FEASIBILITY OF TIME-LAPSE GRAVITY GRADIOMETRY FOR RESERVOIR MONITORING

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geophysics).

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ABSTRACT

Monitoring fluid movement within a reservoir is essential to ensuring efficient reservoir development. To date, time-lapse monitoring has been dominated by seismic technology, but there is a desire to find additional technologies that can supplement seismic data and potentially lower the overall monitoring cost. Potential field methods, such as gravity and gravity gradiometry, may be suitable for time-lapse monitoring due to their ability to track fluid through density changes within the reservoir. While gravity has been previously studied, there has been very little work done in the field of time-lapse gravity gradiometry.

In this thesis, I present a series of feasibility studies designed to determine whether or not gravity gradiometry is capable of detecting the small density contrasts associated with various reservoir monitoring problems. Here, considering both the current and predicted next generation of gravity gradiometry technology, I evaluate the signals from a variety of conventional and unconventional reservoirs to understand the potential value at these different sites. I likewise analyze the ability of gravity gradiometry to recover fluid movement by inversion for a set of specific reservoir sites that contain detailed site geometries developed from seismic data and prior site studies.

The results of this work indicate that gravity gradiometry may provide a powerful tool for reservoir monitoring in the near future. However, as with all geophysical methods, the true application is site dependent as the final signal will vary based on the reservoir’s fluid densities, saturations, depths, thicknesses and other parameters.
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ACKNOWLEDGMENTS

This research would not have been possible without the dedicated efforts of my adviser, Dr. Richard Krahenbuhl, and the head of the Center for Gravity, Electrical & Magnetic Studies, Dr. Yaoguo Li. I thank them both for all they have done to sponsor, coach and support my research and growth as a student and a person. A special thank you goes to the rest of my committee that included Dr. Tom Davis and Dr. Mike Batzle who provided me with information and asked the tough questions. I would also like to thank Dr. Terry Young for being an outstanding department head and guide through all my years at Mines.

I would also like to extend gratitude to my colleagues at CGEM, who provided me with friendship and scholarly advice, the industry professionals who have helped me with this work (particularly Dan DiFrancesco, Mark Dransfield and Dave Hatch), members of the Reservoir Characterization Project for their insightful discussions (including Kelsey Schiltz and Loren Ziegler), and all the sponsors of the Gravity & Magnetics Research Consortium for funding my research.

Last, a special thank you to my friends and family. Catie, Brent, Emily, Rachel, Ashley, Paden, Dad, Mom...I love you for your unwavering support. And finally, my cat, Harley, who probably understands more about gravity than I do.
The application of geophysical technologies to reservoir monitoring is a relatively young field compared to their applications in exploration. The need for such monitoring tools stems from the simple concept of maximizing injection and production efficiency at a field through informed reservoir management decisions. For example, understanding how fluid moves at a site can provide direct insight into regions of the field where low-permeability boundaries may be impeding sequestration or enhanced oil recovery efforts. The application of this technology can lead to more educated design decisions, influence production strategy and ultimately improve the economic return on investment of a field.

To date, monitoring efforts have been dominated by the seismic method due to the resolution of the data as well as the advancement of instrumentation and interpretation technologies. The first published applications of time-lapse seismic appeared in the 1980s for understanding the effects of heat on seismic velocity, such as at steam injection sites (Lumley, 2001). Regardless of the specific application, the underlying goal of these studies is universal: understanding fluid movement within the subsurface. Since these early studies, 4D seismic has continued to evolve and demonstrates a powerful tool for reservoir monitoring.

The most significant drawback to repeated seismic surveys is the cost. While the data resolution is often superior to other geophysical methods, it is not always economically feasible as a routine method to monitor reservoir performance. Furthermore, in some regions the environment may present a significant obstacle to large-scale seismic operations. In these instances, it is particularly relevant to identify alternative or complementary methods that are capable of detecting fluid movement in the reservoir.

Potential fields is one such technology that has proven itself useful in the reservoir monitoring community. For example, the time-lapse gravity study of Brady, Ferguson, Hare and
colleagues at Prudhoe Bay, Alaska, proved highly successful for monitoring movement associated with gas cap water injection (GCWI) (Brady et al., 1996; Hare et al., 1999; Ferguson et al., 2008). At that site, as well as other EOR and geo-sequestration reservoirs, the strong density contrasts can provide a significant anomaly at the surface. This in turn can provide insight into the dynamics of the reservoir, including zones where fluid movement may be proceeding in an unexpected fashion.

A natural extension of the gravity method for time-lapse reservoir monitoring is the application of time-lapse gravity gradiometry. Gravity gradiometry, like gravity, is sensitive to density changes within the subsurface, and may also be capable of tracking fluid movement within the reservoir. Furthermore, the multicomponent nature of gradiometry data provides additional horizontal information about the density distribution, which may allow for improved recovery of fluid distribution over gravity.

The most significant challenge that gravity gradiometry faces presently for time-lapse monitoring applications is the detection limits of current technology. Relatively small density contrasts within the reservoir, coupled with great reservoir depths and thin beds, may produce a subtle signal that it is not detectable by current instrumentation which features noise levels of 2-5 E or higher (Dransfield, 2011). Moreover, current legislation restricts data collection to 30 m above the surface of the earth, which leads to further decay of the measurable signal.

Fortunately, recent and anticipated improvements in instrumentation may provide the next generation of sensors with the capability to expand gravity gradiometry beyond its traditional role of exploration and into the field of reservoir monitoring (DiFrancesco et al., 2009; Reitz et al., 2012). Furthermore, as this technology continues to prove its value for energy related problems, it is likewise anticipated that current flight-height restrictions could be eliminated entirely. The added benefit of such policy change would be the ability to move to ground-based instruments in static mode, to further improve the noise level and increase the likelihood of detection of the subtle signals often associated with fluid movement.
Time-lapse applications of gravity gradiometry have not been widely explored in the past. In the late 1990s and early 2000s, Talwani, DiFrancesco and colleagues produced a series of groundbreaking studies, including field tests (Talwani et al., 1999; DiFrancesco & Talwani, 2002). There have also been small feasibility studies presented to evaluate specific sites and data types (e.g., Vasilevsky et al., 2003; Vasilevsky et al., 2005; Amano & Yamamoto, 2013) as well as the data resolution of time-lapse gradiometry data (Kirkendall & Li, 2007). However, to date there has not been an extensive study on the general feasibility of time-lapse gravity gradiometry for monitoring the various reservoir types. Therefore, it is the topic of this study to expand upon the initial works of Talwani and colleagues and further investigate the potential of time-lapse gravity gradiometry for reservoir monitoring.

In this thesis, I begin here with the introduction and motivation for exploring time-lapse gravity gradiometry as a potential reservoir monitoring tool. In the following chapter, Chapter 2, I provide a brief overview of the theory behind gravity gradiometry, and discuss how it might be applied to reservoir monitoring applications. I also discuss the history of gradiometry instrumentation, and the signal levels that must be achieved in the field in order to detect fluid movement with both current and next-generation technology.

I begin the feasibility tests in Chapter 3, where I explore the signal predicted for several conventional reservoir monitoring projects, including CO₂ injection and waterflood for sequestration and enhanced oil recovery. I first present a general approach to approximate the time-lapse geometry of an expanding plume (swept zone) for typical fluid injection/replacement situations. I then extrapolate these results to several well-known reservoirs. From these, I finally present a general approach to estimate the maximum signal predicted for these and other reservoir sites. The results in this chapter therefore provide a baseline understanding and general approach to predict whether or not gravity gradiometry would be a useful monitoring tool for different conventional reservoir sites.

In Chapter 4, I expand upon the results of Chapter 3 for conventional reservoirs by developing a framework for a more detailed feasibility study at specific reservoir sites. For this,
I analyze two well-known reservoirs that have undergone extensive time-lapse monitoring: Delhi Field in Louisiana, and Prudhoe Bay in Alaska. To this end, I focus on improving the geometry of each field using various available sources, such as seismic data and previous site studies available in literature. By improving upon the geometry of these sites, I am able to present an approach that utilizes and complements available seismic data, thus providing a better estimate of the gradiometry signal and a more realistic representation of fluid movement and recovery through inversion.

Lastly, I investigate unconventional reservoirs in Chapter 5, where I analyze the feasibility of monitoring heavy oil production at steam assisted gravity drainage, or SAGD, sites. SAGD reservoirs are generally shallow and will exhibit a high density change as steam replaces the heavy oils. This combination makes SAGD an attractive candidate to evaluate gravity gradiometry for monitoring. This study is performed in three parts. It starts with a general framework from the approximation of the geometries of SAGD steam chamber growth with various first-order sensitivity tests. These include sensitivity of the data to depth of the reservoir and horizontal well-pair separation. I then present sensitivity of the data through inversion to second-order deviations of SAGD steam chamber movement due to reservoir heterogeneity. To close, I present a detailed SAGD site example where I utilize time-lapse seismic data collected over a 9-year period to demonstrate that gravity gradiometry can detect and monitor steam chamber growth during production.

Finally, in Chapter 6, I discuss the relevance of my time-lapse gravity gradiometry results for reservoir monitoring by summarizing the general conclusions presented in Chapters 3-5.
CHAPTER 2
BACKGROUND

Time-lapse reservoir monitoring is an important component of the energy industry. Monitoring fluid movement within a reservoir, whether for recovery or sequestration purposes, is vital to reservoir development and design. While this area is dominated by time-lapse seismic, there is benefit to evaluating and incorporating additional methods that may provide complementary data, particularly for reservoirs where acquisition of seismic data may present environmental or legislative challenges. Potential field methods, such as gravity and gravity gradiometry, are sensitive to the property changes within the reservoir over time and may be useful tools for tracking subsurface fluid movement as a complement to seismic data. Gravity has a long history of monitoring fluid movement; however, very little work has been done to understand gradiometry for the same problems.

2.1 Gravity Gradiometry

The earliest known gravity gradiometer was the torsion balance, developed around 1891 by Baron Loránd von Eötvös (Heiland, 1943). This instrument was first deployed for oil exploration in 1916 over the Egbell oil field near Gbely, Slovakia. However, following the first major oil field discovery by gradiometry in 1924 at the Nash Dome in Ft. Bend County, TX, (LaFehr, 1980) the torsion balance soon became superseded by the gravity meter, and the idea of gradient measurements was effectively shelved until the 1970s when the United States military took interest in the technology (DiFrancesco et al., 2009). When the Cold War ended, the technology was declassified by the US and commercialization of gradiometry began in the late 1990s and early 2000s. Since that time, it continues to demonstrate successful application in marine studies (Hatch & Annecchione, 2010; Huston et al., 1999; O’Brien et al., 2005), mining (Keating & Pilkington, 2013; Martinez et al., 2013; Mataragio & Kieley, 2009) and petroleum exploration (Bell et al., 1997; Ennen & Hall, 2011).
The theory behind gravity gradiometry is well understood (e.g. Blakely, 1996; Telford et al., 1990). The technique seeks to measure the rate of change of the gravity field by taking multiple point measurements of the field and calculating the gradient from those data. As the gravity field, $g$, is the gradient of the gravity potential, $\phi$, the gradient of the three component gravity field is a tensor comprised of the second partial derivatives of the potential, \[
abla g = \nabla \nabla \phi = \begin{pmatrix}
\frac{\partial^2 \phi}{\partial x^2} & \frac{\partial^2 \phi}{\partial x \partial y} & \frac{\partial^2 \phi}{\partial x \partial z} \\
\frac{\partial^2 \phi}{\partial y \partial x} & \frac{\partial^2 \phi}{\partial y^2} & \frac{\partial^2 \phi}{\partial y \partial z} \\
\frac{\partial^2 \phi}{\partial z \partial x} & \frac{\partial^2 \phi}{\partial z \partial y} & \frac{\partial^2 \phi}{\partial z^2}
\end{pmatrix} = \begin{pmatrix}
T_{xx} & T_{xy} & T_{xz} \\
T_{yx} & T_{yy} & T_{yz} \\
T_{zx} & T_{zy} & T_{zz}
\end{pmatrix}. \tag{2.1}
\]

This tensor is traceless (meaning that the sum of the diagonal components are equivalent to zero) and symmetric, which leads to five independent components. As a result of measuring the gradients of the field, there are several advantages to gravity gradiometry data over gravity. These include measuring a higher decay rate for increased resolution, higher spatial sampling, and rejection of common mode noise (Bell et al., 1997; Dransfield & Christensen, 2013). In Equation 2.1, the gravity field is a measure of acceleration in m/s$^2$ while the gradients are in 1/s$^2$. The common units for these methods in geophysical applications are the milligal (mGal) and microgal ($\mu$Gal) for gravity (Equation 2.2), while gradiometry is measured in eotvos (E) (Equation 2.3).

\[
1 \ \mu\text{Gal} = 10^{-3} \text{mGal} = 10^{-8} \text{m/s}^2 \tag{2.2}
\]

\[
1 \ E = 10^{-9} \text{Gal/cm} = 10^{-9} \text{1/s}^2 \tag{2.3}
\]

### 2.2 Gradiometry Error Levels

Currently, gravity gradiometry technology is generally limited to the detection of signals greater than 2 - 5 E (Dransfield, 2011). While this level has demonstrated useful for many geophysical applications, such as mining exploration (Martinez et al., 2013) and salt body imaging (Ennen & Hall, 2011; Hatch & Annecchione, 2010; O’Brien et al., 2005), the research in this thesis demonstrates that lower error levels are often desired for monitoring
applications. Along this line, experience and improvements by operators during collection and processing have seen error levels approaching 1 E (Dransfield, 2013: personal communication).

Gradiometry systems on the horizon are predicted to have the potential of performing at the 1 E level for routine collection (Hatch: personal communication, 2013). It is also noteworthy that in the late 1990s, Lockheed Martin conducted a series of tests with a static-mode, ground-based instrument. The purpose of the study was both to test the system for accuracy and viability in a time-lapse environment. Data was collected at fourteen stations in the San Joaquin Valley. The results of the data collection demonstrated instrument repeatability between 0.1 and 0.2 E, with an average of 0.16 E in the horizontal components when all measurement errors were accounted for (Reitz et al., 2012). While remnants of the classified technology currently restrict gradiometry surveys to ground clearance no less than 30 m, thus eliminating ground surveys at the moment, the instrumentation and its potential has been demonstrated. These combined factors of evolving instrumentation, improved operator experience, improved processing, and the anticipated removal of legal restrictions on survey height, open the possibility of the application of gravity gradiometry as a cost effective option to monitor reservoir performance through time.

To evaluate the feasibility of gravity gradiometry for reservoir monitoring, both current and “on the horizon” instruments are considered. Gradiometry signals are evaluated within respect to the error levels defined here, specifically 5 E, 1 E, and 0.16 E.

2.3 Time-lapse density contrast

Every reservoir site, whether for sequestration or enhanced oil recovery, has geometric properties unique to the site. These include the depths, thicknesses, lateral extents, geologic dip, topography, depositional environment, porosity and permeability distributions, etc. As a result, the geometries of each field must be defined on a case-by-case basis. In contrast, the source of the underlying physical property of the time-lapse problems for gradiometry can be defined here.
For potential field studies, the initial density state of a reservoir can be defined by the combined reservoir and in-situ fluid properties prior to injection or production,

$$\rho_i = \rho_m (1 - \phi) + \phi (S_w \rho_w + S_g \rho_g + S_o \rho_o)$$  \hspace{1cm} (2.4)

Here, $\rho_m$ and $\phi$ are the rock matrix density and porosity of the reservoir, respectively. $\rho_w$, $\rho_g$ and $\rho_o$ are the fluid densities for the water, gas and oil within the field. $S_w$, $S_g$ and $S_o$ are the respective saturations of these fluids. At a later state, the updated density of the reservoir can also be defined by Equation 2.4 by defining the new saturations of the fluids at that time.

The final density change, $\Delta \rho$, within the swept zones can be defined by the difference between the initial and final density states. In most reservoirs, the rock matrix density is assumed to remain constant through time. It is the relative concentrations of the pore fluids that are variable. Therefore, to determine the density change over time, the densities defined in Equation 2.4 for each state can be differenced, the first terms for the unchanging matrix drop out, and the final time-lapse density contrast can be written as,

$$\Delta \rho = \phi(\Delta S_w \rho_w + \Delta S_g \rho_g + \Delta S_o \rho_o)$$  \hspace{1cm} (2.5)

In essence, Equation 2.5 demonstrates that the final time-lapse density change in most reservoirs can be simplified to the saturation changes within the swept zones. Typically, the fluid density will not change through time, but this is not always the case. For example, in Chapter 5, I demonstrate the case of steam assisted gravity drainage, where the high reservoir temperatures after steam injection have a significant impact on the final oil density. However, in most conventional reservoirs, the initial fluid densities and final fluid densities will be negligibly different.
In this chapter, I explore a general approach to monitoring conventional hydrocarbon-bearing reservoirs, or geo-sequestration projects, using time-lapse gravity gradiometry. In addition to the development an understanding of the geometry of the problem, I also categorize the feasibility of various fields using a simple first-order approach to approximating the signal strength.

3.1 Introduction

There are two main purposes for injecting fluid into the subsurface in the oil and gas industry. The first is for enhanced oil recovery, or EOR. In this scenario, production has dropped off due to decreased reservoir pressure or poor fluid mobility within the reservoir of interest. When this happens, additional fluid such as water or carbon dioxide may be injected into the reservoir in order to mobilize existing hydrocarbons for production.

The second is for geo-sequestration, or storage deep within the subsurface of undesirable by-products of the extraction process such as CO$_2$. Injecting this fluid into deep reservoirs can provide an effective solution for long-term storage.

Reservoir monitoring has become an important part of measuring the effectiveness of these two types of fluid injection. In the first case, it is important to understand where the fluid is moving in order to improve the efficiency of the process and ensure that maximum recovery is being achieved. In the second case, government regulations are very strict and require that once injected, no fluid is able to escape the storage reservoir. Reservoir monitoring can determine whether or not this is the case by tracking where the fluid settles out and determine if there is fluid depletion within the reservoir.

Traditionally, time-lapse seismic has been used to track fluid movement through time within deep reservoirs. It provides excellent resolution and depth of investigation in most
cases, but often at a high cost.

Non-seismic methods have been gaining traction in the geophysical community as effective tools under certain reservoir conditions. For example, Prudhoe Bay in Alaska featured the first major time-lapse gravity survey (Brady et al., 2008). The multi-year efforts there yielded promising results about gravity’s ability to track fluid movement within an immense, deep reservoir.

In this chapter the feasibility of gravity gradiometry as a reservoir monitoring tool for conventional reservoirs is investigated. I first analyze at the geometry of the conventional reservoir, and the range of density contrasts that can be expected from various types of common fluid injection. For the final part of this chapter, I design a series of general examples using fields from literature in order to understand whether or not their signal exceeds the limits for gravity gradiometry discussed in the previous chapter.

3.2 Generalized Geometry

A natural representation for a time-lapse reservoir undergoing fluid injection is a uniform front that expands away from and injection site, which can be approximated by a vertical cylinder model with expected density change. It is important to note that this serves as a first-order approximation to the behavior of the injected fluid. The simplified geometry will break down in the presence of complex reservoir geometry, significant petrophysical heterogeneity and complicated injection patterns. In this chapter, I focus on the understanding provided by a general model form, and I further expand to reproduce realistically complex reservoir geometries and properties in Chapter 4 for improved site-specific analysis.

The concept of using a fluid cylinder to quantify the approximate signal is not new. Because of the relative simplicity of this method, it has been applied successfully for several first-order gravity studies in order to understand the instrument sensitivity to reservoir thickness and depth. Examples of this can be found in Stenvold et al. (2008) and Young & Lumley (2012).
For my modeling here, I assume a flat, homogeneous reservoir with thickness $h$ and depth of $z$. As fluid is injected through a vertical injection well, the fluid seeps evenly in all directions throughout the entire reservoir height $h$. This creates a cylindrical zone of injected fluid with radius $r$ that expands with time. This expanding swept zone has a density contrast, $\Delta \rho$, that can be adjusted to the specific time-lapse problem and it is a product of reservoir and fluid properties. An illustration of this geometry can be seen in Figure 3.1.

For example, Telford et al. (1990) defines the relationship for calculating the vertical component of the gravity field for such a model as:

$$g_z = 2\pi \gamma \Delta \rho (L + \sqrt{z^2 + R^2} - \sqrt{(z + L)^2 + R^2}), \quad (3.1)$$

where $\gamma$ is the gravitational constant, $z$ is reservoir depth, $\Delta \rho$ is density change, $L$ is the reservoir thickness and $R$ is the radius of expansion for the fluid front. We can then modify Equation 3.1 for the vertical component of the gradient tensor ($T_{zz}$) by taking the partial
derivative in the z-direction:

\[ T_{zz} = 2\pi \Delta \rho \gamma \left( \frac{z}{\sqrt{z^2 + r^2}} - \frac{h + z}{\sqrt{(h + z)^2 + r^2}} \right). \]  

(3.2)

With Equation 3.2, it is then possible to quickly generate a first-order response for a variety of different reservoir types. This can provide sensitivity information for varying reservoir depths, thicknesses, injection radii and final density change when the observation station is located directly above the injection site. The primary goal with this approach is therefore garnering a general understanding of the feasibility of gravity gradiometry monitoring at a particular site.

### 3.3 Demonstration

In this section, I demonstrate application of the gravity gradiometry to the swept zone geometry model described in the previous section. I look at a collection of well-known fields that have undergone two types of fluid injection: waterflood for EOR and CO\(_2\) sequestration. By supplying representative density contrasts, reservoir depths and thicknesses for these fields, one can then gain an understanding about whether or not fluid movement can be detected using time-lapse gravity gradiometry.

#### 3.3.1 Waterflood

For the first time-lapse problem, I show two sample fields that have undergone waterflood injection: Prudhoe Bay, AK (Brady et al., 1996) and the Adena Field, CO (Weyler & Sayre, 1959). The general properties for these fields are listed in Table 3.1.

The properties of these reservoirs were extracted from previous studies. Prudhoe Bay is an example of gas cap water injection (GCWI), where water is injected directly into the gas cap to maintain reservoir pressure and improve overall oil recovery downdip (Brady et al., 1996). In the case of Adena Field, water was injected into the gas-oil contact to improve production (Weyler & Sayre, 1959). Both scenarios provide the possibility of large density contrasts due to the effect of water replacing lighter gas within the reservoir.
Prudhoe Bay, AK, has undergone a series of time-lapse gravity studies that have spanned decades. These have been conducted by Brady, Hare, Ferguson and colleagues and include a comprehensive look at how to model, predict, execute and interpret a time-lapse gravity study (e.g., Brady et al., 2008, 1996; Ferguson et al., 2007, 2008; Hare et al., 1999, 2008). I chose this as a candidate for my general example due to the availability of information about the geometry, density contrast, and fluid expansion radius.

Adena Field is the largest oilfield in the Denver Basin. The initial proposition and methodology for injecting water to improve production was presented by Weyler & Sayre (1959). While the reservoir is shallower than Prudhoe Bay, it is significantly thinner, particularly in the up-dip gas cap portions of the reservoir, thus providing an alternative scenario to evaluate gravity gradiometry for fluid movement detection.

For each field, I incorporate an average density contrast of 0.12 g/cc recovered from the Prudhoe Bay GCWI study (Hare et al., 1999), although each field will have a unique density contrast determined by the specific fluid and reservoir properties. In this case, a density change of 0.12 g/cc is a good approximation for both Prudhoe Bay and the Adena Field.

Table 3.1: General properties of the fields described in literature that have undergone waterflooding and displayed on Figure 3.2.

<table>
<thead>
<tr>
<th>#</th>
<th>Field Name</th>
<th>Depth</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prudhoe Bay</td>
<td>2500 m</td>
<td>150 m</td>
</tr>
<tr>
<td>2</td>
<td>Adena Field</td>
<td>1700 m</td>
<td>5 - 10 m</td>
</tr>
</tbody>
</table>

Figure 3.2 summarizes the results of the waterflood study. To construct these, I created a sequence of contour maps predicting the maximum Tzz gradiometry signal for four swept zone radii. The four increasing radii are representative of an increase in size of the swept zone through time. For each image, which correspond to a unique swept zone radii, the horizontal axis represents increasing reservoir depth and the vertical axis represents increasing reservoir thickness. The data contours are selected based on the noise levels previously discussed in Chapter 2. In Figure 3.2, the green region represents signal that would be de-
tectable using current technology; yellow represents signal that may be detectable with next
generation technology or current technology when data errors are small; orange represents
signals that are predicted for on-the-horizon technology; and red represents signals that are
likely undetectable.

Overlying each of the contour plots in Figure 3.2, I have also included two point markers
representing the average depth and thickness, listed in Table 3.1, for the two example fields,
Prudhoe Bay (#1) and Adena Field (#2). Additionally, there is an ellipse plotted around
these markers to encompass the variations in depth and thickness for each fields. The
collective results from this analysis predict that while fluid expansion may not be detectable
for these fields at early times, it is possible that detection of water movement by gravity
gradiometry may be possible at later times at Prudhoe Bay. However, Adena Field, being
relatively deep and shallow, likely would not be detectable even at later times. The value of
these results, summarized in Figure 3.2, is that they demonstrate a means of predicting the
overall signal strength for similar waterflood activities at different sites with similar density
change, but with varying reservoir depths and thicknesses.

From this, I can conclude that Prudhoe Bay would have been a plausible candidate for
time-lapse gradiometry. If the results in Figure 3.2 indicate that gradiometry may success-
fully detect water movement at a site, the next steps in analyzing that field would be a
follow-up site-specific study with more field information, such as demonstrated in the next
chapter.

Next, I perform a similar assessment for reservoirs that has undergone a different type of
fluid injection: carbon dioxide.

3.3.2 CO₂ Flood

Carbon dioxide is a popular fluid for EOR operations due to the fact that it not only
serves as a pressure maintenance system but also provides a means to sequester harmful
greenhouse gasses within the subsurface. While its use is common, it presents more of a
challenge than waterflooding for time-lapse gravity gradiometry as the final density contrast
Figure 3.2: First-order approximation of gravity gradiometry signal (Tzz) for two study fields, summarized in Table 3.1, that have undergone waterflooding. Four swept-zone radii are presented here: 100, 250, 500 and 1000 m. The contour colors represent various stages of gravity gradiometry instrumentation detectability described in Chapter 2. The thicknesses presented here range between 0 - 350 m and the depths range between 0 - 3000 m. Fields (indicated by numbered points) that are thin and deep, such as Adena Field (#1) are undetectable even when the swept zone is large; however, Prudhoe Bay (#2) may be a good candidate for this technique.
within the swept zones is more subtle. This is due to a number of factors, though it is primarily caused by the fact that carbon dioxide becomes a supercritical fluid at certain pressures and temperatures. In this state, the density approaches that of water or oil, thus decreasing the likelihood of detecting fluid movement.

Similar to the waterflood example in the previous section, I have selected a number of representative reservoirs that have undergone carbon dioxide flooding either for EOR purposes or sequestration. A complete list of the selected fields and their depth/thicknesses can be seen in Table 3.2.

Table 3.2: Fields described in literature that have undergone carbon dioxide flooding and displayed on Figure 3.3.

<table>
<thead>
<tr>
<th>#</th>
<th>Field Name</th>
<th>Depth</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Delhi Field</td>
<td>1000 m</td>
<td>0 - 100 m</td>
</tr>
<tr>
<td>2</td>
<td>Sleipner Field</td>
<td>800-1100 m</td>
<td>200-300 m</td>
</tr>
<tr>
<td>3</td>
<td>In Salah Field</td>
<td>1850-1950 m</td>
<td>30 m</td>
</tr>
<tr>
<td>4</td>
<td>Snøvhit Field</td>
<td>2600 m</td>
<td>60 m</td>
</tr>
<tr>
<td>5</td>
<td>Weyburn Field</td>
<td>1450 m</td>
<td>20 m</td>
</tr>
</tbody>
</table>

The first field is Delhi Field located in Louisiana. This field has been undergoing CO$_2$ injection since 2009 as a way to improve oil recovery. It was first discovered in 1944, and was flooded with water until 2009 when the continuous CO$_2$ injection process was initiated. It has been regularly monitored by the Reservoir Characterization Project (RCP) at the Colorado School of Mines using seismic data since the beginning of CO$_2$ injection; to date, three seismic surveys have been acquired (one baseline and two monitoring surveys) (Cui et al., 2013). The field has also been used extensively by the Center for Gravity, Electrical & Magnetic Studies (CGEM) at Colorado School of Mines as a detailed simulation site for testing the feasibility of surface and borehole gravity through integration with seismic data (e.g., Krahenbuhl et al., 2011). I have selected this field due the significant site information available and the broad range in reservoir thickness. As both the generic model study here, as well as detailed study in Chapter 4 will show, this varying thickness may result in field
dynamics that are only partially detectable by gradiometry.

The Sleipner Field is located in the North Sea, and is one of the world’s largest, oldest active CO₂ sequestration projects. Injection began in 1996 and has been continuous since that date. The carbon dioxide being injected is filtered at an offshore facility from producing reservoirs within the Sleipner Field and then injected into the Utsira formation (Wright et al., 2009). It has been monitored using both seismic data and time-lapse gravity (Alnes et al., 2008, 2011). While injection is into a somewhat deep formation, between 800-1100 m, it is relatively thick, between 200-300 m. Therefore, this field provides another combination of reservoir depth and thickness to evaluate detection of CO₂ injection for comparison.

The In Salah field is another large-scale sequestration project that began in 2004 in Algeria (Wright et al., 2009). The CO₂ is taken from several local producing fields, compressed, and re-injected deep into a saline formation. The injection geometry and sequestration project is described in detail in Mathieson et al. (2010). The challenge predicted for gradiometry at this reservoir is that it is both deep (between 1850-1950 m) and very thin (an average of 30 m thick). Unlike the previous two fields, the In Salah field does not vary significantly in depth or thickness, providing another reservoir class for evaluation.

The Snøvhit CO₂ storage project is located in the Barents Sea (Wright et al., 2009). Carbon dioxide is continuously injected at a depth of 2600 m, making this a very challenging site and it represents the deepest CO₂ injection site I investigate here for gradiometry monitoring. The formation that is being injected is brine-filled with thickness between 45-75 m.

Last included in this study is the Weyburn Field in Canada. This is an onshore CO₂ flooding project located in Saskatchewan that was also monitored by RCP between 2000-2001 (Davis et al., 2003). The reservoir underwent CO₂ injection at an average depth of 1450 m. With an average thickness of 20 m, this site has been selected as the thinnest field for evaluation.
To select an appropriate time-lapse density change for the CO\(_2\) study here, I adopted the parameters of the Delhi Field, LA. The final density contrast of 0.06 g/cc is based on previous time-lapse gravity study (Krahenbuhl et al., 2011) of the field that takes into account the average fluid and petrophysical properties of the field. Similar to selected density for the waterflood examples, the final change in density from CO\(_2\) injection is ultimately a site-specific value that includes fluid and reservoir parameters.

Similar to the previous waterflood simulations, the results for CO\(_2\) injection are presented as four data contour plots, each representing an increased swept zone radii, with the axes representing reservoir thickness and depth (Figure 3.3). The data contours are selected based on the noise levels previously discussed in Chapter 2. In Figure 3.3, the green region again represents signal that would be detectable using current technology; yellow represents signal that may be detectable with next generation technology or current technology small data error; orange represents signals that are predicted for on-the-horizon technology; and red represents signals that are likely undetectable. Overlying each of the contour plots, I have again included point markers representing the average depth and thickness for the five CO\(_2\) fields in this study. The dashed ellipses plotted around these markers likewise encompass the known variations in depth and thickness for each field. The Delhi and Sleipner Fields have the largest spread in reservoir thickness and depth.

The collective results presented in Figure 3.3 again allow us to make early predictions about the feasibility of time-lapse gravity gradiometry for CO\(_2\) flood monitoring. Deep, thin fields, such as In Salah, Snøvhit, and Weyburn are predicted to always produce small gradiometry signal, even at late injection times with large swept zones. CO\(_2\) movement at depths of 1 km, such as at Delhi and Sleipner, will likely be undetectable using gravity gradiometry at early injection time but detectable as the swept zone expands further. Additionally, the increased thickness rage of the Sleipner Field predict that it would be detectable earlier during injection, and using current technology. It is interesting to note, and further studied in the next chapter as a detailed site investigation, that the thickness of the Delhi
Field ranges from 0 m to 100 m here. In response, the predicted gradiometry over the field ranges from undetectable over the thinnest section, to potentially detectable over the thicker regions.

Similar to the waterflood demonstration, the methodology and results presented here provide a general means of predicting the gradiometry \( (T_{zz}) \) signal from similar \( \text{CO}_2 \) injection at a range of sites with similar density change, but with varying reservoir depths and thicknesses.

From Figure 3.3, we also note that fields such as Delhi may straddle the detectability limits. We can see that in zones where the field is thicker and shallower, it may be possible to detect; however, the deeper, thinner parts will present a challenge.

Figure 3.3 supports further study of both Delhi and Sleipner field, as they seem to fall within detectable ranges.

### 3.4 Discussion

First-order studies are valuable tools to test the feasibility of new applications, as well as old methodologies at new sites. In this chapter, I provided a background to the conventional time-lapse reservoir monitoring problem, and presented a first-order approach for understand whether or not time-lapse gravity gradiometry could be a useful tool for this purpose. The method calculated the maximum gravity gradiometry response in \( T_{zz} \) above an expanding swept zone that is generalized by a vertical cylinder with density appropriate to the time-lapse problem. I focused on two classes of reservoir monitoring problems for demonstration: waterflood and \( \text{CO}_2 \) injection. For each category, I demonstrated the methodology for specific fields to gain a first-order understanding of the predicted gradiometry response, and thus determined whether or not they would be good candidates for further detailed site study and ultimately data acquisition.

The results predict that time-lapse gravity gradiometry may be feasible for specific sites, particularly sites with shallower \(<1500\,\text{m}\) and thicker \(>100\,\text{m}\) reservoirs. In contrast, deep thin reservoirs with small density change, such as Adena, In Salah, Snøvhit, and Wey-
Figure 3.3: First-order approximation of the gravity gradiometry signal (Tzz) for two study fields, summarized in Table 3.2, that have undergone CO₂ injection. Four swept-zone radii are presented here: 100, 250, 500 and 1000 m. Here, the contour colors represent various stages of gravity gradiometry instrumentation detectability described in Chapter 2. The thicknesses presented here range between 0 - 350 m and the depths range between 0 - 3000 m. Fields (indicated by numbered points) that are thin and deep, such as In Salah, Snohvit and Weyburn Field (#3, #4 and #5) are undetectable even when the swept zone is large; however, these contours suggest that Delhi and Sleipner (#1 and #2) may be a good candidates for this technique.
burn are predicted undetectable with current and future gradiometry instrumentation. The general study presented here provides a good overall understanding of the value of gradiometry for time-lapse monitoring. However, the large range of results from field to field clearly show that once a site is determined feasible, a more thorough evaluation must then be undertaken on a site-by-site basis with improved reservoir detail such as known field boundaries from seismic data.

In the following chapter, I expand upon these results by looking at two field sites that have been identified here as potential candidates for time-lapse gravity gradiometry monitoring: the Delhi Field CO₂ injection and the Prudhoe Bay waterflood.
CHAPTER 4
CONVENTIONAL RESERVOIRS: DETAILED FEASIBILITY STUDIES

In this chapter, I present two conventional reservoirs introduced in the previous chapter for detailed site study to better assess the monitoring potential of gravity gradiometry. The purpose of these reservoir specific studies is to expand upon the general conclusions for these sites drawn from the cylinder based feasibility study performed in Chapter 3. To accomplish this, I incorporate information such as the field geometry from seismic data and previous reservoir studies.

For the first example, I analyze the difficult CO\textsubscript{2} storage/EOR problem by looking at the Delhi Field, a large CO\textsubscript{2} storage project in Louisiana. The reservoir has been routinely monitored with 4D seismic (Cui \textit{et al.}, 2013) as well as evaluated through simulation for 4D gravity monitoring (Krahenbuhl \textit{et al.}, 2011). For the second site, I present a very deep, extensive waterflood example: Prudhoe Bay, AK. This site is well known for its time-lapse gravity monitoring project that has taken place over the last two decades and demonstrated excellent results (e.g., Brady \textit{et al.}, 2008, 1996; Hare \textit{et al.}, 1999).

4.1 Delhi Field, LA

I first evaluate the feasibility of time-lapse gravity gradiometry for the difficult CO\textsubscript{2} flood problem. The reservoir test site is the Delhi Field, LA, that has been extensively studied at Colorado School of Mines by the Reservoir Characterization Project using time-lapse seismic (Cui \textit{et al.}, 2013), and the Center for Gravity, Electrical & Magnetic Studies for time-lapse gravity (Krahenbuhl \textit{et al.}, 2011). As concluded in Chapter 3, the reservoir likely straddles the edge of detectability for time-lapse gravity gradiometry due to the varying thickness of the field. By reproducing the reservoir’s geometry from seismic data the application of gravity gradiometry can be further evaluated to understand which segments of the field may be monitored, and which cannot.
4.1.1 Time-Lapse density model

As described in Chapter 3, Delhi Field is a mature field that is currently undergoing secondary recovery. The CO$_2$ EOR project began in 2009, though the field has been producing since its discovery in 1944. Prior to CO$_2$ injection, a baseline seismic survey was performed in 2008, with two additional surveys performed since for monitoring.

The 4D test model for this study is a reproduction of the Delhi Field in time-lapse density contrast form. The test model was initially constructed for time-lapse gravity experiments by Krahenbuhl et al. (2011) from seismic data and reservoir parameters. It is natural to expand upon this previous work and extend the time-lapse monitoring efforts from gravity to gravity gradiometry. The seismic horizons defining the upper and lower extent of the Delhi Field are illustrated in Figure 4.1. From these surfaces, it is apparent that the reservoir pinches out in the north while thickening and dipping to south.

The Delhi density model constructed from the seismic data is presented in Figure 4.2. The field is approximately 1 km deep with a density contrast of -0.06 g/cc calculated from the fluid and petrophysical properties of the field. Density change and depths can be adjusted for additional study, as I demonstrate in later sections; however I begin with the depths and density contrast consistent with the field site.

4.1.2 Forward Modeling

I begin with an evaluation of gradiometry applied to the base test model presented by Krahenbuhl et al. (2011). The model, shown in Figure 4.2(c), is at a depth of approximately 1 km with a uniform density contrast of -0.06 g/cc. The gravity gradiometry data calculated at the surface for this test are illustrated in Figure 4.3 for the five independent components of the gradient tensor plus Tzz. The largest response is identified within Tzz at approximately -0.5 E, and four of the remaining components are above the noise minimum of 0.16 E discussed in Chapter 2. This implies that gravity gradiometry may be able to detect CO$_2$ movement at the field with future gradiometry sensors with sub-eotvos accuracy. The data are likewise
consistent with the findings in Chapter 3, where first order modeling suggests that CO₂ movement within the field may be partially detectable, at least within the thicker sections of the reservoir.

### 4.1.3 Inversion

To evaluate the information content that can be recovered from the predicted gravity gradiometry signal, I next invert the data to determine the level of recovery of the CO₂ swept zone. For this, I add 0.16 E Gaussian noise to the simulated data. The true and noisy data are illustrated in Figure 4.4(a) and Figure 4.4(b), respectively, for T_xx. To invert the data, I perform a generalized density inversion of the gravity gradiometry data based on the method of Li (2001) with the top of the reservoir incorporated as prior information. The
Figure 4.2: Delhi Field test model for time-lapse gravity gradiometry simulations. a) Full reservoir model is very thin to the north. b) Model example after CO$_2$ injection has occurred, creating a large swept zone in the north-east of the field. c) Close-up view of the region of interest for this study.
Figure 4.3: Synthetic gravity gradient data calculated above the Delhi test model (Figure 4.2a). Except for Txy, all independent components plus Tzz are above 0.2 E.
recovered model (Figure 4.5) successfully identifies the movement throughout the thicker down-dip sequences of the model in the southern region. As anticipated, there is a clear boundary along strike above which no movement can be detected due to limited volumes for the thinning up-dip region to the north. This simulation demonstrates that CO\textsubscript{2} flood in a reservoir consistent with the Delhi Field may be successfully monitored, at least within the thicker sections of the field, with next generation gravity gradiometry instruments.

![Figure 4.4: Example difference between the observed and predicted data for Txx. a) True data. b) Noisy data for inversion. c) Predicted data after inversion. d) Data difference.](image)

The inversion is considered successful due to the fact that the predicted data, (c), closely matches the original data, (a).

### 4.1.4 Effect of increasing depth

I next evaluated the broader application of gradiometry for CO\textsubscript{2} monitoring for a Delhi-type field at different reservoir depths and density contrast. For the first component I vary
the depth of the Delhi model between 500 m and 2 km, and evaluating both the signal
response and recovery of the swept zone by inversion. Figure 4.6 is a plot of anomaly
amplitude, for the Tzz component, with increasing depths to approximately 2 km. Recovery
of fluid movement at decreasing depths, shallower than 1 km used in the previous example,
is expected with increased signal. I am interested in the more difficult problem of increasing
reservoir depth until the signal decreases to 0.16 E. This limit is identified around 1.8 km
depth, and I choose my next simulation at a depth of 1.5 km with a data response of 0.22 E.

The inversion result, Figure 4.7, shows the recovered density contrast from fluid move-
ment is limited entirely to the thicker down-dip section of the test model to the south. The
thinner sequences in the northern volumes do not hold enough mass to influence the data
from 1.5 km depth, and they are less resolved than from the inversion at shallower depths
(Figure 4.5). It is clear that continuing to increase depth for this reservoir geometry will
quickly approach the limitation of gravity gradiometry for this problem entirely.
Figure 4.6: Tzz response on the surface versus depth to the reservoir. It is clear that fluid movement is detectable to depths of the true field site (1 km). As the same thin field increases in depth to approximately 1.8 km, the response will be undetectable at the current noise threshold (0.16 E, indicated by the red dashed line).

4.1.5 Effect of varying density contrast

The final density contrast within a swept zone is largely due to the change in fluid saturations, and densities of the fluids. The range of values vary from site to site and the final density change likewise varies from site to site. I close the Delhi Field study by demonstrating the influence of changing density contrast with the test model. The density contrast for this simulation is increased to -0.1 g/cc at the original reservoir depth of 1 km. Upon first inspection, the final inversion result in Figure 4.8 does not appear to provide significant additional information about fluid movement over the first test (Figure 4.5) with a -0.06 g/cc density contrast. For example, there is very little difference in the thin northern section of the field with limited volume storage. However, the fluid movement in the thicker southernmost portion of the field is better recovered with the increase in density contrast. The reason behind this is that the Delhi Field dips to the south, and this deeper section did not produce a significant signal with the lower density contrast. By increasing the density in
Figure 4.7: Inversion for Delhi Field at greater depth. The field is at a depth of 1.5 km. As the gradient response on the surface approaches instrument accuracy, the recovered swept zone is significantly smaller than at true reservoir depth.

In this case, the gradiometry data now contain the necessary signal to recovery fluid movement in the deeper sections of the field. This final example demonstrates that the application of gravity gradiometry for time-lapse monitoring of CO$_2$ sequestration/EOR sites is ultimately defined by the balance between instrument accuracy, reservoir geometry, depth and density. Every site must therefore be properly simulated in advance to make the most informed decision.

4.1.6 Conclusions

The Delhi Field is a good example of the trade-off between thickness, depth and density contrast that influences whether or not gravity gradiometry can be a useful reservoir monitoring tool. In this example, I have expanded the feasibility study of gradiometry at the Delhi Field from the first-order understanding, Chapter 3, to a site-specific reservoir evaluation using available reservoir information. By incorporating seismic data and reservoir property
Figure 4.8: Inversion result for Delhi Field with density contrast increased to -0.1 g/cc. The most significant improvement over Figure 4.5 (-0.06 g/cc density contrast) is increased recovery in the southern down-dip sequence of the field, which has greater reservoir depth.

information, it is now possible to make more specific predictions about the application and limitation of gravity gradiometry for monitoring at Delhi Field. Specifically, fluid movement with the Delhi Field should be detectable within the thicker southern portion of the field. In contrast, the thinner up-dip volumes of the field where the reservoir pinches out are not predicted to produce a strong enough signal to be detectable or recoverable using gravity gradiometry. These conclusions are consistent with the previous gravity feasibility study performed for the Delhi Field (Krahenbuhl et al., 2011).

4.2 Prudhoe Bay, AK

For my next example, I examine the feasibility of gradiometry for monitoring a different reservoir problem: gas cap water injection (GCWI). The study is based on Prudhoe Bay, one of the largest GCWI projects in history. Fluid movement at the site results in a significantly higher density contrast than the previous CO₂ flood example (Hare et al., 1999). The
reservoir in this case is significantly deeper than Delhi Field, with a stronger density contrast, thicker reservoir, and larger fluid volumes. This site therefore provides a significantly different target to evaluate the feasibility of gravity gradiometry for reservoir monitoring.

4.2.1 Site Background

Prudhoe Bay is one of the most well known fields for monitoring with time-lapse potential field data. Located on the North Slope of Alaska, it lies beneath an extensive variety of terrain that make 4D seismic a difficult and expensive monitoring tool. Two of the reasons the site has demonstrated success for gravity monitoring are the size of the reservoir and high density contrast of the production activities taking place. The field sits at approximately 2500 m depth, covers a 250,000 acre region and is among the largest hydrocarbon reservoirs in North America. In order to improve production pressure, water is currently being injected into the gas cap of the reservoir, pushing gas and oil towards the production wells. As a result, the density contrast within the swept zone, approximately 0.12 g/cc (Hare et al., 1999; Brady et al., 2004), is larger than most conventional reservoir EOR problems.

To date, Prudhoe Bay has been extensively studied using time-lapse gravity but not gravity gradiometry. The initial proposal by Brady et al. (1996) suggested using both borehole and surface gravity to track gas cap movement within the reservoir following gas re-injection. Later, waterflooding was proposed to maintain reservoir pressures as oil production declined. Hare et al. (1999) investigated the possibility of studying the water movement using micro-gravity, and found that it could be a suitable candidate for such activity. This was followed up by a series of studies (Brady et al., 2008, 2004; Ferguson et al., 2007, 2008; Hare et al., 2008) that verified the applicability and collected real-world data, proving that gravity can be a useful tool in waterflood monitoring.

4.2.2 Time-lapse density model

To construct the time-lapse density models for the Prudhoe Bay GCWI problem, I have reproduced the reservoir simulation data presented by Brady et al. (2004) to construct a
sequence of expanding water flood fronts throughout the life of the Prudhoe GCWI project. This expanding fluid front prediction by Brady et al. (2004), along with top of the gas cap zone, is shown in Figure 4.9.

I began by constructing a reservoir model which features geometry that mimics the general structure of Prudhoe Bay. To accomplish this, I extract the upper surface, dip and gas cap thickness information available in Brady et al. (2004). It is then possible to build a reservoir model, or sequence of reservoir models, that are encapsulated by these data and can be adapted for gravity gradiometry modeling. The final simulated 3D reservoir volume of the Prudhoe Bay GCWI zone is presented in Figure 4.10. The model contains 212976 cells, each with dimensions of 200 m by 200 m by 10 m. The expanding flood front and density information appropriate to Prudhoe Bay GCWI flood are then incorporated from this base model.
I next reproduce the fluid front boundaries simulated by Brady et al. (2004) to build the expanding swept zone within the 3D gas cap model. The original expanding front is illustrated in Figure 4.9 and the final sequence of time-lapse simulations developed for gravity gradiometry is presented in Figure 4.11 from a top view. I have created a total of five unique models, each adhering to the structure of the reservoir and following the fluid front predicted by Brady et al. (2004). The models represent the 2, 5, 10, 15, and 20 year marks predicted for the GCWI project.

For each of these unique models, I assign a density contrast of 0.12 g/cc. This value is supported by the predicted gravity models in Brady et al. (2004) and Hare et al. (1999)
Figure 4.11: Fluid front contours overlain on the reservoir structure to produce the expanding water flood within the Prudhoe Bay GCWI model. As the life of the project increases, the volume infiltrated by water grows.

that use average porosity, fluid densities and saturations. Additional reservoir information from well logs and history matching, such as 3D distributions of these reservoir and fluid parameters, could improve upon this model if available.

4.2.3 Forward Modeling

Following model construction, the first step in feasibility testing is to calculate the gravity gradiometry response at the surface and evaluate the predicted signal strength for each flood front. The gravity gradiometry data for the ten year flood mark is presented in Figure 4.12 for six tensor components: Txx, Txy, Txz, Tyy, Tyz, and Tzz.

A summary of the time-lapse gravity gradiometry sequences can be found in Figure 4.13, where I have taken the maximum value of each tensor component through the 20-year project lifespan. This provides information on when the signal is predicted to become detectable at the surface. As expected, as the flood front increases in volume, the signal likewise increases. The vertical component, Tzz, has a stronger signal than the horizontal components, but all
components exceed the minimum instrument level by year 20 and all but Txy exceed 0.16 E by year 5.

In Chapter 3, the general feasibility study suggests that Prudhoe would be at the limit of detection with predicted future instrumentation. This is consistent with the combined data, Figure 4.13, from the site model here. However, it is important to note that the first study was limited to a swept zone radius of 1 km, while the full scale of Prudhoe Bay project is significantly larger, as addressed here. After approximately four years of waterflood at Prudhoe, the front expands well beyond the 1 km radius of the generic cylindrical model for
the site, and the gravity gradiometry signal likewise continues to increase in strength.

4.2.4 Inversion

The final steps for assessing the potential of gravity gradiometry for GCWI monitoring at Prudhoe Bay is to evaluate the information that can be recovered about the water flood through inversion. For this, I have added 0.25 E of Gaussian noise to the true data. I apply the same generalized density inversion as with the previous example. Like the Delhi example, I am again able to incorporate the top of the reservoir as prior information for the inversion. The inversion results for the 10-year flood front is presented in Figure 4.14.
Figure 4.14: Inversion results for 10-year waterflood of Prudhoe Bay. a) The true model. b) The recovered model. c) Top-down view comparison of the true model (outlined in black) and the extent of recovered model.

The swept zone recovered by the inversion has excellent shape and position consistent with the true water flood in this example. An important feature of the recovered model is that the center of mass is shifted towards the southwest within the gas cap. This is consistent with known information about the shape of the reservoir, as it thickens towards the southwest (Figure 4.10). There is a larger volume of the field undergoing density change from water injection in this region, and an equivalently stronger influence on the gradiometry data.
4.2.5 Conclusions

The Prudhoe Bay reservoir provides a different example of a time-lapse monitoring problem to the previous Delhi Field example. In this case, the reservoir was significantly larger in both scale and density contrast. The previous first-order understanding from Chapter 3 was expanded using detailed site geometry information available from previous time-lapse reservoir studies. The results of the feasibility study here have shown that future gravity gradiometry instrumentation may be capable of monitoring the flood front created by gas cap water injection for such a site, similar to the results of the time-lapse gravity study in Brady et al. (2008). While with the geometry of the Delhi example the maximum depth for detection was around 1.8 km, I demonstrate here that the geometry of Prudhoe Bay is such that detection at a depth of 2.5 km is feasible. This is due to the difference in reservoir volume (both thickness and extent) and fluid density contrast. This demonstrates the important trade-off between depth, density contrast and volume of fluid that must be considered when evaluating a reservoir for time-lapse gravity gradiometry monitoring.

4.3 Discussion

In this chapter, I explored the feasibility of gravity gradiometry for monitoring two conventional reservoirs introduced in the previous chapter. The studies were designed to provide improved understanding of the proposed method by creating or employing detailed site specific information for the fields.

The first demonstration was the CO₂ injection site, Delhi Field, LA. For this study I have adapted a realistic site-model previously developed from seismic and reservoir data for gravity studies. The results of this study demonstrate that next generation gradiometry instrument may be able to monitor the small density changes at Delhi following CO₂ injection. The results additionally hint that because the field thins and pinches to a close in the north, the total volume in that region will not produce a significant enough anomaly to be monitored with gradiometry. Gradiometry may only provide value for monitoring the thicker southern
sequences of the field. This is an important outcome for the study that demonstrates the need to represent a field site as accurately as possible to best predict the applications and limits of the monitoring method.

In addition to using the Delhi Field density model directly, I have expanded the study to evaluate similar geometry fields at varying reservoir depths and density contrast. The results demonstrate the trade-off between a reservoir’s depth, thickness and density contrast that is inherent and must be considered when determining whether or not gravity gradiometry would be a useful tool.

The second study simulates gas cap water injection at Prudhoe Bay, AK, and was selected to provide a significantly different category of reservoir monitoring for gravity gradiometry. In contrast to the Delhi Field, the Prudhoe GCWI site is significantly deeper, thicker and undergoes a larger density change within the swept zone. For this study, I was able to construct a reservoir model representative of the site from site specific information to further expand upon the results of the general study in Chapter 3. The results predict that Prudhoe Bay could provide an excellent candidate for time-lapse gravity gradiometry monitoring.

From the studies presented here, it can be concluded that time-lapse gravity gradiometry, in consideration of predicted next generation tools, could be a useful geophysical tool for conventional reservoir monitoring. However, it would not be appropriate for all sites. Following the flow of the site studies I have presented here, individual reservoir sites can be reliably reproduced and evaluated.
Heavy oil reservoirs are a valuable resource to the energy industry. It is estimated that up to 434 billion barrels of technically recoverable heavy oil, roughly equivalent to 60% of conventional reserves or 25% of the world's total reserves, fall into this category. In Venezuela and Canada alone, where two of the largest heavy oil reservoirs in the world are located, there are an estimated 3.6 billion barrels of oil in place (Meyer & Attanasi, 2003).

In this chapter, I turn my attention to unconventional reservoirs to analyze the feasibility of monitoring heavy oil production at steam assisted gravity drainage, or SAGD, sites. SAGD reservoirs are generally shallow and will exhibit a high density change as steam replaces the heavy oil. This combination makes SAGD an attractive candidate to evaluate gravity gradiometry for monitoring. The study presented here is performed in three parts. I start with a general understanding by approximating the geometries of SAGD steam chamber growth and perform various first-order sensitivity tests. These include sensitivity of the data to depth of the reservoir and horizontal well-pair separation. I then present sensitivity of the data through inversion to second-order deviations of SAGD steam chamber movement due to reservoir heterogeneity. Finally, I present a detailed SAGD site example where I utilize time-lapse seismic data collected over a 9-year period to demonstrate that gravity gradiometry may be capable of detecting and monitoring steam chamber growth during production.

5.1 Introduction

Heavy oil is classified as oil with an API gravity of 20° or lower. Extra heavy oil, or bitumen, such as that found in Canadian and Venezuelan reservoirs, has API gravity of 10° or lower. Such high densities generally correlate to similarly high viscosities, which makes the deposits more difficult to produce than conventional hydrocarbon reservoirs. For this reason, they are considered an unconventional resource.
Due to the rising cost of oil, it has become increasingly economic to exploit the many heavy oil resources around the planet. Extraction methods that were once too expensive to utilize are now becoming common practice in countries such as Venezuela and Canada.

There are a number of ways to approach extraction of bitumen. For reservoirs less than 100 m depth, it is possible to extract the resource through mining due to the high viscosity and rock-like composition of the oil in combination with the shallow depths. For deeper reservoirs, mining the bitumen is not considered an economic option for recovery, and additional production methods, such as those utilizing transfer of thermal energy, must be employed. Steam-assisted gravity drainage, or SAGD, is one such method wherein steam is injected into the reservoir to decrease the viscosity of the bitumen via heat transfer.

The concept of thermal energy transfer for production of heavy oils became widely discussed during the 1950s, beginning with the work of Winkler (1951). The technique involves the injection of a heated fluid into a reservoir in order to transfer that energy to the heavy oil. This lowers the oil viscosity, making it possible to produce using conventional technologies. Originally, reservoir production was enhanced by cyclical steam stimulation (CSS), or the “huff and puff” method, which involved short-term steam saturation followed by a period of production in a vertical borehole.

Modern steam-assisted gravity drainage (SAGD) was developed by Dr. Roger Butler in the 1970s as a means of extracting extra heavy oils (Butler et al., 1981). In this method, two horizontal wells, referred to as a well-pair, are drilled parallel to one another with a vertical separation of 5-10 m. Steam is injected into the upper well, creating a chamber of high temperature steam that rises until it contacts the cap rock of the reservoir (Figure 5.1). At that stage, the chamber begins to spread laterally away from the axis of injection and into the reservoir. The region surrounding these steam chambers is a transition zone where heat is transferred from the central chamber to the bitumen. In response, the bitumen within these zones decreases in viscosity, becoming mobile and flowing around the edges of the steam chamber to drain under the influence of gravity into the production wells at the base.
Monitoring SAGD activity and steam movement through time is important for two reasons. The first is safety. If the SAGD steam chamber migrates beyond the cap rock barrier of the reservoir, it can reach the surface and result in destructive explosions that can have significant impact on the production facilities. An example of this scenario is the Joslyn Creek project in Alberta, Canada, operated by Total E&P in 2006 (Uweira-Gartner et al., 2011). The cause of the breach was hypothesized to be related to a pressurized column of steam creating a fracture in the cap rock; however, it is equally possible that the caprock itself had natural fractures or that drilling activity contributed to the failure. Regardless of source, the final result at the surface was a 75 m by 125 m crater with rock displacement of up to 300 m (Uweira-Gartner et al., 2011). The entire site was shut down following the explosion. While the Joselyn Creek project was the shallowest SAGD site attempted in Canada at the time at a depth of 60m, the accident reinforced the need to effectively monitor these migrating steam chambers at all SAGD sites in order to prevent similar incidents in the future.

The second purpose for monitoring steam movement in SAGD reservoirs is related to the economics of the project. In contrast to conventional fields, injected water must be brought to extremely high temperature and pressure in order to maintain the gaseous state required for mobilization of bitumen within the reservoir. This requires a significant amount of energy consumption that generally comes from natural gas. The reservoirs often have low permeability zones that act as baffles to normal steam migration. Identifying these zones, and shutting off steam injection near them, can save significant energy during production to improve the overall economics of the field.

Gravity gradiometry is a natural candidate to evaluate its feasibility for monitoring the growth of SAGD steam chambers. This is because the density contrast between bitumen and steam within the steam chamber is significantly higher than those of the swept zones for conventional production problems. Additionally, the shallow nature of most SAGD fields, particularly in Canada, lends to the possibility of a strong gradiometry signal.
In this chapter, I explore the feasibility of gravity gradiometry for monitoring steam chamber growth in SAGD operations. I begin next with the development of a sequence of steam chamber models as they grow through time as the foundation for this study.

5.2 Time-lapse SAGD model

The geometry of the SAGD problem is significantly different than that of conventional waterflood or CO$_2$ sequestration projects. Two horizontal wells are drilled parallel to one another at the base of the field, with a small vertical separation between them. Steam is injected into the top well and grows upward and outward to form a chamber in the upper portion of the reservoir. Heat is transferred around the edges of the steam chamber to the bitumen, causing the viscosity to decrease and making the bitumen mobile. The bitumen then drips down the boundary of the steam chamber to the lower horizontal well, where it is produced. A concept diagram of this technique, adapted from Butler (1985), is shown in Figure 5.1.

![Figure 5.1: Diagram of the steam chamber in the SAGD process. Adapted from Butler (1985). Two horizontal wells are drilled parallel to one another. Steam is injected into the upper well, forming a chamber around which heavy oil flows into the lower production well.](image)

To properly construct a time-lapse density model that represents an expanding steam chamber, it is important to understand how the steam chamber grows through time, the level of density contrast expected within the steam-swept zone, and the typical field geometry for fully mature SAGD sites. For the following study, I use the geometries and properties of
the Athabasca Oil Sands as an analog for real-world steam chamber growth during SAGD production.

### 5.2.1 Steam chamber growth

In the late 1970s and 1980s, Butler and colleagues studied the growth of the steam chamber using small-scale laboratory models (Butler et al., 1981). This initial research yielded two separate phases of growth: the rising chamber and the spreading chamber. At earlier times in the injection process, the steam enters the reservoir and rises in a thin column until it encounters the caprock barrier. At this point, it begins the spreading chamber phase, where the steam begins to spread laterally out from the axis of injection, taking the form of an inverted triangle.

The early rising chamber is considerably smaller than the later spreading chamber. During this initial period, the steam is limited to a small area above the injector. As a result, the gravity gradient signal will be undetectable and I therefore focus on the time-lapse density change during the spreading phase of steam chamber growth.

The early theoretical predictions of steam chamber growth by Butler and colleagues fit their collections of empirical data relatively well. However, there were observed differences in overestimation of oil drainage rates, unrealistic asymptotic interfaces, and additional geometric complexities (Butler, 1985; Butler & Stephens, 1981; Butler et al., 1981). In the early 1990s, a simplified linear model was proposed for SAGD steam chamber growth (Reis, 1992). This new model better fit the experimental data, and presented a more practical approach to model a growing SAGD steam chamber.

Following this formulation (Equation 5.1), the steam chamber geometry is modeled by an inverted triangular prism whose half-width ($W_s$) is a function of dimensionless time ($t'$), the height between the production well and the top of the reservoir ($H$), and a dimensionless temperature coefficient ($a$). This temperature coefficient is related to the exponentially decaying temperature profile of the interface. In early studies, it was treated as a constant as it is not dependent on interface velocity. Reis (1992) identified that a value of $a = 0.4$
fit the empirical data of Butler and colleagues and it continues to prove a reliable value for SAGD studies. In my SAGD modeling here, I likewise adopt the temperature coefficient of Reis (1992) as his original experimental models were created for Cold Lake bitumen, a deposit similar to and near the Athabasca Oil Sands that I mimic for my SAGD modeling.

\[ W_s = t' H \sqrt{\frac{2}{a}}. \]  

(5.1)

Dimensionless time, \( t' \), was first proposed by Butler as a means of simplifying and generalizing the steam chamber growth model. It was designed to create a positive correlation between oil production and steam chamber area. It additionally contains information about reservoir petrophysical properties, thermal diffusivity, and steam chamber geometry. Ultimately, as \( t' \) increases, this represents a later time of production and chamber growth; however, the exact time units are specific to individual projects.

The predicted steam chamber interface, as it grows with \( t' \), is shown in Figure 5.2.

![Linear Steam Chamber Model](image)

**Figure 5.2:** Progression of steam chamber interface based on the linear model developed by Reis (1992). The equation for the interface is shown in equation 5.1. Steam chamber half-width and height have been normalized and are dimensionless. From Reis (1992).

Following this formulation, I have constructed 3 time-lapse density models to represent three increasing half-widths of the steam chamber: 11, 28 and 56 m. These correspond to \( t' \) of 0.2, 0.5 and 1.0. The reservoir model was assigned a thickness of \( H = 25 \) m, which is an
average thickness for the Athabasca Oil Sands in Alberta, Canada (Hinkle & Batzle, 2006). An example of the mid-time model, where $W_s = 28$ m, is presented in Figure 5.3a.

While this linear model is a good first-order approximation for many studies, it can be further expanded to incorporate deviations in chamber growth to account for heterogeneity within the reservoir. For this, I also develop a second set of deviating models (Figure 5.3b) that take non-uniform geometry of the steam chambers into account. In this model, the steam chamber has slightly varying widths and flow paths along the length of the injection well. By incorporating these additional perturbations, I seek to better understand the sensitivity of gravity gradiometry to subtle steam chamber variations.

For each of the SAGD models, Figure 5.3, the horizontal length of the well-pairs is 800 m. This is a standard length for SAGD operations, though they can be longer.

Figure 5.3: Example of the two time-lapse steam chamber models used in this study. (a) The linear model, constructed in the form of Reis (1992) with constant density contrast. Here, $t = 0.5$, which translates to a half-width $W_s = 28$ m. (b) A more realistic representation of the SAGD process with varying density contrast along the transition zone of the steam chamber, and deviations in flow path due to reservoir heterogeneity.
5.2.2 Density contrast

The next step in developing the steam chamber model is to identify an appropriate density contrast for the steam-swept zone. The expected density contrast depends on a number of factors, including porosity ($\phi$), fluid and steam saturations at initial and late times ($S_w$ for water, $S_o$ for oil, and $S_s$ for steam), initial oil density ($\rho_{o1}$), heated oil density ($\rho_{o2}$), and the density of steam at the injection pressure and temperature ($\rho_s$). The final time change in density within the steam chamber can be calculated by:

$$\Delta \rho = \phi([\rho_{o2}S_o + \rho_sS_s] - [\rho_{o1}S_o + \rho_wS_w]).$$  (5.2)

For secondary recovery (or sequestration) operations in a conventional reservoir, the majority of the density change is associated with changes in fluid saturation, as discussed in Chapter 2. For SAGD, this is not the case. Thermal energy is introduced into the reservoir, and the effect of temperature on fluid density must also be considered. Similar to viscosity, density of the oil decreases with increasing temperature. Figure 5.4 illustrates the relationship between oil density and temperature. The difference in density at normal reservoir temperature (typically between 8-10°C for Athabasca) and injection temperature (240-250°C) is significant. The relationship between injection pressure and density is significantly weaker and is therefore not considered here.

To calculate a time-lapse density change appropriate for SAGD production, I use properties consistent with the Athabasca Oil Sands (Hinkle & Batzle, 2006). For the models illustrated in Figure 5.3, I use an oil density of 8.5° API gravity, 35% porosity, initial oil saturation of 80%, final oil saturation of 15%, injection pressure of 2 MPa, initial temperature of 10°C and injection temperature of 250°C. This yields a final maximum density change of -0.25 g/cc within the center of the steam chamber.

5.3 Reservoir Depth: Single well study

I first assess the ability of gravity gradiometry to detect the density change from a single SAGD steam chamber at varying reservoir depths. While it is uncommon for long-term
Figure 5.4: Diagram showing the relationship between oil density and temperature. There is a significant difference between the density at normal reservoir temperatures and SAGD operation temperatures (250°C).

Projects to have only a single well-pair, it is not uncommon to drill single pilot wells during initial reservoir assessment (Butler, 2001). Additionally, it is desired to understand whether the response of a single chamber is detectable within the bulk signal from full pad production.

To understand detectability versus depth, I calculate the gravity gradiometry signal across a range of depths consistent with Athabasca Oil Sands. I start with a depth of 100 m. Although though the Athabasca Oil Sands have surface expression in some regions, most heavy oil reservoirs shallower than 100 m are mined from the surface and I do not consider these depths here.

The gravity gradiometry data for the single well at 100 m depth are shown in Figure 5.5. The maximum signal in this case exceeds 1 E in four of the six calculated components. The Txx and Txy data are notably smaller due to the well-pair orientation for the constructed SAGD model.
I next simulate the gravity gradient data as reservoir depth increases from 100 m to 400 m depth and evaluate the maximum signal of $T_{yy}$, $T_{yz}$ and $T_{zz}$ and increasing production time. The results are presented in Figure 5.6.

In Figure 5.6, I show the maximum predicted signal at three production times ($t' = 0.2, t' = 0.5, t' = 1.0$) which correspond to steam chamber half-widths of 11, 28 and 56 m respectively. The results demonstrate that at early production times where there is little volumetric change within the field, it will be difficult for gradiometry to detect these small steam chambers below depths of approximately 150 m. However, as the steam chamber continues to grow at later times, the signal continues to increase, staying above the detection limits discussed in Chapter 2 to depth of 400 m. It is important to note that a single injection well is not common practice, and multiple well-pairs over an entire pad should produce a significantly stronger signal.

5.4 Well-pair separation: Two well study

In the previous section, I demonstrated the potential of gravity gradiometry to detect the response of a growing SAGD steam chamber at increasing reservoir depths. In this section,
I seek to understand the gradiometry response for another important factor that can vary during SAGD production, which is the well-pair separation. For this, I next design and present a study that increases the lateral separation between two well-pairs.

Pad design in SAGD is extremely site dependent. For example, a production pad may have anywhere from three to over nine well-pairs extending from it, with multiple pads defining the complete project site. These pads and well-pairs are generally separated by some uniform distance chosen to maximize coverage in a given field while at the same time minimizing drilling cost. Typical well-pair separation distances at an individual pad are between 75 and 125 m, with larger separations rarely seen in practice.
In the following study, I analyze the gravity gradiometry signal for two well-pairs at three separations between 75 m and 125 m and at increasing reservoir depths. The goal is to identify whether or not the separate anomalies for each steam chamber are distinguishable. For this, I calculate the L2 norm of the Tzz and Tyy components as the signal as they are the two strongest components of the tensor for the current well-pair orientation, and they may additionally reveal the sought anomaly separation when present.

The simulations are performed at three reservoir depths: 100 m, 200 m and 400 m. Additionally, three steam chamber widths ($W_s = 11$ m, $W_s = 28$ m, $W_s = 56$ m) are employed to evaluate the effect on the signal as the steam chambers begin to merge over time.

The results are presented in Figure 5.7. In this figure, each row represents a single reservoir depth each column represents a single steam chamber size. The colored plots show the profile signal over two horizontal well-pairs separated by the distances depicted in the legend. The range of separation distance varies depending on depth. From this study, it can be concluded that gravity gradiometry may detect the individual steam chambers at shallow SAGD sites (upper row) for larger well-pair separations, even at later production times. However, as reservoir depth increases, the signal from the individual steam chambers become indistinguishable except at very large and impractical well-pair separations. As expected, at later times where steam chambers begin to merge, the gradiometry anomaly likewise begins to merge.

5.5 Deviating steam chamber growth

The final study in assessing the capability of gravity gradiometry for steam chamber detection is to analyze non-uniform steam chamber growth above the injector and determine whether or not these second-order deviations are detectable. To accomplish this, I simulate three deviating steam chambers (Figure 5.9a) spaced 125 m apart at 100 m reservoir depth. The forward-modeled signal is shown in Figure 5.8.
Figure 5.7: Lateral separation study for two SAGD steam chambers. For each depth (rows) and steam chamber expansion time (columns), results are displayed for three well-pair separations. Anomaly separation is only apparent at large well-pair separation and shallow depths.

Figure 5.8 indicates that the predicted signal in this case is above the noise limit discussed in Chapter 2. I also note that the deviating structures within the model can be seen in the nonuniform structure within the anomalies. This hints that we should be able to recover information on steam chamber quality within the reservoir through inversion, and I demonstrate next.

To better understand the potential of gravity gradiometry for quantitative interpretation during SAGD production, I next contaminate the data with 0.25 E Gaussian noise prior to inversion. In this case, I perform a generalized density inversion of the gravity gradiometry
Figure 5.8: Calculated gravity gradiometry signal above the three-well deviating steam chamber model in Figure 5.9a. The data is non-uniform, which indicates some information content about the lateral deviations within the steam chambers.

Data based on the method of Li (2001) with top and base of the reservoir incorporated as prior information. The inversion result is presented in Figure 5.9.

The model in Figure 5.9b shows good horizontal placement of the steam chambers, recovering the continuous and discontinuous structures within true model (Figure 5.9b). The general structure of the steam chamber is well defined and the second-order details are well accounted for. We note that the recovered structures in the vertical direction are less resolved than in the horizontal. However, it is clear that gravity gradiometry has the potential to detect and recover significant deviations within the steam chamber in this case.

5.6 Real site feasibility study

The previous examples were designed to test the general feasibility of gravity gradiometry for steam chamber detection. The results indicated that though it is a site-dependent problem, gravity gradiometry may be a feasible monitoring tool for certain reservoirs. To further test this, I now present a more realistic site example that incorporates steam chamber
vertical resolution is poor, but the horizontal distribution of steam is well recovered, indicating that this method is sensitive to small lateral steam chamber deviations.

geometry derived from seismic data. This exercise additionally provides a general workflow that incorporates gravity gradiometry into SAGD monitoring efforts as a complement to the additionally available seismic data.

5.6.1 Site background

The field that I am presenting here is located within the Athabasca Oil Sands in Alberta, Canada. The sands here are unconsolidated and contain extremely viscous oil (6-9° API). The reservoir sits at an average depth of 180 m in the Wabiskaw-McMurray reservoir unit and the average thickness is approximately 60 m. The McMurray formation is typically separated into three units: lower, middle and upper. Early deposition occurred in a fluvial environment, but at later times a marine transgression led to estuarine and marine environments. As a result the top of the formation has significantly lower quality reservoir than the base, as there are more fine-grained particles. A more comprehensive explanation of the site and its geologic history can be found in Schiltz (2013). As shown in the previous sections, this
shallow depth, combined with the high oil density and reservoir thickness, may provide an excellent target for gravity gradiometry.

Steam injection at this site began in 2007, and production has been steadily increasing since then as more wells have come online. As of 2012, there were 16 operational well pads. The study area presented here covers 4 of these pads, for a total of 17 well-pairs (Figure 5.10). A baseline seismic survey was shot in 2002 prior to production and drilling at the site. The follow-up seismic monitor survey was shot in 2011 over the region highlighted by Figure 5.10. The average site properties are listed in Table Table 5.1 and are extracted from Schiltz (2013).

Figure 5.10: Area of the 4D seismic survey used to develop the time-lapse gravity gradiometry model for the realistic site example. The area features four well pads and 19 well-pairs over a 2.5 km² area. From Schiltz (2013).
Table 5.1: Average reservoir properties for the Athabasca Oil Sands realistic field example.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>60 m</td>
</tr>
<tr>
<td>Depth</td>
<td>180 m</td>
</tr>
<tr>
<td>Velocity</td>
<td>2400 m/s</td>
</tr>
<tr>
<td>Oil Density</td>
<td>8° API</td>
</tr>
<tr>
<td>Porosity</td>
<td>31%</td>
</tr>
<tr>
<td>Water Saturation</td>
<td>26%</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>10° C</td>
</tr>
<tr>
<td>Injection Temperature</td>
<td>250° C</td>
</tr>
<tr>
<td>Injection Pressure</td>
<td>2 MPa</td>
</tr>
</tbody>
</table>

5.6.2 Site geometry

The geometries of the SAGD steam bodies were calculated by Schiltz (2013) using a model-based post-stack seismic inversion for the p-impedance change over the 9 year period of the 4D study. Zones where the rate of decrease was >10-20% were considered steam zones. An example of this steam chamber geometry is presented in Figure 5.11. The cutoff shown in this steam geobody model is for zones where the p-impedance decrease exceeds 15%.

An important note about the site represented in Figure 5.11 is the severe deviation from the original SAGD models presented in the previous examples, Figure 5.3 for example. There are several factors that contribute to this. First, steam injection is not typically continuous along the length of the injector well. A series of vents, spaced meters apart, are generally located along the length of the well. This creates a non-continuous injection pattern not accounted for in the original models. Second, the heterogeneous lithology within the reservoir is more significant at this site, containing numerous lenses that act as baffles to the steam migration. In this case, there are a number of pockets of low-permeability shales that are the result of a variety of depositional environments, from fluvial to marine. While some degree of this heterogeneity was accounted for in Figure 5.3b, this example demonstrates the reality of geological complexity versus pure simulation.

The next step was to convert the steam geobodies shown in Figure 5.11 to a time-lapse density model that could be studied using gravity gradiometry. I assumed here that
Figure 5.11: Steam geobodies based off of a post-stack p-impedance inversion. The cutoff here is zones where p-impedance decreased $\geq 15\%$. From Schiltz (2013).

The geometries of the geobodies recovered by Schiltz (2013), Figure 5.11, are an accurate representation of the density distribution of the steam chambers. The seismic data were converted from time to depth using the average properties provided in Table 5.1 and the upper and lower seismic surfaces interpreted by Schiltz (2013). The average density change in the steam zone was calculated using Equation 5.2 and found to be -0.25 g/cc. This assumed a final oil saturation of 25% within the steam chamber.

The final time-lapse density model constructed for this study is presented in Figure 5.12. It is a good representation of the reservoir depth, thickness and SAGD steam chamber distributions and it provides the foundation for this real site feasibility study.
Figure 5.12: Final density model for the realistic example, derived from the seismic data presented in Figure 5.11. The expected density contrast within the steam zones is -0.25 g/cc.

5.6.3 Time-lapse gravity gradiometry response

To determine whether or not this site would be a probable candidate for time-lapse gravity gradiometry monitoring, I forward-modeled the signal of the steam chamber density model from Figure 5.12 with a station spacing of 25 m. The resulting data are shown in Figure 5.13. The maximum signal in all components except Txy exceeds 1 E; in Tzz, we note the response exceeds 2 E.

5.6.4 Inversion

To evaluate the method for quantitative interpretation through inversion, I first contaminated the data, Figure 5.13, with 0.25 E Gaussian noise. Similar to the previous section, I
Figure 5.13: Gravity gradiometry data calculated from the time-lapse model presented in Figure 5.12. The data signal exceeds 1 E in nearly all components, and displays non-uniformity, indicating there is some information about the steam chamber geometry available in the signal.

then perform a generalized density inversion of the gradiometry data via a Tikhonov regularization approach (Li, 2001). For this, I incorporate prior information in the form of:

- Density bounds of (-0.3, 0.01) g/cc
- Reservoir top and thickness
- Spatial limits of the SAGD field
- Reference model of -0.25 g/cc
Figure 5.14: Inversion results for comparison with the true model shown in Figure 5.12. The geometry is very close to the original model, but has difficulty with recovering second-order small deviations.

The inversion result for this site example is presented in Figure 5.14. The recovered structures are a good representation of the true steam chamber distributions. While smaller geobodies and subtle deviations within the steam chambers are less defined than the original seismic interpretation, the overall shape and distribution is well accounted for across the pads. This demonstrates that time-lapse gravity gradiometry may provide a monitoring tool, complementary to and building off of seismic information, for similar SAGD production sites.

5.6.5 Field example: Conclusions

The inversion results presented here are from a relatively blind inversion that is weakly constrained by upper and lower density bounds. By incorporating stricter constraints on the
time-lapse density, or incorporating known shale-rich zones additionally recoverable from seismic data, it is possible to improve upon the results presented for this site. Additionally, alternative inversion techniques such as binary inversion (Krahenbuhl & Li, 2006) and surface inversion have demonstrated significant value for time-lapse problems where density information appropriate to the site is well defined. Regardless of these possibilities, it is clear from the current field study that time-lapse gravity gradiometry can provide complementary information to seismic for SAGD monitoring efforts.

5.7 Discussion

In this chapter, I have presented a comprehensive feasibility study for using time-lapse gravity gradiometry as a monitoring tool for SAGD operations. I first presented a sequence of steam chamber density models for first-order detection testing, including reservoir depth, well-pair separation and steam chamber deviations. The results have shown that gravity gradiometry, considering predicted noise limits of next generation sensors, may be capable of detecting the signal in shallow reservoirs and at later times in the SAGD project life. Gradiometry may also detect smaller, second-order characteristics of the steam chambers, including separation between individual horizontal well-pairs and lateral deviations in steam chamber quality along the borehole.

Finally, I presented a workflow for a more realistic SAGD site study where seismic data was used to design a site-specific steam chamber feasibility model. The results show that gravity gradiometry could provide value as a monitoring tool at this particular field. The signal is predicted detectable at reservoir depth and the inversion result showed excellent horizontal recovery of major steam chamber zones from production. Additional inversion constraints from available a-priori information, particularly from seismic data, could further improve these results.

From the results presented here, I believe that gravity gradiometry could provide a useful inter-seismic monitoring tool and serve to lower the overall cost of monitoring SAGD operations. While the resolution will likely not be at similar levels as seismic, it is capable
of providing significant information about the steam chamber distribution in the subsurface. Finally, it is noted that the application of time-lapse gravity gradiometry for SAGD monitoring is a site dependent problem, and that must be evaluated on a case by case basis.
Time-lapse reservoir monitoring is an important component of the energy industry. Monitoring fluid movement within a reservoir, whether for recovery or sequestration purposes, is vital to reservoir development and design. While this area is dominated by time-lapse seismic, there is benefit to incorporating additional methods that may provide complementary data, particularly for reservoirs where acquisition of seismic data may be expensive or logistically challenging. Potential field methods, such as gravity gradiometry, are sensitive to property changes within the reservoir over time and may be useful tools for tracking subsurface fluid movement as a complement to seismic data.

The objective of this thesis was to evaluate the feasibility of time-lapse gravity gradiometry as an additional reservoir monitoring tool. While current gradiometry technology is generally limited to the detection of signals greater than 2 - 5 E, experience and improvements by operators during collection and processing have seen error levels approaching 1 E. Additionally, gradiometry systems on the horizon are predicted to have the potential of performing at the 1 E or lower level, and a previous ground based gradiometry survey has even demonstrated sub-eotvos repeatability as low as 0.16 E. These combined factors of evolving instrumentation, growing operator experience, improved processing, and the anticipated removal of legal restrictions on survey height, open the possibility of applying gravity gradiometry for monitoring.

In this work, I presented a series of feasibility tests to determine whether or not gravity gradiometry could be a viable reservoir monitoring tool. The first component focused on the case of conventional reservoirs, where I evaluated both the general application for first-order understanding, and more detailed site assessments for a collection of time-lapse reservoirs. For the second component, I have investigated application to the unconventional case of
steam-assisted gravity drainage (SAGD) reservoirs.

Based on the works presented here, it is concluded that time-lapse gravity gradiometry can provide an additional and valuable monitoring tool for a number of reservoirs. These include both conventional and unconventional fields. However, it is important to understand that the application of gradiometry for monitoring is not universal. Additional considerations must be accounted for. Following are the main conclusions that can be drawn from this study:

1. The most important conclusion that can be drawn from this study is that the gravity gradiometry may be used as a monitoring tool for certain sites. Geometry of fluid movement within the reservoir can be recovered, which may provide a complement to seismic surveys and allow for longer periods of time between seismic shoots, decreasing the overall cost of monitoring.

2. The application of gravity gradiometry to reservoir monitoring is site-dependent. There are a number of factors that influence the gravity gradiometry signal, including density change from fluid movement, reservoir thickness and depth, and the amount of fluid that has been injected into the reservoir (i.e. production time). All of these factors, with as much detail as possible, must be brought together to understand the method’s benefit at a field.

3. Shallower sites are better candidates than deeper sites as a whole. The time-lapse problem of reservoir production or sequestration result in relatively small density changes within the swept zones. To counter the reduced effect of these small densities, a shallower field in general is required to reduce the distance between the target and sensor for a measurable signal. Furthermore, for this reason unconventional sites, in particular SAGD reservoirs, have the potential to provide larger time-lapse gradiometry signals, as they are typically shallow and feature higher density contrasts.

4. Thicker fields will produce a stronger signal than thinner fields. While the previous conclusion makes the general statement that deeper fields are less likely to be detectable
than shallower ones, the final gradiometry signal is influence by distance and total mass change during production. Fields such as Prudhoe Bay with significant thickness have the potential for large swept zones and large gradiometry signal from fluid movement.

5. Early production times with small swept zones are more difficult to monitor with gravity gradiometry than later times.

6. Applying prior reservoir information, such as geometry from seismic, improves the reliability of early feasibility studies for a site as well as later data interpretation following collection. While first-order approximations may be adequate for many reservoirs, such as the cylindrical example presented in Chapter 3, it is desirable to use additional information whenever possible as this will provide a more accurate picture of the reservoir. The Delhi Field example in Chapters 3 and 4 demonstrated that a reservoir that straddles detectability using the first-order cylindrical approximation may in fact be feasible when detailed geometry information is applied.
REFERENCES CITED


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Uweira-Gartner, M., Carlson, M., Walters, D., & Palmgren, C. 2011. Geomechanical simulation of caprock performance for a proposed, low pressure, steam-assisted gravity drainage pilot project. *CSUG.*


Winkler, A.K. 1951. The exploitation of oil-fields of extremely high oil-viscosity by wells, under the application of thermal energy. *In: 3rd World Petroleum Congress, May 28 - June 6.*
