GEOPHYSICS, VOL. 45, NO. 1 (JANUARY 1980); P. 75–93, 19 FIGS.

Topographic effects in resistivity and induced-polarization surveys

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We have made a systematic study of dipole-dipole apparent resistivity anomalies due to topography and of the effect of irregular terrain on induced-polarization (IP) anomalies, using a two-dimensional (2-D), finite-element computer program.

A valley produces a central apparent resistivity low in the resistivity pseudosection, flanked by zones of higher apparent resistivity. A ridge produces just the opposite anomaly pattern—a central high flanked by lows. A slope generates an apparent resistivity low at its base and a high at its top. Topographic effects are important for slope angles of 10 degrees or more and for slope lengths of one dipole-length or greater. The IP response of a homogeneous earth is not affected by topography. However, irregular terrain does affect the observed IP response of a polarizable body due to variations in the distance between the electrodes and the body.

These terrain-induced anomalies can lead to erroneous interpretations unless topography is included in numerical modeling. A field case demonstrates the importance of including topography, where it is significant, in interpretation models. A technique for correcting apparent resistivity for topographic effects uses the finite-element program to compute correction factors.

INTRODUCTION

Resistivity and induced-polarization (IP) surveys play an important role in geothermal and mineral exploration. Resistivity surveys of geothermal areas usually are carried out to delineate low-resistivity zones related to a hydrothermal system. In mineral exploration, IP measurements are made in conjunction with resistivity measurements to delineate zones of sulfide mineralization. Much of this work is done in mountainous terrain where topographic effects can produce misleading anomalies. Hence, it is important to understand these effects and to include them in interpretation models.

Topographic effects in resistivity surveys basically are caused by the use of flat-earth geometric factors in the computation of apparent resistivity when the measurements are made over an irregular terrain. Figure 1 illustrates the general effects of topography on current lines and equipotential surfaces in a homogeneous earth for a distant current source. Current lines diverge beneath a hill and converge beneath a valley. Therefore, the associated equipotential surfaces, which are normal to current lines, also diverge under a hill; they produce lower potential differences relative to a flat earth, and hence low apparent resistivities. In a valley, the converging equipotential surfaces result in high apparent resistivities. Of course, the current lines and equipotential surfaces are more complex for the dipole-dipole array. When a hill occurs between the transmitting and receiving dipoles, current focusing causes an apparent resistivity high. When there is a valley between the trans-

Manuscript received by the Editor March 19, 1979; revised manuscript received July 20, 1979.
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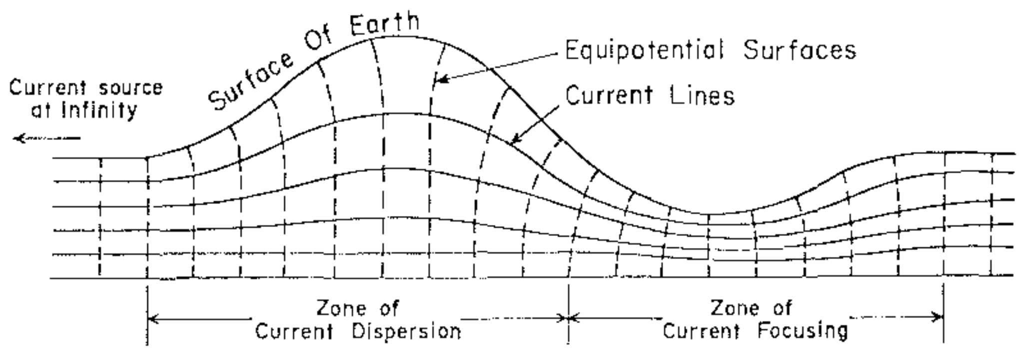

FIG. 1. Effect of topography on equipotential surfaces and current lines.

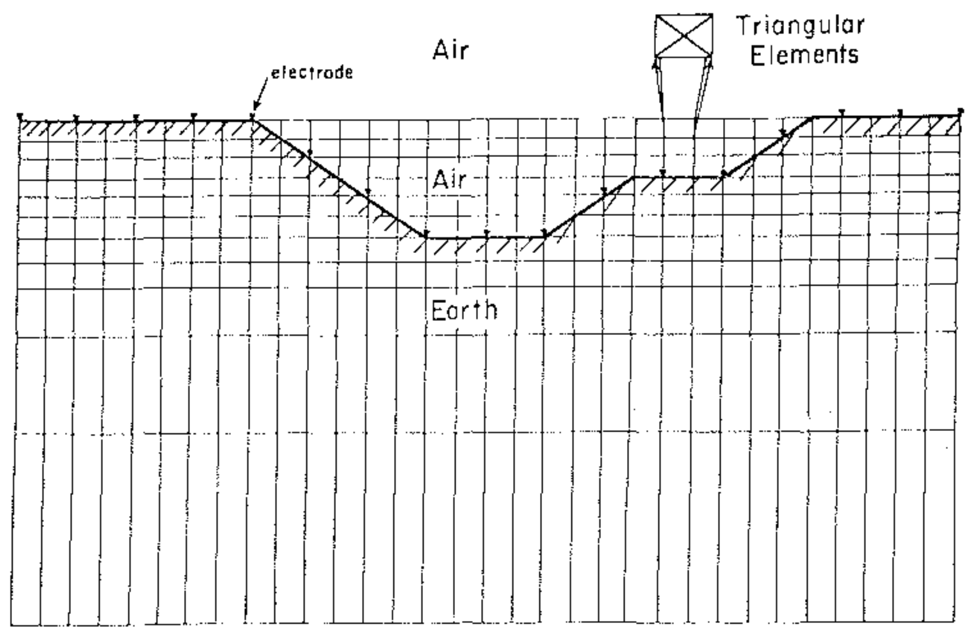

FIG. 2. Finite-element mesh showing terrain modeling technique.

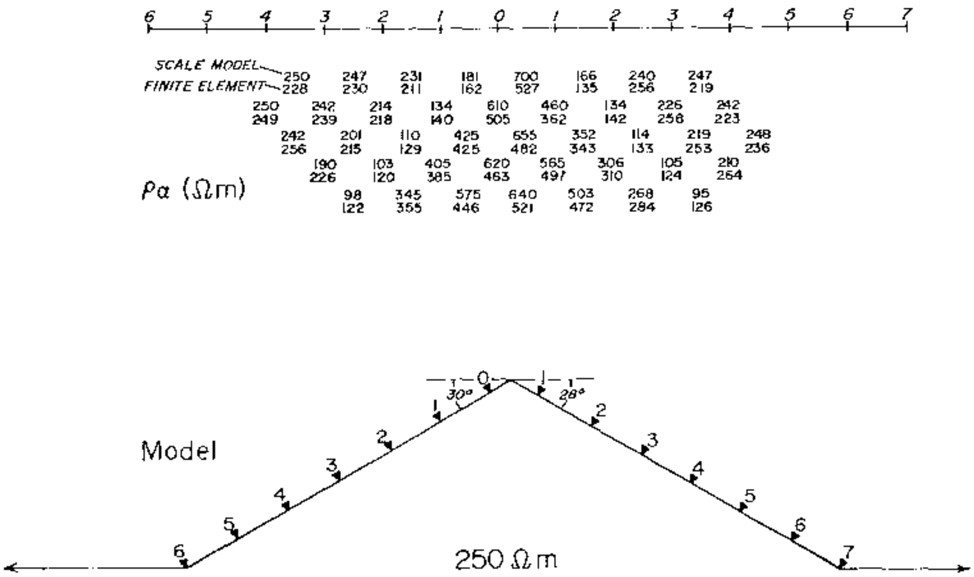

FIG. 3. Comparison between finite-element and scale-model results.

mitting and receiving dipoles, current dispersion produces an apparent resistivity low.

Because IP is a normalized measurement, current focusing and dispersion produced by an irregular terrain surface do not significantly affect IP data. However, topographic effects in IP surveys are introduced by variations in the distance between the surface electrodes and a polarizable body relative to a flat earth.

While many computer algorithms and model studies for inhomogeneities beneath a flat surface have been reported in the literature, there has been no systematic study of topographic effects. Coggon (1971), Hallof (1970), and Rijo (1977) each illustrated topographic effects for a few simple models. Because topographic effects can be so important in geothermal and mineral exploration, we have used Rijo's (1977) two-dimensional (2-D), finite-element program to conduct a systematic study as an aid to interpretation. The same program is used for interpreting data in terms of complex models with the topographic surface included, if it is significant.

We present a summary of our study of a series of valley, ridge, and slope models, illustrate the effects of electrode positioning, and give examples of the characteristic resistivity anomalies associated with the three basic terrain features. Then we describe a means of correcting apparent resistivity data for topographic effects and demonstrate this technique with examples. The effect of topography on IP response is demonstrated by comparing the anomaly of a dike within a flat earth to anomalies of a dike beneath a valley and a ridge. Our theoretical and field examples show that topography must be included in numerical models used to interpret resistivity and IP data taken over irregular terrain to ensure the validity of the interpretation. We have studied only the in-line, dipole-dipole electrode array because of its resolution, field efficiency, and common usage.

NUMERICAL MODELING TECHNIQUE

Topography can be simulated easily with the finite-element method due to the flexibility of the triangular elements used. The other main numerical techniques, finite-difference and integral-equation, are not easily adapted to topographic analysis. In the former method, rectangular grids are used, and in the latter, the mathematics become difficult.

In the finite-element method, the earth is divided into a mesh of triangular elements in each of which the unknown potential is expressed in terms of a simple linear function defined by the unknown poten-

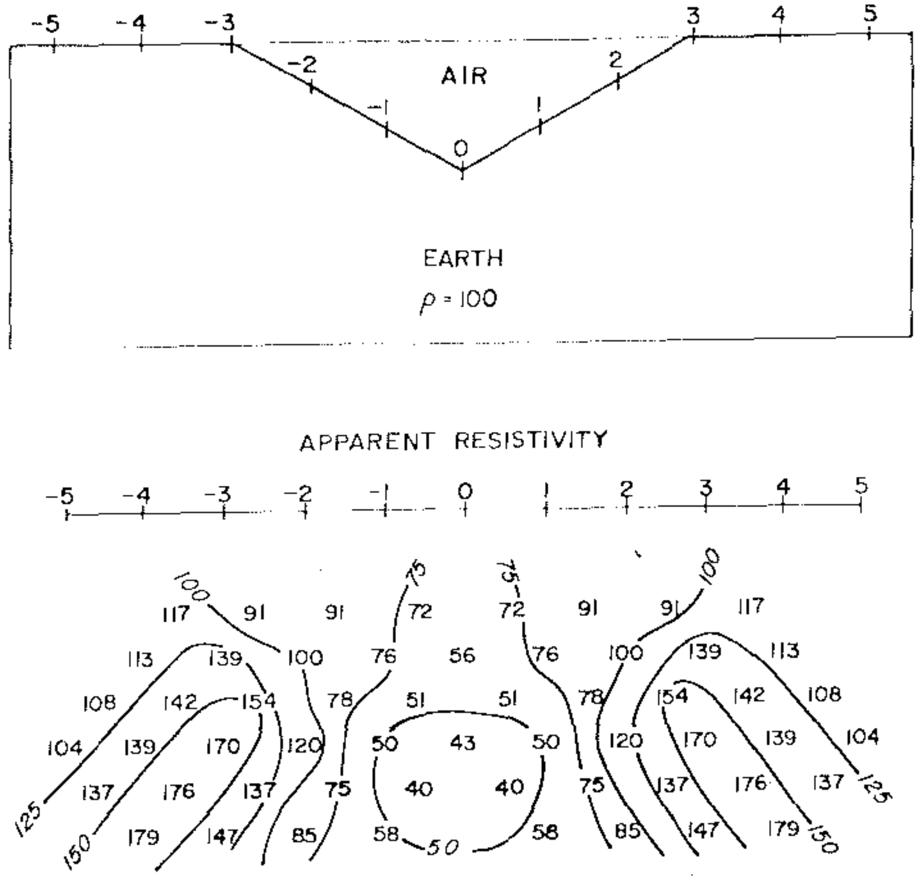

FIG. 4. Apparent resistivity anomaly due to a valley with 30-degree slopes. Contour interval on pseudosection is 25 Ω-m.

tial at element corners, coordinates of the element vertices, and electrical properties of the element. Since the source is three-dimensional (3-D), it is necessary to remove its variation in the y-direction (strike direction) by Fourier transformation in order to solve the simpler 2-D problem.

Substituting the linear functions into the Fourier-transformed Helmholtz equation, we obtain an error or residual because these linear functions are only an approximation of the true solution at each element.

Applying the Galerkin technique which states that the residual must be orthogonal to the basis functions (functions defined in terms of the coordinates of vertices of the elements) at each element, one obtains a set of linear equations from which the Fourier-transformed potential is determined. This system of equations is assembled and solved for each particular λ (Fourier transform parameter for the y-direction).

The final potential is obtained by carrying out the inverse Fourier transform using the solution of the linear system for each λ. The apparent resistivity is calculated from these potentials; calculating the IP response requires a second solution for perturbed resistivities.

Figure 2 illustrates the finite-element mesh. The topographic surface is defined by assigning a high resistivity to the "air" portion of the mesh. Resistivity contrasts of 10^3 to 10^5 between air and earth yield accurate results. Higher contrasts result in numerical instability, while lower contrasts allow significant electrical conduction in the air.

Electrodes are located at their correct positions on the terrain surface, with distances measured either horizontally (Figure 2) or along the slopes as in the usual field procedure. Slope distances are used for computing all of the model results given here.

We have verified our numerical solution by comparison with scale-model results. Hallof (1970) published a limited set of scale-model cases showing the effects of topographic features on in-line, dipole-dipole resistivity measurements. A finite-element model was designed to approximate one scale-model case of Hallof's study (case T-h30°-250-). The scale model is eight dipole units in length, while the finite-element model has infinite strike-length. However, agreement between the numerical and analog model results is good, as shown in Figure 3. For all corresponding points, the mean ratio and standard deviation of computed values to scale-model values are 0.99 and 0.15, respectively.

Internal checks on our solution consist of comparisons between results for smooth and sharp inflections in the terrain surface, results for different mesh sizes and textures, and results for different air-earth resistivity contrasts. Other checks for flat topography are discussed by Rijo (1977).

Depending upon mesh size and complexity, resistivity and IP calculations for one model require between 3 and 4 minutes of computer time on the Univac 1108 computer.

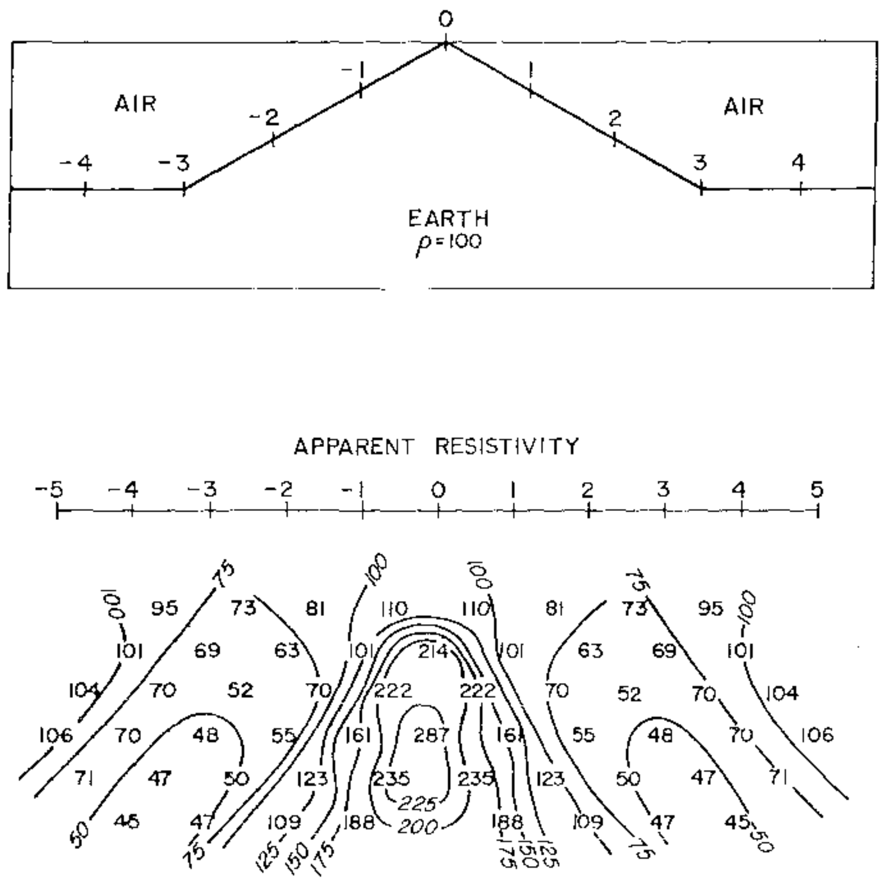

FIG. 5. Apparent resistivity anomaly due to a ridge with 30-degree slopes. Contour interval on pseudosection is 25 Ω-m.

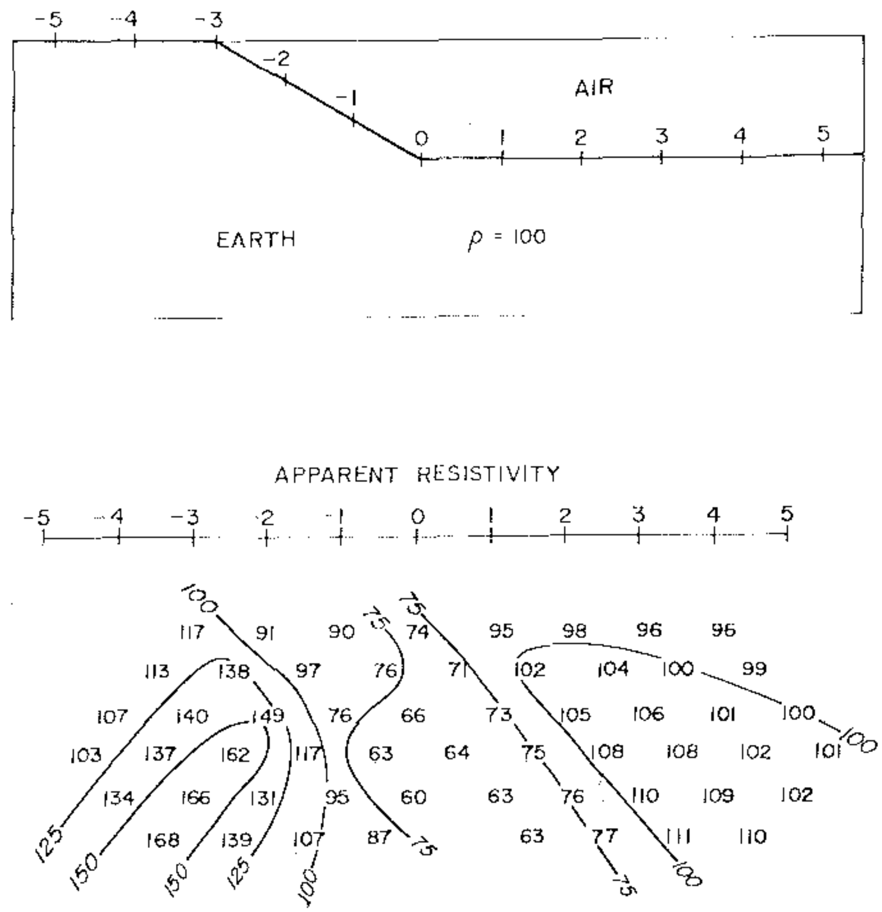

Fig. 6. Apparent resistivity anomaly due to a 30-degree slope. Contour interval on pseudosection is 25 Ω-m.

ANALYSIS OF TERRAIN-EFFECT RESISTIVITY ANOMALIES

We have made a systematic study of terrain-effect resistivity anomalies by analyzing three basic topographic features: a valley, a ridge, and a slope. For each topographic feature we computed the anomaly for a series of models with different slope lengths, slope angles, and electrode positions. Examples of the characteristic anomalies associated with the basic topographic features, a summary of our study of systematic variations in slope angle and slope length, and an example of the effect of electrode positioning are presented in this section.

As shown in Figure 4, a valley causes a central apparent resistivity low flanked by zones of high apparent resistivity in the pseudosection. The low is most pronounced when the transmitting and receiving dipoles are on extreme opposite sides of the valley. This example shows that a valley can produce a large, spurious, low-resistivity anomaly which could easily be misinterpreted as evidence for a buried conductor.

The effect of a ridge is shown in Figure 5. Its resistivity anomaly is opposite that of a valley, showing a central resistivity high flanked by zones of low resistivity. The high is most pronounced when the transmitting and receiving dipoles are at the extreme flanks of the ridge. The well-defined low resistivity zones on either side of the high could be mistaken as indicative of buried conductive bodies. On the other hand, the terrain-effect high could mask the expres-

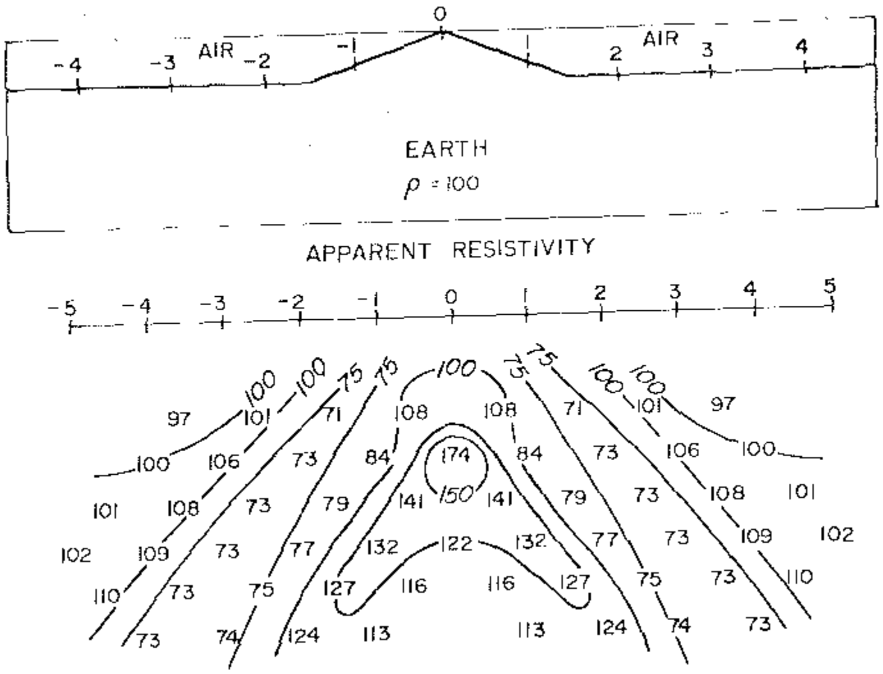

FIG. 7. Apparent resistivity anomaly due to a ridge. Transmitting dipole at top of ridge. Contour interval on pseudosection is 25 Ω-m.

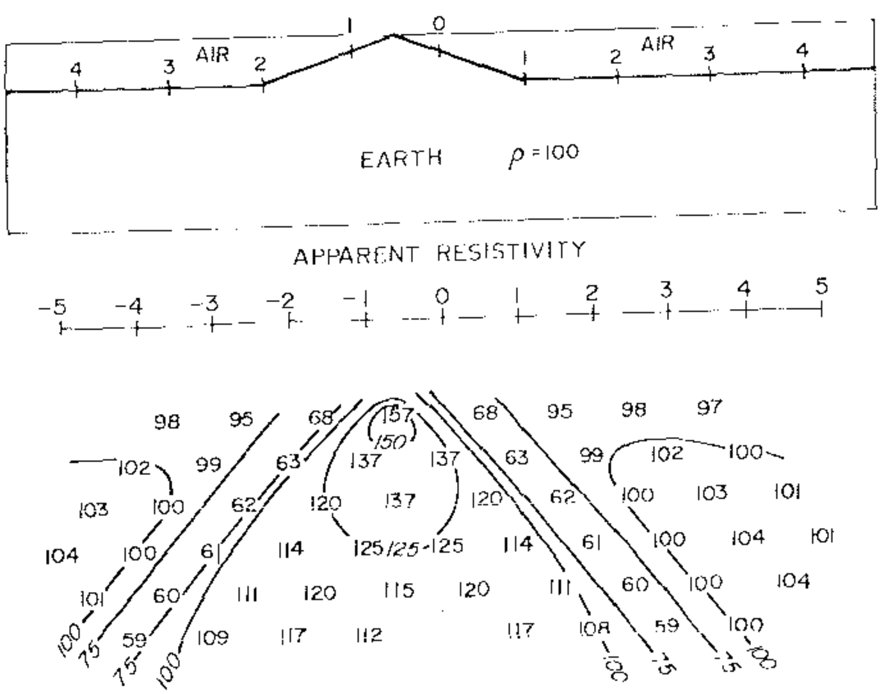

FIG. 8. Effect of changing dipole positions for the ridge model of Figure 7. Contour interval on pseudosection is 25 Ω-m.

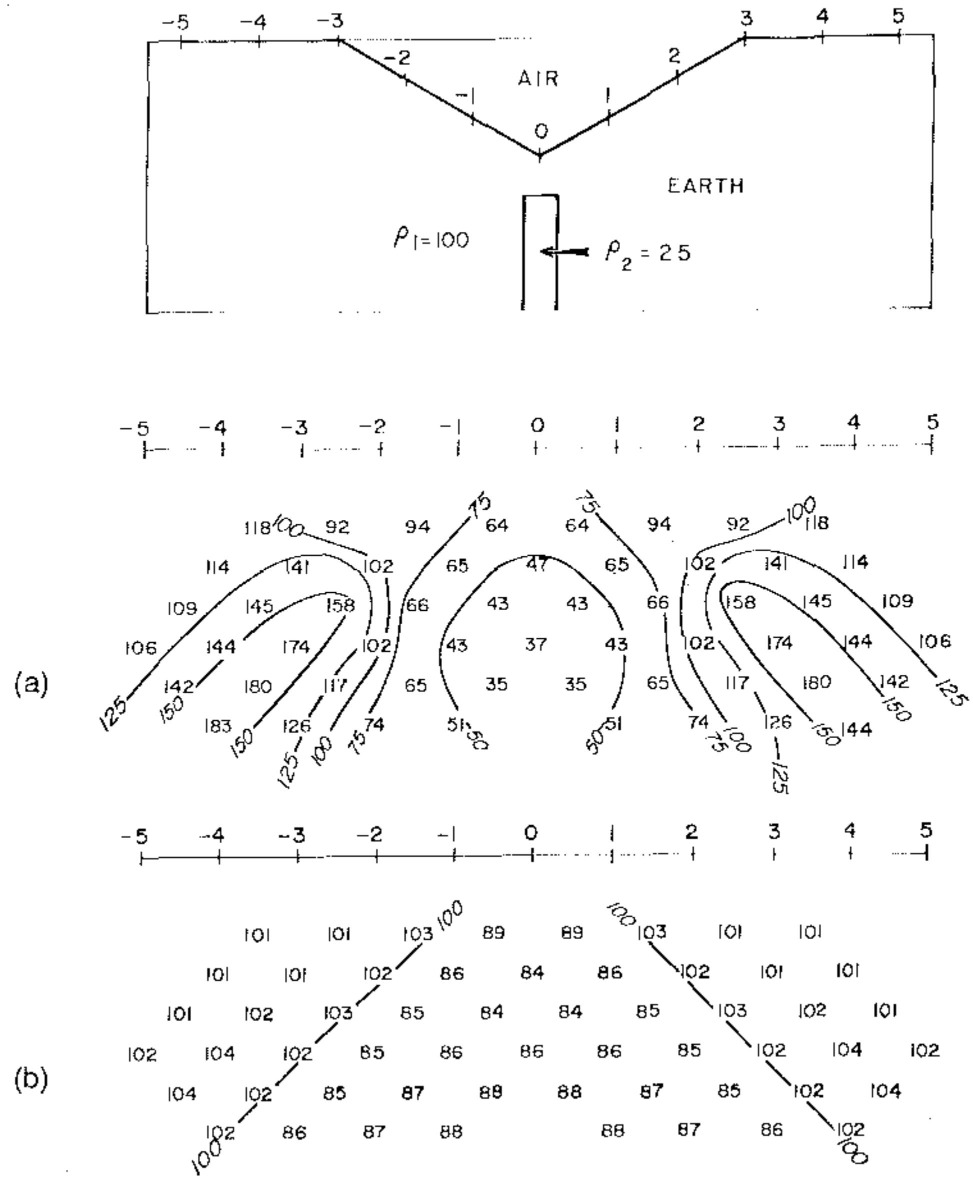

FIG. 9. Apparent resistivity over a buried dike under a valley: (a) topographic effect included, (b) corrected for topography. Contour interval on pseudosections is 25 Ω-m.

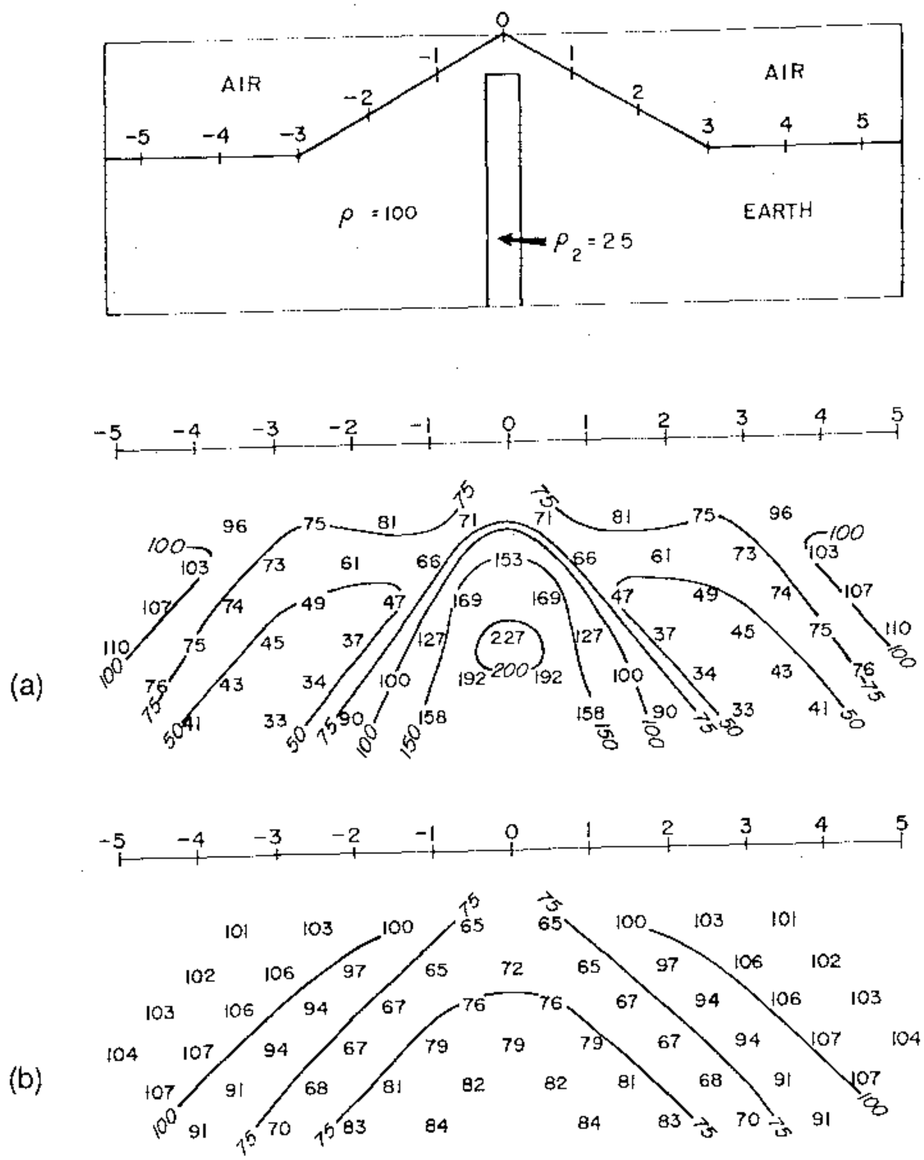

FIG. 10. Apparent resistivity over a buried dike under a ridge: (a) topographic effect included, (b) corrected for topography. Contour interval on pseudosections is 25 Ω-m.

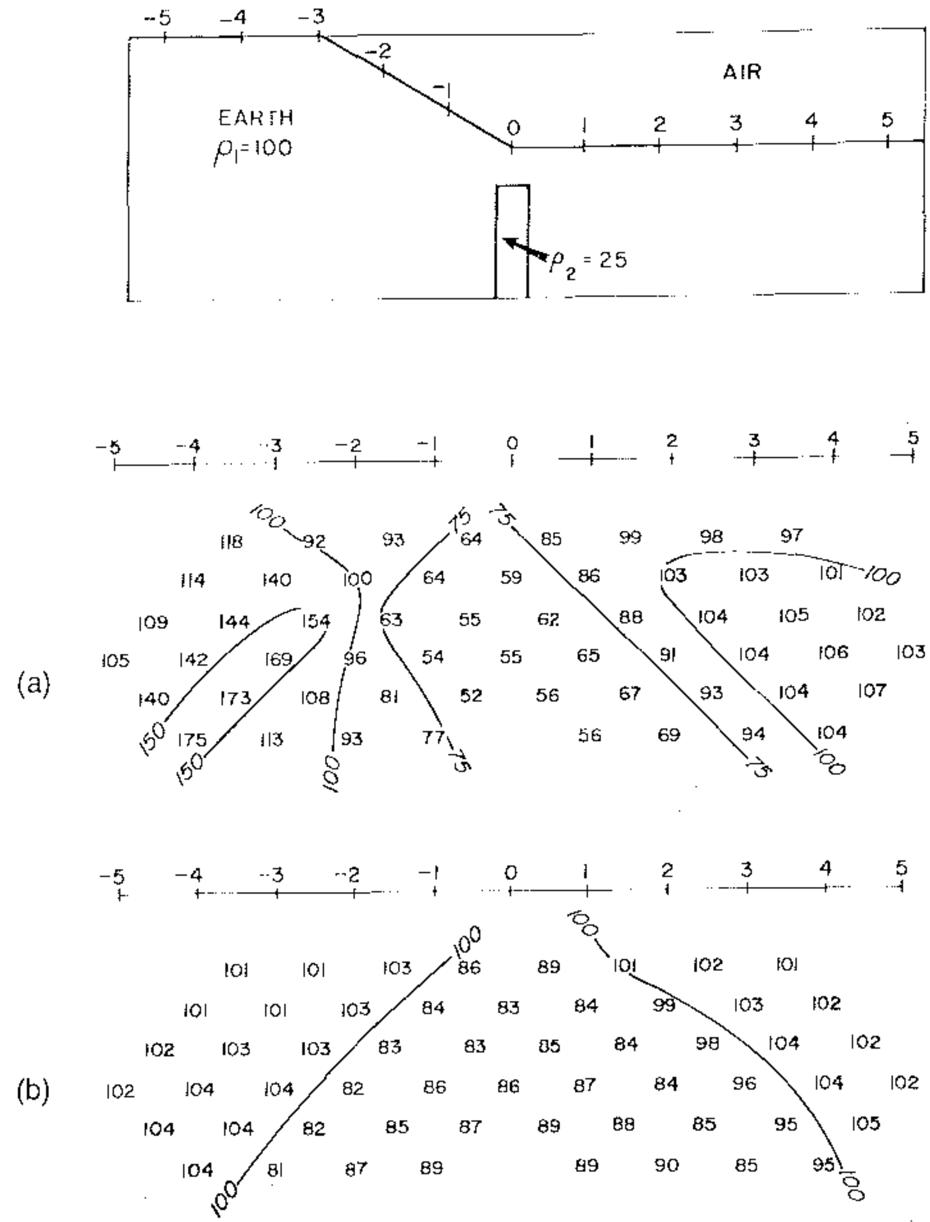

FIG. 11. Apparent resistivity over a buried dike under a slope: (a) topographic effect included, (b) corrected for topography. Contour interval on pseudosections is 25 Ω-m.

sion of an actual conductive zone below the ridge.

The resistivity anomaly produced by a slope is shown in Figure 6. A resistivity low occurs when the transmitting dipole is on the slope (positions −2, −1) and the receiving dipole is positioned to the right at increasing distances. A resistivity high occurs when the transmitting dipole is on the slope and the receiving dipole is positioned to the left at increasing distances. Again, the terrain-effect low could be erroneously interpreted as due to a conductive zone in the earth.

To determine when topographic effects are significant, we systematically modeled each of the basic features for slope lengths (*SL*) of 0.5, 1.0, 1.5, 2.0, 3.0, and 6.0 dipole-lengths and for slope angles (*SA*) of 10, 20, 30, and 40 degrees. We computed results for dipole separations of 1 through 6 dipole-lengths.

In general, the terrain-effect anomaly increases with increasing slope length for all three basic features and reaches a maximum between 3 and 6 dipole-lengths. Terrain features with slope length less than 1 dipole-length produce negligible anomalies. In all cases, except for some values observed at slope lengths of 0.5 and 6 dipole-lengths, the terrain anomaly increases with increasing slope angle for any given slope length. Anomalies generally are unimportant for slope angles of 10 degrees or less.

For the valley cases, the maximum and minimum computed terrain effects occur at dipole separations of 6 and 5 dipole-lengths, respectively. Maximum values greater than 200 percent and minimum values less than 50 percent are observed. For the ridge cases, the maximum and minimum computed values occur at dipole separations of 4 and 6 dipole-lengths, respectively, with observed values greater than 400 percent and less than 50 percent, respectively. The maximum computed terrain-effect value for the slope cases occurs at a dipole separation of 6 dipole-lengths

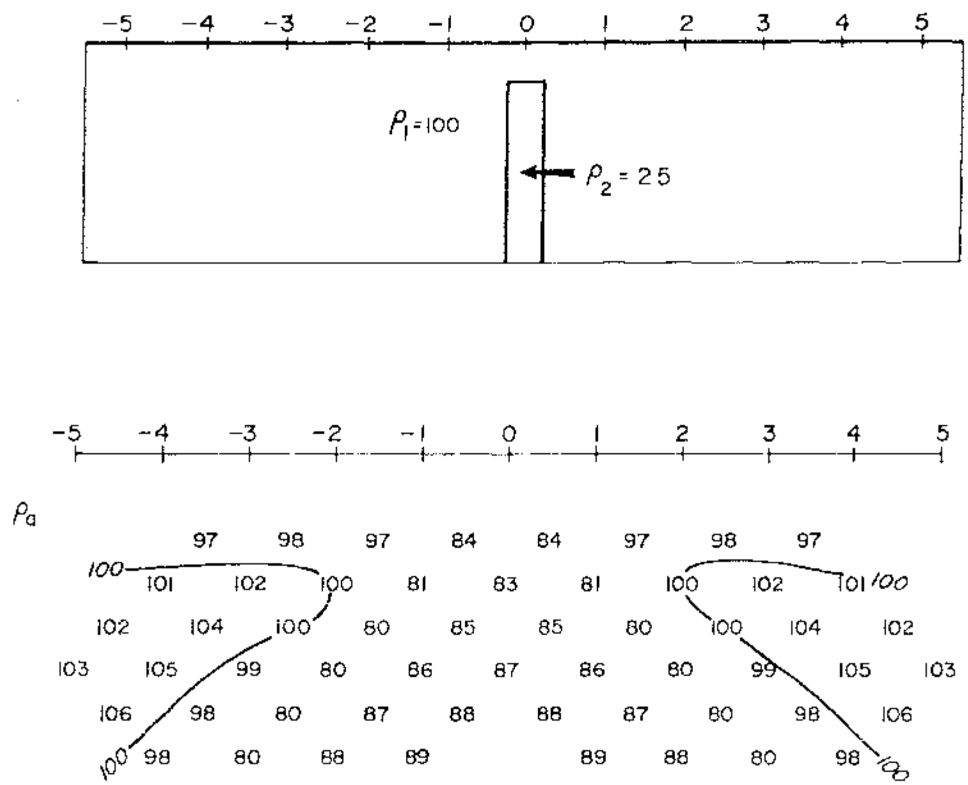

FIG. 12. Apparent resistivity due to a dike beneath a flat surface. Compare with Figures 9b, 10b, 11b. Contour interval on pseudosection is 25 Ω-m.

and the minimum at dipole separations of both 5 and 6 dipole-lengths; they are greater than 150 percent and less than 60 percent, respectively.

In order to limit the number of cases, we kept the center electrode of the dipole dipole array at the axis of symmetry for the valley and ridge models and at the base of the slope for the slope models. The effect of changing this electrode position is shown in Figures 7 and 8. When the electrode is centered at the top of the ridge (Figure 7), the maximum apparent resistivity (174) occurs at a dipole separation of 2 dipole-lengths, and the minimum value (71) occurs at a dipole separation of 1 dipole-length. When the dipole is centered at the top of the ridge (Figure 8), the maximum (157) and minimum (59) values occur at dipole separations of 1 and 6 dipole-lengths, respectively. Although the anomalies are generally similar, the differences could be important in detailed interpretation. These results show that accurate electrode position, relative to the terrain feature, is required for detailed modeling.

TERRAIN-CORRECTION TECHNIQUE FOR APPARENT RESISTIVITY DATA

The apparent resistivity of a homogeneous earth is equal to its real or intrinsic resistivity; terrain effects are due only to the use of an inappropriate geometry factor in computing the apparent resistivities. Apparent resistivity ρ_a is given by:

$$\rho_a = \frac{V}{I} G,$$

where V is the measured potential difference, I is the applied current, and G is the geometric factor. The geometric factor accounts for the decrease in the

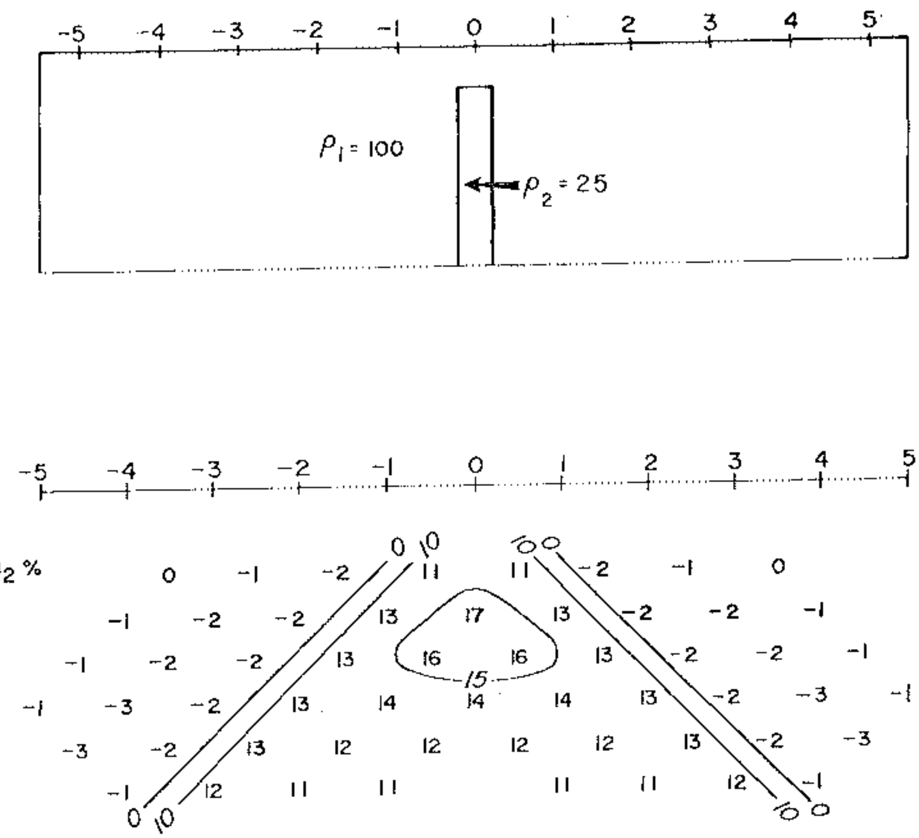

FIG. 13. IP anomaly of a buried dike for a flat earth. Response given as percent of intrinsic response in the body.

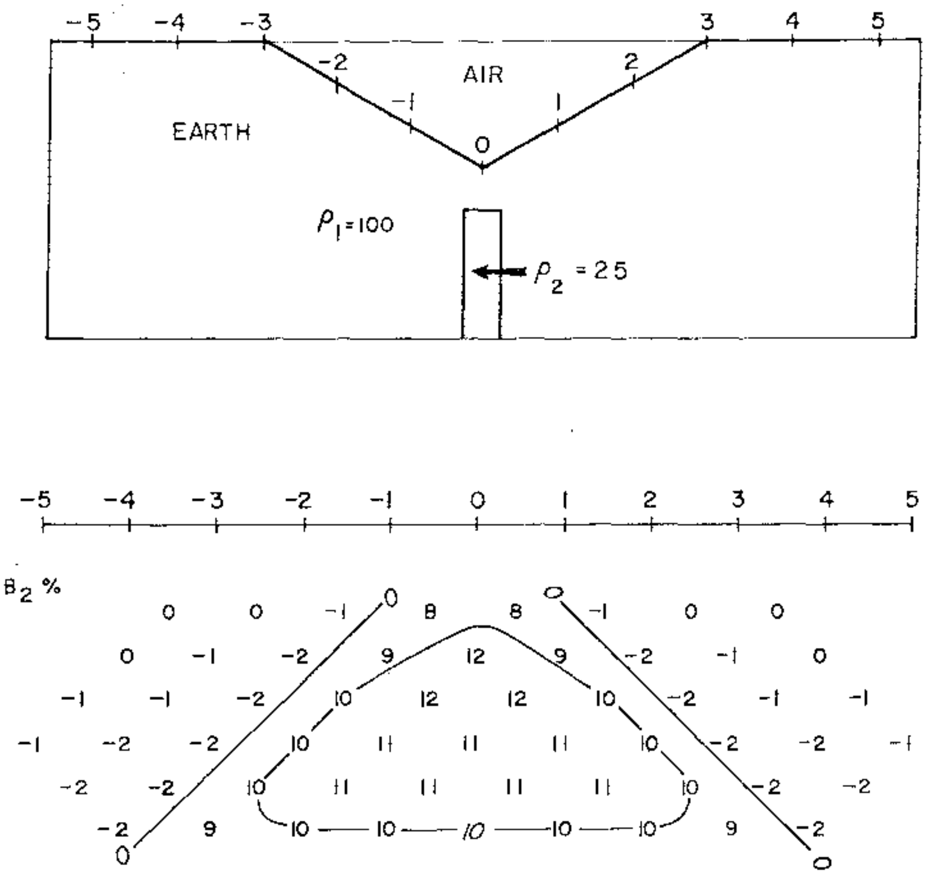

FIG. 14. IP anomaly of a dike buried beneath a valley.

potential field with distance from the current electrodes and depends upon the electrode array used. Apparent resistivities are usually computed assuming a flat earth where, if the earth is homogeneous, the electric field is an analytic function. However, the electric field under an irregular surface cannot be defined analytically, and thus it would be necessary to compute the correct geometric factors numerically. If, for example, the correct geometric factors were known for our homogeneous-earth terrain models, then the computed apparent resistivities would equal 100 Ω-m, which is the intrinsic resistivity of these models. Since we assumed flat-earth geometric factors, our computed values can be thought of as percent correction factors for ρ_a. For example, a computed value of 125 indicates a 25 percent increase in apparent resistivity due to using the flat-earth geometric factor.

For field cases that are approximately 2-D, numerical modeling provides a straightforward means to correct the apparent resistivities for terrain effects. The terrain profile along the survey line is modeled for a 1 Ω-m homogeneous earth, and the observed apparent resistivities are divided by their corresponding computed values. The adjusted data then more accurately show the effects of the actual earth resistivity structure, making qualitative interpretations more valid. For quantitative interpretation using numerical modeling, the apparent resistivities are first corrected for terrain effects to facilitate a good initial guess to the resistivity structure of the earth.

To demonstrate the significance of the apparent resistivity terrain-correction scheme, we show the apparent resistivity anomalies associated with a buried conductive dike for the valley, ridge, and slope cases, uncorrected and corrected, in Figures 9, 10, and 11, respectively. The response of the same dike beneath a flat earth is shown in Figure 12. For the valley case (Figure 9), correction factors are taken from Figure 4, which shows computed apparent resistivity values for a 100 Ω-m homogeneous earth with the identical topography. The terrain-corrected anomaly compares favorably with the flat-earth anomaly. The small differences remaining are due to the varying distances between the body and the electrodes. In like fashion, the apparent-resistivity anomalies for the ridge and slope cases (Figures 10 and 11) are corrected by the "correction factors" for the identical, homogeneous earth, topographic models shown in Figures 5 and 6, respectively. Again, the terrain-corrected anomalies compare quite well with the flat-earth anomaly. Obviously, the terrain-corrected pseudosections give a much better indication of the resistivity structure of the earth under an irregular terrain surface than do the uncorrected pseudosections.

ANALYSIS OF TERRAIN EFFECTS ON IP ANOMALIES

IP is measured as percent frequency effect, phase angle, or chargeability. In each case, the IP parameter is the ratio of polarization current to normal current, both of which are affected in the same way by topography. Hence, the geometric effects which cause topographic resistivity anomalies for a homogeneous earth are cancelled in IP measurements by this normalizing process.

However, an irregular topographic surface does affect the observed IP response of a finite source

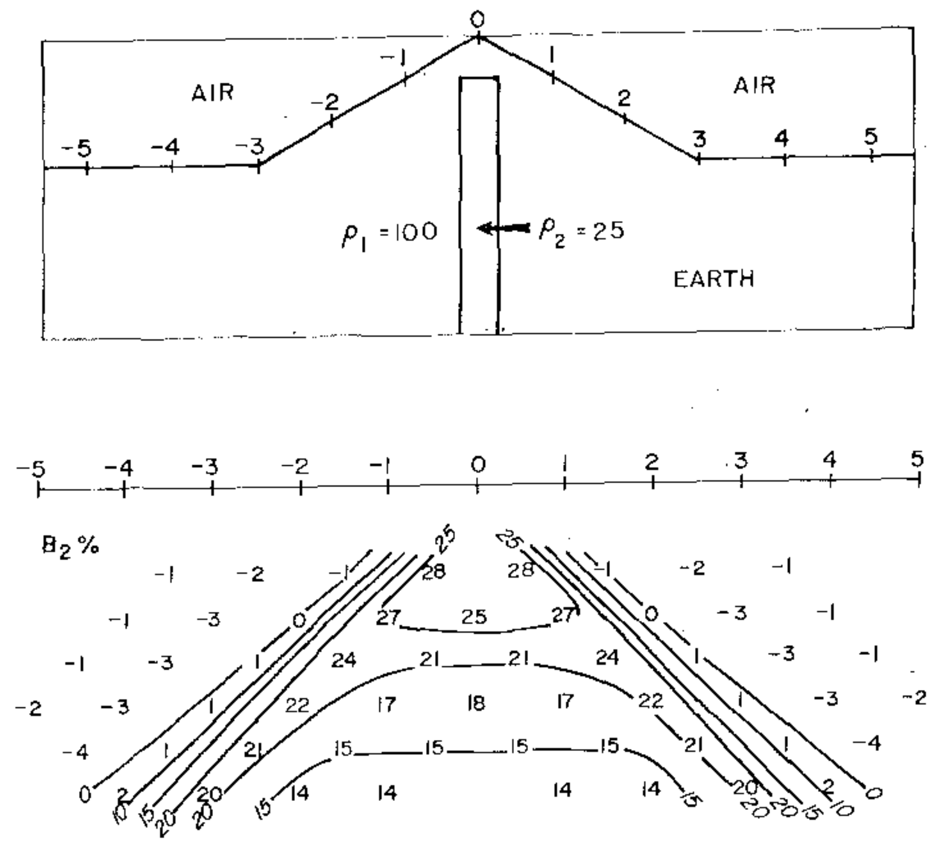

FIG. 15. IP anomaly of a dike buried beneath a ridge.

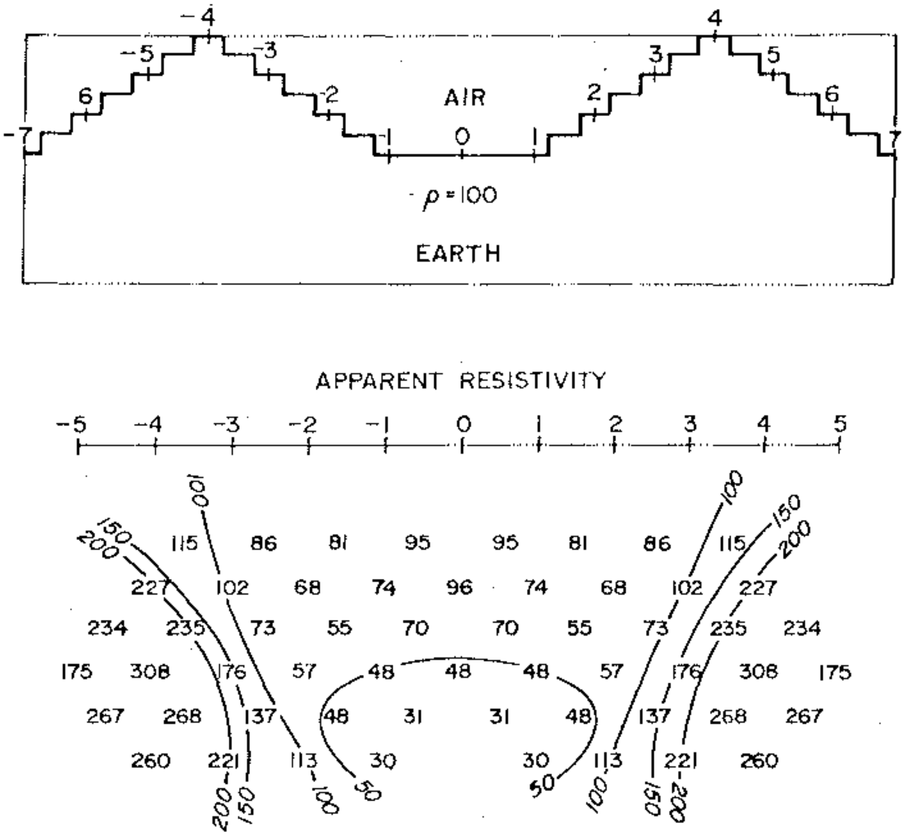

FIG. 16. Apparent resistivity anomaly due to parallel ridges on a homogeneous earth. Contour interval on pseudosection is 50 Ω-m.

because of variations in the distance between the surface electrodes and the source. This effect is demonstrated in Figures 13, 14, and 15 which show the IP response of a dike under a flat earth, a valley, and a ridge, respectively. It is convenient to plot the IP response as a percentage of the intrinsic response in the source (B_2 percent) which then applies to various IP parameters such as phase, percent frequency effect, and chargeability. The depth to the responsive body from the zero electrode is constant in all three cases.

For the flat-earth case (Figure 13) the maximum observed IP response is 17 percent of the intrinsic response. The IP anomaly is reduced in amplitude for the valley case (Figure 14) since all the electrodes except that at zero are farther from the body than for the flat earth case. In Figure 15, the electrodes on the slopes of the ridge are closer to the source relative to the flat-earth case, thus amplifying the anomaly.

If the computed IP and apparent resistivity values for these three cases were taken as field data, only the flat-earth values would yield a valid interpretative model and true intrinsic IP and resistivity values. Flat-earth interpretation of the valley or ridge theoretical data would yield invalid models and misleading intrinsic IP and resistivity values.

The significance of an IP anomaly often depends upon its associated resistivity anomaly. For example, an IP anomaly due to sulfide mineralization may have a corresponding resistivity low associated with hydrothermally altered host rock. The resistivity high caused by a ridge could mask an actual low-resistivity zone associated with an IP anomaly, suggesting a source in fresh rather than altered host rock. A moderately anomalous IP response associated with the resistivity low caused by a valley could be interpreted as positive evidence for significant sulfide mineralization, when in reality the anomaly would be high-background response in a high-resistivity rock.

Both qualitative and quantitative interpretations of IP data taken over irregular topography can benefit from terrain-corrected apparent resistivity anomalies.

RESISTIVITY INTERPRETATION EXAMPLES

Figures 16 and 17 illustrate the erroneous interpretations that result if one does not include topography, where it is important, in numerical models. The resistivity anomaly of Figure 16 is due to a homogeneous earth with two ridges. Attempting to fit this apparent resistivity data with an inhomogeneous, flat-earth

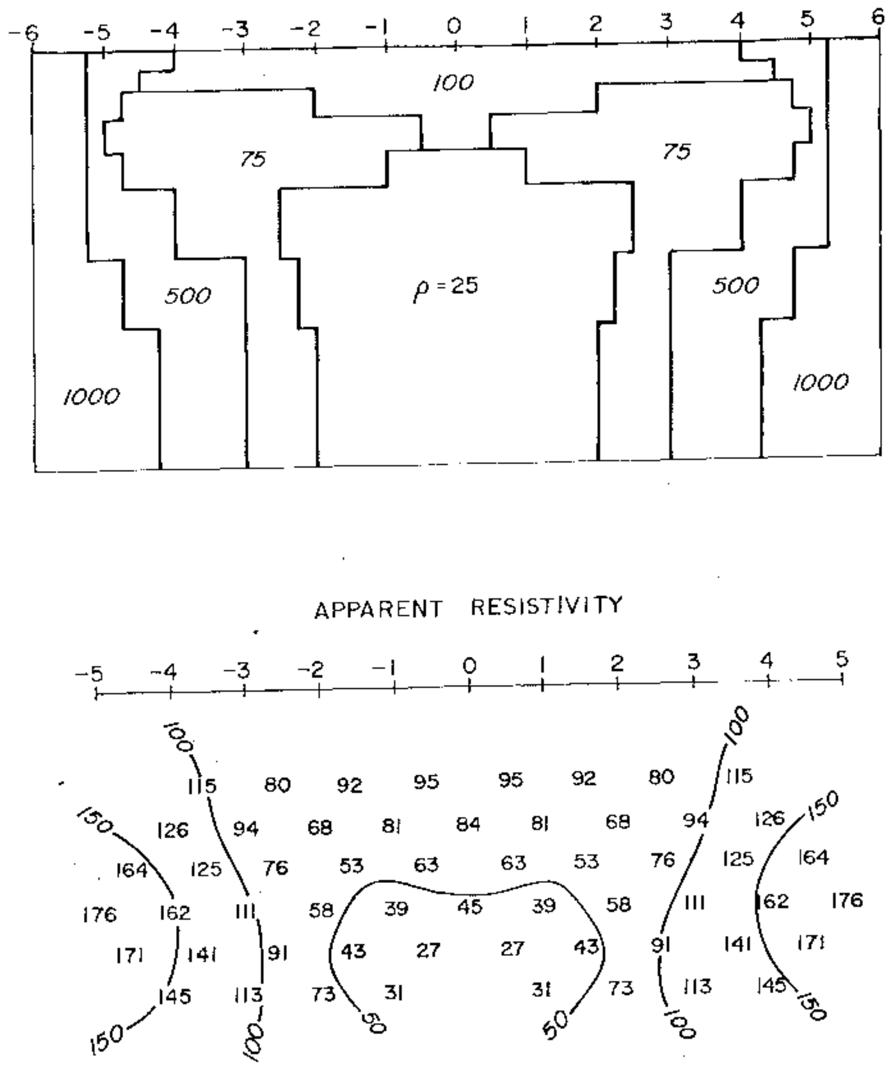

FIG. 17. Earth resistivity structure required to fit anomaly of Figure 16 if interpreted with a flat-earth model. Contour interval on pseudosection is 50 Ω-m.

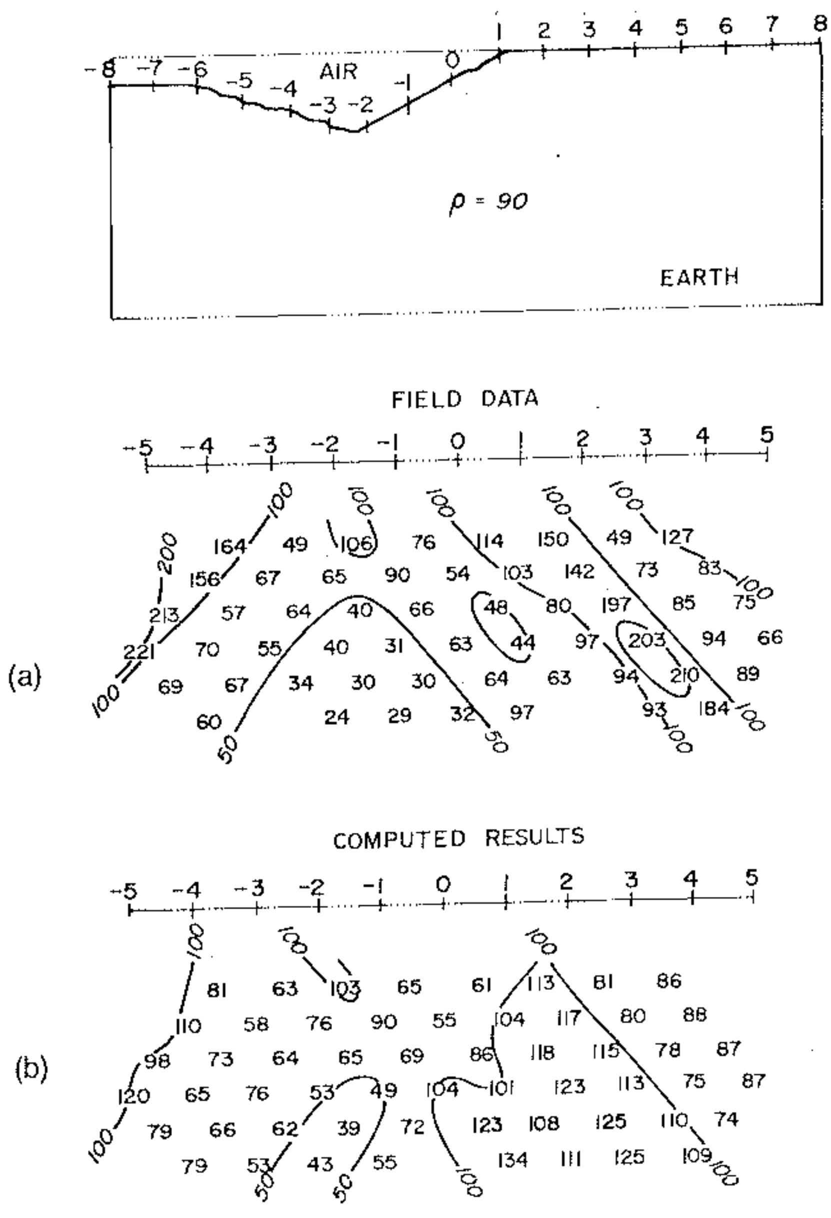

FIG. 18. Comparison between (a) field data and (b) computed results for actual topography on a homogeneous earth. Contour interval on pseudosections is 50 Ω-m.

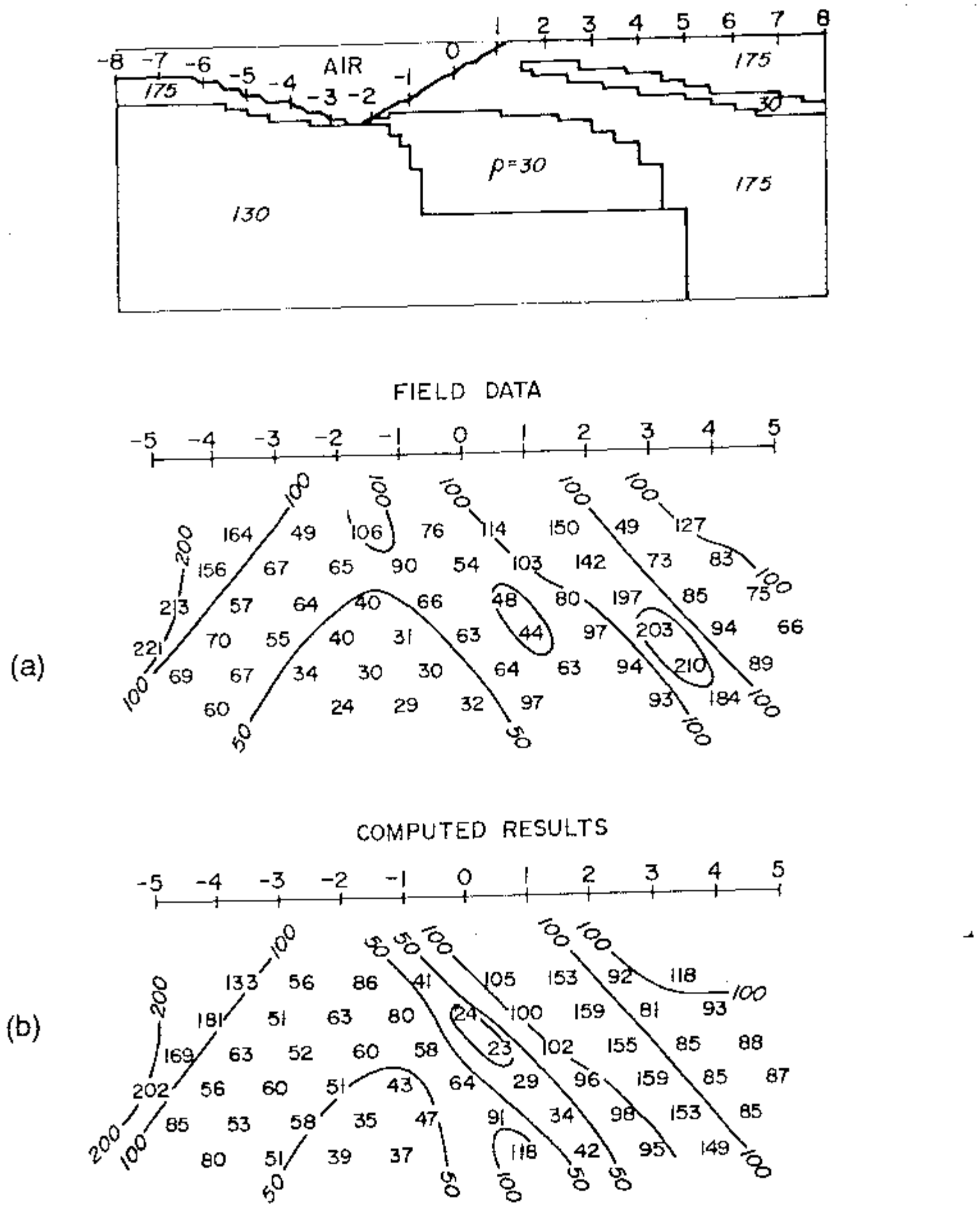

FIG. 19. Comparison between (a) field data and (b) computed results for interpreted model including actual topography. Contour interval on pseudosections is 50 Ω-m.

model yields the erroneous subsurface resistivity distribution shown in Figure 17. Except for the details of the apparent resistivity highs at each end of the line, the response of the inhomogeneous model is quite similar to that of the topography on a homogeneous earth. The most important feature of this erroneously interpreted model is the large low-resistivity zone at depth which could be mistaken as evidence for a hydrothermal feature.

Comparisons between computed results and field data from a resistivity survey in an area of rugged terrain are shown in Figures 18 and 19. In Figure 18, the field data are compared with calculated values for the actual topography on a homogeneous earth. General agreement is fair, and the effect of the valley is obvious. However, it is apparent that an inhomogeneous model is required for a good fit. Figure 19 shows our interpreted model after several iterations. The topographic effects and variable earth resistivity combine to yield a calculated apparent resistivity pattern which is in good agreement with the field data. As Figures 16 and 17 demonstrated earlier, modeling these field data without accounting for topography would indicate an erroneous low-resistivity zone below the valley.

CONCLUSIONS

The results of this study show that:

(1) topographic resistivity anomalies are significant in areas where slope angles are 10 degrees or more, for slope lengths of one dipole-length or more;

(2) the 2-D finite element computer technique provides a method for effectively treating this problem; and

(3) topographic effects must be accounted for to ensure valid interpretative models of resistivity and IP survey results.

A full catalog of models from our systematic study and a documented copy of the finite-element program are available from the Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, UT 84112.

ACKNOWLEDGMENTS

The research was funded by the Department of Energy, Division of Geothermal Energy, Contract DE-AC07-78ET28392 (formerly, EG-78-C-07-1701). Thanks are due James Lunbeck for his help in computer processing the models. The concept of terrain effect corrections benefited from discussions with Dr. W. E. Glenn.

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