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Downhole Electrode Resistivity Interpretation
With Three-Dimensional Models

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ABSTRACT

Using an integral equation numerical solution, the theoretical results for 1) the potential, 2) the apparent resistivity calculated from the total horizontal electric field, and 3) the apparent resistivity calculated from the potential due to different three-dimensional bodies in plan and cross-section views have been computed. The transmitter consists of a remote electrode and a downhole electrode embedded in the body or located near the body.

For hole-to-surface work, the potential offers little information about the parameters of a deep body. The apparent resistivity from the total electric field, with its distinctive patterns, best resolves the width, length, and dip of the model, while the apparent resistivity from the potential is more difficult to interpret.

The cross-section views, for analysis of hole-to-hole surveys, theoretically define the body for the potential and the apparent resistivity derived from the potential, but their use in practice is limited.

INTRODUCTION

Only two published papers consider downhole electrode modeling for three-dimensional bodies. Daniels (1977), using a modified form of Barnett's surface-integral technique, studied six buried electrode configurations. His figures have normalized apparent resistivity or apparent polarizability plotted against configuration parameters such as 1) source and receiver depth, 2) depth/bipole length, 3) receiver distance from body, 4) depth, and 5) distance from body center. With a buried sphere model, the IP and apparent resistivity responses resulting from a buried current pole in the presence of a three-dimensional target have been studied by Snyder and Merkel (1973). Their plots are center-line profiles for normalized apparent resistivity and normalized IP response.

With a numerical modeling technique described by Hohmann (1975), the theoretical results due to a three-dimensional body composed of simple prisms were computed. The results are presented in terms of 1) the potential, 2) the apparent resistivity calculated from the total horizontal electric field, and 3) the apparent resistivity calculated from the potential. In practice, the total electric field would be measured with short orthogonal dipoles.

The approach that I have taken is to consider two electrode configurations for each model. Each configuration consists of a pair of electrodes, where one of the electrodes is remote and the second

electrode is located either in the body, for mise-a-la-masse or applied potential, or outside the body, simulating a "near miss."

Due, in part, to the lack of interpretational models, there have been few field examples presented in the literature. Some mise-a-la-masse studies for mineral exploration targets have been reported by Ketola (1972), McMurry and Hoagland (1956), Parasnis (1967) and Witherly (1980).

METHOD OF CALCULATION

The integral equation solution that was used to simulate the response of three-dimensional bodies has been described by Hohmann (1975). The integral equation is formulated by replacing an inhomogeneity by a volume of polarization currents. The polarization current is found via the method of moments with pulse basis functions and delta weight functions. The secondary electric field at the surface of the earth is then obtained by utilizing the appropriate half-space dyadic Green's function and treating the polarization current as the source of the secondary field.

Because it is necessary to solve for the polarization currents only in the inhomogeneity, the integral equation is well suited to evaluating a field technique using simple prisms comprised of basic cubes. On a PRIME 400 computer, for example, a model consisting of 16 cubes requires about 1 1/2 minutes of computing time. As the number of cubes increases, the computing time rapidly increases to about 6 minutes for 35 cubes.

The modeling program evaluates and contours the gridded values of the potential or the apparent resistivity calculated from either the total electric field, E , or the potential, V . The apparent resistivity is defined as the half-space resistivity that would produce the calculated E or V . In the figures, the potential is captioned as "in-phase potential."

Figures 1 and 2 illustrate the parameters of the body and electrode locations in plan and cross-section views, respectively. The depth, denoted as D , is the distance from the surface to the top of the uppermost prism. The width of the model's projection to the horizontal plane is referred to as horizontal extent, HE , for models dipping less than or equal to 45° . For dips greater than 45° and less than 90° , the projection is onto the vertical plane and is referred to as the vertical extent, VE . This convention is used to keep the number of prisms and the extent uniform for comparing bodies with different dips. The strike length of the model is designated as L . The cube thickness is 1 unit for all models except where noted otherwise. The angle of dip, r , of a body can be approximated by offsetting the prisms as seen in Figure 2. When r is 0° or 90° , the usual meanings for depth, width, length and depth extent for the model apply. The resistivity of the background, ρ_1 , is 100 ohm-m, while the resistivity of the model, ρ_2 , is 10 ohm-m. The asterick denotes the electrode position which may be located in or near the body.

Because of the many possibilities for theoretical and programming errors, it is important to verify the accuracy of any new numerical solution. Therefore, I have checked convergence of the results when an electrode is located in the body by subdividing the cube containing the electrode into smaller subcubes. Figure 3 illustrates the subdividing of such a cube. Figure 3(a) contains an electrode where $NDIVID$ is 1, since the cube is not subdivided. In 3(b), $NDIVID$ is 2 and the cube is subdivided into 8 subcubes, $((NDIVID)^3)$. Figure 3(c) has 27 subcubes, since $NDIVID$ is 3. Note that in 3(a) and 3(c) the

electrode is located at the center of a cube or subcube; whereas in 3(b) the electrode is located at the corners of 8 subcubes.

Figures 4 through 12 are plan views and Figures 13 through 21 are cross-section views which illustrate the accuracy check using a model with the following parameters: $D = 2.5$, $W = 3$, $L = 1$, $DE = 3$ and $\theta = 0$. It should be noted that when NDIVID is 1, the computing time is negligible since our model has only 3 prisms (9 cubes). But when NDIVID is 2 or 3 there are 16 or 35 cubes, and computing time has then been increased from negligible to $1\frac{1}{2}$ to 6 minutes. In comparing the accuracy check figures, notice that when NDIVID = 1 and NDIVID = 3 (see Figures 4 and 6, 7 and 9, 10 and 12, 13 and 15, 16 and 18, 19 and 21) the plots are almost identical. The discrepancy arising when NDIVID is 2 (see Figures 8, 11, 14, 17 and 20) results from the electrode being located at cube corners instead of being at the center of a cube. Thus there is convergence, and the rest of the modeling is done with NDIVID = 1 which uses less computer time or allows utilizing more complex models.

THEORETICAL MODELS

To aid in determining the effects of parameter changes, a standard model was selected for comparison. The standard model, shown in Figures 22 and 23 (plan and cross-section respectively), approximates a 30° dipping body simulating a geothermal reservoir by offsetting the prisms 0.6 units ($r = 30^\circ$). The other parameters are: $D = 2.4$, $HE = 4$, and $L = 4$. All the models have a resistivity contrast of 10, with a background resistivity, ρ_1 , of 100 ohm-m and a body resistivity, ρ_2 , of 10 ohm-m, except where stated otherwise. The arrows on the plots indicate the direction of the total electric field.

The plan view represents a hole-to-surface survey, while the cross-section view corresponds to a hole-to-hole survey. The data are presented on a two-dimensional grid. In plan view, the upper left corner of the grid is the origin at (0.0, 0.0, 0.0) with the x-axis along the horizontal and y-axis positive down the vertical axis (Figure 22). The origin for the cross-section views is (0.0, 5.5, 0.0) through the y-coordinate of the electrode positions, with the x-axis along the horizontal again while the vertical axis is now the z-axis, positive downward (Figure 23). The cross-section plot contains the transmitting electrodes and is oriented perpendicular to the strike of the models studied, although other cross-section views could be generated. For convenience, the potential values have been

contoured with a scale factor of 100, i.e., the actual values have been multiplied by 100 and then contoured.

Most of the models will be examined with two transmitter configurations, each considered in plan and section views (Figures 22 and 23). In both of the configurations, one of the transmitting electrodes is remote and located at $(-50.0, 5.5, 0.0)$. The second transmitting electrode is located either in the body (a) at $(5.5, 5.5, 3.5)$, or a half unit from the body (b) at $(3.5, 5.5, 4.5)$.

Hole-To-Surface (Plan View)

The hole-to-surface plots were examined to determine how changes in the body parameters such as depth, horizontal extent, length, depth extent, and dip affect the response seen on the surface. I have, in addition considered: 1) the tracing of a change in direction of the body, 2) the determination of whether a body is continuous between two drill hole intercepts, and 3) the detection of a second body when a drill hole intercepts another body.

Electrode in Body

The mise-a-la-masse electrode configuration is discussed in this section with the embedded electrode located at $(5.5, 5.5, 3.5)$, for most of the plots. We will examine the results for the potential and for the apparent resistivity calculated both from the total electric horizontal field and from the potential.

Potential. Figure 24 shows the potential for the standard model which is used to compare the effects of various parameter changes. The potential plots for the models examined all look similar to the

standard model's response, and show slight deviations from concentric circles with a maximum located over the electrode position. Figures 25, 26, and 27 show the effects of increases in depth, horizontal extent and length, respectively. The resulting plots are so similar that it is impossible to distinguish which parameter increase applies to which figure. The resistivity contrast is changed from 10 to 100 in Figure 28, which shows a slight decrease in the maximum value from the standard model's response.

Figures 29 through 32 are a sampling of some of the other models generated for the potential. Figure 29 is a vertical body striking north, while Figure 30 approximates a vertical body striking northeast, and Figure 31 exemplifies a 90 degree change of direction. The contours of the potential for the three figures do not give much indication of the direction of the body. The ability of the potential to detect a second body is addressed in Figure 32. The contours do not give any indication of the existence of the second body.

Apparent Resistivity - From E. The contours for the apparent resistivity from the total horizontal electric field have a distinctive pattern and, for most of the models, resemble a lima bean as the standard model (Figure 33) shows. This shape outlines an apparent resistivity low over the body with a high adjacent to it; the electrode is located in the middle. The body is inscribed in the first smooth contour. Examination of the contour plots where one of the parameters has been changed illustrates how the contours define the boundaries of the body.

The length is changed from the standard model's 4 units to 6 units in Figure 34, and 2 units in Figure 35. As the distance between the edge of the body and the electrode increases (see Figure 34), the resolution of the body's boundaries decreases, since the effects from the extra length are not as strong. In Figure 35, the true boundaries of the body are not as obvious from the contours, but the increase of the apparent resistivity high with an accompanying decrease in the apparent resistivity low would seem to indicate that the target is indeed a small body.

For a flat body, a change in horizontal extent would be the same as a change in the length. Since our standard model is dipping, we see that an increase in horizontal extent (Figure 36), to 5 units, broadens the contour spacings over the deeper end of the body. A decrease in the horizontal extent to 2 units (Figure 37), builds up the apparent resistivity high as a similar decrease in length did. If you compare that figure (Figure 35) to Figure 37, it is apparent how the lima bean shape rotates so the apparent resistivity low remains over the most responsive part of the body. In Figure 35, ($L = 2$), because the body is dipping, the concentration of contours overlies the upper part of the body. In contrast, Figure 37 is long and narrow with the body at or above the electrode, and the contours extend over the length of the body.

In Figure 38, the thickness of the standard model is increased from 1 to 2 units. This change increases the body's response and slightly decreases the value of the apparent resistivity low. Similarly, an increase in the resistivity contrast (Figure 39)

increases the body's response. The enhanced response does not greatly alter the shape of the contours, although the range of values over the body is greater.

Changing the depth of the body and leaving the electrode position constant changes the position of the electrode within the body. In Figure 40, the depth is at 1.2 and the electrode is located in the lowest row of prisms. This configuration gives a strong response since all of the body is above the electrode. Increasing the depth of the body to 3 units (Figure 41) moves the body down slope so that the electrode is located in the uppermost portion of the body. The response is much weaker since the body is below the electrode, but the lima bean shape distinguishes the body.

Now to examine the effects of different dips for the body. Figures 42, 43, and 44 are gently dipping bodies with dips equal to 0° , 15° , and 37° , respectively. The dips of Figures 45, 46, and 47 are, respectively, 60° , 75° , and 90° . With the exception of the vertical fault, there are two related trends as the dip angle is increased. The first is the rotation of the lima bean shape to remain over the most responsive part of the body, i.e., nearest the surface. The second trend is the increase in the apparent resistivity high as the angle of dip increases, particularly for dips greater than 30° . With an increase in dip, there is less surface projection to cover and the contours overlying the body are concentrated. The vertical body (Figure 47) has a different response and is not as easily interpreted. The lima bean shape is now the apparent resistivity high and does not define the body's boundaries.

Tracing a buried body is an important application of downhole electrode surveys. To evaluate this application, several models were run using a narrow vertical body with a depth and depth extent of 3 units, and the same transmitting electrode locations. Figure 48 is a north-south-trending body, while a northeast-trending body is approximated by offsetting the prisms in Figure 49. These two figures illustrate that the orientation of the body with respect to the axes is irrelevant except that the staggering of the units may have increased the minimum valued contour. But, notice that a peanut shape indicates the trend of the body under investigation. A subtle change in direction, as seen in Figures 50 and 51, results in a subtle change in response. The peanut shape still follows the general trend with a slight deviation in direction and shape to differentiate the two responses.

Figures 52 and 53 are for bodies with a 90° change in direction. Again, the lima bean shape is present, which tends to average these directions and could possibly be mistaken for a broad body, as Figure 54 indicates. Figure 54 is a horizontal body with the electrode in the corner with its basic shape agreeing with that of Figures 52 and 53, although this time the response is much stronger.

It is important to establish the continuity of bodies intersected in different drill holes or to determine whether a second body is present. Figure 55 is for a large horizontal body with an embedded electrode located on an outer edge of the body and the distinctive lima bean pattern. A dual purpose is served by the Figure 56, which is for two bodies. First, given that two drill holes each intersect a

body, the continuous and discontinuous cases can be distinguished. In Figure 55, the contours over the continuous body are evenly spaced. This is in contrast to Figure 56, where the spacing increases away from the excited body. Figure 56 also shows that if the presence of a second body is unknown, the deflections of the contours over the body in Figure 56 would suggest that a second target is possible.

Figures 57 and 58 also address these applications, using a body that is almost U-shaped. The left 3 columns are dipping towards the center as are the right 3 columns (see Figure 99 for a cross-section view). We are using a different electrode position of (7.50, 5.5, 3.0) embedded in the right side of the large body in Figure 57, and second (right) body in Figure 58. Figure 57 resembles the lima bean shape although the adjacent high is not present. The U-shape of the body has increased the values slightly since the center of the body is deeper and less responsive when compared to the horizontal body (Figure 55). In Figure 58, where two bodies are present, the familiar response over the body containing the electrode occurs. The response of the nearby body produces a larger anomaly because the electrode is closer to the nearby body than it was in Figure 56, where the response was weaker.

Apparent Resistivity - From V. Interpretation of the plots of the apparent resistivity calculated from the potential is more difficult as the standard model (Figure 59) shows. The contour pattern for the apparent resistivity from the potential is a low over and near the electrode. The contours over the body remain fairly evenly spaced while outside the body the spacing between contours

increases. This is referred to as contour spacing contrast.

In Figure 60, where the length of the model is increased to 6 units, the response of the body is increased; the minimum value is decreased. The contours continue to pass over the body in fairly even spacings. Outside the body, the contour spacing is increased. An increase in the body's horizontal extent from 4 to 5 units is shown in Figure 61. Since the increase in horizontal extent is a change at depth below the electrode position, the pattern change is slight. Over the right side of the body, the contours are slightly towards the center. Otherwise, the result is the same as for the standard model. When the thickness is increased to 2 units (Figure 62), the most significant change in the response pattern is a decrease in the minimum value. This increases the range of the contour values and also increases the density of the contour lines through the body. In addition, the contour spacing contrast is poor, making interpretation difficult.

The resistivity contrast is increased to 100 in Figure 63. As expected, this change increases the body's response, and so it decreases the minimum and the density of the contour lines. The contour spacing contrast remains good.

Figures 64, 59, 65, and 66 examine models with dips of 15° , 30° , 60° , and 90° , respectively. With an increase in the dip there is a shift of the minimum location down the dip. The contour spacing contrast remains good. The vertical body in Figure 66 is unusual in its response when compared with other vertical bodies such as Figure 67. The difference may arise from the electrode being located near

the end of the body and/or from its depth in the body ($1\frac{1}{2}$ units in Figure 66 and $\frac{1}{2}$ unit in Figure 67).

To evaluate the ability of the apparent resistivity from the potential to trace a buried body, we examine several models. The first, Figure 67, is a body striking north with a length of 9. The most important feature here is the drawing in of the contours to maintain fairly evenly spaced contours over both ends of the body. This yields elongation of the contours centered over the electrode. In Figure 68, the model approximates a northeast-striking body. Note how the orientation of the body is detected by following the short axis of the elliptical contours. In Figure 69, the 90° change in direction is detected by the contour spacing contrast but may be mistaken for a body of $L = 5$ and $W = 4$ instead. The more subtle change in directions of Figures 70 and 71 is detected by the contour spacing contrast. A line normal to the closest spaced contours approximates the body's strike.

Figures 72 and 73 illustrate the ability to determine continuity of two intercepts and the presence of a second body. The response of the two bodies, Figure 73, is weaker than for the large continuous body. The response over the second body, if its presence is unknown, is not indicative enough to suggest its existence.

Electrode Outside Body

For the rest of the hole-to-surface plots, the electrode is located outside the body at (3.5, 5.5, 4.5). This electrode position enables one to study the ability to detect a nearby body and the effects of changes in parameters of the body.

Potential. The potential results are similar to those with the embedded electrode, except that since the electrode is now outside the body, so is the center of the equipotential contours. Figure 74 is the potential plot for the standard model. In comparison with Figure 24 (embedded electrode), the response is less, which is to be expected. The contours again are circles which give little information about the body's parameters.

Apparently Resistivity - From E. As the standard model (Figure 75) shows, we again have a lima-bean shaped low with a neighboring high, indicating the presence of a nearby body. The low is over the body with the contours on the right side of the body getting further apart.

Figures 76 and 77 illustrate the effects of changes in length, and here the shape changes significantly with an increase or decrease in the length. In Figure 76, the length is increased to 6 units. The elongation of the contours reflect this change. The contraction of the contours indicates the decrease in length of the body in Figure 77. These figures indicate that the length can be easily estimated.

The effects of changes in horizontal extent are examined in Figures 78 and 79. The horizontal extent of 2 units (Figure 78) is well resolved but, since the body is dipping, horizontal extents greater than 3 units are not as well defined as illustrated by Figures 75 and 79 where the horizontal extent is 4 and 6 units, respectively.

In Figure 80, the thickness of the body is increased from 1 to 2 units. As expected, the response is much stronger than the standard model's, particularly the adjacent high. Because of the increased

response, the horizontal extent is better resolved.

A decrease in response is expected as the distance between the electrode and the body is increased, shown by Figure 81. Despite this decreased response, an anomaly is present over the body, although little can be inferred about the target's parameters.

As we change the dip in Figures 82, 75, 83, and 84 (0° , 30° , 60° , and 90° , respectively), note that several things happen. With an increase in dip, the upper part of the body moves farther from the electrode while the lower part of the body is getting closer. For the horizontal body (Figure 82), the contours are more evenly spaced than for the 30° dip of the standard model (Figure 75). With an increase in dip, the horizontal projection of the body's width is less and, accordingly, the surface area covered by the anomaly is less. For steeply dipping bodies, the anomaly does not adequately define the perimeter of the body, only its presence.

Apparent Resistivity - From V. The electrode is now outside the body and the response is much weaker; otherwise, it is similar to the embedded electrode models. The contour plots for the apparent resistivity from the potential are again recognizable by the constant spaced contours. In Figure 85 of the standard model, the same type of contours occur, but since the response is weaker they are farther apart and not as evenly spaced. There also is not as definitive an anomaly pattern, such as for the apparent resistivity from the electric field. It would be extremely difficult to locate a body and resolve its parameters from the contours in Figure 85.

Hole-To-Hole (Section View)

In studying the cross-section views, the following applications are considered: 1) mise-a-la-masse, 2) determining the continuity of two intersected targets, and 3) detection of a body between two drill holes. The cross-section views show what would be measured in any drill hole and are evaluated by comparing changes along a vertical line.

Electrode in Body

This first set of cross-section views is a mise-a-la-masse application where the electrode is embedded in the body at (5.5, 5.5, 3.5).

Potential. The standard model (Figure 86) illustrates how the equipotentials are distorted to define the body. Why the surface potentials resemble concentric circles may be partly explained by the lack of distortion a short distance from the body. Note, however, that with a vertical line greater than 2 units from the body, the values remain fairly constant with depth to the depth of the electrode where they begin to decrease. The pattern in the vicinity of the standard model is: 1) to the left of the body the potential values increase and then decrease with depth, 2) over the body and to the left of the electrode the potential values increase rapidly with depth, 3) over the body and to the right of the electrode the values increase less rapidly with depth and 4) to the near right of the body the potential values also slowly increase with depth.

Figure 87 shows the effects of an electrode located at the top of the body. The response patterns of a drill hole 1 unit to the left, and 1 unit to the right -- (likewise, 1 unit to the right of the

electrode in Figure 86) -- are the same until the hole to the right intersects the body. This implies that near the body you can not determine whether or not the body extends below the last measurement in the hole.

Determination of length, thickness, and resistivity contrast from hole-to-hole measurements is difficult since the response pattern remains the same. This is observed in Figures 88, 89, and 90, respectively. An increase in these parameters yields a small decrease in the range of potential values.

The parameters most likely to be resolved in a hole-to-hole survey are the horizontal extent and dip, which are closely related. In Figure 91, the horizontal extent has been extended to 6 units. Over the fourth and fifth prisms the potential values gradually increase, indicating that the body extends below the hole. Over the sixth prism, the values remain almost constant. If the hole is deep enough, it is inferred that the body extends below or at least near the second hole, since the values do not start to decrease, and the depth is below that of the electrode.

Different dips are examined in Figures 92 through 96. The equipotential contours define the dipping bodies fairly well. The downhole pattern over the body for gentle slopes (Figures 92, 93, and 86) is an increase in the potential values until the body is intercepted. Far outside the body the values remain constant to the electrode depth where it starts to decrease. For steeply dipping bodies (Figures 94, 95, and 96), over and near the body the downhole trend is an increase followed by decreasing or constant values. In

comparing the near right side (body is at depth) to the near left side (no body below), it is clear that, if the decrease occurs before the depth of the electrode is reached, the body possibly exists below at depth and indicates a steeply dipping body.

If two holes have each intersected a body of interest, it would be important to know if they are the same body or two distinct bodies. To evaluate this, a wide horizontal body (Figure 97) is compared with two smaller distinct bodies (Figure 98). Over the latter two prisms on the right (Figure 97) the contours increase down the hole until the body is intersected. Over the same two prisms, where the center two are missing (Figure 98), the potential values are almost constant down the hole. This suggests that we can distinguish between a continuous body and two distinct bodies. Figures 99 and 100 also examine this problem, but the bodies are offset and the electrode is now located on the interior. The results agree favorably with the previous figures, indicating that when the potentials increase the body is continuous and when they are constant down the hole the intercepts are in two distinct bodies.

Apparent Resistivity - From E. Although the horizontal electric field can not be measured in a drill hole, the theoretical response pattern for the standard model is illustrated in Figure 101. If the resistivity is calculated from the vertical electric field, then the response for the standard model (Figure 102) has a zero contour through the electrode and blows up at the surface.

Apparent Resistivity - From V. From the standard model, Figure

103, we observe that the contours for the apparent resistivity from the potential are drawn in through the body and define the body. The depth is increased to 3.0 units in Figure 104 and the horizontal extent is increased to 6 units in Figure 105. These figures also show the contours drawn in to define the body, but there does not appear to be any distinctive feature down a vertical hole to enable us to describe the model.

Changes in dip are examined in Figures 106 through 110. The pattern, when the electrode is embedded in an interior prism, is of a slightly distorted oval shape which rotates with an increase in dip such that the minor axis remains along the dip of the body. Unfortunately, the plots do not lend themselves easily to interpretation.

The apparent resistivity from the potential may be able to aid in the evaluation of the continuity of two intercepted zones, as illustrated in Figures 111 through 114. Figure 111 is of a horizontal body with width extent of 6 units. Over the body the values decrease downhole near the electrode and increase farther away. Assuming that we have intercepted a second zone in one of the two prisms on the right, notice that the values increase faster nearer the body. In Figure 111, there are two distinct bodies, each 2 units wide (the center 2 units are removed). The values over the second body are almost constant or very gradually changing. Figures 112 and 113 illustrate this same feature, only the body is offset with the electrode moved inside 1 unit. The pattern over the left two prisms in the continuous case (Figure 112) is slightly increasing downhole

over the far left prism and almost constant over the right one. This pattern is distinguishable from the pattern for the discontinuous intercepts of Figure 114. Over the second intercept, the far left prism exhibits an almost constant range of values while the right prism shows the values decreasing. Thus, the apparent resistivity from the potential may be very useful in determining the continuity between multiple intercepts.

Electrode Outside Body

The electrode is now located outside the body at (3.5, 5.5, 4.5) to determine the possibility of detecting a body located between two drill holes. The electrode is placed lower than part of the body, which is necessary since we want to see the effect from the body.

Potential. In Figure 115, the standard model, we see how the equipotentials are distorted as they pass through the body. Since the goal is to detect the presence of the body from the response pattern down a drill hole, we need to know how the body changes the response. If the body were not present, the expected response on the right side of the electrode would mirror the response on the left side, where there is not a body. In comparing the response pattern down a vertical line over the body to its mirror on the other side without a body, the same general trend of increasing potential values is found. The rate of increase varies more over the body, but the difference is subtle so the presence of the body probably cannot be inferred.

Apparent Resistivity - From V. The response for the apparent resistivity from the potential is given for the standard model in

Figure 116. The contours appear to identify the body's presence, but there does not appear to be a detectable trend down a vertical hole that can be used to predict the presence of a body.

CONCLUSIONS

For hole-to-surface measurements, the apparent resistivity from the total horizontal electric field, because of its distinctive patterns and its sensitivity to a change in width extent, length, and dip, shows the most promise for resolving those parameters of a body. This was especially true for the mise-a-la-masse examples, but also when the electrode was outside the body. The apparent resistivity from the electric field proved to be able to 1) trace a change in direction of a long, narrow body, 2) determine the continuity of a body between two drill hole intercepts, and 3) detect the presence of another body.

The potential, which is usually measured, did not have an indicative response for the changes in the parameters of the models in this study.

The apparent resistivity from the potential is more difficult to interpret than the apparent resistivity from the electric field. By examining the evenly spaced contours, the horizontal extent, length, and dip can be approximated. The ability of the apparent resistivity from the potential to determine 1) changes in direction, 2) continuity of two intercepts, and 3) the presence of a second body is not as good as the apparent resistivity from the electric field. When the electrode is not in the body, the response is less, and interpretation becomes almost impossible.

Although the theoretical plots simulating a hole-to-hole survey of the potential and apparent resistivity from the potential define the body, their use in practice is more limited. Their most useful application may be in determining the continuity of two intercepted zones. The potential may also be able to give some idea of the existence of the body below a hole, inferring its width extent and dip.

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FIGURES

FIGURE 1: Illustration of horizontal extent (HE) for bodies with dip $\theta \leq 45^\circ$ and length (L) in plan view.

FIGURE 2: Illustration of depth (D), horizontal or vertical extent (HE or VE), and dip θ in cross-section view.

FIGURE 3: Illustrating the subdivision of the basic cube.

FIGURE 4: Accuracy Check; prism containing electrode is not subdivided (D=2.5, W=3, L=1, DE=3).

FIGURE 5: Accuracy Check; prism containing electrode is subdivided into 8 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 6: Accuracy Check; prism containing electrode is subdivided into 27 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 7: Accuracy Check; prism containing electrode is not subdivided (D=2.5, W=3, L=1, DE=3).

FIGURE 8: Accuracy Check; prism containing electrode is subdivided into 8 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 9: Accuracy Check; prism containing electrode is subdivided into 27 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 10: Accuracy Check; prism containing electrode is not subdivided (D=2.5, W=3, L=1, DE=3).

FIGURE 11: Accuracy Check; prism containing electrode is sub-divided into 8 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 12: Accuracy Check; prism containing electrode is sub-divided into 27 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 13: Accuracy Check; prism containing electrode is not subdivided (D=2.5, W=3, L=1, DE=3).

FIGURE 14: Accuracy Check; prism containing electrode is subdivided into 8 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 15: Accuracy Check; prism containing electrode is subdivided into 27 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 16: Accuracy Check; prism containing electrode is not subdivided (D=2.5, W=3, L=1, DE=3).

FIGURE 17: Accuracy Check; prism containing electrode is sub-divided into 8 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 18: Accuracy Check; prism containing electrode is sub-divided into 27 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 19: Accuracy Check; prism containing electrode is not subdivided (D=2.5, W=3, L=1, DE=3).

FIGURE 20: Accuracy Check; prism containing electrode is subdivided into 8 subcubes (D=2.5, W=3, L=1, DE=3).

FIGURE 21: Accuracy Check; prism containing electrode is subdivided into 27 subcubes (D=2.5, W=3, L=1, DE=3).

(0.0, 0.0, 0.0)

FIGURE 22: Plan view of standard model (D=2.4, W=4, L=4, DE=1, $\theta=30^\circ$) showing 2 cases for the electrode position.

(0.0, 5.5, 0.0)

FIGURE 23: Cross-section view of standard model ($D=2.4$, $W=4$, $L=4$, $\theta=30^\circ$) showing 2 cases for the electrode position.

FIGURE 24: Standard model's potential response to compare with effects of changing parameters ($D=2.4$, $HE=4$, $L=4$).

FIGURE 25: Effect of increasing depth to 3 units
(D=3.0, HE=4, L=4).

FIGURE 26: Effect of increasing horizontal extent to 5 units
(D=3.0, HE=5, L=4).

FIGURE 27: Effect of increasing length to 6 units
($D=3.0$, $HE=4$, $L=6$).

FIGURE 28: Effect of change in resistivity contrast to 100
($D=2.4$, $HE=4$, $L=4$).

FIGURE 29: Vertical body striking north to compare with effects of changing direction (D=3.0, W=1, L=6, DE=3).

FIGURE 30: Effect of changing strike direction of vertical body to northeast (D=3, W=1, L=8, DE=3).

FIGURE 31: Effect of 90-degree change in direction of vertical body ($D=3$, $W=1$, $L=8$, $DE=3$).

FIGURE 32: Effect of a second body (both bodies have same parameters of $D=3.0$, $W=2$, $L=4$, $DE=1$).

FIGURE 33: Standard model's response to compare with the effects of changing parameters ($D=2.4$, $HE=1$, $L=4$).

FIGURE 34: Effect of increasing length to 6 units ($D=2.4$, $HE=4$, $L=6$).

FIGURE 35: Effect of decreasing length to 2 units (D=2.4, HE=4, L=2).

FIGURE 36: Effect of increasing horizontal extent to 5 units (D=2.4, HE=5, L=4).

FIGURE 37: Effect of decreasing horizontal extent to 2 units (D=2.4, HE=2, L=4).

FIGURE 38: Effect of increasing thickness to 2 units (D=2.4, HE=4, L=4).

FIGURE 39: Effect of increasing resistivity contrast to 100 (D=2.4, HE=4, L=4).

FIGURE 40: Effect of decreasing depth to 1.2 units (D=1.2, HE=4, L=4).

FIGURE 41: Effect of increasing depth to 3.0 units
(D=3.0, HE=4, L=4).

FIGURE 42: Effect of changing dip; $\theta=0^\circ$
(D=3.0, W=4, L=4, DE=1).

FIGURE 43: Effect of changing dip; $\theta=15^\circ$
($D=2.7$, $HE=4$, $L=4$).

FIGURE 44: Effect of changing dip; $\theta=37^\circ$
($D=2.2$, $HE=4$, $L=4$).

FIGURE 45: Effect of changing dip; $\theta=60^\circ$
($D=2.0$, $VE=4$, $L=4$).

FIGURE 46: Effect of changing dip; $\theta=75^\circ$
($D=2.0$, $VE=4$, $L=4$).

FIGURE 47: Effect of changing dip; $\theta=90^\circ$
($D=2.0$, $W=1$, $L=4$, $DE=3$).

FIGURE 48: Vertical body striking north to compare with effects
of changing direction ($D=3$, $W=1$, $L=9$, $DE=3$).

FIGURE 49: Effect of changing strike direction of vertical body to northeast ($D=3$, $W=1$, $L=8$, $DE=3$).

FIGURE 50: Effect of slight offset of north-trending vertical body ($D=3.0$, $W=1$, $L=8$, $DE=3$).

FIGURE 51: Effect of 90-degree offset of vertical body ($D=3.0$, $W=1$, $L=8$, $DE=3$).

FIGURE 52: Effect of 90-degree change in direction of vertical body; electrode in corner ($D=3$, $W=1$, $L=8$, $DE=3$).

FIGURE 53: Effect of 90-degree change of direction of vertical body; electrode in leg of body ($D=3$, $W=1$, $L=8$, $DE=3$).

FIGURE 54: Effect of a horizontal body with electrode in corner ($D=3.0$, $W=4$, $L=5$, $DE=3$).

FIGURE 55: Effect due to large horizontal body; electrode on edge ($D=2.5$, $W=6$, $L=4$, $DE=1$).

FIGURE 56: Effect due to 2 small horizontal bodies (each having $D=2.5$, $W=2$, $L=4$, $DE=1$).

FIGURE 57: Effect of U-shaped body with electrode on inside (D=2.5, HE=6, L=4).

FIGURE 58: Effect of 2 bodies dipping towards each other (both having D=2.5, HE=2, L=4).

FIGURE 59: Standard model's response to compare with the effects of changing parameters ($D=2.4$, $HE=4$, $L=4$).

FIGURE 60: Effect of increasing length to 6 units ($D=2.4$, $HE=4$, $L=6$).

FIGURE 61: Effect of increasing horizontal extent to 5 units (D=2.4, HE=5, L=4).

FIGURE 62: Effect of increasing thickness to 2 units (D=2.4, HE=4, L=4).

FIGURE 63: Effect of increasing resistivity contrast to 100 (D=2.4, HE=4, L=4).

FIGURE 64: Effect of changing dip; $\theta=15^\circ$ (D=2.7, HE=4, L=4).

FIGURE 65: Effect of changing dip; $\theta=60^\circ$
($D=2.0$, $VE=4$, $L=4$).

FIGURE 66: Effect of changing dip; $\theta=90^\circ$
($D=2.0$, $W=1$, $L=4$, $DE=3$).

FIGURE 67: Vertical body striking north to compare effects of changing direction (D=3.0, W=1, L=9, DE=3).

FIGURE 68: Effect of changing strike direction of vertical body to northeast (D=3.0, W=1, L=8, DE=3).

FIGURE 69: Effect of 90-degree change in direction of vertical body (D=3.0, W=1, L=8, DE=3).

FIGURE 70: Effect of slight offset of north-trending vertical body (D=3.0, W=1, L=8, DE=3).

FIGURE 71: Effect of 90-degree offset of vertical body
($D=3.0$, $W=1$, $L=8$, $DE=3$).

FIGURE 72: Effect due to large horizontal body
($D=2.5$, $W=6$, $L=4$, $DE=1$).

FIGURE 73: Effect due to 2 small horizontal bodies; electrode on edge (each having $D=2.5$, $W=2$, $L=4$, $DE=1$).

FIGURE 74: Standard model's response to compare with the effects of changing parameters ($D=2.4$, $HE=4$, $L=4$).

FIGURE 75: Standard model's response to compare with the effects of changing parameters ($D=2.4$, $HE=4$, $L=4$).

FIGURE 76: Effect of increasing length to 6 units ($D=2.4$, $HE=4$, $L=6$).

FIGURE 77: Effect of decreasing length to 2 units (D=2.4, HE=4, L=2).

FIGURE 78: Effect of decreasing horizontal extent to 2 units (D=2.4, HE=2, L=4).

FIGURE 79: Effect of increasing horizontal extent to 6 units (D=2.4, HE=6, L=4).

FIGURE 80: Effect of increasing thickness to 2 units (D=2.4, HE=4, L=4).

FIGURE 81: Effect of increasing distance between electrode and body from 1/2 to 2 1/2 units ($D=2.4$, $HE=4$, $L=4$).

FIGURE 82: Effect of changing dip; $\theta=0^\circ$ ($D=3.0$, $W=4$, $L=4$, $DE=1$).

FIGURE 83: Effect of changing dip; $\theta=60^\circ$
($D=3.0$, $VE=4$, $L=4$).

FIGURE 84: Effect of changing dip; $\theta=90^\circ$
($D=2.0$, $W=1$, $L=4$, $DE=3$).

FIGURE 85: Standard model's response for electrode outside the body ($D=2.4$, $HE=4$, $L=4$).

FIGURE 86: Standard model's response to compare with the effects of changing parameters ($D=2.4$, $HE=4$, $L=4$).

FIGURE 87: Effect of increasing depth to 3.0 units (D=3.0, HE=4, L=4).

FIGURE 88: Effect of increasing length to 6 units (D=2.4, HE=4, L=6).

FIGURE 89: Effect of increasing thickness to 2 units
(D=2.4, HE=4, L=4).

FIGURE 90: Effect of increasing resistivity contrast to 100
(D=2.4, HE=4, L=4).

FIGURE 91: Effect of increasing horizontal extent to 6 units (D=2.4, HE=6, L=4).

FIGURE 92: Effect of changing dip; $\theta=0^\circ$ (D=2.4, W=4, L=4, DE=1).

FIGURE 93: Effect of changing dip; $\theta=15^\circ$
($D=2.7$, $HE=4$, $L=4$).

FIGURE 94: Effect of changing dip; $\theta=60^\circ$
($D=2.0$, $HE=4$, $L=4$).

FIGURE 95: Effect of changing dip; $\theta=75^\circ$
(D=2.0, HE=4, L=4).

FIGURE 96: Effect of changing dip; $\theta=90^\circ$
(D=3.0, W=1, L=4, DE=3).

FIGURE 97: Effect due to a large horizontal body with electrode on edge ($D=2.5$, $W=6$, $L=4$, $DE=1$).

FIGURE 98: Effect due to 2 small horizontal bodies (each having $D=2.5$, $W=2$, $L=4$, $DE=1$).

FIGURE 99: Effect of U-shaped body with electrode on inside (D=2.5, HE=6, L=4).

FIGURE 100: Effect of 2 bodies dipping towards each other (both having D=2.5, HE=2, L=4).

FIGURE 101: Standard model's response calculated from total horizontal electric field (D=2.4, HE=4, L=4).

FIGURE 102: Standard model's response calculated from vertical field (D=2.4, HE=4, L=4).

FIGURE 103: Standard model's response to compare with changing parameters (D=2.4, HE=4, L=4).

FIGURE 104: Effect of increasing depth to 3.0 units (D=3.0, HE=4, L=4).

FIGURE 105: Effect of increasing horizontal extent to 6 units (D=2.4, HE=6, L=4).

FIGURE 106: Effect of changing dip; $\theta=0^\circ$ (D=3.0, W=4, L=4, DE=1).

FIGURE 107: Effect of changing dip; $\theta=15^\circ$
(D=2.7, HE=4, L=4).

FIGURE 108: Effect of changing dip; $\theta=60^\circ$
(D=2.0, VE=4, L=4).

FIGURE 109: Effect of changing dip; $\theta=75^\circ$
($D=2.0$, $HE=4$, $L=4$).

FIGURE 110: Effect of changing dip; $\theta=90^\circ$
($D=2.0$, $W=1$, $L=4$, $DE=3$).

FIGURE 111: Effect due to large horizontal body with electrode on edge ($D=2.5$, $W=6$, $L=4$, $DE=1$).

FIGURE 112: Effect due to 2 small horizontal bodies (each having $D=2.5$, $W=2$, $L=4$, $DE=1$).

FIGURE 113: Effect due to U-shaped body with electrode on inside (D=2.5, HE=6, L=4).

FIGURE 114: Effect due to 2 bodies dipping towards each other (each having D=2.5, HE=2, L=4).

FIGURE 115: Standard model's response with electrode outside body (D=2.4, HE=4, L=4).

FIGURE 116: Standard model's response with electrode outside body (D=2.4, HE=4, L=4).