NUMERICAL INVESTIGATION OF COAL SEAM GAS
DETECTION USING AIRBORNE
ELECTROMAGNETICS

by
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ABSTRACT

The use of airborne electromagnetic (AEM) techniques has been mostly utilized in the mining industry. The various AEM systems enable fast data acquisition to detect zones of interest in exploration and in some cases are used to delineate targets on a production scale. For coal seam gas (CSG) reservoirs, reservoir thickness and the resistivity contrast present a new challenge to the present AEM systems in terms of detectability. Our research question began with the idea of using AEM methods in the detection of thin reservoirs. CSG reservoirs resemble thin reservoirs that have been and are currently being produced. In this thesis we present the results of a feasibility analysis of AEM study on coal seam reservoirs using synthetic models. The aim of the study is to contribute and bridge the gap of the scientific literature on AEM systems in settings such as CSG exploration. In the models we have chosen to simulate both in 1-D and 3-D, the CSG target resistivity was varied from a resistive to a conductive target (4 Ωm, 150 Ωm, and 667 Ωm) to compare the different responses while the target thickness was fixed to resemble a stack of coal seams at that interval. Due to the differences in 1-D and 3-D modelling, we also examine the differences resulting from each modelling set up.

The results of the 1-D forward modeling served as a first order understanding of the detection depths by AEM for CSG reservoirs. Three CSG reservoir horizontally layered earth model scenarios were examined, half-space, conductive/resistive and resistive/conductive. The response behavior for each of the three scenarios differs with the differing target resistivities. The 1-D modeling in both the halfspace and conductive/resistive models shows detection at depths beyond 300 m for three cases of target resistivity outlined above. After the 300-m depth, the response falls below the assumed noise floor level of 5% response difference. However, when a resistive layer overlies a conductive host, the resistive/conductive model, the signal is reduced for the resistive target cases, but the response is unchanged for the conductive target layer.

For a better understanding of the responses from more complex reservoirs, a 3-D model was developed to incorporate additional geology. The 3-D models were based on the 1-D models and the modeling parameters were not altered except for the finite extent of the layers. The system properties such as the transmitter waveform, moment and time gates did not change. For the 3-D coal seam reservoir models, the same level of response is not observed for the 240 x 240 m areal extent target. For the halfspace and conductive/resistive model, the AEM response is small.
Also noticeable is the decreased response below 50-m target depth. For the assumed noise floor level, the different targets would not be detectable in these instances beyond 50-m when compared to detection depths of up to 300-m in the 1-D scenario. If, however, a resistive overburden exists, i.e. the resistive/conductive model scenario, the 3-D response for the conductive case target is strong compared to the other target cases due to the preferential current flow. In this scenario, a conductive target seam can be detected at a depth of 150-m and possibly deeper depending on the thickness of the overburden layer. In contrast, for the case of the resistive targets, the anomalous body would be undetectable beyond 50-m depth.

I apply the same modeling techniques to a more complex model adopted from the Queensland Surat Basin CSG reservoir. I simulate responses in both 1-D and 3-D. The 1-D responses show promise for detecting targets at up to 500 m deep. The 3-D models with an embedded a target with an areal extent of 240 x 240m display small responses and indicate shallow detection depths. However when I increased the target’s areal extent to 480 x 480 m, a stronger response is observed that is larger than the 5% noise floor level for all three target cases. This is a good indication that the size of the CSG target is important for AEM application.

From this study, a few conclusions can be draw; if the target is not large enough in lateral extent, it is unlikely that we would be able to detect it. Additionally, if production of a coal seam group does not produce a resistivity contrast that is measurable, the AEM method such as modeled here would also not be beneficial. As for the exploration case, with laterally continuous targets, AEM might may prove useful if the resistivity contrast is large enough between target and host. In 1-D the responses were significant and indicated a good possibility of using AEM methods for this task at depths reaching 500 m. However, the 3-D responses show limited detection depths of 150 – 200 m for laterally confined targets. To the best of my knowledge, this study is a first pass on the topic, it is recommended that an even more thorough investigation of the scenarios be examined in greater detail with the hope of providing quantifiable results that would aid in the better understanding of these reservoirs.
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I would like to dedicate this work to my parents and family.
Chapter 1

INTRODUCTION

Coal seam gas (CSG) is a clean burning fossil fuel extracted from coal seams in the subsurface. The gas is produced after dewatering the saturated coal seams. The dewatering process provides flow pathways for the gas to reach the annulus of the producing well. Coal seams are considered as gas reservoirs and are naturally fractured in the coalification process; as the organic matter is converted to coal, the coal units form natural fracture systems known as cleats. The properties of the coal seam reservoirs vary depending on the degree of coalification the organic matter has gone through. Similar to conventional hydrocarbon reservoirs, the properties of the fluid/gas influence the change in properties within the target zone. In CSG reservoirs, both the source rock and the majority of the gas lie within the same formation and changes in the different physical properties enables geophysical techniques locating such targets.

Seismic exploration and time lapse seismic have been predominantly used in the detection and monitoring of CSG reservoirs due to their resolution and the reservoir properties. The most common property exploited by seismic geophysicists is impedance, the product of density and velocity, which can be identified using seismic reflection surveys. Bright spots within the seismic data in known coal provenances are usually of interest. Studies such as Gochioco (1991), Davis et al. (2007) and Ramos and Davis (1997), indicate a high success rate in detection of the coal seams as well as fracture delineation within the coals. However, seismic surveys are expensive and for an exploration based surveying can be costly.

On the other hand, airborne gravity or electromagnetic surveys are much more cost effective and with the advancement of instrumental technology, new equipment can be used to survey vast areas with acceptable signal-to-noise ratio (S/N) with depth. However, there seems to be a lack of EM literature in the public domain with regards to CSG exploration or monitoring. With this thesis study, we hope to bridge that gap with a valid contribution.

In this thesis, the airborne electromagnetic (AEM) survey is simulated for CSG reservoirs in order to better understand applicability and the limitations of such a system for CSG
prospecting. For our research, we pose the following research questions that relate to the topic: are AEM systems useful for “shallow” targets, say approximately 1000 feet in depth? Are coal seams detectable using AEM systems? Can we further monitor production of these coal seams using the AEM systems? and most importantly, how deep below the surface can a signal be detected, given that the change is occurring within the coal seams only? In this thesis, we will tackle the question of the depth of detection and also shed some light on the detectability of the coal seams with changing electrical resistivity contrasts i.e. for exploration and also during the coal seam dewatering phase.

Many geophysical techniques use electromagnetism principles in their measurements of the physical properties of the subsurface. Electromagnetic (EM) techniques usually involve a source, passive or active, which generates electrical current in the surface. The measurements made are of the electromagnetic fields emitting from the Earth, these data are then interpreted to obtain the spatially variable physical properties of the subsurface (West and Macnae, 1991). The variability of the measurements is primarily dependent on the structure and the variation of resistivity of the target within the Earth. From Ohm’s law, resistivity (Ohm meters) of a rock is defined as the ratio of the voltage (in volts) to the electric current (in amperes) which flows through it. Conductivity, measured in Siemens per meter, is the reciprocal of resistivity. EM techniques have been used onshore as well as offshore to locate targets of value, e.g. offshore petroleum reservoirs in the controlled source EM systems or onshore in the mining industry to locate massive sulfide deposits.

The development of airborne electromagnetic (AEM) methods was primarily pioneered by and for the mining industry where large areal coverage and rapid acquisition times would help companies hone in on conductive targets of interest (Palacky and West, 1991) or image the geologic structure favorable for hosting mineral deposits. In the last decade, the number of systems and their complexity has increased in order to meet the industry’s exploration demands. Such systems are Geotech’s VTEM (Versatile Time Electromagnetic) system, ZTEM (Z-Tipper Electromagnetic) system, Sky’s SkyTEM (Sky Time Electromagnetic) system and in general these systems fall under two categories: time domain and frequency domain EM systems.

The different types of systems, frequency and time domain, offer various platforms for geophysical exploration. Frequency domain methods operate at usually higher frequencies (40 to >1400 Hz) and are their development mostly occurred in Canada and Scandinavia where
background resistivities are generally relatively very high (Frischknecht et al., 1988). However, in areas where a highly weathered, variable and conductive overburden exists, frequency domain technique success is limited and in general ineffective. Time domain methods are used in these areas because of the advantage that the absence of the primary field in the measured response and therefore can be distinguishable from the background. The theoretical maximum depth at which a signal can be detected for time domain systems is given by Spies (1989) as follows:

\[
\text{Diffusion depth } D = \sqrt{\frac{2t}{\sigma \mu}} \tag{Eq. 1.1}
\]

where, \(t\) is time in seconds after the primary EM field has been switched off, \(\sigma\) is the ground conductivity in S/m and \(\mu\) is the magnetic permeability of the medium in Henry/m. The measurement time, \(t\), depends on the signal strength measured which is in turn a function of the conductivity of the ground surface, the transmitter moment and the system noise levels.

The VTEM system from Geotech has been a successful equipment set up in the mining industry. Published Geotech case studies present high S/N ratio and depth of investigation (DOI) when compared to other available systems. In our study we have decided to implement a similar set up with the AEM simulations where the transmitter loop is traversed through flight lines of the area of interest and the receiver measurement being centered within the transmitter loop. We have not used any proprietary VTEM software or parameters for this study and hence in the following content, I will refer to the simulation based responses as AEM responses rather than specific VTEM responses.

Forward modeling the electromagnetic response of different scenarios has long been a difficult task and prior to the computational advances “master” curves of relatively simple models were produced in order to fit the data measured. However, with the computational advancements the complexity of the models used increased. One dimensional electromagnetic modeling algorithms became robust and provide quick means to forward model layered half space Earth models (Farquharson, 1995). Also, with the technological advancements of computers, algorithms to compute electromagnetic responses in two-dimensions became available and soon followed by algorithms in three-dimensions. However, not until the recent introduction of parallelization on multi-processors did three dimensional electromagnetic modeling become feasible on a routine basis and thus more complex models can now be tested. Such algorithms
can be used to determine signal detection from different system set ups in feasibility studies to provide companies with an efficient way to determine if a survey executed will result in the measurement of acceptable and more importantly useful data.

Feasibility studies can provide valuable insights in different situations. For example modeling can be used to verify system responses from known geology. The main advantage in conducting feasibility studies is to answer specific queries such as: how deep can a certain system configuration detect? Or in other words, can I detect a target at a certain depth? before spending time and money in designing the system and testing it on the field. The main focus of this thesis is to perform an AEM feasibility study on coal seam gas (CSG) reservoirs and contribute to public domain information with regards to the detection and production monitoring of these subsurface targets.

Coal seam gas reservoirs have gained increased attention from natural gas producing corporations due to the wide availability and relatively cheap cost of production of the resource. In the past, the methane contained in coal mines was considered a nuisance to the miners and was vented to the atmosphere. With the technological advancement of drilling and with the realization of the importance of this clean burning methane gas present in the coal seams, operators have been drawn to producing the gas for a profit (Rogers et al., 2007). To better produce this resource we must obtain a better understanding of the interactions that take place between our exploration systems and the subsurface geology.

A good understanding of the processes that take place when a coal seam is detected and drilled for production can enable geophysicists to design surveys in a manner that optimally utilizes the acquisition system properties. The task at hand is two-fold: understanding the physics that alters the electrical resistivity of the coal seams at different stages of exploration and production and providing educated estimates for model parameters; testing the applicability and limitations of the AEM system of choice on such models and determining useful conclusions that corporations could benefit from and that could have an economical impact on future prospecting.

The rest of the thesis will outline the work carried out, namely numerical modeling, to understand the detection capabilities of the AEM system configuration chosen. The second chapter of this thesis will discuss the state of the art present nowadays, namely seismic reflection methods, in detecting and characterizing coal seam gas reservoirs in different settings, both
geologically and petrophysically. AEM systems have been used in the monitoring of the water produced from coal seams yet no public record, to my knowledge, exists in actually using AEM systems for exploration or production monitoring of these reservoirs. Also in Chapter 2 we will present the assumptions used and the analyses of potential errors from these assumptions.

In the Chapter 3, I discuss the model construction and parameters that I will be using for the feasibility analyses and examine the one-dimensional (1D) modeling approach in the detection of the modeled resistive target. Subsequently, a three-dimensional (3D) approach to the problem is examined in Chapter 4 and the obtained results being compared to the 1D models in the conclusions section of the thesis. In Chapter 5, I simulate a more complex model that resembles the geology from the known Surat Basin in Queensland, Australia and answer the question: can we detect coal seams in such a setting under these assumed conditions? In Chapter 6 I conclude my research work and provide recommendations for future work as the work presented in this document is a first step forward in the use of AEM methods in detecting and monitoring reservoirs other than what they have traditionally been used for in the mining industry.
Chapter 2

COAL SEAM GAS GEOPHYSICS WITH THE AEM SETUP: A REVIEW

To review the coal seam gas reservoir and the applicable geophysical methods, we need to understand its geological origin and the different geophysical properties that influence the recorded signal. The geological origin of the coal seams provide information of the different settings in which the coals are situated. This can aid in understanding the various factors that can vary the response of the target such as the coal type itself and the host geology properties. Also, from the geology we can extract information regarding the formation thicknesses and the type of surrounding environment in which the coal seams are embedded and, therefore, the building of synthetic models that closely resemble actual settings and bed thicknesses can aid in better interpretation of the results obtained.

The knowledge about the geophysical properties of coal seams are essential to interpret the measured signal or help in analyzing it. For our AEM study, the geophysical property which affects the measured signal is the electrical resistivity of the coals and their surrounding environment. Understanding the interaction of the different processes that alter this property can aid in setting up realistic models for simulation based work and also in analyzing the results obtained from these simulations in order to build up our knowledge with regards to these targets.

The literature review section is divided into four sections that are directly related to the research carried out in this thesis; A coal seam geology section that describes the geologic origin of the coal seam and how the gas is generated and stored within the seams. The next section will focus on the dominant method used for coal seam gas exploration, the seismic reflection method and the processes that affect the coal seam during different stages of the discovery/production. The third section of the review lays out the background for AEM systems with an emphasis on the VTEM-like acquisition systems as well as relate the geophysical properties of the coal seams in terms of electrical resistivities of the coals and their surrounding media. Finally, the fourth section of the review will discuss the assumptions taken and provide a short description of the potential errors in the study.
2.1 Coal Seam Geology

Coal seam gas, also widely known in the USA as coal bed methane has long been produced commercially, even though it was on a very small scale. The early production started in 1920 when gas emitted out of the Mulky coal seam in southeastern Kansas was thought as of “shaly gas” (Stoekinger, 1990). For miners, the methane contained in the seams being mined was a hazard and in most cases was vented using large fans placed within the mines or venting boreholes (Flores, 1998, Rogers et al., 2007). However the main driving force in capturing the methane was the mine safety and with the advancement of technology in capturing the methane gas, a commercial incentive became apparent as the amount of gas collected was substantial for on-site power uses or even for the possibility of transporting it through pipe lines (Rogers et al., 2007). The wide availability of coal seam gas, proven and probable reserves estimated in hundreds of trillion cubic feet (TCF) worldwide (EIA, 2012), and its ease of production compared to other natural gas reservoirs, has attracted companies to this resource.

The formation of coal occurs with the start of the deposition of plants in swampy areas which are submerged and decay with time to create what is known as peat. The peat then undergoes the first coalification process in which the transformation of peat occurs where it is converted to lignite or commonly known as brown coal, which is also known as lower rank coal. The coalification process, Figure 2.1, which is dependent on the time, pressure and temperature, continues on the lignite converting it into higher coal ranks such as bituminous and anthracite. The maturation temperature is the decisive factor as in which coals form through coalification. Different coal ranks can exist within the same coal seams. As by-products of the coalification process, gas and water are produced. It is worthy to note that the higher rank coals, which contain the higher carbon content, store the most natural gas by-product. The natural gas produced consists of predominantly methane and is stored on the coal surface via adsorption.

The cleat system in the coal seams is the primary storage volume of water whereas the methane gas is adsorbed to the coal unit surface. Figure 2.2 shows a schematic of the cleat system, their size and the complexity in which they reside in. The surface area of the micropore structure within coals contains the methane gas and according to Kuuskraa and Bradenburg (1989), 1 lb of coal can hold 55 football field’s worth in surface area, is equivalent to 1 billion square feet per ton. Hence, the methane present within coal seams can be a significant energy
source. The water is usually stored in the natural fracture system, termed the cleat system, within coals.

![Figure 2.1 - Coalification process over geologic time (Kentucky Geologic Survey)](image)

To understand the properties that affect the resistivity of the coal seams we take a closer look at the coal units. Coals are a dual porosity medium: the macropores which represent the spaces within the coal cleat system, Figure 2.2, and any fractures contributing to the overall pathways in which water and methane are transported within the seam. The macroporosity in coal reservoirs is responsible for the permeability within the coal seams and is the main water storage facility within the beds. The microporosity, which is defined as the pores of molecular dimensions within the coal matrix itself, is responsible for the gas storage. Gray (1987) has estimated that about 98% of the gas is typically stored in the adsorbed state in the micropore structure within the coal seam beds.

The production of CSG is best described in Figure 2.3, once a well is drilled into place, the water filling the cleat system is drained (dewatering), either naturally due to the pressure differential caused by intrusion of the well or by using submersible pumps to decrease the lag time from well placement and methane gas production. The methane is then either produced naturally from the seam by allowing the gas to desorb from the coal micropores and move along the cleat system through the pore space and to the well bore or by using stimulation techniques and also by enhanced recovery techniques such as Nitrogen (N₂) or carbon dioxide (CO₂) injection.
to increase production. This latter process serves two purposes: decrease the lag time for methane to flow naturally by preferential CO₂ adsorbing to the coal and desorbing the methane into the cleat system. This process is highly dependent on the reservoir pressure and coal rank, but can increase production from the well and also the sequestering of CO₂ in an adsorbed state enabling long term storage (Pashin, 2004). The water within the seams is drained out while methane production ramps up till the well is abandoned when being non-profitable.

![Cleat system schematic](image)

*Figure 2.2 - Cleat system schematic, modified from Tremain (1991) and Laubach (1993)*

### 2.2 Seismic Geophysical Properties of Coal Seams

The water properties, such as salinity, differ from one basin to another and usually differ within the same basin. The quantity of water produced poses a new challenge of water management for the operators as the seams are thin but laterally homogenous and continuous on large scales spanning vast areas of the basin. The growing concern of water management by governmental agencies has imposed certain laws on CSG producers in the USA and Australia amongst other countries. The different solutions for disposing of the water produced, based on its properties, are 1) pumping the water into local aquifers if the water properties permit, 2) using the water for agricultural purposes, etc. If the produced water does not conform to the local standards, it is treated and then disposed in the above mentioned ways.
Figure 2.3 - Typical CSG production curve (Ayers, 2002, modified from Schraufnagel, 1993)

The CSG process cycle begins with the drilling of a well, which can either be vertical or horizontal, and draining the water present within the coal seam by the pressure difference mechanism or by installing submersible pumps to decrease the water production time.

The detection of these horizontally lateral seams/beds has mostly been done using seismic reflection techniques due to the impedance (the product of density and velocity of a rock type) contrast that coal layers can have with their surroundings. As Table 2.1 illustrates, coals have low impedance when compared to their shale or sandstone surroundings and this usually generates what is known as a “bright spot” in seismic data.

Table 2.1 - Density, Velocity and Resistivity value comparison (*values from Gochioco, 1991)

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Density * (g/cc)</th>
<th>Velocity* (km/s)</th>
<th>Resistivity (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2.65</td>
<td>4570</td>
<td>100s</td>
</tr>
<tr>
<td>Coal</td>
<td>1.35</td>
<td>2500</td>
<td>10,000s</td>
</tr>
<tr>
<td>Shale</td>
<td>2.40</td>
<td>3650</td>
<td>10s</td>
</tr>
</tbody>
</table>

The use of seismic reflection techniques to detect, monitor and characterize (using three component data) coal seams is well documented and some of these example works are by
Henson and Sexton (1991), Shuck et al. (1996) and Davis et al. (2007). It can be stated that the seismic reflection technique is an effective tool in the detection and characterizing of coal beds along with their complex properties such as fracture orientations and anisotropy. However, the seismic reflection technique is usually expensive when compared to other geophysical techniques available and is also restricted in some ground terrains as well as time consuming in terms of the acquisition and processing phases.

The introduction of airborne EM (AEM) techniques in the detection and monitoring of coal beds can be beneficial as it would cut costs, be much quicker in terms of acquisition and processing time. The advantages of using the AEM methods compared to the traditional seismic reflection method used can be; 1) faster survey set up times as no receivers need to be geographically placed, 2) no ground access is required for source or receiver devices.

2.3 Airborne Electromagnetics (AEM) with emphasis on the VTEM-like System and Electromagnetic Properties of Coal Seams

AEM Systems were developed in the late 1940s while the turning point of experimental based AEM systems to commercial exploration systems began in the Canada in 1954 with the discovery of the Heath Steele deposit (copper, lead and zinc) located in New Brunswick (Fountain, 1998). Morrison et al. (1998) also state that the development of airborne electromagnetic (AEM) systems began in Canada and Scandinavia within the mining industry to aid in the exploration for electrically conductive sulfide ore deposits within resistive host environments.

The resistivity of coal depends on their rank and the variations between each rank are large due to the different depositional and geological environments as well as their geochemical composition. Angenheister (1982) indicated different laboratory measured resistivities for coals ranging from 160 to 150,000 Ωm for coal and 1 to 200,000 Ωm for anthracite. These laboratory measurements might be unrealistic in in-situ situations, however, these measurements imply that coals can either be a conductive or resistive target depending on the host in which they are embedded within. Since coals can either be considered as a resistive or conductive target, the next step in analyzing the coal seams is to define the properties by which the resistivities change within. Some of these properties have been related to the water saturation and shale content of the beds in which they are present and resistivities in such cases can be calculated empirically using equations such as the Waxmann-Smit’s (1968) petrophysical model for the prediction of
resistive properties of oil bearing shales. However, the Waxman-Smit’s model requires a well log describing the properties of the subsurface and hence cannot be used with this case. On the other hand, Archie’s (1942) petrophysical model, Equation 2.1, is not constrained by the availability of a log and can be used by knowing some information about the properties of the formation and the water resistivity present within whilst assuming the tortuosity factor, cementation and saturation exponents.

\[
R_t = aR_w \phi^{-m} S_w^{-n}\tag{Eq. 2.1}
\]

where, \(R_t\) is the formation resistivity, \(a\) is the tortuosity factor, \(R_w\) is the water resistivity, \(\phi\) is the porosity of the layer, \(S_w\) is the water saturation and \(m\) and \(n\) are the cementation and saturation exponents respectively.

The use of Archie’s equation can be debated but for the sake of this work, the Archie equation was used to estimate, on a first approximation basis, the resistivities one would expect within the coal seams. Now that we have a sense of the resistivity distribution of the subsurface, the selection of the AEM system is dependent on its main characteristic, depth of penetration.

Different systems have been used in the mapping of the integrity of containment basins which hold the excessive water produced by the production of CSG. A helicopter FDEM (namely Fugro’s RESOLVE EM system) survey was undertaken in the Powder River Basin to map out the fate of leaking water at the near subsurface (Hammack et al., 2003). An attempt by Sattel (2004), to understand the limits AEM systems on horizontal targets shows interest towards AEM systems detection capabilities and his work involved numerical modeling and the comparison of the different system responses and the detection requirements based on the areal extent of target. However, a tailored AEM feasibility study with the focus of detecting and monitoring CSG reservoirs, to my knowledge, has not been published in the public domain and this is the main objective of the thesis.

The airborne electromagnetic systems in use today can be divided into two main categories based on their working mechanisms: frequency-domain electromagnetic (FDEM) methods use a varying sinusoid wave transmission (AC current) at fixed frequencies and measure the response of the earth while time-domain electromagnetic (TDEM) methods supply DC current to the transmitter and, at a certain time, the supplied current is switched off and the response is
measured at the receiver. TDEM systems enable the isolation of the secondary anomalous responses from the background unlike the FDEM systems which measure the anomalous response with the presence of the primary (background) response. The main differences between TDEM and FDEM systems, keeping in mind the wide variety of available systems, are given in Table 2.2.

Table 2.2 - The main differences between FDEM and TDEM systems

<table>
<thead>
<tr>
<th></th>
<th>Frequency domain electromagnetic (FDEM) systems</th>
<th>Time domain electromagnetic (TDEM) systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter – Receiver separation</td>
<td>Very sensitive to the separation</td>
<td>Not sensitive – no primary field present at time of measurement</td>
</tr>
<tr>
<td>Topographical effects</td>
<td>Strong influence</td>
<td>Minimum influence</td>
</tr>
<tr>
<td>Conductive overburden or host rock effects</td>
<td>Strong effect and therefore limited success</td>
<td>Weaker effect and therefore satisfactory success</td>
</tr>
</tbody>
</table>

In most documented cases AEM systems have been used to detect mining targets such as massive sulfides or kimberlite deposits due to the high contrast between the anomalous body and the background depositional environment in which it resides. The response detected at the receiver is dependent upon the target depth, size and namely surface area in which the induced current is present. A detailed physical and mathematical description of most present-day electromagnetic techniques is given by Nabighian (1991). Based on published case histories from different corporations such as Geotech’s VTEM (Versatile Time EM) system and Fugro’s HeliTEM (Helicopter Time EM) system and other public domain literature, the acquisition system configuration selected to forward model the subsurface response is the VTEM system for its theoretical depth of investigation and the data quality it measures. The modeling carried out in this work is based on time-domain systems.

For this task, we have chosen to simulate our models using the VTEM-like configuration of a horizontal loop attached to a helicopter with 5 m station spacing, and with a flight line spacing of 100 m and a flight height of 30 m across our target, Figure 2.4. The choice of this system is due to the maximum depth of penetration published in case histories on the VTEM system as well as the comparison of the system with other available options on the market. The VTEM recorded signal to noise ratio is relatively high.
The resolution of the VTEM system is comparable to ground TEM systems as discussed by Cunion (2009). In the kimberlite-rich area of interest, VTEM surveys were able to resolve 90% of the targets in the area and aided in understanding the magnetic data collected prior to the ground TEM survey. In essence, the VTEM survey could be used as reconnaissance tool prior to detailed mapping of anomalies using ground TEM crews.

![Figure 2.4 - VTEM system configuration (modified from VTEM brochure by Geotech, Canada)](image)

The VTEM-like system to be simulated measures the derivative of the magnetic flux intensity field (B-field) which is denoted by dB/dt in three dimensions, x, y and z. The dB_z/dt component is the most intuitive and also gives the most change with the slightest change within the subsurface. Therefore responses covered in this thesis, we will consider the dB_z/dt component for the 3-D modeling or the B_z-field component for 1-D as the primary indicator of the presence of the target.

### 2.4 Assumptions and potential errors

All the numerical modeling carried out in this thesis is based on synthetic models, so there are a few assumptions built into the models to simplify the process. The assumptions are detailed below:
• The coal rank used to estimate the resistivities of the target layers was considered to be subbituminous and anthracitic. This means that the coals contain a high methane content and are therefore resistive.

• Flat topography is assumed with the different models and this simplifies the task at hand as no corrections would need to be applied to the data. The data can be interpreted as calculated.

• Noise free data – perhaps one of the most important assumptions yet is simulating noise free data, we assumed a 5% noise floor level cut off to the percentage responses calculated. Anything below this level is undetectable in real scenarios. However, this is also a subjective choice as depending on the system used and the configuration as well as the technological advancements, the noise threshold can fluctuate accordingly.

• The data computed using the software packages used does not undergo any other processing other than the actual calculation of the responses by solving Maxwell’s equations. This means that the responses are ideal if compared to real systems.

• The modeling code used to determine the responses of the different scenarios could differ in its approach from other available codes or software packages. The aim of this work is to move a step forward in exploring the different possibilities using AEM systems.

For all modeling scenarios, three cases are considered: a conductive target with resistivity of 4 Ωm, a slightly resistive target with resistivity of 150 Ωm and a highly resistive target of 667 Ωm. The goal for these is to determine the interactions of different targets with the host environments.
Chapter 3

1-D FORWARD MODELING

One dimensional (1-D) modeling has and is still being used in the EM community to predict target responses for different systems. The advantage of using 1-D modeling code over 3-D modeling codes is the computational time involved. Code such as UBC-GIF’s “EM1DTMFWD” and Flosadottir and Constable’s (1996) code make 1-D modeling attractive as it is minimizes computational time and does not require a lot of computational power. The advantage of such a code is that building a library of modelled responses from different models can be quick and computationally inexpensive. In a comparison by Constable and Weiss (2006), the results from 1-D modeling and 3-D modeling marine controlled source electromagnetics (CSEM) concluded the following: “1D modeling predicts the observed response to very high accuracy”.

To understand the responses of thin layers (≤ 30 m) with differing resistivities in a coal seam environment, the use of 1-D EM modeling is vital. The different layered models’ 1-D responses can be used to understand first order responses since 1-D models are easy to set up. Thus, the use of 1-D modeling of the seams at different depths and differing coal seam resistivities becomes feasible. The modelled responses would also aid in understanding the limitations of detection of thin beds using AEM methods.

In this chapter the 1-D numerical modeling performed for the problem stated is detailed with the introduction of the method, the program code used to perform the modeling is briefly explained, the input parameters of the program and the choice of models used for this thesis are justified and the results for the 1-D modeling are presented. The target resistivity would vary within the model space and an understanding of the responses is built.

3.1 Introduction

A good understanding of the EM responses for the different scenarios of the CSG reservoirs is vital in order to understand the type of responses that are generated by such CSG models and
also the amount of information that can be provided through such geophysical techniques with coal seams. Our aim is to reach an understanding of what parameters, including target thickness, depth, and resistivity affect the signal observed and the limitations of the method in detecting, characterizing and monitoring the reservoir.

For forward modeling the different scenarios we use University of British Columbia – Geophysical Inversion Facility’s (UBC-GIF) 1-D time domain forward modeling program “EM1DTMFWD”. The method used to compute the magnetic field values for a set of source-receiver pair over a 1-D layered earth model utilizes the matrix propagation approach described in Farquharson and Oldenburg (1996) and in Farquharson, Oldenburg and Routh (2003).

The computations that occur in the forward modeling program EM1DTMFWD are carried out in the frequency domain and then the resulting field responses transformed to the time domain. The transmitter loop is assumed to be horizontal and above the ground surface. The fields for the horizontal transmitter are calculated by adding together the fields for the horizontal electric dipoles which are joined together to make the loop. Since the computation method of the fields is carried out by integration around a closed loop, the magnetic field contributions are neglected while the inductive effect from the current flowing within the wire is considered hence only the vertical or z-component of the Schelkunoff F-potential is required (Farquharson, 1995). Following Ward and Hohmann (1987), the Schelkunoff F-potential is defined as follows:

\[ E = -\nabla \times F, \quad \text{Eq. 3.1} \]

\[ H = -\sigma F + \frac{1}{\omega \mu} \nabla (\nabla \cdot F), \quad \text{Eq. 3.2} \]

where \( E \) and \( H \) are the electric and magnetic fields respectively, \( \sigma \) and \( \mu \) are the conductivity and permeability of the uniform medium in consideration. The computation of these equations is performed through recursion, Figure 3.1, where the solution of the above equations in a layered Earth model starts in the \( N^{th} \) layer of the model and recursively progresses to the \( N-1^{th} \) layer then through to the first layer. Also, the computation assumes a quasi-static approximation and the magnetic permeability of the layer is equal to that of free space \( \mu_0 = 4\pi \times 10^{-7} \) henry/m. This enables a faster calculation than would be permitted solely in the time domain. See Farquharson (1995) for the details of the underlying computations.
3.2 Numerical modeling

We start our 1-D analysis by taking the simplest case of a half space in which an anomalous, coal seam resembling, layer is embedded at various depths. This will enable us to determine the simplest-case response and hence build our understanding of the results until we reach to the layered earth model that will contain our anomalous multi-layered coal seams.

A 30-m thick coal seam layer is embedded at different depths ranging from 50 to 500 m in 50-m intervals, Figure 3.2. The resistivity of the half-space was set to 10 $\Omega$m, resembling shale. Shales in many basins have been the impermeable aquitards in which the coal seams (that act as aquifers) are embedded along with the gas and water produced after the coalification process. Also, the anomalous layer resistivity was altered for three cases: a relatively conductive layer in which the resistivity of the anomalous layer is set to 4 $\Omega$m, a slightly resistive anomalous layer with a resistivity value set to 150 $\Omega$m, and a highly resistive anomalous layer with resistivity of 667 $\Omega$m. The air resistivity of the model domain was set to $10^8$ $\Omega$m.
To increase the complexity of the modeling we introduce a two-layer model that consists of a 200-m layer acting as an overburden or a different stratigraphic depositional environment. The resistivity value chosen represents typical sandstone material of 100 Ωm.

For the purpose of our modeling we considered both cases in which the first layer was conductive, i.e. shale, and when it is kept resistive, i.e. sandstone, and the reverse where the sandstone layer is situated above the shale. For future reference, we shall call the former the “conductive/resistive” model and the latter the “resistive/conductive” model. These models are shown in Figures 3.3 and 3.4 respectively with their corresponding resistivity values.

The forward modeled EM response for the 1D scenario was calculated, with a transmitter and receiver pair located 30 m above the ground surface, i.e. simulating the loop hanging down from a helicopter in a typical VTEM-like survey. The sounding is considered to resemble a center loop measurement above a 1-D model. The modelled loop size was is a square with 23-m side length.

The EM1DTMFWD code can be used with any general transmitter current input waveform as well as the AEM system where any specific waveform can be entered into the system. The waveform used at the transmitter is a step off current as shown in Figure 3.5 schematically. The choice for this waveform was that is a simple enough waveform to interpret the modeled results. The waveform time interval used was from 1 µs to 0.1 s to encompass the measurement time gates show in Table 3.1. The time gates used for measurement interval 18 µs to 8.69 ms, these values were chosen from the public domain published case studies by Geotech regarding their VTEM system and were modified to fit our modeling need as measurement time decay curves can give us a sense of how deep the target is embedded.

The EM1DTMFWD code outputs the results within a second on a standard laptop configuration. The robustness of the 1-D code can be utilized in certain scenarios, however, as we will see in the next chapter that the 1-D semi-infinite layer assumption causes differences with the calculated responses.
Figure 3.2 - 1-D halfspace model showing dimensions and resistivity values used

Figure 3.3 - 1-D conductive/resistive model showing dimensions and resistivity values used
Table 3.1 – The list of time gates used for measurement of the model response after current is switched off

<table>
<thead>
<tr>
<th>Gate No.</th>
<th>Time (s)</th>
<th>Gate No.</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.80 \times 10^{-5}$</td>
<td>23</td>
<td>$4.72 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>$2.30 \times 10^{-5}$</td>
<td>24</td>
<td>$5.43 \times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>$2.90 \times 10^{-5}$</td>
<td>25</td>
<td>$6.23 \times 10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>$3.40 \times 10^{-5}$</td>
<td>26</td>
<td>$7.16 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Table 3.1 – The list of time gates used for measurement of the model response after current is switched off - continued

<table>
<thead>
<tr>
<th>Gate No.</th>
<th>Time (s)</th>
<th>Gate No.</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.90 x 10⁻⁵</td>
<td>27</td>
<td>8.23 x 10⁻⁴</td>
</tr>
<tr>
<td>6</td>
<td>4.50 x 10⁻⁵</td>
<td>28</td>
<td>9.45 x 10⁻⁴</td>
</tr>
<tr>
<td>7</td>
<td>5.10 x 10⁻⁵</td>
<td>29</td>
<td>1.09 x 10⁻³</td>
</tr>
<tr>
<td>8</td>
<td>5.90 x 10⁻⁵</td>
<td>30</td>
<td>1.25 x 10⁻³</td>
</tr>
<tr>
<td>9</td>
<td>6.80 x 10⁻⁵</td>
<td>31</td>
<td>1.43 x 10⁻³</td>
</tr>
<tr>
<td>10</td>
<td>7.80 x 10⁻⁵</td>
<td>32</td>
<td>1.65 x 10⁻³</td>
</tr>
<tr>
<td>11</td>
<td>9.00 x 10⁻⁵</td>
<td>33</td>
<td>1.89 x 10⁻³</td>
</tr>
<tr>
<td>12</td>
<td>1.03 x 10⁻⁴</td>
<td>34</td>
<td>2.17 x 10⁻³</td>
</tr>
<tr>
<td>13</td>
<td>1.18 x 10⁻⁴</td>
<td>35</td>
<td>2.50 x 10⁻³</td>
</tr>
<tr>
<td>14</td>
<td>1.36 x 10⁻⁴</td>
<td>36</td>
<td>2.87 x 10⁻³</td>
</tr>
<tr>
<td>15</td>
<td>1.56 x 10⁻⁴</td>
<td>37</td>
<td>3.29 x 10⁻³</td>
</tr>
<tr>
<td>16</td>
<td>1.79 x 10⁻⁴</td>
<td>38</td>
<td>3.78 x 10⁻³</td>
</tr>
<tr>
<td>17</td>
<td>2.06 x 10⁻⁴</td>
<td>39</td>
<td>4.34 x 10⁻³</td>
</tr>
<tr>
<td>18</td>
<td>2.36 x 10⁻⁴</td>
<td>40</td>
<td>4.99 x 10⁻³</td>
</tr>
<tr>
<td>19</td>
<td>2.71 x 10⁻⁴</td>
<td>41</td>
<td>5.73 x 10⁻³</td>
</tr>
<tr>
<td>20</td>
<td>3.12 x 10⁻⁴</td>
<td>42</td>
<td>6.58 x 10⁻³</td>
</tr>
<tr>
<td>21</td>
<td>3.58 x 10⁻⁴</td>
<td>43</td>
<td>7.56 x 10⁻³</td>
</tr>
<tr>
<td>22</td>
<td>4.11 x 10⁻⁴</td>
<td>44</td>
<td>8.69 x 10⁻³</td>
</tr>
</tbody>
</table>

3.3 Results and Discussion

Among the three scenarios considered in this study for the 1-D transient electromagnetic numerical modeling each had three different target resistivities that varied within the same model. The results of each scenario along with its three target resistivity cases are shown in Figures 3.6 to 3.8; the half-space, conductive/resistive and resistive/conductive models respectively. On all figures, the abscissa displays the target layer depth in meters and the ordinate displays the absolute peak percentage change value of the calculated z-component of the B-field \( (B_z) \). The percentage value is calculated by taking the difference as follows,

\[
\text{Percentage difference} = \frac{\text{total} - \text{background}}{\text{background}} \times 100. \quad \text{Eq. 3.3}
\]
For the sake of showing the small differences throughout the different target depths, the graphs (Figures 3.6 t 3.8) show the peak difference value clipped at 50% and any values exceeding the abscissa maximum would be set to the maximum.

As for the half-space model, Figure 3.6, a general trend appears in all three cases as one would expect. As the target layer is moved deeper, the peak response decreases non-linearly. However, the peak response in the conductive target is higher than the resistive cases to about a target depth of 300 m. After 300 m, the peak responses of all three cases show little difference and therefore it would be hard to differentiate if our target is a conductor or a resistor from the absolute difference response unless we consider the sign of the anomaly. For the resistive target cases, the highly resistive (667 Ωm) layer and the slightly resistive (150 Ωm) layer show approximate responses, which indicates that we cannot distinguish a production zone from a unswept zone for example.

To relate these measurements with real data, we assume the calculated responses contain 5% noise within them and thus for all three cases of the varying resistivity of the target layer, the depth to which we can detect anything would be limited to 300 m as well. This gives us an indication of the detection depth in such models. Also, the depth at which the induced current can penetrate through the subsurface and the signal decrease given the setting of the system and the assumptions used can change some of the results obtained.

For the conductive/resistive model in Figure 3.7, where a resistive basement is overlain by a conductive layer, the peak percentage values calculated from the B_z-field measurements with target depths ranging from 50 to 200 m show again a difference between the conductive layer case and the resistive layer cases. The conductive layer response is higher than the resistive layer response overall. Once the target is embedded deeper than the 200 m and below the shale-sandstone interface, the response to the resistive layers drops drastically whilst the conductive layer case shows an increase in response just at the interface and then reduces with depth non-linearly with depth. However, the decreasing response of the conductive target does not approach the 5% assumed noise floor level even after embedding the layer at 500 m below ground. This suggests that conductive targets in resistive hosts are detected with ease by such a system configuration.

As for the third scenario, the resistive/conductive model, shown in Figure 3.8, where a resistive layer overlies a conductive basement. Since the resistive layer is hosting the conductive target layer, the same phenomenon of high responses is seen in the first three responses which
correspond to depths of 50 m, 100 m, and 150 m. Since these depths are within the resistive overburden, the conductive layer response compared to resistive layers is relatively high and in Figure 3.8 they are clipped at 50% peak value. Observing that the two resistive-layer cases do show a sharp decrease in calculated responses with depth, the highly resistive layer is more likely to be detected than the lower resistive layer as seen in Figure 3.8, which is expected. This can be explained physically by the induced current diffusing away faster from the highly resistive layer quicker than the less resistive layer and therefore increase the response measured by the receiver. The detection of the resistive layers embedded within the resistive overburden would not be possible below 150 m if we assume a noise floor level of 5% for the data collected. However, as with the second scenario, a change in the resistivity of the basement shows the different resistive target layers responding differently as their responses increase at the 200 m boundary to 20% difference change and then decrease with depth till they reach the 5% noise floor level at around 400 m target depth. The conductive target response for the first three target depths (50 – 150 m) is relatively high when compared to the target response beyond 200 m. The conductive target response at the 200 m boundary is detectable with 30% difference and continues to decrease with depth until it reaches the assumed 5% noise floor level at 450 m. The response in general for a conductive layer is higher than the resistive layers.

The two layered model’s responses differ depending on the second layer’s resistivity, i.e. from resistive to conductive and vice versa, with the conductive target layer being detectable above the 5% noise floor level in both cases at a depth of 450 m. The resistive layers that are embedded in conductive hosts have responses relatively high when compared to their responses if they are embedded in resistive hosts as seen in figures 3.7 and 3.8. The depth of detectability is highly dependent on the zones which they are embedded within as the depth of detectability for the conductive/resistive model is 150 m whilst the detectability of the target for the resistive/conductive model shows multiple depths: 50 m for the highly resistive layer if embedded in the resistive first layer, 100 m for the slightly resistive layer within the resistive first layer, 400 m in total depth if any of the two resistive layers are embedded within the conductive basement.

3.4 Summary

In this chapter, the results of the 1-D forward modeling for the coal seam layers in three scenarios, half-space, conductive/resistive and resistive/conductive, have been presented. The
response behavior for each of the three scenarios differs along with the differing target resistivities. In the half-space model, the exponential decrease in the response is observed and the conductive target case having the most percentage response than the other two resistive cases. However, at 300 m target depth, the response for all three target resistivities reaches the 5% noise floor level we assumed.

The conductive/resistive scenario shows a different behavior in the three target cases. The conductive target layer shows the highest of the 3 cases’ response peaking at above 50% difference. The two resistive target layers show similar difference changes to one another throughout different depths. At the 200 m boundary between conductive overburden and resistive host, the response for the conductive target layer increases than what it was at 150 m depth and decreases exponentially and even at the 500 m target depth, the response was above the 5% noise level. This is a good indication on which geological scenarios have the maximum response for conductive targets. On the other hand, the resistive target layers show a steep drop in response after the 200 m boundary where their responses approach zero difference.

For the resistive/conductive scenario, we observe relatively high responses for the conductive case for the 50 – 150 m target depths and beyond the 200 m boundary, the response decreases to 30% and exponentially decreases with deeper targets. The highly resistive (667 Ωm) target shows a more detectable response at 50 m and 100 m target depths than the less resistive (150 Ωm) target. Beyond the 200 m boundary, both resistive target cases show increase in their response which similarly starts at 20% at 200 m and decrease exponentially till the 400 m target depth where it reaches below the 5% noise floor level assumed.

With the 1-D forward modelled results for these scenarios, we can understand how calculated target responses can vary according to the environment they are embedded in. Also, the 1-D calculated responses can serve as a first order approximation in understanding the limitations of AEM systems in these settings.
Figure 3.6 - Results of the 1-D numerical modeling for a halfspace model scenario. The results are shown as a function of absolute peak percentage values vs target depth.

Figure 3.7 - Results of the 1-D numerical modeling for the conductive/resistive model scenario. The results are shown as a function of absolute peak percentage values vs target depth.
Figure 3.8 - Results of the 1-D numerical modeling for the resistive/conductive model scenario. The results are shown as a function of absolute peak percentage values vs target depth.
Chapter 4

3-D FORWARD MODELING

Three dimensional (3-D) modeling has become a key element in understanding target responses due to the inherent 3-D nature that exists in reality. 1-D modeling is used for first order approximations where the target can be simplified into an infinite layer and is computationally inexpensive. In some cases, such as when a target is tabular, 1-D and 3-D modeling can yield similar results (Constable and Weiss, 2006). However, since the subsurface is 3-D in nature it is necessary in general to simulate responses to different EM systems using 3-D models that closely resemble true geology. This will allow for a better understanding of the factors that affect target responses as well as aid in measuring system sensitivity in detecting targets at depth. The computational cost of 3-D modeling is greater than 1-D or 2-D since Maxwell’s equations are solved in 3-D, and in an AEM like survey simulation, they would be solved for every transmitter location. However, for models with less tabular geometry, the 3-D calculated response would be closer to the measured response than a 1-D approximation. In this chapter, we carry out three dimensional (3-D) transient electromagnetic forward modeling for models with the same depth characteristics of the target and host as presented in Chapter 3. The results of the forward modeling are shown and discussed in the context of depth of detection and measurement sensitivity.

4.1 Introduction

The assumption for an ideal laterally homogenous layered media is used in 1-D modeling and such modeling could yield satisfactory results when targets are laterally extensive and continuous. However, in reality the subsurface is three dimensional and is heterogeneous throughout due to the complex processes that the rocks and minerals undergo through geologic time. The ability to model the earth in 3-D and extract predicted signals from numerical modeling is useful as the calculated responses are likely more consistent with reality. Such simulations would be more useful for understanding the anomaly and designing surveys. The aim of this
chapter is to discuss the 3-D modeling of the coal seams in a limited set of scenarios, similar to those tested in Chapter 3.

To forward model the responses of different 3-D models we use the H3DTD software package developed by UBC. H3DTD solves Maxwell’s equations in the time domain by discretizing the equations in time and using the backward Euler method whilst discretizing in space using a finite volume technique on a staggered grid (H3DTD manual, Haber et al., 2007). The program solves the problem by factorizing the forward modeling matrix and is facilitated using MUMPS (MUltifrontal Massively Parallel sparse direct Solver) and is parallelized using MPI (Message Passage Interface) standard. The output can be a combination of the components of the E-field, H-field and dB/dt field or all of them. It is worthy to note that the VTEM-like system measures the three components of the dB/dt field and calculates the E and H field and hence all components are available. The program can run on a modern laptop or desktop yet the size of the problem is constrained by the memory of the computer system. For our case, the computer available was quad-core machine with 24GB of RAM.

3.2 Numerical Modeling

For H3DTD to solve the forward problem of a certain 3-D model it requires as input a model mesh to outline the number of cells as well as the cell dimensions. The mesh file will then be used with a resistivity model file which contains resistivity values for every cell within the model. The program also requires transmitter-receiver locations with respect to the model as to where the measurements would be taken for each transmitter-receiver pair. The program additionally requires a transmitter waveform to describe the kind of current as a function of time is used to excite the earth. The output of the program can be selectively chosen in terms of measurement time gates by supplying a list of time gates which the program uses.

The transmitter waveform used in this chapter is a step off function quite similar to the waveform used for the 1-D modeling in chapter 3, Figure 3.5. The duration of the measurement time, i.e. how long the transmitter is switched off, was chosen to range from 10 µs to 100 ms to cover the range of time gate measurements, i.e. the receiver measurement times of the emitting response. Since we are forward modeling synthetic data from the VTEM-like system, a circular loop configuration for the transmitter with a radius of 13 m, and were simulated to be flown at 30 m height above ground level. The station spacing was set to 5 m as compared to the minimum
spacing of 3 m for the VTEM system. The flight line spacing of the survey was set to 100 m. This represents a fine flight spacing. Figure 4.1 shows a schematic of the target, model, flight lines and transmitter-receiver pairs.

Figure 4.1 - Schematic of the model space used for 3-D numerical modeling showing the different elements of the survey

For constructing the models that represent the half-space and two-layered subsurface scenarios in 3-D and using H3DTD, a mesh is required to define the volume of interest and the cells of the mesh represent blocks containing properties of the Earth. For our problem, a regular rectangular mesh was designed to accommodate the model volume. The mesh is described by the number of cells in the North, East and depth directions along with the dimensions of each. Since H3DTD is a memory intensive program, the mesh size chosen was limited to 46 x 46 x 97 cells. The minimum cell size, which correspond to the cells within the region of interest, was set to 20 x 20 x 10 m. Padding cells were added beyond that region in all three directions, using a scale factor of 1.4 – 1.8 from the previous cell width, to ensure the electromagnetic solution was stable and unaffected by boundary conditions that are chosen. Hence the volume of the region of interest was 520 x 520 x 875 m with the target having an areal extent of 240 x 240 m and a thickness of 30 m. The target location varied with depth and was incremented by 50 m for every scenario starting from an initial depth of 50 m to 500 m below ground. The total model volume was 9,760 x 9,760 x 10,215 m with 5,475 m as the subsurface depth and the rest being the air
height within the model. Figure 4.2 shows the model mesh used, the dense lines within the center of the model represent the small cell blocks within the region of interest. The mesh is visualized using MeshTools3D; a data visualization software created by UBC-GIF (webpage: www.eos.ubc.ca/ubcgif/).

The 3-D models in this study were based on, in terms of depth and resistivity characteristics, the models described in Chapter 3. The first model scenario is a half-space with 10 Ωm resistivity, Figure 4.3. The second model, conductive/resistive model, has a conductive 200 m thick layer overlying a resistive basement with resistivity of 10 Ωm and 100 Ωm respectively, Figure 4.4. The third model scenario was the opposite of the previous model, called the resistive/conductive model, Figure 4.5. With all three model scenarios, just as was done with the 1-D modeling, the embedded target resistivities varied once with a conductive resistivity of 4 Ωm, a more resistive target of 150 Ωm and a highly resistive target of 667 Ωm.

The goal in this chapter is to understand how each target responds with the VTEM-like system and also to find the range of detection depth. An important point to consider is that the target in the 3-D models is confined in its lateral extent and it is closer to real geology.

Figure 4.2 - A perspective view of the mesh for the 3-D numerical modeling using H3D TD
Figure 4.3 - 3-D halfspace model slice showing dimensions and resistivity values used

Figure 4.4 - 3-D conductive/resistive model slice showing dimensions and resistivity values used
4.3 Results and Discussion

As with the 1-D numerical modeling, a good way to illustrate the detectability of the target is to extract the peak percentage value of the response at the sounding which corresponds to the center of the areal extent of the target. The results for the halfspace, conductive/resistive and resistive/conductive model scenarios and presented in Figures 4.6 - 4.8. Another more intuitive way to display the data is through the decay curves from the station located in the middle of the survey area which shows greatest response since it is directly over center of the target. The decay curves are presented as a percentage difference, ratio of the model responses with a target to the model without a target divided by the model response without the target, against the prescribed time gates. We have chosen to show the target depths starting from 100 m and ending where the dBz/dt response decays to 0. The decay curves for the halfspace, conductive/resistive and resistive/conductive models are shown in Figures 4.9 – 4.12, 4.13 – 4.16, and 4.17 – 4.20 respectively.

Considering Figure 4.6, the halfspace scenario, the responses decrease with depth non-linearly and quickly. At 50 m depth, the percentage difference of the response of the conductive target is approximately 5% more pronounced than the resistive cases. However, when the depth
is increased to 100 m, the difference is less significant and below 100-m the target difference response approaches zero, irrespective of the resistivity value. If the data were contaminated by noise of 5%, the resolution of any target beyond 100-m depth would be difficult. This indicates that the detection of any resistivity difference caused by physical properties or production of CSG is not resolvable under the conditions tested. As for the decay curves in Figures 4.9 – 4.12 presenting the target’s depth change, a few features can be identified, only at the 100-m depth does the target response exceed the 5% noise threshold. The response is positive for the conductive target and negative for the resistive targets. This differences allows us to differentiate conductive and resistive targets. However, even with the difference in target resistivity of 150 Ωm to 667 Ωm, the difference in calculated response is negligible in this case. Also, as expected with deeper targets, the target response appears at later time gates.

For the conductive/resistive model, i.e. a conductive layer overlying a resistive basement, Figure 4.6, the peak responses calculated also decrease with depth. The limit of the detection depth of any target is at 100 m. The AEM system will not detect anything below that depth if the noise levels were greater than a few percentage of the signal calculated. The decay curves for the conductive/resistive model with different targets are presented in Figures 4.13 – 4.16 and they show the same trend and features as the halfspace model scenario. The detection of any target begins at late times and detection beyond 100-m depth lies below 5% response. In this model scenario, the conductive overburden decrease the responses that we would measure from a conductive target embedded in a resistive host.

As for the resistive/conductive model, i.e. a resistive layer overlying a conductive basement (Figure 4.8) the response for the conductive target is high even as it approaches the 100-m depth limit suggested by the previous two model scenarios. This can be explained as the conductive target embedded within the resistive layer has a high resistivity contrast to which the AEM system is sensitive. The highly resistive target shows a response higher than the 5% noise threshold at 50-m depth but the response drops off rapidly and falls below 5% at 100-m depth. This suggests an even weaker detection capability of the AEM system with such cases. The slightly resistive target seems to be the least detectable as the response at 50-m depth is below the 5% noise level threshold. The contrast is not high enough to produce a large response to be measured. Another observation is that the response does increase for resistive targets in the resistive/conductive model scenario. At 150-m depth, the targets do not seem to have any response. At the 200-m depth, the target response increases a few percentage. However, the response is still not above the 5% noise level we assume and is not detectable. From this model’s
decay curves, Figures 4.17 – 4.20, there is a noticeable change in response characteristics when compared with the previous model decay curves. The conductive target shows a high response compared to the resistive targets in the same model at 100-m and 150-m depths (Figures 4.17 and 4.18), i.e. when the conductive target is embedded in the resistive overburden layer. However, with depths of 200 m and 250 m (Figures 4.19 and 4.20) the conductive and resistive targets show similar responses that are still below the 5% noise threshold. Also, due to the resistive overburden, the responses at the different target depths are received in earlier time gates than the previous model scenarios.

Plan maps showing the response at each time gate channel for the model area can also be used to study the diffusion of the energy in the subsurface and delineate targets of interest. For our study, plan maps displaying the response at different measurement time gates were generated for all scenarios and their different target resistivities. For brevity, we have chosen to include a few to show the anomaly characteristics in the modeling. Figures 4.21 – 4.23 show the halfspace model scenario with the three target cases; conductive (4 Ωm), slightly resistive (150 Ωm) and resistive (667 Ωm). The figures show the plan layout of the model area and the colors show the ratio of the models with the background model in terms of percentage. As suspected, all three figures show an anomaly in the center of the map. The difference lies in the magnitude of the response; for the conductive target, the response is positive showing a high at the center and for the resistive targets, the response is negative and showing a low at the center of the map. However, since conductive and resistive targets are distinguishable the same cannot be said about differentiating resistive targets

4.4 Summary

In this chapter, the results of the 3-D forward modeling for the confined coal seam layers in three scenarios, namely, half-space, conductive/resistive and resistive/conductive, have been presented. The results are categorized using three characteristics: peak percentage value plots, decay curves and response plan maps.

For the halfspace model, the plot of the peak percentage values (Figure 4.6) shows a maximum peak percentage response of approximately 25% for the conductive target case. The resistive targets show a weaker response for the same depths. In general, the exponential decay
trend holds and the response falls at the 5% noise floor level at 100-m. This is an indication of the
detection ability of a VTEM-like system within such a subsurface setting. Also, from Figures 4.9 –
4.12 we observe the decay trend with respect to the calculated time gate intervals. As for the
response plan maps, the polarity/magnitude element is apparent as a positive polarity result is
obtained for a conductive target and a negative polarity result for a resistive target as shown in
Figures 4.21 – 4.23. The target depth for the plots mentioned lies at 100-m depth.

The conductive/resistive scenario shows similar behavior when compared to the halfspace
model (target embedded in a halfspace) in the three target cases. The conductive target layer
shows the highest response among the three cases response, peaking at above 20% difference.
All three target responses reach the 5% noise floor level at 100-m target depth. Anything beyond
the 100-m depth mark is sub-noise level and is approximately 0. This is better seen in the decay
curves which exaggerate the percentage response from 100 m to 250 m depths – Figures 4.13 –
4.16.

As for the resistive/conductive scenario, we observe relatively high responses for the
conductive case for the 50 – 150 m target depths. The highly resistive (667 Ωm) target is
differentiated from the less resistive (150 Ωm) for the 50-m target depth. Beyond the 200 m
transition boundary from resistive to conductive host, the response for all three target cases
decreases to 1 – 2% indicating that the detectability of the target would not be possible with a 5%
noise floor level. An explanation to the sudden drop in responses would be the conductive host
diffusing the current away from the targets and thus no measurable response is recorded.

With the 3-D forward modelled results for these scenarios there seems to be a limit for the
detection depth for the AEM setup chosen. An observation can also be made that the calculated
target responses can vary according to the environment they are embedded in but only slightly in
this case. One can conclude through these limited simulations that such AEM systems are able
to detect responses at depths and the response is a function of depth, host resistivity, target
resistivity and its lateral extent.
Figure 4.6 - Results of the 3-D numerical modeling for a halfspace model scenario. The results are shown as a function of absolute peak percentage values vs target depth.

Figure 4.7 - Results of the 3-D numerical modeling for the conductive/resistive model scenario. The results are shown as a function of absolute peak percentage values vs target depth.
Figure 4.8 - Results of the 3-D numerical modeling for the resistive/conductive model scenario. The results are shown as a function of absolute peak percentage values vs target depth.

Figure 4.9 – Decay plot at center receiver for the halfspace model with 100-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.
Figure 4.10 – Decay plot at center receiver for the halfspace model with 150-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.

Figure 4.11 – Decay plot at center receiver for the halfspace model with 200-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.
Figure 4.12 – Decay plot at center receiver for the halfspace model with 250-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.

Figure 4.13 – Decay plot at center receiver for the conductive/resistive model with 100-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.
Figure 4.14 – Decay plot at center receiver for the conductive/resistive model with 150-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.

Figure 4.15 – Decay plot at center receiver for the conductive/resistive model with 200-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.
Figure 4.16 – Decay plot at center receiver for the conductive/resistive model with 250-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.

Figure 4.17 – Decay plot at center receiver for the resistive/conductive model with 100-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.
Figure 4.18 – Decay plot at center receiver for the resistive/conductive model with 150-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.

Figure 4.19 – Decay plot at center receiver for the resistive/conductive model with 200-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.
Figure 4.20 – Decay plot at center receiver for the resistive/conductive model with 250-m deep target. The decay is plotted as a function of the percentage of the ratio of the calculated responses.

Figure 4.21 – Map view for the calculated response at time gate 34 of a 100-m deep conductive (4 Ωm) target in the halfspace model. The axes are distance in meters with the color coding of the map being percentage difference from the halfspace model without any target.
Figure 4.22 – Map view for the calculated response at time gate 34 of a 100-m deep slightly resistive (150 $\Omega$m) target in the halfspace model. The axes are distance in meters with the color coding of the map being percentage difference from the halfspace model without any target.

Figure 4.23 – Map view for the calculated response at time gate 34 of a 100-m deep resistive (667 $\Omega$m) target in the halfspace model. The axes are distance in meters with the color coding of the map being percentage difference from the halfspace model without any target.
Chapter 5

CASE STUDY: QUEENSLAND’S SURAT BASIN, AUSTRALIA

The CSG industry in Queensland, Australia is currently in a booming stage. It is already a major contributor of the total gas produced in Queensland and it is expected that the CSG industry will become more substantial in fueling New South Wale’s energy demand in the near future. Exploring for new reservoir zones to increase current production and also to aid in determining field life is a vital task for companies. In addition, detecting unswept zones by current production techniques is necessary to stabilize production from a field. For the abovementioned reasons, careful monitoring of these thin reservoirs is beneficial and can aid in maximizing profits. The traditional seismic reflection technique can be used as the impedance contrast of coal seams with the surrounding subsurface can yield a bright spot. However, the seismic technique is costly and is time consuming. As an alternative method, the AEM technique is an alternative to be considered as it enables fast acquisition and does not require land access in agricultural or vegetated areas that can cause restrictions to the seismic techniques. Also, the AEM technique has the advantage over seismic techniques in areas containing volcanic depositions, such as some parts of the Surat Basin, as the seismic source wave will be highly attenuated. The AEM technique may provide exploration and production monitoring capabilities to the producing companies.

Evaluating the feasibility of AEM systems, primarily a VTEM-like system, to detect changes within these relatively shallow coal seams can provide economical benefit and scientific insight to companies that are exploring and producing this clean energy source.

5. 1 Introduction

The Surat Basin is a prolific CSG producer situated in Queensland, Australia. The geologic set up of the basin is mainly fluvial, lacustrine sediments, and coal bearing successions. The coal seams are shallower than other basins known for major CSG production in the world. The coal seam depths range from 300 – 600 m within the basin. The simplified geology that is modelled here is of a typical section of the Surat Basin excluding any dipping beds. The Middle Jurassic Walloon Subgroup formation contains two coal measures (seam stacks) that have been targeted
for years for their gas content, namely the upper Juandah and the lower Taroom coal measures (Scott et al., 2007).

Figure 5.1 displays a litho-stratigraphic column of the Walloon Subgroup, which shows the individual coal seams within the Juandah and Taroom coal measures. The depths of the individual seams range from 5.9 m to 25.7 m. The coals within the basin contain a high carbon content, indicating they are mature and thus contain economical gas adsorbed to the coal (Scott et al., 2007). The coal seams within the Surat Basin and other basins present in West Australia are known to be laterally continuous in stratigraphy; however, the physical properties of the coal seams are heterogeneous. For the approach we have taken so far, the heterogeneity of the different layers within the model are neglected and the focus is on the first order detectability of the coal seams using AEM.

5.2 Numerical Modeling

Taking the stratigraphic column shown in Figure 5.1 into consideration as well as other public domain data available on the Surat Basin, we have designed a model that contains the main features of the basin, Figure 5.2. The model is composed of alternating shale and sandstone layers above the zone of interest where the coal seams are embedded. The depths at which the coal seams are embedded are on average at 350 and 550 m. The coal measures (groups) contain coal seams with varying thickness, the thinnest being 10 m and the thickest being 20 m. The model represents a more complex scenario to evaluate the application of AEM for CSG exploration and monitoring.

Both 1-D and 3-D forward modeling were carried out with the same model, survey and transmitter waveform parameters used in previous modeling examples. For the 1-D modeling, a step off waveform was used along with resistivity values set to 10 Ωm for the shales, 100 Ωm for the sandstone layers and the three target resistivities of 4 Ωm, 150 Ωm and 667 Ωm. The center loop sounding measurement of the B-field was modelled using a square loop with a 23-m side and at a height of 30 m above ground. For the 3-D modeling, a step off current waveform was also used with the same resistivities as the 1-D case for the host geology and the coal targets. The survey was modelled with a flight line spacing of 100 m, transmitter-receiver pair spacing of 5 m, and a flight height of 30 m above ground. The dB/dt measurement used for comparison is from the transmitter-receiver pair centered above the target.
Figure 5.1 – The litho-stratigraphic column of the Surat Basin (Scott et al., 2007)
The areal extent of the CSG target, as well as the mesh and model sizes are similar to those used in the previous examples in Chapter 4 for the first set of models here. In addition, a second extended model is constructed here in which the areal extent of the target is doubled in size to 480 x 480 m while maintaining the thicknesses of the seams as discussed previously.

5.3 Results and Discussion

Upon first inspection, the results obtained from the 1-D and 3-D models in chapters 3 and 4 respectively, hint that the Queensland model may be detectable by the 1-D approach but undetectable by the 3-D modeling due to the thicknesses of the targets and their corresponding depths. We next evaluate the data from the simulated Queensland model directly. Table 5.1 displays the peak value responses calculated from the two modeling approaches, along with the
3-D responses for different areal extents of the target layers, i.e. the 240 x 240 m and the 480 x 480 m target areas.

Table 5.1 – The results of the 1-D and 3-D modeling carried out on the Queensland case study model

<table>
<thead>
<tr>
<th>Model/target</th>
<th>Conductive</th>
<th>Slightly Resistive</th>
<th>Highly Resistive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-D</td>
<td>37.42</td>
<td>30.05</td>
<td>32.00</td>
</tr>
<tr>
<td>3-D</td>
<td>0.47</td>
<td>0.36</td>
<td>0.34</td>
</tr>
<tr>
<td>3-D extended</td>
<td>11.69</td>
<td>7.45</td>
<td>7.93</td>
</tr>
</tbody>
</table>

The results show a consistent trend for each of the models (1-D, 3-D, and 3-D extended), where the conductive target generates a higher response with the receiver. For the resistive cases, the highly resistive target creates a better contrast with the surrounding and has a higher response than the slightly resistive target for all three modeled scenarios. However, the difference in the response between the resistive targets is not as significant. The signal difference could be increased by further increasing the resistivity difference between the two resistive cases.

Additionally, it is noted that while the target’s areal extent is relatively small, and as a result the response of the system is low and would be difficult to detect in noisy data. This implies that the detection of CSG targets with high contrast is possible if the areal extent of the target is large enough. However, it may not be possible to detect smaller confined CSG targets by AEM.

To further examine the differences between the calculated 1-D, 3-D and extended 3-D responses, we display the decay curves for the full model, i.e. all coal seams present from 300 – 600 m depth. Also, to differentiate between the coal seams we display the decay curves for only the upper coal seam group as well as the lower coal seam group. These decay curve responses are displayed only for the 3-D model. Figure 5.3 illustrates the decay curve obtained at the center of the survey area for the 1-D CSG model discussed in Figure 5.2. In this case, both the conductive and resistive targets display responses in excess of 30% difference from the background model. In contrast, the 3D response (Figure 5.4) is significantly lower with less than 1% difference from the background. Next, we examine the extended 3-D model response (Figure 5.5). In this case, the signal increases to approximately 10% difference. These data lead to a conclusion that 1-D modeling can be used as an approximate tool for CSG AEM interpretation yet
in our case it may over calculate the response. Additionally, in 3D the areal extent of the target, has a strong effect on the data, indicating that AEM application for CSG is site dependent.

So far, we have studied the AEM response for all coal seams within the upper and lower groups combined. In our final simulations, we investigate the response of the individual coal seam groups to understand the signal versus target depth. Figure 5.6 illustrates the response calculated for only the top coal group. In comparing this data to the response obtained for both coal seam groups combined (Figure 5.4), we note that they are similar in magnitude and decay time, indicating that the deeper coal seam group may not be detectible here. To verify this, we next calculate the response for the lower coal group, Figure 5.7. Results show that there would be measurable response in this case and that the depths at which the lower target seams are located are too deep for our AEM method to detect here.

5.4 Summary

The work carried out in this chapter aims to bridge the gap between the fully synthetic study that we performed and a more realistic geologic scenario in which a simplified basin stratigraphy is adopted from the Surat Basin in Queensland, Australia. The main objective in designing such a model is to test the detectability power of the AEM method in a multilayered model with challenging target thickness and depths.

The model proved rather challenging for the AEM system when modelled in 3-D as the measured response was below 1% difference from background. However, when a horizontally extended model was used, the 3-D response increased above the noise floor level. For the 1-D case, a relatively high response was calculated indicating that AEM may detect changes at these depths and coal seam thicknesses.

Finally, we examined the individual responses for the different coal seam groups in the 3-D model and observed that most of the measured response was due to the shallow coal seam group with little to no contribution from the deeper coal seam group.
Figure 5.3 Decay plot at center receiver for the 1-D Queensland CSG model for all coal seam layers (300 – 600-m depth). The decay is plotted as a function of the percentage of the ratio of the measured responses.

Figure 5.4 Decay plot at center receiver for the 3-D Queensland CSG model for all coal seam layers (300 – 600-m depth). The decay is plotted as a function of the percentage of the ratio of the measured responses.
Figure 5.5 Decay plot at center receiver for the extended 3-D Queensland CSG model for all coal seam layers (300 – 600-m depth). The decay is plotted as a function of the percentage of the ratio of the measured responses.

Figure 5.6 Decay plot at center receiver for the 3-D Queensland CSG model for the upper coal seam layers (300 – 480-m depth). The decay is plotted as a function of the percentage of the ratio of the measured responses.
Figure 5.7 Decay plot at center receiver for the 3-D Queensland CSG model for the lower coal seam layers (520 – 600-m depth) The decay is plotted as a function of the percentage of the ratio of the measured responses.
Chapter 6

CONCLUSIONS AND FUTURE WORK

In this thesis we have examined the nature of coal seam gas (CSG) reservoirs in terms of their geological settings and used the details provided in geology to build a set of geophysical models of these reservoirs. The overall objective of this work is to contribute to the sparse literature focusing on addressing a recent question: can the Airborne Electromagnetic (AEM) method be used to explore for or monitor CSG reservoirs. This feasibility study was carried out to aid in a first order understanding of the problem, and to help answer this research question.

The work began with a thorough geologic examination into CSG reservoirs to obtain an understanding of the physical processes that take place in these reservoirs. We then relate these processes to physical properties that can be adapted to the problems of exploration and monitoring, such as when the coal seams undergo change in the resistivity during production. We next simulate the response of an AEM system for this study. In particular, we reproduced a VTEM-like system to simulate the responses. The next step was to design a set of models that provide basic understanding of the AEM output response. For this, we constructed 1-D and 3-D multilayered models, as well as a representation of the Surat Basin for a more representative CSG test study. The reservoir properties that we varied in our work include target and host resistivities, target depth and horizontal extent. To summarize the findings of our work, we discuss each chapter separately with relative results.

The first section of the thesis, Chapter 3 demonstrated the use of one dimensional forward modeling for different scenarios of coal seam reservoirs to obtain a general first order understanding of the detection depths by AEM of CSG reservoirs. The 1-D modeling in both the halfspace and conductive/resistive models shows response detection below 300 m for three cases of target resistivity, where the measured responses are above the 5% noise floor level. However, when a resistive layer overlies a conductive host, the resistive/conductive model, the signal is significantly reduced for the resistive target cases, but the response for the conductive target layer is unaffected. A plausible explanation for this is that there is a strong contrast between the host and target, and that induced currents preferentially flow through conductors embedded within resistor hosts than when it is embedded in a slightly more conductive environment. In order
to better understand the responses from more complex reservoirs, a 3-D model was developed to incorporate additional geology into the problem. Chapter 4 presented the modeling results for the 3-D models where the target body was confined to the same depth increments as in Chapter 3.

For the 3-D CSG models in Chapter 4, the same level of response is not observed for the 240 x 240 m areal extent target. For the halfspace and conductive/resistive model, the AEM response is small, as expected since the 1-D assumption is not fully met in this case. Also noticeable is the decreased response below 50-m target depth. Assuming a 5% noise floor level, the different targets would not be detectable these instances beyond 50-m while, detection depth reaches to 300-m in the 1-D scenario. If, however, a resistive overburden exists, i.e. the resistive/conductive model scenario, the 3-D response for the conductive case target is strong compared to the other target cases. In this scenario, a conductive target can be detected at a depth of 150-m and possibly more depending on the thickness of the overburden resistive layer. In contrast, for the case of the resistive targets, the anomalous body would be undetectable beyond 50-m depth if the resistivity contrast is not large enough, as observed between the 150 $\Omega\text{m}$ and 667 $\Omega\text{m}$ responses at 50-m depth. Finally, Chapter 4 discusses the decay curves of the different models and distinguishing of target resistivity types based on the magnitude and polarity of the responses. This was presented by decay plan maps generated at constant time gates and indicating the presence of a conductive or resistive target.

Lastly, we apply the same modeling techniques to a more complex model in Chapter 5 adopted from the Queensland Surat Basin CSG reservoir. Here, the 1-D responses show promise for detecting targets at up to 500 m. From the 3-D models with a target areal extent of 240 x 240m, the responses are small and indicate shallow detection depths. However when we increased the target’s areal extent to 480 x 480 m, a stronger response is calculated above the 5% noise floor level for all three target cases. This is a good indication that the size of the CSG target is important for AEM application.

From this study, if the target is not large enough in lateral extent, it is unlikely that we would be able to detect it. Additionally, if production of a coal seam group does not produce a resistivity contrast that is measurable, the AEM method such as modelled here would also not be beneficial. For the exploration case, with laterally continuous targets, AEM might may prove useful if the contrast is large enough between target and host keeping in mind the depth limitation
observed in different modeling scenarios. In most cases these were limited to 150 – 200-m depth. Therefore, an AEM tool such as the one simulated here may be useful in the following cases:

- Shallow reservoir depths – As seen from the 3-D modeling, the AEM method would be limited to approximately 150 – 200-m deep targets.
- Thick reservoirs – In our modeling we strictly used a fixed reservoir thickness of 30 m for all models except the Queensland Surat Basin model where the individual coal seam thickness varied from 10 – 20 m. Thicker coal seam layers would generate a higher response and a stacked coal group would resemble an even thicker target.
- Resistivity contrast – As seen from most of the results, the conductive target shows a higher response when compared with the two resistive targets even when they are in the same setting. This indicates that AEM systems might be more useful for conductive targets, such as with their uses in the mining industry.

These points with regards to the exploration and production monitoring of CSG reservoirs are good yet not complete. For a better understanding and more accurate estimation of the responses that are generated from these reservoirs, a more complete modeling suite should be carried out in order to further build our understanding. Therefore I propose future work along these lines:

1) The use of more detailed petrophysical data into the models. Modeling with real geologic resistivity values measured at the site for example could yield accurate results tailored to the site under consideration. This can take the modeling work a step closer and be able to compare with real data, if available.

2) Since not all coal seam reservoirs are water saturated or wet, models that use refined resistivity values that resemble dry coal seam reservoirs could add value as to test for the detectability depths of a wide range of CSG reservoirs.

3) More complex models that take into consideration dip and anisotropy can also aid in the understanding of the resulting responses that would be site specific and yet could provide valuable information. Sweet spots are favorable targets in CSG production and being able to identify these highly fractured, high permeability zones can prove beneficial. Future models would need to incorporate local confined sweet spot targets within the
greater coal seam zone and test its detectability. Also, directional anisotropic models can be designed to test an AEM system's ability to detect these directions indicating flow pathways.

4) Detailed geologic characterization of the surface and overburden features such as topography and volcanics and their incorporation into the models to be simulated can add more complexity to the model as well as the interpretation of the results. However, they will resemble the geology and geography of the basin and therefore be comparable to the results obtained in the field and therefore they will improve our understanding regarding these features with respect to the CSG reservoir detectability.

5) Testing different thicknesses of the target to tackle the issue of resistivity-thickness parameter that is available in the literature. Also in our case, the lateral extent of the target is another parameter to be used in order to ensure proper calculated responses. This could have impact on the well spacing and areal coverage of production wells.

6) The testing of different AEM systems for the task and comparing them together will serve as a means of distinguishing which systems would be best suited for the job. Also, changing the input parameters of the system and comparing them side by side would give insight into which parameters (e.g. waveform) can be beneficial to certain targets. In published case histories, some systems show improvements over others in some target setting. Also the use of borehole to surface EM techniques could be promising in such a scenario as the instruments are in proximity to the target being detected.

7) Since the properties, density and resistivity of coal make it detectible using other techniques, using multiple data sets, such as gravity and EM data, could highlight zones of interest and aid in decreasing uncertainty for identifying CSG reservoirs.
REFERENCES


