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ON THE PHYSICS OF GALVANIC SOURCE ELECTROMAGNETIC GEOPHYSICAL METHODS FOR TERRESTRIAL AND MARINE EXPLORATION

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ABSTRACT

A numerical study was conducted to investigate the governing physics of galvanic source electromagnetic (EM) methods for terrestrial and marine exploration scenarios.

The terrestrial exploration scenario involves the grounded electric dipole source EM (GESTEM) method and the examination of how the GESTEM method can resolve a thin resistive layer representing underground gas and/or hydrocarbon storage. Numerical modeling studies demonstrate that the loop transient EM (TEM) and magnetotelluric (MT) methods are insensitive to a thin horizontal resistor at depth because they utilize horizontal currents. In contrast to these standard EM methods, the GESTEM method generates both vertical and horizontal transient currents. The vertical transient current interacts with a thin horizontal resistor and causes charge buildup on its surface. These charges produce a measurable perturbation in the surface electric field at early time. The degree of perturbation depends on source waveform. When the GESTEM method is energized with step-off waveform, the perturbation due to a thin horizontal resistor is small. This is because the step-off waveform mainly consists of low frequency signals. An alternative is taking the time-derivative of the step-off responses to approximate the impulse response which includes higher frequency signals. In order to improve degree of perturbation especially due to a localized small 3-D resistor, the diffusion angle of the vertical transient current, 45º should be considered to make vertical currents coupled to a resistive target efficiently. The major drawback of the GESTEM method lies in the fact that GESTEM
sounding can not be interpreted using 1-D inversion schemes if there is near-surface inhomogeneity.

The marine exploration scenario investigates the physics of marine frequency-domain controlled source EM (FDCSEM) and time-domain controlled source EM (TDCSEM) methods to explore resistive hydrocarbon reservoirs in marine environments. Unlike the marine MT (MMT) method, these two methods are very sensitive to a thin hydrocarbon reservoir at depth because their sources generate vertical as well as horizontal currents. As for the FDCSEM method, the normalized EM peak response occurs where the airwave starts to dominate the seafloor EM response in the background model. This point is a function of source frequency, seawater depth and seafloor resistivity. The peak magnitude of the normalized EM response depends on whether the high concentration of vertical currents can reach and interact with the reservoir effectively. Noise levels of the EM receivers are important factors for successful FDCSEM and TDCSEM survey design. The major benefit of using magnetic field responses over electric ones is that the noise level of magnetic receiver theoretically allows for greater surface coverage compared to that of the electric receiver. Like the GESTEM method, the TDCSEM method also requires the use of a proper transient EM pulse such that the relatively high frequencies are produced. The impulse response of the TDCSEM method is characterized by two-path diffusion of the EM signal. The initial response is caused by faster signal diffusion through the less conductive seafloor, while the later arrivals result from slower diffusion through the more conductive seawater. Therefore, at larger separations, the effects of the seafloor and
seawater are separable. This can be useful in reducing the airwave problem associated with the FDCSEM method in shallow marine environments.
1. INTRODUCTION

Conventional inductive electromagnetic (EM) methods have been widely used in hydrogeological investigations because of their ability to detect electrically conductive targets, but it is well known that they are insensitive to electrically resistive thin layers (Hordt et al., 2000). As EM imaging of resistive targets is aligned with many important geophysical applications (e.g. hazardous waste site characterization, petroleum exploration, underground gas storage monitoring), a new EM acquisition strategy and interpretation scheme should be developed to delineate resistive targets successfully.

The work presented here has investigated the physics of time-domain and frequency-domain EM methods with galvanic sources, and compared them to conventional standard inductive EM methods through numerical modeling examples for terrestrial and marine applications. This allows us to determine the benefits of galvanic source EM methods over the conventional inductive source EM methods.

Chapter 2 provides a literature review of EM geophysical methods employed in the study. Terrestrial EM geophysical methods are somewhat different from marine EM methods in scope, and therefore were treated separately in the two subsections in Chapter 2. Chapter 3 describes an overview of the time-domain and frequency-domain finite difference algorithms employed in this study.

The physics of a grounded electric dipole source, as employed for transient EM geophysical methods (GESTEM) on land is explored in chapter 4. This method’s sensing
ability is compared to the other two standard terrestrial EM methods (the magnetotelluric and loop transient EM methods).

Chapter 5 includes numerical modeling analysis of marine frequency-domain and time-domain EM methods to understand how sensitive galvanic sources are to a thin resistive hydrocarbon reservoir in a marine environment. Numerical modeling results for the marine magnetotelluric method are also considered here for comparison.
2. ELECTROMAGNETIC GEOPHYSICAL METHODS

2.1 TERRESTRIAL ELECTROMAGNETIC GEOPHYSICAL METHODS

2.1.1 INTRODUCTION

EM geophysical imaging methods are commonly employed as near surface characterization tools for hydrogeological and environmental problems due to their sensitivity to the amount and quality of the fluid filling the pore space, and for mineral exploration due to sensitivity to metallic minerals. The most widely employed surface EM sounding tools are the transient EM (TEM) and magnetotelluric (MT) methods. The descriptions of these two methods are briefly summarized from Nabighian and Macnae (1991) in the following subsections.

2.1.2 THE MAGNETOTELLURIC METHOD

The natural source MT method is based on the measurement of natural EM field fluctuation at the earth’s surface in the period range of $10^3$ to $10^{-1}$ s (Reynolds, 1997). Natural EM energy has two main sources: solar-wind induced flow of charged particles in the ionosphere; and, distant thunderstorm activity causing field disturbance. The magnetic field disturbances penetrate the ground and induce time-variable telluric currents that in turn generate secondary EM fields which can be measured at the surface. The strength of MT lies in the use of natural EM sources that allow exploration of the earth to greater
depths. According to theory (Cagniard, 1953), for a wave polarized in the horizontal plane (x-y) and propagating downward in the ground, the plane-wave scalar apparent resistivity, $\rho_a$, and impedance phase, $\phi$, are given by

$$\rho_a(\omega) = \frac{1}{\omega \mu_0 |Z(\omega)|^2}$$

and

$$\phi = \tan^{-1}\left(\frac{\text{Out-Of-Phase } Z(\omega)}{\text{In-Phase } Z(\omega)}\right)$$

where $\omega$ is angular frequency; $\mu_0$ is permeability of free space and $Z(\omega)$ is equal to $\frac{\tilde{E}_x/H_y}{\text{or } \frac{\tilde{E}_y/H_x}}$, i.e. the ratio of orthogonal components of the electric and magnetic fields. Thus, apparent resistivity can be calculated from simultaneous measurement of $\tilde{E}_x$ and $\tilde{H}_y$ (or $\tilde{E}_y$ and $\tilde{H}_x$) at different frequencies. Since depth penetration increases as frequency decreases, the calculation of $\rho_a$ for a number of decreasing frequencies provides resistivity information at progressively increasing depths. The phase difference of the two orthogonal components provides additional information about the resistivity structure of the earth. Over a uniform earth, the phase between the two orthogonal components differs by $\pi/4$. A measured phase difference that is not $\pi/4$ is indicative of the ground being non-uniform.

The audio-frequency MT (AMT) method is an extension of the MT sounding technique (Sharma, 1997). The natural-source MT method uses the frequency range $10^{-3}$ to 10 Hz while the AMT method operates at $10^{-1}$ to $10^{4}$ Hz using spherics as the main energy source to achieve the moderate exploration depth to about 2000 m depending on the terrane.
conductivity. The main disadvantage with the natural-source MT method is the erratic signal strength. The variability in source strength and direction requires substantial amounts of stacking time (5-10 hours) per site, thus making MT sounding expensive and production rate slow. AMT measurements can be made faster owing to the slightly higher frequencies, but variability of local thunderstorm sources and signal attenuation around 10 and $10^4$ Hz can degrade the data quality (Reynolds, 1997).

For the interpretation of MT methods in detail, various 1-D and 2-D inversion schemes are currently available and 3-D inversion solutions are become available (Newman and Alumbaugh, 2000).

### 2.1.3 THE TRANSIENT ELECTROMAGNETIC METHOD

Like any other EM methods, EM fields generated with the TEM method are also governed by Maxwell’s equations. A transmitter creates a steady-state current in a ungrounded loop of wire, which then generates a magnetic field in the earth via Faraday’s Law (Nabighian and Macnae, 1991)

$$\vec{j}(\vec{r}, t) = \nabla \times \vec{h}(\vec{r}, t),$$  \hspace{1cm} (2-3)

where $\vec{j}$ is the current density (A/m$^2$); and $\vec{h}$ is the magnetic field (A/m); $\vec{r}$ is position vector and $t$ is time. The current source is then suddenly turned off in a few tens of milliseconds, resulting in a rapid change in the magnetic field. This changing magnetic field induces a time-varying electric field in the earth governed by Ampere’s Law:
\[
- \frac{\partial \vec{b}(\vec{r}, t)}{\partial t} = \nabla \times \vec{e}(\vec{r}, t), \\
\vec{b} = \mu \vec{h}
\]  

(2-4)  

(2-5)

where \( \vec{b} \) is the magnetic induction (Teslas); \( \vec{e}(\vec{r}, t) \) is electric field (V/m) and \( \mu \) is permeability.

The resulting current density, \( \vec{j}(\vec{r}, t) \) is defined by

\[
\vec{j}(\vec{r}, t) = \sigma(\vec{r}) \vec{e}(\vec{r}, t)
\]

(2-6)

where \( \sigma(\vec{r}) \) is electric conductivity.

The current flow produces a secondary magnetic field governed by Faraday’s Law. At a receiver, either the magnetic field or induced voltage in a receiver loop of wire is measured over time. The measurement is then interpreted to determine the electric resistivity structure of the earth. The diffusion pattern of the transient EM field depends on the geometry of the transmitter and transmitter waveform. Nabighian and Macnae (1991) pointed out that for a step-off function excitation, transient EM response of a loop transmitter can be represented by a downward and outward moving current filament called smoke rings (Figure 2.1), with diminishing amplitude and having the same shape as the transmitter loop.

The other promising TEM system shown in Figure 2.2 is the long offset transient electromagnetic (LOTEM) technique developed by Vozoff and Strack (Strack, 1992). The LOTEM method employs a long grounded electric dipole as the source. This LOTEM
source is energized with a square wave current and the time-derivative of the resulting transient magnetic field is measured in a small loop (Gunderson et al., 1986). It is common to present the measured transient-field sounding data as apparent resistivity curves at early time or late times. The measured response at early time is largely from the near-surface, whereas at late time the response mainly comes from the deeper part of the underground. As a common practice, late-time response (considered to be more diagnostic of the structure) is used to obtain apparent resistivity sounding curves (Sharma, 1997). While classic 1-D inversion schemes are being dominantly used in the interpretation of TEM data, they are sometimes inappropriate to apply to 3-D models. 3-D inversion routines are largely still research-based and computationally intensive. Consequently, such scheme has yet to be applied routinely to TEM projects when 3-D modeling is required (Reynolds, 1997).

2.1.4 THE GROUNDED ELECTRIC DIPOLE SOURCE TRANSIENT ELECTROMAGNETIC METHOD

The TEM and MT methods have been successfully used to study hydro-geophysical problems and to explore for hydrocarbons where the terrain is unsuitable for seismic reflection surveys (Reynolds, 1997). Limitations have also been reported by geophysicists. For example, it is well known that electrically resistive structures at depth are difficult to be delineated by both the conventional loop TEM and MT methods (Hordt et al., 2002 and Ellingsrud et al., 2002). The primary reason for this failure is that the response of these two EM methods mainly relies on the inductive effect of the horizontal source fields
which are parallel to and continuous along the boundaries of the resistors. Even though LOTEM method employs a grounded electric dipole source which generates both horizontal and vertical transient fields, it mainly uses a broadside configuration and measures vertical magnetic field responses. Because magnetic fields depend only on horizontal current flow penetrating into the ground through inductive coupling, their magnetic field responses are not strongly influenced by thin resistors in depth (Hordt et al, 2000).

Because delineating resistive structures is important to many geophysical applications which include monitoring underground gas storage facilities, and improving oil exploration, Alumbaugh (2002) proposed GESTEM method to detect and image resistive targets.

The GESTEM method was originally derived from the LOTEM method. A grounded electric dipole source generates various transient source waveforms. Unlike the LOTEM method, the GESTEM method employs relatively short source-receiver offset so that the measurement can be more focused below the source. The GESTEM method also equally utilizes electric field responses as well as magnetic field responses. Measuring electric fields over time has a potential advantage to sense resistive targets in depth because electric field measurements are more sensitive to charge buildup along the boundaries of electric resistivity when the vertical transient currents interact with the horizontal layers.
The research starting point for the GESTEM method will be to investigate its basic physics and then to compare it to the conventional loop TEM and CSAMT methods using finite difference forward modeling codes. The final result of this numerical study is to determine what advantages the newly proposed GESTEM method can offer over the conventional TEM and MT methods.

2.2 MARINE ELECTROMAGNETIC GEOPHYSICAL METHODS

2.2.1 INTRODUCTION

The advent of greater computational capabilities and recent developments in more accurate instrumentation have spawned increasing interest in the use of EM methods for seafloor exploration (Chave et al., 1991). The most widely employed marine EM methods are the marine MT (MMT) and marine frequency-domain Controlled Source EM (FDCSEM) methods. The other seaborne EM method employed in this numerical study is the marine time-domain Controlled Source EM (TDCSEM) method (Cheesman et al., 1987). These methods are briefly summarized in the following subsections.

2.2.2 THE MARINE MAGNETOTELLURIC METHOD

The theory and principles behind terrestrial MT are not changed appreciably for MMT but there are two major physical phenomena which differentiate the two techniques (Chave et al, 1991). The downward propagating MT source fields provide an MT impedance for the
sub-seafloor section that is independent of the overlying conductive layer. However, conductive seawater rapidly attenuates the magnetic source field at frequencies above 0.01 Hz and the amplitude reduction of seafloor fields is an important constraint in instrumental and experimental design. The generation of EM noise by sea water motion also contaminates low frequency MT data. These two phenomena result in a band-limited seafloor EM spectrum.

2.2.3 THE MARINE FREQUENCY-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHOD

The most commonly used technique for marine electromagnetic method is the MMT method. However, MMT suffers from a serious limitation in the deep oceans (Sinha et al., 1990). The presence of a few hundred meters of highly conductive seawater effectively screens the seabed from the ionospheric sources of magnetotelluric signal at all frequencies higher than a few cycles per hour. In addition, MMT source fields are horizontal and thus can not sense thin resistive hydrocarbon targets effectively. An alternative approach to MMT sounding is to generate artificial source currents in the water column and measure the resulting electric and magnetic fields at the seabed.

From this point of view, the marine frequency-domain controlled-source electromagnetic (FDCSEM) method uses time-varying electric or magnetic dipole source of known geometry to induce currents in the conducting media (Chave et al., 1991). The electric or magnetic response due to induced currents can be used to estimate the electric
conductivity structure of the seafloor. There are four basic source types: vertical and horizontal electric dipoles (VED and HED), and vertical and horizontal magnetic dipoles (VMD and HMD). A VMD system mainly measures the inductive response due to horizontal current flows and hence is relatively insensitive to thin resistive zones representing a hydrocarbon reservoir. HED, HMD and VED systems employ both vertical and horizontal current flow. Thus, these three source types are preferred when resistive zones have to be mapped. In contrast to a land-based frequency domain survey, the marine FDCSEM method has both the source and receiver immersed in conductive seawater. Thus, the electric structure of both the seawater and sub-seafloor materials affects the electromagnetic response measured on the seafloor. In cases involving shallow seawater, the boundary conditions given by the air-seawater interface also have to be taken into consideration. (Chave et al., 1991) A typical layout for the marine CSEM methods is shown in Figure 2.3.

During a typical survey, the source is towed at a height (usually 50m) from the seafloor within an array of seafloor receivers which measure two orthogonal components of the horizontal electric (magnetic) field. By studying the variation in amplitude and phase of the received electric (magnetic) field as a function of source-receiver separation geometry, and the frequency of the signal, the resistivity structure of the underlying seafloor can be determined. Frequencies in the range 0.25 Hz to 40 Hz are used in typical surveys (MacGregor et al., 2000). At too low frequency, FDCSEM responses tend to lack resolution of structures of interest, and are more likely to be affected by seafloor
electromagnetic noise from microseismic and ionospheric sources. At higher frequencies, only electromagnetic response at the very short source-receiver separations can be detected above the ambient noise due to significant attenuation of electromagnetic fields in the conductive media. Such electromagnetic response contains little information about the sub-seafloor resistivity structure. As a result, the useful range of the frequencies in practice is quite limited.

Another important factor for success or failure of marine FDCSEM method in practical applications related to hydrocarbon reservoir is survey geometry (Ellingsrud, 2002). The survey geometry can be defined in terms of the source-receiver azimuth, i.e. the angle between the source dipole axis and the line joining the source and receiver (Figure 2.4). At an azimuth of 90 degrees, inductive response dominates. In orthogonal direction at an azimuth of 0 degree, both galvanic and inductive responses are effective. Strong dependence of the response on source-receiver geometry is exemplified in this numerical modeling study.

2.2.4 THE MARINE TIME-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHOD

Previous works regarding the marine time-domain controlled source electromagnetic (TDCSEM) method mainly involve theoretical studies of the transient step-on responses for towed survey configurations. Cheesman (et. al., 1987) showed that the horizontal, in-line electric dipole-dipole configuration, and the horizontal, coaxial magnetic dipole-
dipole configuration are capable of measuring the relative low conductivity of the sea floor in the presence of more conductive seawater.

In order to compare the marine FDCSEM method to marine TDCSEM method consistently in this numerical modeling study, the frequency-domain HED source is replaced by the time-domain HED source and then step-off synthetic responses are computed. Any other survey configurations for the marine TDCSEM method are held identical to that for the marine FDCSEM method.

The theories applied to terrestrial TEM methods are not changed to explain the marine TDCSEM method, but Edwards (1998) numerically demonstrated the important difference between terrestrial and marine TEM responses: the characteristic step-on response of a double half-space model representing conductive seawater and less conductive seafloor to a towed dipole-dipole system near the seawater-seafloor interface consists of two distinctive parts. As time in the transient measurements progresses, two changes in field strength are observed: one caused by the relatively fast diffusion of the EM field through more resistive seafloor, and a second caused by the relatively slow diffusion through the more conductive seawater. The sense of the separation of the parts of the transient is opposite to that in the air, where the direct part propagating in the air arrives almost instantaneously due to its low conductivity (Chave et al., 1991). This distinctive diffusion pattern in each marine medium will also be observed in Chapter 5 and utilized to detect a thin resistive hydrocarbon reservoir.
2.3 FIGURES

**Figure 2.1** Conceptual diagram of diffusing currents called ‘smoke ring’ due to loop TEM source (Nabighian and Macnae, 1991).

**Figure 2.2** LOTEM field configuration with the current waveform (left) and the receiver signal (right) (Strack, 1992).
Figure 2.3 Diagram of the marine CSEM method, showing the deep-towed frequency-domain (or time-domain) HED, the surface research vessel, and a seafloor receiver (from Sinha, M., 1990).

Figure 2.4 Source-receiver geometry for the marine CSEM methods (From Eidsmo, T., 2002).
3. NUMERICAL FORWARD MODELING ALGORITHMS

3.1 INTRODUCTION

Numerical modeling algorithms are useful for generating accurate, synthetic data sets to help understand the fundamental physics of EM methods. In this numerical modeling study, a 1-D analytical modeling algorithm and two types of 3-D finite difference forward modeling algorithms are employed to compute synthetic time-domain and frequency-domain EM responses.

3.2 1-D ANALYTICAL CODE

The 1-D analytical method that K.H. Lee employed for his EM 1-D code is based on a general theory for the EM fields of dipole sources embedded in isotropic stratified media by Stoyer (1977). The computations consider the case where a dipole source is placed within one of several stratified layers with air body and earth half space at the top and bottom respectively of the stack of layers. The geometry and the coordinate system are presented in Figure 3.1. There are n layers below the source layer and m layers above it, and layers n and –m are semi-infinite. Each layer is homogeneous and isotropic, and is assigned a value of permeability μ, permittivity ε, electric conductivity σ, and thickness h. The bottom of the ith layer is at \( z = z_i \), and the horizontal dipole is located at \( (0, 0, -d) \).

Two of Maxwell’s equations provide the starting point of this method. These are
\[ \nabla \times \vec{E}(\vec{r}) = -i\omega \mu(\vec{r})\vec{H}(\vec{r}) - \vec{M}_r(\vec{r}) \quad \text{[Faraday’s law]} \quad (3-1) \]

and

\[ \nabla \times \vec{H}(\vec{r}) = \sigma(\vec{r})\vec{E}(\vec{r}) + \vec{J}_r(\vec{r}) \quad \text{[Ampere’s law]} \quad (3-2) \]

In these equations, the electric conductivity as a function of position is denoted by \( \sigma \), the electric and magnetic fields are defined by the vectors \( \vec{E} \) and \( \vec{H} \), respectively, and the source vectors \( \vec{J}_p \) and \( \vec{M}_p \) are current densities for imposed electric and magnetic sources.

We set the magnetic permeability of the earth, \( \mu \), to \( \mu_0 \left( 4\pi 10^{-7} \text{ H/m} \right) \) since magnetic permeability changes are generally very small except for the case of magnetic ore bodies.

For convenience, the Hertz potentials are employed, instead of dealing with the field components themselves. Using \( \Pi \) and \( \Pi' \) for the electric field and magnetic field Hertz potentials, respectively, the fields are derived via the relations,

\[ \vec{E} = -\jmath \omega \mu \nabla \times \Pi' + k^2 \Pi + \nabla(\nabla \cdot \Pi) \quad (3-3) \]

\[ \vec{H} = \sigma \nabla \times \Pi + k^2 \Pi' + \nabla(\nabla \cdot \Pi') \quad (3-4) \]

where \( k \) is the wave number and is defined as \( k^2 = \varepsilon \mu \omega^2 - i\mu \sigma \omega \).

For a unit electric dipole source, \( I_{ds} \) in the layer number 0, the Hertz potential in each layer satisfies the following relation

\[ (\nabla^2 + k_r^2)\Pi_i = \delta(i)\delta(x)\delta(y)\delta(z + d) \frac{I_{ds}}{\sigma} \quad (3-5) \]

For a unit magnetic dipole,

\[ (\nabla^2 + k_r^2)\Pi'_i = \delta(i)\delta(x)\delta(y)\delta(z + d) j\mu \mu m \quad (3-6) \]

The solutions of (3-6) for horizontal magnetic dipole are of the form
\[ \Pi'_y = \frac{\text{i} \omega \mu m}{4\pi} \int g \left[ \delta(i)g / u_o \exp(\pm u_o(z)) + D'_y(g) \cdot \exp(-u_o) + U'_y(g) \exp(u_o) \right] J_o(gp) dg \quad (3-7) \]

\[ \Pi'_{iz} = \frac{\text{i} \omega \mu m}{4\pi} \frac{\partial}{\partial y} \int g \left[ D'_z(g) \exp(-u_o) + U'_z(g) \exp(u_o) \right] J_o(gp) dg \quad (3-8) \]

where \( u_i = (g^2 - k_i^2)^{1/2} \)

The coefficients, \( D \) and \( U \) are derived from the boundary conditions, the continuity of tangential \( E \) and \( H \), and reduce to the following for each interface \( z=z_i \):

\[ k_i^2 \Pi'_y(z_i) = k_{i+1}^2 \Pi'_{i+1y}(z_i) \]

\[ \frac{\partial}{\partial y} \Pi'_y(z_i) + \frac{\partial}{\partial z} \Pi'_z(z_i) = \frac{\partial}{\partial y} \Pi'_{i+1y}(z_i) + \frac{\partial}{\partial z} \Pi'_{i+1z}(z_i) \]

\[ \mu_i \Pi'_z(z_i) = \mu_{i+1} \Pi'_{i+1z}(z_i) \quad (3-9) \]

and

\[ \mu_i \frac{\partial}{\partial z} \Pi'_y(z_i) = \mu_{i+1} \frac{\partial}{\partial z} \Pi'_{i+1y}(z_i) \]

Once the coefficients in the source layer are derived, the coefficients in other layers can be derived recursively.

In equations (3-1) and (3-2), each term of the equations is symmetric and can be utilized to simplify the calculations. In other words, with a few simple substitutions of each corresponding term in the two equations, the electric fields can be derived directly from those for the magnetic dipole. Once the expressions for the fields are developed in the frequency domain, it is easier to find the inverse (time) Fourier transforms for transient electric and magnetic dipoles rather than begin the derivation with time-domain version of Maxwell’s equations. K. H. Lee’s EM1D code utilizes this approach: first it computes
frequency domain response and then generates time-domain response via inverse Fourier transforms.

3.3. 3-D FREQUENCY-DOMAIN FINITE DIFFERENCE CODE

In order to solve Maxwell’s equations numerically in the frequency domain, finite difference algorithm, EM1D2D3D, was used. The following description originates from Newman and Alumbaugh (1995), and Ludwig (2004).

Assuming a time harmonic dependence of $e^{i\omega t}$, where $i = \sqrt{-1}$, and frequencies $\omega = 2\pi f$ below 1 MHz such that displacement currents can be ignored for the known resistivity range of rocks, the differential form of Maxwell’s equations are reintroduced.

$$\nabla \times \vec{E}(\vec{r}) = -i\omega \mu_0 \vec{H}(\vec{r}) - \vec{M}_p(\vec{r})$$  \hspace{1cm} (3-1)

and

$$\nabla \times \vec{H}(\vec{r}) = \sigma(\vec{r})\vec{E}(\vec{r}) + \vec{J}_s(\vec{r})$$ \hspace{1cm} (3-2)

The rapidly changing fields in the vicinity of the source require a very fine grid that can exceed memory capacity near the source and receiver. In order to avoid this problem, the scattered field version of Maxwell’s equations is employed.

$$\nabla \times \vec{E}_s(\vec{r}) = -i\omega \mu_0 \vec{H}_s(\vec{r})$$ \hspace{1cm} (3-10)

$$\nabla \times \vec{H}_s(\vec{r}) = \sigma(\vec{r})\vec{E}_s(\vec{r}) + \vec{J}_s(\vec{r})$$ \hspace{1cm} (3-11)

In (3-4), $J_s(r)$ is a ‘scattered field source vector’ defined by

$$\vec{J}_s(\vec{r}) = (\sigma(\vec{r}) - \sigma_p(\vec{r}))\vec{E}_p(\vec{r})$$ \hspace{1cm} (3-12)
where $E_p$ and $\sigma_p$ are the primary electric field and background conductivity respectively.

After the scattered fields are computed, the total fields are calculated from the expressions

$$\tilde{E}(\vec{r}) = \tilde{E}_s(\vec{r}) + \tilde{E}_p(\vec{r})$$  \hspace{1cm} (3-13)

and

$$\tilde{H}(\vec{r}) = \tilde{H}_s(\vec{r}) + \tilde{H}_p(\vec{r})$$  \hspace{1cm} (3-14)

In (3-13) and (3-14), the primary fields ($E_p$ and $H_p$) are calculated using EM1D previously described. These primary fields include fields generated by the transmitter plus the response of a layered half space.

In order to solve these weakly coupled equations, we take the curl of (3-10) and substitute in (3-11) to arrive at a vector Helmholtz equation for the electric field

$$\nabla \times \nabla \times \tilde{E}_s(\vec{r}) + i\omega \mu_0 \sigma(\vec{r})\tilde{E}_s(\vec{r}) = -i\omega \mu_0 \tilde{J}(\vec{r})$$  \hspace{1cm} (3-15)

This expression can now be written as a system of equations in the form of:

$$\overline{A\overline{f}} = \overline{S}$$  \hspace{1cm} (3-16)

where $\overline{f}$ is the scattered field vector that we are solving with $N$ unknowns, $\overline{A}$ is an $N \times N$ matrix containing the approximate spatial derivatives from the left side of (3-15) as well as electric resistivity information of the model, and $\overline{S}$ is the right side of (3-15), the equivalent source vector. Further detailed numerical study has appeared in the literature (Newman and Alumbaugh, 1995).
An additional simple algorithm (Ludwig, 2004) is added to the above finite difference scheme to allow for complicated sources of finite length. The main function of the algorithm is to divide the source into a number of segments and then to numerically integrate EM response for each segment as an individual infinitesimal source. This approach enables us to get the EM response for the complicated sources.

Model discretization is a special concern in numerical modeling studies. Finer model discretization increases the accuracy of forward modeling but increases the amount of CPU time and memory needed (Pellerin et al, 1996). Besides this general consideration, Newman and Alumbaugh (1995) suggested other discretization conventions for maximum and minimum cell size when this code is employed. As the ratio of the dimensions of the largest cell to those of the smallest cell increases, the time that it takes for the solution to converge increases. Hence, in this modeling study using this code, this ratio was set to less than 10. The maximum cell size is dictated by considering skin depth and is set to one-half of the skin depth of the most conductive medium in the model.

3.4. 3-D TIME-DOMAIN FINITE DIFFERENCE CODE

The 3-D finite difference time domain (3-D FDTD) algorithm employed here was developed by Commer and Newman (2004). The algorithm solves the TEM problem by stepping the coupled first-order Maxwell’s equations forward in time using a staggered grid approach (Wang and Hohmann, 1993). The TEM fields in a linear, isotropic and
source-free media using the quasi-static approximation are expressed by the following equations.

\[ \vec{j}(\vec{r},t) = \nabla \times \vec{h}(\vec{r},t) \]  

(3-17)

\[ -\frac{\partial \vec{b}(\vec{r},t)}{\partial t} = \nabla \times \vec{e}(\vec{r},t) \]  

(3-18)

where \( \varepsilon \) is the dielectric permittivity, \( \vec{e} \) is the electric field, \( \vec{r} \) is position vector, \( t \) is time, \( \vec{j} \) is the conduction current density, and \( \vec{h} \) is the magnetic field.

The constitutive equations are

\[ \vec{j}(\vec{r},t) = \sigma(\vec{r})\vec{e}(\vec{r},t) \]  

(3-19)

\[ \vec{b}(\vec{r},t) = \mu(\vec{r})\vec{h}(\vec{r},t) \]  

(3-20)

where \( \vec{b} \) is the magnetic flux density and \( \mu \) is the magnetic permeability of the earth.

We also need to enforce divergence-free condition on the fields.

\[ \nabla \cdot \vec{b}(\vec{r},t) = 0 \]  

(3-21)

\[ \nabla \cdot \vec{j}(\vec{r},t) = 0 \]  

(3-22)

The finite difference approximations for (3-19) and (3-20) are used to solve transient EM fields in a staggered grid shown in Figure 3.2 (Wang and Hohmann, 1993). In the staggered grid, the electric fields are calculated along the cell edges and the magnetic fields are calculated at the center of the cell face. This approach satisfies Ampere’s Law such that the curl about the electric field produces a magnetic field, and vice versa (Faraday’s Law), and the staggered grid locates the magnetic and electric field in the correct place with relation to each other. The time stepping is carried out in a leapfrog
fashion such that the electric fields are computed at \( t_1 \), magnetic fields at \( t_{1+1/2} \), electric field at \( t_2 \), magnetic field at \( t_{2+1/2} \) and so on. This is done as the magnetic fields are a result of the electric fields and vice versa and thus the two different fields can not be calculated at the same time. To provide for a stable solution, the maximum time step is defined to be

\[
\Delta t_{\text{max}} = \alpha \left( \frac{\mu \min \sigma I}{6} \right)^{1/2} \Delta \min
\]  

where \( \Delta t_{\text{max}} \) is the maximum time step, \( \alpha \) ranges from 0.1 to 0.2 depending on required accuracy and \( \Delta \min \) is the minimum cell size. Subsurface boundaries are represented by Dirichlet boundary condition in which the tangential electric fields are set to zero at the side and lower boundaries. This is possible because we can simply extend the subsurface boundaries sufficiently far from the source position. A conceptual diagram for time-domain 3-D EM model grids is presented in Figure 3.3. At the earth-air interface, an upward-continuation boundary condition is used to avoid having to include the air layer in the finite difference grid (Oristaglio and Hohmann, 1984). This requires a 2D Fourier transform at the interface. Otherwise, according to (3-23), approximating the air with a highly resistive layer would require very small initial time steps (Commer and Newman, 2004).

In the loop source TEM code, the four current elements forming the transmitter loop are extrapolated to the nearest cell edge. The static magnetic fields every where in the model due to the four current elements are then computed and used as the initial conditions (Schaper, 2002). In the grounded source TEM code, the initial direct current (DC) conditions can be computed for an arbitrarily geological media. This involves the
solutions of a 3D Poisson problem prior to the time-stepping process in order to treat the presence of static DC electric field caused by the galvanic source (Commer and Newman, 2004).
3.5 FIGURES

**Figure 3.1** Horizontal dipole imbedded in stratified media. Source is at \( z = -d \) in layer 0 (Stoyer, 1977).

**Figure 3.2** (a) A staggered grid. The electric field is sampled at the centers of the prism edges, and the magnetic field is sampled at the centers of the prism faces. (b) Interaction between an electric loop and a magnetic loop (Wang and Hohmann, 1993).
Figure 3.3 Discretization of a 3-D earth model. The thick arrow represents the source. Grid spacing increases laterally and vertically away from the source (Wang and Hohmann, 1993).
4. 3-D NUMERICAL ANALYSIS OF GROUNDED ELECTRIC DIPOLE SOURCE
TRANSIENT ELECTROMAGNETIC METHOD

4.1 INTRODUCTION

It is well known that conventional inductive EM methods do not provide accurate images
of thin resistors compared to those of thin conductors (Hordt et al., 2002). In contrast to
conventional inductive EM methods, the GESTEM method can generate vertical transient
currents as well as horizontal transient currents, and therefore will be better able to detect
a thin resistor at depth. While the previous work (Gunderson et al., 1986 and Newman,
1989) concerning a grounded electric source mostly focused on broadside vertical
magnetic field measurements and explanations of the governing physics, the work done
here provides more comprehensive modeling results for various grounded electric source
– receiver configurations.

4.2 NUMERICAL MODELING METHODS

To investigate how transient EM fields of the GESTEM method diffuse and how they are
different from those of the standard loop TEM method, the step-off EM responses of the
two EM methods were calculated for three different one-dimensional models: a
background model, a resistor model, and a conductor model (Figure 4.1). The layered
earth model code, EM1DSheet from Lawrence Berkeley Laboratory was used for these
computations. Even though EM receivers can only be placed on the earth’s surface in
practice or limited number of boreholes, a number of imaginary EM receivers were
employed within the earth along cross-sections of the models of interest. This methodology allows us to analyze how the transient fields diffuse below the surface with time and how they interact with target layers. Thus, the physics of the EM methods can be directly observed.

The 250 m long GESTEM source was placed on the earth’s surface. The loop TEM method employs a 250 m *250 m square source loop for a consistent comparison to the GESTEM response. The ramp-off time for the two methods is set to 1.0E-4 seconds. The driving current is set to 40 A. The electric receiver noise level is set to 1.0E-10 (V/m) and the magnetic receiver noise level to 1.26E-5 (nT) (Ed Nichols, personal communication).

The GESTEM survey geometry can be defined in terms of the source-receiver azimuth, i.e. the angle between the source dipole axis and the line joining the source and receiver. At an azimuth of 90 degrees (broadside configuration), an inductive response dominates. In the orthogonal direction at an azimuth of 0 degrees (in-line configuration), both galvanic and inductive responses are effective. Strong dependence of the response on source-receiver geometry will be exemplified in this numerical modeling study. As for the AMT method, the source frequencies from 1.0E-3 Hz to 1.0E5 Hz were employed to generate an apparent resistivity sounding curve and impedance phase curve.
4.3 NUMERICAL MODELING RESULTS

4.3.1 HOMOGENEOUS HALF SPACE MODEL

In order to compare the physics of the Loop TEM method to that of the in-line GESTEM method, the successive snapshots of transient current distribution in the background model are plotted in Figure 4.2 for the Loop TEM method and Figure 4.3 for the in-line GESTEM method. Nabighian (1979) described the time domain induced current system shown in Figure 4.2 as resembling a “smoke ring” blown by the transmitter. In the homogeneous background model, the current maximum of the Loop TEM method moves outward and downward from the loop source edge at an angle of approximately 30 degrees with the surface. As is known well, this induced current system consists of only horizontal currents. In contrast to the Loop TEM method, the in-line GESTEM method can generate both horizontal and vertical transient current fields. Therefore, the induced current system of the in-line GESTEM method can be examined effectively with three types of plots as shown in Figure 4.3: total current plots; horizontal current plots; and vertical current plots. To supplement Figure 4.3, the 3-D snapshots of current density are shown in Figure 4.4.

The horizontal currents with the in-line GESTEM source consist of two parts. The upper horizontal current system, ‘the image of the source’ diffuses equally in the x- and y-directions, but the locus of its maximum remains very close to the source over the whole measurement time. The lower horizontal current system, the so-called ‘return current’
(Gunderson et al, 1986), diffuses downward relatively quickly but has a much smaller amplitude than the upper currents. As the horizontal current maximum remains close to the source over the time, the magnetic and electric responses of the GESTEM method have a static shift problem if there is an inhomogeneity near the source (Newman, 1989).

The vertical current system shows important aspects. First, the vertical current maximum diffuses rapidly in depth, but its amplitude decays as slowly as the horizontal current maximum decays over time. This rapid-depth-diffusion is illustrated by plotting locus of the current maximum at each measurement time (Figure 4.5), while the amplitude of the current maximum as a function of time, and the amplitude of current maximum as a function of depth, are plotted in Figure 4.6a and Figure 4.6b respectively. Notice that the total current maximum of the GESTEM method is not the sum of vertical current maximum and horizontal current maximum because they exist at different locations. Hence, the locus of the GESTEM total current maximum is the same as the locus of the horizontal current maximum. At a given time, the amplitude of the GESTEM vertical current maximum is about 30% of that of the GESTEM horizontal current maximum as shown in Figure 4.6a, but, at a given depth, the amplitude of the GESTEM vertical current maximum is always larger than the other components. Thus, Figure 4.6 implies that the responses due to this fast diffusing and highly concentrated vertical current can sense a target in depth at earlier time than other components. This characteristic will be illustrated in section 4.3.3.
Second, the diffusion angle of the vertical current maximum is about 45 degrees from the source edge on the surface as observed in Figure 4.3 and Figure 4.5. That is, the vertical current for the GESTEM method is more focused below the source than the horizontal current for the Loop TEM method.

Third, the GESTEM vertical current maximum and most of the GESTEM vertical currents stay on, or in the vicinity of the plane, which contains the source (Figure 4.4) while the GESTEM horizontal currents diffuse evenly in the x- and y- directions.

Unlike the in-line GESTEM method, the standard LOTEM method (vertical magnetic field measurement using the broadside GESTEM method) utilizes the time-derivative of the transient vertical magnetic field. The snapshots of transient currents in the background model are plotted in Figure 4.7 for the broadside LOTEM method. Notice that there are only horizontal currents along the broadside cross-section. Therefore, the measured magnetic responses for the LOTEM method are mainly inductive arising from horizontal current flow.

Lastly, the induced current field for the AMT method at 100 Hz is presented in Figure 4.8. Notice that there are only horizontal induced currents in the earth and their amplitudes decrease as the depth increases.
4.3.2 1-D RESISTOR MODEL

The primary reason to use the GESTEM method over others is to delineate the geometry of thin resistive bodies in depth. This section provides the 1-D numerical modeling examples that demonstrate how the Loop TEM method and the AMT method fail to sense a thin resistive layer shown in Figure 4.1b, while the GESTEM method detects it.

The Loop TEM responses are shown for different receiver locations in Figure 4.9. There is no distinguishable difference between the 1-D resistor model and the background model. The cause of the identical response is verified by viewing the difference between transient current distribution for the 1-D resistor model (Figure 4.10) and the background model (Figure 4.2). The locus of current maximum for the two models is in similar positions at each time and the overall patterns of the current distribution for the two models are also similar in space.

For easier analysis, the locus of the current maximum at each measurement time is plotted in Figure 4.11, which can be compared to Figure 4.5. The standard loop TEM system measures vertical magnetic fields which entirely originate from horizontal current flows in the earth. The similar horizontal current distributions in the two models at each time induce similar magnetic field response on the surface. As a result, the magnetic field measurements of the loop TEM method fails to detect a thin resistor in depth.
The in-line GESTEM responses are computed and shown for a few different receiver locations in Figure 4.12 for dB/dt measurements, and in Figure 4.13 for E_x measurements. While the dB/dt measurements for the 1-D resistor model are identical to those for the background model, the E_x measurements show small differences between the two models. The nearly identical magnetic field response results are explained by the small differences noted when comparing the horizontal current field distribution for the background model (Figure 4.3) to that for the 1-D resistor models (Figure 4.14). However, the vertical current system shows differences between the two models. As indicated in Figure 4.11 and Figure 4.14, the vertical current maximum of the 1-D resistor model moves downward quickly, develops along the upper boundary of the thin resistor, and diffuses rapidly from the center of the model. In contrast, the vertical current maximum of the background model (Figure 4.3 and Figure 4.5a) just diffuses at 45 degrees. The vertical current interacts with the 1-D resistor over time, resulting in charge buildup along the boundary of the horizontal reservoir in order to satisfy the continuity of normal current. The electric fields from these extra charges distort the geometry of the transient electric field, providing the grounded electric field receivers with the small perturbation as shown in Figure 4.13. In addition to the electric field response at a few receiver locations, 2-D snapshots of transient electric field in the 1-D resistor model are plotted in Figure 4.15. The interaction of the transient vertical currents with the resistor results in strong electric fields both in and around the resistor.
As shown in Figure 4.13, the degree of $E_X$ perturbation due to the 1-D resistor varies as the source-receiver separation increases. In order to highlight the degree of the perturbation as the function of source-receiver separation, the 1-D resistor response was normalized by the background response at each receiver location in Figure 4.16. As source-receiver separation increases, the difference of the step-off response between the two models decreases. This is because large source-receiver separation is sensitive to the electrical properties of a much larger volume of the subsurface. Notice that the relatively large differences at a larger separation in early time are due to a time-delayed direct current (DC) response, and do not represent the electromagnetic sensing ability of the GESTEM method.

Based on Figure 4.13, the electric field measurements of the GESTEM method are able to sense a thin resistor in depth, but the difference between the two models is still small and the DC effect dominates the transient electromagnetic response coming from the thin resistor. A way to eliminate the flat (zero-slope) DC responses in Figure 4.13 and Figure 4.16 is to take the time-derivative of $E_X$ responses. These calculations are shown in Figure 4.17. Even though taking the time-derivative results in numerical noise at early times, this mathematical manipulation clearly enhances the response coming from the thin resistor at larger separation. For smaller source-receiver separation, the difference of the time-derivative between the background and resistor models is less but the shapes is sharper. For the larger separation, the difference between the twos is larger but the amplitude is smaller and broader.
A different way to think of Figure 4.17 is that the time-derivative of the response of a step-off source having short ramp-off time is an estimate of the impulse response. The major difference between the two transmitter waveforms is frequency spectrum: the step-off transient response mainly consists of low frequency signals which are unsuitable for sensing the thin resistor in this given exploration scenario while the impulse response has a broad range of frequencies in its EM spectrum including high frequency signals and thereby gives much more information about subsurface resistivity. This modeling result with the time-derivative of step-off response illustrates that it is necessary to choose and/or design a proper transient EM pulse such that the relatively high frequencies required for reservoir detection are produced.

The LOTEM method (broadside long offset GESTEM method) has been studied by many authors and it is well known that magnetic field responses from the broadside configuration are insensitive to thin resistive layers because magnetic responses purely come from horizontal current flow in earth (Hordt et al, 2000). The broadside dBZ/dt and broadside EX responses are plotted in Figure 4.18 and Figure 4.19 respectively. As expected, dBZ/dt responses fail to sense the thin resistor in depth. Broadside EX responses still detect the presence of the thin resistor but their amplitudes are 5-6 times smaller than the amplitudes of in-line EX responses (Figure 4.13).
Lastly, the AMT sounding results over the background model, the 1-D resistor model, and the 1-D conductor model are plotted in Figure 4.20. The 1-D resistor does not produce significant perturbations in its apparent resistivity sounding result. The induced current system of the AMT method between the background model (Figure 4.8) and the 1-D resistor model (Figure 4.21) does not show any meaningful difference because the AMT method utilizes a purely inductive source. Thus, the AMT method is inappropriate for the detection of such a thin resistive layer at depth solely.

### 4.3.3 1-D CONDUCTOR MODEL

In this subsection, the GESTEM method is employed to sense the thin conductive layer shown in Figure 4.1c. Delineating conductive targets is not a main concern of GESTEM application because the Loop TEM method is able to detect a thin conductor with reasonable accuracy, and does not require implanting a transmitter and receivers into the ground. However, the numerical study of the 1-D conductor model is added here for the complete understanding of the GESTEM method and for its comparison to the other methods.

The Loop TEM responses are shown for a few different receiver locations in Figure 4.9. The difference of the measured magnetic field between the background model and the 1-D conductor model in Figure 4.9 can be explained by comparing the locus of the current maximum in the background model (Figure 4.2) to that in the 1-D conductor model (Figure 4.22). The current maximum in the background model diffuses outward and
downward from the loop source edge at an angle of approximately 30 degrees with the surface (Nabighian et al., 1991). In the 1-D conductor model, the current maximum quickly diffuses into the thin conductor and stays within it. This different locus of the current maximum between the two models over the measurement time produces the different magnetic responses, and enables an interpreter to detect the presence of the thin conductor. For easier analysis, the locus of the current maximum in the 1-D conductor model at each measurement time is plotted in Figure 4.23 and compared to Figure 4.5.

The in-line GESTEM responses are computed for a few different receiver locations in Figure 4.12 for dBv/dt measurements and in Figure 4.13 for EX measurements. The snapshots of the in-line GESTEM current system in the 1-D conductor model are plotted in Figure 4.24. The magnetic field response of the GESTEM method senses the thin 1-D conductor in the same way as the loop TEM method does. That is, the horizontal current maximum is confined within the conductor. For completeness, the 2-D snapshots of transient electric field in the 1-D conductor model are plotted in Figure 4.25.

The EX measurements also sense the thin conductor but give much smaller response than the other two methods investigated. Results shown in Figure 4.13 demonstrate that GESTEM EX measurements sense both the 1-D thin resistor and the 1-D conductor equally. This is possible because the sensing ability of GESTEM EX measurements result from the charge buildup. That is, the polarity of charge buildup on the surface of the 1-D resistor is opposite to that on the 1-D conductor. A comparison of the depth sensitivity
versus time for sensing thin conductors between the Loop TEM method and the GESTEM method is shown in Figure 4.17b and Figure 4.9b. It is clear that the GESTEM method senses the thin conductor much earlier than the Loop TEM method does. However, there is no reason to employ the GESTEM method to sense a thin conductor because the degree of its electric field perturbation is relatively small for this type of model.

A few broadside GESTEM magnetic and electric responses for the 1-D conductor model are illustrated in Figure 4.18 and Figure 4.19 respectively. The magnetic field responses distinguish between the background model and the 1-D conductor model because the current maximum is confined to the thin conductive layer as shown in Figure 4.26.

Finally, the AMT method also works to sense the thin conductor as shown in Figure 4.20. The 1-D conductor produces much larger perturbations in its apparent resistivity sounding result than the 1-D resistor. This difference can be explained by comparing the induced current system between the background model and the 1-D conductor model. This current distribution in the 1-D conductor model (Figure 4.27) is different enough compared to that in the background model (Figure 4.8).
4.3.4 EFFECT OF NEAR-SURFACE INHOMOGENEITY ON GESTEM RESPONSES

In order to investigate the effect of near-surface inhomogeneity on GESTEM sounding results, the magnetic and electric field responses were calculated at the three receiver locations for the following models shown in Figure 4.28: the center of the near-surface conductor varies from (0m, 0m, 0m), (-300m, 0m, 0m) to (-600m, 0m, 0m).

The electric field sounding results are presented in Figure 4.29 and the magnetic field sounding results in Figure 4.30. For model 1, the magnetic and electric field responses at the three receiver locations are “shifted” down in amplitude for the entire measurement time, leading to misinterpretation of electric resistivity structure of the subsurface.

Compared to the responses for model 1, the EM responses for model 2 and model 3 show varying degrees of shift at the different receiver locations. The $E_X$ measurements at (1 km, 0 km, 0 km) and (0 km, 1 km, 0 km), and the $dB_Y/dt$ measurements at (1 km, 0 km, 0 km) do not suffer severely from a static shift and are roughly equal to the responses for the background model. In contrast, the $E_X$ measurements at (-1 km, 0 km, 0 km), the $dB_x/dt$ measurements at (0 km, 1 km, 0 km) and the $dB_Y/dt$ measurements at (-1 km, 0 km, 0 km) have severe static shift problem over the entire measurement time.

To understand the calculations presented in Figures 4.29 and 4.30, the snapshots of current distribution were plotted in Figure 4.31 for the background model, Figure 4.32 for
model 1, Figure 4.33 for model 2, and Figure 4.34 for model 3. In model 1, both the horizontal and vertical current maximums are trapped within or in the vicinity of the conductor without lateral and downward migration over the entire measurement time. Therefore, the measurements at all the receiver locations are affected by the near-surface conductor over the entire measurement time, and do not converge to the background model response even at later times. Notice that the vertical current distribution shown in Figure 4.32d is asymmetrical with respect to the center of the model. This numerical artifact is because a finite numbers of receiver positions on the cross-section can not capture the vertical current distribution perfectly, and thus the interpolation provided by the graphics package employed is subject to error. When the center of the conductor is offset to the left of the source, more current on the right side of the source (Figure 4.33 and 4.34) diffuses outward. In addition, the separation between the center of the near-surface conductor and the measurement location becomes larger. Thus, the degree of static shift is somewhat reduced.

The modeling results illustrate that the GESTEM sounding is under strong influence of near-surface inhomogeneity and the current 1-D inversion scheme for the grounded wire source can not be a robust, reliable imaging solution to process GESTEM sounding data if these types of inhomogeneities are present.
4.3.5 3-D RESISTOR MODEL

To investigate more complicated scenarios, the previous 1-D resistor is replaced by the 3-D resistive block described in Figure 4.35. For consistency reasons, all other modeling parameters for the 3-D forward modeling are the same as those for the 1-D forward modeling. Two 3-D block models are considered in this subsection: Model 4 (Figure 4.35a) has the 3-D block 500m directly below the GESTEM source; In Model 5 (Figure 4.35b), the same 3-D block is located along the diffusion path of vertical current maximum within the background model. Thus, the effect of coupling of the vertical transient currents to the 3-D block versus position can be examined.

The numerical modeling results for the two models and the background model are shown in Figure 4.36 for the magnetic field responses and in Figure 4.37 for the electric field responses. As illustrated before, the magnetic field responses do not sense the presence of the block. In contrast, the electric field measurements show the different degree of sensing ability on the block between model 4 and 5: the presence of the block is more clearly identified in model 5 than in model 4.

In order to explain the observed electric field responses, the snapshots of the transient current system are shown in Figure 4.38 for model 4 and in Figure 4.39 for model 5. Because the block is off the path the vertical current maximum took in model 4, the vertical currents have little opportunity to interact. This results in small perturbation in the measured electric fields. When the block is moved 500m to the right from the center of the
source as shown in Figure 4.35b, the vertical current can be more efficiently coupled to the 3-D block and optimize the galvanic effect.

This modeling example demonstrates that the GESTEM method is very dependent on source-receiver configuration to sense a small localized target, and that the diffusion angle of the vertical transient currents should be considered as an important survey factor in practice.

4.4 CONCLUSIONS

The GESTEM method has been investigated numerically and compared to the other two standard terrestrial EM methods in this section. The important characteristics of the GESTEM method and its transient fields are summarized below.

First, the vertical current maximum diffuses downward at 45 degrees from the edge of the source and the fast diffusing and highly concentrated vertical currents of the GESTEM method help sense a deep resistive target in early time. Making vertical transient currents coupled efficiently to a resistive target is a crucial factor to get large perturbation.

Second, the majority of the vertical currents are confined within or near to the plane which contains the source while the GESTEM horizontal currents diffuse evenly in the x- and y-directions and slowly downward over the entire measurement time.
Third, the GESTEM method can sense both thin conductive and resistive targets equally because its response relies on galvanic response. In contrast, Loop TEM and MT methods are much more sensitive to conductive targets but fail to sense thin resistive ones because they employ purely inductive sources.

Finally, this study confirms the well known modeling result by Newman (1989) that the GESTEM sounding is very sensitive to near-surface inhomogeneity and thus can not be interpreted accurately using 1-D inversion schemes if these types of inhomogeneities are present.
4.5 FIGURES

Figure 4.1. The three 1-D models: (a) background model, (b) 1-D resistor model and (c) 1-D conductor model.
Figure 4.2. Normalized y component of the current density as a function of position in a plane bisecting 250 m * 250 m loop source in the background model at the four different measurement times.
Figure 4.3. Normalized current density as a function of position in the cross-section including a 250 m long grounded source in the background model at the four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.4. 3-D normalized current density in the background model at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.4. Continued.
Figure 4.5. Locus of the current maximum in the background model.
Figure 4.6. The characteristics of the current maximum for the loop TEM and the GESTEM in background model. (a) the current maximum amplitude as a function of time in the background model and (b) the current maximum amplitude as a function of depth.
Figure 4.7. Normalized current density as a function of position in the cross-section bisecting a 250 m long grounded source in the background model at the four different measurement times. The direction of current at every position is parallel to the source orientation.
Figure 4.8. Normalized in-phase and out-of-phase current density in the background model due to 100 Hz AMT plane wave source.

(a) In-phase

(b) Out-of-phase
Figure 4.9. Magnetic field responses at the three different receiver locations with 250 m * 250 m loop TEM source. The arrow in the (b) represents the time when the loop TEM method first starts to sense the presence of the thin conductor. The green lines represent receiver noise level.
Figure 4.10. Normalized current density as a function of position in a plane bisecting a 250 m * 250 m loop source in the 1-D resistor model at the four different measurement times.
Figure 4.11. Locus of the current maximum in the 1-D resistor model for different times during the decay.
Figure 4.12. In-line magnetic field response at the three different receiver locations with a 250 m long grounded source.

Figure 4.13. In-line electric field response at the three different receiver locations with a 250 m long grounded source. The green lines represent receiver noise level.
Figure 4.14. Normalized current density as a function of position in the cross-section including a 250 m long grounded source for the 1-D resistor model at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.14. Continued.
Figure 4.15: Normalized electric field as a function of position in the cross-section including a 250 m long grounded source for the 1-D resistor model at the four different measurement times. Total electric field (left), horizontal electric field (middle) and vertical electric field (right).
Figure 4.15. Continued.
Figure 4.16. Normalized $E_X$ fields for the 1-D resistor model at different source-receiver separations. Normalization is that of the background model.
Figure 4.17. Time-derivatives of in-line GESTEM $E_x$ response at different source-receiver separations. The arrow in (b) represents the time when the GESTEM method first starts to sense the presence of the thin conductor.
Figure 4.18. Broadside magnetic field response for a 250 m long grounded source.

Figure 4.19. Broadside electric field response for a 250 m long grounded source. The green lines represent receiver noise level.
Figure 4.20. (a) AMT apparent resistivity curves and (b) impedance phase curves
Figure 4.21. Normalized in-phase and out-of-phase current density in the 1-D resistor model due to 100 Hz AMT plane wave source.
Figure 4.22. Normalized y component of the current density at the four different measurement times as a function of position in a plane bisecting a 250 m loop source in the 1-D conductor model.
Figure 4.23. Locus of the current maximum in the 1-D conductor model.
Figure 4.24. Normalized current density as a function of position in the cross-section including a 250 m long grounded source for the 1-D conductor model at the four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.24. Continued.
Figure 4.25. Normalized electric field as a function of position in the cross-section including a 250 m long grounded source for the 1-D conductor model at four different measurement times. Total electric field (left), horizontal electric field (middle) and vertical electric field (right).
Figure 4.25. Continued.
Figure 4.26. Normalized $x$ component of the current density as a function of position in the cross-section bisecting a 250 m long grounded source for the 1-D conductor model at four different measurement times.
Figure 4.27. Normalized in-phase and out-of-phase current density in the 1-D conductor model due to 100 Hz AMT plane wave source.
Figure 4.28. The three near-surface inhomogeneity models. The center of the 250m long \( x \)-directed grounded source is placed at \((0\, m, 0\, m, 0\, m)\). The dimension of the near-surface-conductor modeled as 1 Ohm-m is \(600\, m(x) \times 600\, m(y) \times 100\, m(z)\) and the background is modeled as 10 Ohm-m.
Figure 4.29. Transient electric field responses at the three different receiver locations for the three near-surface conductor models.

Figure 4.30. Transient magnetic field responses at the three different receiver locations for the three near-surface conductor models.
Figure 4.31. Normalized current density as a function of position in the cross-section including a 250 m long grounded source for the background model at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.31 Continued.

(c) 1.99E-2 seconds

(d) 0.32 seconds
Figure 4.32. Normalized current density as a function of position in the cross-section including a 250 m long grounded source for model 1 at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.32 Continued.
Figure 4.33. Normalized current density as a function of position in the cross-section including a 250 m long grounded source for model 2 at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.33. Continued.
Figure 4.34. Normalized current density as a function of position in the cross-section including a 250 m grounded source for model 3 at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.34. Continued.
Figure 4.35. The 3-D resistive block models. (a) Model 4: the block is 500m below the center of the grounded source and (b) Model 5: the center of the block is moved 500m away from the center of the grounded source.
Figure 4.36. The magnetic field responses at the two receiver locations for 3-D resistive block models.
The electric field responses and their time-derivatives at the two receiver locations for 3-D resistive block models.
Figure 4.38. Normalized current density as a function of position in the cross-section including a 250 m long grounded source for model 4 at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.38. Continued.
Figure 4.39. Normalized current density as a function of position in the cross-section including a 250 m grounded source for model 5 at four different measurement times. Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 4.39. Continued.
5. 3-D NUMERICAL ANALYSIS OF FREQUENCY-DOMAIN AND TIME-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHODS IN MARINE ENVIRONMENT

5.1 INTRODUCTION

The 3-D seismic reflection method is a principal tool to explore for marine hydrocarbon reservoirs. It yields relatively high resolution information about the sub-bed structure and can identify structures that may contain hydrocarbon. However, the associated drawback of using seismic reflection method solely lies in not defining whether the potential hydrocarbon reservoir contains hydrocarbon or seawater. Approximately, 90% of the seismic finds contains water, and not of hydrocarbon and gas (Thirud, 2002).

EM methods have the potential to reduce the risk of drilling dry wells because they can distinguish seawater saturated reservoirs (low electric resistivity) from hydrocarbon-saturated reservoir (high electric resistivity) (Wright et. al., 2002). In the past, the sub-seafloor electric resistivity was mainly obtained as supplementary information by wire line logging of wells (Eidesmo et. al., 2002). However, utilizing non-invasive marine EM methods offer clear cost-effective advantages over conventional logging methods.

This numerical modeling study evaluated the sensing ability of the three different marine EM methods to sense a thin hydrocarbon reservoir in deep marine environments. The MMT, the marine FDCSEM and marine TDCSEM methods were selected in this study
and their synthetic responses and the related physics were investigated using numerical modeling techniques.

5.2 NUMERICAL MODELING METHODS

To investigate how marine EM methods sense a thin resistive hydrocarbon reservoir and what the factors governing their responses are, synthetic EM responses for the hydrocarbon reservoirs and background models were calculated using the two layered-earth analytical codes ((i) formulated by Ki-Ha Lee and (ii) provided by K. –M. Strack), a modified version of 3-D frequency-domain finite difference modeling code (Newman and Alumbaugh, 1995) and the parallel version of 3-D time-domain finite difference modeling code (Commer and Newman, 2004).

For the marine FDCSEM modeling, eleven source frequencies, from 0.01 to 1 Hz were considered, and five different 3-D finite difference grids were employed to simulate the different source frequencies. The average dimensions of these grids were 84 * 84 * 111 cells, and the smallest cell size in z-direction was 12.5 m (at high frequencies) or 25 m (at low frequencies) to handle large contrast of electric resistivity at the air-seawater interface and at the boundaries of the hydrocarbon reservoir. The largest cell size in the finite difference grids is set so it does not exceed 20 times the smallest cell size. These 3-D forward finite difference models were computed on UW-Madison’s Condor platform, a large collection of distributively owned serial computers.
For the MMT modeling, ten different 3-D finite difference grids were employed to simulate the different source frequencies from 1E-4 to 0.4 Hz. The average dimensions of these grids were 80 * 80 * 120 cells. Again, the smallest cell size in z-direction of 12.5 m or 25 m was used to handle large contrast of electric resistivity at the air-seawater interface and at the boundaries of the hydrocarbon reservoir. All these 3-D forward models were computed on PC workstation platforms.

Synthetic EM responses of the marine TDCSEM method were computed by the parallel version of the 3-D FDTD code (Commer and Newman, 2004). The finest cell size near the source was 50m. Beyond the vicinity of the source, the cell size increases by a growth factor of 1.25 and finally, x, y and z boundaries were at ± 20 km. These large model dimensions were used so that the effects caused by boundary conditions could be neglected.

5.3 NUMERICAL MODELING RESULTS

5.3.1 1-D HYDROCARBON RESERVOIR MODEL

The 1-D reservoir model (Figure 5.1a) consists of a 100 m thick, 100 Ohm-m layer representing a hydrocarbon reservoir, embedded at a depth of 1km below a 0.7 Ohm-m seafloor. A 1km thick, 0.3 Ohm-m seawater layer overlies the seafloor. As the background model (Figure 5.1b), the same seafloor model was employed without the reservoir.
The marine FDCSEM method employed a 250 m long, 100 A, x-directed HED which was placed 950 m below the air-water interface. Seafloor EM receivers were densely deployed on the seafloor in a grid pattern with 400 m spacing. The electric receiver noise level is set to $1.0 \times 10^{-10}$ (V/m) and the magnetic receiver noise level to $1.26 \times 10^{-5}$ (nT) (Ed Nichols, personal communication). The marine TDCSEM method utilizes the same survey configuration as the marine FDCSEM method employs. The same size time-domain HED is employed instead of the frequency-domain HED and the ramp-off time is set to $1.0 \times 10^{-4}$ seconds.

### 5.3.1.1 THE MARINE MAGNETOTELLURIC METHOD

For the MMT method, the apparent resistivity plots are calculated and compared for the background and 1-D reservoir models in Figure 5.2. The true resistivity contrast between the background sediment and the hydrocarbon reservoir varies from 5 to 200. Although the conversion of the synthetic data into apparent resistivities is a normalization procedure, the apparent resistivity can be a good approximation to actual subsurface resistivity and thus, apparent resistivity plots can serve to evaluate how the MMT method is sensitive to a thin hydrocarbon reservoir. If there is no significant difference in the apparent resistivity of the two models, the MMT method is deemed inappropriate for the detection of such a resistive hydrocarbon reservoir (Pellerin et. al., 1996).

Figure 5.2 shows that the MMT method is insensitive to the thin resistor and the response for the conductive sediment is dominant. Figure 5.2 also demonstrates the insensitivity of
the MMT method to the variation of the electric resistivity of the reservoir. There is little change in response as the resistivity contrast between the reservoir and its surrounding increases beyond a ratio of 10:1 (Hoversten et al, 1998).

In order to explain this characteristic of the MMT method, the electric field and current density vector along the 2-D cross-section are plotted at 0.04 Hz in Figures 5.3 and 5.4, respectively. In Figure 5.3, there is no noticeable difference in the electric field distribution between the background model and the 1-D reservoir model. This is because the source fields consist of purely horizontal fields as shown in Figure 5.3, and horizontal electric fields should be continuous along resistivity boundaries. Therefore, the current density distribution plots of the 1-D reservoir model (Figure 5.4b) merely show the thin missing layer of current density in the place of the 1-D reservoir, and the overall current distribution patterns, between the two models, are the same as Figure 5.4. As a result, the electric and magnetic responses on the seafloor are essentially the same for the two models. This modeling result indicates that the MMT technique can not solely sense the presence of the 1-D hydrocarbon reservoir as its response depends mainly on the inductive response.
5.3.1.2 THE MARINE FREQUENCY-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHOD

5.3.1.2.1 HORIZONTAL ELECTRIC FIELD RESPONSE

To understand how the marine FDCSEM method senses a thin resistive target, synthetic EM responses for the background and 1-D reservoir models were generated. Figure 5.5 shows the in-line and broadside x-directed electric field amplitudes ($E_X$) calculated at the seafloor for both the background and 1-D reservoir models. The normalized responses shown in Figure 5.5d are computed by dividing the 1-D reservoir responses by the background responses.

As source-receiver separations increase in Figures 5.5a and 5.5b, the $E_X$ of the background model decays exponentially on a semi-log plot up to approximately 4.9 km in separation. Beyond this distance, the slope of $E_X$ for the background model becomes constant on the same plot. Notice that this distance also corresponds to the position of the last inflection point on the $E_X$ phase curves for the background model shown in Figure 5.5c. At larger separation values, the $E_X$ phase for the background model becomes constant as the slopes of the $E_{X_{IP}}$ and $E_{X_{OP}}$ for the background model decay at the same constant rate.

When the $E_X$ plot for the background model is compared to that of the 1-D reservoir model, it is possible to separate response into the three distinct zones. For separation
distances from 0 km to 1.4 km, there is no difference between the two model responses. From 1.4 km to 4.9 km, the 1-D reservoir model starts to produce larger responses than the background model, and the difference in the amplitudes between the models grows until the source-receiver separation distance reaches about 4.9 km. Beyond 4.9 km, the gap between the two curves starts to narrow. As a result, the peak of the normalized $E_X$ field occurs at 4.9 km (Figure 5.5d) when the reservoir responses are normalized by the background responses. The difference in the position of the peak between in-line and broadside configurations is insignificant, but there is a large difference in the peak amplitudes between both configurations.

To help explain the observation in Figure 5.5, cross-sectional views of the electric field in both models are shown in Figure 5.6 (the in-line configuration) and Figure 5.7 (the broadside configuration).

First, the xz cross-sectional view of the in-line electric fields at $y=0$ (m) is examined in Figure 5.6 to explain the response of the in-line configuration. In the vicinity of the HED (zone 1), the induced electric field of the background model is identical to that of the 1-D reservoir model. The seafloor receivers close to the source in both models record the same $E_X$ field which mainly passes through the seawater and partly through very shallow seafloor sediment. Hence, the $E_X$ plots for both models overlap each other up to 1.4 km on the X-axis in Figures 5.5a and 5.5b. Beyond this point, the amplitude and direction of the seafloor electric field in the 1-D reservoir model is different from that of the background
model, as seafloor receivers start to sense the electric responses that are affected by deep seafloor sediment.

The HED-induced electric field drives both horizontal and vertical currents in the conductive marine media. As vertical current is normally incident upon the boundary of the horizontal reservoir, charge buildup occurs along the boundary in order to satisfy one of the electromagnetic boundary conditions: continuity of normal current. The electric fields from these charges: (i) superimpose on the initial HED induced fields, (ii) distort the geometry of the initial induced fields, and (iii) contribute extra strength of electric field to the seafloor receivers. Hence, the electric field measured on the seafloor for the 1-D reservoir model is much larger than that for the background model.

When the 3-D geometry of the electric fields of the HED is considered, it is obvious that the inductive responses dominate the broadside configuration. On the yz cross-section of the two models at x=0 (m) in Figure 5.7, the electric field produced by the HED is induced horizontally around the reservoir without being incident upon it. Comparing to Figure 5.6, there is less difference in the seafloor electric field distributions between the two models. Thus, the inductive dominated response of the broadside configuration yields a much smaller anomaly than that of the in-line configuration (Figure 5.5d). Note that strong anomalous $E_X$ fields are developed along the upper and lower boundaries of the reservoir in Figures 5.7c and 5.7d but they do not affect the electric fields on the seafloor.
Next, where the normalized peak amplitude occurs in Figure 5.5d is directly related to the effect of the air-seawater interface. The diffusing EM wave from the source arrives at the air-seawater interface, then propagates in the air along the interface without attenuating as the resistivity in the air can be assumed to be infinity. Thus the only decrease in its amplitude in this path occurs due to geometrical spreading. However, as it propagates through the air it continually excites EM energy to be ‘refracted’ back into the seawater. The critical angle of refraction is nearly 90°, resulting in the lateral EM wave, or the so-called airwave, in the seawater (Eidesmo et al., 2002). Note that this strong airwave contains no information about the seafloor resistivity structure.

The airwave dominates the seafloor EM response when the source-receiver offset is much larger than the sea-water depth. This is possible because the airwave propagates with minimal loss in energy though the air while the seafloor EM response is significantly attenuated in the conductive media. Thus at those distances where the airwave is the dominant arrival at the seafloor, the decay rate of the measured EM fields appears to be smaller on a semi-log plot (Figure 5.5). As a result, the gap between the $E_X$ values for both models begins to decrease at around 4.9 km and thus the peak of the normalized electric field occurs at this same distance. In addition, the phase of the electric field becomes constant as the phase of the airwave does not change as it propagates across the air-seawater interface. Thus, the peak location is also where the phase of the background seafloor response becomes constant. For convenience, FDCSEM critical distance is
defined as the point where the maximum value occurs and (or) the point where the phase of the background field becomes constant.

A few factors control where the FDCSEM critical distance exists. The primary factor to determine the FDCSEM critical distance is the depth of seawater. The airwave is attenuated more rapidly in a thicker water column before it reaches the seafloor. As a result, the seafloor EM response can withstand masking effect of the airwave even at larger source-receiver offset. Hence, the FDCSEM critical distance becomes more distant from the source in deeper marine environment. Lower source frequencies and a more resistive background of the seafloor also make the FDCSEM critical distance larger because of low attenuation of the seafloor EM responses in conductive media.

To illustrate how the peak location changes with different model parameters, the locations of the maximum normalized electric fields are calculated as a function of source frequency, sea depth and background resistivity of the seafloor in Figure 5.8. The peak location is determined uniquely by the background model parameters. However, the peak amplitude is a function of the size of the resistive reservoir, its depth, and source strength, and can not be tabulated as a universal reference.

Next, a number of source frequencies ranging from 0.01 Hz to 10 Hz were employed to calculate the normalized $E_X$ responses shown in Figure 5.10 for the same models. As the source frequency increases, the normalized responses become very narrow for the largest
amplitude peaks. At very low and very high frequencies, the marine FDCSEM method does not yield favorable results. To evaluate what happens at the extremes of frequencies investigated, the 2-D electric field responses were calculated and plotted in the same way as done in Figure 5.6 for the lowest and highest frequencies (0.01 Hz in Figure 5.11 and 10 Hz in Figure 5.12).

At 0.01 Hz, the vertical currents develop broadly and the FDCSEM response comes from a much larger volume of the subsurface and seawater. Thus, the FDCSEM responses tend to lack resolution for the structures of interest. At 10 Hz in Figure 5.12, the vertical electric fields that are above the receiver noise level are very localized in the vicinity of the source due to attenuation. Elsewhere, the effects of attenuation make the electric field too small to consider. In addition, the horizontal electric fields due to the airwave exists even at large depths below the seafloor in Figures 5.12a and 5.12b. As a result, at the higher frequencies, there is no noticeable effect of the 1-D reservoir on the seafloor electric field seen in Figures 5.10, 5.12c and 5.12d. Hence the 10 Hz source fails to sense the target.

In the described 1-D modeling study, the frequencies from 0.4 Hz through 1 Hz yield the best survey results. Although other higher frequencies, between 1 and 10 Hz, show larger responses (Figure 5.10), using these frequencies in practice is limited by the receiver noise level. This will be discussed later.
Electric field distributions at 0.63 Hz are shown in Figure 5.6. The vertical currents develop high concentration around a depth of 2 km, the target depth in Figures 5.6a and 5.6b. Thus, the vertical currents can efficiently interact with the horizontal layer. As a result, the 0.63 Hz source yields a noticeable and measurable difference of the electric field amplitude on the seafloor between the two models.

Another interesting feature shown in Figure 5.10 is the sharp, high magnitude peaks of the normalized response at the frequencies of 2.5 Hz and 4.0 Hz. To investigate this feature, the $E_X$ response for the in-line configuration along the survey line, and the cross-section of the electric field distribution at 2.5 Hz were plotted in Figure 5.13. It is clear that in Figure 5.13a, the dip of the $E_X$ plot around 4 km from the source for the background model causes this sharp peak. Comparing Figure 5.13a to Figures 5.13b and 5.14c, it is seen that dips of $E_{X, IP}$ plot and $E_{X, OP}$ plot correspond to the location of a phase reversal in both the $E_{X, IP}$ and the $E_{X, OP}$ on the seafloor. If $E_{X, IP}$ and $E_{X, OP}$ change their phases at approximately the same location on the survey line, the $E_X$ plot for the background model has the dip, resulting in an additional peak. For convenience, this additional peak is defined here as ‘phase reversal peak.’ In Figure 5.13a, the location of the phase reversal is close to the FDCSEM critical distance. Thus, this phase reversal peak superimposes on the peak due to the FDCSEM critical distance, yielding the sharp peak in Figure 5.10a. From this, it is possible to predict what happens if a phase reversal peak is far from a FDCSEM critical distance. In this case, the peak of the normalized $E_X$ may not occur only at the
FDCSEM critical distance but where the phase reversal of the field occurs. Furthermore, the phase reversal peak can be larger than the peak due to the FDCSEM critical distance.

To this point, the normalized $E_X$ response along a single survey line has been analyzed to understand the physics of the marine FDCSEM method. Due to the 3-D nature of the HED-induced fields, it is worth analyzing the normalized horizontal electric field responses over the entire seafloor. The amplitude of the total horizontal electric field, $\sqrt{E_x^2 + E_y^2}$ was calculated on the seafloor in both models and then normalized at a few selected frequencies (Figure 5.14). Note that at 2.5 Hz, the peak of the normalized response can not be measured in practice with current technology due to receiver noise level. Again the two facts that were verified along a single survey line are double-checked: the sensing ability of the marine FDCSEM method in broadside configuration is poor compared to that of the in-line FDCSEM configuration. In addition, the peak location of the normalized horizontal electric field is mainly defined by the boundary beyond which the phase of $E_X$ for the background model becomes constant due to airwave.

5.3.1.2.2 VERTICAL ELECTRIC FIELD RESPONSE

A conventional marine EM receiver is designed to measure horizontal EM fields on the seafloor. However, the behavior of the vertical component of the electric field on the seafloor is of interest in this study. Considering the geometry of an x-oriented HED-induced field, the vertical component of electric field does not exist along the broadside (y-oriented) survey line or is too small to be measured in a practical sense. Hence, only
the $E_Z$ response for the in-line configuration is shown in Figure 5.15. This result illustrates that the vertical electric field measurement can be a useful additional measurement for the marine FDCSEM survey. Notice that there is no effect of the airwave on the vertical electric fields because the airwave is totally horizontal. A number of source frequencies ranging from 0.01 Hz to 10 Hz are employed to calculate the normalized $E_Z$ responses for the same models in Figure 5.16 and Figure 5.17. Huge normalized $E_Z$ responses along the in-line survey line are observed, as $E_Z$ of the background model, the denominator of normalization process, reduces to zero beyond its FDCSEM critical distance.

5.3.1.2.3 HORIZONTAL MAGNETIC FIELD RESPONSE

Magnetic field responses are an additional and useful measurement for CSEM methods. The difference of the magnetic fields between the background and reservoir models depends on how the HED-induced currents in conductive seawater and below conductive seafloor are distorted by the 1-D reservoir as the different current flow patterns produce different magnetic fields at a given point.

Figure 5.18 shows the $B_Y$ field response of the two models along the in-line and broadside survey line on the seafloor. As with the electric fields, the normalized magnetic field response for the in-line configuration behaves differently from that for the broadside configuration.
First, the response for the in-line configuration is observed in Figure 5.18a. For a source-receiver separation from 0 km to 1.6 km, there is no difference in $B_Y$ amplitudes between the two models. From 1.6 km to 6.1 km, the 1-D reservoir model starts to give larger response than the background model. The difference in the $B_Y$ amplitudes between the models gets larger until the source-receiver separation distance reaches 6.1 km. As the slope of the $B_Y$ component for the background model becomes less steep at 6.1 km, the gap between the two plots starts to narrow. As a result, the peak of the normalized $B_Y$ field occurs at 6.1 km (Figure 5.18d). The $B_Y$ phase of the background model also becomes constant around 6.1 km in Figure 5.18c. Compared to the normalized $E_X$ field for the in-line configuration (Figure 5.5d), it is distinctive that the normalized $B_Y$ field for the in-line configuration (Figure 5.18d) has the second peak around 4.2 km on the source-receiver separation axis.

To explain the observation in Figure 5.18, cross-sectional views of the complex $B_Y$ field are presented in Figure 5.19 for the two models. The 1-D reservoir model produces fields that are laterally stronger than that of the background seafloor model, resulting in large normalized $B_Y$ response on the seafloor. Because this anomalous magnetic response is the direct result from the difference in the current patterns between the two models, it is required to analyze induced current distribution, as shown in Figure 5.20 which is very similar to induced electric fields in Figure 5.6. As the vertical currents interact with the horizontal resistive reservoir, charge buildup occurs along the upper and lower boundaries of the reservoir. This extra charge buildup on the surface of the reservoir produces an
increase in electric potential which can drive currents in conductive media. Therefore, more intense current flows are developed above and below the 1-D reservoir in Figures 5.20c and 5.20d. As a result, the 1-D reservoir model yields larger a magnetic field than the background model.

The two interesting differences between the normalized magnetic fields (Figure 5.18) and the normalized electric fields (Figure 5.5) are that (a) the width of the normalized magnetic fields is broader than that of the normalized electric fields, and (b) the normalized magnetic field has the dual peaks.

The reason for the broad width of the anomaly in the normalized magnetic fields is due to the fact that, in the near and intermediate zones of the source, the decay rate of the magnetic field is smaller than that of the electric field. For example, in the near field zone which is the domain of small values of R, the amplitude of the magnetic field decreases approximately as $1/R^2$ while the amplitude of the electric field decreases as $1/R^3$ (where R is the radial distance from the center of the dipole to the measurement point). As a result, the magnetic field curve has broader width than the electric field. This broad pattern of the magnetic field may be considered unfavorable from the detection point of view of a sharp anomaly due to the reservoir. However, this slower decay rate has an advantage: the magnetic field has better opportunities to overcome ambient electromagnetic noise and receiver noise problem. For example, the electric field for the in-line configuration for the 1-D reservoir model can be measured up to 8.5 km from the source location in Figure 5.5
while the magnetic field for the in-line configuration for the 1-D reservoir model can be measured over 10 km from the source location in Figure 5.18.

In order to determine what causes the secondary peak of the normalized magnetic field for the in-line configuration in Figure 5.18d, it is necessary to observe the background $B_{Y \text{ IP}}$ and $B_{Y \text{ OP}}$ plots in Figure 5.18a. It is obvious that the phase reversal of $B_{Y \text{ IP}}$ and $B_{Y \text{ OP}}$ is responsible for gentle decrease in the slope of $B_Y$ (the black-dashed contour) in Figure 5.18a. For the normalized electric field response in Figure 5.10a, the phase reversal of the seafloor $E_{X \text{ IP}}$ and $E_{X \text{ OP}}$ occurs around the FDCSEM critical distance, and hence, we see a single peak. However, if the phase reversal occurs away from the FDCSEM critical distance, dual peaks can be produced. As for the broadside configuration in Figure 5.18d, the peaks of the normalized $B_Y$ field occur at around 3.6 km due to sign reversal and at around 5.6 km due to the FDCSEM critical distance on the source-receiver separation.

The broadside magnetic fields in the background and the 1-D reservoir models in Figure 5.21 show less difference at the seafloor-seawater interface than those in Figure 5.19. Hence the normalized peak for the broadside configuration is relatively small in Figure 5.18d. This is because the nearly horizontal currents around the seafloor on the $x=0$ cross-section for the broadside configuration are not distorted as much by the 1-D reservoir as for the in-line configuration. Notice that strong anomalous $J_X$ fields are developed along the upper and lower boundaries of the reservoir in Figures 5.22c and 5.22d but the perturbation tends not to reach the seafloor.
To illustrate how the peak location changes with different model parameters, the locations of the maximum normalized magnetic field were calculated as a function of source frequency, sea depth and background resistivity of the seafloor in Figure 5.23. The overall pattern of the plots in Figure 5.23 follows what is expected: the peak location gets close to the source location as the source frequency increases, water depth decreases, and resistivity of seafloor decreases.

The corresponding peak amplitudes for cross-referencing are presented in Figure 5.24. For completeness in the 1-D modeling study, a number of source frequencies ranging from 0.01 Hz to 10 Hz were employed to calculate the normalized $B_Y$ responses in Figure 5.25. When the 2-D normalized horizontal magnetic field plots with noise level contour of magnetic receiver are observed at a few selected frequencies (Figure 5.26), the frequencies from 0.4 Hz through 1 Hz are chosen as the optimal frequency band for the magnetic field analysis. Note that the noise level contours of the magnetic receiver in Figure 5.26 cover a larger area than that of the electric receiver in Figure 5.14 because the decay rate of the magnetic field is smaller than that of the electric field within the shown source-receiver separation (non-perfect far field zone). In Figure 5.26, the peak locations correspond well to boundaries beyond which the $B_Y$ phase becomes constant.
5.3.1.3 THE MARINE TIME-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHOD

In order to compare the marine TDCSEM method to the marine FDCSEM method, the time-domain HED source, and any other modeling parameters were kept identical to those used in the marine FDCSEM modeling. The only difference is that the step-off synthetic responses for the background, the 1-D reservoir, and the 3-D reservoir models were computed.

The in-line $E_X$ and $E_Z$ responses are shown in Figure 5.27, the broadside $E_X$ and $dB_Y/dt$ responses in Figure 5.28, and the in-line $dB_Y/dt$ and broadside $dB_Z/dt$ responses in Figure 5.29. The marine TDCSEM method senses the presence of the 1-D reservoir. However, the observed difference in the in-line $E_X$ responses between the 1-D reservoir and background models in Figure 5.27a-c are relatively small, and most of the differences are a DC response in early time rather than a transient response within the decay. The broadside $E_X$ measurements in Figure 5.28 are also overwhelmed by a DC response, and show more complicated responses with a sign-reversal. This is because the $E_X$ receivers in the broadside configuration initially record the return currents, which has the opposite direction to the source polarization in early time, but then are affected by the image current at late time.

While the horizontal magnetic field measurements at the air-land interface can not sense a thin resistor at depth as discussed in Chapter 4, the horizontal magnetic field
measurements (Figure 5.28d-f and 5.29a-c) on the seafloor sense the presence of the 1-D resistive reservoir. This is possible because the transient vertical currents are not canceled out at the seawater-sediment interface, and hence both horizontal and vertical transient currents contribute to the measured horizontal magnetic fields on the seafloor. In contrast, the vertical magnetic field measurements (Figure 5.29d-f) along the broadside survey line do not discern the 1-D reservoir because they are generated by horizontal current flows.

Compared to the marine FDCSEM in-line $E_X$ responses (Figure 5.5), the marine TDCSEM in-line $E_X$ responses suggests a poorer sensing ability than the marine FDCSEM method even though time-domain responses should be transformable into frequency domain ones using Fourier’s theorem (Cheesman et al., 1987). These counterintuitive results can be explained by the fact that the step-off transient response consists of the Fourier Transform of $1/(f*FD(f))$ where $f$ is the frequency, and $FD(f)$ represents the frequency-domain response. Thus the high frequency signals which are most sensitive to the reservoir are down-weighted.

This small difference of the measured responses between the two models in the marine TDCSEM method is verified by viewing the current distribution between the background model (Figure 5.30) and the 1-D reservoir model (Figure 5.31). In both models, the strong horizontal transient currents are mainly confined in the most conductive seawater, and this current distribution dominates the overall responses in the two models. The electric field snapshots are also shown in Figure 5.32 for the background model and in Figure 5.33 for
the 1-D reservoir model. Even though the charge build-up along the boundary due to vertical currents produces strong electric fields, colored as red, near the reservoir, the effect of these electric fields is limited around the reservoir boundary, and thus its contribution to the seafloor electric field is insignificant.

An alternative to the step-off is to analyze the impulse response which can be approximated by taking the time-derivative of the step-off response. The impulse response should provide better results due to the fact that higher frequency information is introduced through the impulsive source current. This argument is also applied to explain why the time-derivatives of the horizontal magnetic fields (Figure 5.29) senses the reservoir better than the in-line horizontal electric field responses (Figure 5.27).

The time-derivatives of the in-line $E_x$ and $E_z$ responses are plotted in Figure 5.34, and the time-derivatives of the broadside $E_x$ response in Figure 5.35. They indicate the presence of the 1-D reservoir more clearly than the step-off responses (Figure 5.27). The electric field response for the background model in Figure 5.34 consists of two parts (Edwards, 1988). The first perturbation is caused by the fast diffusion of the EM field through the less conductive marine sediment, and the second perturbation is by slow diffusion through the most conductive seawater. As the source-receiver separation becomes shorter, the electric field perturbation by the diffusion through the marine sediments is overlaid with the perturbation by the diffusion through the seawater. The two-path diffusion becomes more visible as the source-receiver separation becomes larger. This is because the
difference in diffusion velocity between the two media is highlighted at larger offset. However, it is suggested to find an optimal source-receiver separation rather than to choose the possible largest source-receiver separation, because the impulse signal becomes smaller and broader due to dispersion with distance.

This two-path diffusion of the impulse EM signal helps the TDCSEM method to overcome the ‘air-wave’ problem associated with the FDCSEM method in shallow marine environments. The 1-D FDCSEM and TDCSEM responses with varying seawater depth are shown in Figure 5.36. The FDCSEM method does not work effectively at shallow seawater depth because the airwave dominates the seafloor EM responses. As for the TDCSEM method, the two-path diffusion phenomenon becomes complicated in shallow water by the effects of the air but there are still large differences between the responses with and without the 1-D reservoir. This is possible because the seawater response lags behind the seafloor response due to the difference of electric conductivity between the seafloor and the seawater.

Shown in Figure 5.27 and 5.34, the vertical electric field (E_Z) measurement can be a useful additional measurement for the TDCSEM method. The smaller amplitude of E_Z implies that developing more sensitive seafloor receivers and more powerful transmitters is a critical factor to measure E_Z on the seafloor successfully. As for the time-derivatives of the broadside E_X responses in Figure 5.35, it is difficult to define the two-path diffusion visually in the same way as done for the time-derivative plots of the in-line E_X responses.
This is because the effect of sign reversal becomes dominant when time-derivative of the broadside $E_x$ response is taken.

### 5.3.2 3-D HYDROCARBON RESERVOIR MODEL

For a more realistic marine EM forward model, the previous 1-D hydrocarbon reservoir is replaced by a 3-D anticline reservoir. The description of the 3-D hydrocarbon reservoir and the associated survey configuration are shown in Figure 5.37. All other modeling parameters for the 3-D forward modeling were kept the same as the 1-D forward modeling for consistency.

#### 5.3.2.1 THE MARINE MAGNETOTELLURIC METHOD

The MMT apparent resistivity and impedance phase plots for the background and 3-D reservoir models are given in Figure 5.38. The $Z_{XY}$ mode corresponds to the impedance calculated using x-directed electric field and y-directed magnetic field. In this study, the $Z_{XY}$ response is the same as the $Z_{YX}$ response when the $Z_{XY}$ response is rotated by 90 degrees due to the two fold symmetry of the 3-D reservoir. Shown in Figure 5.38, the MMT method is not useful in detecting the anomalous responses due to the 3-D hydrocarbon reservoir.

Meanwhile, the sides of the 3-D reservoir are delineated better on the $y=0$ plane in the $xy$ apparent resistivity plot than on the $y=0$ plane in the $yx$ apparent resistivity plot. In order
to explain this characteristic of the MMT method, the $Z_{XY}$ electric field and current distribution plots for the 3-D reservoir model are presented in Figure 5.39. Comparing Figure 5.38a to Figure 5.4, the telluric currents around the 3-D reservoir sides do contain a normally incident component upon the sides of the reservoir. When these currents interact with the sides, charge buildup occurs along the boundaries of the reservoir sides in order to satisfy one of the EM boundary conditions: continuity of normal current. The electric fields from these charges distort the local electric field slightly. However, the boundary charges do not contribute to the $Z_{YX}$ response because the $Z_{YX}$ electric field is parallel to the strike direction of the sides of the reservoir. As a result, the $Z_{YX}$ response on the $y=0$ plane does not sense the boundary of the reservoir as well as the $Z_{XY}$ response on the $y=0$ plane. This modeling study clearly demonstrates that boundary charges play an important role in the amplitude of a resistive reservoir anomaly.

Another interesting aspect of the MMT technique is the spatial variation of the vertical electric field on the sea floor when the section below the sea floor contains 2-D or 3-D inhomogeneity. Hoversten et al (1998) theoretically explained that vertical electric field measurements on the sea floor may be a useful additional measurement for the MMT method in order to detect 2-D or 3-D structures, because, at the sea-floor interface, the vertical component of electric field can be non-zero. In this study, the ratio of vertical electric field to horizontal electric field was computed along the profile at 0.04 Hz in Figure 5.40. This ratio value will be zero if the section below the sea floor is 1-D. Figure 5.40 illustrates that the vertical electric field measurement is sensitive to the presence of 2-
D or 3-D inhomogeneity below the seafloor. However, this measurement may not be useful in practice because of its small amplitude. For example, at x=1.1 km, the amplitude of the vertical electric field is only 2% of that of the horizontal electric field.

### 5.3.2.2 THE MARINE FREQUENCY-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHOD

#### 5.3.2.2.1 ELECTRIC AND MAGNETIC RESPONSES

Figure 5.41 shows the normalized horizontal E field response of the 3-D reservoir model at four different x-oriented HED positions along the survey line on the x-axis (colored green in Figure 5.37b): (0 m, 0 m, 950 m), (1000 m, 0 m, 950 m), (2000 m, 0 m, 950 m) and (3000 m, 0 m, 950 m). Comparing the normalized electric field responses here to those from the 1-D reservoir modeling in Figure 5.14, the 3-D reservoir modeling results yield a few interesting features. The peak amplitudes of the normalized electric fields of the 3-D reservoir model are much smaller than those of the 1-D reservoir models, and vary with source position. The normalized field responses of the 3-D reservoir model decrease relatively quickly after the peak, while the normalized field responses of the 1-D reservoir model fall off more gradually.

To understand the difference of the normalized responses between the 1-D and the 3-D reservoir models, 2-D electric field distribution plots (Figure 5.42) and the 2-D current distribution plots (Figure 5.43) were plotted for the background, 1-D and 3-D reservoir
models. Two different x-oriented HED positions, (0 m, 0 m, 950 m) and (2000 m, 0 m, 950 m) were employed for the 3-D reservoir model.

Figures 5.42 and 5.43 imply that the magnitudes of the normalized horizontal electric fields in Figure 5.14 and 5.42 are related to the location of the hydrocarbon reservoir with respect to the highest concentration of the HED-induced vertical currents. In the case of the 1-D reservoir in Figure 5.43b, all vertical components of the HED-induced currents at 1000 m depth below the seafloor interact with the infinite horizontal slab of the reservoir. Therefore, the degree of charge-buildup on the surface of the 1-D reservoir is maximized. The additional electric fields from these electric charges are vector-superimposed on the electric fields from the HED, resulting in the large normalized electric field response shown in Figure 5.14.

If the 1-D reservoir is replaced by the localized 3-D reservoir shown in Figure 5.37, the degree of charge buildup depends on whether the high concentration of vertical currents can reach and interact with the reservoir effectively or not. For example, in Figure 5.43c, the 3-D reservoir is placed where the horizontal component of HED-induced currents are dominant. As a result, the minimal charge buildup on the surface of the 3-D reservoir does not significantly affect the electric field patterns between Figure 5.42a and Figure 5.42c. Thus the amplitude of the normalized horizontal electric field is insignificant in Figure 5.41a.
In contrast, when the HED position is changed from (0m, 0m, 950m) to (2000m, 0m, 950m) in Figure 5.43d, a high concentration of the currents normal to the reservoir boundary effectively interacts with the reservoir in the left side of the HED. Thus, a more distorted and higher amplitude electric field pattern is observed in Figure 5.42d, resulting in a larger normalized response in Figure 5.41c. Because the marine FDCSEM response is very dependent on source-receiver configuration when sensing a small localized hydrocarbon reservoir, high source-position density is required to ensure good coupling to the reservoir.

In order to analyze the horizontal electric field responses for the 3-D reservoir model in more detail, the seafloor $E_X$, $E_{X_{IP}}$, $E_{X_{OP}}$ and phase plots along the $y=0$ survey line for a source, (2000 m, 0 m, 950 m) are plotted in Figure 5.44. The FDCSEM critical distance for the background model defines the peak location of the normalized field at -2.8 km. In the 3-D reservoir model, the charge buildup around the finite 3-D reservoir just slightly extends the FDCSEM critical distance beyond that of the background model. Thus, beyond this critical distance, the amplitude of the electric field of the 3-D reservoir model quickly converges to the background value. As a result, the anomalous response after the peak is roughly confined between the two FDCSEM critical distances.

When the x-directed HED is towed along the diagonal survey line in Figure 5.37b, the normalized response looks more complicated as shown in Figure 5.45. Figures 5.41 and
5.45 illustrate that it is very difficult to predict the real boundary of the 3-D reservoir from
the normalized response in practice.

Figure 5.46 shows the normalized horizontal magnetic field responses over the 3-D
reservoir. The overall pattern of the normalized horizontal magnetic fields is very similar
to that of the normalized horizontal electric fields. The major benefit of using horizontal
magnetic field response is that the noise level contour of magnetic receiver in Figure 5.46
theoretically allows for greater aerial coverage compared to that of the electric receiver in
Figure 5.41. For the completeness in the 3-D reservoir modeling, the electric and magnetic
responses for the same 3-D reservoir model with the y-oriented HED are shown in Figures
5.47 and 5.48 respectively. Again, these plots demonstrate that the amplitude of the
FDCSEM response is very dependent on source-receiver configuration and the maximized
response occurs when the survey configuration provides max-coupling of the normal
currents to the reservoir.

The vertical electric field responses for the 3-D reservoir model and normalized
amplitudes are presented in Figure 5.49. As the source-receiver separation increases in
Figures 5.49a and 5.49b, the vertical electric field responses for the 3-D reservoir model
start to be distinguishable from those for the background model, indicating the presence of
the 3-D reservoir. In addition, its receiver level contours cover roughly the same region as
those for the horizontal electric fields in Figure 5.41a and 5.41c. Thus, vertical electric
field measurements on the sea floor will be a useful additional measurement for the marine FDCSEM method.

### 5.3.3.2.2 EFFECTS OF 2-D BATHYMETRY

Seafloor topography is an additional parameter that will affect the results of the marine FDCSEM method. Irregular topography does not allow seafloor EM receivers to be at the same depth from the air-seawater interface, and can also produce different electric field distributions locally in the seawater column. In this sub-section, the 1-D and 3-D reservoir models employed previously have a simple 2-D bathymetric profile introduced as shown in Figure 5.50. This 2-D bathymetric profile includes an exaggerated vertical cliff. As the background model, the same 2-D seafloor model was used without the reservoir. The other modeling parameters and the description of the reservoir are the same as those described in the previous sub-sections.

The horizontal E field responses of the 1-D reservoir model (Figure 5.50a) were computed at two x-oriented HED locations: (-2000 m, 0 m, 950 m) and (2000 m, 0 m, 950 m). When the HED is placed at (-2000m, 0m, 950m), the asymmetry of the normalized E_X responses (Figure 5.51c) clearly shows how this simple topographic change affects the marine FDCSEM results. The survey line on the right side yields larger normalized E field response since the seafloor EM receivers on the right side of the HED are closer to the 1-D reservoir than those on the left side. In contrast, the peak location from the source on the right side is not significantly different from that on the left side. Figure 5.51c suggests that the topographic effects mainly come from the receiver-reservoir distance and not
from the airwave effect. This argument can be verified directly by viewing the 2-D electric field plots in the background and 1-D reservoir models shown in Figure 5.52. The forward modeling results at the other HED position are shown in Figures 5.53. The same explanation can be applied to Figure 5.53c. Besides the analysis of the E field responses, the B field responses are shown in Figure 5.54 for completeness in the modeling study. As explained before, they are basically the same as the E field responses but their width is broader than E field responses.

For a more realistic investigation for the topographic effect, the previous 1-D reservoir was replaced by the 3-D reservoir (Figure 5.50b). The E and B field responses for the model were computed, and then compared to those for the 1-D flat seafloor model bearing the same 3-D reservoir. Figure 5.55 clearly shows that the peak magnitude is highly affected by seafloor topography as well as the size of the reservoir, and the coupling of vertical currents to reservoir. Thus, the magnitude of the seafloor response can not be interpreted accurately without bathymetry information.

Figure 5.55 illustrates how the topographic variation of the seafloor can affect the normalized response in the marine FDCSEM survey, and suggests that high quality topographic information should be collected for any marine FDCSEM survey.
5.3.2.3 THE MARINE TIME-DOMAIN CONTROLLED SOURCE ELECTROMAGNETIC METHOD

The time-derivatives of the horizontal magnetic fields ($B_Y$), the horizontal and vertical electric fields ($E_X$ and $E_Z$) for the in-line configuration are computed for the 3-D reservoir model in Figures 5.56, 5.57 and 5.58 respectively. In order to examine the effect of the different geometrical coupling of the vertical transient currents to the 3-D hydrocarbon reservoir, the time-domain HED source was placed at the center of the reservoir, (0 km, 0 km, 0.95 km) and at the edge of the reservoir, (2 km, 0 km, 0.95 km). The source-receiver separations were 1 km, 4 km, and 8 km. The time-derivatives of the electric and magnetic responses for the broadside configuration were similar to those for the in-line configuration but yielded much smaller difference. Thus, they were not considered in this sub-section.

The computed responses in Figures 5.56, 5.57 and 5.58 are analogous to the marine FDCSEM responses for the 3-D reservoir model. That is, the anomalous responses due to the 3-D reservoir model are much smaller than those due to the 1-D reservoir, and vary with source positions relative to the body. Even though analytical and numerical forward modeling codes that can compute the impulse response are not currently available, making it impossible to generate the current distribution-snapshots for the impulse source, viewing the current distribution snapshots for the step-off source provides alternative insights to understanding Figures 5.56, 5.57 and 5.58.
The current distribution snapshots around the 3-D reservoir for the two source positions, (0 km, 0 km, 0.95 km) and (2 km, 0 km, 0.95 km) are presented in Figures 5.59 and 5.60 respectively. As the time-domain HED is moved from the center of the reservoir (Figure 5.59) to the edge of the reservoir (Figure 5.60), the vertical transient currents in the seafloor are coupled to the reservoir more efficiently, producing the larger anomalous responses as seen in Figures 5.56b, 5.57b and 5.58b.

Like the marine FDCSEM method, the marine TDCSEM method is very dependent on source-receiver configuration when over and adjacent to a small localized 3-D reservoir, and the diffusion angle of the vertical transient currents should be considered as an important survey factor to maximize the anomalous perturbation in the response.

5.4 CONCLUSIONS

Two types of galvanic source marine EM methods, the marine FDCSEM method and the marine TDCSEM method, have been investigated numerically, and compared to the MMT method.

As perceived in recent publications, the MMT method can not be used solely to determine if a seismic find is a hydrocarbon reservoir or brine reservoir. The primary reason for this failure is that the MMT method mainly relies on the inductive effect of horizontal source field which is inherently insensitive to thin resistors. The MMT method can at most
determine the vertical boundaries of a reservoir, if the structure of the reservoir changes rapidly in 3-D space, and thus the sides of the reservoir can cause charge buildup on themselves.

In contrast to the MMT method, the marine FDCSEM method is very sensitive to thin resistive hydrocarbon reservoirs at depth, since the response is both galvanic and inductive. The peak location of the normalized EM response is a function of source frequency, seawater depth and background resistivity of seafloor.

The peak magnitude of the normalized EM response depends on whether the high concentration of vertical currents can reach and interact with the reservoir effectively or not. Therefore, the normalized EM response of a localized 3-D reservoir is inherently much smaller than that of a 1-D reservoir. When the potential hydrocarbon reservoir has a strong 3-D nature and is localized, survey design becomes very important so that the vertical current can be more efficiently coupled to a localized 3-D reservoir yielding a maximized galvanic effect. Receiver noise level is also an important factor for successful survey design. The major benefit of using horizontal magnetic field response is that the noise level contour of the magnetic receiver theoretically allows for greater aerial coverage compared to that of the electric receiver.
The FDCSEM bathymetry modeling suggests that good quality bathymetry data should be collected during the survey cruise for an accurate interpretation of the FDCSEM data, because the magnitude of EM responses is noticeably affected by change of bathymetry.

The marine TDCSEM method is another promising EM geophysical tool for marine hydrocarbon exploration. Its response can be explained by two-path diffusion of the initial excitation through the more conductive seawater and the less conductive seafloor. When a 1-D resistive reservoir is inserted into the background model, the vertical transient currents interact with the horizontal resistive reservoir, producing charge buildup which causes the perturbation of the background electric fields. In order to enhance the degree of the anomalous perturbation, a proper transient EM pulse is required such that the relatively higher frequencies required for reservoir detection are produced. In this study, the time-derivatives of the step-off responses were taken alternatively to mimic the impulse source responses. Like the marine FDCSEM method, the marine TDCSEM method is also very sensitive to source-receiver configuration because the magnitude of the anomalous response depends on whether the vertical transient currents can be coupled to the reservoir efficiently or not.

This modeling study exemplifies that the vertical electric field measurements on the sea floor can be a useful additional measurement for both the marine FDCSEM and TDCSEM methods. In contrast, the vertical electric field measurement is not useful for the MMT method since its amplitude is too small to be measured in practice.
5.5 FIGURES

**Figure 5.1.** The 1-D seafloor models. (a) the 1-D reservoir model and (b) the background model.

**Figure 5.2.** MMT apparent resistivity sounding curves for the background and 1-D reservoir models. The resistivity of the reservoir varies from 3.5 Ohm-m to 140 Ohm-m.
Figure 5.3. Electric field distribution plots due to 0.04 Hz MMT plane wave source for the background and 1-D reservoir models.
Figure 5.4. Current distribution plots due to 0.04 Hz MMT plane wave source for the background and 1-D reservoir models.

(a) In-phase (left) and out-of-phase (right) current distribution for the background model

(b) In-phase (left) and out-of-phase (right) current distribution for the 1-D reservoir model
Figure 5.5. Ex responses at 0.63 Hz for the background and 1-D reservoir models. The partition of the left plots is based on the in-line responses and that of the right the broadside responses.
Figure 5.6. In-phase and out-of-phase E field distribution plots on the x-z plane at y=0 m for the background and 1-D reservoir models with a 0.63 Hz x-oriented HED source placed at (0 m, 0 m, 950 m). The same partition shown in Figure 5.5 is applied here.
Figure 5.7. In-phase and out-of-phase $E_x$ field distribution plots on the yz plane at $x=0$ m for the background and 1-D reservoir models with a 0.63 Hz x-oriented HED source placed at (0 m, 0 m, 950 m).
Figure 5.8. The distance from the source along the in-line survey line (in km) at which the normalized Ex peak occurs. An infinitesimal HED source is placed 50m above the seafloor and the resistivity of sea water was set to 0.3 Ohm-m.
Figure 5.8. Continued.
Figure 5.8. Continued.
Figure 5.9. The peak amplitudes of normalized in-line Ex fields. The infinitesimal HED source is placed 50m above the seafloor and the resistivity of sea water was set to 0.3 Ohm-m.
Figure 5.9. Continued.
Figure 5.9. Continued.
Figure 5.10. Normalized $E_X$ responses at the frequencies ranging from $1.0E^{-2}$ Hz to 10 Hz. (a) the in-line $E_X$ responses and (b) the broadside $E_X$ responses.
Figure 5.11. In-phase and out-of-phase electric field distribution plots on the xz cross-section at y=0 m for the background and 1-D reservoir models with a 0.01 Hz x-oriented HED source placed at (0 m, 0 m, 950 m).
Figure 5.12. In-phase and out-of-phase electric field distribution plots on the xz cross-section at y=0 m for the background and 1-D reservoir models with a 10 Hz x-oriented HED source placed at (0 m, 0 m, 950 m).
Figure 5.13. In-line $E_X$ field responses and the cross-sectional views of electric field distribution with a 2.5 Hz x-oriented HED source.
Figure 5.14. Normalized horizontal electric field plots (left column) for the 1-D reservoir model and $E_x$ phase plots (right column) for the background model. The black contours represent the electric receiver noise level and the white ones represent the boundary beyond which the $E_x$ phase becomes constant.
Figure 5.14. continued.
Figure 5.15. In-line Ez responses with a 0.63 Hz x-oriented HED source for the background and 1-D reservoir models.
**Figure 5.16.** Normalized in-line $E_z$ responses at the frequencies ranging from $1.0 \times 10^{-2}$ Hz to 10 Hz.

**Figure 5.17.** Normalized vertical electric field responses for the 1-D reservoir model. (a) has the linear scale color chart and others the log scale color chart. Black contours represent the electric receiver noise level.
Figure 5.17. Continued.
Figure 5.18. $B_y$ responses with a 0.63 Hz x-oriented HED source for the background and 1-D reservoir models. The partition of the left plots are based on the in-line responses and that of the right ones the broadside responses. The arrows in (d) indicate the secondary peaks.
The air – seawater boundary

(a) $B_Y_{IP}$ for the background model

Seawater-seafloor boundary

(b) $B_Y_{OP}$ for the background model

1-D reservoir boundaries

(c) $B_Y_{IP}$ for the 1-D reservoir model

(d) $B_Y_{OP}$ for the 1-D reservoir model

**Figure 5.19.** In-phase and out-of-phase $B_Y$ distribution plots on the xz cross-section at $y=0$ m for the background and 1-D reservoir models with a 0.63 Hz x-oriented HED source placed at (0 m, 0 m, 950 m).
Figure 5.20. In-phase and out-of-phase current distribution plots on the xz cross-section at y=0 m for the background and 1-D reservoir models with a 0.63 Hz x-oriented HED placed at (0 m, 0 m, 950 m).
Figure 5.21. In-phase and out-of-phase B distribution plots on the yz cross-section at x=0 m for the background and 1-D reservoir models with a 0.63 Hz x-oriented HED source placed at (0 m, 0 m, 950 m).
The air–seawater boundary

Seawater-seafloor boundary

1-D reservoir boundaries

Figure 5.22. In-phase and out-of-phase Jx amplitude distribution plots on the yz cross-section at x=0 m for the background and the 1-D reservoir models with a 0.63 Hz x-oriented HED source placed at (0 m, 0 m, 950 m).
Figure 5.23. The distance from the source along the in-line survey line (in km) at which the normalized By peak occurs. An infinitesimal HED source is placed 50m above the seafloor and the resistivity of sea water was set to 0.3 Ohm-m.
Figure 5.23. Continued.
Figure 5.23. Continued.
Figure 5.24. The peak amplitudes of normalized $B_y$ field for the in-line configuration. An infinitesimal HED is placed 50m above the seafloor and the resistivity of seawater was set to 0.3 Ohm-m.
Figure 5.24. Continued.
Figure 5.24. Continued.
Figure 5.25. Normalized $B_Y$ responses at the frequencies ranging from $1.0E^{-2}$ Hz to 10 Hz. (a) the in-line responses and (b) the broadside responses.
Figure 5.26. Normalized horizontal magnetic responses (left column) for the 1-D reservoir model, and \( B_Y \) phase plots (right column) for the background model. The black contours represent magnetic noise level and the white ones represent the boundary beyond which the \( B_Y \) phase becomes constant.
Figure 5.26. Continued.
Figure 5.26. Continued.
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**Figure 5.27.** The in-line $E_X$ and $E_Z$ responses at different receiver locations using the marine TDCSEM method.
Figure 5.28. The broadside $E_x$ and $dB_y/dt$ responses at different receiver locations using the marine TDCSEM method. The aqua lines represent the receiver noise level.
Figure 5.29. The in-line $d\mathbf{B}_y/dt$ and broadside $d\mathbf{B}_z/dt$ responses at different receiver locations using the marine TDCSEM method. The aqua lines represent the receiver noise level.
Figure 5.30. Current distribution snapshots at four different measurement times on the xz cross-section for the background model with a 250m long x-oriented time-domain HED source at (0 m, 0 m, 950 m). Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 5.30 Continued.
Figure 5.31. Current distribution snapshots at four different measurement times on the xz cross-section for the 1-D reservoir model with a 250m long x-oriented time-domain HED source at (0 m, 0 m, 950 m). Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 5.31 Continued.
Figure 5.32. Electric field distribution snapshots at four different measurement times on the xz cross-section, for the background model with a 250m long x-oriented time-domain HED source at (0 m, 0 m, 950 m). Total electric field (left), horizontal electric field (middle) and vertical electric field (right).
Figure 5.32 Continued.
Figure 5.33. Electric field distribution snapshots at four different measurement times on the xz cross-section for the 1-D model with a 250m long x-oriented time-domain HED source at (0 m, 0 m, 950 m). Total electric field (left), horizontal electric field (middle) and vertical electric field (right).
Figure 5.34. The time-derivatives of the in-line $E_X$ and $E_Z$ responses at different receiver locations the using the marine TDCSEM method.
Figure 5.35. The time-derivatives of the broadside Ex responses at different receiver locations using the marine TDCSEM method.

(a) 
(b) 
(c)
Figure 5.36. The 1-D FDCSEM and TDCSEM responses with varying depth of seawater. The four different seawater depths (100 m, 200 m, 400 m and 1000 m) are considered here. The previous 1-D hydrocarbon reservoir is embedded a depth of 1km below the seafloor.
Figure 5.37. The 3-D hydrocarbon reservoir model and the survey configuration. (a) the cross-sectional view of the 3-D hydrocarbon reservoir, and (b) the plan view of the 3-D hydrocarbon reservoir.
Figure 5.38. Volume representation of pseudo-sections for the MMT forward modeling of the 3-D reservoir model. (a) Z_{XY} apparent resistivity, (b) Z_{YX} apparent resistivity, (c) Z_{XY} impedance phase and (d) Z_{YX} impedance phase.
Figure 5.39. $Z_{XY}$ electric field and current density distributions due to 0.04 Hz MMT plane wave source for the 3-D reservoir model. (a) In-phase and out-of-phase current density vector field, and (b) in-phase and out-of-phase electric field.
Figure 5.40. The ratio of the vertical electric field to the horizontal electric field due to 0.04 Hz MMT plane wave source on the seafloor for the 3-D reservoir model.
Figure 5.41. Horizontal electric field responses for the 3-D reservoir model at four different x-oriented HED positions along y=0 m axis. Normalized horizontal electric field plots (left), $E_x$ phase plots for the background model (middle), and $E_x$ phase plots for the 3-D reservoir model (right). The black contours represent the receiver noise level and the grey-colored boxes show the boundary of the 3-D reservoir.
(c) X-oriented HED at (2000 m, 0 m, 950 m)

(d) X-oriented HED at (3000 m, 0 m, 950 m)

Figure 5.41. Continued.
Figure 5.42. In-phase and out-of-phase electric field distribution plots with a 0.63 Hz x-oriented HED source for three different models.
Figure 5.42. Continued.
Figure 5.43. In-phase and out-of-phase current density distribution plots with a 0.63 Hz x-oriented HED source for three different models.
Figure 5.43. Continued.
Figure 5.44. Electric field responses for the 3-D reservoir and background models along the y=0 survey line with the x-oriented HED at (2000 m, 0 m, 950 m)
Figure 5.45. Normalized horizontal electric field responses with a x-oriented HED source along the diagonal survey line shown in Figure 5.37b. The grey-colored boxes show the boundary of the 3-D reservoir.
Figure 5.46. Horizontal magnetic field responses at four different x-oriented HED positions along the x-axis. Normalized horizontal magnetic field plots (left), $B_X$ phase plots of the background model (middle) and $B_X$ phase plots of the 3-D reservoir model (right). The black contours represent the receiver noise level and the grey-colored boxes show the boundary of the 3-D reservoir.
(c) X-oriented HED at (2000 m, 0 m, 950 m)

(d) X-oriented HED at (3000 m, 0 m, 950 m)

Figure 5.46. Continued.
Figure 5.47. Horizontal electric field responses at four different y-oriented HED positions along the x axis. Normalized horizontal electric field plots (left), $E_Y$ phase plots of the background model (middle) and $E_Y$ phase plots of the 3-D reservoir model (right). The black contours represent the receiver noise level and the grey-colored boxes show the boundary of the 3-D reservoir.
(c) Y-oriented HED at (2000 m, 0 m, 950 m)

(d) Y-oriented HED at (3000 m, 0 m, 950 m)

Figure 5.47. Continued.
(a) Y-oriented HED at (0 m, 0 m, 950 m)

(b) Y-oriented HED at (1000 m, 0 m, 950 m)

Figure 5.48. Horizontal magnetic field responses at four different y-oriented HED positions along the x axis. Normalized horizontal magnetic field plots (left), $B_Y$ phase plots of the background model (middle) and $B_Y$ phase plots of the 3-D reservoir model (right). The black contours represent the receiver noise level and the grey-colored boxes show the boundary of the 3-D reservoir.
(c) Y-oriented HED at (2000 m, 0 m, 950 m)

(d) Y-oriented HED at (3000 m, 0 m, 950 m)

Figure 5.48. Continued.
Figure 5.49. \( E_z \) responses over the 3-D reservoir model for the in-line configuration at 0.63 Hz on the seafloor. (a) \( E_z \) responses with an x-oriented HED at (0 m, 0 m and 950 m), (b) \( E_z \) responses with an x-oriented HED at (2000 m, 0 m and 950 m), (c) normalized \( E_z \) response over the 3-D reservoir model with an x-oriented HED at (0 m, 0 m, 950 m), and (d) normalized \( E_z \) response over the 3-D reservoir model with an x-oriented HED at (2000 m, 0 m, 950 m).
Figure 5.50. The 2-D seafloor topography models. (a) the 1-D reservoir model and (b) the 3-D reservoir model. The red arrows represent HED positions.
Figure 5.51. $E_x$ responses for the seafloor models having the 2-D seafloor with a 0.63 Hz HED source at (-2000m, 0m, 950m).
Figure 5.52. In-phase and out-of-phase E field distribution on the xz plane at y=0(m) for the background model and the 1-D reservoir model with a 0.63 Hz HED source placed at (-2000 m, 0 m, 950 m).
Figure 5.53. $E_x$ responses of the seafloor model having the 2-D seafloor with 0.63 Hz HED at (2000 m, 0 m, 1150 m).
Figure 5.54. The normalized magnetic field responses at 0.63 Hz for the 1-D reservoir model at the two HED positions.
Figure 5.55. Comparison of the 2-D seafloor FDCSEM responses and the 1-D seafloor FDCSEM responses over the 3-D reservoir at 0.63 Hz. The x-oriented HED is 50m above the seafloor. (a) the HED in the 2-D seafloor model: (-2 km, 0 km, 0.95 km), (b) the HED in the 1-D seafloor model: (-2 km, 0 km, 0.95 km), (c) the HED in the 2-D seafloor model: (2 km, 0 km, 1.15 km), and (d) the HED in the 1-D seafloor model: (2 km, 0 km, 0.95 km)
Figure 5.56. The in-line dB/dt responses using the marine TDCSEM method. Two source positions and three source-receiver separations are considered. The aqua lines represent the receiver noise level.
Figure 5.57. The in-line dE/dt responses using the marine TDCSEM method. The two source positions and three source-receiver separations are considered.
### Table 5.58

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### Figure 5.58

The in-line dEz/dt responses using the marine TDCSEM method. The two source positions and three source-receiver separations are considered.
Figure 5.59. Current distribution snapshots at four different measurement times on the x-z cross-section for the 3-D reservoir model with a 250m long x-oriented time-domain HED at (0 km, 0 km, 0.95 km). Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 5.59. Continued.
Figure 5.60. Current distribution snapshots at four different measurement times on the x-z cross-section for the 3-D reservoir model with a 250m long x-oriented time-domain HED source at (2 km, 0 km, 0.95 km). Total current density (left), horizontal current density (middle) and vertical current density (right).
Figure 5.60. Continued.
6. CONCLUSIONS

This numerical modeling study has investigated the fundamental physics of galvanic source EM methods and demonstrated how galvanic source EM methods can sense a thin resistor effectively.

Unlike the loop TEM and MT methods, the GESTEM method generates vertical as well as horizontal transient currents. The rapidly diffusing and highly concentrated vertical current interacts with a thin horizontal resistor and thus can produce a measurable perturbation in the surface electric field. In contrast, the loop TEM and MT methods fail to sense a thin horizontal resistor because their responses are inductive. In using the GESTEM method, the magnitude of perturbation to a thin resistor depends on the source waveform. When the step-off waveform that mainly consists of low frequency signals is employed, the perturbation due to a thin resistor is relatively small. An alternative to analyzing the electric fields directly from the step-off responses is to take the time-derivatives in order to approximate impulse responses and thus provide higher frequency information. The detailed analysis of non-standard transient EM transmitter waveforms and their sensitivities to resistors is necessary and left for future work. In order to improve the magnitude of perturbation, especially due to a localized small 3-D resistor, the diffusion angle of the vertical transient current, 45° should be considered to make vertical currents coupled to a resistive target efficiently. The major drawback of the GESTEM method lies in the fact that the GESTEM sounding is very sensitive to near-surface
inhomogeneity. Thus, it is required to develop 2-D or 3-D interoperation schemes rather than force layered-earth models to fit the responses of 2-D or 3-D structures.

The marine FDCSEM and TDCSEM methods have been investigated numerically, and compared to the MMT method. In contrast to the MMT method, the marine FDCSEM and TDCSEM methods are very sensitive to thin resistive hydrocarbon reservoirs at depth, since their response is both galvanic and inductive. For the FDCSEM method, the location of the normalized peak response is determined by where the airwave starts to dominate seafloor EM responses in the background model. This point is a function of source frequency, seawater depth and seafloor resistivity. The peak magnitude depends on whether the high concentration of vertical currents can reach and interact with the reservoir effectively or not. Bathymetry is another important factor for the peak magnitude and thus high quality bathymetry data should be collected for an accurate interpretation of the FDCSEM data. The magnetic field responses are similar to electric ones but the benefit of using magnetic field responses is that the noise level contour of the magnetic receiver theoretically allows for greater surface coverage compared to that of the electric receiver.

Like the GESTEM method, the TDCSEM method also requires the use of a proper transient EM pulse such that relatively high frequencies are produced. The impulse response of the TDCSEM method is characterized by two-path diffusion of the EM signal. The initial response is caused by faster signal diffusion through the less conductive
seafloor, while the later arrivals result from slower diffusion through the more conductive seawater. Therefore, at larger separations, the effects of the seafloor and seawater are somewhat separable. This can be useful in relieving the airwave problem associated with the FDCSEM method in shallow marine environments. The detailed investigation of non-standard TDCSEM source waveforms and their responses is left for future work.

This modeling study illustrates that the vertical electric field measurements on the sea floor can be a useful additional measurement for both the marine FDCSEM and TDCSEM methods. In contrast, the vertical electric field measurement is not useful for the MMT method.
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8. REFERENCES


Cagniard, L., 1953, Basic theory of the magnetotelluric method of geophysical prospecting, Geophysics, 18, 605-635.


Nabighian, M. N., 1979, Quasi-static transient response of a conductive half-space – An approximate representation, Geophysics, 44, 1700-1705.


Nichol, Edward, personal communication, 2004


Pellerin, Johnston and Hohmann, 1996, A numerical evaluation of electromagnetic methods in geothermal exploration, Geophysics 61, 121-130.


Schaper, D., and Alumbaugh, D., 2002, Limitations of 1D TEM inversion over 2D structure; Proceedings of the Symposium on the Application of Geophysics for Environmental and Engineering Problems (SAGEEP)'02


Thirud, A. P., 2002, EMGS article, Scandinavian Oil-Gas Magazine No. ¾, 8-9
