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TOPOGRAPHIC EFFECTS IN RESISTIVITY SURVEYS

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ABSTRACT

The nature and significance of topographic-effect resistivity anomalies are discussed and a two-dimensional, finite element computer technique is described that provides a means for: 1) analyzing the nature of these anomalies, 2) correcting apparent resistivity data for topographic effects, and 3) incorporating topography in interpretative models. We have studied the effects of slope length and slope angle on the shapes and amplitudes of these anomalies for a valley, a ridge and a slope.

For an inline, dipole-dipole electrode array, a valley produces a central resistivity low flanked by zones of higher resistivity. A ridge produces just the opposite anomaly pattern, a central high flanked by zones of lower resistivity. A slope generates a resistivity low at its base and a high at its top. Topographic effects increase with slope length until the terrain feature becomes large with respect to the dipole length. Increasing the slope angle causes larger effects irrespective of slope length. Electrode positioning has an important effect on anomaly shape and amplitude, especially when detailed modeling is required.

A technique for correcting apparent resistivity for topographic effects uses the finite element program to compute the correction factors. The accuracy of these corrections depends upon how closely the actual case approximates an ideal two-dimensional model.

Examples are given to show how topographic effects produce anomalies that can lead to erroneous interpretations. An actual field case is included to

demonstrate the importance of including topography in the interpretative model.

The results of this study show that:

- 1) topographic effect resistivity anomalies are significant in areas where slope angles are 10 degrees or more,
- 2) topography must be included to insure valid interpretative models of survey results, and
- 3) the two-dimensional finite element technique provides a method for effectively treating this problem.

INTRODUCTION

Resistivity surveying plays an important role in geothermal exploration and assessment. The usual purpose is to delineate low-resistivity zones related to hydrothermal systems. However, much of the work is carried out in mountainous terrain where topographic effects can produce similar low-resistivity anomalies. Hence it is important to understand these effects and to include topography in interpretation models.

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 each illustrated topographic effects for a few simple models. Because topographic effects can be so important in geothermal work, we have used Rijo's (1977) two-dimensional, finite element program to conduct a systematic study as an aid to interpretation. We use this same program for interpreting data in terms of complex models with the topographic surface included, if it is significant.

Topographic effects are actually geometric effects which are associated with the relative locations of the current and the potential electrodes. Figure 1 illustrates the general effects of topography for a distant current source. For this case current flow lines diverge beneath a hill and converge beneath a valley. Therefore the associated equipotential surfaces, which are normal to current flow lines, also diverge under a hill, producing lower potential differences and hence low apparent resistivities. In a valley the converging equipotentials result in high apparent resistivities. The flow

Figure 1. General topographic effects on current flow and equipotential lines.

lines and equipotential surfaces are more complex for the dipole-dipole array. Figure 2 shows the dipolar electric field for a flat earth. In contrast, the schematic diagram, Figure 3, shows the distortion of this field due to an irregular surface. For the dipoles shown, the zones of current focusing and dispersion create potential differences greater or less than those observed for the equivalent flat earth case. When the topographic surface creates an angle of less than 180 degrees, the flat earth case, between transmitting and receiving dipoles, current focusing causes an apparent resistivity high. For angles greater than 180 degrees, current dispersion produces apparent resistivity lows. Topographic effects are uniquely related to the particular electrode array used.

This report illustrates topographic resistivity anomalies for a systematic series of valley, hill, and slope models and describes a means for correcting apparent resistivity data for topographic effects. Theoretical and field examples show that topography must be included in numerical models used to interpret resistivity data taken in irregular terrain. We have studied only the dipole-dipole array because of its resolution, field efficiency, and common usage in geothermal work.

Figure 2. Dipolar Electric Field for a Flat Earth

Figure 3. Schematic Diagram Showing Distortion of Dipolar Electric Field Due to Irregular Terrain.

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 potential at element corners, the coordinates of the element vertices, and the electrical properties of the element. Since the source is three-dimensional, it is necessary to Fourier transform out the variation in the y direction (strike direction) in order to solve a simpler two-dimensional 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 error or residual must be orthogonal to the basis functions (functions defined in terms of the coordinates of the 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 of 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 . Finally the apparent resistivity is calculated from the potentials.

Figure 4 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, as in Figure 4, or along the slopes in the usual field procedure. Slope distances are used for computing all of the model results in this report.

We have verified our numerical solution by comparing with scale-model results. Hallof (1970) published a limited set of scale-model cases showing the effects of two-dimensional topographic features on inline, dipole-dipole resistivity measurements. A finite element model was designed to approximate the scale model, Case T-h30⁰-250- $\perp$, of Hallof's study. 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 5. For all corresponding points, the mean ratio and standard deviation of computed values to scale model values is 0.99 and 0.15 respectively.

Internal checks on the solution consist of comparisons between results for smooth and sharp inflections in the terrain surface, results for different

Figure 4. Finite element mesh showing terrain modeling technique.

Figure 5. Comparison of finite element with scale model results.

mesh sizes and textures, and results for different air-earth resistivity contrasts. Other checks for flat topography are discussed by Rijo (1977).

Depending upon the mesh size and complexity, the calculations for one model require between one and two minutes of computer time on a UNIVAC 1108 computer.

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. The full series of models with various slope lengths and slope angles is included in Appendix A. Examples of the characteristic anomalies associated with the basic topographic features and of the effects of electrode positioning are shown in this section.

The apparent resistivity of a homogeneous earth is equal to its real or intrinsic resistivity, and 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 potential field with distance from the current electrodes and varies for the electrode array used. Apparent resistivities are usually computed assuming a flat earth, where the electric field is an analytic function. The electric field under an irregular surface cannot be defined analytically, and thus it would be necessary to compute the geometric factors numerically. If the correct geometric factors were known for our terrain models, then the computed apparent resistivities would equal 100 ohm-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 the assumed flat earth G.

For field cases that approximate the ideal, two-dimensional model, where: 1) the terrain features and resistivity structure are two-dimensional and parallel, and 2) the data are taken along a line perpendicular to them, numerical modeling provides a straightforward means to correct the apparent resistivities for terrain effects. The given terrain surface is modeled for a 100 ohm-m homogeneous earth and the observed apparent resistivities are divided by their corresponding computed terrain effect values. The adjusted data then more accurately show the effects of the actual resistivity structure making qualitative interpretations more valid. For quantitative interpretation via numerical modeling, the topographic surface is simply included in the model as discussed below. Where induced polarization (IP) measurements are taken in conjunction with apparent resistivity, the significance of an IP anomaly could be altered if its associated resistivity anomaly is corrected by this technique. For example, an IP anomaly due to sulfide mineralization may have a corresponding resistivity low associated with its 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 actuality the anomaly would be high-background response in a high-resistivity rock.

As shown in Figure 6, a valley causes a central resistivity low in the pseudosection flanked by zones of high resistivity. The low is most pronounced when the transmitting and receiving dipoles are on extreme opposite sides of the valley, causing the greatest amount of current dispersion. 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 on Figure 7. 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 could be mistaken for indications of buried conductive bodies. On the other hand, the terrain-effect high could mask the expression of an actual conductive zone below the ridge.

The resistivity anomaly produced by a slope is shown on Figure 8. Current dispersion at the base of the slope causes a resistivity low when the transmitting dipoles are on the slope and the receiving dipoles are to the right. Current focusing occurs at the top of the slope, causing a resistivity high when the transmitting dipoles are on the slope and the receiving dipoles are to the left. Again, the terrain-effect low could be erroneously interpreted as due to a conductive zone in the earth.

To determine at what point topographic features significantly contribute to the apparent-resistivity anomaly, each of the basic features were modeled for slope lengths (SL) of 0.5, 1.0, 1.5, 2.0, 3.0, and 6.0 in units of dipole

Figure 6. Effect of a valley on apparent resistivity.

Figure 8. Effect of a slope on apparent resistivity.

length and for slope angles (SA) of 10, 20, 30, and 40 degrees (Appendix A).

In general, the terrain-effect anomaly increases with increasing SL for all three basic features and reaches a maximum between three and six dipole-lengths. Additional models with SLs between three and six dipole-lengths are required to determine the maximum anomalies for all cases. Terrain features with SL less than one dipole length produce negligible anomalies. In all cases, except for some values observed at SLs of 0.5 and 6 dipole-lengths, the terrain anomaly increases with increasing SA for any given SL.

For the valley cases the maximum computed value occurs at the sixth-separation and the minimum at the fifth. Maximum values greater than 200 percent and minimum values less than 50 percent are observed. For the ridge cases the maximum computed value occurs at the fourth-separation and the minimum at the sixth, 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 the sixth separation and the minimum at both the fifth and sixth separations, greater than 150 percent and less than 60 percent, respectively.

In order to limit the number of cases, the center electrode of the dipole-dipole array was kept 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 9 and 10. When the electrode is centered at the top of the ridge, Figure 9, the maximum value, 174, occurs at the second separation and the minimum value, 71, occurs at the first separation. When the dipole is centered at the top of the ridge, Figure

Figure 9. Effect of electrode position on terrain-effect anomaly, electrode centered at top of ridge.

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10, the maximum value, 157, occurs at the first separation and the minimum at the sixth. 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.

INTERPRETATION EXAMPLES

A hypothetical geothermal case is shown in Figure 11. The model represents an outcropping bedrock area with 100 ohm-m resistivity. The parallel ridges produce an apparent resistivity low between the two ridges as shown in Figure 11a. The effect of a 10 ohm-m 'geothermal-feature' (conductive fault zone), superimposed on the terrain model emphasizes the low at depth, Figure 11b. However, the topographic anomaly dominates the pseudosection, and the 10 ohm-m zone would be difficult to detect without detailed modeling.

Figures 12 and 13 illustrate the erroneous interpretations that result if one does not include topography, where it is important, in numerical models. The resistivity anomaly of Figure 12 is due to a homogeneous earth with two ridges. Attempting to fit this apparent resistivity data with an inhomogeneous, flat-earth model yields the erroneous subsurface resistivity distribution shown in Figure 13. 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 an area of rugged terrain are shown in Figures 14 and 15. In Figure 14 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

Figure II. Hypothetical geothermal case, topographic resistivity anomaly produced by parallel ridges on a homogeneous earth, with and without a conductive fault zone.

Figure 12. Resistivity anomaly produced by parallel ridges on a homogeneous earth.

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fit. Figure 15 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 12 and 13 have demonstrated, modeling these field data without accounting for topography would indicate an erroneous low-resistivity zone below the valley.

Figure 14. Comparison between computed and field results for observed terrain on a homogeneous earth.

Figure 15. Comparison between computed and field results for observed terrain on an inhomogeneous earth.

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APPENDIX A

Topographic-Effect Resistivity Anomalies for Valley, Ridge, and Slope Models

The apparent resistivity anomalies, in percent, for a valley (V), a ridge (R), and a slope (S), have been computed for slope lengths (SL) of 0.5, 1.0, 1.5, 2.0, 3.0, and 6.0 in units of dipole length and for slope angles (SA) of 10, 20, 30, and 40 degrees. Starting with valley cases, the models are coded in the form V-SL0.5-SA10, etc.

Model Results

(Cont.)

<u>Case</u>	<u>Page</u>	<u>Case</u>	<u>Page</u>
V-SL0.5-SA10	A1	R-SL0.5-SA30	A37
V-SL1.0-SA10	A2	R-SL1.0-SA30	A38
V-SL1.5-SA10	A3	R-SL1.5-SA30	A39
V-SL2.0-SA10	A4	R-SL2.0-SA30	A40
V-SL3.0-SA10	A5	R-SL3.0-SA30	A41
V-SL6.0-SA10	A6	R-SL6.0-SA30	A42
V-SL0.5-SA20	A7	R-SL0.5-SA40	A43
V-SL1.0-SA20	A8	R-SL1.0-SA40	A44
V-SL1.5-SA20	A9	R-SL1.5-SA40	A45
V-SL2.0-SA20	A10	R-SL2.0-SA40	A46
V-SL3.0-SA20	A11	R-SL3.0-SA40	A47
V-SL6.0-SA20	A12	R-SL6.0-SA40	A48
V-SL0.5-SA30	A13	S-SL0.5-SA10	A49
V-SL1.0-SA30	A14	S-SL1.0-SA10	A50
V-SL1.5-SA30	A15	S-SL1.5-SA10	A51
V-SL2.0-SA30	A16	S-SL2.0-SA10	A52
V-SL3.0-SA30	A17	S-SL3.0-SA10	A53
V-SL6.0-SA30	A18	S-SL6.0-SA10	A54
V-SL0.5-SA40	A19	S-SL0.5-SA20	A55
V-SL1.0-SA40	A20	S-SL1.0-SA20	A56
V-SL1.5-SA40	A21	S-SL1.5-SA20	A57
V-SL2.0-SA40	A22	S-SL2.0-SA20	A58
V-SL3.0-SA40	A23	S-SL3.0-SA20	A59
V-SL6.0-SA40	A24	S-SL6.0-SA20	A60
R-SL0.5-SA10	A25	S-SL0.5-SA30	A61
R-SL1.0-SA10	A26	S-SL1.0-SA30	A62
R-SL1.5-SA10	A27	S-SL1.5-SA30	A63
R-SL2.0-SA10	A28	S-SL2.0-SA30	A64
R-SL3.0-SA10	A29	S-SL3.0-SA30	A65
R-SL6.0-SA10	A30	S-SL6.0-SA30	A66
R-SL0.5-SA20	A31	S-SL0.5-SA40	A67
R-SL1.0-SA20	A32	S-SL1.0-SA40	A68
R-SL1.5-SA20	A33	S-SL1.5-SA40	A69
R-SL2.0-SA20	A34	S-SL2.0-SA40	A70
R-SL3.0-SA20	A35	S-SL3.0-SA40	A71
R-SL6.0-SA20	A36	S-SL6.0-SA40	A72

-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6

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