Interpretation of Crone pulse electromagnetic data

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ABSTRACT

Time-domain electromagnetic (TEM) prospecting systems, including the Crone pulse electromagnetic (PEM) system, are becoming more widely used in the search for massive sulfides. We have developed interpretation aids for the moving-source configuration of the Crone PEM system using the PLATE and SPHERE programs developed by the University of Toronto. PLATE models a thin rectangular sheet in free space and SPHERE models a two-layer sphere in free space.

The effects of varying the model parameters, particularly the dip, depth, and conductance for large plates, are shown. As the dip of a plate goes from 0 to 90 degrees, the negative side lobe over the conductor becomes less pronounced. The depth can be estimated from the amplitude of the positive peak over the edge of a conductor. The depth of exploration for the Crone PEM system is approximately twice the coil separation for shallow dipping plates, and one coil separation for steeply dipping plates when there is not a significant half-space or overburden response. The ratio of the on-conductor and off-conductor side-lobe areas gives an estimate of the dip if the depth of the target has been determined. The resolution of dip for plates dipping more than 60 degrees is poor. The conductance of a plate can be determined from either channel-ratios or the estimated time constant. Channel-ratios sometimes provide better estimates, because they have less dependence on the size of the conductor at earlier times. At early times, the target response can be obscured by conductive overburden. Only at late times would interpretation aids be useful in evaluating the target parameters.

A dip-depth nomogram and channel-ratios gave good first estimates of the target parameters of three field examples interpreted by computer modeling.

INTRODUCTION

The Crone pulse electromagnetic (PEM) system is a time-domain electromagnetic (TEM) prospecting system designed to delineate conductors in the Earth. It can be used in a large fixed-loop, in-loop, or moving-source configuration, depending upon conditions. Frequency-domain electromagnetic (FEM) prospecting systems were widely used in the past for exploration of massive sulfide mineral deposits; but recently TEM systems have become more popular, particularly in areas of high geologic noise.

The first TEM prospecting system in North America was described by Wait (1956), who proposed sending a pulse of current through a wire loop and measuring the time rate of decay of the secondary magnetic field in another loop. The secondary magnetic field is the field that exists after the current in the transmitting loop is turned off, due to the induction of eddy currents in the conductive target and in the Earth. Developments by Newmont Exploration Ltd. and Crone Geophysics Ltd. led to the Crone PEM system in 1972 (Crone, 1975). The system’s many features make it attractive for reconnaissance or follow-up exploration of conductive bodies in all types of terrain. Other widely used TEM systems were described in Velikin and Bulgakov (1967), Lamontagne (1975), Palacky and West (1975), Busselli and O’Neill (1977), Spies (1980a, b), Lodha and West (1980), Dickson and Boyd (1980), Nabighian (1982), and Eaton (1984).

To develop interpretation aids for the moving-source configuration of the Crone PEM system, we computed models using numerical solutions for a thin, rectangular sheet in free space (Annan, 1974) and a two-layer sphere in free space (Nabighian, 1970, 1971). Computer programs based on these solutions were developed at the University of Toronto (Dyck et al., 1980). The effects of varying some of the geometrical and electrical parameters for each model target (thin plate and sphere) were studied. A dip-depth nomogram and a channel-ratio diagram to interpret PEM readings for dip, depth, and the conductivity-thickness (σt) product are included. Finally, three field examples are presented and interpreted in terms of the available target models. Previously, few scaled or computer model results or interpretation aids for the Crone PEM system existed, particularly for bodies with shallow dip.

**CRONE PEM SYSTEM**

For this model study we consider the two-loop, moving-source mode of operation with a transmitting loop, which when laid out forms a circle 13.7 m in diameter. In this mode of operation, the Crone PEM system consists of six pieces of equipment: transmitter, transmitter battery, transmitting loop (two pieces), receiver, and receiving coil. The signal strength of the transmitting loop allows for separations between transmitting and receiving coils of up to 200 m. Other modes of operation are described in Crone (1977b) and Crone (1980). Contact between the transmitter and receiver for accurate timing of the current pulses is made using a radio link or an optional cable link. For moving-source surveys, only the vertical secondary field component is routinely measured.

The current in the transmitter is a pulse train of alternating polarity. The pulse is turned on exponentially with a time constant of 1.0 ms. The pulse turn-off is a one-quarter cosine wave for older transmitters (Dyck et al., 1980) and a linear ramp for newer transmitters (Crone Geophysics, 1977). For linear-ramp transmitters, the turn-off time can be selected as 0.5, 1.0, or 1.5 ms. For the older transmitters it is set at 1.4 ms. The waveform has two possible periods: 43.2 ms with a current-on time of 10.8 ms, or 83.6 ms with a current-on time of 21.6 ms. Figure 1 shows the old and new transmitter waveforms for the 43.2 ms period.

Readings for the Crone PEM system are normalized by the primary field component that the receiver is measuring and are displayed in parts per thousand (ppk) on an analog meter. The primary field measurement, or primary pulse (pp), is measured during the current turn-off ramp. Besides the normalization, each of the eight channel readings has a gain factor applied to allow display of all the channels on a single scale. Table 1 shows the channel windows and gain factors for the two different current pulses.

**MODELING PROGRAMS**

Recent advances in solutions to electromagnetic (EM) scattering problems have led the way from largely scale-model studies (e.g., Woods, 1975; Spies, 1980a) to computer case studies. Solutions to the EM scattering problem used in this paper are by Annan (1974) for the thin, rectangular sheet in free space, and by Nabighian (1970, 1971) for the two-layer sphere. Both solutions were programmed at the University of Toronto, as described by Dyck et al. (1980).

The EM response of a thin, rectangular sheet in free space (the PLATE program) has been used as the basis for several modeling studies: Lodha and West (1980), Dyck and West (1984), and Gallagher (1984), to name a few. The original solution to the scattering problem was by Annan (1974), but it was extended by Dyck et al. (1980) to include almost all time-domain and frequency-domain systems. The solution technique separates the geometrical, spatial, and electrical property portions of the problem. The major portion of the solution is the geometrical one which requires only one calculation for each width-to-length ratio of the thin sheet. For each ratio, the EM response is a sum of currents (eigencurrents) circulating in different portions of the plate (Annan, 1974; Kaufman, 1978). High-order eigencurrents correspond to early times, low-order eigencurrents to late times. Fifteen eigencurrents are normally used by PLATE.

The EM response of a two-layer sphere in a conductive whole space was originally derived by Nabighian (1970, 1971). This solution was programmed for the case of a sphere in free space and for use in modeling a wide range of EM prospecting systems by Dyck et al. (1980). The SPHERE solution construction is similar to that of the PLATE program except that the eigencurrent construction in SPHERE is for each induced multipole. For each of ten multipoles, 150 eigencurrents are typically used in SPHERE.

The EM response of the target in each program (PLATE and SPHERE) can be calculated for several EM systems. For time-domain problems, the magnetic field impulse response is first calculated and then convolved with the time derivative of the current waveform to get the true system response. A modification in the original program allows for calculation of the system response using the new current waveform, as shown in Figure 1b.

Model parameters for the PLATE and SPHERE programs are shown in Figure 2. For this study, the transmitting and receiving coils lie parallel to the profile line and on the surface. The separation of the transmitting and receiving coils (subsequently referred to as "coil separation") is 100 m throughout the study.

![Fig. 1. Old and new PEM waveforms for 10.8 ms current pulses: (a) old transmitter current waveform, (b) new transmitter current waveform (adapted from Crone Geophysics, 1977; Dyck et al., 1980).](image-url)
Table 1. PEM time windows. PP denotes the primary pulse or measurement of the primary field. Zero time is at the bottom of the current ramp (see Figure 1).

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>10 ms PULSE CENTER</th>
<th>20 ms PULSE CENTER</th>
<th>WIDTH</th>
<th>CENTER WIDTH</th>
<th>GAIN FACTOR</th>
</tr>
</thead>
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<tr>
<td>PP</td>
<td>0.5 ms</td>
<td>1 ms</td>
<td>1 ms</td>
<td>2 ms</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>5.5</td>
<td>11</td>
<td>6</td>
<td>5.75</td>
<td>1.0</td>
</tr>
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<td>9</td>
<td>18</td>
<td>8</td>
<td>9</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>1.45</td>
<td>29</td>
<td>14</td>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>2.4</td>
<td>48</td>
<td>24</td>
<td>6.5</td>
<td>1.0</td>
</tr>
<tr>
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<td>4</td>
<td>80</td>
<td>40</td>
<td>7.20</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>6.4</td>
<td>128</td>
<td>56</td>
<td>10.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

EFFECTS OF MODEL PARAMETERS

Now we consider the effects of changing the following important target parameters for a plate: conductance (conductivity-thickness product), dip, depth, strike length, and profile position. For a sphere, we study the effects of the conductance of a homogeneous sphere. We also illustrate the approximate effects of a conductive overburden. The standard model used for plates (unless otherwise stated) is: plate dimensions, 600 by 600 m; depth, 50 m; dip, 30 degrees; conductance, 30 S; and coil separation, 100 m. The upper edge of the plate for each model is at zero distance. Various other effects such as type of turn-off ramp and coil separation are also discussed. The PEM plotting scale is in ppk, being logarithmic from 10 to 1000 (and -10 to -1000), and linear from -10 to 10.

Conductance

First, consider the variation in the PEM response with changes in the conductance of a thin plate. Figure 3 compares the responses of dipping plates with conductances of 3, 10, 30, and 100 S. As the conductance increases, an anomalous response is seen over a larger number of channels. The response generally dies off as time increases, except when the conductance is large. For a plate with conductance 100 S, the response increases until channel 5, and then begins to decay. This apparent increase in the response is due to the gain factor being applied to a slowly decaying voltage response in the receiving coil. For thin plates with conductance less than 1 S, there is no measurable anomalous response.

Dip

With a horizontal plate model, the effects of both edges are evident in the profiles, as shown in Figure 4. These edge effects consist of a positive peak over the edge of the conductor and a small negative side lobe off the edge of the conductor. The positive peak migrates slightly toward the center of the thin plate through time, indicating a migration of the eddy currents toward the center of the plate, as seen in other modeling studies (Velikin and Bulgakov, 1967; Dyck and West, 1984). When the plate is not horizontal, and if the lower edge of the plate is shallow enough, an edge effect will also be seen from this edge (Ramaprasada Rao and Kabra, 1983). Otherwise, only an updip edge effect remains, as seen in Figure 4. Migration of the positive peak diminishes as the target becomes more nearly vertical. Determination of the dip of a steeply dipping target is difficult. The small oscillations in the central region of the horizontal plate profiles shown in Figure 4 are believed to be due to slight inaccuracies in the PLATE program.

Depth

Depth of the target also affects the edge effects described earlier. Both the positive peak and the negative off-conductor side lobe essentially disappear when the depth reaches approximately 1.5 times the coil separation, as shown in Figures 5 and 6 and by Lodha and West (1980). Horizontal and shallow dipping plates deeper than one coil separation have only a negative response over the conductor (Figure 5). In these cases, the updip edge can be identified by the sharper lateral attenuation of the negative response. Vertical and near-vertical thin plates are more drastically affected by depth, and only a very small anomalous response is seen when the depth is greater than the coil separation (Figure 6). Similar results were found for dipole-dipole TEM systems in general by Ramaprasada Rao and Kabra (1983).

Strike length

As the size of the conductive target is made smaller, the eddy currents generated on the surface of the plate decay more
Fig. 3. Variation with $\sigma r$ product ($L = W = 600$ m, $D = 50$ m, $\theta = 30$ degrees, coil separation = 100 m.)

Fig. 4. Variation with dip ($L = W = 600$ m, $D = 50$ m, $\sigma r = 30$ S, coil separation = 100 m.)

Fig. 5. Variation with depth for dip of 30 degrees ($L = W = 600$ m, $\sigma r = 300$ S, coil separation = 100 m.)

Fig. 6. Variation with depth for vertical plate ($L = W = 600$ m, $\sigma r = 30$ S, coil separation = 100 m.)
rapidly with time (Veilkin and Bulgakov, 1967). In Figure 7, the strike length varies from 120 to 600 m. At early times, the plate of 120 m strike length has a response similar to that of the plates with 300 and 600 m strike lengths. The response at later times for the plate of 120 m strike length decays more rapidly than that for the plate of 600 m strike length, as if the conductance were smaller. Changing the depth extent has the same effect as changing the strike length, except that the horizontal extent of the anomaly is also changed. Consequently, Figure 7 shows that even if the strike length is three times the coil separation, there is an effect from edges at late times.

Profile position

Positioning of the profile line with respect to the anomalous body is important. In general, the strike of a body can be inferred from the local geology, and the profile line should be run perpendicular to the strike of the target. The profiles presented so far were evaluated over the center of a 600 by 600 m plate; when the profile is at the end of the plate for a dip of 30 degrees (Figure 8), the response is greatly attenuated. Only for horizontal plates is there an appreciable response when the profile is off the end of the plate, as shown in Figure 9. For smaller plates, the response decays more rapidly away from the center.

Sphere conductivity

Figure 10 compares the responses of spheres with different conductivities. The spheres have uniform conductivity throughout, even though the modeling program allows for a two-layer sphere of differing conductivities in each layer. The response of a sphere looks similar to that of a vertical plate, but the central peak of the anomaly decays more rapidly with time than the associated negative trough. For a vertical plate, the positive peak and negative trough decay at the same rate. This difference can be exploited to distinguish between inductively thin and inductively thick conductors.

Thin and thick conductors differ in the way currents circulate after the primary field is shut off. No matter what the orientation of the primary field, eddy currents of a thin plate are in the plane of the plate, and they move inward with time. For a sphere, the initial eddy currents are perpendicular to the primary field, whose direction depends upon the position of the transmitting loop with respect to the sphere. Through time, these currents decay inward and across the surface to become an equatorial ring current (Dyck and West, 1984).

Conductive overburden

Conductive overburden is a problem in EM exploration in many portions of the world. Conductive overburden delays and attenuates the response from a conductive target if the overburden and target are not in contact. If they are not in galvanic contact, a first-order approximation of the late-time results may be made by adding the separate responses of the overburden and target (Nabighian, 1982). Superposition of the results should also, in this case, give us a good indication of the effect of overburden at early times since the conductors are not in galvanic contact. The model chosen for the overburden was a 10 Ω·m layer, 30 m thick, over a 10,000 Ω·m half-space. The response was originally formulated in the frequency domain (G. Newman, 1983, pers. comm.) and then transformed into the time domain by the method of Tripp (1982).

The transient response of a half-space due to a current loop on the surface can be approximated by a moving current filament, or “smoke ring,” that expands and moves downward through the Earth (Nabighian, 1979). For a conductive layer, the smoke ring tends to remain within the conductive layer (Hoversten and Morrison, 1982). Since we have a conductive top layer, the downward movement is inhibited, but expansion still occurs. Using this analysis, the smoke ring is beyond the position of the receiving coil by the time the first channel is measured, and the PEM response is therefore negative. Figure 11 shows the effect of this conductive overburden on our standard model of a 600 by 600 m plate when the two are not in contact. At early times, because of the large negative anomaly due to the overburden and the PEM linear-logarithmic plotting scale, the target response is hardly seen. Only at later times has the overburden response decayed enough that the target response is clearly seen.

The location of the current smoke ring during measurement times must be reanalyzed for each problem because it depends both on the coil separation and on the chosen layered earth model. For a uniform half-space, the location of the smoke ring can be calculated (Nabighian, 1979).

If the smoke ring has not passed the position of the receiving coil at a particular measurement time, in contrast to the situation in Figure 11, the secondary field is in the same direction as the primary field; hence the PEM response is positive. As the smoke ring passes beneath the receiver in time, the vertical portion of the secondary field is zero. Still later, the sign of the secondary field is opposite that of the primary field, and the PEM response is negative as in Figure 11. In field data, the crossover time changes along a profile due to slight changes in the thickness and conductivity of the overburden. Thus, a profile for a particular measurement time near the passage of the smoke ring along a profile has large positive and negative fluctuations due to changes in the overburden, as in the PEM data from the Elura deposit (Crone, 1980) and Steeple Hill (Gunn and Brook, 1978). Conductive host rock also changes the anomaly, but the manner in which it does so is less well understood. Lewis and Lee (1981) presented a summary of various approaches to the problem.

Type of turn-off ramp

Changing between the two types of turn-off ramp for the current waveform illustrated in Figure 1 has minor effects on the anomalous response due to a conductive body. The anomalies with the new current waveform (Figure 1b) are slightly greater than those with the old current waveform (Figure 1a) with the same turn-off time. The difference is almost the same as the increase in the area of the time derivative of the current waveform. However, this change in anomaly magnitude does not appreciably change the model effects discussed here, nor does it change the interpretation aids we discuss next. Changes in the type of turn-off ramp affect only the early-time data, and eventually the response looks like that for a step current excitation (Eaton, 1984; Raiche, 1984).
FIG. 7. Variation with strike length ($W = 600$ m, $D = 50$ m, $\theta = 30$ degrees, $\sigma t = 30$ S, coil separation = 100 m).

FIG. 8. Variation with profile position for dip of 30 degrees ($L = W = 600$ m, $D = 50$ m, $\sigma t = 30$ S, coil separation = 100 m).

FIG. 9. Variation with profile position for horizontal plate ($L = W = 600$ m, $D = 50$ m, $\sigma t = 30$ S; coil separation = 100 m).
Separation of transmitting and receiving coils

For the moving-source configuration, decreasing the coil separation attenuates the PEM response because the response is normalized by the primary field. Although the secondary field remains approximately constant with respect to the coil separation, the primary field increases rapidly as the coil separation is decreased, leading to a reduction in the response. Hence the depth of exploration increases with coil separation. However, increasing the separation eventually reaches the limits of the transmitter power and receiver accuracy (approximately 200 m with the portable transmitter).

INTERPRETATION

With any geophysical data set, interpretation may take two different forms: preliminary and detailed. Preliminary interpretation is crucial in the field, and can be made quickly by an experienced interpreter. Quantities that can be quickly estimated include the dip, depth, and conductance of the target. Such interpretation includes the use of nomograms, type curves, and model catalogs. Trial-and-error data fitting with a computer model is a detailed interpretation method to find specific geometrical and/or electrical properties of the target or targets causing the anomaly.

Many target properties can be interpreted quickly from Crone PEM readings, assuming that topography and/or noise (instrument or natural) does not greatly affect the readings. The transition in the anomaly response when the profile line is moved from over the target to off the target is marked and is easily seen (Figures 8 and 9). Thus, from a series of parallel profiles, the strike length of the conductor can be estimated. Direction and dip of the body can be estimated by the extent and magnitude of the on-conductor negative side lobe, which is greater than the off-conductor negative side lobe (Figure 4). When the on-conductor side lobe is much greater than the off-conductor side lobe, the dip angle is small. Figures 5 and 6 show that the positive peak over the edge of the conductive body is nearly zero when the top of the body is deeper than the coil separation. Relative conductance of the target body or bodies can be estimated by the number of channels showing an anomalous response (Figure 3). This type of ranking, based on the number of channels showing an anomalous response, is the same as for airborne TEM surveying. The geometry of a target, i.e., whether it is a plate or a sphere or something else, is perhaps the most difficult property to identify qualitatively, because as seen from Figures 4 and 10, a vertical plate and a sphere can have similar responses. The key element in distinguishing a thick conductor from an inductively thin one is the decay of the positive peak in relation to the negative portion of anomaly. In many instances, the geometry of the target can be assigned from the known regional geology.

**Fig. 10.** Homogeneous sphere response for different conductivities, radius 50 m, depth to top 50 m, coil separation 100 m.

**Fig. 11.** Approximate effect of conductive overburden (a) Plate response with no overburden \(L = W = 600 \text{ m}, D = 50 \text{ m}, \theta = 30 \text{ degrees}, \epsilon = 30 \text{ S}, \) coil separation = 100 m; (b) response with overburden, numbers on far right indicate base line for each channel, other numbers indicate channel response curves; (c) overburden model.
Dip-depth nomogram

As alluded to earlier, the ratio of the areas of the on-conductor and off-conductor negative side lobes can lead to an estimate of the dip of the target; such a method was used previously to interpret horizontal-loop FEM data (Strangway, 1966). However, by examining this ratio by numerical integration using the trapezoidal rule for a number of models, we also find a dependence on the depth of the target. Figure 12 shows the result of such a study. The curves are not smooth, due to errors in both the numerical solution and numerical integration. The numerical integration is performed using the readings on a linear scale, which are easily performed if the data are on a computer. While it may seem that finding the ratio leads to an inconclusive coupled estimate of the dip and depth, an independent estimate of the depth is obtained from the strength of the positive peak at the updip edge of the target (Figures 5 and 6). If a significant positive peak exists, then the depth of the body is somewhat less than the coil separation. Using this estimate of the depth, the ratio leads to a reasonably accurate estimate of the dip. Note from Figure 12 that resolution of dip is low for steeply dipping bodies, as with most EM techniques. In practice, the ratio should only be used from those channels showing a response to a conductive body. Also, the host response was ignored.

The effect of a conductive overburden or host can sometimes be reduced, in order to use at least this interpretation scheme. If the field data appear to agree with the assumption of Nabighian (1982) that, when not in contact, the overburden and target responses are merely additive, then the overburden response can be “stripped off.” A new base line for each channel, which is not necessarily the zero line, could be determined in order to find the ratio of the on-conductor to off-conductor side-lobe areas. Once the overburden response is stripped off (assuming it can be), the target response is easier to interpret. For the case shown in Figure 11, this procedure could easily be used for channels 3 through 8. A similar procedure was used by Crone (1980) with Elura deposit PEM data.

Crone (1977b) suggested a method for finding the depth of a conductive target which entailed using a vertical transmitting loop and measuring with horizontal and vertical receiving loop positions. Perpendicular lines from the resultant dip angles should converge at the eddy-current axis of the target. However, as Lee (1978) pointed out, an erroneous result over conductive ground resulted, due to the smoke ring effect discussed earlier in connection with conductive overburden.

Rai and Verma (1984) chose to use the difference in amplitude of the on-conductor and off-conductor side lobes related to the amplitude of the positive peak at the edge to determine the dip and depth of a target. Their nomograms are also highly dependent upon the product of the conductance of the plate and the coil separation.

Conductivity-thickness estimation

The decay of the PEM response at any one station over an anomaly can be used to determine a measure of the conductivity of the target. Either the channel ratios or the time constant can be used. In the case of a large thin plate, only the \( \alpha \tau \) product can be determined.

Channel ratio.—Crone Geophysics (1980) uses the following formula and constants to determine the \( \alpha \tau \) product of a large, thin, near-vertical conductor:

\[
\alpha \tau = k_{ij}/(\log_{10} S_i - \log_{10} S_j + 0.14),
\]

where \( S_i \) is the reading for the \( i \)th channel and the \( k_{ij} \)'s are:

\[
\begin{align*}
  k_{12} & = 2.09 \\
  k_{23} & = 3.48 \\
  k_{34} & = 4.88 \\
  k_{45} & = 7.67 \\
  k_{56} & = 13.2 \\
  k_{67} & = 22.3 \\
  k_{78} & = 33.4.
\end{align*}
\]

This formula can be thought of as a channel-ratio. The later samples should give a better indication of the true conductance, since higher modes and any overburden and/or other geologic noise response should have decayed away. Analysis shows that only for very high conductances (approximately 100 S) is the estimate from the formula close to the true conductance as determined from models using the PLATE program. The factor 0.14 is present in the equations because PEM readings have a gain factor applied to them corresponding to 10 raised to the \( \frac{1}{4} \) (0.14) power (Table 1).

Verma and Rai (1982) used the ratio of the responses of two different channels to evaluate the homogeneous or layered-earth PEM response. Figure 13 shows how different channel-ratios help determine the conductance of a plate-like target. These ratios were determined by averaging the ratios from many PLATE models. For bodies of low conductivity, the late channel-ratios will be difficult to measure in field conditions because of the small response. Size of the plate has less effect on the early channel-ratios (those concerning channels 3 and 4) than on the late channel-ratios. For small bodies, the late channel-ratios yield a smaller conductance than the other channel-ratios. Crone's formula (above) can be compared with Figure 13. The ratio for channels 3 and 4 from the formula is almost the same as the ratio for channels 3 and 5 in Figure 13, and the ratio for channels 4 and 5 is almost the same as the

![Fig. 12. Dip-depth nomogram; lines represent ratio of on-conductor side-lobe area to off-conductor side-lobe area.](image-url)
ratio for channels 4 and 6 in Figure 13. The channel-ratios have no significant variance with respect to dip or depth (also seen by Rai and Verma, 1984) and may be taken from the negative or positive peaks of the readings. Note that the effect of the gain factor applied to PEM readings by the receiver was not eliminated.

**Time constant.**—Discussion of the decay of the PEM response also leads to evaluation of the time constant. To look effectively at the voltage decay, the gain factors, which vary with channel, must be eliminated (Crone Geophysics, 1980). The time constant can then be determined from the late-time slope of the decay curve (Ballantyne, 1981). The empirically derived formula for the time constant for a thin plate (Lambertagne, 1975) is

\[ \tau = \frac{\mu_0 \alpha t L}{10} \]

where \( L \) is the smaller areal dimension of the plate. This formula accurately describes the time constant for the many PLATE models generated. The exceptions to this seem to be large plates with either a high or a low conductance. A high conductance leads to a high estimate of the time constant, and a low one, a low estimate. For spheres, the time constant given by Velikin and Bulgakov (1967) and Spies (1980a),

\[ \tau = \frac{\mu_0 R^2}{\pi^2} \]

works well.

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**FIELD EXAMPLES**

In order to illustrate the uses of the models chosen and applications of the interpretation aids, we present three examples of interpreting field results. The first, a near-vertical conductor, is the Maydan deposit in the Sultanate of Oman (Crone, 1977a). The response of the Maydan deposit (Figure 14a) was chosen because of the near lack of surficial overburden response. The Maydan deposit is a massive sulfide deposit composed mainly of pyrrhotite and chalcopyrite. Drilling and other geologic information shows that it is 40 m thick, is weathered to a depth of 10 m, and dips steeply to the north, or to the right on Figure 14a.

Using the interpretation procedures developed previously, we attempt to model the field data. We have no real information concerning the size of the deposit, except that it has both a large strike length and depth extent, so we chose our standard 600 m by 600 m plate size. The \( \alpha t \) product is estimated at 65 to 100 S from Crone's formula; whereas from the channel-ratios (Figure 13), the estimate is 30 to 80 S. In each case, the earlier channels give the lower estimates. The ratio of the side-lobe areas suggests a nearly vertical deposit, and the dip direction is discerned from the known geology or from the migration of the left-hand zero crossing.

We fit the response by trial-and-error modeling with the PLATE program. Due to program limitations (Dyck et al., 1980) the depth of the plate is larger than the known depth of weathering. The best fit to the Maydan deposit is shown in Figure 14b. The model is a 600 by 600 m plate, with a dip of 80 degrees to the right, depth of 20 m, and a \( \alpha t \) product of 60 S. The fit is good through the positive peak, particularly through the middle and late channels. A perfect fit to the positive peak data could not be made because the Maydan deposit is not inductively thin, and because the geology is more complex than our simple model. Some of the early channel noise is due to surficial weathering.

The second field example concerns the Arctic deposit near Bornite in the Brooks range of Alaska. The Crone PEM data, along with Crone shootback EM data, were taken during the summer of 1982 (Figures 15a and 15b). The Arctic deposit, which is well-defined by drilling, consists of a series of semi-connected massive sulfide sheets in a highly metamorphosed terrain of metarhyolite, muscovite-quartz schists, and graphitic schists; the latter are poor conductors in this environment. Although there is a large negative trough in the readings to the left of the positive peak representing the downdip side, its sudden attenuation is because of a topographic effect in the survey line (see Figure 15c). Thus, the updip edge appears to be dipping steeply, while the major portion of the deposit...
Interpretation of Crone Pulse EM Data

FIG. 14. Interpretation of PEM data from the Maydan deposit, Oman: (a) field data, (b) best fit plate response \( L = W = 600 \text{ m, } D = 20 \text{ m, } \theta = 80 \text{ degrees, } \sigma t = 60 \text{ S, coil separation } = 100 \text{ m.} \)

Response (−240 to −1 200 m) appears to be from a largely horizontal sheet. The edge of a second, deeper sheet that was not modeled is at approximately −540 m. Interpretation of the PEM and shootback EM data shows that the conductor begins down-dip of the deposit outcrop. There is no discernible shootback EM anomaly, but a significant PEM anomaly, over most of the conductor which is buried 100 to 150 m deep. On the left-hand side, the PEM response is attenuated as the conductor thins.

Only the up-dip edge, or right-hand portion, of the deposit is easily modeled. This portion of the response appears to be steeply dipping, with a \( \sigma t \) product in the range of 40–70 S (Crone's formula) or 20–50 S (by Figure 13). The depth is significantly less than one coil separation, which was 91 m (300 ft) for this survey. The final modeled response for the right-hand portion of the field data is shown in Figure 16. The dip was calculated as 35 degrees to the southwest, and the depth at 30 m. The \( \sigma t \) product used to calculate Figure 16 was 37 S, but this could be slightly low, since the amplitude on the last channel is not matched well. The depth extent of the plate was taken as 480 m, with the strike length being larger (600 m). The difficulty in modeling this particular field data set is due to insufficient sampling of the off-conductor side lobe and the preponderance of topographic effects to the left of the edge of the conductor as shown in Figure 15a.

The portion of the Arctic PEM response not modeled is that from −240 to −1 200 m. The response in this region appears to be from a sheet approximately parallel to the ground surface. The depth is approximately 30 to 50 m, and the \( \sigma t \) product as previously modeled was 37 S. The slight attenuation of the response in the region of −540 m is due to the semiconnected nature of the sulfide sheets. From −1 000 to −1 200 m, the PEM response attenuates gradually. This agrees with a thinning of the conductor as determined by drilling.

A third field example, while not modeled by the PLATE program, shows the usefulness of the interpretation aids. The PEM data are from the Woodlawn deposit in Australia (Crone, 1981). Figure 17 shows there is little background response past the first channel. The dip-depth nomogram yielded a dip between 40 and 50 degrees to the left (west), compared to the actual dip of 37 degrees to the west, assuming that depth/coil separation ratio is approximately 0.5. The known depth (Malone et al., 1981) is about 20 m, yielding a depth/coil separation ratio of 0.33. However, in this region of the dip-depth nomogram, the depth does not have much effect. The channel-ratios for Woodlawn PEM data yielded \( \sigma t \) values of 50 to 100 S. Given the published resistivity of the ore at 0.1 Ω·m (Malone et al., 1981), an estimated thickness would be 10 m; however, the deposit averages 10 to 20 m thick. Thus, the average bulk resistivity of the orebody as seen by the PEM system may be a little higher than the published value, or the conductance may be underestimated. The latter would be the case if the deposit is not inductively "thin" at the times considered. The PEM time constant appears to average about 3.5 ms over the orebody, which would give a length \( L \) from the time constant of a thin plate of about 300 m (assuming \( \sigma t = 100 \text{ S} \) from the later samples). This length appears related to the depth extent. As Crone (1981) pointed out, this particular survey line is near an abrupt change in the strike direction of the body which affects interpretations based on a survey orthogonal to a thin plate. Still, the PEM response and interpretation warrant further investigation for such an anomaly.

With these three field examples, the detailed interpretation aids presented were tested. The results from these interpretation aids give a good start for further modeling, particularly for the dip-depth nomogram and the channel-ratio diagram.

CONCLUSIONS

This study has shown the response of the moving-source Crone PEM system to simple, three-dimensional (3-D) bodies in free space. The change in the PEM response with changes in the various electrical and geometrical parameters was shown. The 3-D bodies used are a thin rectangular plate and a
sphere, both in free space, with the anomalous responses computed by the computer programs PLATE and SPHERE (Dyck et al., 1980). A suite of models was generated in order to develop interpretation schemes.

Methods for interpreting the Crone PEM response of a thin rectangular plate and a sphere in free space were developed. These procedures are simple, yet exacting enough to give good estimates of the dip, depth, conductance, and size of an anomalous body. Some of the interpretation procedures (i.e., dip-depth nomogram and channel-ratios) would also be applicable to other targets, such as thick plates.

While many practitioners now employ the Crone PEM system in large fixed-loop or in-loop configurations, the moving-source configuration is used extensively in rugged and brushy terrain. We hope that our work aids in the interpretation of data collected in the past, present, and future with the many existing Crone PEM systems.

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REFERENCES


Fig. 15. Arctic deposit: (a) PEM data, (b) Shootback EM data, (c) generalized cross-section.

Fig. 16. Best fit plate response to the Arctic deposit PEM data (L = 600 m, W = 480 m, D = 30 m, θ = 35 degrees, cr = 37 S, coil separation = 91 m).


