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## AN ANALYSIS OF THE BIPOLE-DIPOLE METHOD OF RESISTIVITY SURVEYING

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**Abstract**—Bipole-dipole (B-D) resistivity mapping has been widely used as a reconnaissance method in geothermal exploration. In this technique, apparent resistivities are plotted at roving dipole receiver locations and the current source (bipole) is left fixed. Interpretation to date has been in terms of simple, layered, dike, vertical contact, or sphere models. In the case of more complicated two-dimensional models the interpretation is much more ambiguous and the detection of buried conductors depends very much on the choice of transmitter location. Since apparent resistivities taken on a line collinear with the dipole are roughly equivalent to the apparent resistivities for one sounding in a dipole-dipole (D-D) pseudo-section, the two methods have been compared for several two-dimensional models.

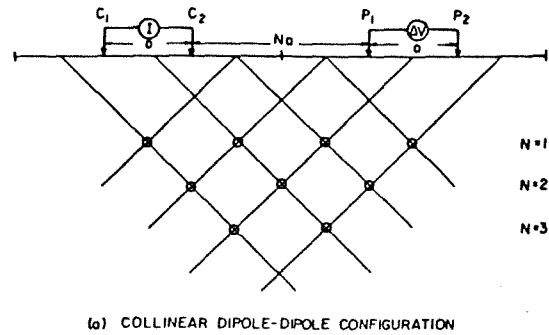
A buried quarter space and a buried horizontal cylinder of rectangular cross section, with or without an overburden layer, have been used in the comparison. Unless the target is very shallow or close to the bipole or dipole, the resolution of the horizontal position or depth extent for the B-D method is very poor. Conductive overburden worsens the situation for both methods but the effect is more drastic for the B-D method. The spatial patterns for these models is complex for the B-D method and in fact for certain transmitter positions only subtle differences exist for the buried cylinder and buried quarter space models. Multiple sources improve the resolution of the B-D method, but many sources coupled with the high sampling density of receivers required to define the spatial patterns would greatly reduce the cost effectiveness claimed for this method. Changing the bipole orientation with respect to the strike of the models contributes little if anything to the resolution of the models. A further experiment of calculating a residual map by subtracting the half-space or layered half-space response from the response of the buried models was also unsuccessful in improving the interpretability of the B-D method. Finally, a model representative of a typical Basin-and-Range valley with and without a hypothesized geothermal reservoir shows that in more complex models the B-D map would not, in a practical survey, reveal the reservoir.

From these model studies it is clear that, except for some simple geologic situations, the B-D method is not effective for subsurface mapping. Selected D-D lines would be far more useful and more cost effective.

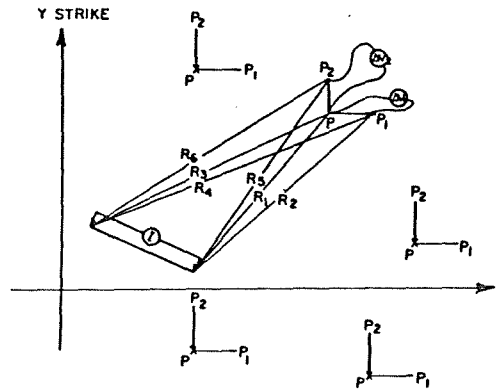
### INTRODUCTION

Electrical resistivity distribution in the earth has been shown to be useful in the delineation of geothermal reservoirs. For the measurement of the electrical resistivity a pair of electrodes is used to inject a known d.c. current in the ground and the distribution of the d.c. potential or field is measured with a second pair in a surrounding area. Various combinations of the electrode deployment have been in use for purposes of sounding (determination of the vertical variation in resistivity assuming no lateral change) or profiling (determination of lateral changes in resistivity extending up to an assumed fixed depth of search).

In geothermal reservoir delineation work two different electrode configurations are commonly employed. One of these is the bipole-dipole mapping method and the other is the collinear dipole-dipole profiling method. In the collinear dipole-dipole configuration, first described by Hallof (1957), a transmitting dipole and a receiving dipole, each of equal length,  $a$ , are deployed in line with a dipole separation of  $Na$ . This configuration is illustrated in Fig. 1(a). The entire configuration is first moved along a survey line with a fixed dipole separation ( $N = \text{constant}$ ), in a resistivity profiling mode. The traversing of the line with this configuration is then repeated with different values of  $N$  ( $= 1, 2, \dots, 10$ ) thus providing successive resistivity profiles with progressively increasing depth of search. The resulting apparent resistivity data is plotted in the standard pseudo-section form, in between the transmitting and the receiving dipole. At the end of a survey along a line, this technique, therefore, yields a combination of both profiling and sounding mode data. The collinear dipole-dipole technique has found widespread application in mineral



(a) COLLINEAR DIPOLE-DIPOLE CONFIGURATION



(b) BIPOLE-DIPOLE MAPPING CONFIGURATION

Fig. 1. The electrode arrangements for (a) the collinear dipole-dipole and (b) the bipole-dipole mapping configurations.

exploration, regional geologic mapping and detailed high resolution structural surveys. The response of this technique generally provides a high resolution of lateral variation in resistivity, good depth of search and relatively small effects from shallow, thin "geologic" noise sources. A comparison of the response of this dipole-dipole method with those of the pole-dipole, Unipole and Schlumberger profiling arrays, over two dimensional resistivity structures, is shown by Dey *et al.* (1975). A similar analysis has been presented by Coggon (1971). A thorough comparison of the Schlumberger and dipole-dipole methods has been made by Beyer (1977).

In the bipole-dipole mapping configuration, the earth is energized by a pair of current electrodes fixed at a given location. The dimension of this transmitting dipole is usually large, of the order of 2-5 km, and the source dipole is called a "bipole". The electric fields or the potential differences between small receiver dipoles, usually oriented orthogonally, are then mapped in detail on the surface of the earth in a region surrounding the transmitting bipole. Variations in electric field behaviour between adjacent receiver locations can be identified with changes in earth resistivity in the proximity of the receiver stations, rather than with earth properties at the source location or at points between the source and receiver (Keller *et al.*, 1975). This method is a variation of the equipotential survey technique described by Heiland (1940) and has recently been extensively used in geothermal reservoir exploration (e.g. Risk *et al.*, 1970; Keller *et al.*, 1975; Stanley *et al.*, 1976).

In the early applications of resistivity techniques to geothermal exploration, the bipole-dipole mapping method gained substantial prominence because of the rapidity and ease of operating procedures as a practical reconnaissance method. In large survey areas for geothermal exploration, it is logistically much more attractive to have a fixed transmitting bipole and a large number of roving orthogonal receiver dipoles. Many more current electrode preparations are

required for collinear dipole surveys to cover the same areal extent. However, it soon became apparent that to define a zone of substantial changes in bulk apparent resistivity, several transmitters at different locations were required together with a rather high density of observation points. In addition, all too often, the resulting maps are used for detailed interpretation of the resistivity structure and further improvements resulted in the use of rotating bipole sources at multiple locations in the survey area (Furgerson and Keller, 1974). With these additions, the logistic complexity and the time required to obtain a full set of data in an area are considerably increased.

To facilitate interpretation of the data obtained with either configuration, it is necessary to understand the response patterns obtained in the presence of two- and three-dimensional inhomogeneous geologic models. If the section of interest is homogeneous or uniformly layered, any of the resistivity techniques yield simple responses that are easily understood and interpreted. In most geothermally promising environments, the assumption of a simple layered subsurface is often untenable. The response patterns for the collinear dipole-dipole method to a wide variety of two- and three-dimensional structural models are fairly well understood from various published work based on analog model studies (McPhar Geophysics, 1966; Dey, 1967; Apparao *et al.*, 1969) as well as numerical simulations (e.g. Coggon, 1971; Van Nostrand and Cook, 1966; Dey *et al.*, 1975; Bakbak, 1977; Dieter *et al.*, 1969; Beyer, 1977). The response for the bipole-dipole mapping method, however, is presently understood only for layered earth, single outcropping contact, outcropping dyke with infinite depth-extent with or without an insulating basement (Van Nostrand and Cook, 1966; Vedrintsev, 1966), and for a buried conducting sphere (Singh and Espindola, 1976). Some of these response patterns have been illustrated by Keller *et al.* (1975) and Doicin (1976). The response of an outcropping hemispherical inhomogeneity was studied by Bibby and Risk (1973). Little information is available (Mazzella and Dey, 1973) to study the response patterns for the bipole-dipole mapping method over buried resistivity inhomogeneities of simple or complex shapes. Consequently, most of the bipole-dipole mapping data, to date, is interpreted using the tenuous assumption that the section under consideration is uniformly layered and by transforming the mapped data to equivalent Schlumberger expansion sounding curves (Zohdy, 1973).

The reported successes of the bipole-dipole technique have been associated with the delineation of resistivity discontinuities outcropping at or very near the surface. An example is the interpretation by Risk (1970) of the Broadlands geothermal region using a hemispherical sink. Continuity of current necessitates a strong electrical gradient across the boundaries of such models. This would be a common feature of any electrical survey. In rough terrain, or in cases with difficult access, where the geothermal systems are shallow the bipole-dipole method offers great logistic advantages and can be used quantitatively for outlining the system.

The purpose of this report is to show the response patterns for the bipole-dipole mapping method for more complex buried inhomogeneities. This analysis has been effected for the most part using two dimensional models. A few examples of three-dimensional models are also presented. The effects of depth of burial, source bipole orientation with respect to the strike, overburden layer thickness and conductivity and distance from the transmitting bipole for a single block-shaped conductive target are illustrated. Certain characteristic diagrams are derived for the response of the single inhomogeneity and the responses are compared to those obtained from a collinear dipole-dipole array over identical models. In a following section, a typical North-Central Nevada valley section is simulated with and without the presence of a postulated conductive reservoir. For this structural model, the source bipole is rotated with respect to the strike direction at two different locations and the response patterns for these various configurations are illustrated. A comparative analysis of the response patterns obtained with the collinear dipole-dipole configuration over the same models, is also made.

## DEFINITION OF PARAMETERS

The geometric configurations of the collinear dipole-dipole and the bipole-dipole mapping arrays are shown in Fig. 1(a and b), respectively. For a specified geometry of the array the potential difference observed at the receiver dipole is converted to an "apparent resistivity" of the earth. "Apparent resistivity" is a traditional interpretive parameter used in resistivity surveys, and it indicates the resistivity of an isotropic, homogeneous half-space that would give rise to an identical potential difference for the specific geometry of the array under consideration.

For the collinear dipole-dipole array with a dipole length of  $a$  and a dipole-separation of  $Na$ , as illustrated in Fig. 1(a), the apparent resistivity,  $\rho_a$ , is defined as:

$$\rho_a = \pi N (N + 1) (N + 2) a \cdot \frac{\Delta V}{I} \quad (1)$$

For the bipole-dipole mapping configuration, an orthogonal set of roving receiver dipoles, usually oriented parallel and perpendicular to the current bipole, is used to measure the potential differences for a fixed location of the transmitter bipole. A commonly used parameter is an apparent resistivity defined in terms of the magnitude of the total  $E$ -field or the total potential difference at a receiver station irrespective of its direction (Risk *et al.*, 1970; Furgerson and Keller, 1974). If the distance to the receiver is large compared to the receiver dipole length and large compared to the transmitting dipole dimension, the potential difference observed at any receiver dipole, normalized by its length, is a close approximation to the component of the electric field at the receiver point. The apparent resistivity could be obtained using the magnitude of the resultant electric field, with the formulation given by Keller *et al.* (1975). However, close to the transmitting dipole (within a radius of 3 bipole lengths) such approximations for the point electric field could lead to gross errors. The changes in the curvature of the current lines and the spatial rate of change of the electric field, in this zone, from an equivalent half-space are rather severe, if the receiver dipole length is greater than 1/50th the transmitting bipole length. An equivalent formulation for the apparent resistivity is, however, easily done for small receiver dipoles, using the potential differences, rather than the electric field, in the direction of each of the orthogonal dipoles. The use of potential differences eliminate the fictitious distortions in calculated apparent resistivity caused by the point electric field approximation made for non-infinitesimal receiver-dipole lengths.

The geometric configuration with the relevant distances for the dipole-dipole mapping array is illustrated in Fig. 1(b). If  $\Delta V_1$  and  $\Delta V_2$  are the potential differences measured between the receiver dipoles  $PP_1$  and  $PP_2$ , respectively, the apparent resistivity,  $\rho_a$ , based on the magnitude of the resultant potential, is given as:

$$\rho_a = 2\pi \frac{\sqrt{\Delta V_1^2 + \Delta V_2^2}}{I} \cdot \frac{1}{\sqrt{G_1^2 + G_2^2}} \quad (2)$$

$$\text{where } G_1 = 1/R1 - 1/R3 - 1/R2 + 1/R4$$

$$\text{and } G_2 = 1/R1 - 1/R3 - 1/R5 + 1/R6 .$$

In bipole-dipole mapping surveys, when the section under consideration is underlain by a resistive electrical basement, the computation of resistivity based on a cylindrical spreading of current through a thin plate is deemed more appropriate (Keller *et al.*, 1975). With these assumptions, the ratio of plate thickness to resistivity ( $h/\rho$ ), known as conductance, may be calculated. Using the observed potential differences between the orthogonal pair of dipoles, illustrated in Fig. 1(b), an "apparent conductance" may be defined as:

$$S_a = \frac{I}{2\pi} \cdot \frac{\sqrt{G_3^2 + G_4^2}}{\sqrt{\Delta V_1^2 + \Delta V_2^2}} \quad (3)$$

where  $G_3 = \log_e (1/R1) - \log_e (1/R3) - \log_e (1/R2) + \log_e (1/R4)$

and  $G_4 = \log_e (1/R1) - \log_e (1/R3) - \log_e (1/R5) + \log_e (1/R6)$ .

It is to be noted that for the bipole-dipole mapping configuration, a measurement parameter similar to apparent resistivity, in concept, could be developed in several other ways. For example, each of the orthogonal receiver dipoles could be individually used to produce two 4-electrode configurations and consequently apparent resistivity maps in two fixed directions (e.g. perpendicular and parallel to the transmitting dipole or to the strike of the geologic section) could be obtained. In addition, since the direction and magnitude of the individual  $E$ -fields in two orthogonal directions are known, it is possible to calculate apparent resistivity in the vector  $E$ -field direction and at each observation point on the surface the deviation of the current lines from an isotropic homogeneous or a hypothesized layered subsection could be mapped as an additional diagnostic parameter.

In its present day use, the dipole mapping data is routinely reduced as an apparent resistivity and an apparent conductance map using the equations (2) and (3). In routine analysis in this laboratory, the additional parameters indicated above are also evaluated. In this paper, however, the comparative analysis will be made based on the apparent resistivity and apparent conductance obtained from the magnitude of the resultant  $E$ -field described above.

### MODEL COMPUTATIONS

The resistivity response of any arbitrarily shaped two-dimensional geologic section to the collinear dipole-dipole and the dipole-dipole mapping configurations are obtained using a numerical technique (Dey and Morrison, 1976). Finite difference approximations are obtained for the Poisson's equation by making a volume discretization of the subsurface. Potential distributions at all points in the set defining the inhomogeneous half-space are simultaneously obtained for multiple point sources of current injection to an absolute accuracy of better than 5%.

In the pseudo-sections and maps described in the following sections, the model dimensions, transmitting and receiving dipole lengths, and the distances in the horizontal and vertical planes are expressed in terms of an arbitrarily scaled unit distance. For routine geothermal exploration, this unit distance could be assumed to be equal to 1 km. Thus for comparison purposes, the dipole lengths in the collinear dipole-dipole configurations are each 1 km in length and dipole separations of up to 10 km are used. For the bipole-dipole mapping method, a transmitting bipole of length 2 km and surrounding areal extent of  $20 \times 14$  km is used for mapping purposes. In the bipole mapping method, the set of orthogonal receiver dipole pairs is assumed to be oriented parallel and perpendicular to the strike of the geologic section. At each observation point the dipoles are extended in the  $+y$  (i.e. strike) and  $+x$  (i.e. perpendicular to strike) direction from a common electrode and their lengths are 0.125 times the bipole length. Such a configuration results in a slight assymetry in the maps in regions of positive and negative  $y$ -axis values. The apparent conductance values for the bipole-dipole mapping method are normalized by the length of the transmitter (in m).

SINGLE CONDUCTIVE INHOMOGENEITY

A comparison of the response patterns of the two configurations can first be made with a simple model of a buried, single conductive block-shaped inhomogeneity in a half-space. For this purpose, a rectangular conductive block of cross-sectional area  $2 \times 2$  km is used. The responses of the block inhomogeneity to the two configurations for various depths of burial, conductivity contrasts and overburden layer conductivities provide significant insight to the anomaly patterns to be expected from simple lateral inhomogeneities. For the bipole-dipole mapping method, the effects of transmitting bipole orientation and distance of the inhomogeneity from the transmitter are also illustrated.

RESPONSES FOR THE BIPOLE-DIPOLE MAPPING METHOD

Figures 2(a) and (b) illustrate the apparent resistivity maps obtained with the bipole mapping method over the single rectangular conductor for transmitter orientations perpendicular and parallel to the strike direction, respectively. The resistivity of the surrounding half-space is  $100 \Omega m$  and that of the inhomogeneity is  $1 \Omega m$ . The depth of burial to the top of the inhomogeneity is  $1.0$

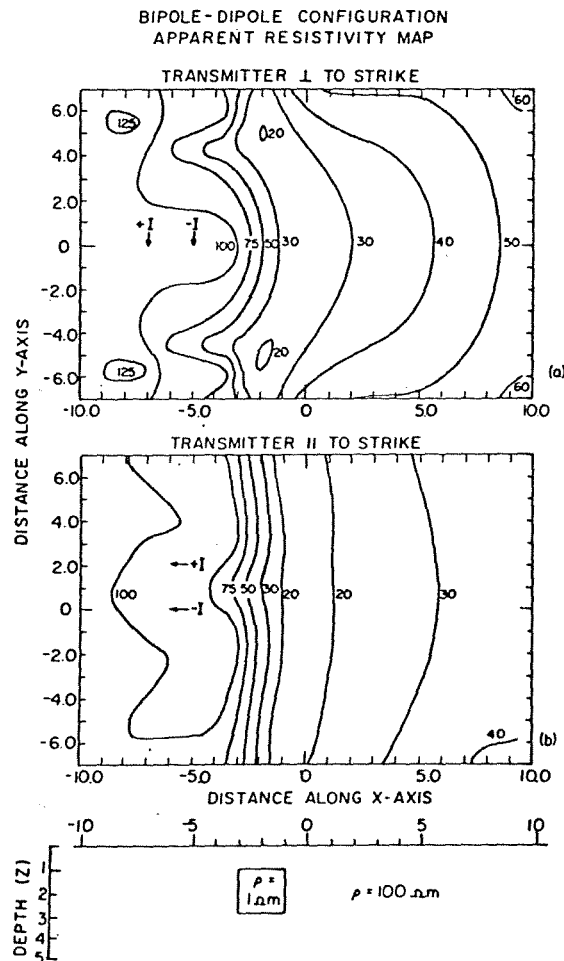


Fig. 2. Bipole-dipole apparent resistivity maps over a single, shallow inhomogeneity with the current bipole oriented (a) perpendicular, and (b) parallel to the strike.

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unit. The transmitting current electrodes are located at (7.0, 0.0) and (5.0, 0.0) for the perpendicular (to strike) orientation and at (-6.0, 0.0) and (-6.0, 2.0), for the parallel orientation, respectively. In the maps illustrated in Figs. 2(a) and (b), the shallow conductive target is located close to the bipole, the horizontal distance to the center of its projection being 4 units from the center of the transmitter. The apparent resistivity contours show a closed low contour of 30 Ω m for the perpendicular transmitter, and a closed low contour of 20 Ω m for the parallel orientation of the transmitter, that almost directly overlies the projection of the block. The contours indicate a steep decreasing gradient as the near boundary of the target is approached and a rather slow rise past the further boundary. The resistivity in the region past the body remains at a low value of 55 Ω m for the perpendicular bipole, and 35 Ω m for the parallel bipole, at distances of 11 units past the projection of the conductive inhomogeneity. In the perpendicular orientation of the transmitter, two spurious regions of closed apparent resistivity highs (125 Ω m) are observed to the left of the transmitter where no resistivity inhomogeneities exist. For the position of the inhomogeneity considered in this example an overlap of the two maps indicate a zone of low resistivity coincident with the location of the target with good resolution.

The apparent conductance maps for this location of the conductive target are presented in Figs.

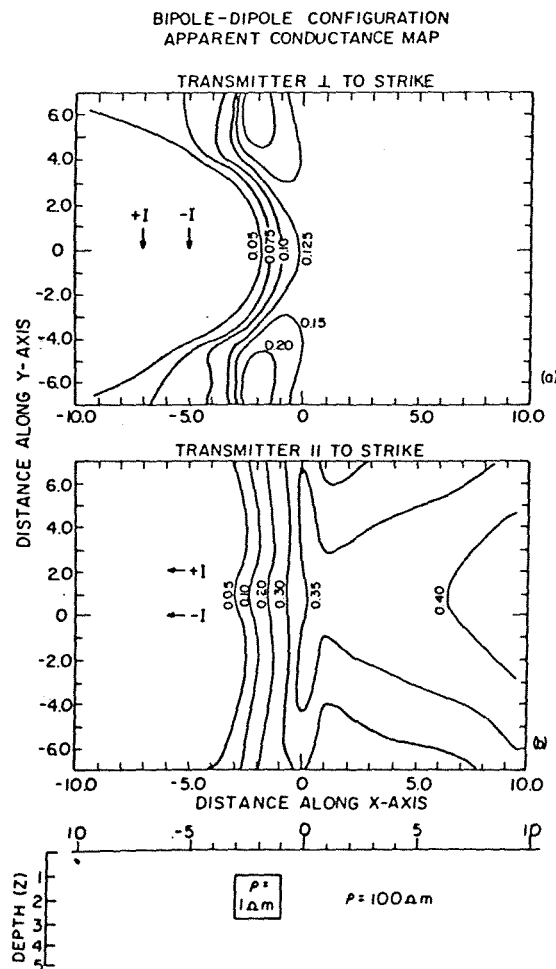


Fig. 3. Bipole-dipole apparent conductance maps over a single, shallow inhomogeneity with the current bipole oriented (a) perpendicular, and (b) parallel to the strike.

3(a) and (b), for the transmitter orientations perpendicular and parallel to the strike, respectively. In the absence of an insulating basement, the apparent conductance parameter does not have any physical significance. However, the computed parameter shows generally high apparent conductance values over the projection of the target. In the parallel bipole orientation, the highest value is reached in regions shifted considerably farther from the projection of the target.

In order to illustrate the effect of increasing distance of the bipole from the projection of the conductive target, the block-shaped inhomogeneity was shifted to the right to a position between +1 and +3 units in the x-direction and at an identical depth of burial of 1 unit. The transmitting bipoles were located at the same positions as in the previous example. The apparent resistivity maps for the bipoles oriented perpendicular and parallel to the strike direction are shown in Figs. 4(a) and (b), respectively. A comparison with Figs. 2(a) and (b) indicates the appearance of further spurious closed *high* and *low* resistivity contours for the perpendicular bipole to the left of the transmitter. The target location is indicated with good lateral resolution, for the perpendicular bipole, with a closed low resistivity contour of 30  $\Omega$  m. The lowest closed contour of 30  $\Omega$  m,

obtained for the boundary of the conductive target. Figures 6 and 7 show the apparent resistivity maps for the bipole oriented perpendicular and parallel to the strike direction. The contours are very precise and the lateral resolution is very good. The apparent conductance maps for the perpendicular and parallel orientations are shown in Figs. 5(a) and (b), respectively. The contours are very precise and the lateral resolution is very good.

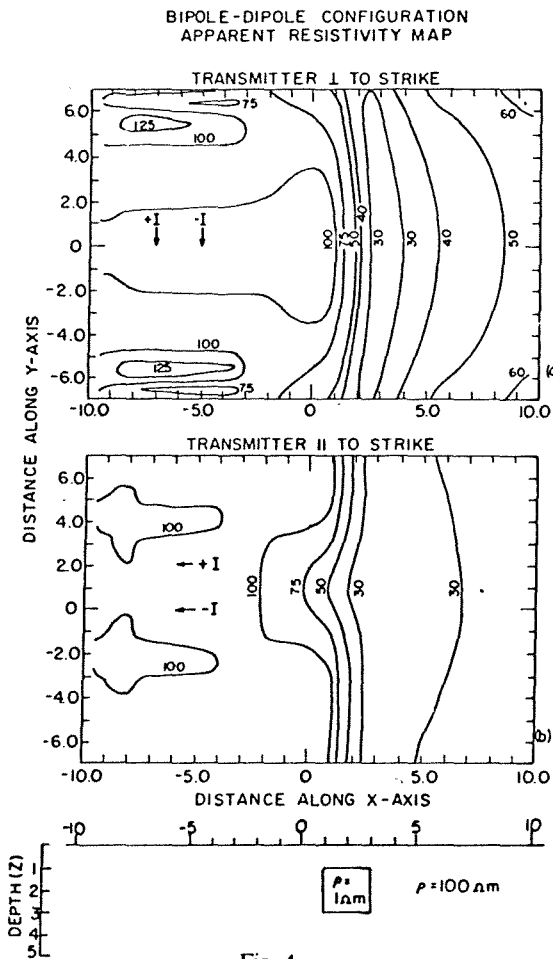


Fig. 4.

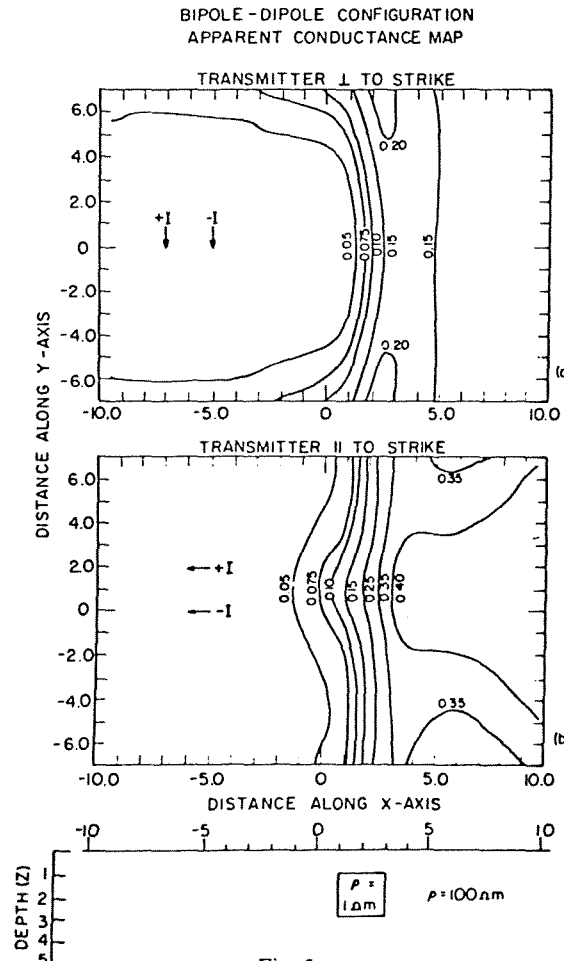


Fig. 5.

Fig. 4.. Bipole-dipole apparent resistivity maps over a single, shallow, distant inhomogeneity, with the current bipole oriented (a) perpendicular, and (b) parallel to the strike.

Fig. 5. Bipole-dipole apparent conductance maps over a single, shallow, distant inhomogeneity with the current bipole oriented (a) perpendicular and (b) parallel to the strike.

Fig. 6. Bipole-dipole apparent resistivity maps over a single, shallow, distant inhomogeneity, with the current bipole oriented (a) perpendicular, and (b) parallel to the strike.

Fig. 7. Bipole-dipole apparent conductance maps over a single, shallow, distant inhomogeneity with the current bipole oriented (a) perpendicular and (b) parallel to the strike.



obtained for the parallel bipole, however, shows a shift farther away from the projection of the far boundary of the target. The apparent conductance maps for this model, shown in Figs. 5(a) and (b) for the perpendicular and parallel bipole orientations, indicate steep gradients with increasing conductance values towards the near edge of the conductor. The resolution in defining the width of the target in this location seems to be worse for the parallel orientation of the transmitting bipole than for the perpendicular.

Figures 6(a) and (b) illustrate the apparent resistivity response patterns for the perpendicular and parallel configurations of the transmitter with the conductive block located in close proximity to the bipole but at a greater depth of burial, as shown in the accompanying section. The apparent resistivity anomalies are considerably broadened and are bounded by much shallower gradients in the contour levels (compared to Figs. 2 a and b). The lateral resolution in the location of the target is very poor, in that the shallow low resistivity trough is approx. 7-8 units in width and is considerably displaced away from the projection of the conductive block. The apparent conductance maps obtained for the model with perpendicular and parallel orientations of the

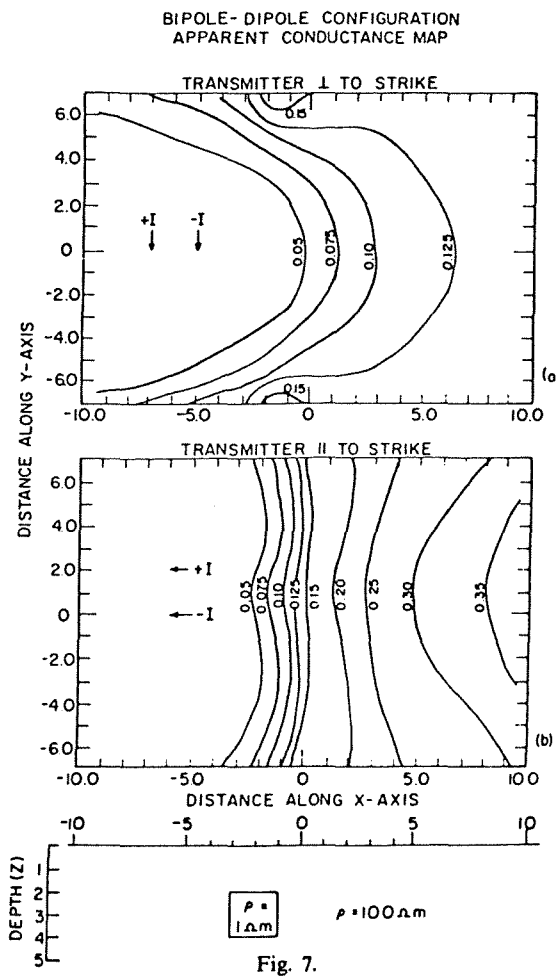
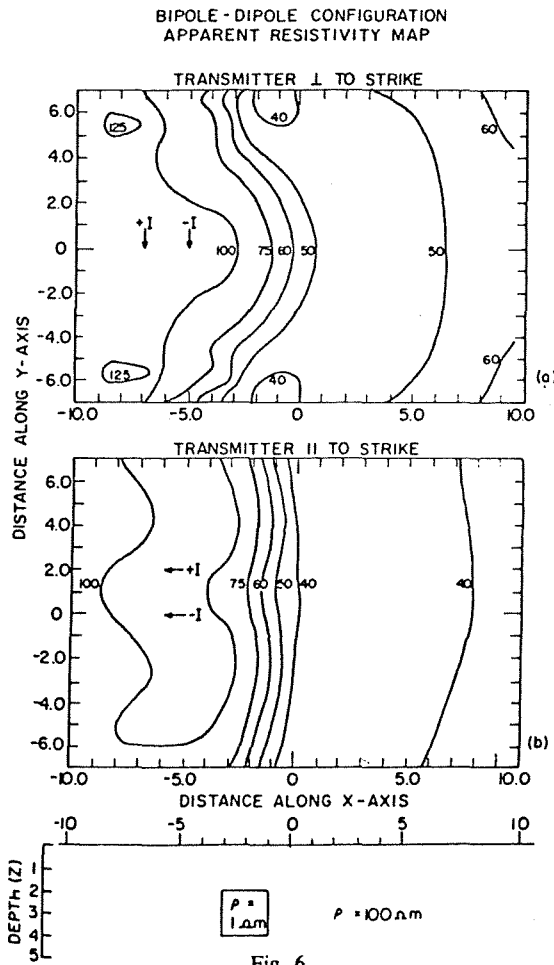


Fig. 6. Bipole-dipole apparent resistivity maps over a single, deep inhomogeneity with the current bipole oriented (a) perpendicular and (b) parallel to the strike.

Fig. 7. Bipole-dipole apparent conductance maps over a single, deep inhomogeneity with the current bipole oriented (a) perpendicular and (b) parallel to the strike.

bipole are illustrated in Figs. 7(a) and (b), respectively. No diagnostic pattern emerges for either map, with the conductance values monotonically increasing away from the transmitter towards the right edge of the map.

RESPONSE FOR THE COLLINEAR DIPOLE-DIPOLE PROFILING METHOD

The standard pseudo-section plots of the apparent resistivity response for the collinear dipole-dipole array are illustrated in Figs. 8(a) and (b), for the  $2 \times 2$  unit conductive block located at depths of burial of 1 and 2 units, respectively. The length of each of the transmitting and receiving dipoles is 1 unit and the pseudo-section is plotted with dipole-separations  $N = 1, 2, 3, \dots, 10$ . The conductive inhomogeneity is of intrinsic resistivity  $1 \Omega \text{ m}$  and the surrounding half-space has a resistivity of  $100 \Omega \text{ m}$ . A higher degree of spatial resolution in terms of the horizontal location of the conductive target at both depths is evident from the simple patterns in the pseudo-section. For the shallow location of the block, the effect of its finite depth-extent is clearly indicated by the closed low resistivity contour underlain by increasing resistivity. For the deeper target, the depth to top is easily estimated. However, with dipole-separations up to  $N = 10$ , the depth extent of the target cannot be estimated. The considerably improved spatial resolution and well-defined anomaly pattern indicate the enhanced diagnosticity achievable with multiple transmitter locations in a profile mode. Their pseudo-section contour patterns are well-defined for simple structures and indicate predictable variations with changing conductivity contrasts, depths of burial, etc. Hence, for such simple shapes, unlike bipole-dipole mapping results, only a few model iterations produce the desired interpretation.

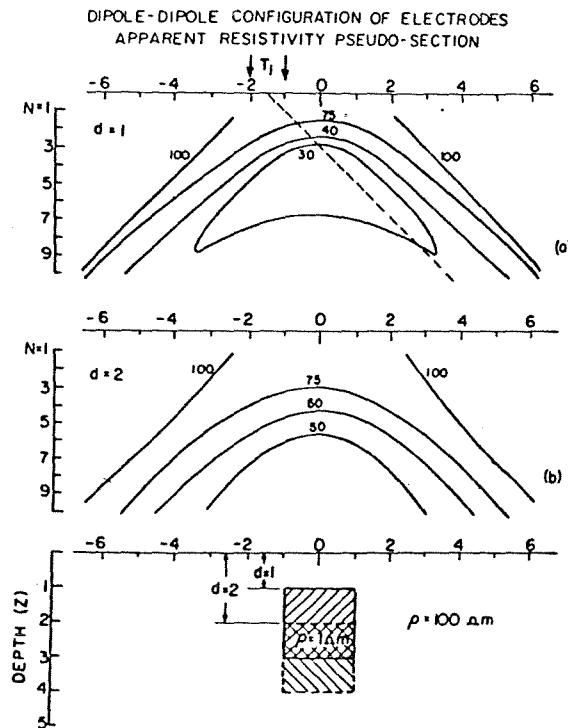


Fig. 8. The dipole-dipole pseudo-sections over a single inhomogeneity located at a depth of burial of (a) 1 unit and (b) 2 units.

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CHARACTERISTIC CURVES FOR THE SINGLE, RECTANGULAR CONDUCTIVE BLOCK INHOMOGENEITY

The apparent resistivity responses obtained by emplacing the 2 × 2 unit conductive block at various depths of burial and by changing its conductivity contrast with respect to the surrounding half-space, for bipole-dipole and dipole-dipole configurations, are summarized in the characteristic diagram shown in Fig. 9. A normalized anomaly index is defined as:

$$A.I. = \frac{\rho_a^{\max} - \rho_a^{\min}}{\rho_{\text{background}}} \times 100\%$$

In the pseudo sections and in the background apparent resistivity surface maps there appear zones of apparent resistivity *high* as well as *low*, due to the presence of a conductive target. If the subsurface were to be isotropic and homogeneous, the apparent resistivity parameter observed with either configuration would have been the intrinsic resistivity of the half-space. In this characteristic diagram, A.I., the anomaly index, is a measure of the distortions produced in a half-space response due to the presence of the lateral inhomogeneity. For this diagram, the conductivity contrasts  $\sigma_{\text{body}}/\sigma_{\text{half space}}$  of 10 and 100 and depth of burial varying for 0.5-3 units are considered. The transmitter orientations and the horizontal projection of the target with respect to the bipoles are identical to those shown in Figs. 2(a) and 2(b). It is evident from Figs. 4(a), 4(b) and 6 (a and b) that, depending on the distance and orientation of the bipoles, the amplitude and location of the spurious closed highs vary, thus resulting in considerable variation in their corresponding A.I. measure.

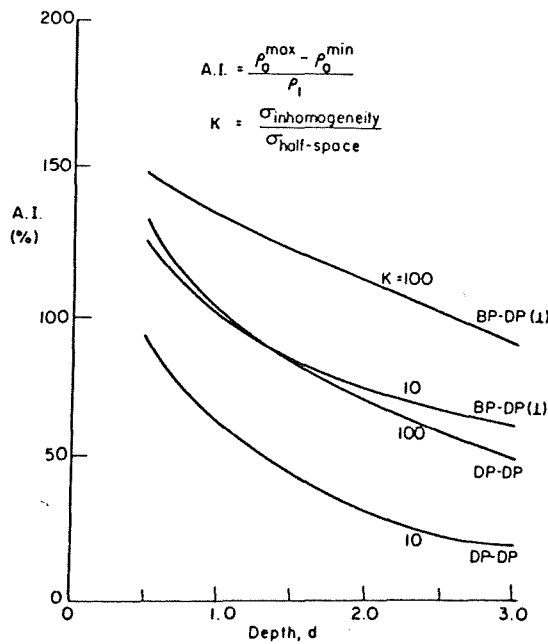


Fig. 9. Characteristic diagram of the anomaly index vs depths of burial of single block-shaped inhomogeneities for the bipole-dipole and the dipole-dipole configurations.

The curves shown in Fig. 9 indicate that the peak to peak anomaly observed with a bipole-dipole map (for the perpendicular orientation of the transmitter) is generally higher than that obtained for the collinear dipole-dipole, for the same model. In practical implementation, however, a technique would be best suited if a higher A.I. in the overall map is combined with a high degree of lateral resolution, so that the target location and dimensions could be easily

interpreted. From the anomaly patterns illustrated thus far, it is apparent that the collinear dipole-dipole array is superior in this regard.

EFFECT OF CONDUCTIVE OVERBURDEN LAYERS

*Bipole-dipole mapping response*

The effect of relatively thin conducting overburden layers over the standard conductive shallow inhomogeneity located close to the bipoles is illustrated in Figs. 10(a) and (b), for the perpendicular and parallel orientations of the bipole, respectively. The overburden layer resistivity is  $10 \Omega \text{ m}$  and the layer thickness is 0.125 of the bipole length used. In the vicinity of the bipoles, the typical response from two-layered earth models is seen for both orientations. A comparison with Figs. 2(a) and (b), however, indicates that even for the shallow depth of burial and close proximity of the target to the bipoles, the associated low resistivity contours are reduced in amplitude and broadened. With the presence of the overburden layer, the parallel orientation of the bipole seems

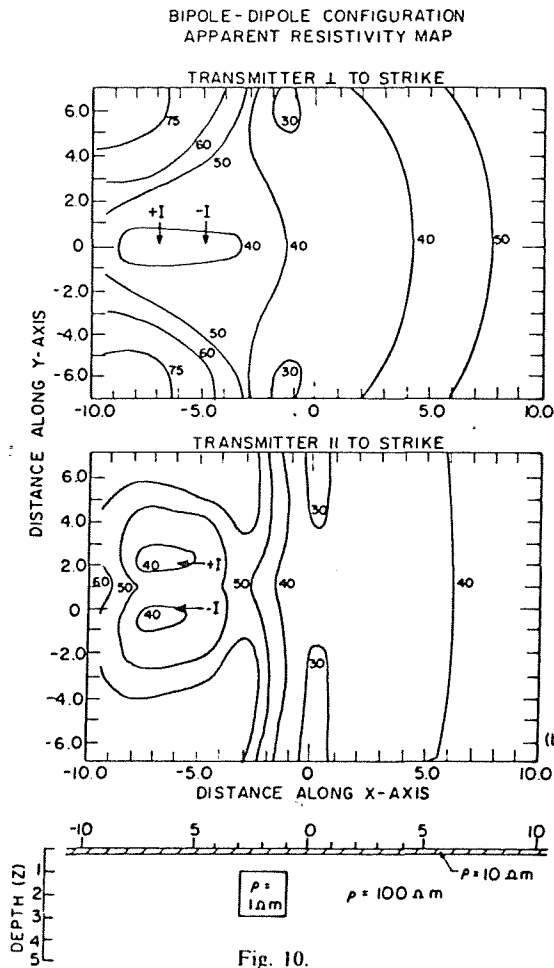


Fig. 10.

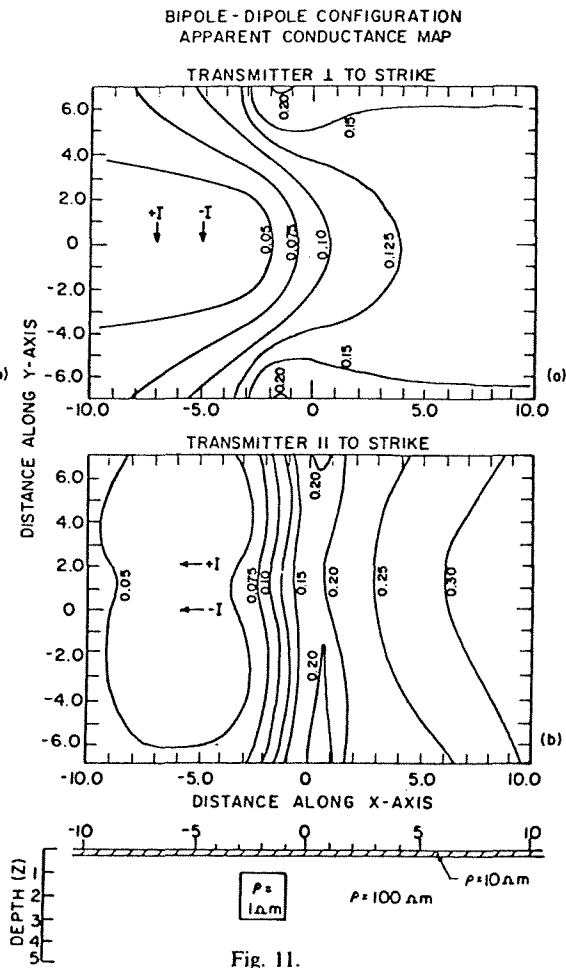


Fig. 11.

Fig. 10. Bipole-dipole apparent resistivity maps over a single, shallow inhomogeneity with a conductive overburden with the current bipole oriented (a) perpendicular and (b) parallel to the strike.

Fig. 11. Bipole-dipole apparent conductance maps over a single, shallow inhomogeneity with a conductive overburden with a current bipole oriented (a) perpendicular and (b) parallel to the strike.

to yield a better definition of the target location. The lateral location of the target as indicated by the  $40 \Omega \text{ m}$  closed contour in both maps is poorly defined.

The apparent conductance maps for this model are shown in Figs. 11(a) and (b), for the two bipole orientations. While the conductance concept is more realistic for these layered models, no diagnostic pattern emerges. For the parallel bipole configuration there is an associated conductance high close to the surface projection of the conductive target.

#### Collinear dipole-dipole response

The response of the  $2 \times 2$  unit conductor located at a depth of 1 unit below the surface and overlain by a conductive overburden layer of thickness 0.25 km and intrinsic resistivity of  $10 \Omega \text{ m}$ , is illustrated in the pseudo-section shown in Fig. 12. The patterns in the pseudo-section away from the lateral inhomogeneity indicate the typical two-layered responses. Over the region of the target, its location and lateral bounds are well defined. The relative resistivity high occurring at large dipole-separation in the center of the section indicates the finite depth extent of the conductive target. The typical pseudo-section pattern thus enables easy interpretation for both the location of the target and the resolution of the overburden layer conductivity and thickness.

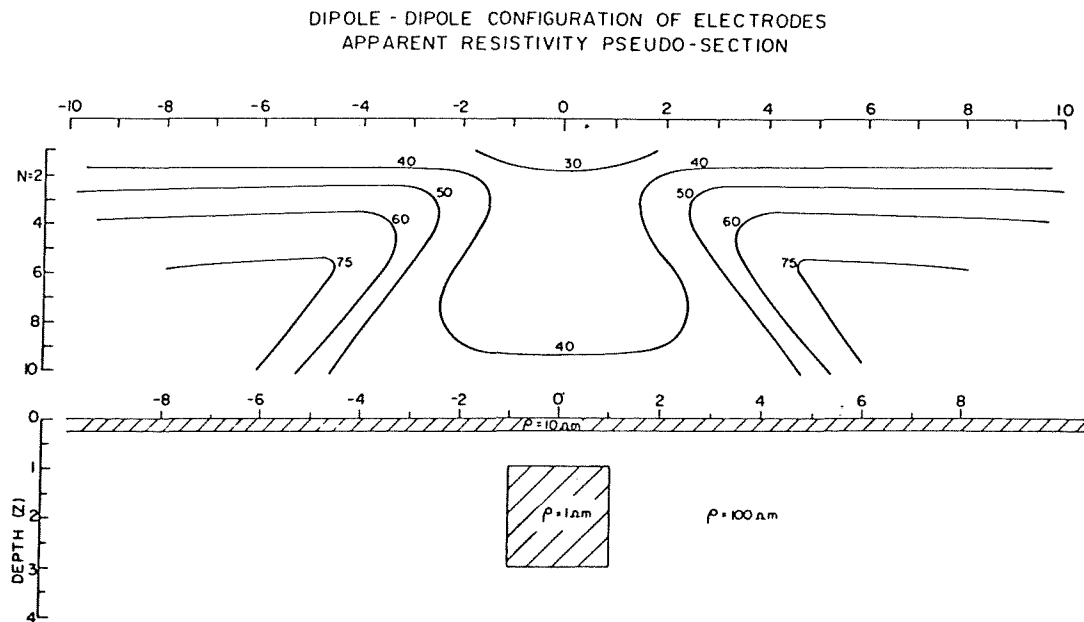


Fig. 12. Dipole-dipole apparent resistivity pseudo-section over a single, shallow inhomogeneity with a conductive overburden.

In the course of this study many other simple block models were simulated. Using a  $2 \times 2$  unit conductive block at a depth of one unit, the bipole-dipole mapping method showed poor detection capability (i.e. A.I. measures of less than 5%) in the following cases:

- (1) for horizontal distances between the block and the transmitter in excess of 6 units.
- (2) for overburden layer thicknesses in excess of 0.5 units, with overburden layer conductivity 10 times that of the lower half space.

Another example of the inherent ambiguity of the bipole-dipole maps is the comparison of the buried conductive block of Fig. 6(a) with a buried conductive quarter space, (Fig. 13). Not only are the patterns for these two radically different models quite similar, but the range of the apparent resistivities is very nearly the same. The apparent resistivity gradients for both models in the right half of the section are also similar.

All of these ambiguities are simply explained by considering the variation that exists along single diagonals in the dipole-dipole pseudo-sections. Each of these represents the apparent resistivity observed in sections collinear with a single bipole location. To illustrate this effect we can consider the diagonals from two specific transmitter locations,  $T_1$  and  $T_2$ , shown in Fig. 8 (buried block pseudo-section) and Fig. 14 (buried quarter space pseudo-section), respectively. The apparent resistivities along the diagonals to the right of each transmitter are similar and give no clue as to the true conductivity structure. Of course, the fortuitous addition of a second bipole transmitter could reduce this ambiguity, but *a priori* information would be required for optimum field location of this transmitter. The dipole-dipole pseudo-sections resolve these models very well.

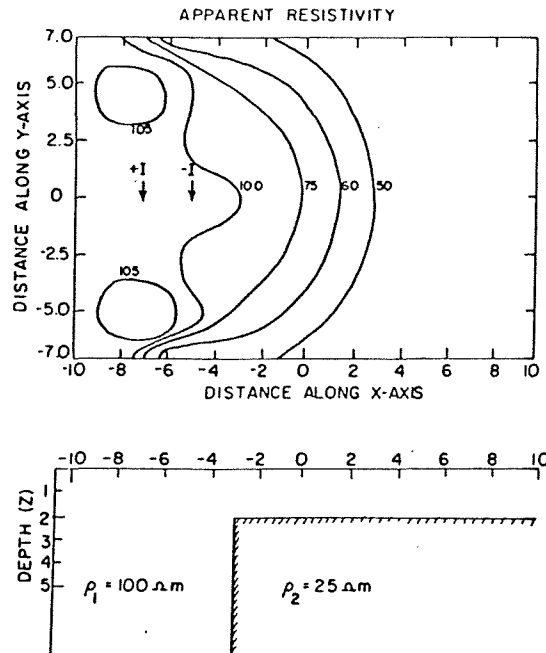


Fig. 13. Bipole-dipole apparent resistivity map over a buried conductive quarter-space with the current bipole perpendicular to the strike.

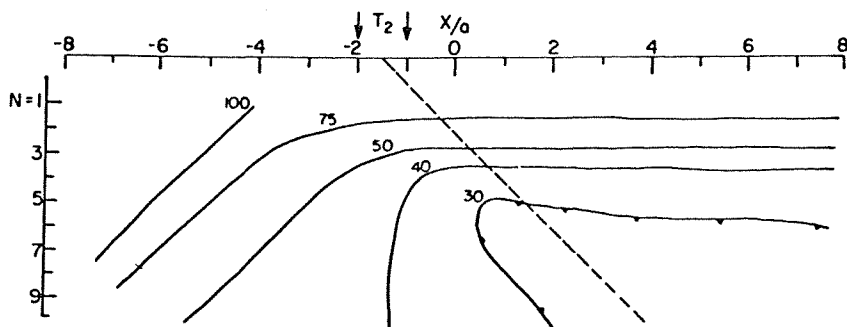


Fig. 14. Dipole-dipole apparent resistivity pseudo-section over a buried conductive quarter-space.

In an attempt to reduce the bipole-dipole data to a more easily interpreted form, we investigated the effects of subtracting assumed half-space or layered half-space models from models containing inhomogeneities. Initially, it seemed reasonable that anomalies from buried electrical inhomogeneities could be enhanced if we were to first calculate the anomaly for the estimated



layered structure and subtract this from the observed data. An example of efforts to test this concept is shown in Fig. 15. The upper map (Fig.15a) shows the effect of a rectangular inhomogeneity buried beneath an overburden layer when energized by the perpendicular bipole. After subtracting the calculated effect of the layering only (Fig.15b) we obtained the so-called residual anomaly shown in Fig. 15(c). Figure 15(c) is not indicative of a bounded inhomogeneity and in fact has the pattern of a buried conductive quarter-space (see Fig. 13). Attempts to interpret residual maps for more complicated geology met with even less success.

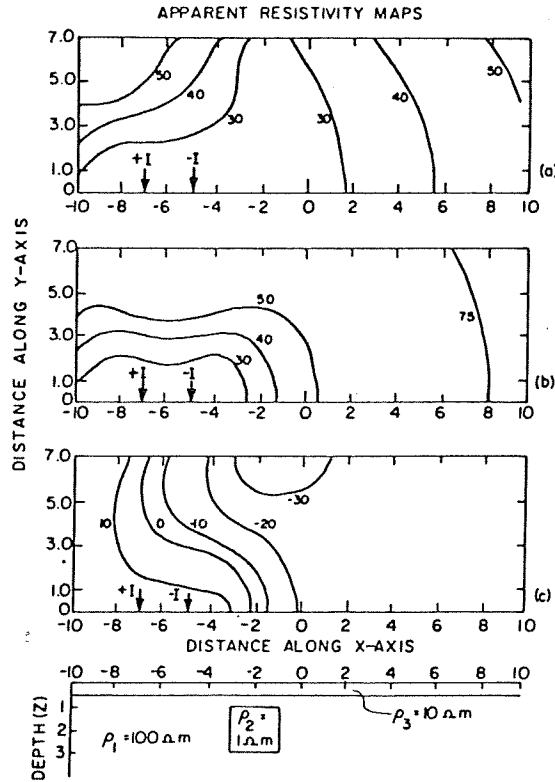


Fig. 15. Bipole-dipole apparent resistivity maps (a) over a conductive inhomogeneity with a conductive overburden layer, (b) over the two-layered earth, and (c) the residual with the current bipole oriented parallel to the strike.

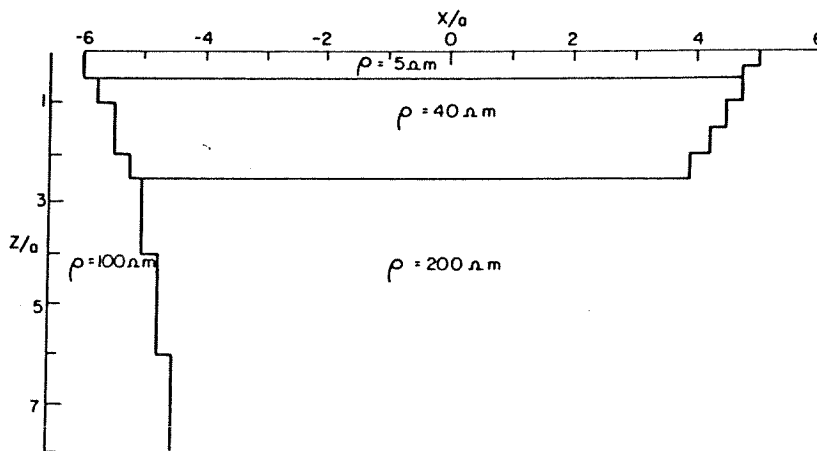


Fig. 16. A resistivity cross-section of a typical North Central Nevada Valley section (Structure A).

### COMPARATIVE RESPONSE PATTERNS OVER MORE COMPLEX GEOLOGIC SECTIONS

The response patterns have been presented for a single conductive inhomogeneity with and without the presence of a conductive overburden. It is generally observed that even for the simplest geometries, the bipole-dipole map has highly complex, non-definitive, patterns of apparent resistivity and conductance. For the identical sub-surface inhomogeneity, conflicting overlays of apparent resistivity patterns are obtained depending on the location and orientation of the transmitting bipoles.

In order to evaluate the practical effectiveness of the bipole-dipole and dipole-dipole techniques in an area of geothermal potential, where the geologic section is often considerably more complex, the methods were applied to two hypothetical Central Nevada Basin-and-Range type electrical cross-sections. Structure A (Fig. 16) shows the electrical section of a typical valley and Structure B (Fig. 17) is the same section with a postulated geothermal reservoir of dimension  $1.5 \times 3.0$  km and resistivity  $1 \Omega \text{ m}$ .

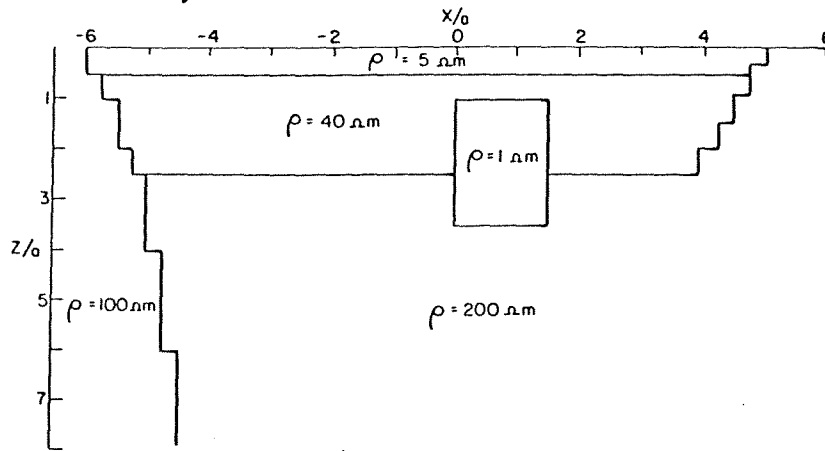


Fig. 17. A resistivity cross-section of a typical North Central Nevada Valley section with a hypothesized conductive zone (Structure B).

The pseudo-section plots of the apparent resistivity responses obtained from the models structure A and structure B are shown in Figs. 18 and 19, respectively. In Fig. 18, the location of the bounding range faults (shown in Fig. 16) are clearly seen. In the central part of the pseudo-section, the relatively flat and uniform pattern at dipole-separations up to  $N = 5$ , indicates a layered valley structure. The pseudo-section in Fig. 19 also indicates the bounding faults with good resolution, but the pattern in the central part, at dipole separations 2 to 10, shows a zone of relatively low apparent resistivity indicating the presence of a large, bounded conductive zone at

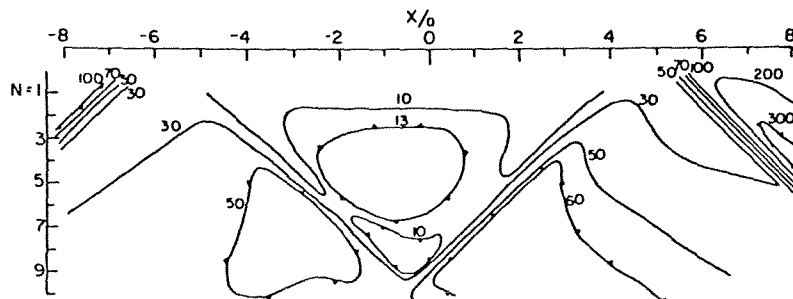


Fig. 18. Dipole-dipole apparent resistivity pseudo-section over the valley structure A.

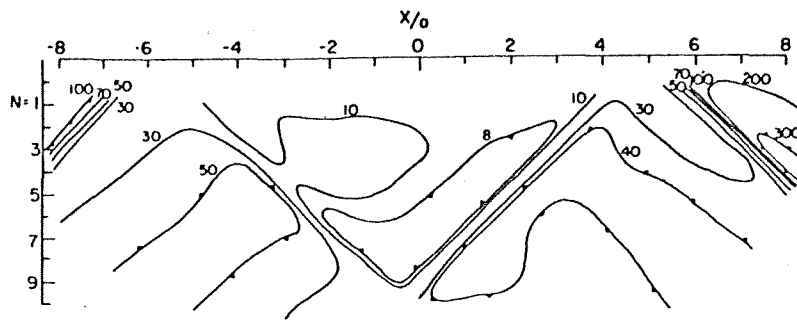


Fig. 19. Dipole-dipole apparent resistivity pseudo-section over the valley structure B.

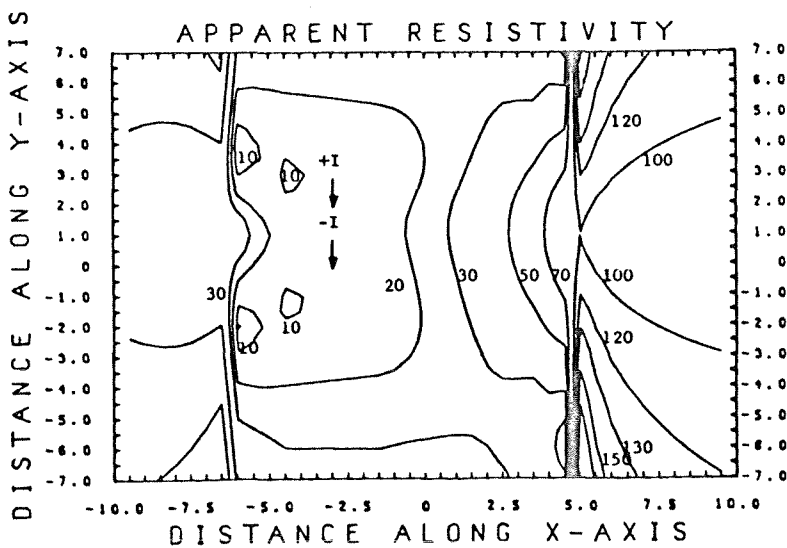
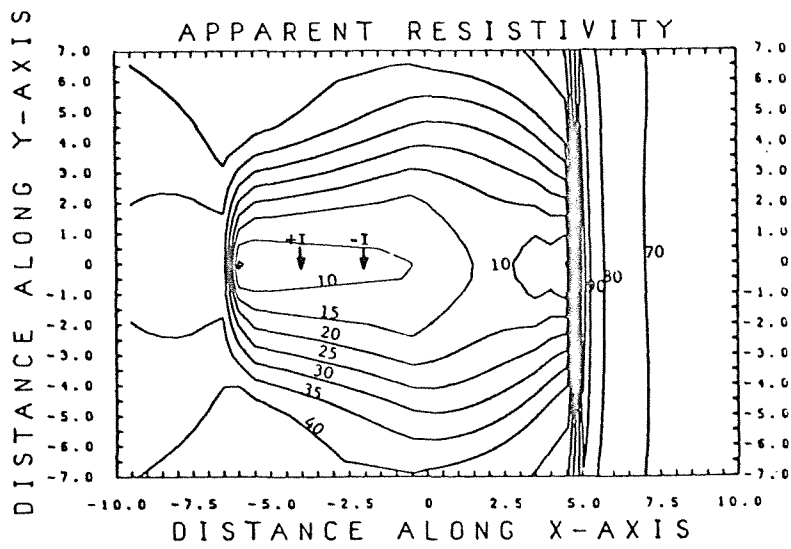


Fig. 20. Bipole-dipole apparent resistivity maps over the valley structure A with the current bipole at  $(-3.5, 0)$  and oriented (a) perpendicular, and (b) parallel to the strike direction.

depth. A comparison of the  $8 \Omega \text{ m}$  contour of Fig. 19 and the  $13 \Omega \text{ m}$  contour of Fig. 18 shows that one could infer the location of the low-resistivity reservoir zone in Fig. 19 without prior knowledge of the valley structure.

Bipole-dipole mapping responses, calculated in terms of apparent resistivity and conductance, are given for both structures A and B. Current bipoles at two locations, centred at  $x = -3.5$  and  $x = +3.5$  (Figs. 16, 17), were chosen. At each location, transmitting bipoles approximately 2 km in length were oriented at angles  $0^\circ$ ,  $45^\circ$ ,  $90^\circ$  and  $135^\circ$  to the strike of the section. The apparent resistivity and conductance maps with the exact location and orientations of the bipole sources are illustrated in Figs. 20–27 for structure A and in Figs. 28–35 for structure B (with the postulated reservoir zone).

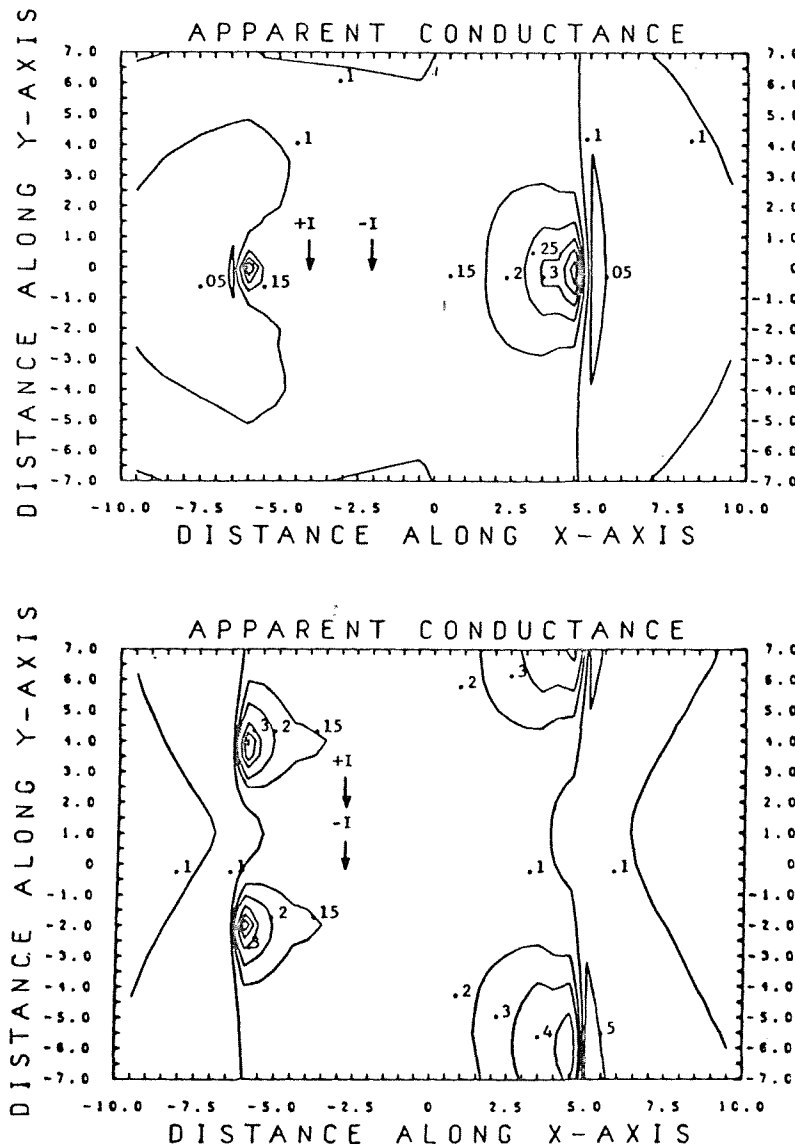


Fig. 21. Bipole-dipole apparent conductance maps over the valley structure A with the current bipole at  $(-3.5, 0)$  and oriented (a) perpendicular and (b) parallel to the strike direction.

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Fig. 2

A comparative study of these maps indicates a layered sub-section very close to the current electrodes, for the parallel and perpendicular orientation of the bipoles. The range front contacts with large resistivity contrasts are outlined rather well by the bipole oriented parallel to the strike. For any other azimuthal orientation of the bipole, either east or west of the center of the section, the fault contact located farther away is more clearly seen. The effect of the nearer (to the transmitter) contact is subtle for the perpendicular orientation and often obscured for azimuthal angles of  $45^\circ$  or  $135^\circ$ . Although the basement in the central part of the valley is electrically resistive, no definitive pattern emerges in the conductance maps to estimate basement depth with good resolution.

A comparison of the responses in the sets of Figs. 20-27 with those in Figs. 28-35 does not indicate a sharp change in the resistivity, or reveal diagnostic resistivity or conductance pattern

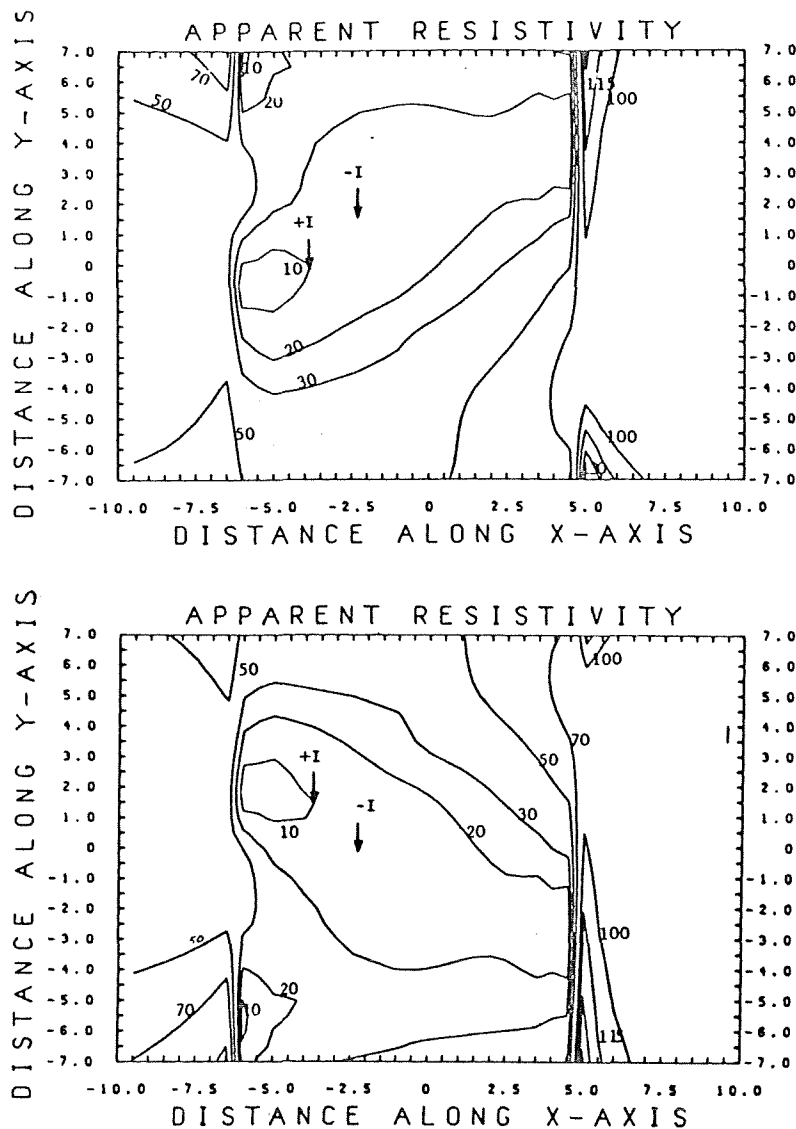


Fig. 22. Dipole-dipole apparent resistivity maps over the valley structure A with the current bipole located at  $(-3.5, 0)$  and oriented at (a)  $45^\circ$ , and (b)  $135^\circ$  to the strike direction.

changes that can be used to determine the location of the large low resistivity reservoir zone. The two sets of patterns are virtually the same and only with an *a priori* knowledge of structure A, could the subtle changes in the low values of resistivity maps in the central part be correlated with the presence of the conductive reservoir zone.

### THREE-DIMENSIONAL EFFECTS

Outcropping hemispheroidal models have been shown by Bibby and Risk (1973) to have strong apparent resistivity anomaly patterns that are directly over the body. Singh and Espindola (1976) have analyzed a buried perfectly conducting sphere at shallow depth in a uniform half-space, and have shown that the apparent resistivity lows for offset current bipoles generally lie above the body.

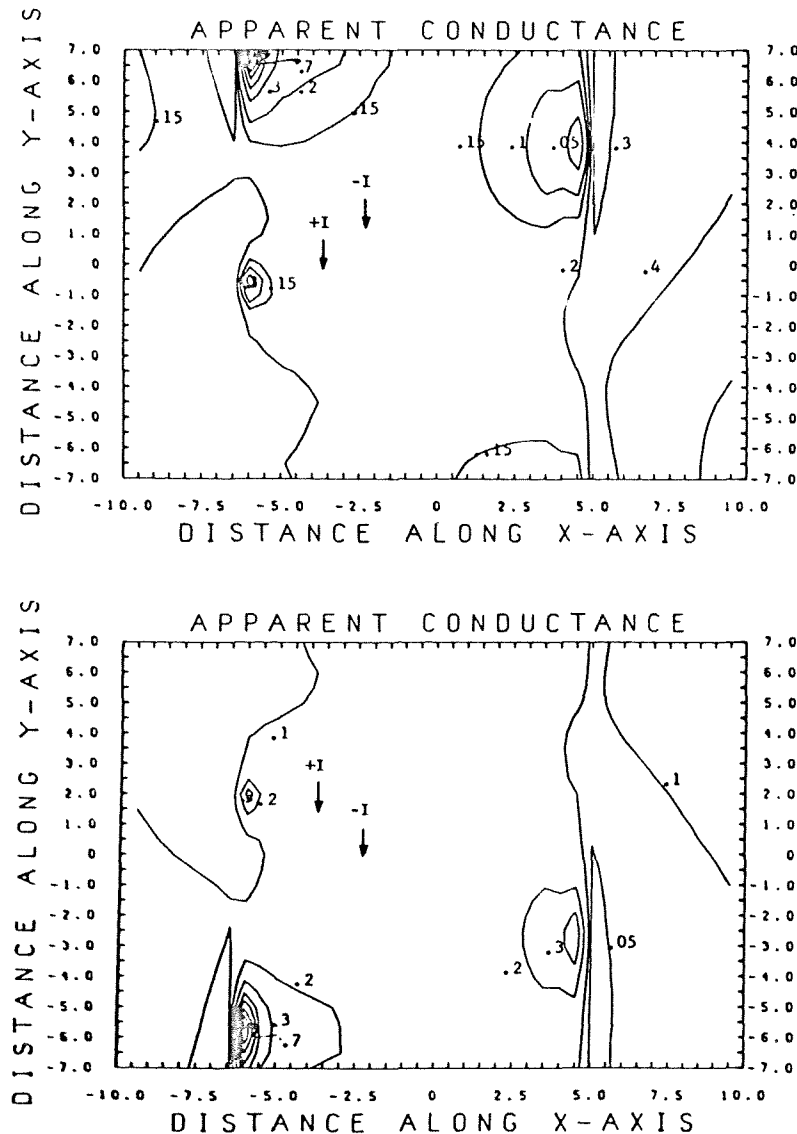


Fig. 23. Bipole-dipole apparent conductance maps over the valley structure A with current bipole located at  $(-3.5, 0)$  and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.

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Fig.



To study a more realistic model we have used a three-dimensional algorithm (Dey and Morrison, 1977) to produce apparent resistivity maps for a buried rectangular body beneath a conductive overburden. The model section is identical to that shown in Fig. 10 but the strike extent of the body is now plus and minus 2 units from the  $x$  axis. A map produced with the bipole perpendicular to strike and at a location identical to that shown in Fig. 10 is shown in Fig. 36.

The pattern is much more complex than that of the two-dimensional case. Most importantly, with the conductive overburden, the low resistivity zones do not lie over the body as observed for the outcropping hemispherical sink or for the buried sphere. A strong pincer or Y shaped pattern of lows extends to the upper and lower right hand edges of the map. They are considerably displaced from the surface projection of the body. In fact, a ridge of relatively high apparent resistivities is present directly over the body. The flanking high resistivity zones to the left of the

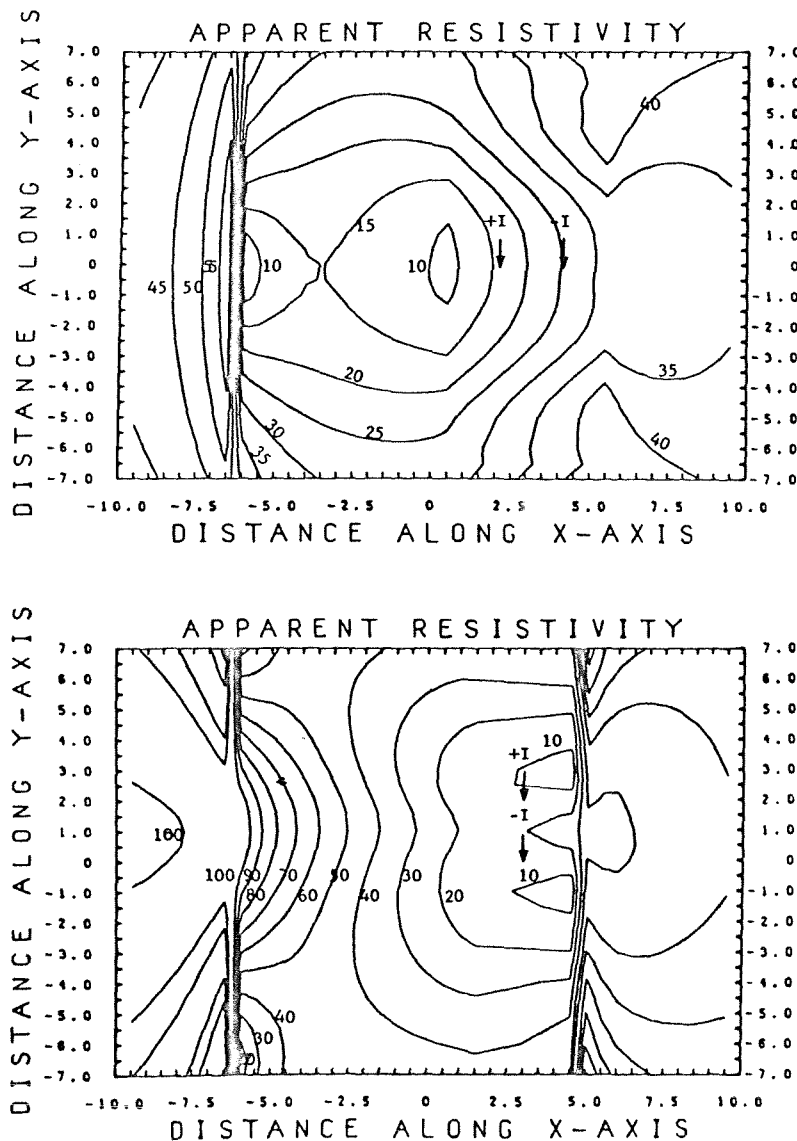


Fig. 24. Bipole-dipole apparent resistivity maps over the valley structure A with the current bipole located at  $(+3.5, 0)$  and oriented (a) perpendicular, and (b) parallel to the strike direction.

body at the upper and lower edges of the map are greater than the corresponding values in the two-dimensional case and are, in fact, higher than any resistivities in the model.

It has been observed in dipole-dipole pseudo sections over three-dimensional models (Dieter *et al.*, 1969; Dey and Morrison, 1977) that an apparent resistivity high occurs beneath the body at large separations. This high causes the apparent resistivity values on the x-axis at the right hand side of the map, Fig. 36, to be considerably higher than the corresponding values in the two-dimensional case, Fig. 10. This high also produces the strong gradients in the strike direction over the three-dimensional model.

Given a map like that of Fig. 36 local geology with wide variations in shallow resistivity could be inferred that would have no relationship to the actual section. Multiple transmitters would help to resolve the situation.

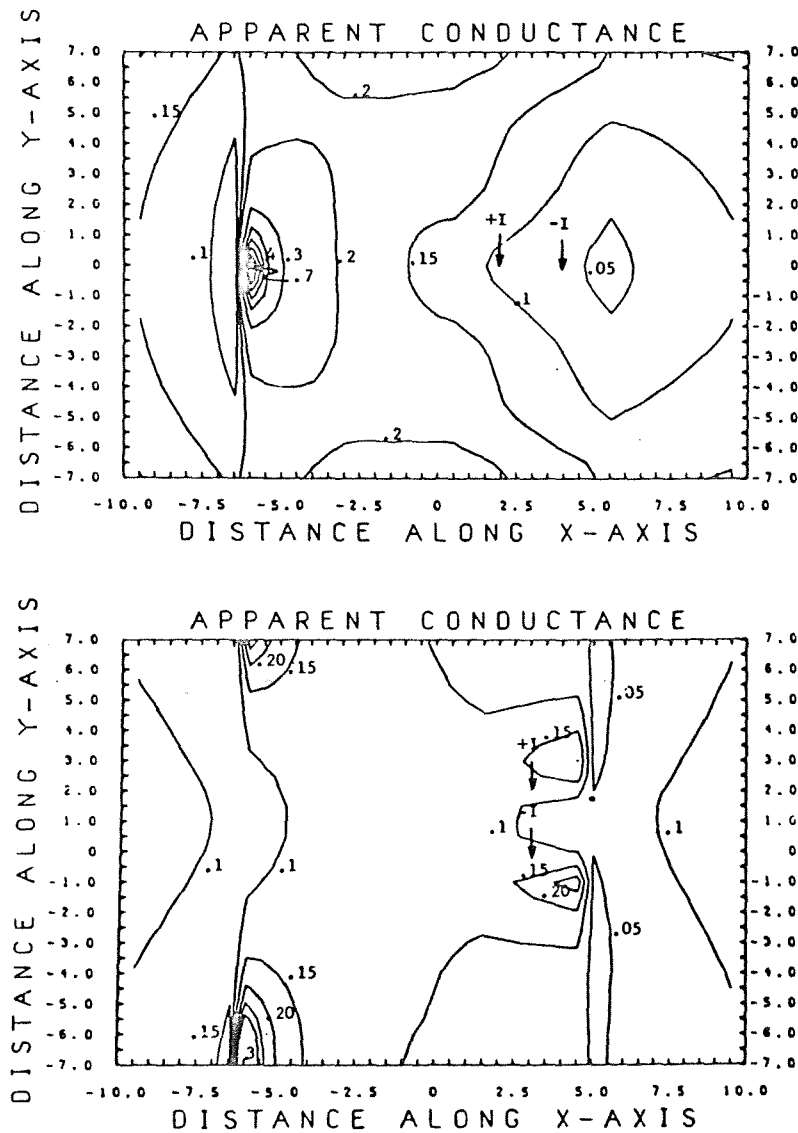


Fig. 25. Bipole-dipole apparent conductance maps over the valley structure A with the current bipole located at  $(+3.5, 0)$  and oriented (a) perpendicular, and (b) parallel to the strike direction.

The very large areal extent and high measurement station density of the map required to define the complex patterns caused by a simple geologic model makes the possibility of interpreting even more complicated models somewhat doubtful.

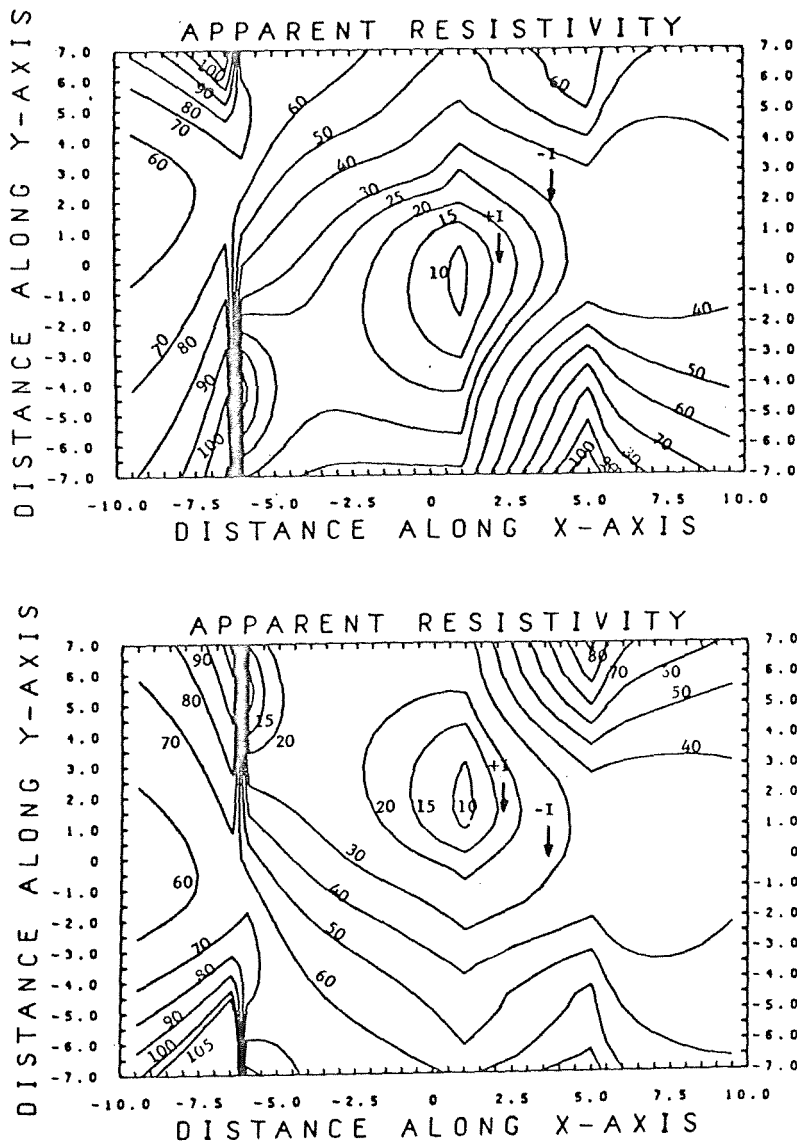


Fig. 26. Bipole-dipole apparent resistivity maps over the valley structure A with the current bipole located at (+3.5, 0) and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.

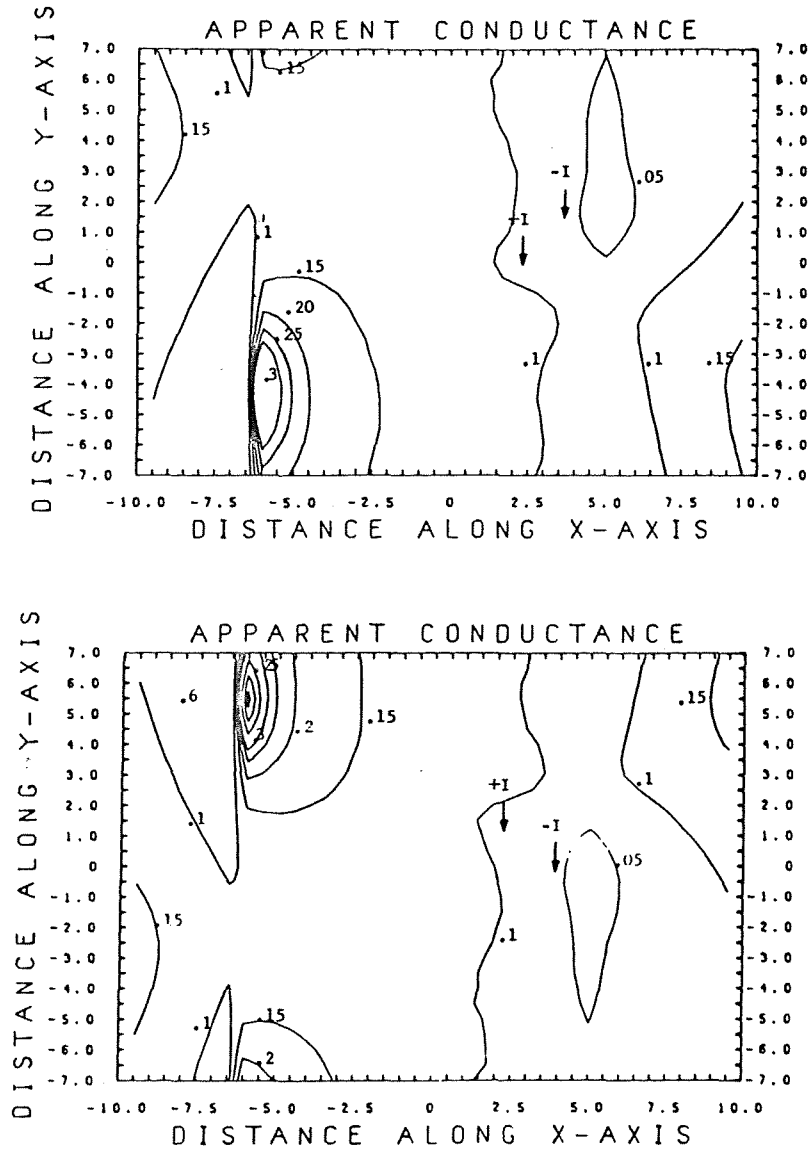


Fig. 27. Bipole-dipole apparent conductance maps over the valley structure A with the current bipole located at  $(+3.5, 0)$  and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.

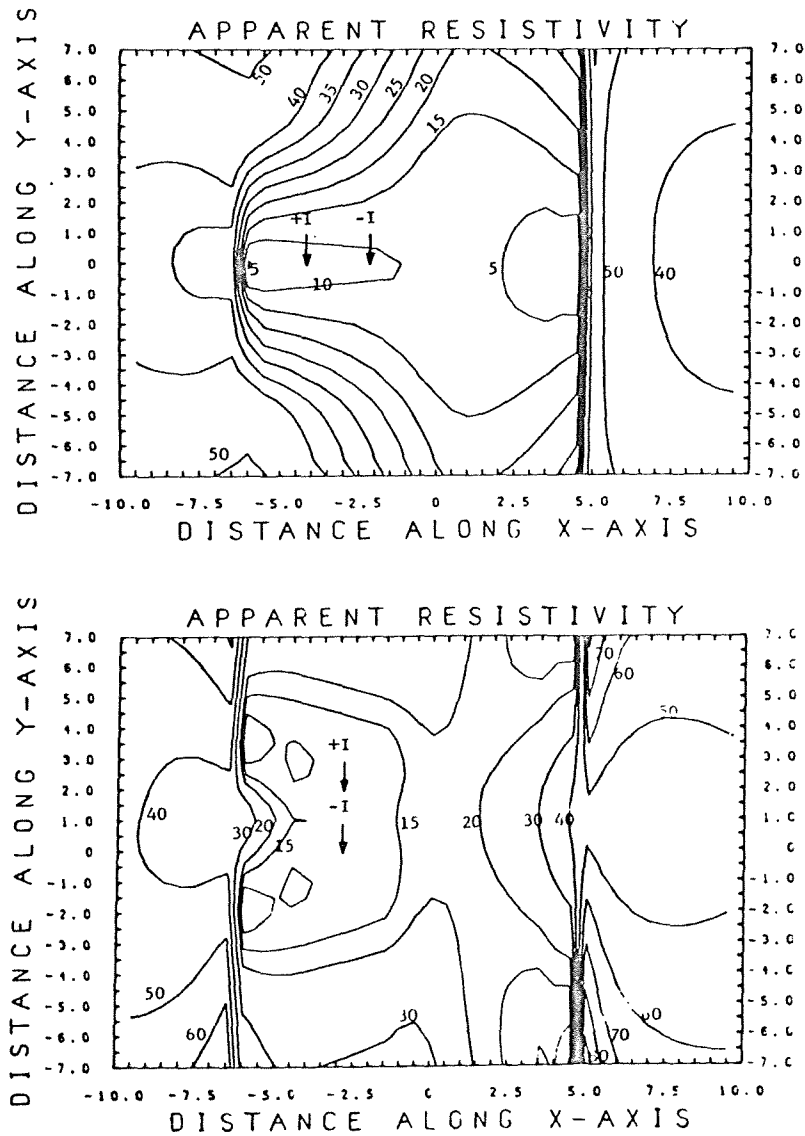


Fig. 28. Bipole-dipole apparent resistivity maps over the valley structure B with the current bipole at (-3.5, 0) and oriented (a) perpendicular and (b) parallel to the strike direction.

+3.5, 0)

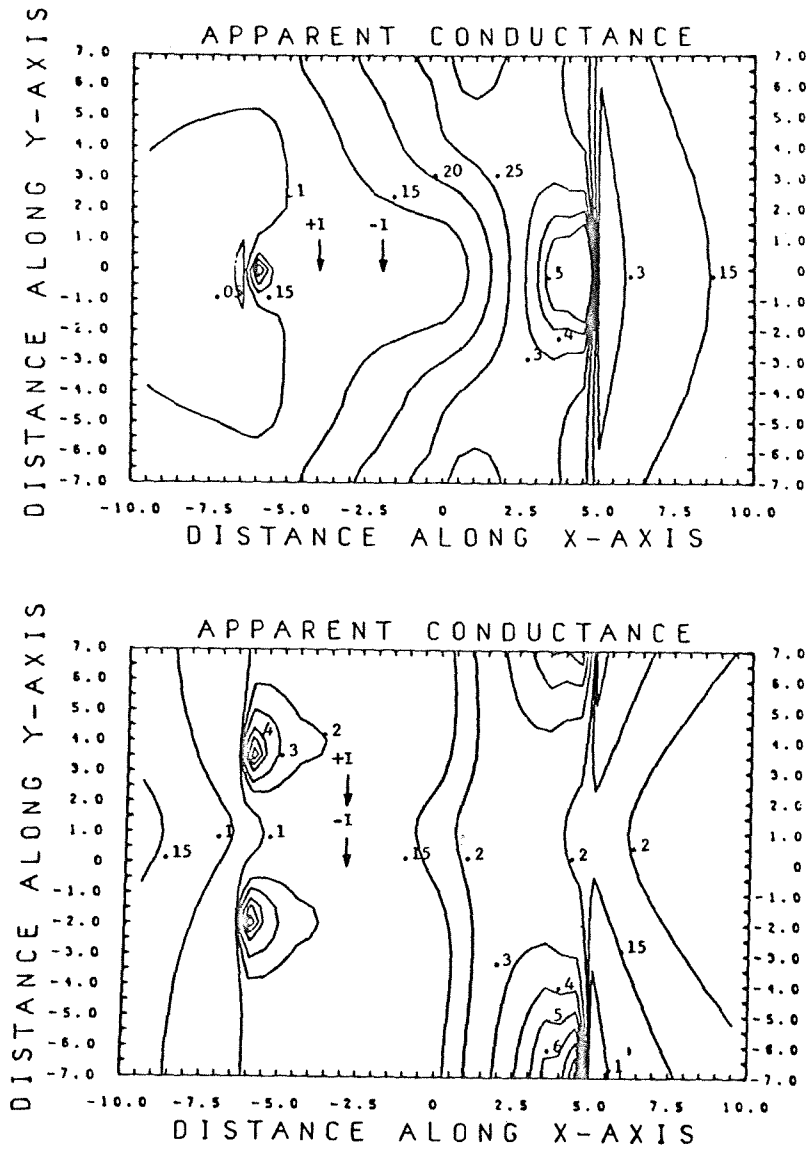


Fig. 29. Bipole-dipole apparent conductance maps over the valley structure B with the current bipole at  $(-3.5, 0)$  and oriented (a) perpendicular and (b) parallel to the strike direction.



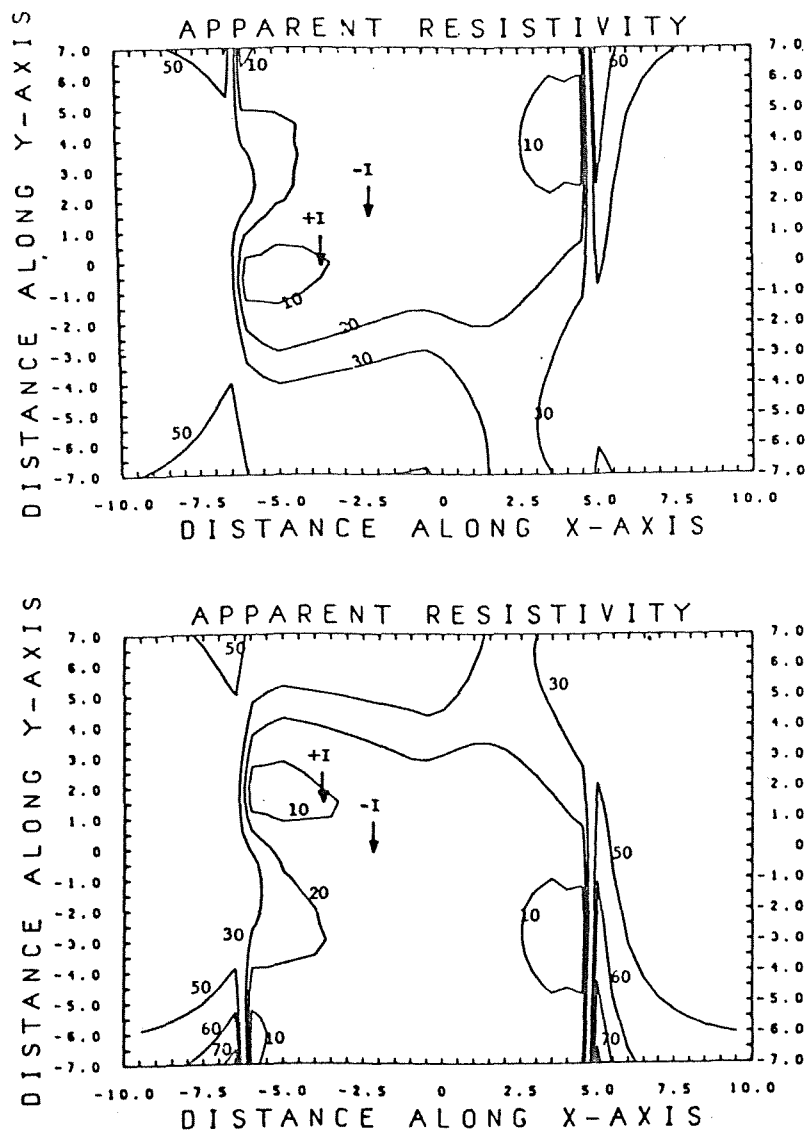


Fig. 30. Bipole-dipole apparent resistivity maps over the valley structure B with the current bipole located at  $(-3.5, 0)$  and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.

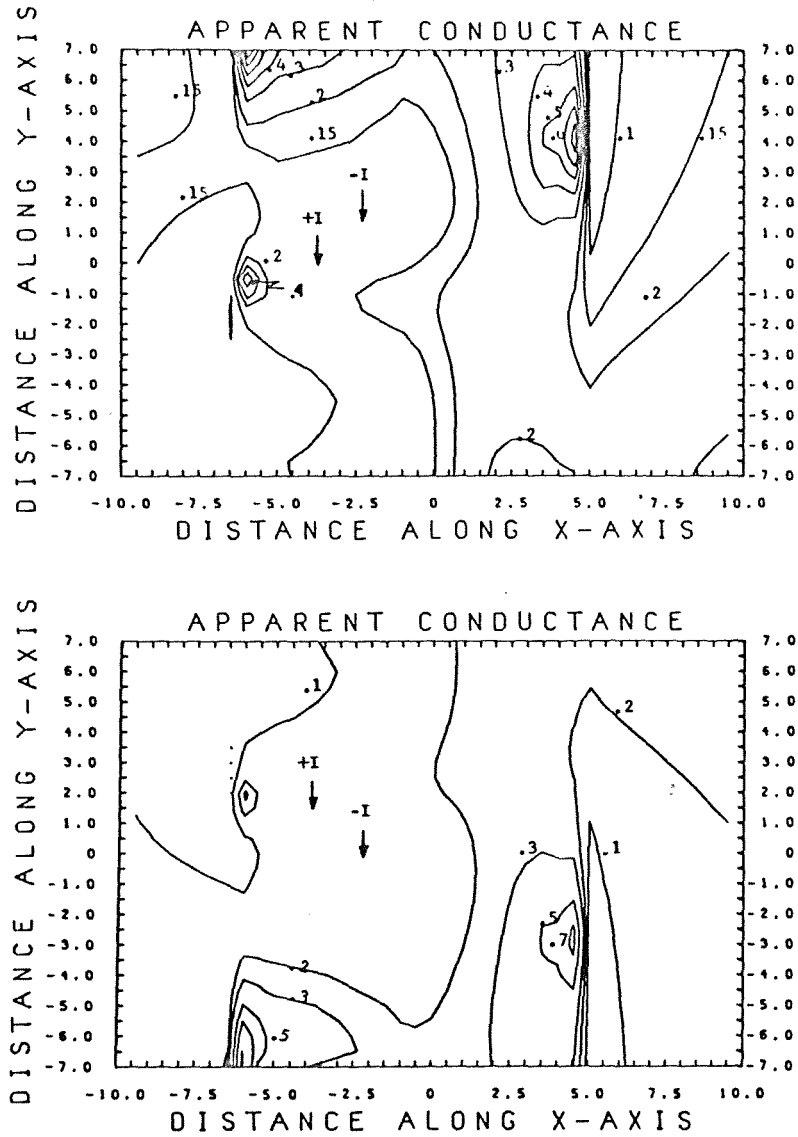


Fig. 31. Bipole-dipole apparent conductance maps over the valley structure B with the current bipole located at  $(-3.5, 0)$  and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.

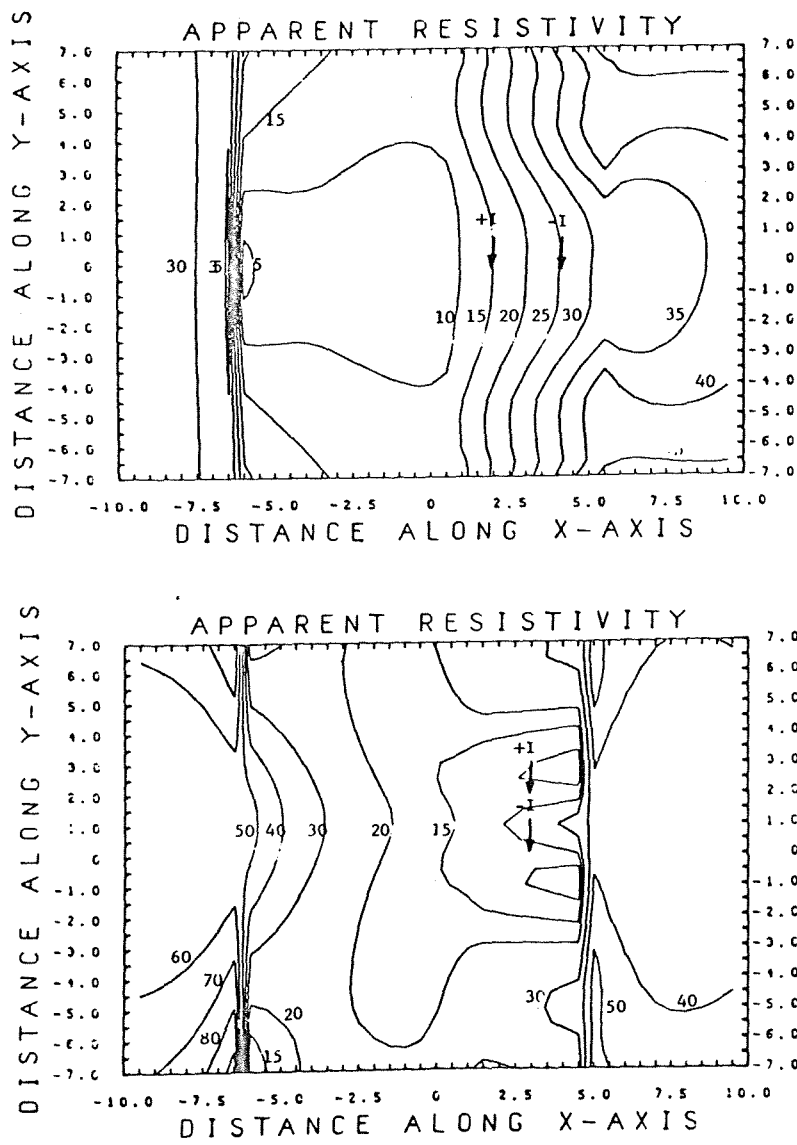


Fig. 32. Bipole-dipole apparent resistivity maps over the valley structure B with the current bipole located at  $(+3.5, 0)$  and oriented (a) perpendicular and (b) parallel to the strike direction.

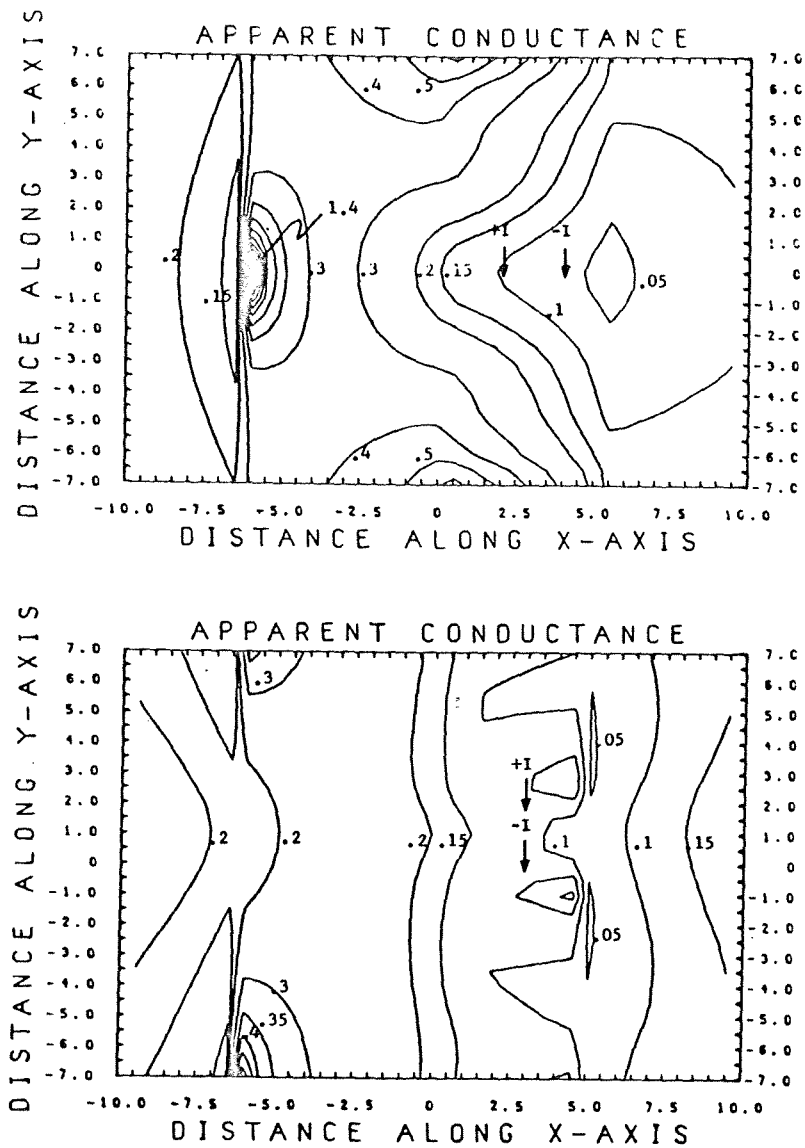


Fig. 33. Bipole-dipole apparent conductance maps over the valley structure B with the current bipole located at  $(+3.5, 0)$  and oriented (a) perpendicular and (b) parallel to the strike direction.

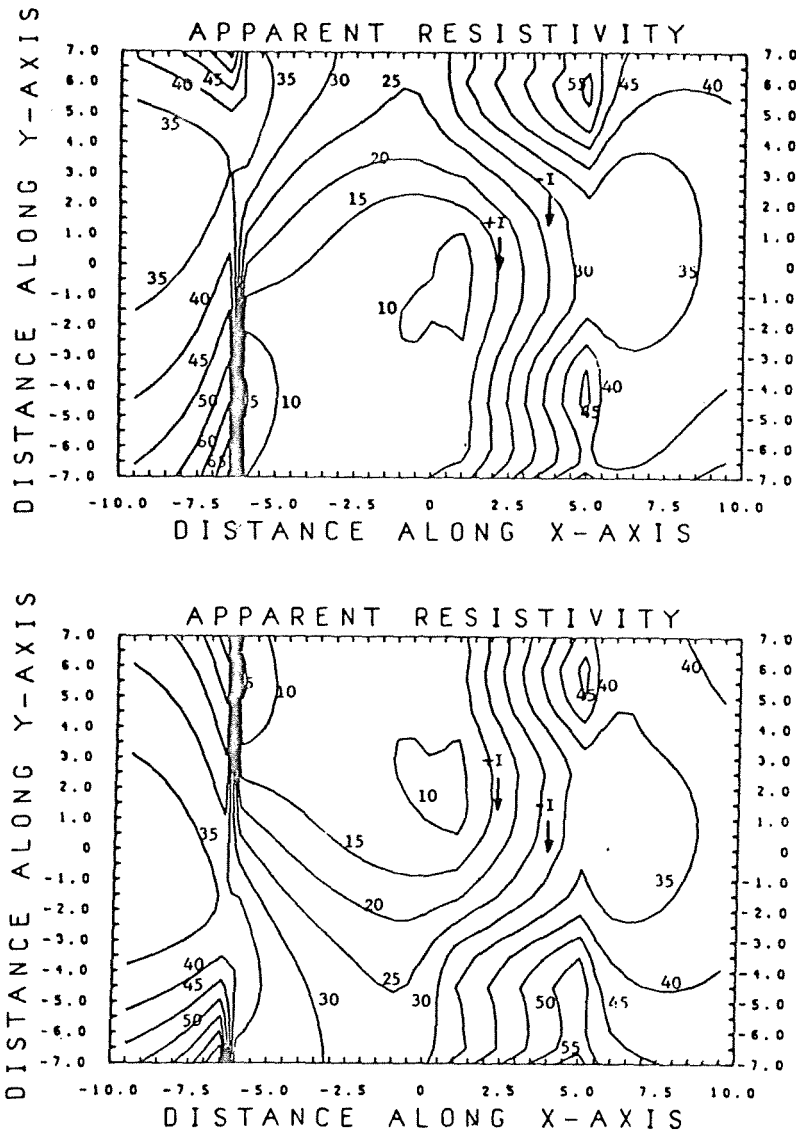


Fig. 34. Bipole-dipole apparent resistivity maps over the valley structure B with the current bipole located at (+3.5, 0) and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.

3.5, 0)

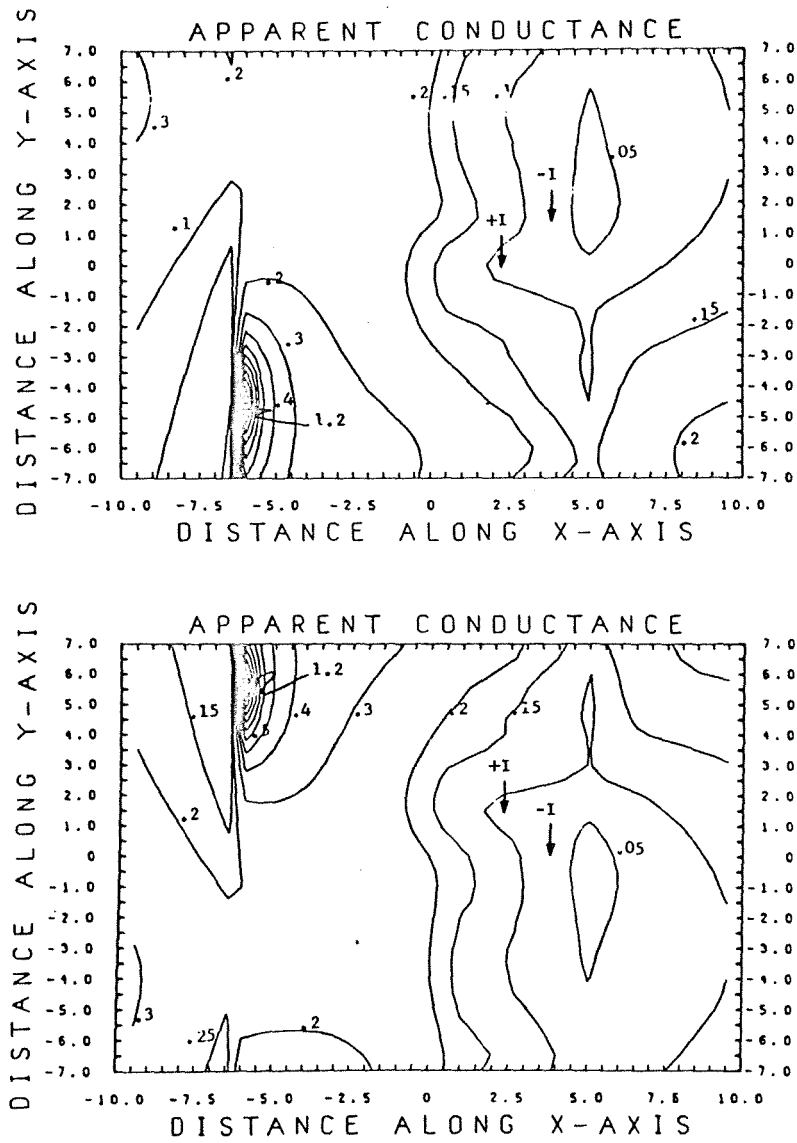


Fig. 35. Bipole-dipole apparent conductance maps over the valley structure B with the current bipole located at  $(+3.5, 0)$  and oriented at (a) 45 degrees and (b) 135 degrees to the strike direction.



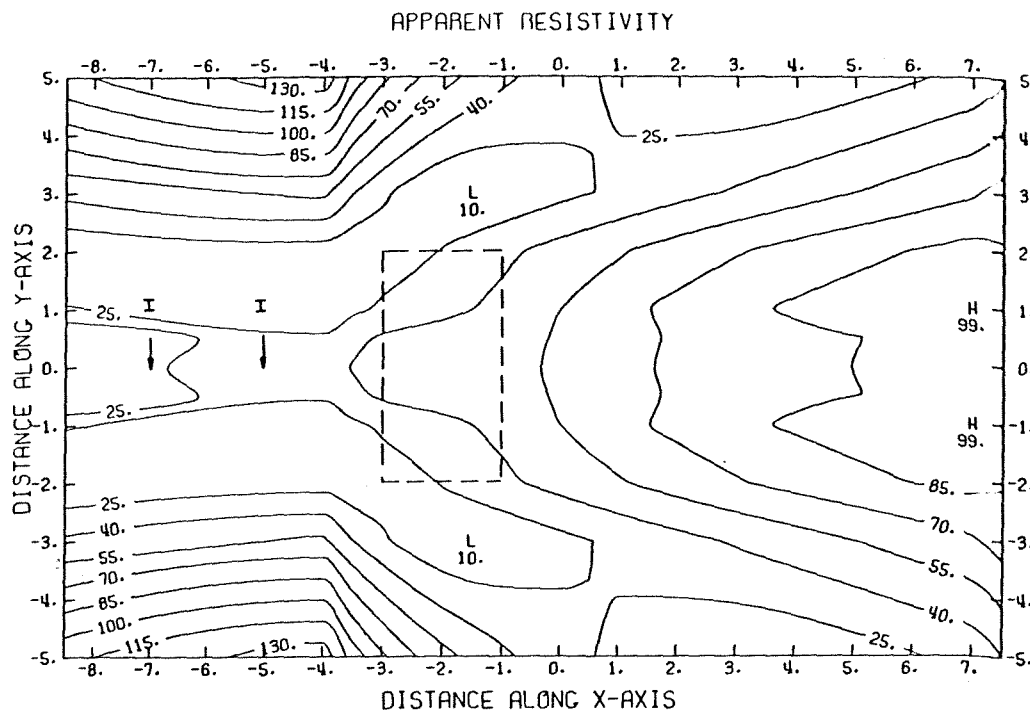


Fig. 36. Bipole-dipole apparent resistivity map over a single, shallow, three-dimensional inhomogeneity with a conductive overburden with the current bipole oriented perpendicular to the strike.

(5, 0)

## CONCLUSIONS

The ability of a particular method to resolve the subsurface resistivity distribution depends on the complexity of the model. Simple outcropping contacts layered earth models are easily interpreted with any configuration. For these cases the bipole-dipole method offers great logistic advantages. With increasing complexity, for example a discrete body beneath an overburden layer, the location and depth extent are generally only resolvable with the dipole-dipole method. For even more complex situations, multiple bodies, variation in overburden thickness and, of course, three-dimensional effects, the response for any method becomes correspondingly more complicated and may be very difficult to interpret.

Based on analyses of the models included in this report and on a wide variety of models which we have used in attempts to interpret field data, the following conclusions may be drawn:

- (1) Multiple sources are required to determine the subsurface resistivity distribution with the bipole-dipole configuration. There is a constant gain in information as the number of sources approaches that of a complete dipole-dipole pseudo-section. Definitive patterns required to differentiate radically different models do not, in general, appear from only two transmitter positions.
- (2) The bipole-dipole method appears to be effective for locating shallow bounded conductive targets, especially if these targets are within two or three bipole lengths from the transmitter.
- (3) The bipole-dipole method is good for locating outcropping dikes or contacts, for any orientation of the bipole, and especially at large distances from the transmitter.
- (4) Conductive overburden severely suppresses the anomalies from conductive inhomogeneities. Patterns for anomaly recognition of lateral inhomogeneities are not definitive even for multiple sources.
- (5) Except when located in very close proximity to the bipole, the bipole-dipole maps show extremely poor resolution in defining the width and the depth extents of bounded inhomogeneities.
- (6) Surface inhomogeneities contribute large distortions with bipole-dipole maps. The dipole-dipole pseudo-sections allow recognition and some differentiation of these features.
- (7) Except for some very simple geometries, bipole-dipole maps for varying bipole orientations (rotations) present little additional information.
- (8) The subtle difference in apparent resistivity maps that characterize different conductivity structures would require a very high density of receiving dipoles.
- (9) For the models studied, high conductances corresponded generally with low apparent resistivities. The patterns of the conductance maps did not add any diagnostic information.
- (10) Except in very special geologic settings, e.g. outcropping faults and dykes, the effectiveness of the bipole-dipole technique as a reconnaissance mapping tool for the location of conductive zones is very poor.

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