The Deep Transient Electromagnetic Sounding Technique: First Field Test in Australia

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Abstract
A test survey was carried out in the Sydney Basin using a wire source, loop receiver, deep transient electromagnetic sounding system. A field system was designed and built, the data acquisition system automated to simplify field operation, and current US processing software adapted to the hardware. A test survey was conducted in the Sydney Basin over horizontally layered strata with resistivity contrasts. Three hundred transients were recorded at eight stations within two days. After processing and interpretation, the geoelectric models obtained from the inversions qualitatively correlate with the basin geology, to a depth of 2 km. These measurements suggest that the deep transient electromagnetic sounding method could be successfully used for deep mineral and oil and gas exploration problems in Australia.

Introduction
The transient electromagnetic method (TEM) which uses a loop transmitter is an established geophysical exploration tool in the minerals industry. The Australian minerals industry has been in the forefront of the application of TEM to their exploration problems (Buselli 1960; Spies 1980). A test survey in the Sydney Basin, with a newly developed field system, demonstrates that TEM can be extended to deeper (1-2 km) geophysical exploration in Australia for both hydrocarbons and minerals.

The deep transient electromagnetic sounding technique has been successfully applied in the USSR during the past 20 years (Kaufman & Keller 1983). This technique uses a wire-loop configuration and was first applied in the USA by G. V. Keller over a decade ago. His research groups at the Colorado School of Mines and Group Seven Inc. improved the technique to the point where it is now commercially available. Recent advances include system design improvements, new data processing techniques and interactive inversions.

The wire-loop configuration consists of a grounded wire transmitter and an induction loop receiver. The transmitter is kept fixed and the receiver is moved about the survey area. At each station, the earth response is recorded. Figure 1 shows a schematic of the survey configuration. A square-wave current is injected into the ground through the transmitter wire which is approximately 1 km in length. This current step induces eddy currents into the earth which diffuse downwards with increasing time. These eddy currents generate a secondary field transient which is measured at the earth's surface. The offset between source and receiver can vary from a few kilometres to a few tens of kilometres. In the USA, offsets of up to 100 km have been used successfully.

FIGURE 1
Deep transient electromagnetic field system configuration with a grounded wire source and wire loop receiver.

Theory
The theoretical development of a wire-loop transient electromagnetic sounding system is in the literature (Kaufman & Keller 1983; Stoyer 1977; Wait 1951, 1970), and a summary of the theory is given by Kauahikaua and Anderson (1977). Only a review of some key theoretical points used in the interpretation of the data is considered here.

For a plane layered-earth model, the one-dimensional frequency domain solution of Maxwell's equations can be expressed in terms of an inverse Hankel transform:

$$H_2(\omega) = \frac{-iL}{4\pi} \frac{\partial}{\partial y} \int_0^\infty \frac{g}{\sqrt{N_0 + N_1/r}} J_0(qr) \, dq$$

(1)

In this expression, $H_2$ is the received vertical magnetic field, $l$ is the source current [A], $L$ is the source length [m], $J_0$ is the Bessel function, $N_0$, $N_1$, and $R_1$ are coefficients determined from the parameters of the layered medium, $y$ is the station coordinate perpendicular to the dipole centre, and $r$ is the transmitter-receiver separation. The time-domain solution can
be calculated via a Fourier transformation of eqn (1) (Kauahikau & Anderson 1977). For a homogeneous earth, the voltage induced in a receiver loop of area $A$ reduces to

$$V(t) = \frac{3\rho M_0 Ay}{2\pi r^5} \left[ \text{erf} \left( \frac{u}{\sqrt{2}} \right) - \frac{\sqrt{\pi}}{2} u \left( 1 + \frac{u^2}{3} \right) e^{-u^2/2} \right]$$

where

$$u = \frac{2\pi r}{\tau} \quad \text{and} \quad \tau^2 = \frac{8\pi^2 \rho t}{\mu_0},$$

$\mu_0$ = magnetic permeability,

$\epsilon_0$ = resistivity of the half-space,

$M_0 = IL$ = transmitter dipole moment,

$A$ = receiver area.

The early time limit ($t \to 0$) of eqn (2) is derived by taking the limit as $r$ approaches zero and thus, as $u$ approaches infinity. It follows that

$$\lim_{t \to 0} V(t) = \frac{3\rho M_0 Ay}{2\pi r^5}$$

Equation (2) can also be expressed in the frequency domain. The high frequency limit of this expression, when measurements are done in the far zone ($\sqrt{\frac{\mu_0}{\epsilon_0}} r \gg 1$), is equal to the early time limit in eqn (3) (Kaufman 1978).

The late time limit ($t \to \infty$) of eqn (2) is similarly derived, where

$$\lim_{t \to \infty} V(t) = \frac{M_0 Ay}{40\pi\sqrt{\pi}} \frac{\mu_0^{5/2} \sigma^{3/2}}{\tau^{5/2}}$$

The late time limit in eqn (4) is not equal to the low frequency limit of the frequency domain expression (Kaufman 1978). The leading term of the quadrature component in the frequency domain expression is proportional to $\omega^2$ whereas the late time-domain expression is proportional to $\sigma^{3/2}/\epsilon_0^{5/2}$ (where $\sigma$, the conductivity, is $1/\epsilon_0$) (Bond et al. 1981; Kaufman & Keller 1983).

The early-time apparent resistivity, $\rho_a^{ET}$, is

$$\rho_a^{ET} = \frac{V(t)_{meas}}{V(t)_{meas}^{ET}}$$

where $V(t)_{meas}$ is the measured transient voltage and $V(t)_{meas}^{ET}$ is the early-time limit for a uniform half-space of resistivity $\rho$. From eqn (5),

$$\rho_a^{ET} = \frac{2\pi r^5}{3M_0 Ay} \frac{V(t)_{meas}}{V(t)_{meas}} = C_A V(t)_{meas}$$

where $C_A = 2\pi r^5/3M_0 Ay$.

Note that the array coefficient, $C_A$, does not depend upon either $\rho$ or time.

The late-time apparent resistivity, $\rho_a^{LT}$, is

$$\rho_a^{LT} = \left( \frac{V(t)_{meas}^{LT}}{V(t)_{meas}} \right)^{2/3}$$

where $V(t)_{meas}^{LT}$ is the late-time limit for a uniform half-space with the resistivity $\rho$. From eqn (7),

$$\rho_a^{LT} = \left( \frac{M_0 Ay}{40\pi\sqrt{\pi}} \right)^{2/3} \left( \frac{\mu_0}{\epsilon_0} \right)^{5/3} \left( \frac{1}{V(t)_{meas}} \right)^{2/3}$$

**Field system**

During 1983, a deep transient electromagnetic sounding field system was designed and built at Macquarie University. A block diagram of the complete system is given in Fig. 2. The transmitter consists of a 25 kW generator, portable switch-box, crystal synchronization clock, a 1 km source wire and corrugated iron electrode plates. The vehicle-borne receiver consists of an induction coil, preamplifier, amplifier and digital data acquisition unit.

The key function of the transmitter is to switch the AC supply between two complementary full-wave rectifier bridges. The resulting current waveform, during the on-time, does contain a 150 Hz AC ripple; however, this ripple generates very little noise due to its small change in current with respect to time. The turn-off of the first rectifier bridge and the turn-on of the

![FIGURE 2](image_url)

Block diagrams of transmitter and receiver units with their respective waveforms.
second rectifier bridge each require a maximum time of one-half AC cycle or 10 ms. So in total the maximum switching time is 20 ms. The transmitter components are rated to a safe 400 A peak-to-peak current operation. During the Sydney Basin field test, a maximum source current of 45 A peak-to-peak was injected into the ground via a 1200 m long wire, with the electrodes implanted in two creeks.

The analog part of the receiver is designed for time-domain signals only. All printed circuit boards in the amplifier units are shielded on both sides to reduce internal noise. The filters are buffered by operational amplifiers to compensate for attenuation, and consist of passive components.

It is important to note that the total system response to a step function input cannot be neglected (Strack et al. 1982). The choice of filter components, active or passive, affects the total system response and thus the deconvolution of the data. An active filter is narrow in frequency and after Fourier transforming, broad in time. If such a filter is used, deconvolution is undesirable in the time domain. The alternative is to use passive components which exhibit a narrow signal in time after Fourier transforming. For accurate deconvolution of the data, a narrow time domain system response is required. Thus passive components were used in the filters.

The digital part of the receiver system is based on Digital Equipment Corporation’s LSI 11 minicomputer, and was built using off-the-shelf components. A description of the basic data acquisition system is in Strack (1981) and Ibrahim (1982).

The operation of the field system requires a minimum crew of three: two people stationed at the receiver, and one at the transmitter. The equipment is straightforward to operate. After the transmitter is set up, the number of receiver locations per day can range from 10 to 17.

Data acquisition and processing
Voltage transients are recorded at the receiver location(s) (Fig. 3). The field operator can control the quality of the data by observing the signal in real-time and rejecting it if necessary. After an analog-to-digital conversion, the raw transients are stacked and stored on floppy disks. A standard average stack is displayed on the computer for every eight transients. Once all data have been acquired, an automated selective stacking process is initiated. The operator then uses this time to pick up the receiver loop and preamplifier.

The selective stacking algorithm (Stoyer 1982) proceeds as follows for $N$ transients sampled in time for $i = 1, 2, 3, \ldots, 1024$:

Step 1
The amplitude of the $i$th sample of all $N$ transients is read from mass storage. These $N$ points are arranged in increasing order by amplitude, where $A_{\text{max}}$ is the maximum and $A_{\text{min}}$ is the minimum amplitude value.

Step 2
A percentage (e.g. 17.5%) of $(A_{\text{max}} - A_{\text{min}})$ is determined. A new amplitude range is calculated where new $A_{\text{max}} = \text{old } A_{\text{max}} - \text{percentage}$, and new $A_{\text{min}} = \text{old } A_{\text{min}} + \text{percentage}$. Those amplitudes lying outside the new $A_{\text{max}}$ and new $A_{\text{min}}$ are discarded as they represent noise.

FIGURE 3
Data acquisition flow chart.

An average and its standard deviation are computed from the remaining points.

Step 3
Each amplitude value is inspected to see whether or not it lies within the standard deviation of the average from Step 2. Outside values are rejected and from the remaining points, a new average and its standard deviation are calculated and stored for the stacked output.

Figure 4a is a transient stack output from standard stack processing. Figure 4b is the result of applying selective stacking to the same data. The selectively stacked transient is virtually free of the spiky cultural noise appearing in the standard transient stack. Selective stacking can improve the signal-to-noise ratio by a decade or more.

The selectively stacked transients are deconvolved and filtered. The apparent resistivities are computed, a calibration factor applied and the data inverted (Fig. 5). For the time-domain iterative deconvolution, a filter is derived from the recording system response and applied to the data. The algorithm is very similar to the one proposed by LaCoste (1982) and loup and loup (1983). The advantages of using this algorithm over a FFT-type deconvolution for deep transient electromagnetic sounding data are that it is highly stable and it reduces high frequency noise. The deconvolved transients are filtered using time varying, recursive digital filters (Shanks 1967; Mooney 1968). The smoothed voltage transients are then converted to apparent resistivities using
FIGURE 4a
Transient stack output from standard average stack processing for 20 stacks (after Walker et al. 1981).

FIGURE 4b
Transient stack output from selective stack processing using the same data as in Fig. 4a (after Walker et al. 1981).

eqns (6) and (8) for the early and late time limits, respectively. A calibration factor is applied which will compensate for the magnetometric resistivity effect generated from the grounded wire transmitter (Edwards et al. 1978), inaccuracies in the source current measurements, dipole length, receiver area and gain. This factor compensates for the above because the integral of the early-time apparent resistivity depends only on the radial distance between source and receiver (Ibrahim 1982). The apparent resistivities are input to a generalized inversion program developed by C. H. Stoyer in 1979. From theory, the inversion applies to horizontally layered media. Thus the inversion output is valid where lateral changes in electrical parameters are gradual and is a representation elsewhere. The inversion output generates a geoelectric cross-section which can be interpreted and correlated with other data.

Sydney Basin field test
In October 1983, a test survey was conducted in the Sydney Basin. The field test area is located 8 km south of Richmond, NSW (Figs 6a and 6b). A general north-south cross-section of the Sydney Basin for Triassic and Permian formations is shown in Fig. 7. An arrow marks the approximate location of the survey area. At this location, the strata are horizontally layered (conformably) to a depth of about 3000 m, and have expected resistivity contrasts due to the lithology. The depth to the basement is not known.

FIGURE 6a
Geographic location of the survey area in the Sydney Basin (after Mayne et al. 1974).
Deep transient electromagnetic sounding

FIGURE 6b
Transmitter site and receiver locations (stations 1-8) for the test survey.

FIGURE 7
General geological north-south cross-section of the Sydney Basin (after Mayne et al. 1974). The arrow marks the approximate location of the survey.
FIGURE 8
Selectively stacked transients for stations 1-8.

Approximately 300 transients were recorded at eight stations in two days. Figure 8 shows the selectively stacked transients for each station. Transients 1-3 are of good quality. Transient 4 contains a DC step because the preamplifier’s 50 Hz notch filter was not switched on. Transients 5-8 have a ‘bump’ at 2.5 s caused by the current waveform.

The data were processed through selective stacking, deconvolution, filtering, apparent resistivity calculations, applied calibration factor and inversion. The data processing was in general straightforward and follows from the above discussion. A percentage of 17.5 was used in the selective stack to remove noise outbursts. A calibration factor of 1 ± 4% was applied to the transients from stations 1-6, indicating that all system parameters were well determined. A calibration factor was not applied to stations 7 and 8 because the data is influenced by the strong ‘bump’ at 2.5 s.

Interpretation
The apparent resistivities were inverted using an interactive inversion process as described in Fig. 9. The inversions were carried out only through the first stage because the data represent a preliminary field test rather than a complete survey. With first stage inversions, none of the inversion parameters are fixed or biased.

A three-layer generalized input model was derived from the known geology of the basin, with a fourth layer half-space included for stability in the inversion routine (Fig. 10). Resistivity values were estimated for the rock types and their compositions.

The first layer in the model consists of a sequence of sandstone, shale, conglomerate and tuff, with an average resistivity of 20 Ω m. The second-layer consists of a sequence of sandstone, shale, conglomerate, tuff, carbonaceous shale and coal. In Fig. 11, the early-time apparent resistivity curves from the data (shown by the squares) have a distinct feature between 0.05 and 0.07 s. This suggests a strong resistivity contrast between a layer and its adjacent layers above and below. An initial guess of 2.0 Ω m for the resistivity of the second layer gives a contrast of

\[
\rho_1 = 25 \Omega m
\]
\[
\rho_2 = 2 \Omega m
\]
\[
\rho_3 = 50 \Omega m
\]
\[
\rho_4 = 1 \Omega m
\]

FIGURE 10
Generalized inversion starting model. A resistivity value for the fourth layer half-space was required for stability in the inversions.

Earth model

<table>
<thead>
<tr>
<th>Layer</th>
<th>Resistivity (Ω m)</th>
<th>Depth (m)</th>
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</thead>
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<tr>
<td>1</td>
<td>35.7</td>
<td>998</td>
</tr>
<tr>
<td>2</td>
<td>1.7</td>
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<tr>
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<td>964</td>
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<tr>
<td>4</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 9
Inversion flow chart.

FIGURE 11
Inversion data (squares) and synthetic curve for the final model (solid line) for station 1.
10.1 between the first and second layer resistivities. The conductivity of this layer could be geoelectrically attributed to high percentages of carbonaceous shale and/or coal within the sequence. The third layer in the model is resistive (50.0 \( \Omega \ m \)) to produce the strong contrast between layers as suggested by the data. It is similar in composition to the second layer minus the carbonaceous shale and coal.

Example apparent resistivity curves and their inversion output models for stations 1 and 5 are given in Figs 11 and 12, respectively. Figure 13 shows the inversion output models from stations 1, 2, 6 and 8. Three distinct geoelectric layers are evident from the sounding data. The first layer is 900-1300 m thick with a resistivity of 20-50 \( \Omega \ m \). Both parameters are well resolved by the inversion. In order to converge, the inversion required an intermediate conductive layer ranging in thickness from 100 to 350 m. Its geoelectric parameters are not well resolved. However, the resistivity-thickness products for all stations except 4 and 7 lie between 150 and 300 \( \Omega \ m^2 \). This range and similarity of product values explain why the inversion required a second layer. The third layer has a resistivity of 50 \( \Omega \ m \) and greater. Only its thickness, from 1000 to 1200 m, is well resolved. A possible fourth layer exists which has a low resistivity of about 1.0 \( \Omega \ m \). However, its geoelectric parameters cannot be well resolved because in the data, the signal disappears into the noise level in late times.

The first stage inversion results are interpreted and correlated within the basin geology in Fig. 14. The interpreted electromagnetic (EM) model is an average of all stations except station 7, with standard deviations computed for resistivities and depths. The interpreted geological section is based on geological and geophysical data from the Bureau of Mineral Resources Bulletin 149 (Maine et al. 1974).
The first layer is an approximately 1000 m thick sedimentary unit interpreted as the Triassic Hawkesbury Sandstone and marine sandstone/shale sequences of the Narrabeen Group. The average resistivity of this unit is 32 ± 10 Ω m. In Fig. 14, the average resistivity has been extended back to mean sea level to include the effective resistivity of those shallow layers whose geoelectrical boundaries the deep transient electromagnetic sounding method cannot resolve. The geoelectric boundary between the first and second layers occurs at 990 ± 150 m. This is correlated to the seismic pick at the base of the Narrabeen Group at 850 m depth.

The second layer is a 200 m thick unit of conductive sedimentary sequences interpreted as late Permian Illawarra Coal Measures. The inversion output models give an average value of 1.6 Ω m which is lower then the initial 2.0 Ω m guess. This could indicate a higher percentage of carbonaceous shale than coal within the sequence; however, because of the standard deviation of the average, the low resistivity is interpreted as a combination of both carbonaceous shale and coal.

In the Sydney Basin, the Central Area late Permian Illawarra Coal Measures are equivalent to the Northern Area Newcastle and upper Tomago Coal Measures (Mayne et al. 1974). At the survey location, the Newcastle Coal Measures (minus the Waratah Sandstone) and correlatives are approximately 300 m thick. The inferred base of the late Permian Illawarra Coal Measures at 1150 m in the interpreted geological section is thought to correlate with the geoelectrical base of the conductive second layer at a depth of 1190 ± 160 m.

The third layer is a 1200 m thick unit of resistive (53.0 ± 3. Ω m) marine sequences interpreted as that part of the Permian Shoalhaven Group overlain by the Illawarra Coal Measures. The average geoelectric boundary at 2430 m depth is thought to correlate to the seismic pick at the top of the Greta Coal Measures and correlative Snapper Point Formation at 2260 m.

The fourth layer is questionable. The average resistivity from the inversion output (2.5 Ω m) is slightly greater than the initial 2.0 Ω m guess. This layer could be interpreted as the onset of the Greta Coal Measures which tend to be very sandy at the survey location, thus resulting in slightly higher resistivities. However, because of the lack of signal in late times, the geoelectric parameters of this fourth layer cannot be well resolved and interpreted.

Basement is not resolved in the inversion because the signal disappears in the noise level at late times. From the aeromagnetic interpretation, basement appears to be at a depth of about 3350 m (Mayne et al. 1974). More work and deeper soundings would be needed to define both the layer boundary at 2500 m and basement.

The A.O.G. Berkshire Park No. 1 well (Australian Oil and Gas Corporation 1968) is located about 12 km south-east of the survey area (Fig. 6a). The well was logged to a depth of 1090 m. The 16° induction log gives an average resistivity of 40 Ω m for the interval from 120 to 1090 m. This approximately correlates with the average values obtained from the sounding data for an interval from mean sea level to 990 m depth. The well geology for this interval is the Triassic Hawkesbury Sandstone and the sandstone, shale and siltstone sequences of the Narrabeen Group.

From the well log, the base of the Narrabeen Group is at 945 m depth, which is slightly deeper than the seismic pick at the survey location. The Caley Formation then rests on the Upper Coal Measures from about 945 to 1050 m. The appearance of coal in a predominantly shaly section from 1050 m to the end of the log is interpreted as part of the late Permian Illawarra Coal Measures. With a complex coastal environment and extensive coal swamps during the late Permian (Mayne et al. 1974), the well log is located too far away from the survey area for an accurate correlation with the sounding data.

Conclusions

The test survey in the Sydney Basin demonstrates that the deep transient electromagnetic sounding method can be successfully used for geophysical exploration in an Australian geologic setting. The data, after processing and interpretation, correlate with the known geology of the basin to a depth of 2 km.

The deep transient electromagnetic sounding field system is unique, vehicle-borne and simple to operate. On a production level, 10 or more stations per day could be acquired. Improved data processing and inversion techniques recover information necessary to exploration. With a safe 400 A peak-to-peak operating source current, the newly developed system is well-suited to exploration in sedimentary environments, and to depths of 1-4 km.

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