

A parametric study of the vertical electric source

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ABSTRACT

Measurement of the vertical magnetic field caused by a vertical electric source (VES) is an attractive exploration option because the measured response is caused by only 2-D and 3-D structures. The absence of a host response markedly increases the detectability of confined structures. In addition, the VES configuration offers advantages such as alleviating masking resulting from conductive overburden and the option of having a source functioning in a collapsed borehole. Applications of the VES, as in mineral exploration, seafloor exploration, and process monitoring such as enhanced oil recovery, are varied, but we limit this study to a classic mining problem—the location of a confined, conductive target at depth in the vicinity of a borehole. By analyzing the electromagnetic responses of a thin, vertical prism, a horizontal slab and an equidimensional body, we investigate the resolving capabilities, identify survey design problems, and provide interpretational insight for vertical magnetic field responses arising from a VES. Data acquisition problems, such as electrode contact within a borehole, are not addressed.

Current channeling is the dominant mechanism by which a 2-D or 3-D target is excited. The response caused by currents induced in the target is relatively unimportant compared to that of channeled currents. At low frequencies, the in-phase response results from galvanic currents from the source electrodes channeled through the target. The quadrature response, at all frequencies, results from currents induced in the host and channeled through the target. At high frequencies, in-phase currents are also induced in the host and channeled through the target. Hence, the

quadrature response and the high-frequency in-phase response are quite sensitive to the host resistivity. Time-domain magnetic field responses show the same behavior as the quadrature component.

Interpretation of low-frequency vertical magnetic field measurements is straightforward for a source placed along strike of the target and a profile line traversing the target. The target is located under a sign reversal or null in the field for a flat-lying or vertical target. A dipping target has an asymmetrical response, with reduced amplitude on the downdip lobe. The target is located between the maximum lobe and the null. Although the vertical magnetic field caused by a VES for a 2-D or 3-D structure is purely anomalous, the host layering can affect signal strength by more than an order of magnitude. A general knowledge of the location of the target and host layering is helpful in maximizing signal strength.

In practice boreholes are not vertical. An angled source can introduce a response because of the horizontal component that can overwhelm the VES response. For low-frequency, in-phase, or magnetometric resistivity (MMR) measurements made with a source angled at less than 30 degrees from the vertical, the host response caused by a horizontal electric source (HES) is negligible, and the free space response is easily computed and removed from the total response leaving a response that can be interpreted as that being caused by a VES. The high-frequency, in-phase response and the quadrature response at any frequency caused by a HES are strongly dependent on the host resistivity and dominate the scattered response. The measured response, therefore, must be interpreted using sophisticated techniques that take source geometry and host resistivity into account.

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INTRODUCTION

The vertical electric source (VES), a grounded source employed down a borehole, has intrigued geophysicists for years because the vertical magnetic field intensity response B_z is caused by 2-D and 3-D structures only. Because the response of the transmitter and the layered host is absent, detectability of confined structures can be increased markedly over that of other transmitter configurations. Applications of the VES using magnetic field measurements include mineral exploration (Asten, 1988; Nabighian et al., 1984; Hohmann et al., 1978), seafloor exploration as with the magnetometric off-shore electrical sounding technique (MOSES) of Edwards et al. (1981), and process monitoring such as enhanced oil recovery (Newman, 1994; Bartel and Newman, 1991). In addition to providing a purely anomalous response, other advantages of the VES include elimination of signal masking due to conductive overburden and allowance for a relatively inexpensive source that can function in a collapsed or open borehole.

As with any borehole technique, signal strength is enhanced over that of surface configurations because the source or the receiver is closer to the target that is generating the secondary or anomalous response. A cross-borehole configuration, where both source and receiver are relatively close to the target, produces the strongest response. Nabighian et al. (1984) found that magnetometric resistivity (MMR) anomaly strength increased by an order of magnitude with the detector placed downhole compared to surface measurements. However, surface measurements are a practical approach worthy of investigation.

With the VES, both cross-borehole and surface electric or magnetic field measurements can be made in either the frequency domain or time domain. This study concentrates on low-frequency vertical magnetic field measurements for three reasons: (1) unlike the electric field, the magnetic field is not strongly affected by near-surface resistivity changes, (2) the response for vertical magnetic field measurements is caused solely by 2-D and 3-D conductivity structures, and (3) data reduction and interpretation of low-frequency, in-phase measurements (MMR) are less complicated. Horizontal magnetic field measurements are also purely anomalous provided the measurements are taken at or above the earth's surface, but the natural, ambient noise is stronger for the horizontal components (Vozoff, 1990), thus reducing the signal-to-noise ratio. Horizontal measurements will not be considered in this study; however, it should be noted that MMR measurements of the horizontal components are useful in determining the direction to a conductor (Oppliger, 1984; Edwards and Nabighian, 1991). Time-domain results follow the behavior of frequency-domain quadrature measurements and, as we shall see, have many problems related to data reduction and interpretation.

By understanding the fundamental physics of a technique, the geophysicist can maximize positive attributes and minimize negative aspects during survey design and interpretation. The intent of this numerical simulation is to investigate the resolving capabilities, identify survey design problems, and provide interpretational insight for magnetic anomalies arising from a VES. This is done by varying key parameters such as target and host resistivity and electrode placement.

Although the results presented apply to any of the above applications, this numerical study is constructed within the context of a classic mining problem—to locate a confined, conductive target at depth in the vicinity of a drill hole.

COMPUTATIONAL CONSIDERATIONS AND MODEL GEOMETRY

Using a direct current (DC) algorithm described by Beasley and Ward (1986), we first describe the behavior of low-frequency electric current flow in the earth to understand magnetic field responses. Low-frequency magnetic field responses for an arbitrarily oriented source are calculated using the MMR algorithm of LaBrecque and Ward (1987). We use the algorithm of Newman et al. (1986) to describe multi-frequency, in-phase, and quadrature electromagnetic (EM) responses due to a horizontal electric source, and a modification of this code (Newman, 1994) to calculate EM responses caused by a VES. Employing different codes overcomes limitations within a particular algorithm. For example, the EM program cannot calculate the response resulting from nonvertical sources, whereas such calculations are possible with the MMR code. However, the MMR code can calculate the response of a 3-D target only in a homogeneous half-space, whereas the EM code can compute the response of a target in a layered host. Comparison of results from these various algorithms, whenever appropriate, ensures accuracy.

Three 3-D models representing extreme cases, or end members, are used for this numerical simulation. Model VES1 is a thin, vertical tabular body illustrated in Figure 1; model VES2 is an equidimensional prism measuring 120 x 120 x 120 m; and model VES3 is a horizontal slab measuring 400 x 320 x 40 m. Model responses are computed for a depth to the top of the target of 500 m. The responses for all

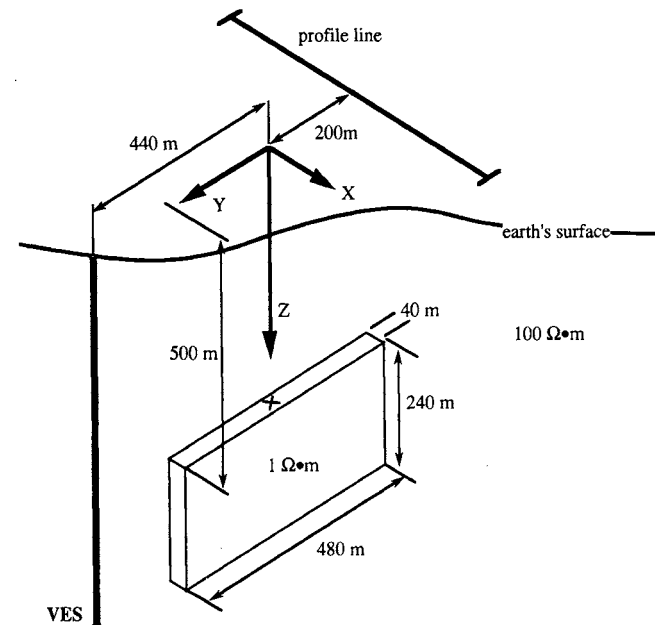


FIG. 1. Geometry of model VES1 illustrating the placement of the vertical electric source and profile line.

three models have similar amplitudes for a host resistivity of 100 ohm-m, a target resistivity of 1 ohm-m, and a bottom electrode depth of 550 m, which is the maximum coupling configuration for a 3-D target in a half-space at a depth of 500 m. We use a variety of models so as not to bias the conclusions of this study. General conclusions are based on the results from all three models; only Model VES1 is shown for brevity.

The top current electrode is at the surface, transmitted current is 1 ampere, and in-phase and quadrature responses are computed at 3 Hz. Available transmitters are capable of 10 to 30 amperes of transmitted current; responses therefore should be increased accordingly for comparison with field data. The profile plots are of B_z (nT) versus receiver location (m) along the profile line denoted in Figure 1. In all plots, open symbols depict negative values and solid symbols depict positive values.

Character of the vertical magnetic field response

In analyzing the vertical component of the magnetic field B_z it is important to understand the nature of the electrical current density because B_z is supported by horizontal currents flowing in an inhomogeneity. Total current for a preferred source-target configuration at low frequencies is depicted as a vector diagram for model VES1 in Figure 2. The cross-section view is along the Y-axis and the target is outlined. The bottom current electrode is at a depth of 550 m, just below the top of the target. The source field is dipolar in shape relative to the target, with current being channeled through the prism and flowing away from the electrode. When the bottom current electrode is lowered to a depth of 2000 m, the source field is polar and current flows

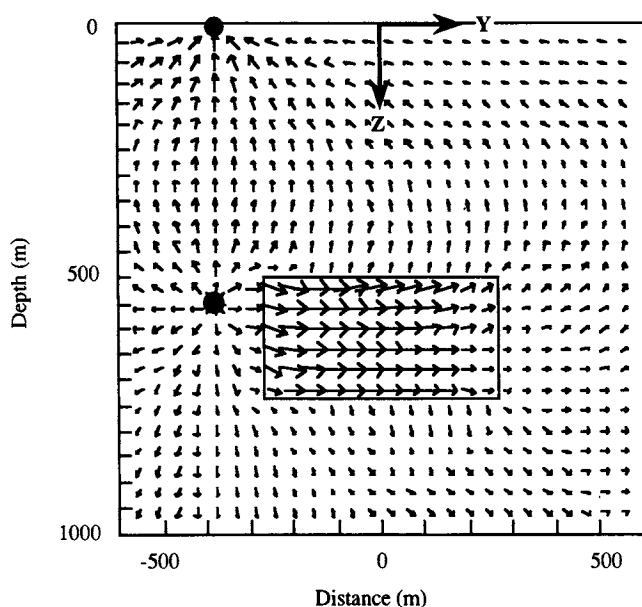


FIG. 2. Vector plot of low-frequency, total electric current density for model VES1. Cross-section view is along the y-axis through the center of the body. Bottom electrode depth is 550 m. Arrows indicate direction and relative magnitude of the total electric field.

toward the electrode, as in Figure 3. This change in direction of current flow results in a change of sign in the B_z field.

The low-frequency, in-phase, B_z response at the surface of the earth for model VES1 is presented in contour format in Figure 4, with the bottom current electrode at $z = 550$ m. The response is characterized by a negative lobe to one side of the target and a positive lobe to the other side. Comparison of Figures 2 and 3 show polarity is determined by electrode depth. The sign reversal, or crossover, locates a vertical or flat-lying target (not shown). The quadrature response has the same form, except with reversed polarity, as the current flows in the opposite direction. In contrast, a dipping target creates an asymmetric response, with an amplitude reduction of the downdip lobe and the target located between the maximum lobe and the crossover.

The vertical location of the target is best determined with downhole measurements. Figure 5 depicts the B_z response down a borehole located at $x = 200$ m, $y = -200$ m for model VES1 in Figure 1. The peak in the in-phase response (Figure 5a) defines the vertical position of the target for both near (550 m) and deep (1750 m) source electrodes. In contrast, the peak for the quadrature component (Figure 5b) changes with electrode depth. For the near electrode a quadrature peak, corresponding to the center of the target occurs. For the deep electrode, the quadrature peak corresponds to the top of the target. Asten (1988) showed a crossover in the cross borehole MMR response when the transmitter intersects the conductive target, as opposed to our case where the borehole does not intersect the conductor.

In general, the mechanism of induction is a function of source geometry, target geometry, and target resistivity. Current channeling, on the other hand, is controlled by source geometry, target geometry, and the resistivity con-

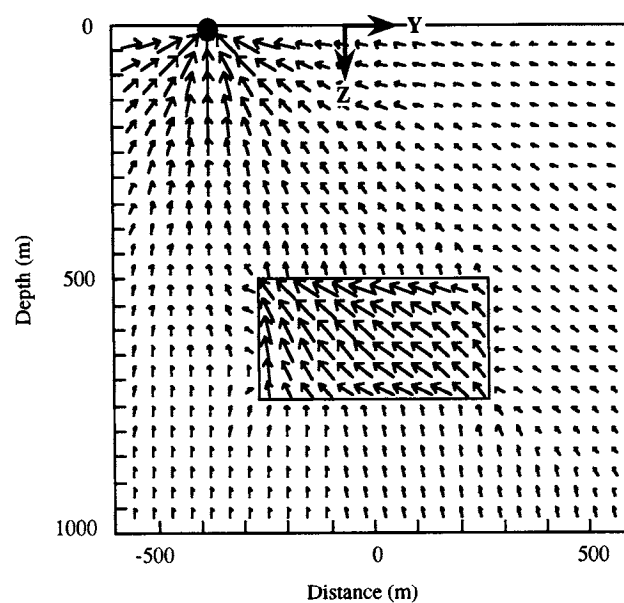


FIG. 3. Vector plot of low-frequency, total electric current density for model VES1. Cross-section view is along the y-axis through the center of the body. Bottom electrode depth is 2000 m. Arrows indicate direction and relative magnitude of the total current density.

trast between the target and host. For the VES, the shape, magnitude, and polarization of the B_z response are functions of absolute host resistivity, target geometry, and resistivity contrast between the host and target, but the B_z response itself is overwhelmingly due to current channeling. The type of current channeled, whether a galvanic current coming from the source electrodes or currents induced in the host, is a function of host resistivity. To determine the relative roles of induction and galvanic current channeling, we varied the host and target resistivities of each model and analyzed the response both along the profile line at 3 Hz and for a frequency sounding at a point on the profile line for various bottom electrode depths.

The low-frequency, in-phase response is sensitive to the target-host resistivity contrast alone, as is expected with channeling of galvanic current from the electrode sources. The quadrature component, on the other hand, is sensitive to both the target-host resistivity contrast and to the absolute value of the host resistivity. Quadrature currents are induced in the host and then channeled through a conductive target, resulting in inductive current channeling. The magnitude of currents induced in the host is a function of host resistivity, while the magnitude of currents channeled into the target is a function of target-to-host resistivity contrast. The quadrature response is strongly dependent on host resistivity. The response with the greater magnitude can be caused by a more conductive host, instead of a larger resistivity contrast.

Modeling results indicate that a frequency/host resistivity ratio of about 1 Hz/ohm-m is the upper limit of the low-frequency range. For higher frequencies, complicated behavior of the response exhibiting oscillations and sign reversals is observed. The high-frequency behavior of the in-phase response is strongly affected by currents induced in

the host and channeled through the target, while the low-frequency behavior is caused by galvanic current channeling. The character of in-phase and quadrature high-frequency responses (not shown) varies considerably for different model geometries, thus indicating that detailed target geometry information is in the high-frequency response. In theory, then, it may seem advantageous to make multifrequency measurements in the high-frequency range, where the response of the target depends on the host resistivity and the target resistivity. However, signal strength decreases rapidly as frequency increases because of

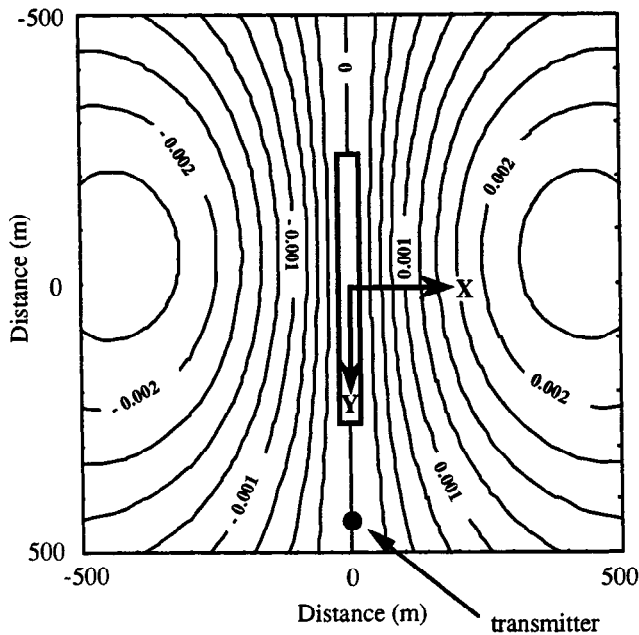


FIG. 4. Contour plot of surface vertical magnetic field response for model VES1. Contour interval is 0.00025 nT. VES is along strike of the target.

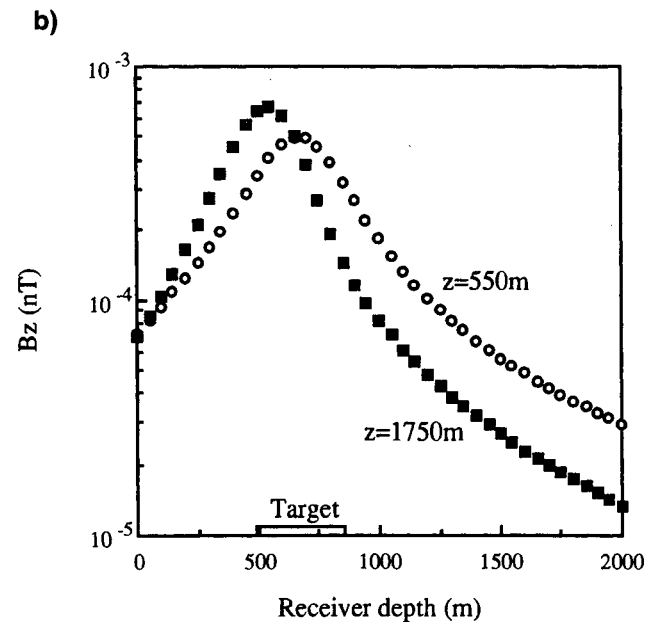
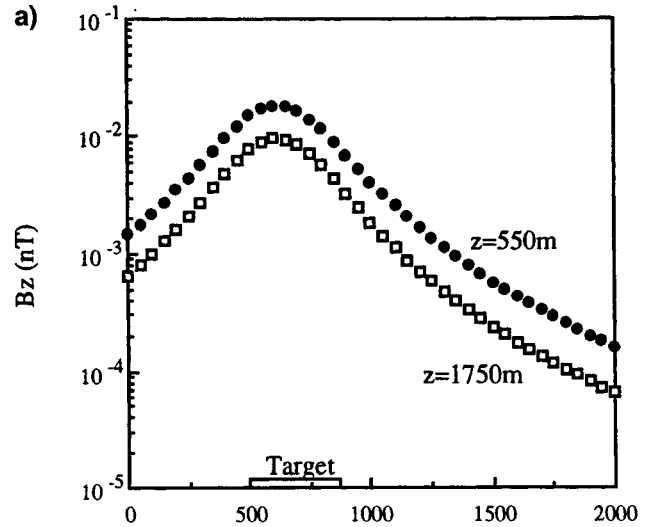


FIG. 5. Downhole in-phase (a) and quadrature (b) vertical magnetic field responses for model VES1. The receiver borehole is located at $x = 200$, $y = -200$. Bottom electrode depth is noted on the curves. Solid and open symbols denote positive and negative values, respectively.

attenuation, and there are profound difficulties in interpreting the complicated signal with reduced signal-to-noise ratio. Interpretation of a crossover as the location of a target is not necessarily valid in the high-frequency range, thus requiring higher level interpretation such as 3-D inversion or imaging techniques.

Low-frequency, in-phase, or MMR measurements are straightforward to interpret compared to both quadrature measurements and in-phase measurements in the high-frequency range. Because the source of the quadrature response is a result of currents induced in the host, the quadrature response is quite sensitive to the host resistivity. For resistive hosts, then, target signal strength is quite low. No interpretational techniques are presently available for measurements in the high-frequency range and signal strength is strongly attenuated with increasing frequency. Also, as we shall see, a borehole angled greater than 1 degree from the vertical generates a primary field response that masks the anomalous B_z response. For sources angled less than 30 degrees from the vertical, MMR measurements can be corrected so that interpretational techniques based on a purely VES can be implemented.

SIGNAL STRENGTH

Strength of background signals, instrument sensitivity, and survey design play important roles in determining whether a signal from a target is detectable. Electrode placement, host layering, and geologic noise influence signal strength. Vertical electrode placement can affect the magnitude of the response by more than an order of magnitude. In an idealized model of a half-space host with no geologic noise, such as near surface conductors, maximum signal strength is attained when the bottom electrode is just below the top of the body. However, if layers in the host or surficial conductors are present, maximum signal strength occurs at other electrode depths.

Electrode placement

The location of a borehole relative to a target and the placement of electrodes in a borehole can have a significant effect on the amplitude and character of a response. For a target that is roughly equidimensional in the v -plane, such as models VES2 and VES3, horizontal placement of the transmitter relative to the target is unimportant. For a structure with the strike extent of model VES1, however, the source should be placed in-line along the strike of the structure, as shown in Figure 1. If a source is broadside to the strike of the structure, current flows out from the center in both directions resulting in a surface B_z response as depicted in contour form in Figure 6. This source-target configuration not only produces a reduced anomaly magnitude but a null value in-line with the transmitter. The null could be erroneously interpreted as the location of a conductive target.

Full 2-D surface coverage and borehole measurements wherever possible are optimal. However, if only surface profiling is possible, the profile line should be roughly perpendicular to the estimated geoelectric strike, with the transmitter located along strike, as shown in Figure 1. Misleading or uninterpretable data may result for other

transmitter-receiver configurations. Hence multiple sources are recommended.

The sign of the signal changes as the source field changes from dipolar to polar relative to the target. Figure 7 shows MMR responses for four source electrode depths—550 m, 750 m, 1000 m, and 1250 m—for model VES2 along a profile

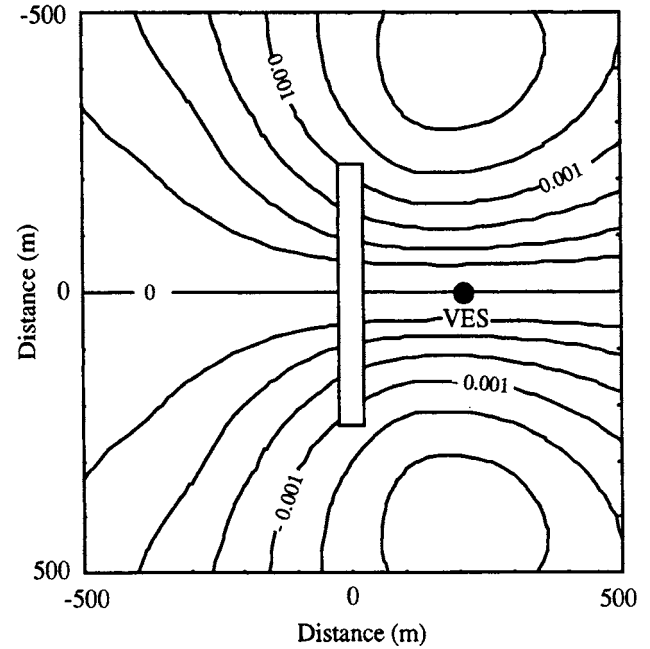


FIG. 6. Contour plot of surface vertical magnetic field response for model VES1. Contour interval is 0.00025 nT . VES is broadside to the target along profile line on Figure 1.

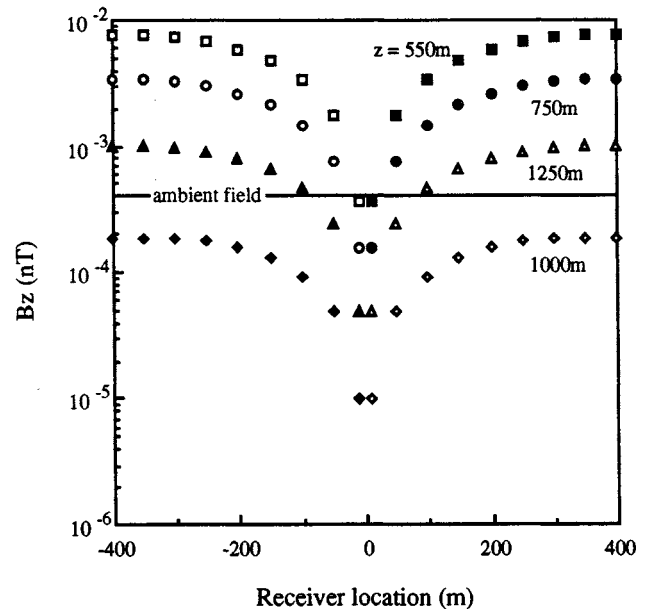


FIG. 7. Surface MMR response for different bottom electrode depths for model VES2. Profile line is centered over target. Electrode depth is noted on each curve. Solid and open symbols denote positive and negative values, respectively. The ambient noise floor at 3 Hz is shown.

line centered over the target and a VES located 200 m from the target center and 400 m from the profile line. The sign reversal occurs at an electrode depth of roughly twice the depth to the target. At a depth of 1000 m, signal strength is near a minimum because the electrode depth is near the point at which the current reverses direction, i.e., a null. Target geometry, host layering, and borehole location influence the electrode depth of this sign reversal. Lowering the top electrode down the hole reduces the moment of the source, resulting in a slightly reduced amplitude of the anomalous response. The decision to place the top electrode at the surface or in the borehole should be based on practical considerations. Lowering the top electrode down the hole enables measurements to be taken near the borehole but creates a problem of energizing the casing that may be present. Energizing the casing would change the situation to that of a line or distributed source instead of a dipole or bipole source energized at two points.

Host layering

Although the VES B_z response for a layered host is zero, host layering can amplify or attenuate the magnitude of the response by more than an order of magnitude. Core logs and well log data can be quite valuable in selecting electrode placement that will maximize signal strength. When the host is complicated by highly resistive layering, signal strength is significantly reduced if the resistive material isolates the target from the bottom electrode or if the bottom electrode is at a great depth, because currents are restricted from flowing through the target. Theoretically the bottom electrode should be placed in the highly resistive layer, but from a practical point of view it may be difficult to inject a significant amount of current in such rock.

Conductive layering, such as graphitic schist, deeply weathered overburden, or a pyrite-bearing horizon barren of economic sulfides, can influence the magnitude of the VES response of the target at depth. Only when the electrode is near or in the target is the response unaffected by the conductive layer. The electrodes placed above or in the conductive layer, or at a great depth, produce an anomaly amplitude reduced by an order of magnitude from the corresponding anomalies when a target is in a homogeneous half-space. Current flows in the conductive layer instead of the target for all but optimal electrode placement. However, when the conductive layer is in contact with the target, the position of the bottom electrode is not important; current will flow in both the layer and the target but amplitude is slightly reduced in the response when no host layering is present. For bottom electrodes near the target, the technique is insensitive to a conductive overburden, which is a great advantage of the VES compared to surface transmitter techniques.

Geologic noise

The response caused by near-surface conductors that are not a part of the target geometry is what we term geologic noise. The amplitude of geologic noise can be equal to or greater than the response resulting from deeper structures, thereby masking the target response. Electric field measurements are more sensitive to near-surface inhomogeneities

than magnetic field measurements because the electric field response results from boundary charges that are a function of the conductivity contrast, irrespective of body size. The magnetic field, however, is a function of the volume of scattered currents. Therefore, the magnetic field responses from small bodies will be negligible compared to those of larger targets.

To illustrate the effect of geological noise, we add near-surface conductors of 10 ohm-m to model VES1. Two bodies measuring 50 m x 50 m x 10 m are placed at a depth of 10 m as shown in cross-section view in Figure 8. Figures 8a and 8b illustrate the in-phase and quadrature responses, respectively, of the total horizontal electric field. Horizontal currents, flowing in the target, support not only a vertical magnetic field but a horizontal electric field. A horizontal electric field anomaly is characterized by a peak over a conductive target resulting from the increased current channeled through the body, but currents also flow in the host supporting a strong host response.

In contrast to the vertical magnetic field response, the in-phase electric field response varies roughly linearly with the host resistivity, while the quadrature response is less sensitive to host resistivity. Both the in-phase and quadrature E_r responses result from the host and near-surface conductors, while responses caused by the deep target are essentially undetectable. At peak amplitude, approximately 70 percent of the signal comes from the host with the remaining 30 percent originating from the near-surface conductors. The relative contributions to the response made by the host, near-surface conductors and the deep target are not affected by electrode placement as can be seen by comparing the response caused by the 550-m electrode length and the 1750-m length.

The in-phase and quadrature B_z responses for the model with geological noise in Figure 8 are shown in Figures 9a and 9b. For magnetic field measurements, bottom electrode position is an important factor. When in the presence of geologic noise, the optimal bottom electrode location is at a great depth so that the near-surface conductors are not significantly energized. The shallow (550-m) transmitter, however, energizes both the target and the noise, but the target dominates the response because it is much larger in size, even though it is at depth. The reduced amplitude of the signal results from the competing nature of the two signals. Because the surficial bodies are energized by an electrode at depth, current flow is toward the transmitter, creating a positive to negative polarity trend in the B_z field across the profile line. The electrode is near the deep target resulting in current flow away from the transmitter and a negative to positive polarity trend in the B_z field along the profile line. Hence, the noise signal and target signal are of opposite signs, resulting in a reduced anomaly.

Ambient noise

The natural magnetic field, generated primarily by electric current in the magnetosphere below 1 Hz and by worldwide thunderstorms above 1 Hz, is noise for all controlled source measurements. Palacky and West (1990) show the overall character of the magnetic field amplitude spectrum. Signal strength steadily increases for frequencies less than 1 Hz.

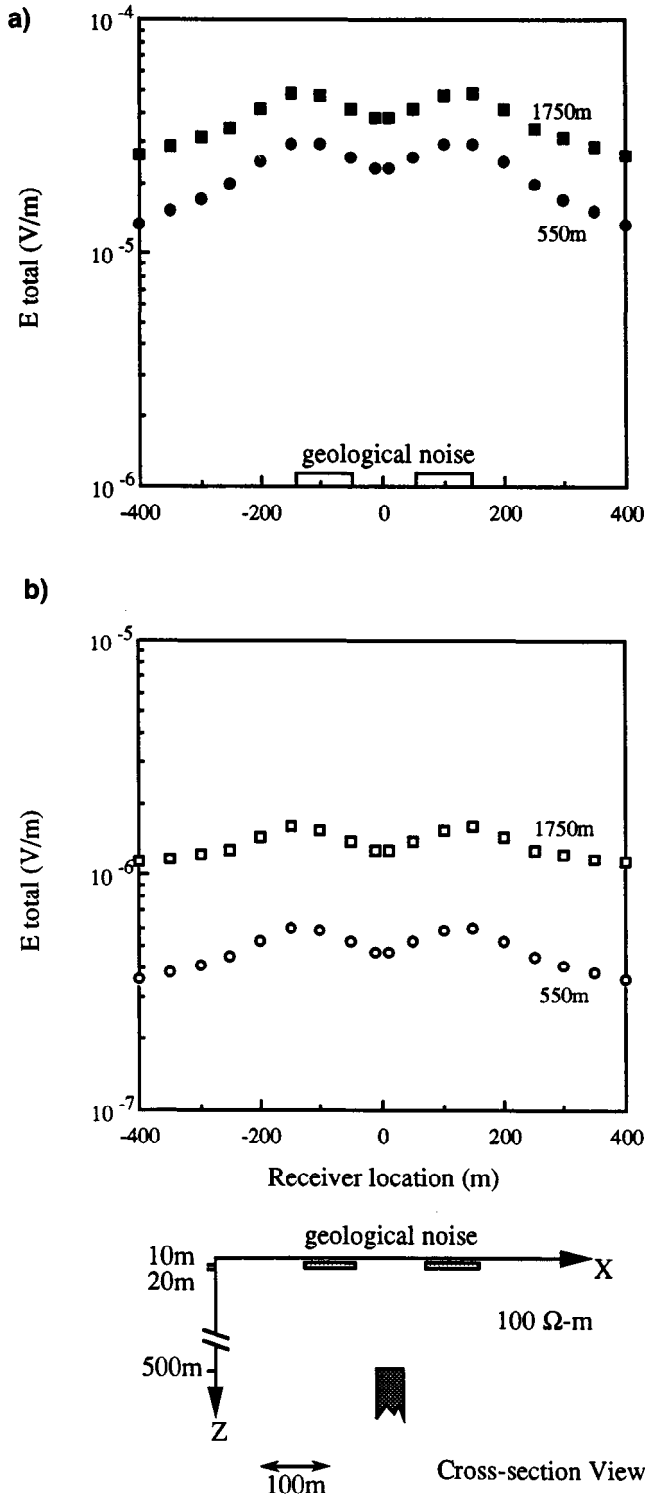


FIG. 8. A cross-section view of the geometry of model VES1 with near-surface conductors added to simulate noise caused by near-surface geological heterogeneities is shown along with the corresponding in-phase (a) and quadrature (b) responses for the total electric field response. Bottom electrode depths are noted on each curve. Solid and open symbols denote positive and negative values, respectively.

There is also a sharp increase in amplitude above 10 Hz leaving an amplitude low in the 1 to 10 Hz range. Although amplitudes again decrease with increasing frequencies from 10 to 1000 Hz, frequencies near 100 Hz (e.g., 60 and 180 Hz) are strongly contaminated by cultural features such as power lines. Choosing a frequency in the 1 to 10 Hz range for MMR measurements is a good compromise. Frequencies are low enough to minimize the effects of induction in the host and high enough to minimize the effects of natural magnetic field noise (Edwards, 1974).

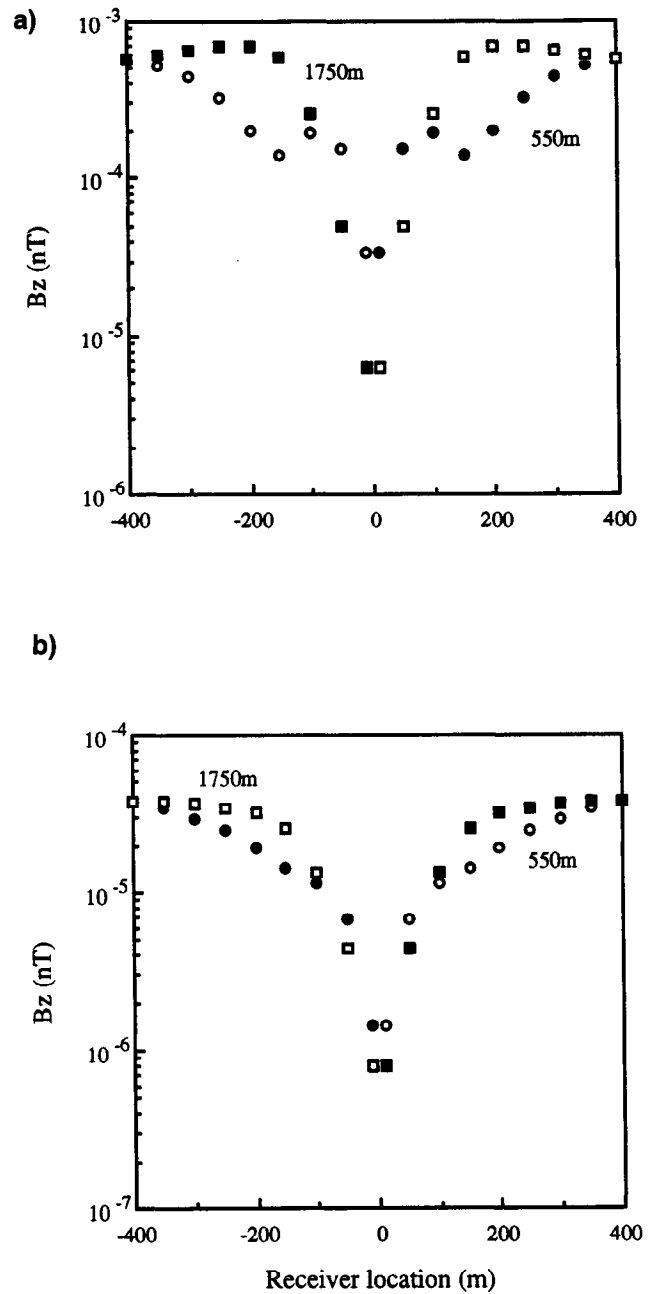


FIG. 9. In-phase (a) and quadrature (b) responses for the vertical magnetic field response along the profile for the noise model of Figure 8. Bottom electrode depths are noted on each curve. Solid and open symbols denote positive and negative values, respectively.

Vozoff (1990) shows typical measurements of the x , y , and z components of the natural magnetic field intensity. In the 1 to 10 Hz range, the amplitude of the vertical field is roughly half an order of magnitude less than that of the horizontal components. The amplitude spectral density of the vertical component of the natural field S_0 is approximately $10^{-4} \text{ nT/Hz}^{1/2}$ at 3 Hz. Cultural noise can be greater than the natural signal, but such noise sources vary from site to site and will not be considered.

To determine the detectability of a recorded signal, consider the output standard deviation σ , of zero-mean, white noise S_0 at the input of a frequency-domain receiver as

$$\sigma = \frac{S_0}{\sqrt{\tau}},$$

where τ is the integration time (San Filippo and Hohmann, 1983). To have a 95 percent probability (about 2σ for a Gaussian or exponential distribution) that the B_z readings are within 5 percent (1 out of 20) of the true value we want

$$B_z \geq (20)(2\sigma) = 40\sigma = \frac{40S_0}{\sqrt{\tau}}.$$

So for an integration time of 100 sec, we require

$$B_z \geq 4 \times 10^{-4} \text{ nT}/\sqrt{\text{Hz}}.$$

This ambient noise floor, at 3 Hz is noted in Figure 7. When the bottom electrode is positioned such that signal polarity is about to reverse, or when the electrode is poorly positioned in the host layering, signal strength drops below this minimum value. However, synchronous detection, additional stacking, and transmitting current of 10 to 30 amperes can increase most signals to measurable levels. These data acquisition techniques are common and should be regularly implemented. Commercially available receivers have thresholds well within the capability of measuring naturally occurring magnetic fields, the predominant noise source, and therefore, can measure signals above this level.

ANGLED SOURCE

The above results assume that the borehole is within 1 degree of vertical. Drilling technology is advanced enough to make this level of accuracy possible but, whether by design or not, boreholes are rarely vertical. In this section, then, we investigate the problem of the B_z response caused by an electric source inclined from the vertical. Figure 10 depicts the source in model VES1, angled 10 degrees from the vertical in the x -direction. The MMR response along the profile line resulting from this angled source is broad and featureless, similar to the in-phase response in Figure 11a. The horizontal component of current introduced by an angled source creates a B_z field that completely overwhelms the VES anomaly of the target. It would be difficult to delineate a target from such a response.

The B_z response caused by an angled source can be decomposed into four components: a secondary (scattered) response resulting from a vertical source component, a secondary response from a horizontal electric source (HES) component, a host (primary field) response caused by an HES component, and the HES Biot-Savart (free-space)

response of a current-carrying wire. There is no B_z host response for a VES. For low-frequency, in-phase (MMR) measurements made with a source angled less than 30 degrees from the vertical, the host response caused by an HES is negligible, and the data can be adjusted so that interpretation based on a pure VES can be made. The HES quadrature response is strongly affected by the host resistivity and can only be interpreted with techniques that take host composition and source geometry into account. To date, no known interpretational techniques are available for this case.

To illustrate the contributions of an HES on the in-phase and quadrature responses, we partition the source into horizontal segments as shown in Figure 10, and compute the response for the bold HES segment, for host resistivity values of 10, 100, 1000, 10 000, and 100 000 ohm-m. The in-phase and quadrature responses for each of these host resistivities are shown in Figures 11a and 11b, respectively: For low-frequency responses, the in-phase response does not vary with half-space resistivity. The quadrature response, however, is strongly affected by the host resistivity, even for very resistive hosts of 10 000 and 100 000 ohm-m at 3 Hz. This is because the quadrature primary field is caused by currents induced in the host, whereas the low-frequency, in-phase primary field is mainly a result of currents in the wire with a relatively small contribution from currents induced in the host.

Correction for an angled source can be implemented easily with MMR measurements. The source is first partitioned into horizontal contributions; then the free-space response is computed and subtracted from the total field. Figure 12 depicts the total angled response, the corrected response, and the response caused by a pure VES for the model of Figure 10. The difference between the corrected and the pure

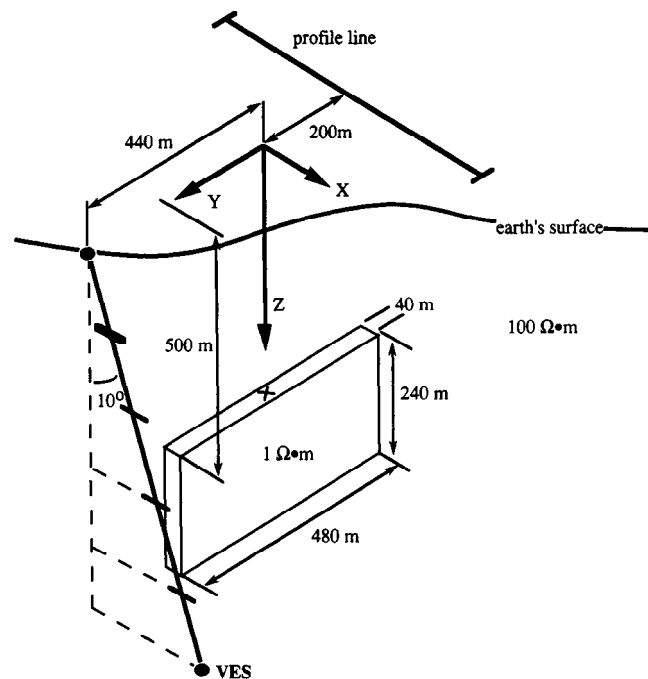


FIG. 10. Geometry of model VES1 illustrating an angled borehole partitioned into horizontal components.

VES response is the scattered field caused by the HES. In general, the HES scattered response will not have the same character as that of the VES. However, for about 75 percent of the models tested, both responses exhibited a crossover at the location of the target resulting in an enhanced response. For the remaining 25 percent, the HES response exhibited a peak rather than a crossover, which competes with the VES anomaly. For large deviation from the vertical (greater than 45 degrees), the scattered HES contribution is larger than the response caused by the VES, so possible differences in the character of the response can be problematic.

It should be noted also that the correction scheme is appropriate for even coarse partitioning of the source. Computing the free-space response for the exact path of the source is the most accurate way to determine the effects of the wire, but simple estimates of horizontal contributions at the appropriate depth are very effective. For the source of Figure 10, we experimented with different numbers of segments. While one or two segments were insufficient to remove the free-space response, three or more were sufficient to correct the response accurately as determined by lack of change in the corrected curve.

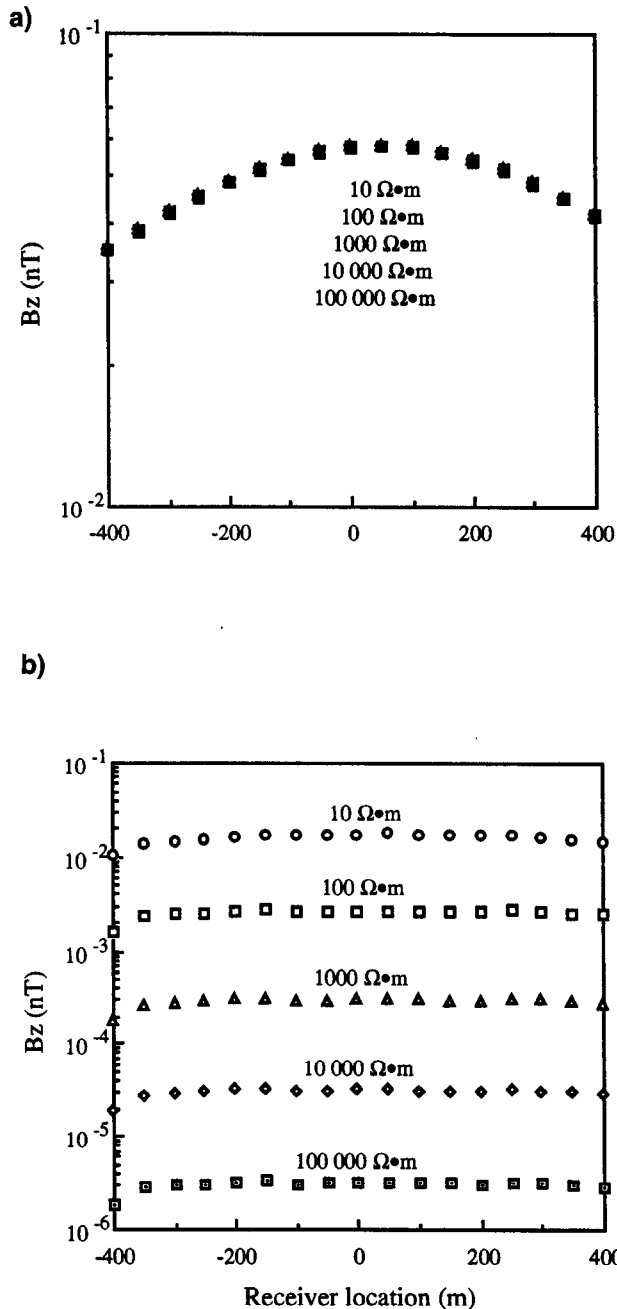


FIG. 11. Primary in-phase (a) and quadrature (b) vertical magnetic field response caused by the horizontal electric source shown in bold in Figure 10 for different half-space resistivities, noted on each curve. Solid and open symbols denote positive and negative values, respectively.

CONCLUSIONS

Modeling of EM responses caused by a vertical electric source indicates that vertical field MMR measurements offer many advantages over those of the other field components. Magnetic field measurements are less sensitive to geologic noise than are electric field measurements. The predominant mechanism of low-frequency responses is current channeling; hence MMR measurements are sufficient to capture the target information. Because the vertical magnetic field, both at the surface and downhole, is attributed only to 2-D and 3-D structures, a target can be delineated by locating the null in surface vertical component MMR measurements. The vertical position of a target is best located by the peak in a downhole profile. MMR data can be corrected for deviations of the source from the vertical and then interpreted assuming a purely VES when the source is angled less than 30 degrees from the vertical. Time-domain and quadrature measurements are dependent on the host resistivity and cannot be corrected with present software for sources deviating from the vertical. High-frequency measurements exhibit compli-

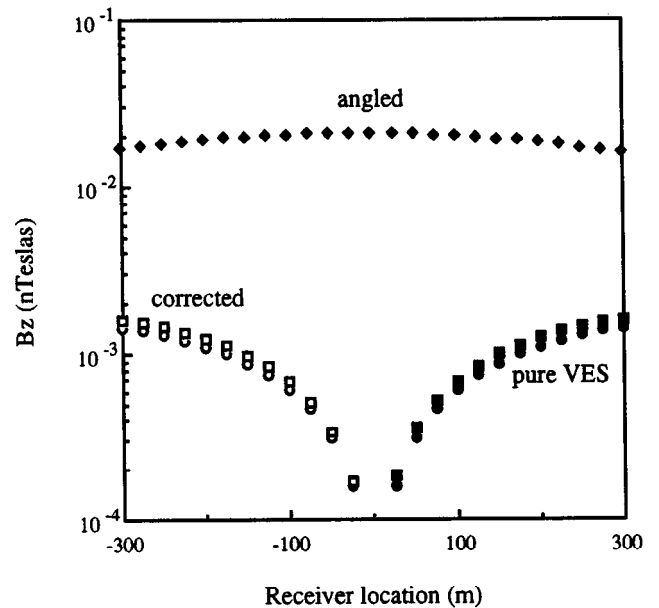


FIG. 12. MMR response for the angled source of Figure 10 along with the corrected response and the response caused by a VES in a truly vertical hole, as noted on each curve. Solid and open symbols denote positive and negative values, respectively.

cated responses and are host-dependent, and no schemes are presently available to interpret such data.

Although there is no host response with the VES, host layering can have a profound effect on the magnitude of the target response. Prior knowledge of the target and host layering can influence survey design. Accurate location of the source can enhance data interpretation. For a target embedded in a homogeneous half-space, the maximum signal amplitude occurs when the bottom electrode is near the top of the target. When extremely conductive or resistive layering in the host can channel current toward or away from the target, the best strategy is to locate the bottom electrode near the top of the target. When geologic noise due to near-surface conductors is present, however, placing the bottom electrode at great depth minimizes the effect of the noise. The location of the top electrode does not significantly affect response amplitude.

MMR data due to an angled source can be corrected easily as long as the orientation of the borehole is known. The free-space response due to a horizontal component of the source is calculated and removed from the total response, leaving a scattered field due to a VES and an HES. The host response for in-phase, low-frequency measurements is negligible. An angled source correction cannot be made for quadrature or time-domain data because of the strong host response due to the horizontal component. Therefore interpretation of such responses requires inclusion of host values and source geometry—a very difficult problem.

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REFERENCES

- Asten, M. W., 1988, The down-hole magnetometric resistivity (DHMMR) method: *Expl. Geophys.*, 19, 12-16.
- Bartel, L. C., and Newman, G. A., 1991, Mapping a 3-D conductivity anomaly using a vertical electric source: Field results: 61st Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 472-475.
- Beasley, C. W., and Ward, S. H., 1986, Three-dimensional mise-a-la-masse modeling applied to mapping fracture zones: *Geophysics*, 51, 98-113.
- Edwards, R. N., 1974, The magnetometric resistivity method and its application to the mapping of a fault: *Can. J. Earth Sci.*, 11, 1136-1156.
- Edwards, R. N., Law, L. K., and DeLaurier, J. M., 1981, On measuring the electrical conductivity of the ocean crust by a modified magnetometric resistivity method: *J. Geophys. Res.*, 86B, 11 609-11 615.
- Edwards, R. N., and Nabighian, 1991, The magnetometric resistivity method, in Nabighian, M. N., Ed., *Electromagnetic methods in applied geophysics*, Vol. II: Soc. Expl. Geophys.
- Hohmann, G. W., Van Voorhis, G. D., and Nelson, P. H., 1978, A vector EM system and its field applications: *Geophysics*, 43, 1418-1440.
- LaBrecque, D. J., and Ward, S. H., 1987, Evaluation of borehole MMR for fracture detection: Univ. Ut. Res. Inst., Rep. 86024-TR.
- Nabighian, M. N., Oppliger, G. L., Edwards, R. N., Lo, B. B. H., and Cheesman, S. J., 1984, Crosshole magnetometric resistivity (MMR): *Geophysics*, 49, 1313-1326.
- Newman, G. A., 1994, A study of downhole electromagnetic sources for mapping enhanced oil recovery process: *Geophysics*, 59, 5345-545.
- Newman, G. A., Hohmann, G. W., and Anderson, W. L., 1986, Transient electromagnetic response of a three-dimensional body in a layered earth: *Geophysics*, 51, 691-706.
- Oppliger, G. L., 1984, Three-dimensional terrain corrections for mise-a-la-masse and magnetometric resistivity surveys: *Geophysics*, 49, 1718-1729.
- Palace, G. J., and West, G. F., 1990, Airborne electromagnetic methods, in Nabighian, M. N., Ed., *Electromagnetic methods in applied geophysics*, Vol. II, Soc. Expl. Geophys., 811-879.
- San Filippo, W. A., and Hohmann, G. W., 1983, Integral equation solution for the transient electromagnetic response of a three-dimensional body in a conductive half-space: *Geophysics*, 50, 798-809.
- Vozoff, K., 1990, The magnetotelluric method, in Nabighian, M. N., Ed., *Electromagnetic methods in applied geophysics*, Vol. II, Soc. Expl. Geophys., 641-711.