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THE INDUCED-POLARIZATION EXPLORATION METHOD

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Abstract

Induced polarization is a current-stimulated electrical phenomenon observed as a delayed voltage response in earth materials. It is important as a method of exploration for buried metallic mineral deposits. With recent improvements in electrical instrumentation and computer analysis techniques, the method has become well developed and is now the most widely used of the ground geophysical exploration methods.

Induced-polarization measurements are made in the time-domain as a voltage decay curve, in the frequency-domain as a voltage difference with variation in frequency, and in the phase-domain as a phase lag angle. The complex-resistivity method requires a time link between the current transmitter and the voltage receiver to obtain the real and imaginary components of the earth's resistivity. A phase-coupled spectral IP response obtained in this way can be analyzed and interpreted to improve signal-to-noise ratio and remove electromagnetic coupling effects from the field data. The electromagnetic coupling between transmitter and receiver can also be interpreted to give an independent structural picture of the earth in the survey area.

Induced-polarization measurements are routinely made down drillholes both to log the near-hole properties and to probe deeper into the earth. Underground surveys are also made. Induced polarization data are used in mining areas to estimate the grade of metallic minerals and to seek a direction toward better mineralization. Also, there is increasing encouragement that it may be possible to make a distinction between the electrode polarization of metallic minerals and the membrane polarization phenomenon of clays.

Research in IP includes investigation into discrimination between metallic mineral species, removal of electromagnetic coupling effects, improvement of signal-to-noise ratio, and measurement of magnetic induced polarization effects. Mathematical modeling of different geometric shapes of polarizable bodies is proving to be an effective way of interpreting IP results, as has been the simulation of the subsurface using analog models. Research in IP instrumentation has been directed toward large-scale integrated circuits and computers used in the field to process, analyze, and interpret data.

The future for IP surveying appears to be favorable, and the method continues to be the best geophysical means for locating small volume percentages of metallic minerals in concealed mineral deposits.

Résumé

La polarisation induite est un phénomène électrique favorisé par le passage d'un courant; une fois que le courant est interrompu, on constate l'existence d'un potentiel transitoire dans le sol. Cette méthode d'exploration est importante pour la recherche des minerais métalliques enfouis. Grâce aux récents perfectionnements de l'appareillage électrique et des techniques d'analyse par ordinateur, cette méthode a pris un développement important, et actuellement, elle est celle que l'on utilise le plus pour l'exploration géophysique au sol.

Les mesures de polarisation induites sont, dans le domaine des temps, une courbe de décroissance du potentiel; dans le domaine des fréquences, la différence caractérisant le potentiel lorsqu'on fait varier la fréquence, et dans le domaine des phases, l'angle de retard de phase. La méthode de résistivité complexe exige que l'on établisse une relation de temps, entre l'émetteur de courant et le récepteur de tension, afin d'obtenir les composantes imaginaires et réelles de la résistivité terrestre. Ainsi, on obtient une réponse IP (de polarisation induite) spectrale, avec couplage de phase, que l'on peut analyser et interpréter afin d'améliorer le rapport signal-bruit, et d'éliminer des données obtenues sur le terrain les effets du couplage électromagnétique. Le couplage électromagnétique entre l'émetteur et le récepteur peut aussi être interprété de manière à donner dans la région étudiée une image structurale indépendante.

On effectue couramment des relevés de polarisation induite dans les trous de forage, à la fois pour établir un log des propriétés du terrain à proximité du trou de forage, et explorer le sol à plus grande profondeur. On effectue aussi des levés souterrains. On utilise les résultats de la polarisation induite dans les zones minières pour évaluer la teneur des minerais métalliques, et chercher les zones les mieux minéralisées. Et de plus en plus, il semble que l'on pourra établir une distinction entre la polarisation d'électrode des minéraux métalliques, et la polarisation de membrane des argiles.

En polarisation induite, la recherche vise aussi à nous permettre de mieux distinguer les unes des autres les espèces minérales métalliques, d'éliminer les effets de couplage électromagnétique, d'améliorer le rapport signal-bruit, et de mesurer les effets magnétiques de la polarisation induite. La modélisation mathématique de diverses formes géométriques des corps polarisables s'avère comme une méthode efficace d'interprétation des résultats IP, de même que la simulation des zones proches de la surface à l'aide de modèles analogiques. La recherche relative à l'appareillage IP s'est orientée vers l'étude de circuits intégrés de grandes dimensions et d'ordinateurs, que l'on pourrait utiliser sur le terrain pour le traitement, l'analyse et l'interprétation des données. Il semble que l'avenir soit prometteur pour les méthodes de levés IP, et cette méthode géophysique semble être la plus appropriée pour localiser des concentrations peu volumineuses de minéraux métalliques, dans les gîtes minéraux dissimulés.

This report is an update review of the induced-polarization (IP) method of geophysical exploration. Since its rediscovery and first extensive field use three decades ago, the method has enjoyed increasing popularity until it is now the most widely used ground geophysical surveying technique employed in exploration for metallic-luster minerals.

METHODS OF IP MEASUREMENT

Whereas 10 years ago there were only two different commonly used ways of measuring the IP phenomenon, more recently the phase and the complex-resistivity systems have gained favour. The measuring method is mainly a matter of desired sensitivity and the availability of field equipment, as will be discussed later. The standardization of units of IP measurements is presently being debated. This writer believes that the results of field measurements should be compatible with those of laboratory measurements and that units relevant to measurements should be used.

Time-domain IP

Prior to 1950 all IP measurements were of the time-domain type using the waveforms shown (Fig. 9.1). A simple on-off step-function current was impressed in the earth by grounded contacts and the analysis of the voltage waveform

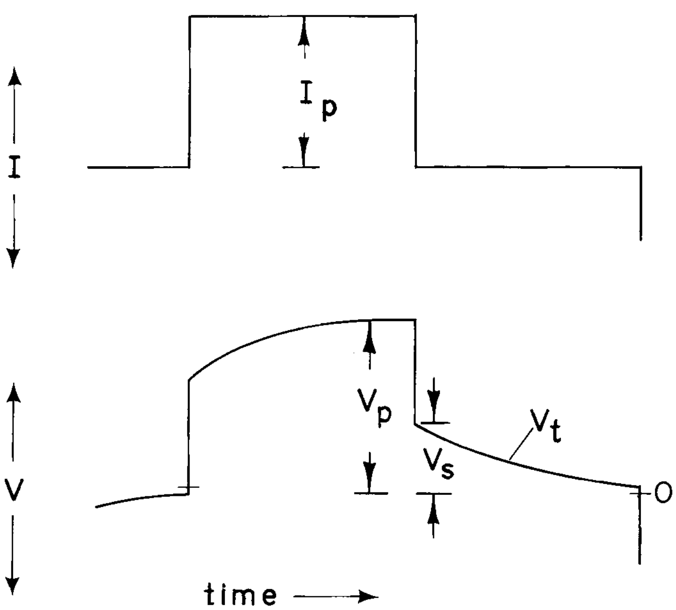

Figure 9.1. *The time-domain transmitted and received voltage waveforms, showing the inducing primary current I_p being detected as a maximum primary voltage V_p. When current is turned off, voltage drops to a secondary level V_s and the transient voltage V_t decays with time.*

gave a measure of the IP effect. A satisfactory theoretical explanation of the IP phenomenon was developed by Seigel (1959), who formulated that since the polarization ($\vec{P}$) was stimulated by electric current the dimensionless chargeability response of V_s/V_p or M, must be directly proportional to polarization and inversely proportional to the current density ($\vec{J}$), or

$$M = -\vec{P}/\vec{J} \tag{1}$$

The minus sign indicates the opposing vector relationship between polarization and current density. The rather unusual feature of equation (1) is that $\vec{P}$ and $\vec{J}$ must have similar dimensional units, which means that the polarization can be physically interpreted either as a blocking resistivity or as the generation in polarizable ground of opposing electrical currents. In any event, induced polarization basically is quite different from the charge separation phenomenon of dielectric materials.

Wait (1959a) pointed out that IP has a linear behavior in materials, at least at low current densities. Induced-polarization linearity is important because it means that IP measurements are repeatable under different current conditions. The IP phenomenon becomes nonlinear at higher currency densities, a fact that may prove useful in identifying the causes of polarization. Also, the depolarization or decay curve is generally logarithmic in shape, although contributing components with different time constants can usually be identified.

Frequency-domain IP

Since the blocking resistivity is a time-dependent behavior, it must also have a frequency dependence because time and frequency values can be related one to the other. Thus polarizable materials can be viewed as having an impedance which is frequency dependent, leading to frequency-domain measurements. Madden et al. (1957) of MIT and Wait (1959b) of Newmont developed frequency-domain equipment and accompanying electrical theory. The frequency method current and waveform patterns are shown on Figure 9.2. The measured parameter, per cent frequency effect (PFE), used now by most field workers is given by

$$PFE = 100 \times \frac{\rho_{dc} - \rho_{ac}}{\rho_{ac}} \left[\log \left(\frac{f_{ac}}{f_{dc}}\right)\right]^{-1} \tag{2}$$

where ρ_{dc} and ρ_{ac} and are the low- and high-frequency apparent resistivities. Early frequency-domain field equipment lacked a capability to measure low frequency voltages accurately, hence the ρ_{ac} rather than the ρ_{dc} in the denominator of equation (2). If ρ_{dc} were used rather than ρ_{ac} there would be an exact proportionality between chargeability and frequency effect. However, these two IP response parameters are nearly proportional at fairly low polarization values.

Groups using the frequency-domain IP method have advocated the use of a ratio factor of the apparent frequency effect with the apparent resistivity, resulting in a parameter dubbed "metal factor". To put the metal factor (MF) into the range of commonly used numbers it is multiplied by 2000,

$$MF = (PFE/\rho_a) \times 2000 \qquad (3)$$

where ρ_a is in ohm metres. Controversies have arisen regarding the merits and significance of the metal factor – with inconclusive results. Table 9.1 is an attempt to summarize the pros and cons of the metal factor argument. There seem to be areas where the metal factor is a useful parameter in estimating the amount of mineralization and in putting a priority on anomaly patterns. Recently Snyder and Merkel (1977) have used a working relationship

$$\%\ \text{wt. sulphides} = (100 \times \sigma)^{1/3} \qquad (4)$$

where σ is the quadrature conductivity (metal factor) in millimhos per metre. However, the metal factor can be misleading if used without regard to threshold IP response and possible low resistivities. Figure 9.3 indicates a simple nomograph relationship between these three factors.

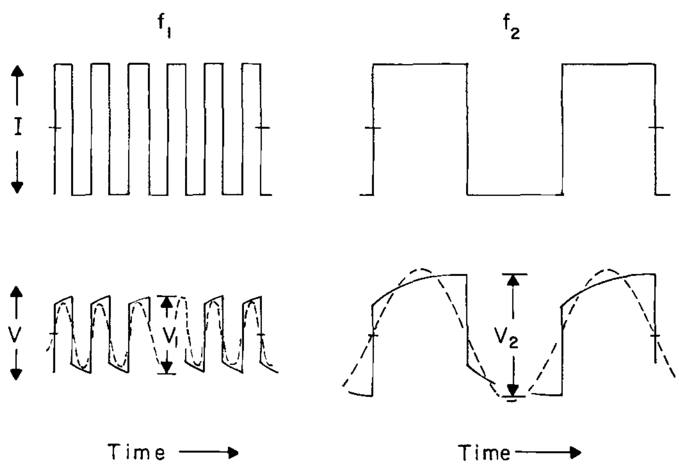

Figure 9.2. *Frequency-method waveforms, showing a controlled constant inducing current I at frequencies f_{ac} and f_{dc} being detected as voltages V_{ac} and V_{dc} where $V_{ac} < V_{dc}$. The dashed line is the sinusoidal filtered voltage.*

Table 9.1

The metal factor debate

For	Against
1. Increases resolution	1a. Emphasizes low resistivities
	1b. Emphasizes EM coupling errors
2. Useful in mineralization estimation	2. No physical basis for sulphide grade estimation
3. Physically related to the dielectric constant	3. No precise physical interpretation
4. Useful as a correlation factor between polarization and low resistivity	4. Exaggerates resistivity anisotropy

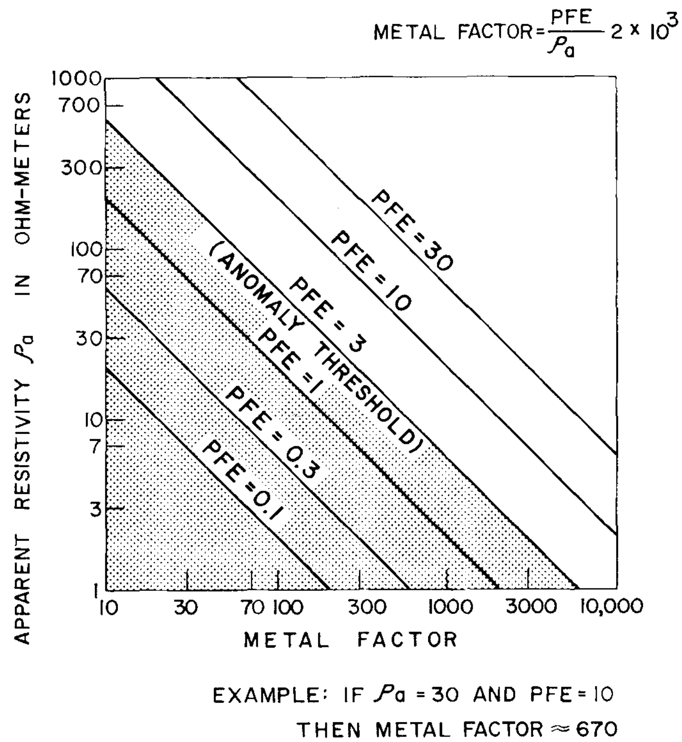

Figure 9.3. *Per cent frequency effect (PFE) plotted as a function of metal factor and resistivity.*

Phase IP measurements

If the current waveform transmitting system and the voltage receiving system are temporally time linked, the phase difference between transmitted and received signals can be measured and this difference, determined either in time or as an angle, gives the polarization of the intervening earth. Significantly, the ratio interval between time and total time (or angular difference and angle) remains generally constant over the measuring range (Fig. 9.4), although other patterns and variations do exist. One advantage in making phase measurements is that only a single waveform need be used, so speedy measurements are possible. However, the necessary time correlation between transmitter and receiver has posed problems in instrumentation. Many reference methods have been proposed and used, including an electrical cable, a precise clock reference, a ground signal, comparison of harmonics, and a radio link.

Phase-angle measurements are usually made by taking a ratio of out-of-phase and in-phase components and then finding the tangent of the defined angle. The rotating phase diagram is illustrated in Figure 9.5. It can be demonstrated that phase angles are closely related to chargeability (Fig. 9.6) relating a phase diagram to the polarization quantities of equation (1). The quadrature polarization vector P_Q leads the resistive component J_R of the total inducing current vector J by $\pi/2$, then

$$\tan \beta = -P_Q/J_R \qquad (5)$$

$$\tan \beta = -M \qquad (6)$$

so that at small phase angles

$$\beta = -M \qquad (7)$$

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The approximate relationship between PFE, chargeability, and phase angle can be summarized as follows

Domain		
Frequency (Per cent over one decade)	Time (Milliseconds) relative to M_{331}	Phase (Milliradians)
1.0	6.6	-5.6
0.15	1.0	-0.83
0.18	1.2	-1.0

The measured IP response voltage lags behind the inducing current, so normal IP phase angles are negative.

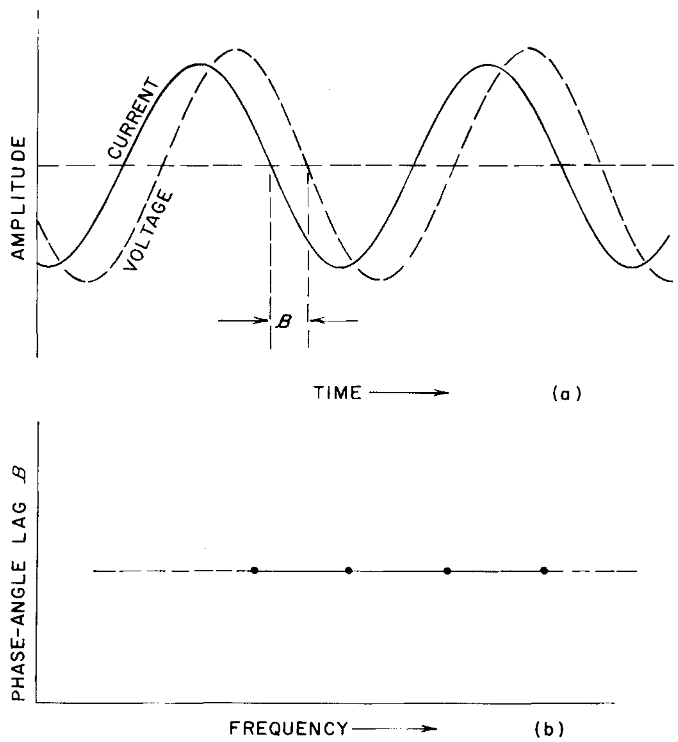

Figure 9.4. *Phase determinations: (a) phase lag angle β between input (solid) and output (dashed) sinusoidal waveforms and (b) an ideal IP phase spectrum diagram.*

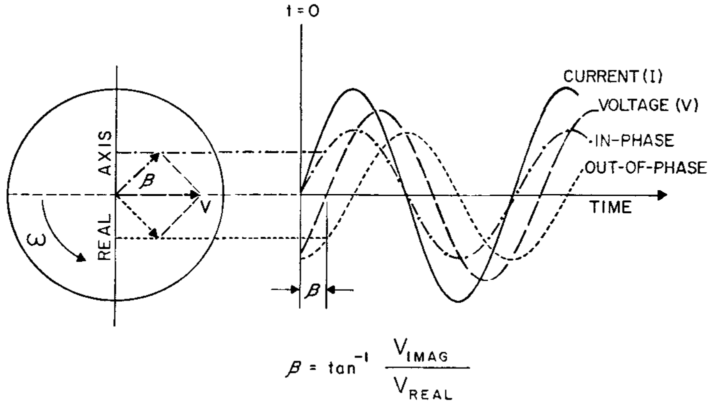

Figure 9.5. *Rotating vector components of a phase diagram, showing the phase lag angle.*

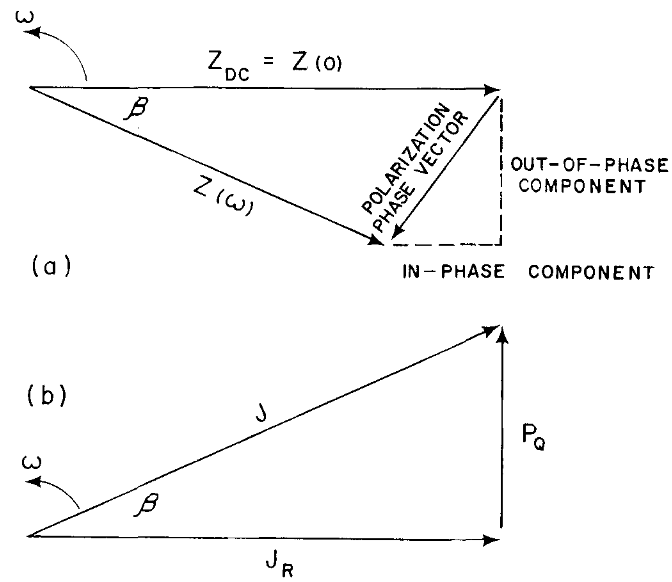

Figure 9.6. *Phasor diagrams showing (a) components of the polarization vector and (b) components of the rotating current vector.*

Complex Resistivity

Even over a continuous range of determinations, ordinary time- and frequency-domain IP measurements measure only absolute values without regard to in-phase and out-of-phase, or vector, components. But in order to measure all effects truly and to be able to transform back and forth from time to frequency the in-phase and out-of-phase IP components over a wide range must be taken into account. The in-phase and out-of-phase components are sometimes plotted in the complex plane of rotating vectors, which leads to the concept of complex resistivity measurements.

Complex impedance measurements of materials have been made at least since 1941 (Cole and Cole, 1941; Grant, 1958) in studies of dielectric phenomena. Van Voorhis et al. (1973) and more recently Snyder (1976) and Zonge (1976) have used the capabilities of minicomputers to observe IP phase component responses at multiple frequencies. One of the ways of graphically plotting complex-resistivity data, bringing out any existing phase and amplitude differences over the spectrum of observing frequencies, is the Cole-Cole plot shown on Figure 9.7. Note that this type of diagram can also be used to relate conventional PFE and phase angle to the complex-resistivity spectrum.

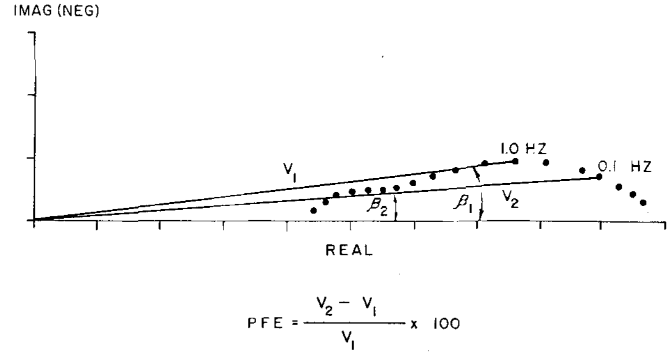

Figure 9.7. *A Cole-Cole plot in the complex plane.*

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IP Measurement Units

Induced-polarization units are, by the unusual nature of the phenomenon, a bit unconventional. Because of the nearly dc frequencies used, most field workers do not use Maxwell's equations and electromagnetic parameters for measurement. However, theoretical electromagnetic relationships can be developed, and some laboratory groups (Olhoeft, 1975) advocate their adoption.

Before changing to other IP units it is probably better that we understand IP theory and that we research the phenomenon more thoroughly and come to closer agreement on reasons for the past units.

FIELD PROCEDURES AND METHODS

Over the years, IP field methods have not changed much. It is still a task and a chore to assemble the equipment, check it out, transport it in good condition to the field site, and conduct field operations in an efficient manner. Miniaturization and simplification of key components, such as the transmitter and receiver, have been a real boon, but upkeep of ancillary equipment, especially on a deep-search survey, remains troublesome.

Surface Arrays

Despite attendant signal-to-noise problems, there has been a continuing trend toward the use of the dipole-dipole array for IP field work. The main arguments for this layout scheme seem to be the advantages in anomaly resolution, depth of exploration, and the flexibility in survey procedure. For shallow exploration the three-electrode or pole-dipole array and gradient (Schlumberger n>10) array are feasible. Figure 9.8 is a summation of the features of the various array geometries. Whiteley (1973) has carefully analyzed the relative advantages and disadvantages of all reasonable arrays, and Table 9.2 summarizes the concepts along these lines.

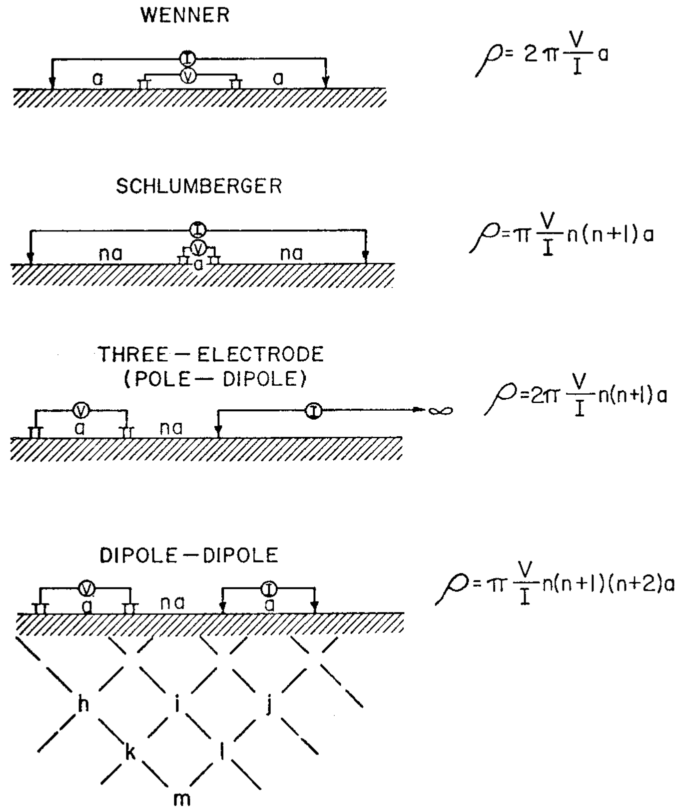

Figure 9.8. *Geometric array factors for the commonly used IP exploration array configurations.*

Table 9.2

Summary of features of IP arrays

	Dipole-Dipole	Pole-Dipole	Gradient	Schlumberger and Wenner
Response amplitude	Good	Fair	Poor	Poor
Dip of structure	Poor	Poor	Good	Fair
Depth of exploration	Good	Good	Fair	Poor
Resolution of mineralization	Good	Good	Fair	Poor
Freedom from EM coupling	Fair	Fair	Poor	Poor
Interpretability of layering	Poor	Poor	Fair	Good
Depth estimates	Fair	Fair	Fair	Fair
Signal-to-noise ratio	Poor	Fair	Good	Good
Labor needed	Poor	Fair	Good	Good
Susceptibility to noise	Fair	Fair	Good	Good

Drillhole IP Methods

The two categories of IP drillhole surveying are: in-hole surveys (near-hole surveys, including hole logging) and downhole surveys (exploration IP surveys), employing one current or potential electrode down the drillhole. Figure 9.9 is an illustration of the in-hole normal array and the downhole azimuthal array. One of the enigmas of IP surveying is the negative response that is often observed in subsurface work, particularly in drillhole surveying. In every analyzed circumstance, the IP response has been explained by the interactive geometric relationship between the orientation of the inducing currents with the polarizable body and its associated secondary electric fields.

While the mise-à-la-masse drillhole resistivity method has often been successful in finding the direction toward better mineralization, mise-à-la-masse polarization effects can be quite peculiar. The reason for this peculiarity is that in most observed instances IP is a dipolar phenomenon; that is, current is passed through a polarizable body and induced secondary currents flow in and around the body between induced current sources and sinks. However, when an inducing electrode is in contact with the body, nonlinear polarization effects occur in regions of high current density and also the secondary current fields can more readily flow in an opposite sense to the inducing currents and this opposing flow is then observed as a negative polarization. Thus, IP mise-à-la-masse interpretation must be approached with some caution.

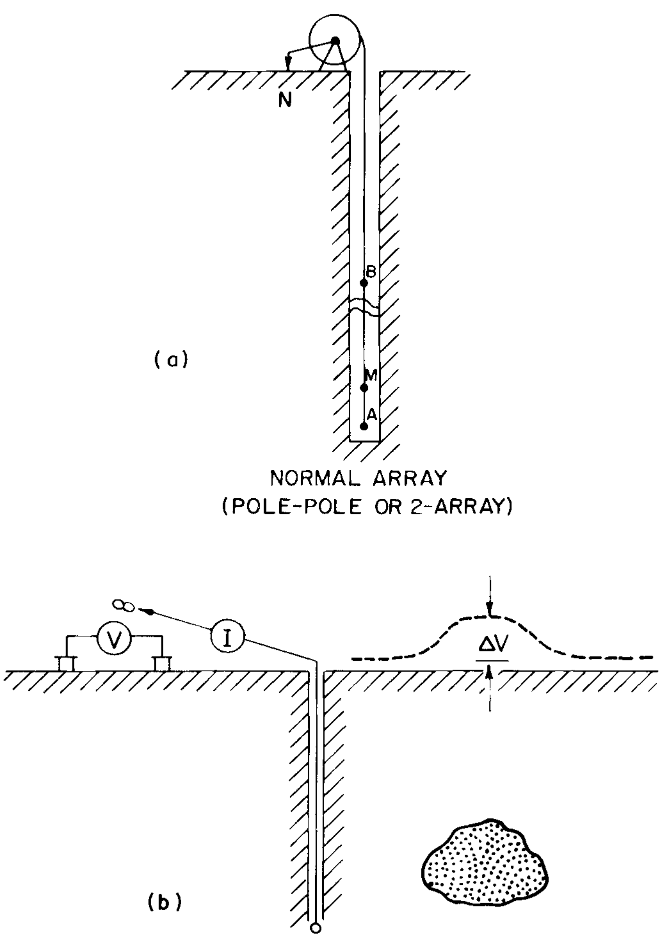

Figure 9.9. *Drillhole IP arrays: (a) the normal in-hole array and (b) the downhole azimuthal array.*

INSTRUMENTATION CURRENTLY EMPLOYED FOR IP SURVEYS

Manufacturers of geophysical field equipment have been quick to take maximum advantage of the use of semiconductor devices in innovating new field instruments. Also integrated circuits and microprocessors are in prominent use. Time- and frequency-domain instruments continue to be improved by their competitive manufacturers, and the inquisitive reader is referred to Hood's (1977), Mineral Exploration Trends and Development article (and those in previous years) for particulars on specific instruments. Research in time-domain equipment appears to be focused on noise elimination by stacking and on decay curve shape determination by observing successive selectable voltage windows. Newer frequency-domain IP receivers are capable of removing first- and second-order EM coupling effects by quadratic curve synthesis using phase measurements.

Phase IP Instruments

Nilssen (1971) has described a phase-measuring IP instrument, which is in popular use by the Boliden Company of Sweden. Parasnis (1973) has mentioned complex measurements in Europe, which because a single frequency is used would be classed here as phase measurements.

Phoenix Geophysics Ltd. employs synchronized crystal clocks at the transmitter and receiver for IP phase measurements. The system can also detect and eliminate most normally encountered EM coupling. Scintrex Ltd. of Canada has developed an interesting single-frequency ground-coupled phase-measuring instrument. The relative phase shift is determined by a comparison of the time or "phase" shift of the fundamental and third harmonic components, so the method does not require a radio link or synchronized crystal clocks.

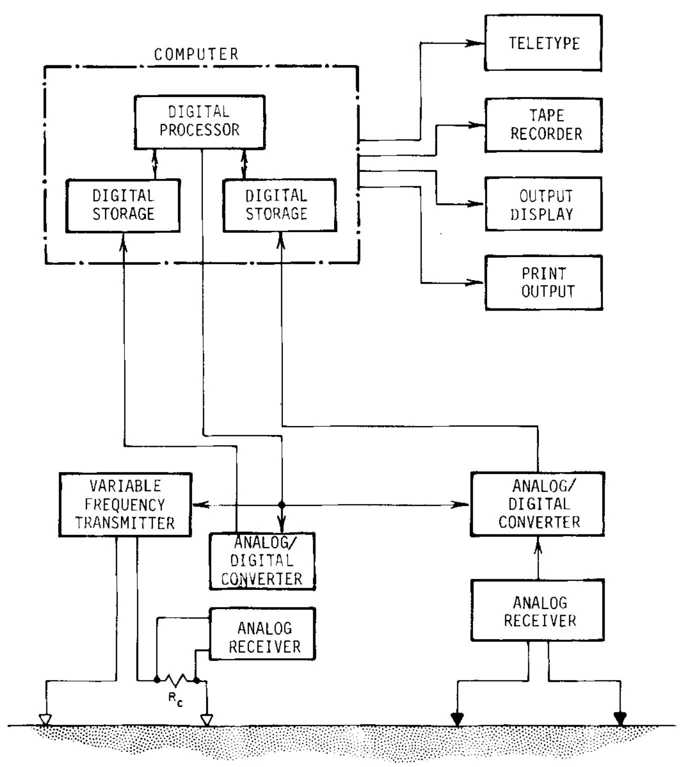

Figure 9.10. *Block diagram of the components of a complex-resistivity system in the dipole-dipole array.*

A major advantage of IP phase instruments is the effective suppression of unwanted noise voltages. This is brought about because a phase shift angle rather than a signal amplitude is measured, and this is a more basic kind of electrical measurement.

Complex-resistivity Instruments

The first complete multispectral phase-coupled IP field system was developed at Kennecott Copper Corporation prior to 1972 by Van Voohris, Nelson, and Drake (1973). Multispectral time- and frequency-domain measurements have previously been studied in the laboratory by many researchers (Collett, 1959; Katsube and Collett, 1973; Fraser et al., 1964; Madden et al., 1957; Zonge, 1972) in the hope that mineralized rocks would have a unique spectral signature or that particular minerals or ions could be identified. Van Voohris et al. (1973) did not find any significant variation using their early equipment, but the method could be used to virtually eliminate bothersome EM coupling effects.

More recently, Miller et al. (1975), Snyder (1976) and Zonge (1976) have used modern microprocessor technology in the field to obtain phase-coupled spectral IP, or complex-resistivity, data. All these systems utilize a computer-controlled variable-frequency current transmitter and a linked voltage receiving system permitting the transmitted and received signal to be compared in amplitude and phase. In order to accomplish this, it is usually convenient to Fourier transform signals from one domain to the other and then deconvolve them. Figure 9.10 is a block diagram of a typical complex-resistivity field system, and Figure 9.11 is a program flow diagram (after Zonge, 1976) showing the computer processing of data. The inputted field data proceed from the control point through a decoder, variable selection step, and command operation step to be printed out finally in a selectable number of forms. Once in digital form the processed data can be displayed in several different ways: as time-domain chargeabilities, frequency-domain per cent frequency effect, phase-domain milliradians, as polar or other types of graphical plots, or in tabular form.

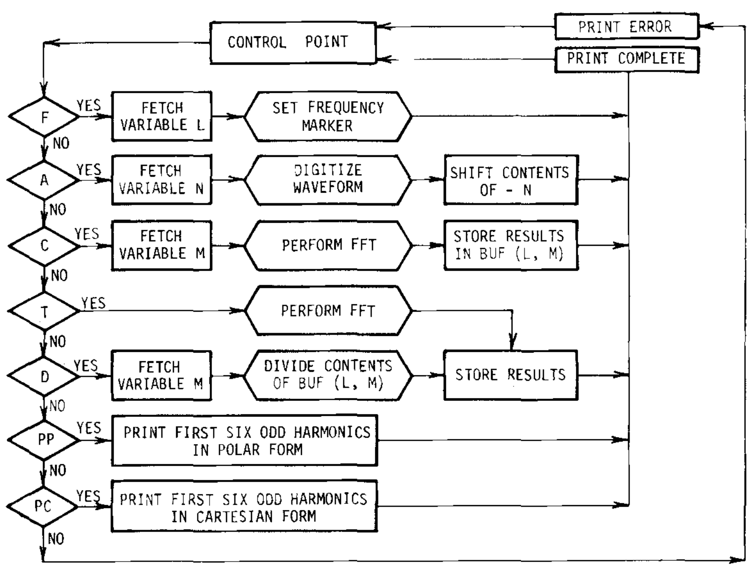

Figure 9.11. *Flow diagram of a complex-resistivity computer program. After Zonge (1976).*

IP INTERPRETATION TECHNIQUES

The methods of interpreting processed IP data have been advanced considerably in the past decade by innovative computer modeling methods. In general, there are two main computer approaches to model interpretation, which can be called the forward solution and the inverse solution. Of course, the interpreter must always be guided by geologically reasonable boundary conditions, and intuition and experience remain important factors.

Forward Solutions in IP Interpretation

Forward solutions are the precomputed models of specified electric potentials over subsurface structures. These can be calculated in any one of several different ways, depending mainly on economic limitations and the subsurface geometry of resistivity and IP contrasts. The four numerical computing techniques have been finite difference, finite element, network analogy, and integral equation. The one-dimensional problem involving a change in electrical property with depth has been extensively treated by Nabighian and Elliot (1974) and a fairly complete thirteen-volume library involving all commonly used surface arrays is available from Elliot Geophysical Company of Tucson. For irregularly shaped, two- and three-dimensional subsurface bodies, Hohmann (1977) has summarized the forward interpretation theory and presents several interesting examples, two of which are shown as Figures 9.12 and 9.13.

Inversion Techniques in IP Interpretation

Comprehensive programs can be written to calculate a model based on the field data using the inversion method. Thus far the method has not been too successful beyond the one-dimensional problem, but even so this can greatly simplify the interpreter's task. It appears likely that with computers now being a part of some IP field equipment, the field geophysicist may be able to interact with a simple inversion model to at least narrow down the large number of possible subsurface conditions.

Complex-resistivity Data Interpretation

It is appropriate to mention some of the interpretational features of the complex-resistivity (CR) method, even though some aspects of the data are not yet well understood. The general frequency trends of spectral response have been called types A, B, and C (Fig. 9.14), and apparently these spectral types are related to alteration and mineralization. The type A response, in which the out-of-phase component decreases with increasing frequency, is usually associated with strong alteration and sulphide mineralization, usually including pyrite. Type B has a constant out-of-phase component over the frequency range, similar to the Drake model of Figure 9.4. Type C has an increasing out-of-phase component with increasing frequency and is not often associated with pyritic sulphide mineralization. At higher CR frequencies, electromagnetic effects become stronger and these are interpretable, giving resistivity contrast ratio and depth to resistivity contrast of up to five or six dipole lengths.

PROBLEM AREAS IN IP

As geophysical exploration techniques continue to mature, old problems tend to be solved, only to have new ones appear – and so it is with induced polarization.

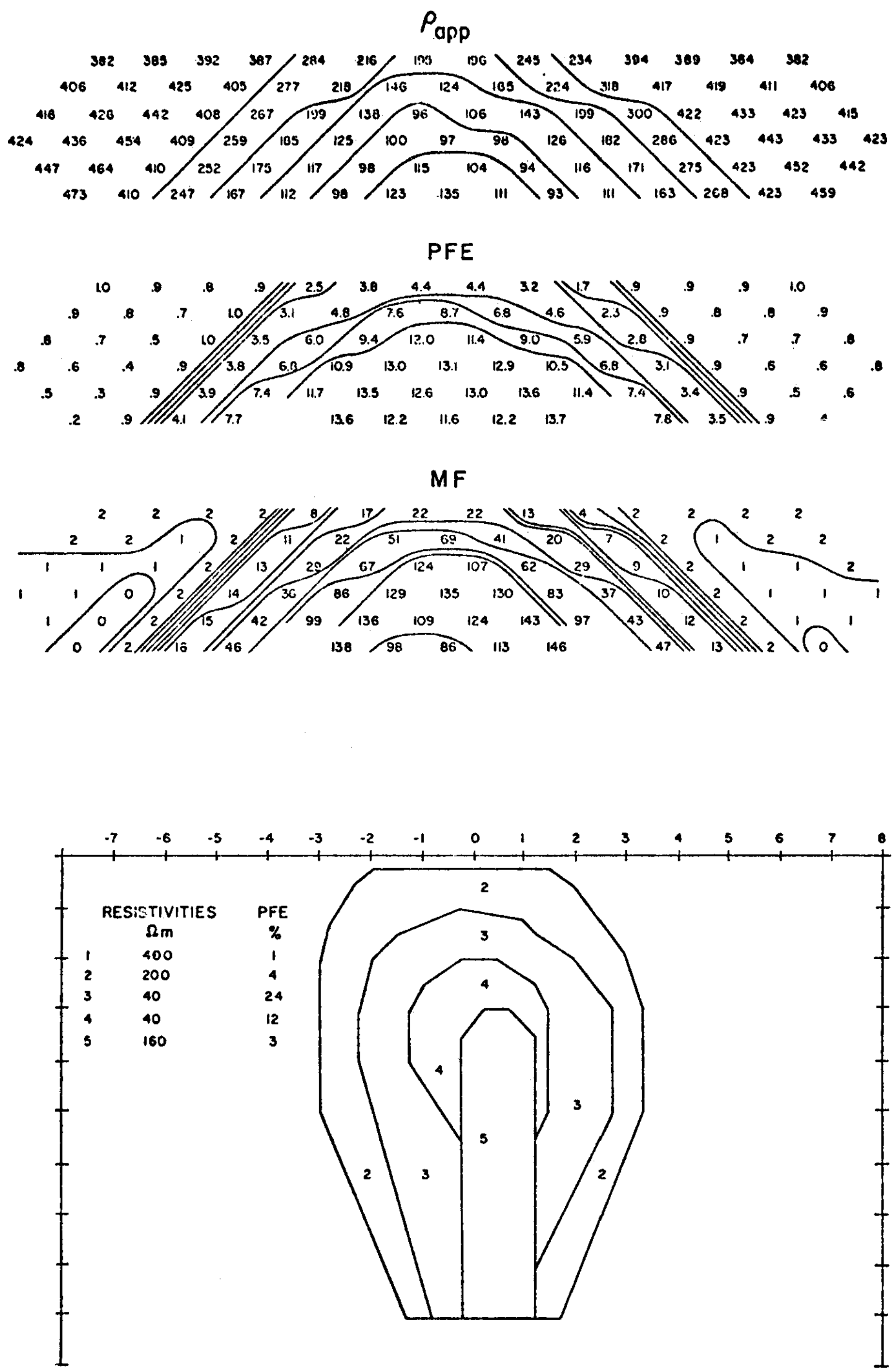

Figure 9.12. Finite element results of the dipole-dipole array for a two-dimensional porphyry copper model. From Hohmann (1977).

EM Coupling Problems

With the availability of lower frequencies and the phase-measuring IP method, electromagnetic coupling is becoming much less of a problem. However, there is a trade-off in combating the uncertainty of whether an anomaly is due to coupling. Additional data must be obtained and interpreted, and the field equipment is more sophisticated and therefore more expensive and complex. Also, the field geophysicist must be trained and experienced in solving these problems. On the brighter side of the EM coupling problem, if complete coupling removal is indeed the fact that it appears to be, then the isolated and interpreted EM effects can constitute an additional facet to the total interpretation of subsurface conditions.

Masking by Resistivity Contrast

The difficult physical environment posed by near-surface low-resistivity layers continues to be bothersome to IP surveys. Of course, this condition must first be recognized to exist and then the thickness and extent of low-resistivity material must be determined in order finally to overcome the masking effects. The problem therefore involves much more than the IP measurements alone and includes making and interpreting resistivity and possibly EM measurements. The interpretation problem due to near-surface, low-resistivity layers would probably be more severe in Australia than in the southwestern United States. As yet complex-resistivity measurements have not been reported from the Australian environment. The magnetic induced polarization (MIP) method when developed to a routine technique, should reduce the masking effect of conductive overburden conditions.

Nonmetallic IP Response

Fine grained clays and fibrous minerals such as serpentinite can produce a moderately strong IP effect, and in the past many exploration holes have been drilled on nonmetallic polarization sources. In many areas over certain of the offending rock types, the clay response can be recognized, even using the polarization signatures obtained with conventional time-domain and spectral frequency-domain instruments. In general, nonmetallic zones have an increasing response with increasing frequencies or shorter times, which is the complex-resistivity response type C of Figure 9.14. In a few problem areas, even the sophisticated spectral patterns obtained by CR equipment give ambiguous results, particularly if small amounts of metallic minerals are present in the nonmetallic zone. Of course, it must be mentioned that the response from nonmetallic sources is generally much lower in amplitude than from metallic-luster minerals.

Metallic Mineralized Zones with a Negligible IP Response

Occasionally the author hears of a mineralized body that does not yield an IP response to an exploration survey. However, on detailed inquiry, it is found that the body was below the depth of exploration or so small that the response

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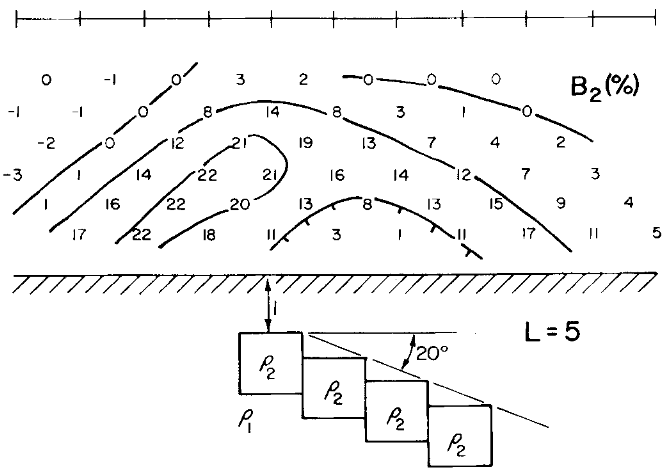

Figure 9.13. *Induced-polarization response for the dipole-dipole array over a dipping conductive body composed of square cells, $\rho_2/\rho_1 = 0.2$. The B_2 (%) on the pseudo-section gives the percentage of the intrinsic IP value of the dipping body; L is the ratio of length to depth of the body. From Hohmann (1977).*

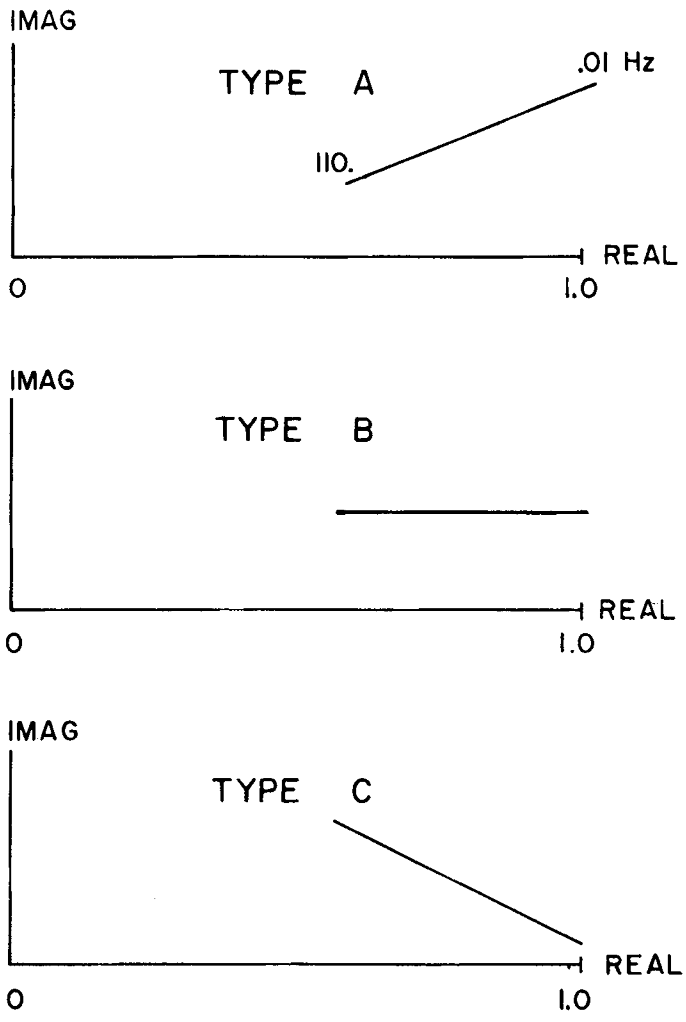

Figure 9.14. *Complex-resistivity spectral response types A, B, and C. As on Figure 9.7, the lowest frequencies are on the right. After Zonge and Wynn (1975).*

was diluted below an anomaly threshold level. In general the presence of pyrite greatly improves the IP response, possibly because of the porous nature of most pyrite in mineral deposits and its high electrochemical activity. Conversely, deposits low in pyrite, as a general rule have a lower IP response.

RECENT ADVANCES, TRENDS, AND NEEDS IN IP SURVEYING

There is little doubt that the complex-resistivity method of IP surveying is an important trend of research activity. Also numerical modeling and particularly inversion techniques deserve attention for future development. Mineral discrimination using spectral frequency-domain equipment has recently been reported by Pelton et al. (1977); Figure 9.15 shows the results of some of their findings.

Magnetic Induced Polarization

Magnetic induced polarization (MIP) was announced by Seigel (1974) in a theoretical analysis, and since then equipment and survey techniques have been developed. The method measures the weak magnetic fields associated with electrical depolarization currents employing a very sensitive magnetometer.

Development of the MIP technique is continuing, but it has yet to be accepted by the exploration fraternity as a routine search scheme. Figure 9.16 shows the concept of the method. The transmitted current I_i encounters a polarizable body and effectively creates subsurface charges, which in turn produce a secondary electrical field at E_s, which can be measured by the relationship of Ampere's law $\nabla \times \vec{H} = \sigma \vec{E}$. Grounded contact receiver wires are not required, so airborne IP is conceivable. Model studies of the MIP response by Hohmann (1977) indicate that the MIP response is relatively smaller than conventional IP, at least for bodies in an electrically homogeneous earth. However, the method has advantages where elongated polarizable bodies are present, and where conductive overburden is a major problem.

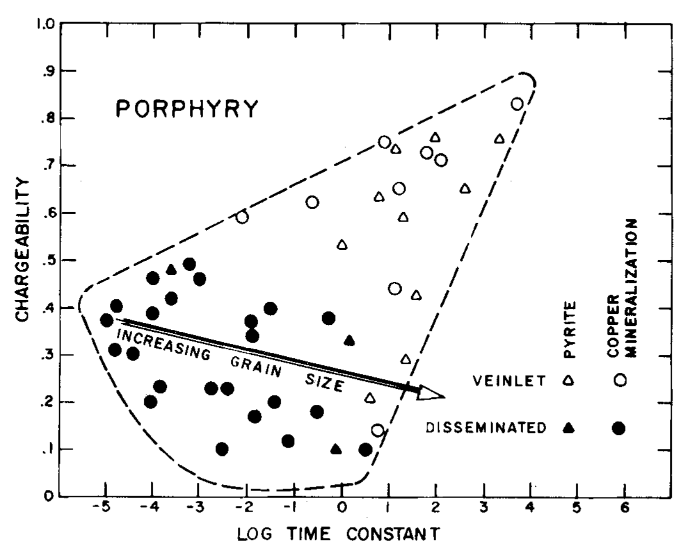

Figure 9.15. *Induced-polarization data from western porphyry copper deposits, showing a grouping of veinlet mineralization (open circles) versus discretely disseminated mineralization (closed circles). From Pelton et al. (1977).*

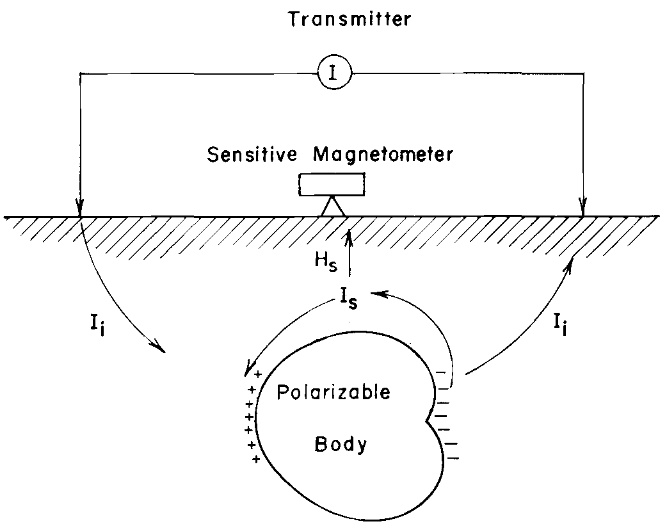

Figure 9.16. *Schematic illustration of magnetic induced polarization.*

Electrochemistry and IP Theory

One of the more important areas for future IP research in this writer's opinion is in electrochemistry. Laboratories of the Geological Survey of Canada (Katsube, 1977), the U.S. Geological Survey (Olhoeft, 1975), and the University of Utah (Klein and Shuey, 1975) have provided useful information about the basic phenomena, but much more remains to be accomplished before the IP mechanism is completely understood.

A stronger foundation of electrochemical principles will assist in establishing better theory for IP. As matters now stand, there are several proposed electrical theories (Seigel, 1959; Patella, 1972; Nilssen, 1971), none of which has a firm modern foundation based on the underlying electrochemical nature of polarizable materials. Also, electrochemistry holds the clues to the reality and meaning of mineral discrimination as gained from spectral IP data.

Prediction of Telluric Noise

As a result of a long-term correlation of interplanetary magnetic field polarity, solar wind speed, and geomagnetic disturbance index during the declining phase of the recent sunspot cycle (1973-1975) it has become apparent that telluric noise patterns can be predicted. This predictability is due to recognition of the source mechanism for low-frequency geomagnetic disturbances and telluric noise. Heretofore sunspots and solar storms in general were thought to be the source of the telluric noise that so plagues IP surveys and low signal conditions caused by wide electrode separations and low resistivities. Now the exact disturbance source and mechanism has been found thanks to Kitt Peak National Observatory research by Sheeley et al. (1976).

The solar wind sources for low-frequency telluric noise are solar surface structures known as "coronal holes", which are associated with the dying phases of sunspots. A coronal hole is a vortex disturbance pattern that is not readily visible on the sun's surface, and it is essentially a north or south magnetic pole. Coronal holes are the origin of most high-speed solar wind streams, and these charged particles are projected into space like high-pressure water from a fire hose. Since coronal holes are detectable from earth several days before they are carried across the central meridian by solar rotation and since two to three days remain before the wind from the hole will reach the earth, we should be able to predict the arrival of the high-speed streams and their associated magnetic effects approximately a week in advance. The accurate prediction of noisy conditions can assist in scheduling IP surveys in problem areas. The correlations by Sheeley et al. (1976) indicate relationships of magnetic field polarity, solar wind intensity, and the magnitude of recorded geomagnetic disturbances.

Of course, the results of this solar research should also be useful for signal prediction for magnetotelluric exploration. Information on solar magnetic distrubances is available from Space Environment Services Center, Space Environment Laboratory, ERL, National Oceanic and Atmospheric Administration, Boulder, Colorado 80302.

FUTURE TRENDS AND DEVELOPMENTS IN IP SURVEYING

Although IP is the newest of the mining geophysical exploration methods, it has progressed to the extent that it has become the most popular despite the fact that costs for IP surveys are comparatively high. A cost reduction would be a major achievement. Innovations in the IP method are still being perfected, but airborne IP surveys do not appear to be feasible at this time.

There is still debate as to the significance of the metal factor in IP interpretation. There is also an uncertainty about the capability of the IP method to discriminate between different polarizing materials. However, the effectiveness of an IP survey is high, and it is readily possible to obtain resistivity, self-potential, and electromagnetic data as well as complex-resistivity information. Indeed it seems likely that as data are compared and correlated at least a limited amount of mineral discrimination will be possible.

The digital computer is becoming a necessary addition to the IP equipment list, and the use of the microprocessor is substantially transforming routine IP surveys. With continuing decreases in cost of computing devices, their inclusion as integral parts of future IP systems can be foreseen.

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