A model study of a thin plate in free space for the EM37 transient electromagnetic system

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ABSTRACT

The computer program PLATE, developed at the University of Toronto, models the electromagnetic (EM) response of an inductively thin plate in free space. We used PLATE to compute two components of the time derivative of the magnetic field for a range of models for the EM37 fixed-source transient system (300 x 600 m loop). Analysis of the response curves produced methods of interpretation for obtaining plate geometry and conductance.

The overall width of an anomaly, the distance between peaks and the width of the updip lobes, can provide an estimate of depth. Dip has the dominant effect on the ratio of the peak amplitudes. A rough estimate of plate size and the position in time (early or late) of the currents is essential before proceeding with interpretation.

Strike length is not obviously reflected in the shape of the curves, but depth extent is indicated by the rate at which the downdip tail returns to the baseline, except for vertical plates. For vertical plates, curve matching may be the only method of obtaining an estimate of depth extent.

Varying conductance for a particular model in free space affects whether a channel represents an early, intermediate, or late time response. The shape of a profile varies with the time of measurement. The estimated time constant can be used to calculate the conductance, provided an estimate of the shortest dimension of the plate is available.

Extinction angles appear frequently for plates of small depth extent but do not occur for plates which are of infinite strike and depth extent with respect to the size of the transmitting loop.

INTRODUCTION

The use of time-domain electromagnetic (TEM) prospecting systems has been widespread in industry for over a decade. Frequent users of a particular system develop methods of interpretation, but their techniques and procedures are not well-recorded in the literature. In this paper a representative group of free-space plate models is presented for the Geonics EM37 system, and some suggestions are made, both quantitative and qualitative, for techniques of interpretation.

Although Lamontagne and West (1971) were the first to obtain a solution to the problem of a confined thin plate in free space, Annan (1974) developed a more efficient method. Dyck (1981) used Annan’s solution and his core routines and developed the computer program PLATE (Dyck et al., 1980), which models the EM response of a plate for time-domain or frequency-domain EM systems.

Using PLATE, we calculated the time derivative of the magnetic field \(\frac{dB}{dt}\) for over 130 plate models. For each plate geometry the conductance is modeled at four values: 100, 30, 10, and 3 S. Only a select few of the models are presented here. The models presented demonstrate the effects of variations of depth, dip, strike length, and depth extent. Many other variations were not studied, for example, variation in the size of the transmitting loop or position and strike or plunge of the plate.

We estimated time constants for the models from decay curves by inverting the slope of the late-time responses; this is not to be confused with the time constant defined by Sheriff (1973, p. 219). From the time constants we then verified a method of computing the conductance. The range of models was sufficient to investigate methods of estimating depth and dip. Plate size was varied to obtain some methods of gauging depth extent from the response curves.

Only recently have we been able to study the applicability of free-space models to a variety of field situations using numerical and analog modeling. In highly resistive host rocks neither current channeling nor mutual coupling between the host and the body take place; hence, currents can exist only in the body. The free-space model accurately depicts this current behavior, but in a conductive host, current channeling and inductive coupling between the body and the host can occur. For the conductive host case there is some intermediate time window, before late-time behavior commences, when the half-space response is decoupled from the body (Kaufman, 1981), or at least the body response is at a maximum with respect to the half-space response (Spies, 1980; Nabighian, 1982; Eaton and Hohmann, 1984). Presumably, during this window the half-space response can be subtracted from the total response and a free-space model can characterize the secondary response; however, this remains to be verified.
PLATE PROGRAM

The program PLATE models the response of a confined, geometrically and inductively thin plate in free space to either a frequency-domain or time-domain EM system. For a plate to be considered thin, its thickness is much less than the product of the other two dimensions and less than 0.6 skin depths in the frequency domain (Hohmann et al., 1978). A system of simple surface loop currents represents the induced eddy currents in the body. The eddy currents close on themselves, forming rings of current which produce a secondary field "moment" perpendicular to the plate.

In PLATE the eddy currents are represented numerically by a set of 15 eigencurrents or eigenpotentials. Each eigencurrent of the set has a unique circulation pattern on the plate surface. The more complex the pattern, the faster the rate of decay and the faster the geometric attenuation of the response. The response of each eigencurrent is independent of the others, and this results in a solution represented by a sum of the set of eigenpotentials, each with its own ratio of inductance to resistance.

At early times the response is due to the effects of all of the eigencurrents, i.e.,

\[ \frac{dB}{dt} = \sum_{n=1}^{15} c_n e^{-\tau_n t} \]

where \( t \) is the measurement time, \( \tau_n \) is the time constant of the \( n \)-th eigencurrent, and \( c_n \) is the corresponding amplitude factor which for the impulse response is determined by plate geometry and the time constant. At late times the response is due almost entirely to the lowest order eigencurrent, i.e.,

\[ \frac{dB}{dt} = c_1 e^{-\tau_1 t}. \]

In PLATE the free-space response is obtained by computing the magnetic field impulse response and convolving it with the current waveform or its time derivative. Convolution with the current waveform produces the magnetic field \( H \), whereas convolution with the time derivative of the current waveform yields the time derivative of the magnetic field \( dH/dt \). Figure 1 depicts the form of the EM37 current and its primary magnetic field. Figure 1b shows the form of the time derivative of the current \( dI/dt \) and \( dH/dt \).

EM37 SYSTEM

The EM37 is a ground transient EM device manufactured by Geonics Ltd. of Mississauga, Ontario, Canada. The field layout is shown in Figure 2. Traverses with a receiving coil are made perpendicular to the long edge of the loop and usually extend on either side of and then through the loop. Three components of the time derivative of the magnetic field can be measured sequentially with an air-cored coil.

The current waveform in the transmitter consists of alternating bipolar current pulses with a slow exponential turn-on and a rapid linear shut-off. The base frequency of operation can be set at 3, 7.5, or 30 Hz, with corresponding maximum window times of 80, 32, or 8 ms, respectively. At the receiver the transient response is measured in 20 logarithmically spaced channels. We used a base frequency of 30 Hz in this investigation.

Although the size of the EM37 transmitting loop can be varied, a single loop size 300 × 600 m was chosen for this investigation. The maximum current available for the standard no. 10 copper wire is 20 A, but the current used will depend upon the inductance and resistance of the loop, which depends on the loop size and type of wire. For the loop size used here 11
A is a typical value for the current amplitude and, hence, 11 A has been used in our investigation.

The time it takes to shut off the current is called turn-off time. For the EM37, with a loop size of 300 \( \times \) 600 m, turn-off time varies between 0.32 and 0.02 ms. The actual turn-off time depends upon the inductance of the wire. For a 300 \( \times \) 600 m loop with a current of 11 A, a typical value of the turn-off time is 0.165 ms, which is the value used in this investigation. The time constant of the slow exponential turn-on will also depend upon the wire size, resistance, and inductance. The turn-on used here is 0.75 ms, a value arrived at after consultation with personnel of Geonics Ltd.

At the receiver the induced voltage in the coil is measured in millivolts. Using the effective area of the coil and the gain of the receiver, these measurements are converted to the time derivative of the magnetic field in nanovolts/meter.

**PLATE ORIENTATION AND MODEL DESCRIPTION**

The plate model and transmitting loop for the models are shown in Figure 2. The center of the coordinate system is the center point along the right edge of the loop. A plate reference point is defined at the midpoint of the left or top edge of the length of the plate. Along the x-axis on the profile, the near-source loop position is always marked as the 0 position and the plate reference point is below the 300 m position. The two plate dimensions are the strike length and depth extent. The depth referred to throughout this paper is the depth to the top of the plate.

The strike direction is parallel to the edge of the transmitting loop and the plunge is 0 degrees for all of the plate models presented. The dip direction is measured clockwise from the positive x-axis. The point of rotation for the plate is the plate reference point. In the models presented, the position of the transmitting loop is to the left of the plate. The profiles presented are perpendicular to the edge of the loop and extend from the center of the loop edge. A description of the plate parameters is included in the figure captions.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( t_1 ) (ms)</th>
<th>( t_2 ) (ms)</th>
<th>Center (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.080</td>
<td>0.097</td>
<td>0.089</td>
</tr>
<tr>
<td>2</td>
<td>0.097</td>
<td>0.121</td>
<td>0.109</td>
</tr>
<tr>
<td>3</td>
<td>0.121</td>
<td>0.158</td>
<td>0.140</td>
</tr>
<tr>
<td>4</td>
<td>0.158</td>
<td>0.195</td>
<td>0.177</td>
</tr>
<tr>
<td>5</td>
<td>0.195</td>
<td>0.224</td>
<td>0.219</td>
</tr>
<tr>
<td>6</td>
<td>0.224</td>
<td>0.316</td>
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<td>0.355</td>
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<td>9</td>
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<td>0.634</td>
<td>0.790</td>
<td>0.712</td>
</tr>
<tr>
<td>11</td>
<td>0.790</td>
<td>0.962</td>
<td>0.876</td>
</tr>
<tr>
<td>12</td>
<td>0.962</td>
<td>1.221</td>
<td>1.090</td>
</tr>
<tr>
<td>13</td>
<td>1.221</td>
<td>1.580</td>
<td>1.400</td>
</tr>
<tr>
<td>14</td>
<td>1.580</td>
<td>1.950</td>
<td>1.765</td>
</tr>
<tr>
<td>15</td>
<td>1.950</td>
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<td>4.425</td>
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<td>4.920</td>
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<td>5.630</td>
</tr>
<tr>
<td>20</td>
<td>6.340</td>
<td>7.900</td>
<td>7.120</td>
</tr>
</tbody>
</table>

The responses are plotted for 20 channels from earliest (channel 1) to latest (channel 20) time. The channel times, with respect to the end of switch-off (see Figure 1a), for a 30 Hz base frequency are listed in Table 1. They range from 89 \( \mu \)s to 7.1 ms.

The secondary magnetic field \( (dB/dt) \) is plotted in nanovolts/meter.

We chose a set of four scales to plot the most commonly modeled plate size, which has an 800 m strike length and a 400 m depth extent (800 \( \times \) 400 m), in an optimum manner for a particular depth. The ratios between these four scales are kept constant in all of the models, although their amplitudes are changed as required by changes in depth or plate size.

The plate models are predominantly of a large plate of dimensions 800 \( \times \) 400 m, which is modeled at various depths and dips. However, for comparison we also calculated responses for plate sizes of 800 \( \times \) 200 m, 800 \( \times \) 100 m, 400 \( \times \) 400 m, and 200 \( \times \) 400 m, at a depth of 100 m, and with dips of 150, 90, and 30 degrees.

**MODEL ANALYSIS**

**Conductance**

In Annan's plate solution the plate is assumed to be sufficiently thin to allow the volume current density to be shrunk to a surface current density. This implies that the magnetic field is uniform across the plate and that the thickness is much less than the skin depth (McNeill, 1980a). Conductivity and thickness, as independent parameters, become unresolvable. Instead, a conductance \( (S) \) is defined which is simply the product of the conductivity and the thickness of the body.

The thickness limits in terms of a critical thickness should be considered. Using the criterion of 0.6 skin depths of Hohmann et al. (1978) with the substitution 2\( \pi \) for the inverse frequency, the critical thicknesses at 0.089 ms (channel 1) for resistivities of 3.3, 1, 0.2, 0.1, and 0.01 \( \Omega \) m are 13., 7.1, 3.2, 2.2, and 0.7 m, respectively. These correspond to conductance values of 3.9, 7.1, 15.9, 22.4, and 71 S. The critical thickness will increase as the time of measurement increases. Dyck (1981, p. 133) presented additional guidelines for observing the limits on plate thickness.

The conductance often reflects the economic rank of a conductor and is therefore important in the geometric interpretation because it governs the rate of decay of the induced currents, thereby governing the position of the secondary field in time. A migration of currents from the perimeter toward the interior of the plate occurs in order to maintain the decreasing primary field on the interior of the plate. In small plates of low conductance the currents diffuse very rapidly; in large plates of high conductance they diffuse very slowly. Figure 3 shows one model with four different conductance values (depth 50 m). The higher the conductance, the lower the initial amplitude and the slower the decay. This is also evident in the decay curves for the four cases at 100 m depth (Figure 4), which are from a point on the profile just off the peak. At late times for low conductances the responses have decayed away, but for high conductances the responses are quite strong.

**Early, intermediate, and late time.**—Comparing models with variable conductances and plate sizes requires the delineation of three relative time periods: early (ET), intermediate (IT), and late time (LT). The early time channels for a body of high...
conductance will be the LT channels for the same body with a low conductance. At ET the currents are near the perimeter of the body. At IT they have diffused inward but are not yet decaying exponentially. The dimensionless number $\theta$ was used to define an ET, IT, and LT for this investigation:

$$\theta = \mu_0 S a^2 / 4t,$$

(3)

where $\mu_0$ is the magnetic permeability of free space, $t$ is the time of the measurement, and $a$ is the shortest length dimension of the plate. Using the formula for $\theta$, the following ranges are defined:

- $\text{ET}: \theta \geq 10.0 - 11.0,$
- $\text{IT}: 9.5 \geq \theta \geq 5.0 - 5.5,$
- $\text{LT}: \theta \leq 2.0 - 2.3.$

(4) (5) (6)

These categories were chosen empirically by observing changes in, for example, the measurements of peak-to-peak distance. Each $\theta$ category is not necessarily represented in each model because the measurement times may not begin early enough or extend late enough.

FIG. 3. Variation in $dB_z/dt$ with conductance. Plate size: 800 x 400 m. Depth: 50 m. Strike, dip, plunge: 90, 90, 0 degrees.
Time constant and conductance estimation.—The estimated time constant \( t \) of a body is a function of its size, position with respect to the transmitting loop, conductance, and permeability. When logarithms of the channel amplitudes at a station are plotted versus their measurement times, LT responses lie on a straight line; \( t \) as used here is the inverse of the slope of this line. The conductance is estimated using \( t \) in the following equation (Svetov, 1960; Khomenyuk, 1963)

\[
S = \frac{\tau^2}{\mu_0 a}
\]  

(7)

where \( \tau \) is in seconds, \( a \) is in meters, and \( \mu_0 \) equals \( 4\pi \times 10^{-7} \) H/m. The time constant \( \tau \) can be reliably determined at LT in a free-space environment if the response can be measured at LT.

The \( \tau \) values were determined for all stations on the profiles of the \( z \) component by computing the slope of a line passing through the last two LT channels. To verify that these two channels were at late time, the slope of the line through them was compared with the slope through the previous channel and the latter of the two channels. If the percent difference between the slopes is 3 percent or less, then these three channels represent LT responses. The \( \tau \) value used was the inverse of the slope through the latter two channels. The cutoff of 3 percent was determined empirically by observing the slope differences for bodies of low conductance when it is known that the responses are at late time. To reduce the error introduced by geologic noise, the peak-to-peak residual amplitudes are sometimes used in the decay curves rather than the absolute amplitudes. This technique was not investigated here.

When \( \tau \) is obtained from decay curves at the peak and crossover (Figure 5a), significant (>10 percent) variations are occasionally observed. These results are peculiar because the time constant at late time should be the same everywhere along the profile. Table 2a lists the ranges of \( \tau \) for each plate size at each of the four values of conductance. All models with that plate size, regardless of dip or depth, were included in the calculation. The \( \tau \) values calculated from equation (7) are listed in Table 2b.

The models with dips of 90 degrees seemed to have the smallest range of \( \tau \) values, both across a profile and compared with other dips. However, histograms (not shown here) of models with dips of 30, 90, and 150 degrees often show only very small variations (<10 percent). Thus, a different formula does not seem warranted to estimate \( \tau \) for plates of shallow dip.

If both plate-length dimensions are important in a \( \tau \) or conductance estimate, we would expect to observe differences in their measured \( \tau \)s when their dimension of shortest length is the same but their dimension of longest length is not the same. For the 800 \( \times \) 200 m and 200 \( \times \) 400 m plates, the measured \( \tau \)s fall within identical numerical ranges except for a plate of 100 S conductance when their ranges differ by only 10 percent. In contrast, the measured \( \tau \) values for the 400 \( \times \) 400 m and the 800 \( \times \) 400 m plates differ by 12 to 25 percent. Thus, from these results conclusive remarks cannot be made concerning the effect of the dimension of greater length.
Modeling of Thin Plate for EM37

Table 2a. Range of 75 percent of the measured values of the time constant (in milliseconds).

<table>
<thead>
<tr>
<th>Plate size (m)</th>
<th>Conductance (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 x 400</td>
<td>100</td>
</tr>
<tr>
<td>800 x 200</td>
<td>100</td>
</tr>
<tr>
<td>800 x 100</td>
<td>100</td>
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<tr>
<td>400 x 400</td>
<td>100</td>
</tr>
<tr>
<td>200 x 400</td>
<td>100</td>
</tr>
</tbody>
</table>

Depth

An increase in the depth to the top of a plate produces a number of effects, including an overall decrease in amplitude and a broadening of the anomaly. The latter causes a reduction in the slopes of the curves, and changes in the positions of peaks and inflection points along the profile. Figure 6 shows the vertical component for a large plate at three depths—50, 100, and 200 m. The vertical scales are reduced at each depth by half of their value at the previous depth in order to accommodate amplitudes which decrease significantly with depth.

In Figure 7 the peak amplitudes of the z component are plotted for plates of 800 x 400 m at 50 to 300 m depth. ET and LT channels are represented. Two empirical observations are: (1) the decay of amplitude with depth is roughly exponential for all models regardless of the dip or time (curves A through F, Figure 7), and (2) for the models with a dip of 30 degrees, the positive (+), updip peak decays 10 to 30 percent faster than the negative (−), downdip peak from the same model (curves C through F, Figure 7).

Although the amplitudes of the unnormalized EM37 responses change considerably with depth, use of amplitudes in determination of depth has limitations, at least with this system. The amplitudes of the responses are directly related to the current amplitude, the turn-off time, the frequency of the transmitted waveform, the distance between the transmitting loop and the plate, and the time constant. The variations in amplitude due to these effects can be modeled because their values are known. However, current channeling and inductive coupling with a half-space also affect the amplitudes of the responses, particularly at early and intermediate time. The Geonics and University of Toronto PLATE programs are free-space modeling programs and, hence, cannot model either of these effects. While it seems quite possible that the amplitudes of the responses in free-space environments may be helpful in determining depth, other methods seem preferable.

Fortunately there are other methods which do yield good depth estimates. These methods rely on the distances between peaks, sides of lobes, and inflection points. Two quantitative methods of determining depth are considered in detail: (1)

Table 2b. Range of the estimated values of the time constant (in milliseconds) using 9.5 and 10.0 to approximate $\alpha^2$ in equation (7).

<table>
<thead>
<tr>
<th>Short plate dimension (m)</th>
<th>Conductance (s)</th>
</tr>
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<tbody>
<tr>
<td>Short plate dimension</td>
<td>400</td>
</tr>
<tr>
<td>800 x 400</td>
<td>100</td>
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<td>800 x 200</td>
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<tr>
<td>800 x 100</td>
<td>10</td>
</tr>
<tr>
<td>400 x 400</td>
<td>3</td>
</tr>
<tr>
<td>200 x 400</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 6. Variation in dBz/dt with depth. Plate size: 800 x 400 m. Conductance: 30 S. Strike, dip, plunge: 90, 90, 0 degrees.
relating the depth to the distance between peaks on a profile of
the \( z \) component, and (2) relating depth to the distance between
the two points which are equal to two-thirds of the amplitude
of the updip peak on a profile of the \( z \) component. These are
referred to as the peak-to-peak distance rule (PPD) and the
two-thirds width (2/3W) rule, respectively. The change in the
position of the inflection points was not studied, nor was the
measurement of the change in slopes. All of the above tech­
niques are hindered by variations of plate size and dip. None of
these techniques will provide a direct estimate of the depth, but
a nomogram made from the results of measuring many models
would provide an estimate of depth.

Peak-to-peak distance method

In the PPD method a depth estimate is made using the
horizontal distance between the two peaks on a \( z \) component
profile (Figure 5a). As depth increases, the PPD increases.
Unfortunately other factors, including the time of measure­
ment, dip, and plate dimensions, also affect the PPD. PPD
measurements were recorded for ET, IT, and LT for a range of
models at the seven channels 1, 4, 7, 10, 13, 16, and 19, using
PLATE data computed at 50 m intervals splined to 10 m
intervals.

Figures 8 and 9 are graphs for estimating depth from early­
time and late-time PPDs, respectively. They are composed of
data from a single plate \((800 \times 400 \text{ m})\), but an adjustment of the
PPD can be made for a change in plate size, as discussed later.

The PPD increases from early through late time because the
currents diffuse into the plate causing the apparent depth of the
plate to increase. Hence, to use the depth interpretation curve it
is important to know what is early and what is late time. The
downdip peak over the plate travels in the downdip direction,
as the currents move sideways, thereby increasing the PPD.
For a vertical plate both the updip and downdip peaks move
away from the crossover as the currents move vertically
through the plate. The effect of dip on PPD is greatest for small
dip angles and for deeper plates \((\geq 200 \text{ m})\). Early-time measure­
ments are not affected by dip except for deeper plates. Below
200 m or for PPD \( > 350 \text{ m} \) another depth interpretation
technique probably is advisable.

PPD increases from early time to the commencement of late
time by 40 m for a vertical plate but by 60 m for a shallow
dipping plate; this applies to plates at depths of 100 and 200 m.
At a depth of 50 m the increase is only 20 m for the vertical
plate for the same time interval. For most of the models the
PPD change during intermediate time is 10 m to 20 m.

For dips greater than 90 degrees the LT PPDs are the same
as those for the corresponding dips that are less than 90 de­

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Fig. 7. Peak amplitude decay as a function of depth. Plate size:
\( 800 \times 400 \text{ m} \). Strike, plunge: 90, 0 degrees. Plate is \( 300 \text{ m} \) from
the loop edge. Plus signs indicate the updip peak and minus
signs indicate the downdip peak for plates dipping 30 degrees.

Fig. 8. Peak-to-peak distance versus depth nomogram for early
time for an \( 800 \times 400 \text{ m} \) plate for different dips.
degrees; hence, the LT lines in Figure 9 can be used. At early time those plates that dip at large angles yield PPDs that are much larger than the PPDs for their complementary dips. The lower part of these plates governs the position of the downdip peak because the primary field is stronger through this portion of the plates due to the proximity of the transmitting loop. In the responses, the downdip peak climbs up the plate and the apparent depth decreases in time, reflecting the current movement from the top of the plate toward the center in the responses as seen with the smaller dip angles (<90 degrees).

Influence of plate size.—The plate size also influences the peak positions. Table 3 shows the change in PPDs with changes in depth extent at 90 and 30 degree dips and the percent decrease in PPD from those for the plate of 400 m depth extent at 100 m depth. At early time the reduction in depth extent causes greater reductions in the PPDs for the vertical plate.

At late time the reduction in depth extent results in slightly larger reductions in the PPD for the 30 degree dipping plate than for the vertical plate. Also, the shorter depth extent limits the amount of current migration and thereby limits the downdip peak movement. This leads to LT PPDs which are only slightly larger than the ET PPDs. Hence an LT PPD measurement from a plate of 100 m depth extent would give a depth estimate which is too shallow when an LT curve for a plate of 400 m depth extent is used.

Table 4 shows the changes in PPDs with changes in strike length for dips of 90 and 30 degrees and the percent decrease in PPD from the plate of 800 m strike length. The reduction in strike length generally appears not to affect the PPD dramatically. The shortest strike length shows the most variation in PPD, but the results here do not lend themselves to a general rule.

To adjust for a reduction in strike length or depth extent, the anticipated decrease in the PPD from the value for the 800 x 400 m plate is added to the PPD value for the smaller plate before the nomograms are used. The effect of changes in plate size on the PPD cannot be predicted at other depths, because plate size variations were modeled at only one depth (100 m); however, the effects are probably similar.

Two-thirds width rule

In the 2/3 W method, the width of the updip lobe where the amplitude is two-thirds of the lobe's peak value (see Figure 5a) is measured on a profile of the z component. The width of the downdip lobe is not used because dip and depth extent influence its width considerably. The 2/3 W depth nomogram is shown in Figure 10 for an 800 x 400 m plate model for dips of 90 degrees or less. Because the updip lobe is much less affected by current migration down the dip than is the downdip lobe, dip has less effect on the 2/3 W than on the PPD. As dip decreases from 90 degrees, the 2/3 W increases by about 5 percent for each 30 degree decrease in dip. Furthermore, for deeper plates the 2/3 W is much less affected by the time of measurement than the PPD. At depths equal to or greater than 200 m the range of 2/3 W values at late time is only 5 to 10 percent greater than the value at early time. The 2/3 W method appears to be a more reliable method for obtaining a depth

<p>| Table 3. Variation in peak-to-peak distance with depth extent. |
|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Dip</th>
<th>Peak-to-peak distance (m)</th>
<th>% decrease from 400 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>ET</td>
<td>200</td>
</tr>
<tr>
<td>90°</td>
<td>LT</td>
<td>220</td>
</tr>
</tbody>
</table>

<p>| Table 4. Variation in peak-to-peak distance with strike length. |
|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Dip</th>
<th>Peak-to-peak distance (m)</th>
<th>% decrease from 800 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>ET</td>
<td>200</td>
</tr>
<tr>
<td>90°</td>
<td>LT</td>
<td>220</td>
</tr>
</tbody>
</table>

FIG. 9. Peak-to-peak distance versus depth nomogram for late time for an 800 x 400 m plate for different dips.
estimate from shallow dipping plates when ET measurements are not available, except at shallow depths (~50 m). At shallow depths the range of 2/3 W values is quite large from early to late time. The 2/3 W method also appears to be a better method for obtaining a depth estimate from deeper plates.

Influence of plate size.—Reductions in the plate size produce decreases in the 2/3 W. For ET measurements each 50 percent reduction in strike length causes a 10 m decrease in the 2/3 W. At late time each 50 percent reduction in strike length causes a 15 m decrease in the 2/3 W. For reductions in depth extent, the ET 2/3 W measurements are reduced 15 m for each 50 percent reduction; the LT measurements barely increase (~10 m) from these ET measurements for these smaller plates.

Plate size, particularly depth extent, must be considered when using the 2/3 W rule for depth estimates. The PPD and 2/3 W techniques may provide convenient checks on each other.

Extinction angle

The extinction angle of a plate is the dip at which the plate and the primary field are oriented totally parallel to one another. The poor coupling which results causes the secondary field to decrease (Bosschart, 1964). The primary field orientation and contours of the field intensity in a vertical plane through the center line of a 300 × 600 m loop are shown in Figures 11a and 11b, respectively. The positions of the extinction angles are evident from studying the field orientation, particularly for a vertical plate directly beneath the transmitting loop. Obviously, the occurrence of extinction angles is related to the depth extent as well as to the dip. For plates with very small depth extents (~100 m) the likelihood of being oriented totally parallel to the primary field is higher.

A plate of 400 m depth extent is shown in ten dip positions in Figure 11 (McNeill, 1980b). It couples well with the primary field at least somewhere along its length in all of these positions. An extinction angle appears at the 150 degree dip position when the depth extent is reduced from 400 to 200 m or less on the plate shown. The smaller depth extents are indicated by tick marks in Figure 11a. For the same 150 degree plate the primary field is nearly parallel to the upper 200 m of the plate; large amplitude reductions result for these shorter plates, as displayed in Figure 12. Note that the vertical scales of the model with a 100 m depth extent have been changed from those of the 200 and 400 m models. Moreover, with a 30 degree dip the amplitudes for these same plates nearly double (Figure 13), despite the fact that the plates are in a primary field of lower intensity.

![Extinction angle diagram](image-url)
A sign change occurs in Figure 12 between the 200 and 100 m models, caused by the change in the orientation of the primary field. The orientation is downward across the length of the plate for the 100 m plate but is both upward and downward across the 200 and 400 m plates. The field intensity is much higher for that part of the field which is upward across these latter two plates, and hence this part of the field governs the signs of the responses.

When bodies of shallow depth extent are suspected, it is essential to use several positions of the transmitting loop in order to increase the likelihood of locating a plate-like body. Extinction angles should be an important consideration in the design of any field survey. Furthermore, the signs of an anomaly might be used to obtain some limits on depth extent when the field orientation is known to change over short distances in the region near the body. Extinction angles become less important as the conductivity of the host increases because current channeling will then ensure a response for all dips and depth extents (Ward et al., 1974), even for a poor inductive response.

**Fig. 12.** Positions of the extinction angle achieved by varying depth extent. Strike length: 800 m. Conductance: 30 S. Depth: 100 m. Strike, dip, plunge: 90, 150, 0 degrees.

**Fig. 13.** Variation in $dB/dt$ with depth extent. Strike length: 800 m. Conductance: 30 S. Depth: 100 m. Strike, dip, plunge: 90, 30, 0 degrees.
Dip

Dips of 0 to 165 degrees were modeled for the 800 x 400 m plate. Responses of vertical and horizontal plates are shown in Figure 14. As dip decreases from 90 degrees, the downdip peak increases in amplitude and the updip peak decreases in amplitude (Figure 15) on the profiles of the vertical component. On the horizontal component profiles the main peak increases slightly in amplitude. The peak that is downdip from the main peak also increases in amplitude (Figure 16), but it is always less than the main peak except for horizontal plates. As dip increases from 90 degrees, the same relationship is observed between the amplitude and the dip (Figures 17 and 18). To distinguish the direction of dip with respect to the transmitting loop, the absolute values of the two principal peaks of either the

![Diagram](image)

**Fig. 14.** Contrast between $dB_y/dt$ responses on the left, and $dB_x/dt$ responses on the right, for horizontal and vertical plates. Plate size: 800 x 400 m. Conductance: 30 S. Depth: 100 m. Strike, plunge: 90, 0 degrees.
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z or x component are used. The down-dip peak is largest for the z component and the up-dip peak is largest for the x component.

The signs of the peaks should not be used to determine the direction of dip with respect to the transmitting coil because the direction of the primary field and depth extent determines the signs, as discussed previously.

Some of the general characteristics of response curves from free-space models reflect the positions of the top and bottom of the plate. The vertical component crossover occurs over the top of the plate at late times. Use of crossovers to determine the top of a plate is limited where the background resistivity is low to moderate. An alternate technique uses the maximum gradient of the vertical component at early time to indicate the top of the plate; this correlates with the main peak of the horizontal component which occurs over the top of the plate in most cases.

Dip nomograms.—The ratio of the smallest peak to the largest peak, in the responses in the vertical component, was used to make dip-to-peak ratio nomograms, shown in Figure 19, for a plate size of 800 x 400 m. A 90 degree dip has a ratio equal to 1, but larger or smaller dips have ratios less than 1. Because the high-amplitude peak decays more slowly than the low-amplitude peak, LT ratios are slightly lower than ET ratios. The ratios decrease with depth for the same reason.

The dip nomogram for late time is effective for dips between 0 and 180 degrees. In most cases the dip nomogram for early time is effective for these same dips, but when the transmitting

**VERTICAL COMPONENT**

![Diagram showing variations in dB/dt with dip](image)

**FIG. 15. Variation in dB/dt with dip ≤ 60 degrees. Plate size: 800 x 400 m. Conductance: 30 S. Depth: 100 m. Strike, plunge: 90, 0 degrees.**
coil and the lower part of the plate are close together, peak ratios at early time are quite variable.

Influence of plate size.—The nomograms are made for the large plate (800 x 400 m) and must be adjusted for a change in plate size. For 90 degree dips, ratios of 1 result, as expected, for all plate sizes.

A reduction in strike length affects peak ratios considerably. At both early and late times (dip 30 degrees) a 50 percent reduction in the 800 m strike length to 400 m results in a 25 to 30 percent decrease in the peak ratios. Another 50 percent reduction in strike length (to 200 m) results in another 30 to 35 percent decrease at early time and another 20 percent decrease at late time. The smaller (200 m) plate has a smaller range of ET to LT peak ratios which accounts for the difference in the effect from early to late time. For the 150 degree dipping plate the effect of a strike length reduction is the same at late time as for the plate dipping at 30 degrees. At early and intermediate times the ratios are about the same as at late time, which suggests that the close proximity between the plate and the source causes anomalous behavior.

A reduction in depth extent does not affect the peak ratios at late time for the 30 degree plate model. At early time the ratios decrease by 8 to 10 percent for each 50 percent reduction. For the 150 degree dip model, at late time irregularities are ob-

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**FIG. 16.** Variation in $dB_t/dt$ with dip ≤ 60 degrees. Plate size: 800 x 400 m. Conductance: 30 S. Depth: 100 m. Strike, plunge: 90, 0 degrees.
served which are probably caused by nonuniformity in the orientation and intensity of the primary field across these three plates at 150 degrees. At early time the reductions in depth extent produce the same changes as are seen for the plate dipping at 30 degrees.

In general, depth extent does not seem to affect the peak ratios at late time; hence, it would be advantageous to use the LT nomogram for estimates of dip. Strike length affects the peak ratios at all times, but when strike length is determined in the field, adjustments can be made in the response ratios based on the change in strike length.

**Depth extent**

Depth extent is frequently the most elusive parameter to estimate. Yet a fairly good estimate of depth extent can be essential in obtaining an accurate conductance estimate and, hence, for determining which channels are at early, intermediate, and late time. Many of the effects observed as depth extent is reduced are also observed as the depth to the top of the plate is reduced. The secondary field is restricted to shallower depths in both cases, causing some similar phenomena.

The reduction in the overall width of the anomaly reflects the

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**FIG. 17.** Variation in $dB_z/dt$ with dip $\geq 120$ degrees. Plate size: 800 x 400 m. Conductance: 30 S. Depth: 100 m. Strike, plunge: 90, 0 degrees.
reduction in the plate size. For the same conductance, the reduction in depth extent from 400 m to 200 m and 100 m increases the rate of the response decay, as indicated in Figure 13. As predicted by equation (7), the time constant is reduced by 50 percent for each of these changes in depth extent. In contrast, a depth increase does not affect the rate of decay, although the amplitude is reduced.

A plate dipping at a shallow angle produces more clues to the depth extent in the responses of the vertical component than a steeply dipping plate, because for shallow dip angles the bottom of the plate is not hidden by the response of the upper part of the plate and it is closer to the surface. For a horizontal plate the crossovers at late time mark the edges of the plate, and depth extent is easily determined. As dip increases, the downdip crossover moves out beyond the end of the plate. The rate at which the downdip tail, defined in Figure 5a, returns to the baseline is a very diagnostic feature of depth extent. As depth extent is reduced, the tail returns to zero much faster, as shown by the early channels in Figure 13, but this is not characteristic of vertical plate responses.

In Figure 20 the responses of the horizontal component for a vertical plate are shown for the three depth extents: 400, 200, and 100 m. The main effect of varying the depth extent on these vertical-plate responses is to change the rate of decay. The other effects are quite subtle for both the horizontal (Figure 20) and the vertical (not shown) components of a vertical plate.

**FIG. 18.** Variation in $dB_v/dt$ with dip $\geq 120$ degrees. Plate size: 800 x 400 m. Conductance: 30 S. Depth: 100 m. Strike, plunge: 90, 0 degrees.
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early-time peak ratios

depth (m)

300
200
100
50

1,0 80 70 60 50 40 30

90° 75° 60° 45° 30° 15° 0°

late-time peak ratios

depth (m)

300
200
100
50

1,0 80 70 60 50 40 30

90° 75° 60° 45° 30° 15° 0°

May not be reliable.
See text

Fig. 19. Nomogram of peak ratio as a function of dip and depth for an 800 × 400 m plate.

HORIZONTAL COMPONENT

\( W = 400 \text{m} \)

\( 200 \text{m} \)

\( 100 \text{m} \)

Fig. 20. Variation in \( dB_z/dt \) with depth extent. Strike length: 800 m. Conductance: 30 S. Depth: 100 m. Strike, dip, plunge: 90, 90, 0 degrees.
The migration of the downdip peak on a profile of the $z$ component frequently records the movement of current up or down the depth extent of the plate. For plates with a small depth extent, the downdip peak moves very little or not at all from early to late time, as discussed previously. The amount of movement in time of the downdip peak may suggest some limits on the depth extent. However, similar effects may result from finite thickness and conductor inhomogeneity.

Depth extent is not difficult to obtain for a plate dipping $\leq 30$ degrees using the downdip tail and crossovers and the inflection points. For a steeply dipping plate, trial-and-error curve matching with a modeling program may be the best way to estimate depth extent. The increase in the rate of decay may also provide a hint of the depth extent. In any case, it may be the most difficult plate parameter to obtain and will influence the estimates of the other parameters.

**Strike length**

The effects of a reduction in strike length are presented in Figure 21 for a plate dipping at 30 degrees with a strike length of 800, 400, and 200 m. The shapes of the response curves are strikingly similar for the three models. The decrease in strike length is reflected mainly in the decrease in amplitudes and for the plate of 200 m strike length it is reflected in the decay rate. The amplitude reductions between the 800 m and the 400 m plates in Figure 21 are due almost entirely to the reductions in the plate size, not to an increase in the decay rate. However, as predicted by equation (7), the decay rate increases when the strike length is reduced to 200 m, and therefore becomes less than the depth extent.

Strike length should be estimated by comparing profiles for different field profile lines in order to obtain better estimates of the other parameters, in particular depth extent, conductance, and dip. Strike length does not affect the shapes of the response curves enough to distinguish a short strike length from a long one. Amplitude will decrease and the decay rate may increase as strike length is reduced, but neither of these is likely to provide an estimate of strike length. Amplitude is affected by too many other factors and the decay rate may be governed by the depth extent.

**Vector plots**

In a vector plot the normal to the resultant of the $x$ and $z$ components is plotted at each station. Vector plots are often used to locate the position of a conductor. Vector plots for a 90 degree and a 30 degree dipping plate, at a range of measurement times, did not provide additional information regarding the location of the plate. In the plots the intersection points of the normals do not converge to a focal point at late time.

In contrast to these results, Adhidjaja et al. (1983) drew vector plots for a two-dimensional (2-D) body in a half-space of varying conductivity. At late time the vectors intersect at a focal point along the body and well below the top of it for plates dipping at 90 degrees and 45 degrees. For a 2-D plate the currents at late time are represented as line sources; hence, at late time the normals are directed toward a common source point and vector plots provide a location of this focal point. For the three-dimensional (3-D) plate at late time the currents are represented as a large, simple loop which covers the plate, i.e., they are similar to a dipole source. For the 3-D plate the vector plots fail to provide information on the depth or location of the plate. Vector plots could be useful in discriminating between a 2-D and a 3-D plate, or possibly, in indicating when current channeling, which can be approximated by a line-current source (2-D), is represented in the responses.

**CONCLUSIONS**

One common target for the EM37 system is the thin, plate-like conductor of this investigation. The character of the re-

![FIG. 21. Variation in $dB_z/dt$ with strike length. Depth extent: 400 m. Conductance: 30 S. Depth: 100 m. Strike, dip, plunge: 90, 30, 0 degrees.](image)
response curves for the thin plate provides a means to estimate the geometry and the conductance of the plate. This investigation was limited to one loop size (300 × 600 m) and to one plate position with respect to the transmitting loop (300 m); hence effects of loop size and position on the response curves cannot be predicted with confidence.

From the z component responses depth can be estimated from the distance between peaks or from the two-thirds width of the updip lobe. A dip estimate can be obtained by measuring the ratios of the two peaks of the z component. None of these techniques provides direct estimates without the use of nomograms. These interpretation methods rely on measurements which are heavily influenced by the plate size. The plate size used most extensively in this study (800 × 400 m) is between a half-plane and a small plate (e.g., 100 × 200 m). An adjustment for changes in plate sizes is an essential part of the interpretation as is consideration of the time of measurement (ET, IT, or LT).

Depth extent is difficult to estimate for vertical plates because it does not exert a strong influence on any part of the response curve. For shallow dip angles (30 degrees or less) it has a major influence on the rate of return of the downdip tail to the baseline. For vertical plates depth extent can be obtained through curve matching with a plate-modeling program. If depth extent is the shortest dimension, then the estimated time constant and decay rate can provide clues to the depth extent if some independent estimate of conductance is available. Strike length should be determined in the field by measuring the necessary profiles. Use of a plate-modeling program is recommended after obtaining initial estimates of the parameters of the plate.

Conductance can be estimated using equation (7), given an estimate of the time constant and the plate dimensions. The shortest dimension of the plate appears to control the value of the estimated time constant, but a fairly good estimate of this dimension is necessary to obtain accurate conductance estimates. Dip does not have a significant effect on a time-constant estimate.

The positions of the extinction angles should be considered in an exploration program, particularly for plates with small depth extents. Although the position of the plate does not appear to influence application of the interpretation techniques in most cases, a close proximity between the transmitting loop and the plate can result in responses which cannot be used reliably for estimating plate geometry. In regions close to the transmitting loop the primary field can change dramatically in intensity and in direction across the length of the plate.

Vector plots can be used to suggest if a plate is two-dimensional or three-dimensional because at late time the vectors intersect at a common source point for the 2-D plate but not for a 3-D plate.

Although the plate is modeled in free space, the results may be used for obtaining estimates of parameters from plates in less resistive hosts, or with less resistive overburden, if superposition applies.

ACKNOWLEDGMENTS

Financial support for this work was provided by the following companies: Amoco Production Co., ARCO Oil and Gas Co., Chevron Resources Co., Conoco, Inc., C.R.A. Exploration Pty. Ltd., Sohio Petroleum Co., Union Oil Co., and Utah International, Inc. We are grateful to R. J. Smith, Associate Editor, and his anonymous reviewers for many helpful suggestions on improving this manuscript. Sandra Bromley and her staff provided excellent illustrations support. Special thanks are extended to J. D. McNeill and the technical staff of Geonics Ltd for providing detailed information on the EM37 system.

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