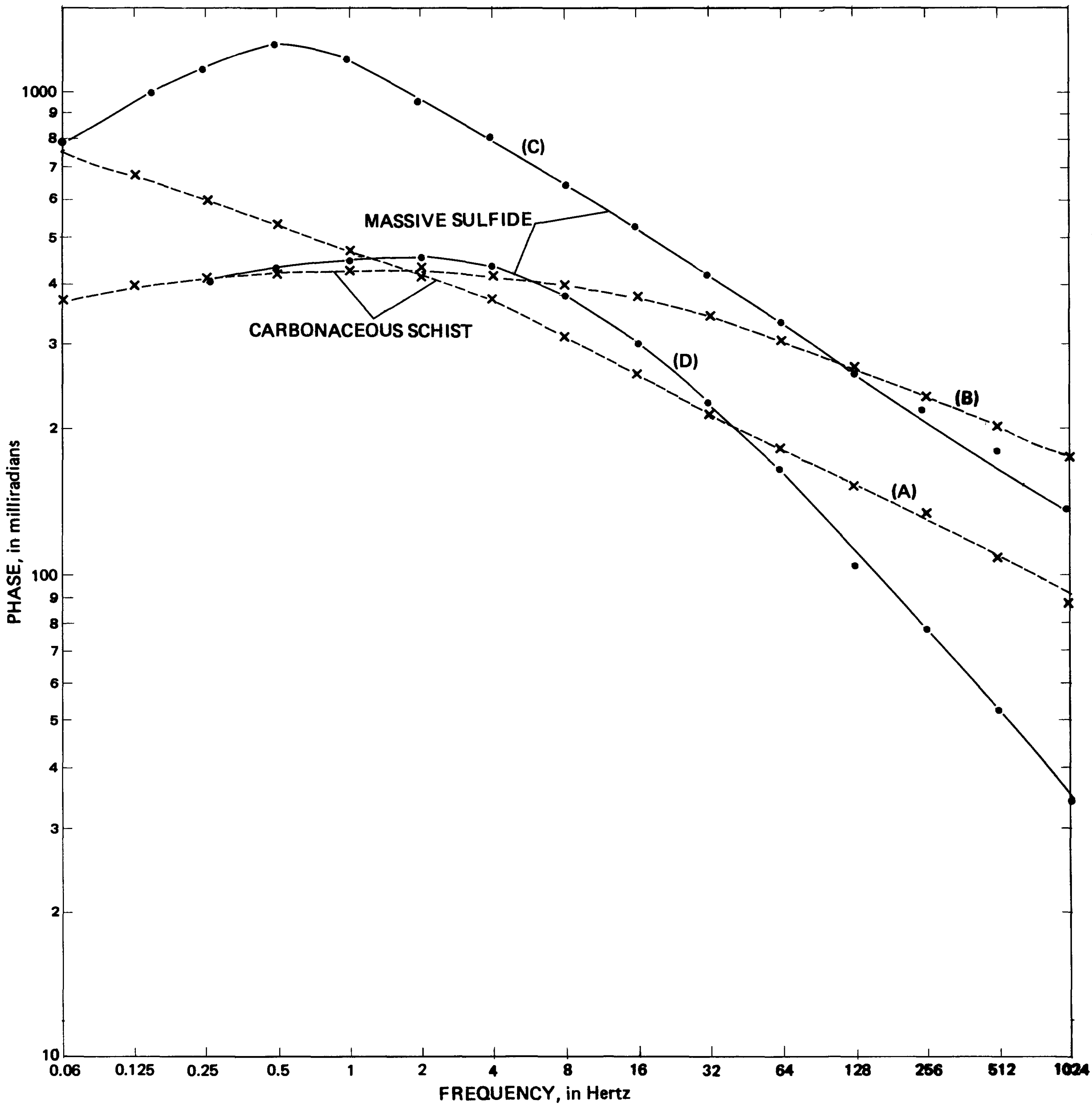


Figure 3.--Graph showing typical phase spectra from laboratory electrical property measurements of carbonaceous schist (curves A and B) and massive sulfide-bearing (curves C and D) samples from the Wadi Bidah district.

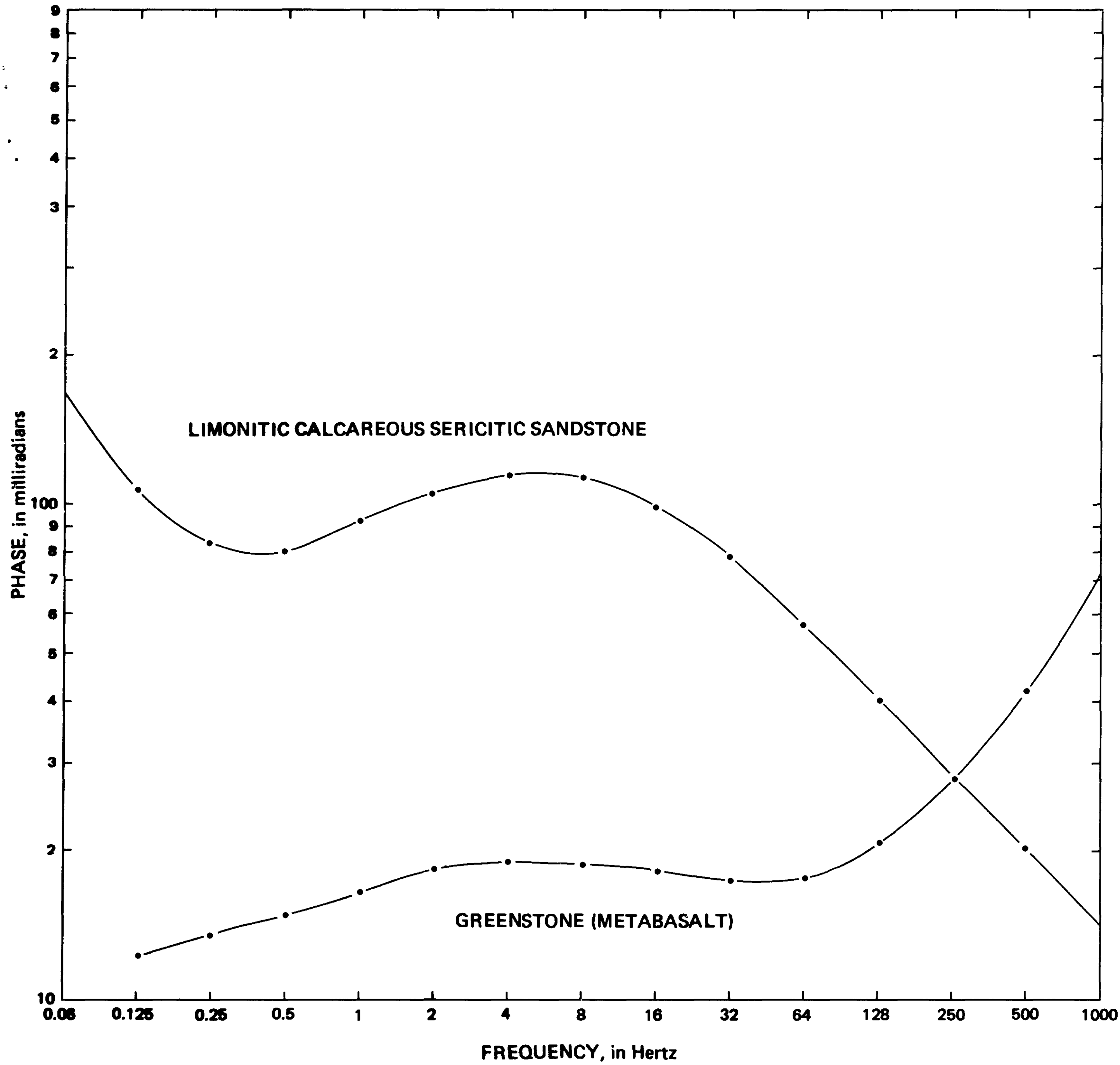


Figure 4.--Graph showing phase spectra from laboratory electrical property measurements of greenstone (metabasalt) and limonitic sandstone samples from the Wadi Bidah district.

larger, more complete sampling of both massive sulfides and their host rocks.

FIELD MEASUREMENTS

The field survey was done at the Rabathan 4 prospect in the Wadi Bidah district (fig. 1). A total of 5 days was spent surveying four lines (fig. 5) by using a 50-m dipole-dipole array. The configuration of this array and a block diagram of the instrumentation is given in figure 6. Before the results of the survey are discussed, the problems of comparing laboratory and field measurements will be briefly reviewed.

The first problem relates to the duplication of the *in situ* conditions of a rock sample in the laboratory. For example, the composition and amount of pore fluid are very important in controlling the electrical response of a rock. The phase spectrum measured for the greenstone sample (fig. 4) was most likely controlled by the fluid (10 ohm-m potassium chloride solution) in which the sample had been soaked prior to measurement. The fluid may or may not bear any chemical resemblance to the ground water in the field. Other factors, such as temperature and pressure, also affect the electrical properties of rocks (Olhoeft, 1979).

A second problem that complicates comparison of laboratory and field measurements relates to differences in scale between laboratory and field IP spectra measurements. These differences can be caused by:

1. the use of a higher voltage transmitter for field measurements that requires a different electronic configuration,

2. electromagnetic coupling resulting from induced electrical currents in the earth that mask the IP effect, or

3. dilution of the spectral measurements resulting from the finite geometry (tabular body and depth of burial) of the source of an IP anomaly.

Each of these has been studied extensively and debated by the scientists working with SIP measurements (Washburne, 1982). The first will not be discussed in this report except to say that most of the electronic components external to the receiver (fig. 6) were designed and built by the U.S. Geological Survey to minimize electronic problems. The other two, coupling and dilution, will be discussed with the interpretation of the two survey lines.

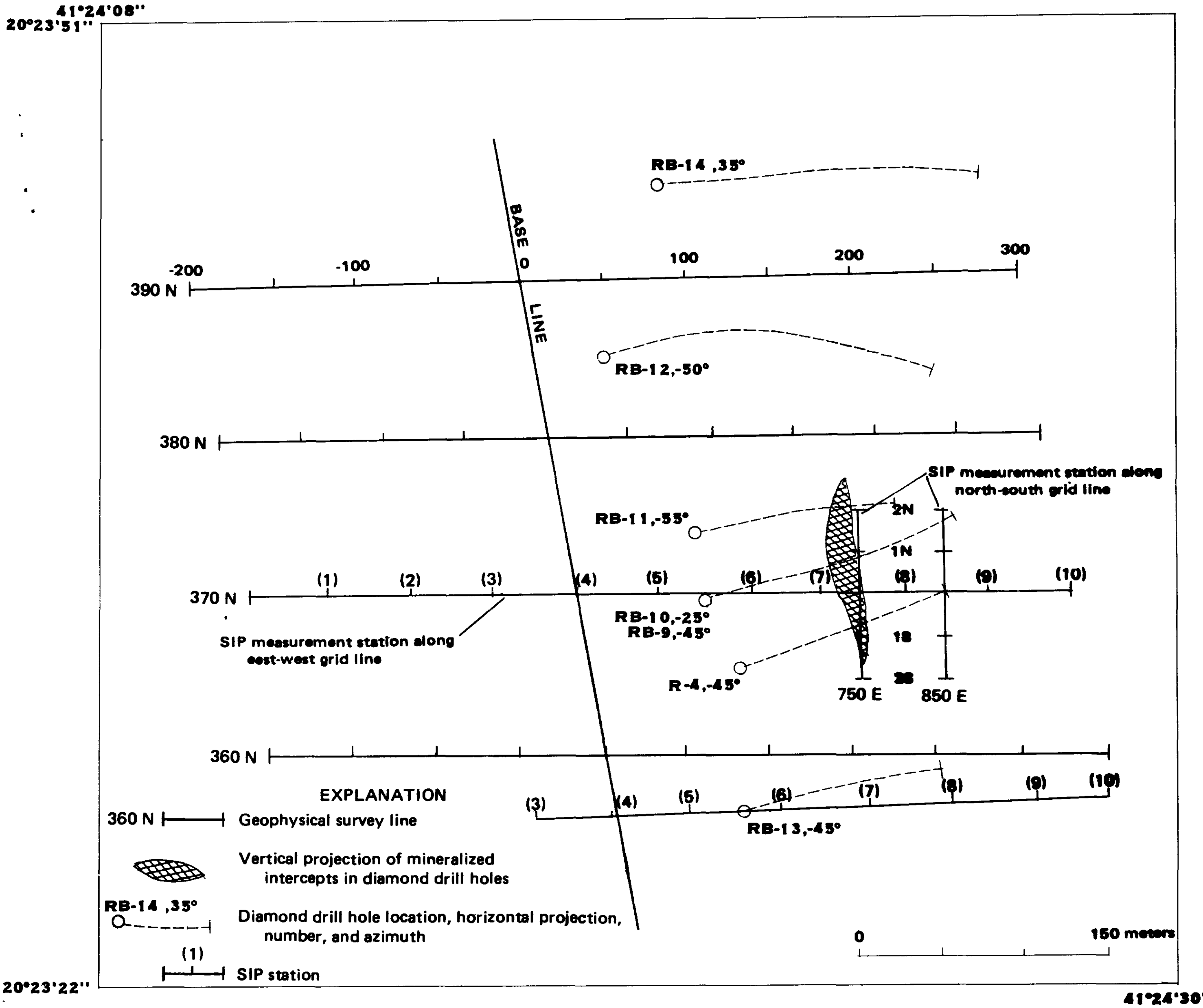
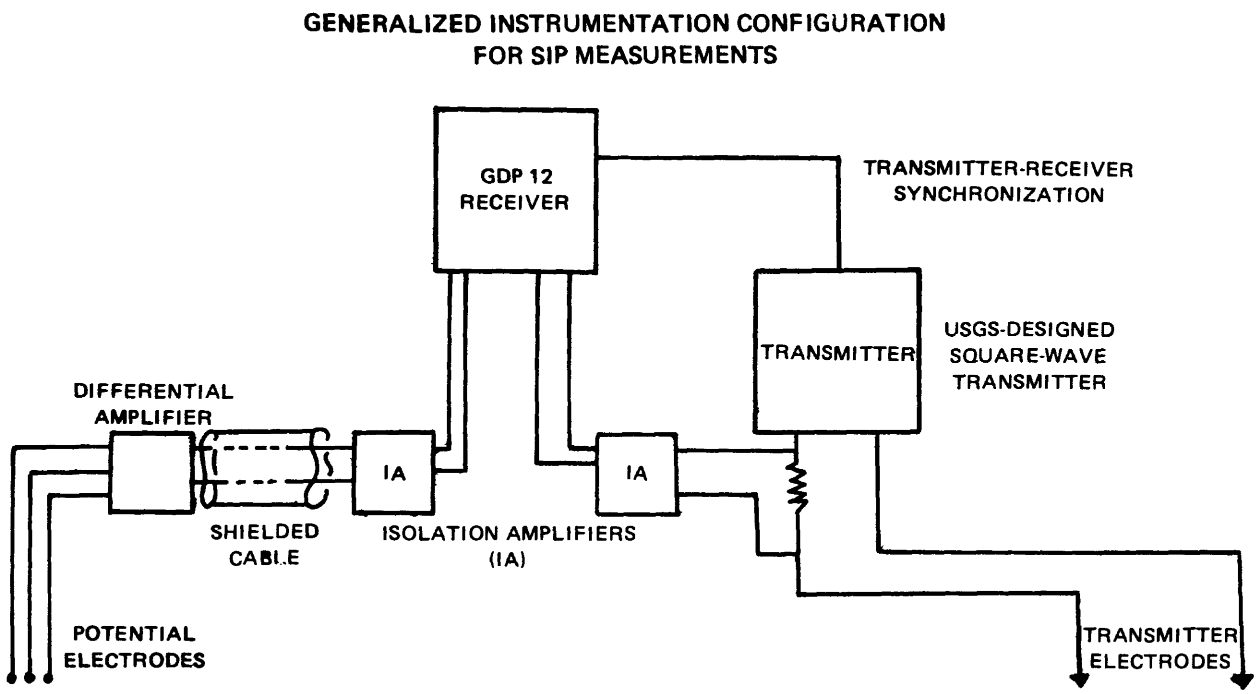


Figure 5.--Map showing the locations of the geophysical survey lines at the Rabathan 4 prospect area (adapted from Flanigan, 1982) and the locations of spectral induced polarization (SIP) measurements (lines 355N, 370N, 750E, and 850E).



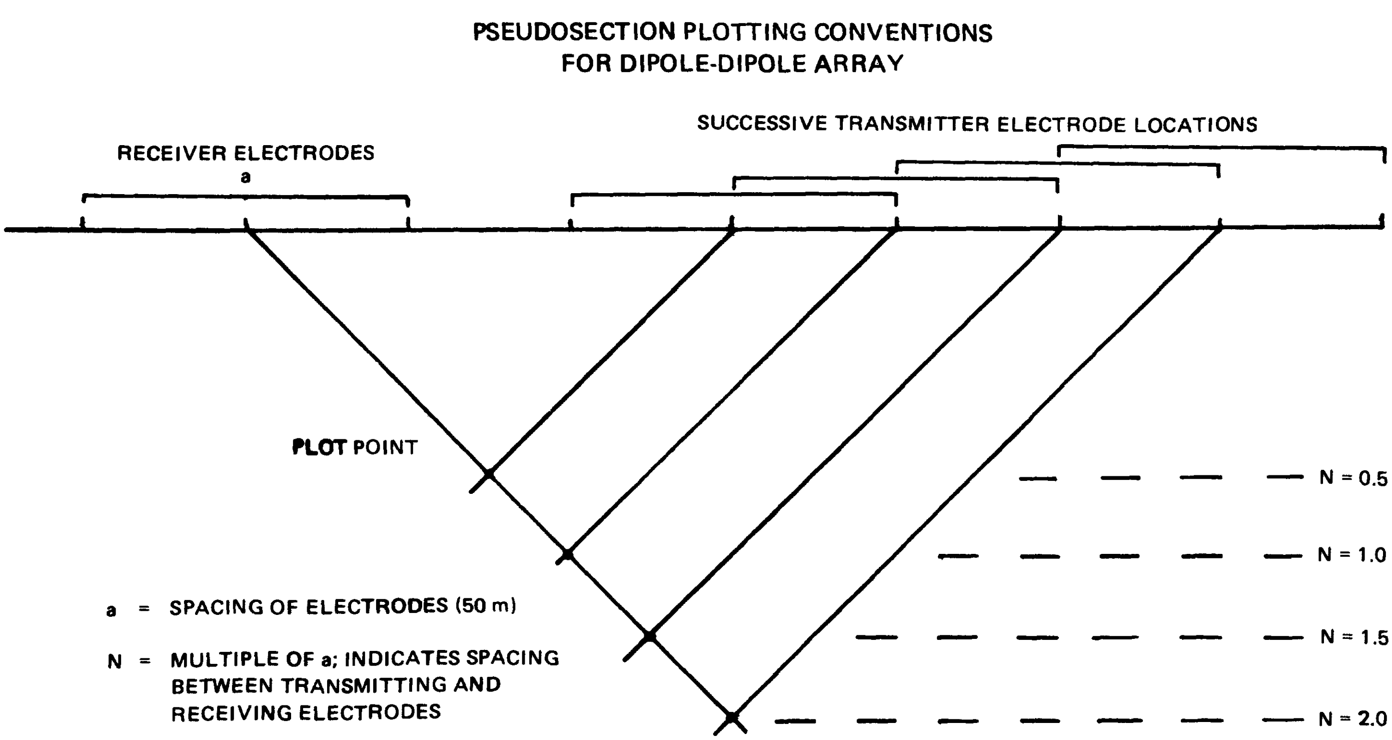


Figure 6.--Block diagram showing spectral induced polarization (SIP) instrumentation configuration and the dipole-dipole array used to make SIP measurements at the Rabathan 4 prospect.

Survey line 370N crosses the collars of drill holes RB-9 and RB-10 in an east-west direction between their horizontal projections (fig. 5). The geology of the Rabathan 4 prospect and the lithology of the drill holes have been described in detail by Kiilsgaard and others (1978), and a generalized geologic cross section is shown in figure 7A. The apparent resistivities measured at 0.0625 Hz are plotted in the form of a pseudosection (fig. 7). (Remember that the pseudosection convention for plotting dipole-dipole resistivity of IP data only crudely reflects variations of these parameters with depth, as explained by Sumner (1976).)

Ground electromagnetic (EM) and self-potential (SP) surveys conducted in 1977 (Flanigan and others, 1981) showed anomalies over the massive sulfide and carbonaceous units. Additional detailed EM and SP work carried out in 1980 (Flanigan and others, 1982) showed a weak EM anomaly along line 370N. Flanigan and others (1982) concluded that it is impossible to separate the larger response of the carbonaceous material from that of the massive sulfide deposit. The apparent-resistivity pseudosection (fig. 7B) shows no dramatic resistivity lows associated with the massive sulfide unit, an observation that correlates with the previous electrical geophysical surveys and with the known small dimensions of the massive sulfide unit.

The standard IP parameter, the phase angle as measured in milliradians at 0.06 Hz, is plotted in pseudosection form in figure 8A. The phase-angle parameter is directly proportional to IP parameters measured by other types of surveys, such as chargeability and percent frequency effect (Sumner, 1976). The only IP anomaly in the area of the massive sulfide is a phase-angle low, located between lines 150E and 200E (figure 8A), that is probably associated with the gossan that lies above the massive sulfide unit. Consequently, none of the standard geophysical exploration methods indicated the presence of the massive sulfide mineralization.

As discussed previously, SIP spectra can be quantitatively characterized. However, a simple qualitative characterization of SIP spectra adequate for this preliminary report can be made based on the phase variation between 0.06 Hz and 0.5 Hz. Decreasing phase spectra in this frequency range are termed type D and increasing phase spectra type I. Various tests using the GDP-12 receiver indicated that the phase measurement accuracy between 0.06 and 0.5 Hz is approximately 0.5 milliradians. Phase changes that are less than the accuracy of the receiver are termed type F spectra because the phase response is essentially flat.

The qualitative spectral characterization can be related to laboratory measurements as follows. Type D spectra are associated with time constants of more than 16 sec, which are

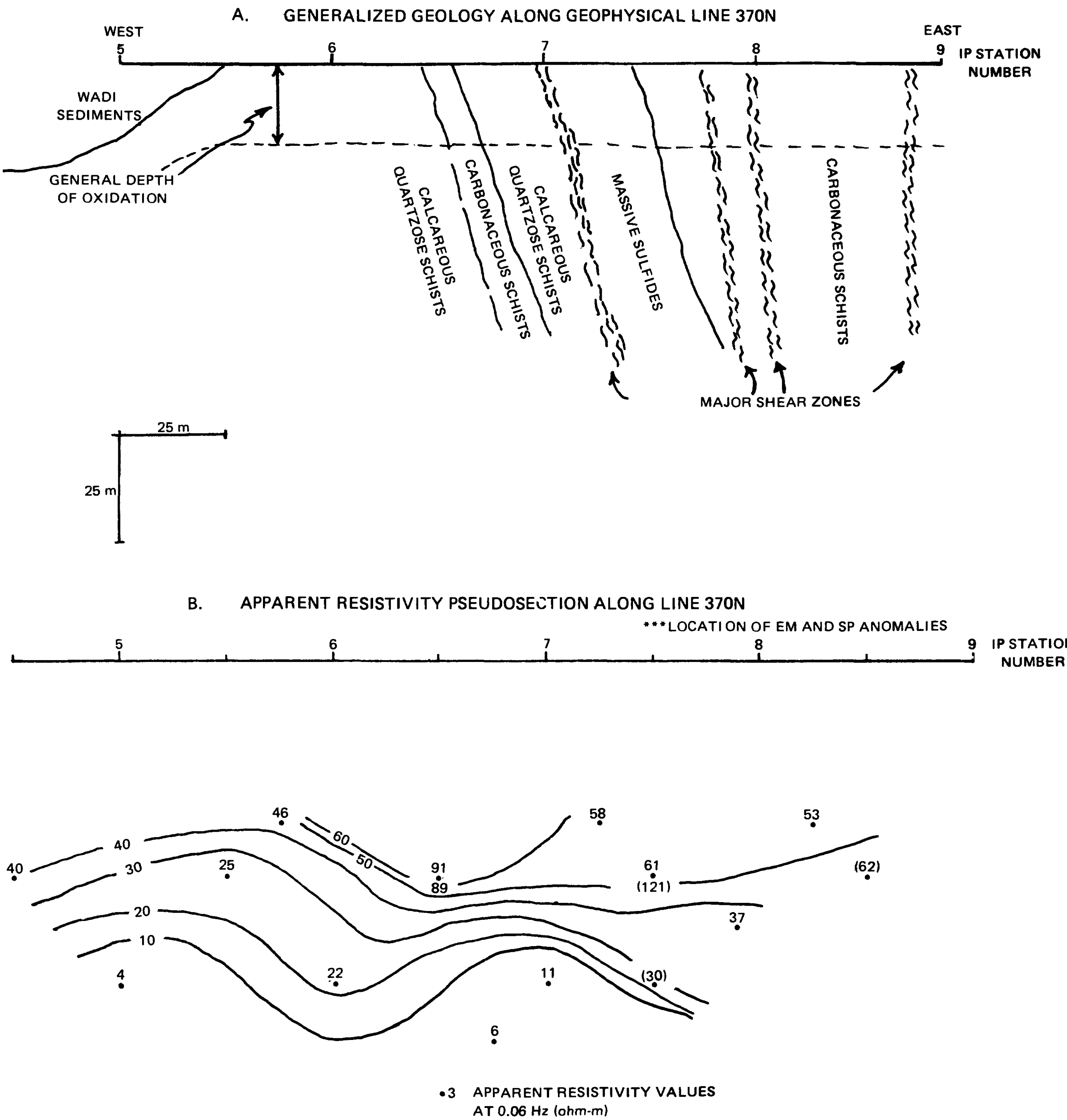


Figure 7.--(A) Generalized geologic cross section and (B) apparent-resistivity pseudosection along traverse line 370N, Rabathan 4 prospect. Numbers in parentheses indicate measurements made parallel to strike.

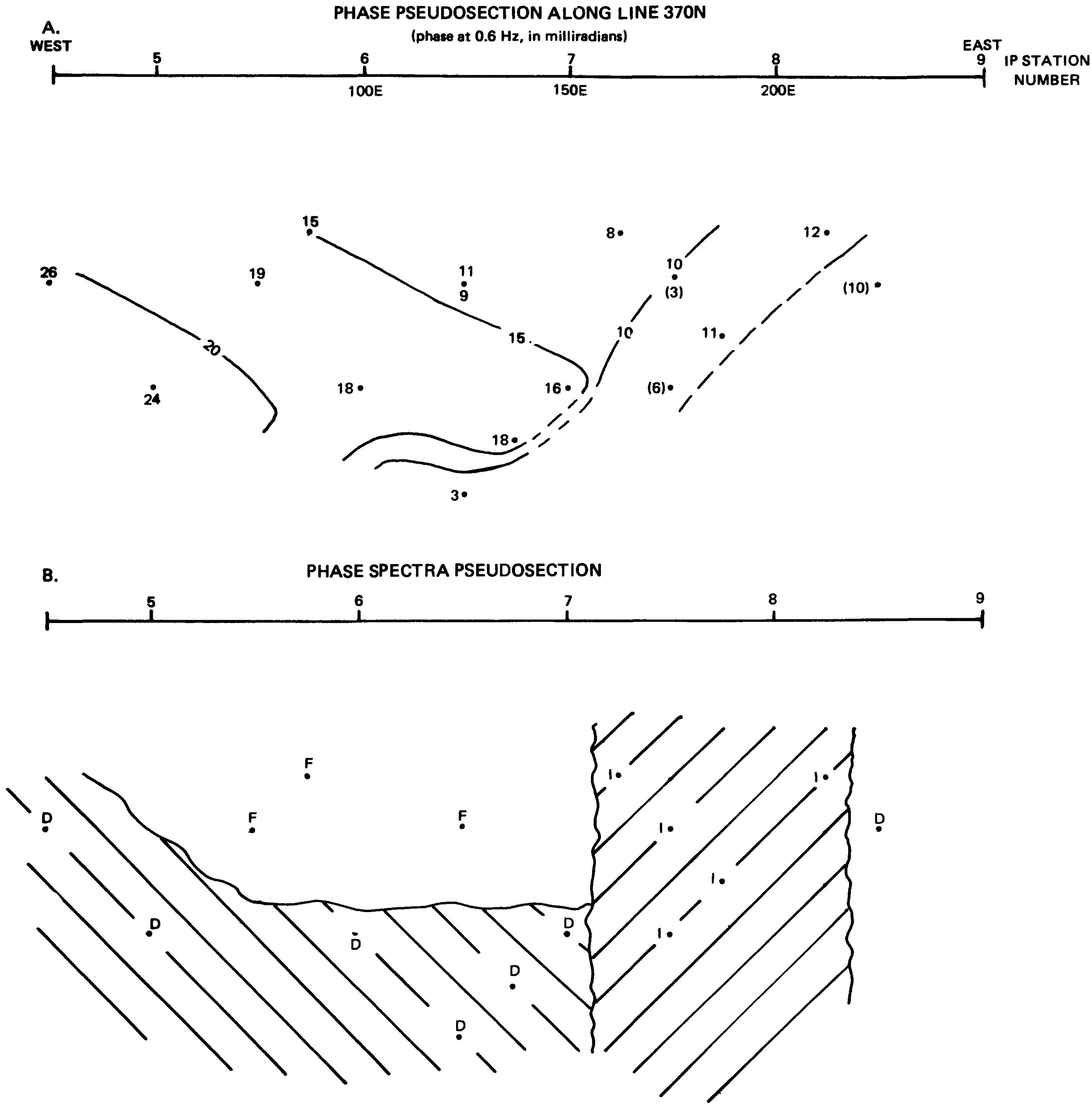


Figure 8.--Pseudosections of induced polarization (IP) measurements along traverse line 370N showing (A) phase and (B) phase spectra type (I, increasing; D, decreasing; F, flat). Numbers in parentheses indicate measurements made parallel to strike.

typical of carbonaceous rocks. Type I spectra are associated with time constants of less than 2 sec, which are similar to the two laboratory measurements of massive sulfides. Flat phase spectra (type F) can result from a combination of several polarization processes having similar time constants.

The various types of phase response can be plotted in pseudosection form, as shown in figure 8B. Type D responses are characteristic of the deeper measurements made over the graphitic zones. Flat phase responses (type F) are characteristic of shallower (smaller N spacing) measurements made west of the known massive sulfide deposit, the vertical projection of which is from 175E to 225E. Because the laboratory measurements did not show any type F spectra, it is very conjectural as to which rock types might correlate with these measurements. Washburne (1982) found, however, that a type F phase response is characteristic of weathered metavolcanic rocks in the West Shasta district of California, and there could be a similar source for the type F spectra along line 370N. Type I responses are found over the known massive sulfide deposit. The western boundary between type I responses and other types of responses is well defined, but, because of difficulties caused by steep terrain, the eastern margin is defined by only one measurement. The type I response below 150E (IP station 7.25) (the shallowest measurement) is probably associated with the gossan above the sulfide. Thus the gossan may have a type of response similar to that of the massive sulfide. More laboratory and field measurements are needed to evaluate the similarities and differences between the electrical responses of gossans and massive sulfides. The phase-spectra-type pseudosection (fig. 8B) is the first electrical geophysical technique in the Wadi Bidah district that indicates a difference between the response of the massive sulfide mineralization and that of the surrounding carbonaceous rocks.

Several mitigating factors should be considered in evaluating the survey results. The first of these factors is obvious from an examination of some of the field phase spectra (fig. 9). Although the spectra are similar to those measured on laboratory samples (fig. 3), there are some important differences. The first difference is that the phase values measured in the field are one or two decades lower in magnitude than those measured in the laboratory. This effect, known as dilution, has been described by Pelton and others (1978), who developed a theoretical basis for estimating the magnitude of dilution by using simple models such as dikes. The unfortunate aspect of this dilution is to shift some of the phase spectra to a level (less than 10 milliradians) at which accurate measurements are difficult to make in the presence of noise. The stacking and averaging required to obtain highly accurate phase values at low frequencies does not speed up field measurements.

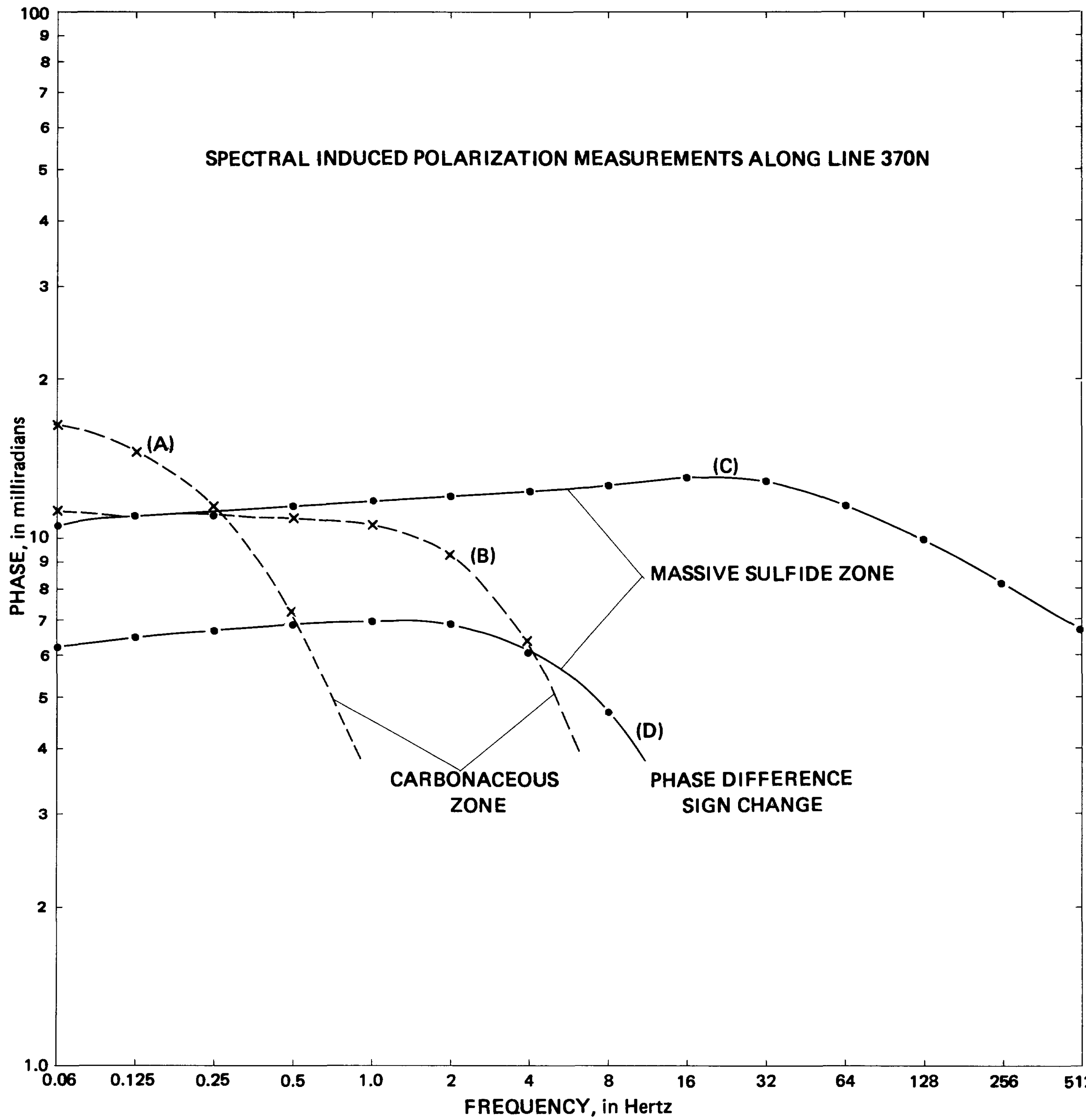


Figure 9.--Graph showing typical phase spectra measured along traverse line 370N for N=2 (see fig. 6). Curves A and B are typical of measurements made over carbonaceous terrane across strike (A) and parallel to strike (B). Curves C and D are typical of measurements made over the known massive sulfide zone across strike (C) and parallel to strike (D).

A second general difference between the laboratory and field SIP measurements is that the field phase values are both positive and negative. For example, because log scales are used, curves A, B, and D (fig. 9) show only the positive values of the phase spectra, although the curves actually change sign from low to high frequency. These negative phase values were the subject of much controversy in the early IP work (Sumner, 1976). Subsequent studies show that negative phase values can result from electromagnetic (EM) coupling (Wynn and Zonge, 1975; Pelton, 1977), and, although various methods have been proposed to remove this coupling effect (Wynn and Zonge, 1975; Pelton, 1977), all require the use of limiting assumptions that are not always satisfactory (Washburne, 1982). The effect of the strong EM coupling present in the field measurements at the Rabathan 4 prospect on lower frequency measurements, although probably small, cannot be accurately estimated. Also, any high-frequency variations in phase spectra, which might be useful in mineral discrimination, are entirely obscured by the EM coupling.

A second mitigating factor in assessing the generality of the results of measurements along traverse line 370N is a lack of other comparative field measurements. A partially encouraging answer is given by the SIP measurements along line 355N, which crosses the collar of drill hole RB-13 (fig. 5). According to Kiilsgaard and others (1978), this hole intersected mixed calcareous, siliceous, and carbonaceous metasedimentary rocks. The thin (less than 1 m thick) intercepts of massive sulfides encountered at 67 and 78 m do not constitute a large enough target to be detected by the 50-m dipole-dipole SIP survey. Results of the SIP traverse along line 355N are shown in pseudosection form in figure 10. The conductive zone that begins at 100E (fig. 10A, IP station 6) and continues to the east correlates with one of two conductive zones defined by the ground EM and SP surveys (Flanigan and others, 1982). The relatively large phase value beneath station 4 (fig. 10B) suggests that there may be another conductive zone east of the base line (station 4), as indicated by the ground EM and SP anomalies (Flanigan and others, 1982). Although standard electrical geophysical exploration methods (Flanigan and others, 1982) defined conductive zones along this traverse, they did not indicate if these conductive zones are more suggestive of a massive sulfide body than do the measurements made along traverse line 370N. The phase-spectra-type pseudosection (fig. 10C) shows, however, that the SIP measurements are mostly type-D phase spectra, which are associated with long time-constant polarization effects indicative of carbonaceous metasedimentary rocks.

Because of the encouraging results obtained on the two SIP lines, a limited experiment was conducted to determine if the phase spectra changes when measurements are made along (parallel with) the axis of the EM conductor. The results of

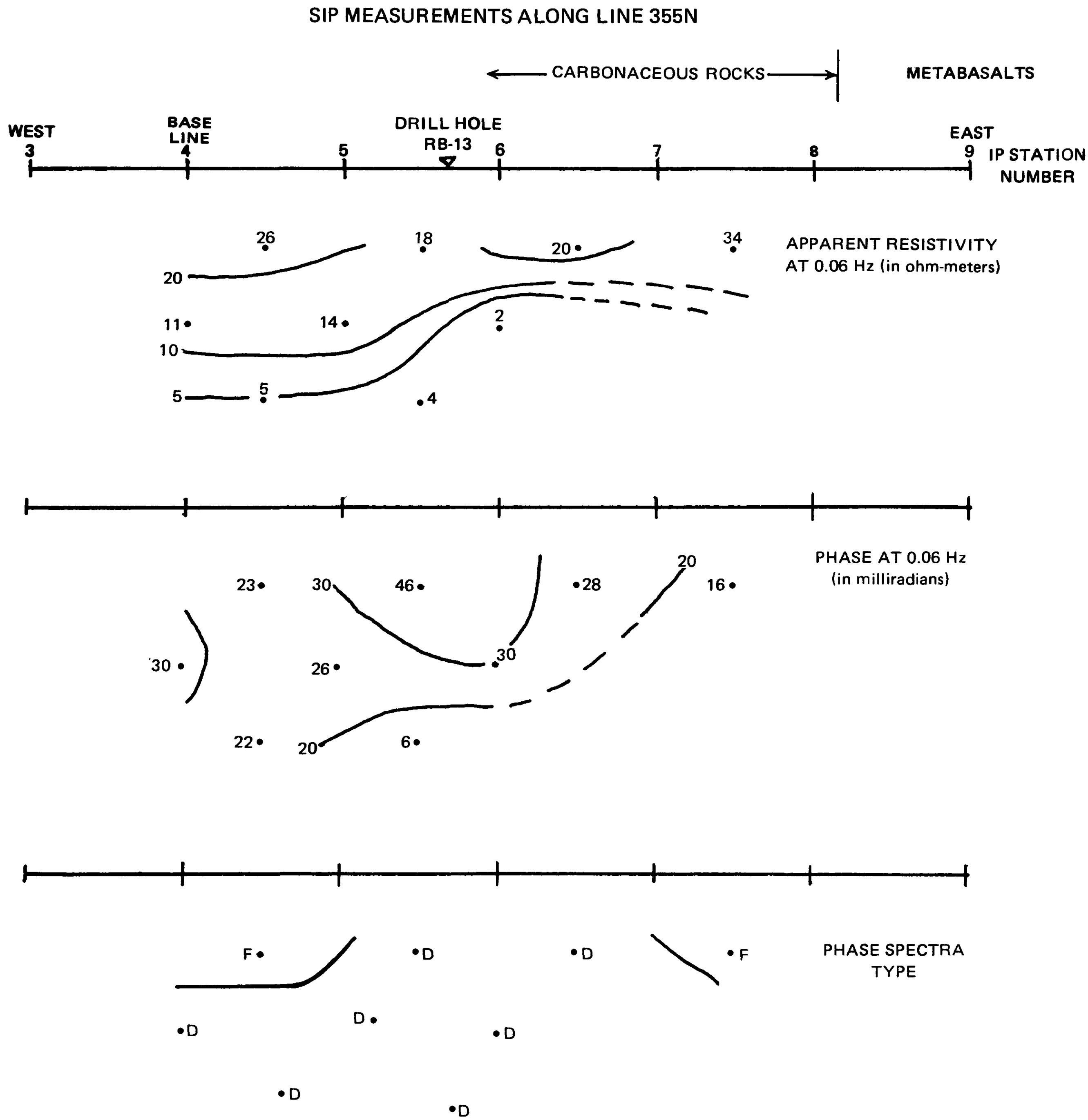


Figure 10.--Pseudosections of spectral induced polarization (SIP) measurements along traverse 355N, Rabathan 4 prospect, showing apparent resistivity, phase, and phase spectra type (D, decreasing; F, flat).

these experiments (figs. 7-9) indicate that the spectra mostly retain their shapes but become somewhat more diluted. Additionally, the differences in EM coupling from measurements parallel and perpendicular to the axis cause a shift in the frequency at which the peak phase response occurs. From these limited measurements, we conclude that SIP surveys conducted along the strike of known conductors may also be able to detect differences in the response of massive sulfides and carbonaceous rocks. SIP surveys along the strike of EM conductors offer a significant time and cost savings that warrants further investigation.

The preliminary results from the two survey lines agree well with results from studies in the Canadian Shield (Hallof and others, 1979), which suggest that for many field surveys in which EM coupling is not a problem (for example, those with short dipole lengths and shallow targets), a limited frequency range can be used to discriminate between massive sulfide-bearing rocks and graphites. The survey data from the Rabathan 4 prospect suggest that EM coupling can be significant at frequencies of 1 Hz or higher. Consequently, mineral discrimination may be possible by making measurements only at low frequencies (less than 0.5 Hz) over a range of at least one decade (0.06 and 0.5 Hz). Additional field data are needed to fully determine the critical frequencies needed for mineral discrimination in the geologic setting of the Arabian Shield.

CONCLUSIONS AND RECOMMENDATIONS

Laboratory electrical property measurements of rock samples and field measurements over known carbonaceous and massive sulfide-mineralized rocks suggest that SIP measurements can be used to discriminate between these two rock types. To date, the SIP survey at the Rabathan 4 prospect is the only geophysical survey that shows the massive sulfide-mineralized rocks to be different electrically from the surrounding carbonaceous rocks. The efficiency of SIP methods may be significantly improved by conducting surveys along (parallel with) the axes of long formational, presumed carbonaceous conductors to define potential areas of massive sulfide-mineralized rocks.

General recommendations based on preliminary results of the SIP survey are as follows:

1. Laboratory electrical property measurements should be made on additional massive sulfide-bearing samples, as well as on a wider variety of massive sulfide host rocks. If possible, these samples should be from drill holes and collected both above and below the zone of oxidation.

2. Additional fieldwork should be conducted at the Rabathan 4 prospect to provide more complete pseudosection coverage and to determine the feasibility of conducting surveys along the axes of EM conductors.

3. Field measurements should be made at other prospects within the Wadi Bidah district, in areas both where access is relatively easy, to provide maximum survey speed, and where there is some geologic control.

4. Field measurement procedures should be established that will enable SIP surveys to be carried out on a production basis.

ACKNOWLEDGMENTS AND DATA STORAGE

The work on which this report is based was performed in accordance with an agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey (USGS).

Acknowledgment is due to the people, too numerous to mention individually, who directly and indirectly helped support the research described here. Particular recognition goes to John Paul Kirby (USGS administrative staff), who spent many hours clearing the electronic equipment through customs in time to do significant fieldwork. James Washburne and Jay Sampson (USGS, Denver) spent much time in the laboratory preparing the rock samples for measurement, making the measurements, and processing the data from the measurements.

Citation of particular manufacturers and specific model numbers is for informative purposes only and does not constitute endorsement by the USGS.

Mineral localities in this report are recorded in the Mineral Occurrence Documentation System (MODS) data bank, and each is identified by a five-digit number. No entries in the data bank were made or updated as a result of this study. Inquiries regarding this data bank should be directed to the Office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah.

No data files were established as a result of this study.

REFERENCES CITED

Flanigan, V. J., Sadek, Hamdy, and Smith, C. W., 1982, Phase 3 geophysical studies in the Wadi Bidah district, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-02-45, 44 p.; also, 1982, U.S. Geological Survey Open-File Report 82-597.

Flanigan, V. J., Wynn, J. C., Worl, R. G., and Smith, C. W., 198?, Preliminary report on geophysics ground follow-up of the 1977 airborne survey in the Wadi Bidah district, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 82-202, (IR)SA-348.

Hallof, P. G., Cartwright, P. A., and Pelton, W. H., 1979, The use of the Phoenix IPV-2 phase IP receiver for discrimination between sulfides and graphites [abs.]: Society of Exploration Geophysicists, 49th Annual Meeting, New Orleans, 1979, Geophysics, v. 47, no. 4.

Kiilsgaard, T. H., Greenwood, W. R., Puffett, W. P., Naqvi, Mohammad, Roberts, R. J., Worl, R. G., Merghelani, Habib, Flanigan, V. J., and Gazzaz, A. R., 1978, Mineral exploration in the Wadi Bidah district, 1971-1976, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 78-771, (IR)SA-237.

Olhoeft, G. R., 1979, Electrical properties, in Initial report of the Petrophysics Laboratory: U.S. Geological Survey Circular 789, p. 1-25.

Pelton, W. H., 1977, Interpretation of induced polarization and resistivity data: University of Utah, Unpublished Ph. D. dissertation, 155 p.

Pelton, W. H., Ward, S. H., Hallof, P. G., Sill, W. R., and Nelson, P. H., 1978, Mineral discrimination and removal of inductive coupling with multifrequency I.P.: Geophysics, v. 43, no. 3, p. 558-609.

Sumner, J. S., 1976, Principles of induced polarization for geophysical exploration: Amsterdam, Elsevier, 278 p.

Washburne, J. C., 1982, Parameterization of spectral induced polarization data and laboratory and in-situ spectral induced polarization measurements, West Shasta copper-zinc district, Shasta, California: Colorado School of Mines, Unpublished M. S. thesis (number T259), 270 p.

Wynn, J. C., and Zonge, K. L., 1975, EM coupling, its intrinsic value, its removal and the cultural coupling problem: Geophysics, v. 40, no. 5, p. 831-850.

Zonge, K. L., and Wynn, J. C., 1975, Recent advances and applications in complex resistivity measurements: Geophysics, v. 40, no. 5, p. 851-864.