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INDUCED-POLARIZATION DEPTH PENETRATION IN EXPLORING FOR PORPHYRY COPPERS

by

C. L. Elliot[1] and H. David MacLean[2]

Abstract

The induced-polarization response of a mineralized system measured at surface is a function of several factors: (1) the spacing of the electrode configuration, (2) the physical dimensions of the mineralized system, (3) the intrinsic response of the system, and (4) the resistivity distribution of overlying or surrounding materials. These factors may be ideally summarized in the response expression

$$R = \Sigma B_j \Delta_j$$

where Δ_j is the physical property contrast and B_j is a weighting coefficient which is primarily dependent on the geometry of the responsive zone and the sensor. The physical property contrast associated with porphyry copper systems is generally small, but in the case of shallow systems, the above equation can be completely dominated by an appropriate electrode spacing that keeps the weighting coefficient associated with the porphyry copper system large in relation to that associated with the surrounding less responsive material. However, if target depths increase, this relationship is maintained only with increasingly greater difficulty.

The resolution of the resistivity distribution of overlying strata is essential to the analysis of the depth penetration of a given IP survey system, and a knowledge of the shallow or near-surface layers becomes increasingly important as the resistivity section becomes more complex. Thus, no matter how great the anticipated depth of a target zone, closely spaced electrode configurations are essential so that the resistivity section can be analyzed and a suitable array for the expected exploration depth can be devised. Under certain adverse conditions where the electrode spacings are limited by electrical noise or target size considerations, the resistivity relationship of the target and overlying media might limit the search depth of conventional IP exploration systems to unacceptably shallow depths.

The depth of penetration of IP systems where the electrode spacing is limited is almost entirely a function of resistivity, and this factor must be critically analyzed before an estimate of search depth can be made. By a careful choice of IP electrode arrays and survey procedures based on measurements from an orientation survey, detection of mineralized systems at depths of 1,500 to 2,000 feet is possible with conventional systems. No doubt detection at even greater depths will be possible under favorable resistivity conditions and as more effective electrical noise suppression techniques become available.

Introduction

The induced-polarization method has found general acceptance in the Southwest and is widely used and regarded for porphyry copper exploration in areas where the thickness of cover is of the order of 300 to 400 feet or less. Recently, interest in exploration to much greater depths has developed; target zones are frequently below 1,000 feet or even as much as 2,500 feet of cover. In order to assess the induced-polarization response from targets at such depths, it might be instructive to compare the theoretical induced-polarization response that can be expected from these deeper targets with that from the shallower features with which we are all familiar. The factors that influence induced-polarization depth penetration are listed below. The relative importance of these factors as target depths increase varies and factors of almost trivial

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[1] Elliot Geophysical Company, Tucson, Arizona 85712

[2] Newmont Exploration Limited, Tucson, Arizona 85704

consequence when exploring for shallow features tend to dominate the surface response if the target is located at a considerable depth.

Any geophysical response measured at the surface from any source is affected or controlled by the following factors:

1. The intrinsic response of the system.
2. The sensor configuration used and the spacing of the sensors.
3. The physical dimensions of the mineralized system.
4. The resistivity distribution of overlying and surrounding material.
5. Noise. Under some circumstances, noise is the dominant observed phenomenon.

The geophysical response, R, from a particular target medium such as that shown in Figure 1 can be stated by the expression

$$R = \Sigma B_j \Delta_j + \text{noise}.$$

where Δ_j is the physical property contrast or intrinsic response of a particular rock unit and B_j is the corresponding weighting coefficient for that same unit. The response R is the sum of the products of the intrinsic response and an associated weighting coefficient for all of the media that affect the geophysical sensor. Generally, this weighting coefficient shown in the equation above is primarily dependent on the geometry of the responsive zone and the point of measurement.

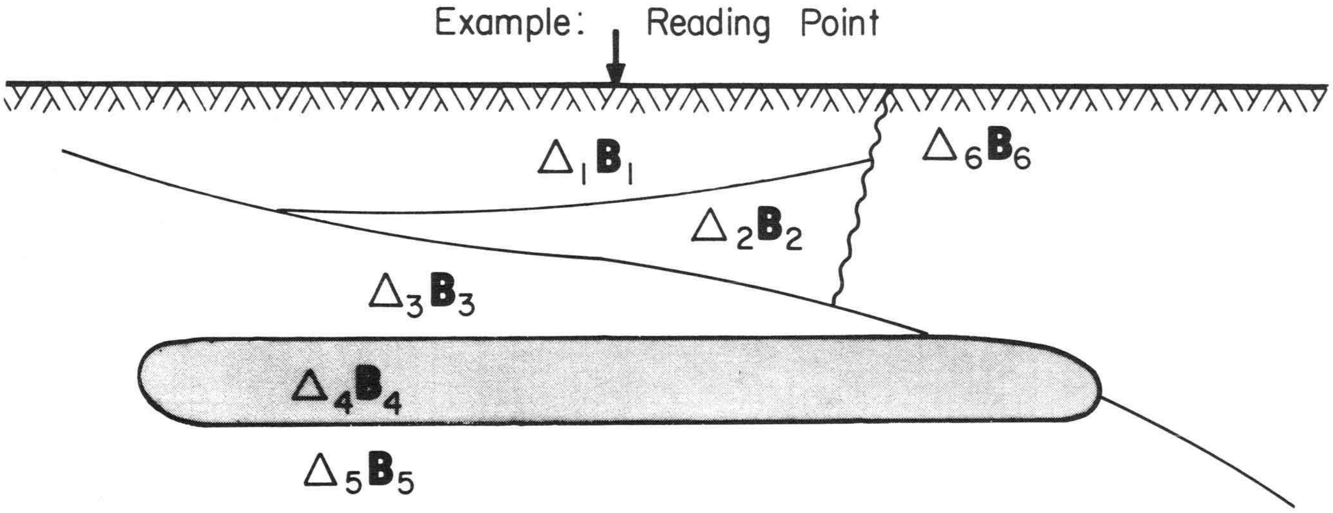
The induced-polarization response differs from the general case, however, in that the weighting factors are dominated primarily by resistivity rather than by geometry as will be demonstrated later in this paper. The IP response at surface from a particular target zone surrounded by other less responsive media such as in the case shown in Figure 1 can be stated just as the general case. The apparent IP response of unit 4, which is the target zone, will be modified by weighting coefficient B4; if this coefficient is large compared to all of the other coefficients and if the intrinsic response or chargeability of the target zone is large compared to the response of all other media, the target zone can be easily observed at surface. If, however, the weighting coefficient B4 is small and the physical property or chargeability contrast of the unit is not appreciable, the anomalous IP response measured at surface would be small and may even be included within the noise envelope for a particular observation site; if this is the case for all survey observation points, the unit will be undetectable by the IP method.

The physical property contrast measured by IP systems, which is variously called chargeability or frequency effect or phase angle (the terms are all mathematically interrelated), is relatively small. Under the best of circumstances, the chargeability of a mineralized body is only 9 to 10 times that of the enclosing media, and it is frequently only 3 to 5 times greater than the intrinsic background level. The IP response of some rock types and overburden material are listed in Table 1 and the intrinsic IP effects associated with some mineralized systems are presented in Table 2. These tables have been summarized from Brant (1966) with some additions of more recently studied areas. Note that the IP response of the mineralized areas is only 3 to 5 times that of the background level associated with many rock types and only in exceptional cases is the IP response as much as 10 times background.

Table 1. Examples of IP response and resistivity encountered in some characteristic southwestern rock types

Rock Type	Resistivity (ohm-meter)	Chargeability ms	PFE
Alluvium	20-100	1-14	≈ 0.5
Gila Conglomerate	30-300	4-15	≈ 2
Tertiary volcanics	20-1000	3-17	1-4
Precambrian volcanics	200-5000	8-20	1-4
Granite, monzonite, diorite	100-1000	6-15	1-2
Precambrian gneiss and schist	50-5000	6-30	1-4
Sandstone	40-1000	3-12	0.5-2.0
Limestone and dolomite	200-10,000	5-15	1-2
Quartzite	100-5000	5-12	≈ 1-2

IP survey systems designed to detect relatively shallow deposits of large extent and at least moderate chargeability contrast can easily be arranged so that the response equation shown above can be dominated by the weighting coefficients B_j. If the IP configuration or electrode spacing can simply be made very



$$R = B_1\Delta_1 + B_2\Delta_2 + B_3\Delta_3 + B_4\Delta_4 + B_5\Delta_5 + B_6\Delta_6 + \text{Noise}$$

Fig. 1. Factors affecting the geophysical response at surface from a target zone surrounded by other material. For the IP response, Δ depends on the IP contrast of the units and B depends on the array geometry, system geometry, and resistivity.

Table 2. Examples of resistivities and IP response encountered in some southwestern porphyry copper deposits

Mineralized Area	Resistivity (ohm-meter)	Chargeability	
		ms	PFE
San Manuel 6% sulfide	<100	75	10
Mission 5% sulfide	<100	80-90	12
Cactus 3-5% sulfide	≈ 100	45	3
Castle Dome 4-5% sulfide	≈ 100	60-70	8-9
San Juan, Safford 5-8% sulfide	4-40	50-150	4-15
Quellaveco, Peru 3-4% sulfide	≈ 100	70-80	10
Vekol 5-6% sulfide	≈ 80	60-70	7-8
Florence 1-2% sulfide	30-40	30-40	3-4
Interconnected and massive sulfides in situ	.01-1	10-30	2-5

large relative to the depth of burial, it is intuitively apparent and can be mathematically demonstrated that the weighting coefficient associated with the overburden and enclosing rocks will be small, and the coefficients associated with the mineralization will be relatively large.

A survey system for just such a target is shown in Figure 2, which is a schematic diagram of the dipole-dipole survey array probing for a well-altered and mineralized zone covered by overburden of variable thickness. Implied in the diagram are the conditions that the size of the target zone is much larger than the IP electrode spacing and that the body is substantially thicker than its depth of burial. This hypothetical mineralized zone might approximate the pyrite halo that surrounds many southwestern porphyry copper deposits where pyrite mineralization might run to 5 or 6 percent; the intrinsic IP response would be as high as 70 milliseconds, or 10% frequency effect so that the response of the body is 10 times background.

The IP response measured at surface of the body (shown in Fig. 2), obtained by commonly used IP survey configurations, can be calculated using algorithms developed by the coauthor of this paper, Elliot, and M. Nabighian of Newmont Exploration (Elliot, 1974). From these operators, the IP effect or chargeability measured at surface using the dipole-dipole array and a spacing of 1,000 feet, for the body shown in Figure 2, buried at 300, 1,000,

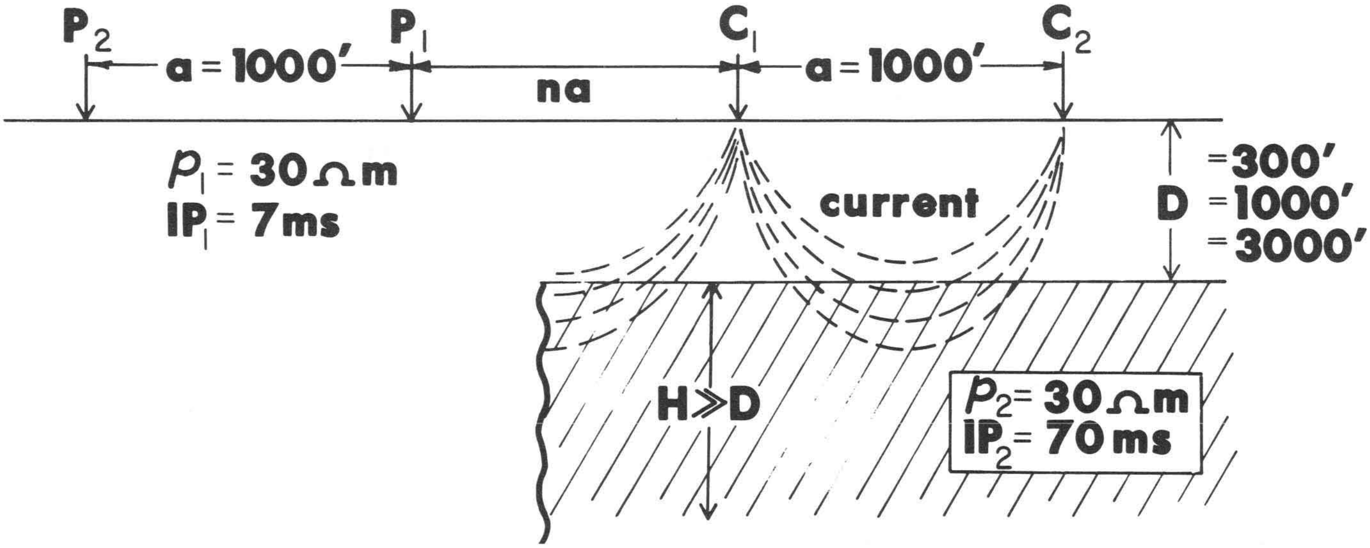


Fig. 2. Schematic diagram showing the dipole-dipole IP survey array and current lines penetrating a buried target zone. The IP response measured at surface for any reading point is $IP_a = B_1IP_1 + B_2IP_2$.

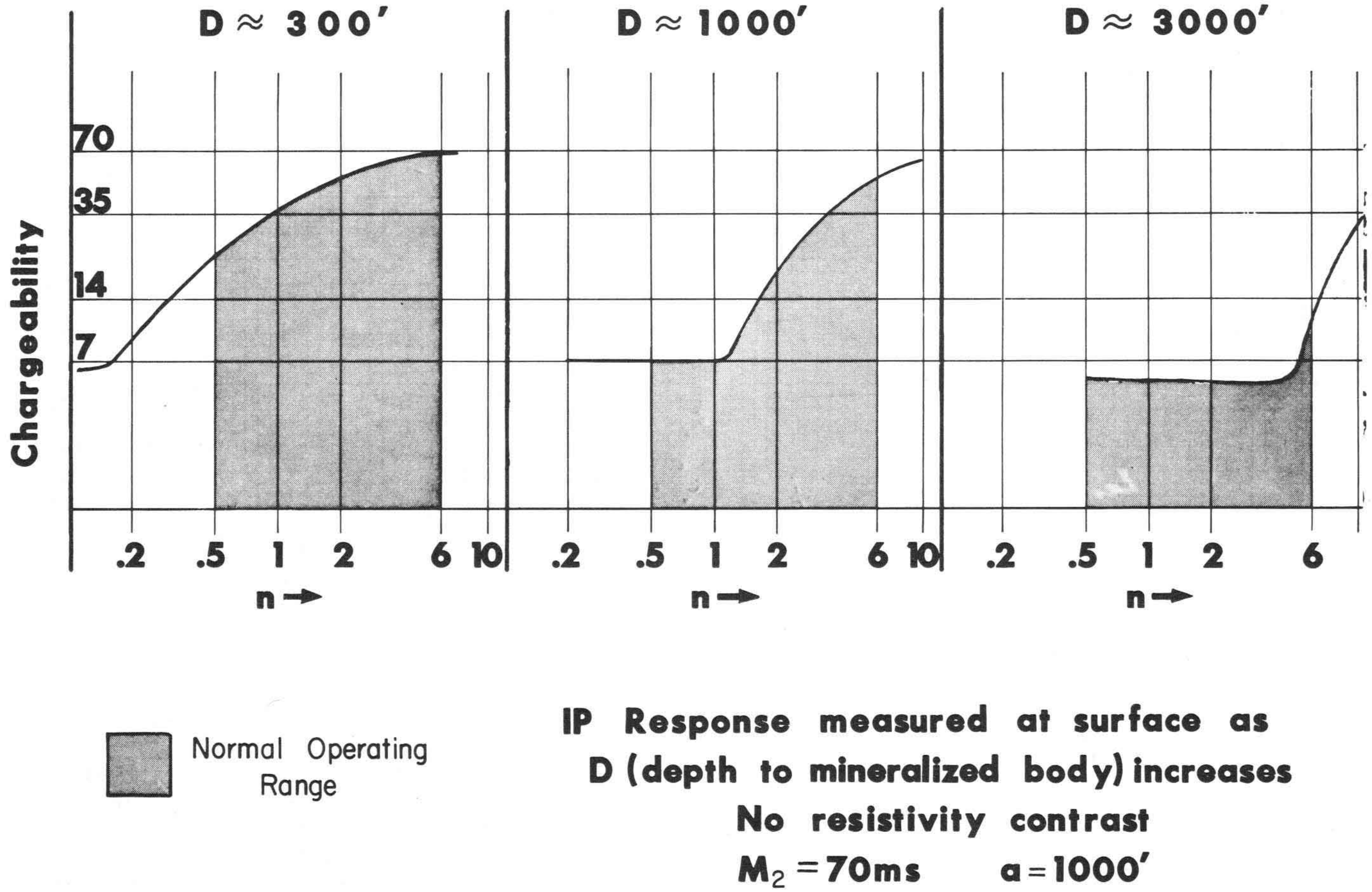


Fig. 3. IP response from the model shown in Figure 2 at depths of 300, 1,000, and 3,000 feet

and 3,000 feet has been calculated and is presented in Figure 3. In these cases there are no resistivity contrasts between the overburden and the target body and the apparent IP at surface is controlled by the intrinsic response and target-sensor geometry only. At a depth of 300 feet, the observed chargeability for n greater than about 2 is almost the same as the intrinsic or theoretical chargeability. Even at an n value of 1, the apparent IP effect is about 36 milliseconds (5 x background) and detection of the body at this depth by the IP method is almost trivial. As the depth to the body increases, the response falls off for any given n value. At a depth of 1,000 feet, an anomalous response is limited to the larger n values, and at 3,000 feet the body is just barely detectable. Within the normal operating range of survey systems, for an electrode spacing of the order of the depth of burial, a strongly anomalous IP effect is obtained from large bodies throughout most of the operating range, perhaps suggesting the popular rule of thumb that the "search depth" of a particular IP survey system should be approximately equal to the electrode spacing. Unfortunately, the interpretation of field cases is not this simple since response factor 4 in the above list, namely the resistivity contrast, has been ignored, and factor 3, the physical dimensions of the system, is assumed to be always much larger than the electrode spacing.

The IP effect at surface of a responsive body falls off appreciably if the size conditions implicit in Figure 2 are not met. Rather than the infinitely large body considered in Figure 2, the target might be a pluglike body, which is approximately 2,000 feet across and buried at depths of 2,000 or 4,000 feet as shown in Figure 4; the intrinsic response of the tabular body is 10 times that of the surrounding media. The IP response measured at surface for this body, using dipole spacings equal to the depth of burial, has been calculated, and is shown in Figure 5. A recognizable anomaly is apparent for the case where the depth of burial is 2,000 feet, but the anomaly almost disappears when the target depth increases to a little over 4,000 feet. Assuming that a survey incorporating a 4,000-foot dipole spacing could be practically executed, the measured anomaly is now barely twice the background and its chances of being detected and recognized under any practical field conditions, where significant amounts of noise will be included in the apparent IP measurement, becomes very much reduced. Further, if the chargeability contrast between the target and enclosing rocks is less than the 10 to 1 shown, the measured anomaly would be even smaller. By using sophisticated electronic circuitry and specialized survey techniques, noise from electrical sources over such dipole lengths can be held low enough so that usable data could be obtained, but noise from geological sources cannot be suppressed inasmuch as it is represented by a true IP signal.

The limitation on depth imposed by the size of the body as illustrated in Figures 4 and 5 is not significant if the IP method is applied to exploration for southwestern porphyry copper systems at shallow depths of 300 to 400 feet. Lowell and Guilbert (1974) describe the "typical" porphyry copper as presenting an oval subcrop pattern having dimensions of 3,000 x 6,000 feet. Frequently the associated pyritic halo is of even larger dimensions. In this case the entire IP survey array of potential and current electrodes can be spread out four or more times the depth of burial and not violate the condition that the target body be large relative to the electrode spacing. Nevertheless, the responses shown in Figure 5 from the models in Figure 4 do suggest an ultimate exploration depth limit imposed by the target size.

Survey conditions encountered in the field produce much less reliable data than the ideal models presented in these figures. Under field conditions physical property contrasts and layer thicknesses are not uniform and the resistivity contrast between the target zone and surrounding materials is usually quite significant. Articles by Rogers (1966) and Maillot and Sumner (1966) point out that porphyry copper systems can be either more resistive or less resistive than the overburden and host rocks. Where porphyry copper systems are shattered and porous, the resistivity will be relatively low; if on the other hand the fractures have been filled with silica, the resistivity of this same basic system will be much higher. Tables 1 and 2 show the resistivity range of some porphyry copper systems and of some typical host rocks. The flow lines of the charging or inducing electrical current from an induced-polarization survey system will tend to concentrate in the lower resistivity material. A distortion of the current flow lines under these contrasting resistivity conditions is shown schematically in Figures 6 and 7. If the overburden or enclosing rocks are less resistive than the target, as illustrated in Figure 6, a greater amount of the current will flow within the enclosing rocks and will avoid the target. Similarly, if the target consists of a low-resistivity material, as in Figure 7, the current flow will be trapped and cannot escape to affect the measuring electrodes.

The response that could be expected from the body illustrated in Figures 6 and 7 for burial depths of 300, 1,000, and 3,000 feet using a dipole-dipole electrode array with a

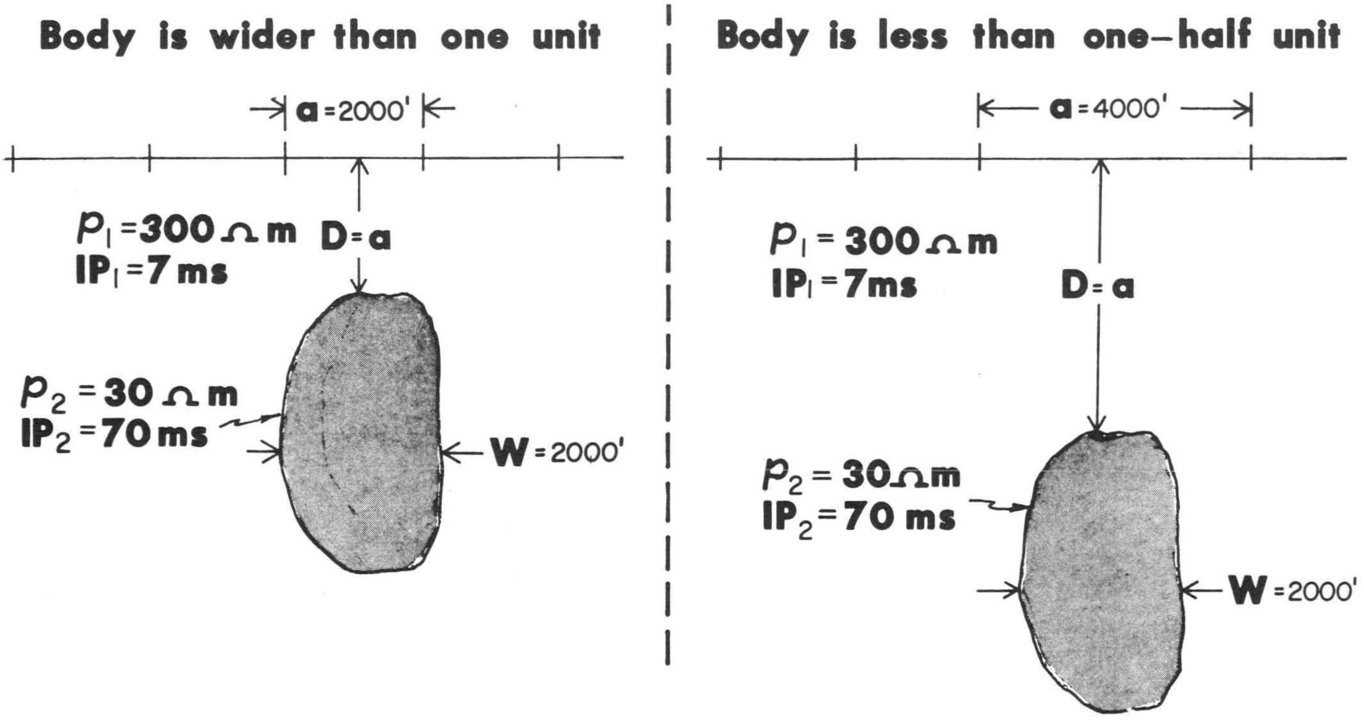
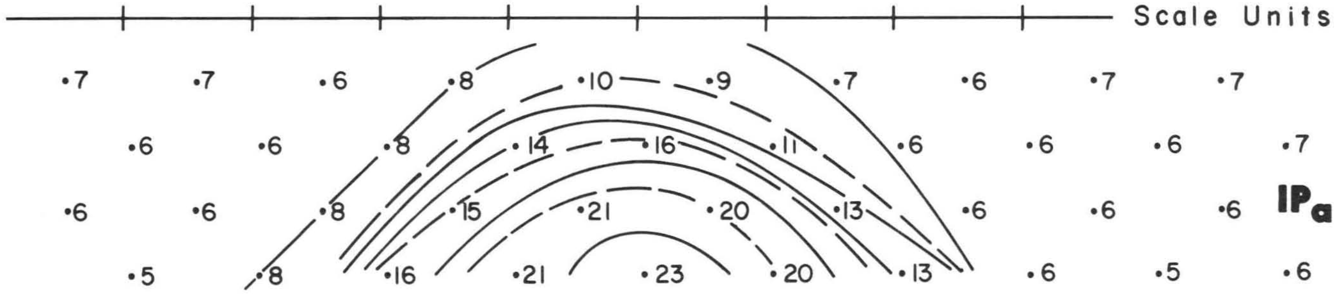
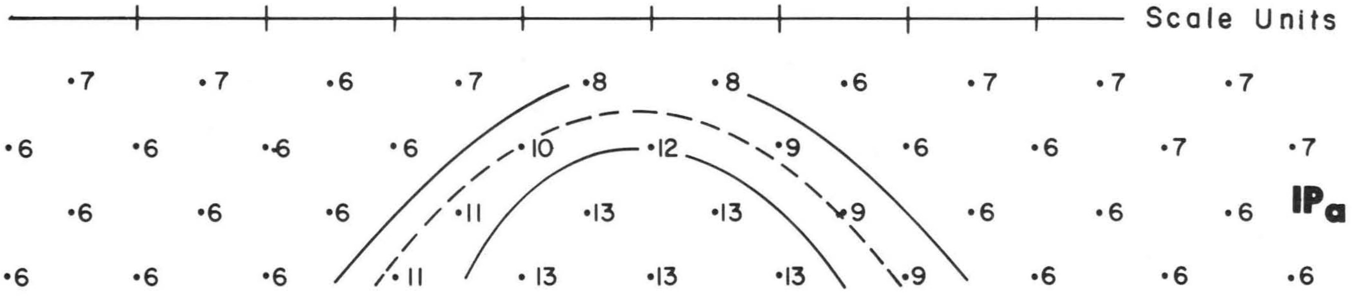


Fig. 4. Model porphyry copper target buried at 2,000 and 4,000 feet



Expected IP Response from a thick wide source.
Scale: 1 unit = 2000'



Expected IP Response from a narrow deep source.
Scale: 1 unit = 4000'

Contour Intervals —— 2ms — — 5ms

Fig. 5. Expected IP response from source shown in Figure 4; response at depth 2,000 feet above and 4,000 feet below. No electrical, cultural, or geologic noise assumed.

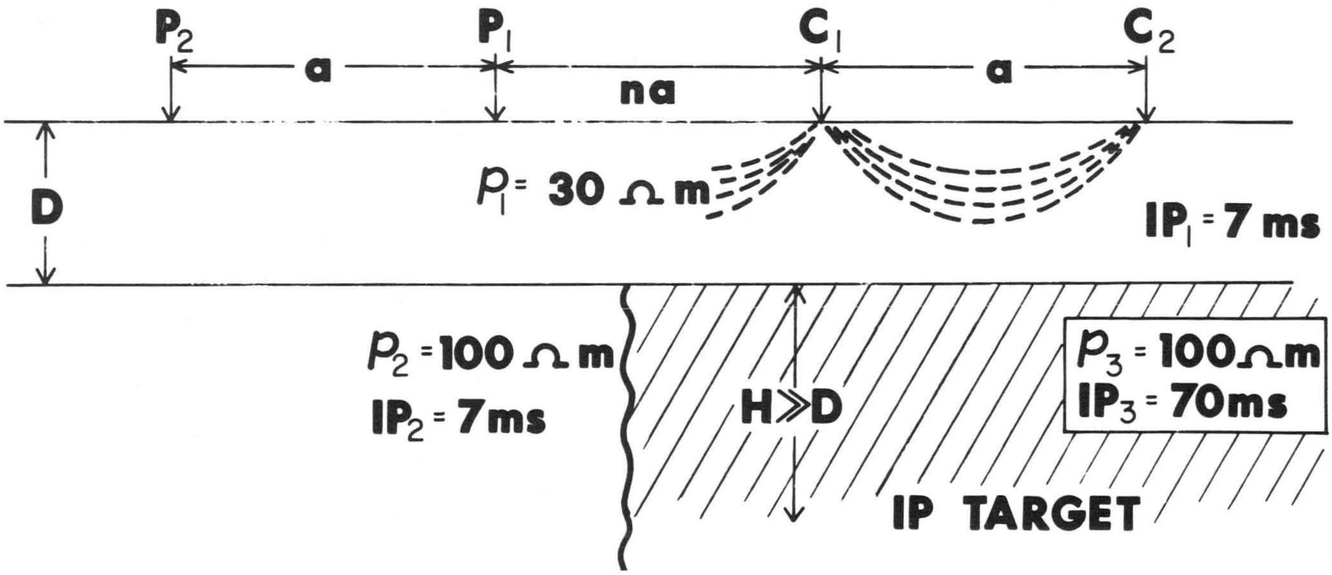


Fig. 6. Schematic diagram showing distortion of current lines from IP survey electrodes if source is more resistive than overlying material. The IP response is $IP_a = B_1IP_1 + B_2IP_2 + B_3IP_3$.

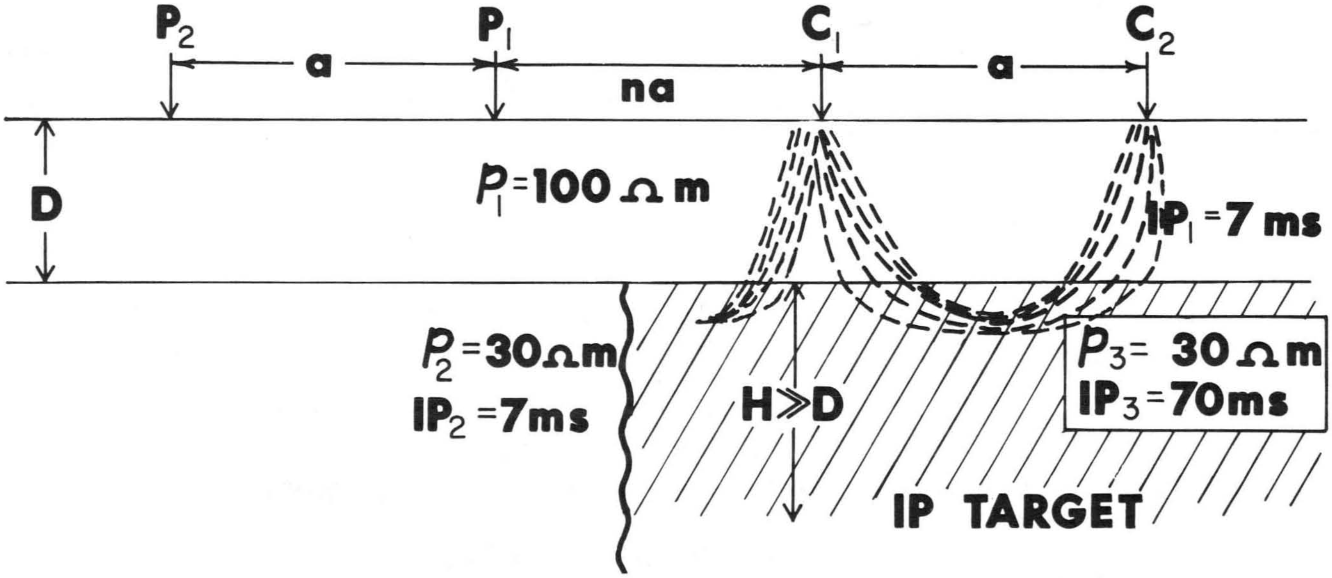


Fig. 7. Schematic diagram showing distortion of current flow from IP survey electrodes if IP target is less resistive than overlying rocks. The IP response is $IP_a = B_1IP_1 + B_2IP_2 + B_3IP_3$.

spacing of 1,000 feet is shown in Figure 8. The solid curve represents the optimum no-resistivity contrast and is simply a repeat of the response shown earlier. The dashed curve indicates the response that could be expected if the overburden resistivity is 1/3 the resistivity of the target material. The dotted curve illustrates the response that could be expected if the overburden resistivity is greater than that of the target zone. In both cases of resistivity contrast, no matter whether the overburden is more or less resistive than the target, the IP response at surface is reduced from the optimum obtained with no resistivity contrast, and if the resistivity of the cover is lower than that of the mineralized target zone, the body is just barely detectable within the envelope of information normally supplied if the <u>a</u> spacing is of the order of the depth of burial. Chances of recognizing a body under these conditions at a depth of 1,000 feet would be improved if the electrode spacing were increased to something like three times the expected depth of burial, but the noise level and logistics problems that would be encountered with 3,000-foot-long dipoles might make the survey unfeasible.

Even the simple resistivity contrast situation shown here is relatively ideal. The material covering porphyry copper systems, particularly those at depth, frequently consists of two or more components of different resistivity. The overburden might consist of dry and wet gravels, or the cover can be unmineralized rock, which is in turn overlain by sand, gravel, or clay. A realistic, if not typical, porphyry copper exploration case is shown in Figure 9 where the total overburden thickness approaches 1,000 feet. Here a high-resistivity silica mineralized zone, which is 10 times more responsive than the enclosing rocks, is covered by 700 feet of lower resistivity volcanics and an additional 300 feet of low-resistivity gravel. A pseudosection showing the apparent chargeability measured at surface for the dipole-dipole array using 1000-foot spacing (the depth of burial of the body) is shown in Figure 10. Within the normal operating range, the body is just barely detectable

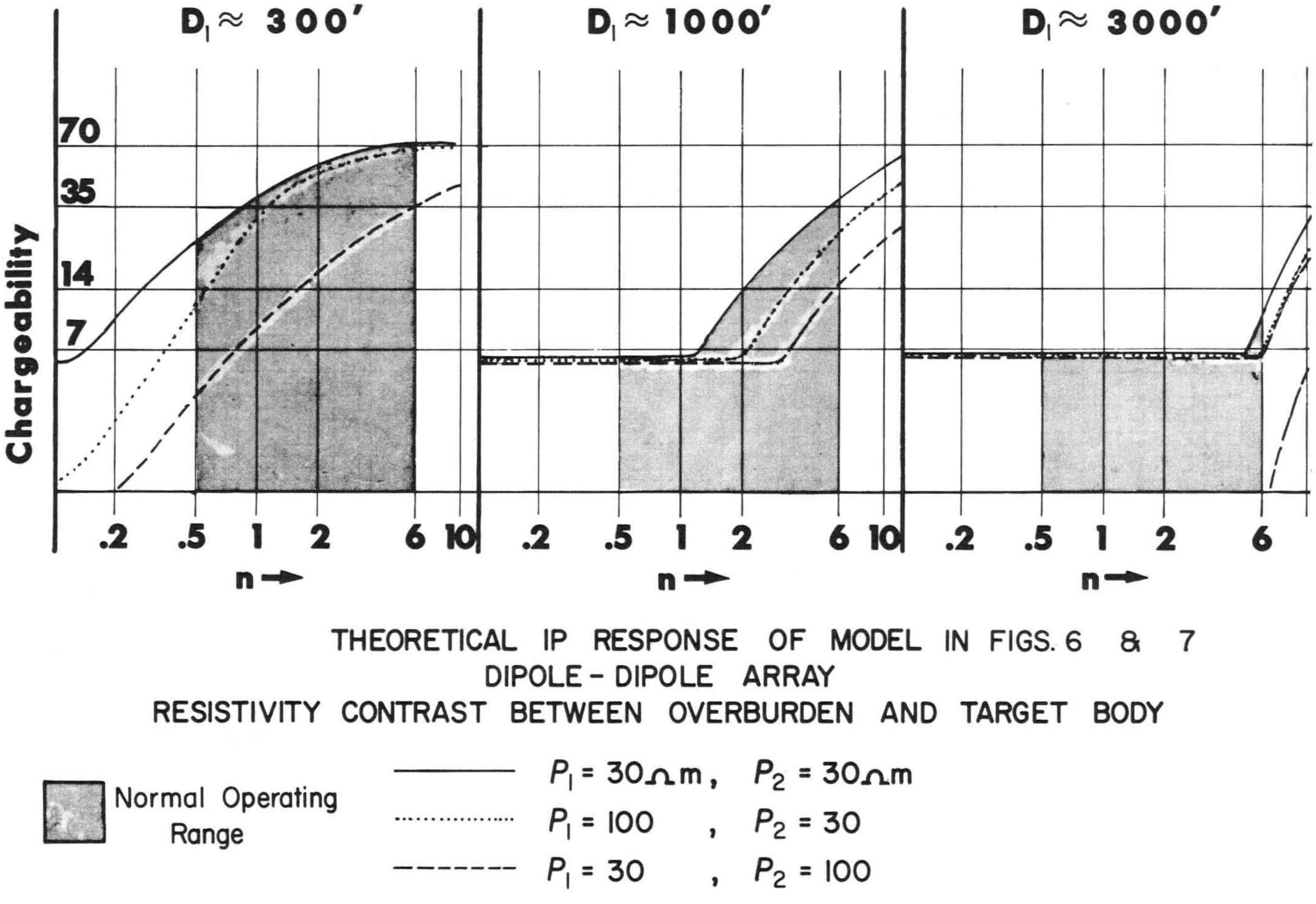


Fig. 8. IP response from model shown in Figures 6 and 7

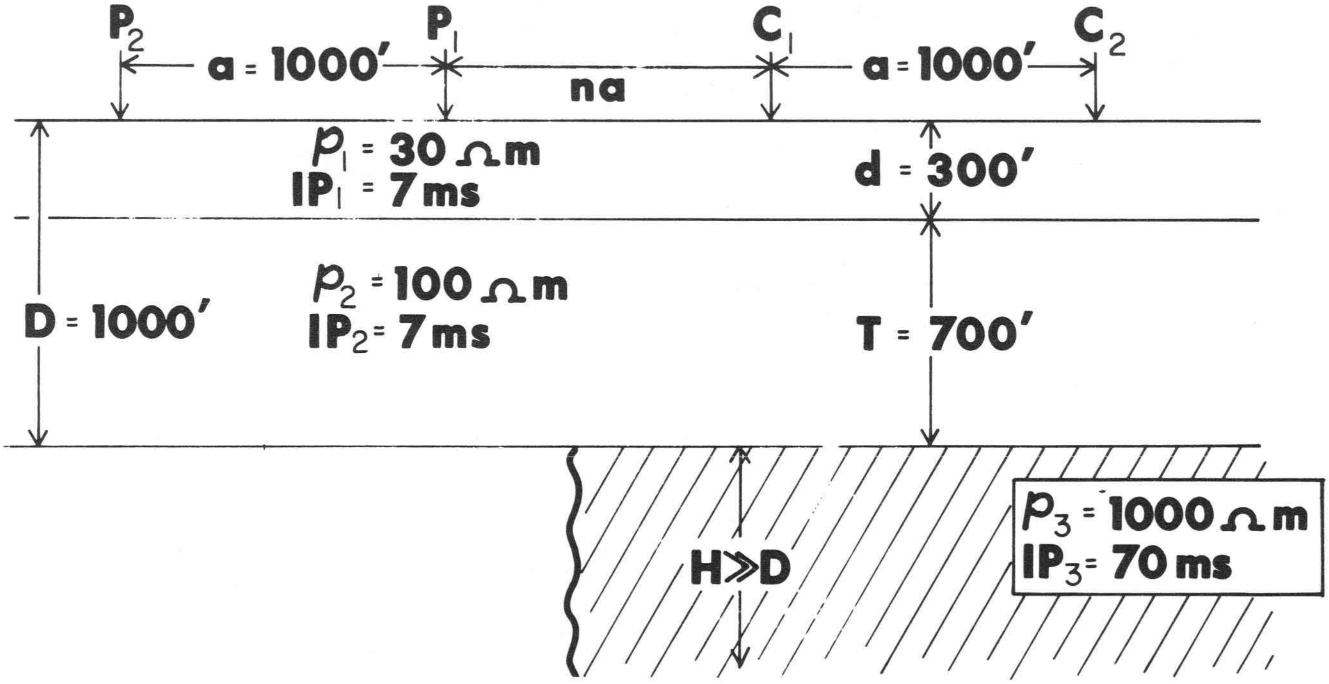


Fig. 9. Three-layer IP target model. High-resistivity target (4% highly silicified sulfide body) overlain by two resistive overburden layers.

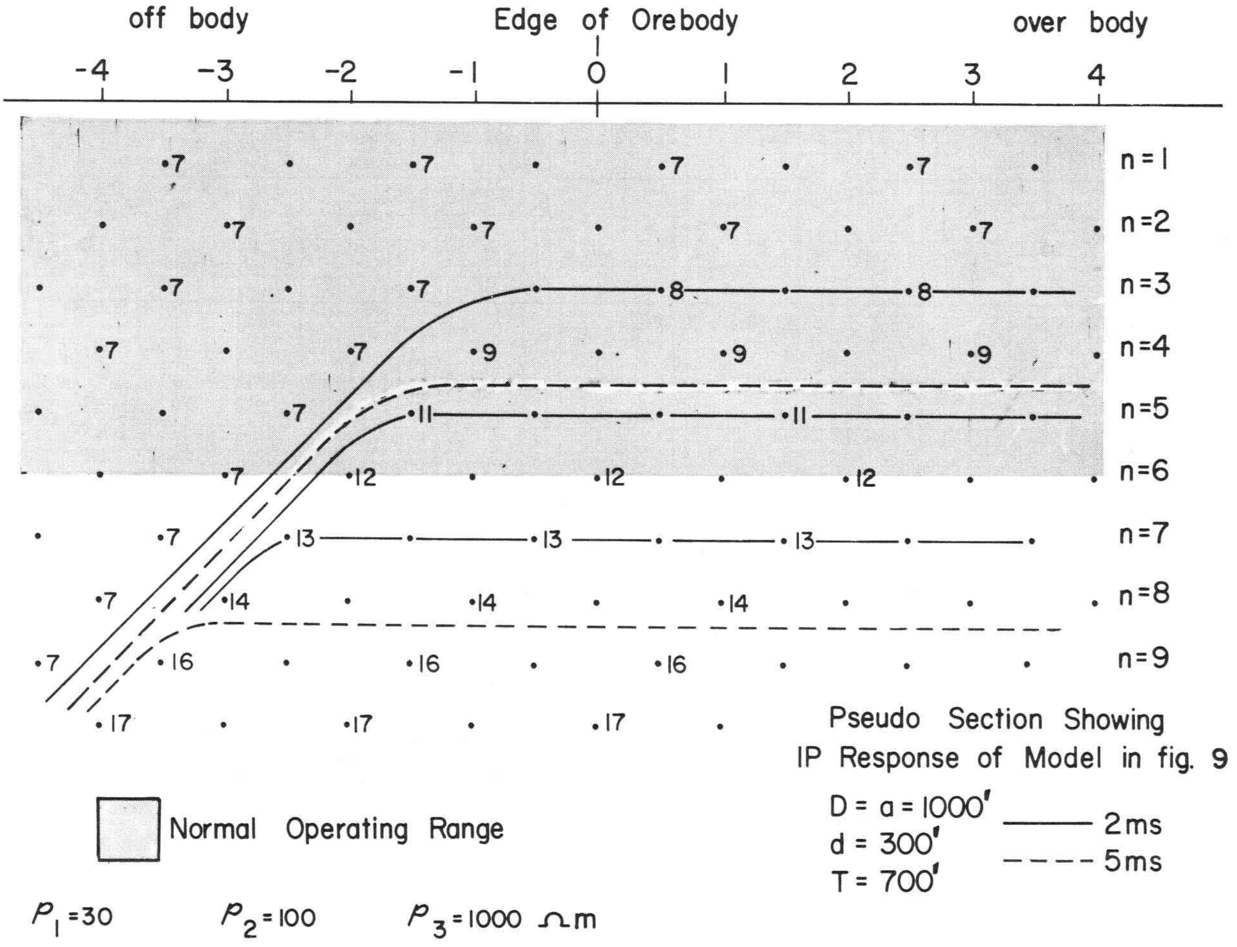


Fig. 10. IP response from model shown in Figure 9

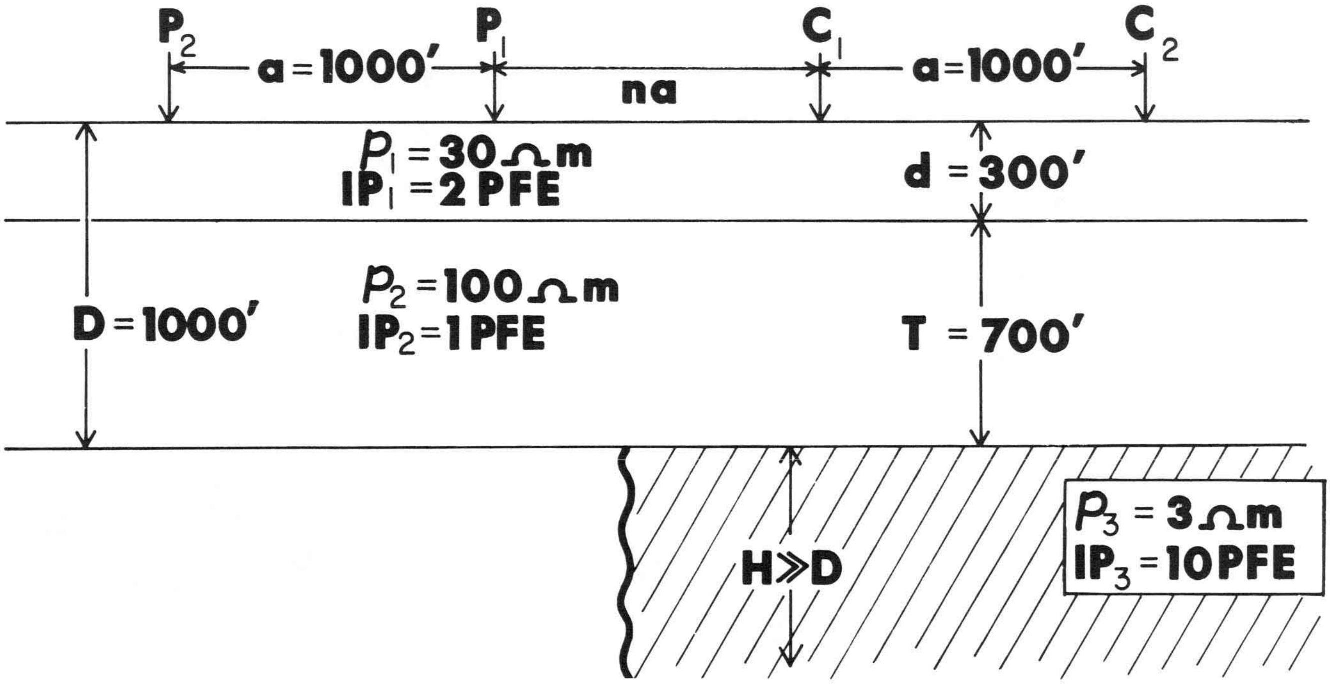


Fig. 11. Three-layer IP target model. Low-resistivity target (4% highly fractured sulfide body) overlain by two-layer resistive overburden.

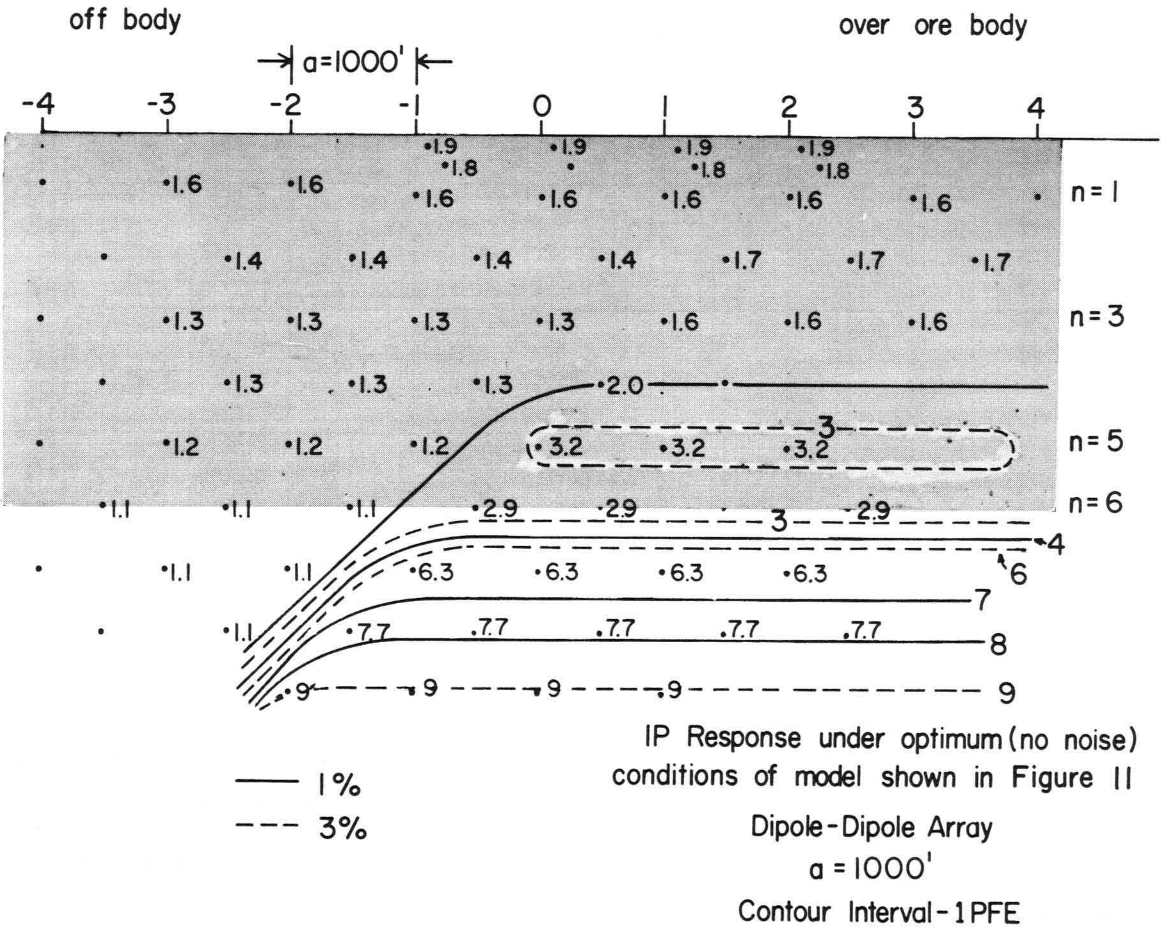


Fig. 12. IP response from target shown in Figure 11

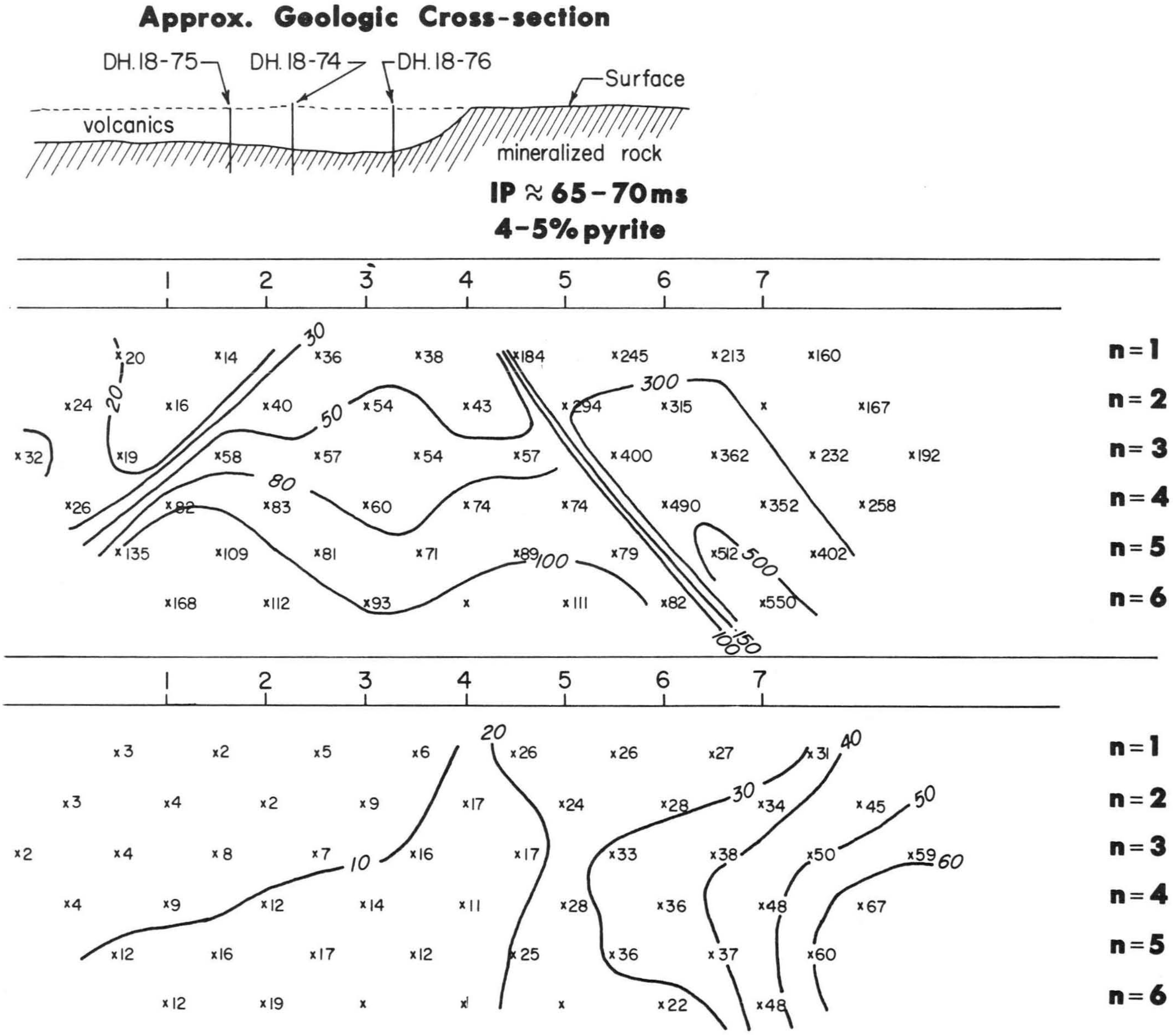


Fig. 13. IP resistivity profile, dipole-dipole array, Silverbell area. Depth to sulfide mineralization only 400 to 500 feet; dipole spacing, 1,000 feet.

under ideal non-noise conditions.

More troublesome masking effects of overburden are encountered if the target zone is well fractured and thus has a resistivity lower than the overlying units. In Figure 11, a body is shown, which is well fractured and covered by the same overburden as supposed in Figure 8, that is, 700 feet of volcanic rock and 300 feet of lower resistivity gravel, but the resistivity of the target is now 1/10 that of the uppermost overburden layer. The percent frequency effect (PFE) of the source body is still 10 times that of the overlying volcanic rock, which is 1 percent, and the response of the gravel is 2 PFE. Under these overburden resistivity conditions, the weighting coefficient for the IP response for the upper layer is negative for certain electrode configurations, and this negative contribution of the IP effect of the upper layer will cancel a portion of the response from the target zone. The theoretical pseudosection for the ideal no-noise condition for this model is shown in Figure 12. Although the body is detectable at very large n values (those of around 10 to 20), these values are impossible to obtain under field conditions.

Noise affects the depth penetration of an IP system only in that it poses some absolute limits on the electrode spacing of a particular IP survey system. With conventional equipment in the dipole-dipole configuration, this limit is somewhere around 1,500 feet under resistivity conditions frequently encountered in the Southwest. Although this spacing can certainly be increased by the use of more modern techniques, the noise from geological sources is ever present and tends to increase as the spacings enlarge.

In exploring for porphyry copper systems at depths of 1,000 feet or more by the IP method, the search depth of the now-limited electrode array spacing is restricted almost entirely by the resistivity distribution of the media enclosing the porphyry copper target. In cases where these resistivities are uniform and equal to that of the target, the depth of penetration of an IP system can be almost twice the maximum obtainable electrode separation; detection of targets at 2,000 to 3,000 feet would not be unachievable. However, in cases where the resistivity contrast between the target and the overburden material acts to masked the response from the targets, the depth of penetration might be limited to half or third of the maximum electrode spacings and could be as little as 500 feet if conventional gear is used under noisy conditions. In this instance, exploration would have to proceed utilizing some other method. The figures quoted above will change for different electrode arrays and configurations, but the search depth of the dipole-dipole electrode array provides a general guide to the limitations of detectability of porphyry copper occurrences that will be encountered under most circumstances.

It is important to note that the response is significantly affected by the upper layer. In cases where depth of burial is of the order of 1,000 feet and the upper layer is only 100 feet or so thick, one might be tempted to ignore this relatively thin layer, but doing so might introduce serious interpretational problems. As IP target depths increase, it is necessary to analyze with increasing detail the resistivity of the overlying materials and particularly that of the near-surface layers.

An example of the masking of IP effects by a relatively thin cover of conductive overburden is shown in Figure 13, which shows the IP pseudosection corresponding to a geologic section through a mineralized area near Silverbell, Arizona; the dipole-dipole array with 1,000-foot a spacings was used in the survey procedure. The mineralized body, which nearly crops out on the east side of the section, dips under cover and is buried by a little over 300 feet of conductive gravel and volcanic rocks. The strong IP response seen on the east side of the pseudosection almost disappears in the covered area. A proper interpretation of the IP section in this area would certainly reveal the mineralized body, but the change in response for a relatively minor change in depth of cover is quite striking. The a spacing is three times the depth of burial, but the measured anomaly is only slightly better than marginal.

This example illustrates the point suggested by all the above material that there is no set search depth or spacing of IP electrodes that will meet all conditions. Each survey situation must be evaluated within the context of its own characteristics and restrictive conditions, and these conditions must be determined in each particular survey area before the depth penetration of an IP system can be evaluated.

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