Seismic Investigations at the Ketzin CO₂ Injection Site, Germany: Applications to Subsurface Feature Mapping and CO₂ Seismic Response Modeling

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Abstract

3D seismic data are widely used for many different purposes. Despite different objectives, a common goal in almost all 3D seismic programs is to attain better understanding of the subsurface features. In gas injection projects, which are mainly for Enhanced Oil Recovery (EOR) and recently for environmental purposes, seismic data have an important role in the gas monitoring phase. This thesis deals with a 3D seismic investigation at the CO₂ injection site at Ketzin, Germany. I focus on two critical aspects of the project: the internal architecture of the heterogeneous Stuttgart reservoir and the detectability of the CO₂ response from surface seismic data.

Conventional seismic methods are not able to conclusively map the internal reservoir architecture due to their limited seismic resolution. In order to overcome this limitation, I use the Continuous Wavelet Transform (CWT) decomposition technique, which provides frequency spectra with high temporal resolution without the disadvantages of the windowing process associated with the other techniques. Results from applying this technique reveal more of the details of sand bodies within the Stuttgart Formation. The CWT technique also helps to detect and map remnant gas on the top of the structure. In addition to this method, I also show that the pre-stack spectral blueing method, which is presented for the first time in this research, has an ability to enhance seismic resolution with fewer artifacts in comparison with the post-stack spectral blueing method.

The second objective of this research is to evaluate the CO₂ response on surface seismic data as a feasibility study for CO₂ monitoring. I build a rock physics model to estimate changes in elastic properties and seismic velocities caused by injected CO₂. Based on this model, I study the seismic responses for different CO₂ injection geometries and saturations using one dimensional (1D) elastic modeling and two dimensional (2D) acoustic finite-difference modeling. Results show that, in spite of random and coherent noises and reservoir heterogeneity, the CO₂ seismic response should be strong enough to be detectable on surface seismic data. I use a similarity-based image registration method to isolate amplitude changes due to the reservoir from amplitude changes caused by time shifts below the reservoir. In support of seismic monitoring using surface seismic data, I also show that acoustic impedance versus Poisson’s ratio cross-plot is a suitable attribute for distinguishing gas-bearing sands from brine-bearing sands.

Keywords: Seismic resolution, Spectral blueing, CO2 seismic response, Continuous Wavelet Transform Decomposition, 3D seismic baseline, CO2SINK project

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“Contradiction is not a sign of falsity, 
nor the lack of contradiction a sign of truth”

(Blaise Pascal)

Dedicated to my parents, Masoumeh and Yasaman
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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Additional publications during my PhD studies, which are not included in this thesis:


Contents

1. Introduction ............................................................................................... 11
   1.1 The CO2SINK Project ....................................................................... 11
   1.2 Role of seismic data in the CO2SINK project.................................... 12
   1.3 Motivations and objectives of the research ........................................ 13

2. Geological setting of the Ketzin site ......................................................... 14

3. Concepts of the reflection seismic method ............................................... 16
   3.1 A brief history of seismic exploration .............................................. 16
   3.2 The nature of seismic reflections...................................................... 17
      3.2.1 Elastic wave equation ................................................................. 17
      3.2.2 Huygens’ Principle .................................................................... 18
      3.2.3 Snell’s law and interface partitioning ......................................... 18
      3.2.4 Seismic Trace.............................................................................. 20
   3.3 Geometry of reflection path ............................................................. 21
   3.4 Common midpoint method ............................................................. 23
   3.5 Disciplines of the 3D seismic studies .............................................. 23
   3.6 Survey design ................................................................................ 23
   3.7 Acquisition .................................................................................... 25
   3.8 Processing ...................................................................................... 27
   3.9 Interpretation ................................................................................ 28
      3.9.1 Structural interpretation ........................................................... 29
      3.9.2 Stratigraphic interpretation ....................................................... 31
      3.9.3 Seismic attribute analysis ........................................................ 31

4. CO2 response modeling ............................................................................. 34
   4.1 Rock physics modeling .................................................................... 34
   4.2 Seismic modeling ............................................................................ 35

5. Seismic resolution ..................................................................................... 36
   5.1 Concepts ......................................................................................... 36
      5.1.1 Vertical resolution ...................................................................... 36
      5.1.2 Lateral resolution ...................................................................... 38
   5.2 Seismic resolution challenge at Ketzin ............................................ 39

6. Seismic and well data ................................................................................ 41
   6.1 2D seismic data ............................................................................. 41
6.2 3D seismic data .......................................................................................... 41
6.3 VSP data .................................................................................................. 42
6.4 Well data .................................................................................................. 42

7. Papers summary .......................................................................................... 44
  7.1 Paper I: 3D baseline seismics at Ketzin, Germany: The CO2SINK project .......................................................... 45
    7.1.1 Summary ......................................................................................... 45
    7.1.2 Conclusion ..................................................................................... 46
  7.2 Paper II: Application of the continuous wavelet transform on seismic data for mapping of channel deposits and gas detection at the CO2SINK site, Ketzin, Germany .......................................................... 48
    7.2.1 Summary ......................................................................................... 48
    7.2.2 Conclusion ..................................................................................... 50
  7.3 Paper III: Monitoring CO2 response on surface seismic data; a rock physics and seismic modeling feasibility study at the CO2 sequestration site, Ketzin, Germany .......................................................... 51
    7.3.1 Summary ......................................................................................... 51
    7.3.2 Conclusion ..................................................................................... 56
  7.4 Paper IV: Enhancing seismic data resolution using the pre-stack blueing technique: An example from the Ketzin CO2 injection site, Germany .......................................................... 57
    7.4.1 Summary ......................................................................................... 57
    7.4.2 Conclusion ..................................................................................... 58

8. Conclusions and future work ....................................................................... 63
  8.1 General conclusions ............................................................................... 63
  8.2 Outlook .................................................................................................. 64
    8.2.1 Sand body mapping and seismic resolution .................................. 64
    8.2.2 CO2 response on surface seismic data ......................................... 64

9. Summary in Swedish .................................................................................. 65

Acknowledgements ......................................................................................... 67

References ..................................................................................................... 71
Abbreviations

1D  One-dimensional
2D  Two-dimensional
3D  Three-dimensional
AVO  Amplitude Versus Offset
CDP  Common Depth Point
CMP  Common Mid Point
CO₂  Carbon dioxide
CWT  Continuous Wavelet Transform
dB  Decibel
DMO  Dip Moveout
Hz  Hertz
km  Kilometer
m  Meter
ms  Millisecond
MSP  Moving Source Profiling
NEGB  Northeast German Basin
NMO  Normal Moveout
OBC  Ocean Bottom Cable
rms  Root mean square
s  Second
S/N  Signal-to-Noise
TTI  Transit Time Integration
TWT  Two Way Time
VSP  Vertical Seismic Profiling
1. Introduction

This thesis focuses on seismic investigations prior to injection at the CO₂ geological storage site in Ketzin, Germany.

After a brief introduction about the CO2SINK project, the role of seismics in this project and the motivation for this research, the geological setting of the site is presented in chapter 2. In chapter 3 and 4, I explain the basic concepts of the seismic common-midpoint reflection method, with emphasis on major seismic study disciplines and CO₂ seismic modeling. Because of the importance and significant effect of seismic resolution in the CO2SINK project, in chapter 5, I review the resolution concepts and specifically highlight the target formation situation at Ketzin site and the limitation of conventional seismic data to resolve it. I continue with describing the seismic and well data used in this research in chapter 6.

The main part of this research is summarized in chapter 7 as papers summary. General seismic information related to CO₂ storage and new geological features interpreted from the acquired 3D seismic data are presented in paper I. In paper II, more details of the subsurface features which are important for CO₂ storage are revealed by using the CWT decomposition and seismic attributes. In paper III, the detectability of the CO₂ response from seismic data is evaluated through a modeling study. Since improving seismic resolution is one of the concerns of the project, the spectral blueing technique is used in a novel way on pre-stack seismic data. The pre-stack blued seismic data with higher resolution is the result of paper IV.

I finalize the thesis by presenting general conclusions and remarks as well as suggestions for future work in chapter 8. All published and submitted papers are also enclosed in this thesis.

1.1 The CO2SINK Project

Increasing greenhouse gases, specifically CO₂, may be causing undesirable climate changes. Recently there has been a great tendency to relate global warming to increasing CO₂ gas emissions into the atmosphere due to increasing fossil-fuel consumption. Among several options for reducing CO₂ emissions, capturing and geological storage of CO₂ is probably the most efficient and safest option (CO2SINK homepage: www.co2sink.org).
By signing the Kyoto Protocol, which legally establishes binding commitments for reducing greenhouse-gas emissions to the atmosphere, EU countries decided to reduce their CO₂ emission by 8% during years the 2008 to 2012. To help achieve this goal, the CO2SINK project was started in April 2004 as the first European onshore CO₂ storage pilot project. The project is supported by the European Commission, the German Federal Ministry of Education and Research, the German Federal Ministry of Economics and Technology, as well as research institutes and industry.

The CO2SINK project deals with the study of different aspects of reducing CO₂ gas emission by capturing and injecting CO₂ into a saline aquifer at the Ketzin site near Berlin. The main objectives of the project are (1) to develop and evaluate scientific and practical processes involved in geological storage of the CO₂, (2) to build confidence for future CO₂ geological storage in Europe and (3) to provide real field scale experience to help development of future regulatory frameworks for CO₂ storage.

The selected CO2SINK injection site, the Ketzin anticline, is located about 25 kilometers west of Berlin close to Potsdam, Germany (Figure 1.1). The site served as a town and natural gas storage facility from the 1970s until 2000. Several factors, such as favorable geological conditions, close proximity to a large metropolitan area for evaluating the public acceptance and the presence of the natural gas storage infrastructure played a role in choosing the Ketzin site for the experiment.

Like any other gas injection projects, geophysical data, and particularly seismic data, have had dominant roles in different stages of the project.

1.2 Role of seismic data in the CO2SINK project

Underground CO₂ storage requires an appropriate trap with both the capacity of accommodating and the ability of sealing gas. Such geological environments usually consist of a reservoir and a cap rock as a seal in a proper structural setting. To find such sets of rocks, information from underground structure, faults pattern as well as lithology and stratigraphy of formations is necessary. In addition, a safe storage requires reliable, sensitive and robust monitoring methods during and after CO₂ injection. To achieve these goals, geophysical data and, in particular, seismic data play a crucial role in mapping subsurface features and monitoring gas flow for possible leakage. Considering the objectives of the CO2SINK project and the particular attention given to the seal quality and the possibility of gas leakage from both geological and artificial pathways, the role of the seismic data were not only to understand the subsurface geology, but also to act as one of the most important components of the monitoring efforts during and after CO₂ injection. Several types of seismic data, such as 3D surface seismic, pseudo-3D (known also as star acquisition), VSP and MSP are involved in the project.
1.3 Motivations and objectives of the research

The sandy layers of the Stuttgart formation are the target for the CO₂ injection at Ketzin. Based on their geological environment, the thickness of these sandy layers can vary over a broad range (Förster et al., 2006). Therefore, there is a concern about the capacity of the formation for accommodating the injected CO₂ and knowledge of the sandy layers distribution is important for the CO₂ injection planning and monitoring. Unfortunately, in most of the area of the Ketzin structure, the sandy layers of the Stuttgart formation have a thickness below the seismic resolution. This implies that conventional surface seismic data processing can hardly resolve these layers.

Another important question is: Under what particular geological circumstances and pressure and temperature conditions will the injected CO₂ at the Ketzin site be detectable from surface seismic data?

The research in this thesis mainly deals with these two issues (i.e. mapping sands considering the resolution limitations and evaluation of the CO₂ seismic response). Main objectives of this research are (1) to obtain more detailed information than what is conventionally extracted from 3D seismic data using novel processing techniques and (2) to model the CO₂ response on the surface seismic data under particular scenarios.
In the CO2SINK project, the CO₂ gas is being injected into a sandy saline aquifer sealed by mudstone and evaporites cap rocks. This set of rocks has been folded as an anticline and forms an appropriate trapping system to accommodate and store injected CO₂.

The Ketzin anticline is the western part of a double anticline structure known as the Roskow-Ketzin anticline, which formed as Mesozoic sediments deformed due to Permian salts uplift in the Northeast German Basin (NEGB). The long axis of the anticline strikes NNE-SSW and its flanks dip at about 15 degrees. The Mesozoic sediments lying on the Permian salts were affected by several uplift and erosion phases resulting in totally 500 m eroded sediments. During the upper Cretaceous era the area was a part of a structural high and, therefore, there was no sedimentation for that period (Förster et al., 2006). The presence of Oligocene transgressive sediments on top of the Jurassic sediments unaffected by anticlinal uplift is the first evidence indicating regional downwarping of the central part of the Northeast German Basin, which is continuing until now.

The stratigraphy of the Ketzin site includes several successions of clastic and evaporite sediments. The target for CO₂ injection is the highly heterogeneous Upper Triassic Stuttgart Formation. This formation is about 75 to 80 m thick at a depth ranging between 500 to 700 m and contains sandy channel facies rocks of good reservoir quality, alternating with muddy flood-plain-facies rocks of poor reservoir quality (Norden et al., 2008). This setting is typical for incised-valley deposits, where sandy channel belts have formed by the amalgamation of individual fluvial channels surrounded by finer flood-plain or playa-type sediments. The thickness and width of the sandy intervals of the Stuttgart Formation may vary from 1m up to 30 m and from tens of meters to several hundreds respectively where sub-channels are stacked (Frykman et al., 2006). Having varying amounts of quartz, feldspar, rock fragments and matrix, lithologically these sands are classified as grey-wacke. They are fine to medium grained weakly cemented mainly by silicates and clay as well as anhydrite (Förster et al., 2006). The degree of cementation controls the porosity, permeability and elastic properties of the Stuttgart sands. Pressure at the Stuttgart depth is measured from 6.21 to 6.47 MPa (Norden, Personal Communication, 2009). The temperature at this depth varies from 34° to 37° C (Förster et al., 2006).
The cap rocks for injected CO₂ reservoir are the Weser and Arnstadt formations containing almost 210 m of mudstone and evaporites. At the top of the Weser formation there is a 10-20 m thick anhydrite layer which produces a pronounced seismic reflection on the seismic sections and is known as the K2 horizon. In the shallower part of the Ketzin structure, Jurassic sandstones interbed with mudstone, claystone and siltstone and form a multi-aquifer system. The cap rock for this system is an 80-90 m thick Tertiary clay which separates the saline waters of the deeper system from the non-saline groundwater in the shallow Quaternary aquifers. The Quaternary deposits are exposed at the surface (Förster et al., 2006).

Figure 2.1 shows the Roskow-Ketzin double anticline as well as a geological profile in well CO2 Ktzi 200/2007.

Figure 2.1: The Roskow-Ketzin double anticline (left) and the stratigraphy of the Ketzin site (right) based on the geological profile of the CO2 Ktzi 200/2007 observation well located on southern flank of the Ketzin structure at the injection site.
3. Concepts of the reflection seismic method

3.1 A brief history of seismic exploration

Seismology is a relatively new science with research starting in the early 1800s, when the theory of elastic wave propagation was developed by Cauchy, Poisson, Stokes, Rayleigh and others (Shearer, 1999). Prior to this time, the way of thinking about earthquakes was superstitious rather than scientific. Moreover, between two main branches of seismology, earthquake seismology and controlled-source seismology, the second one began to be developed later. Apparently Mallet was among the first scientists who carried out some experiments with an “artificial earthquake” in 1845 to measure seismic velocities (Telford et al., 1996). Since that time, other scientists, such as Knott, Zoeppritz and Wiechert, attempted to develop the theory of reflection and refraction for artificial sources. From 1914 to 1918, during World War I, there were extensive attempts towards determining the locations of heavy guns by recording seismic waves generated by the sudden backward movements that the gun makes when it is fired. These attempts were not quite successful, but had significant positive effects on the development of exploration seismology. Later, during the 1920s and 1930s, the methods of using artificial seismic sources were developed in the oil and gas producing areas of Mexico and the United States. Early exploration work was based mostly on refraction techniques, but after the pioneering work of Karcher in the early 1920s and a survey by the Geophysical Research Corporation of the Maud field in Oklahoma, reflection seismograms showed to be particularly applicable for exploration and replaced the earlier refraction techniques.

As the capability of instruments grew, reflection seismic methods developed faster. One of the most important developments in the history of exploration seismology was made in 1956 when the common-midpoint (CMP) method was patented. The method developed fast, especially after digital recording and processing replaced analog systems in the 1960s. Since that time to present time, seismic methods have experienced fast growth. New instruments and new methods are introduced almost every year.

Seismic methods are undoubtedly the most important geophysical methods in terms of funding, wide use, accuracy and high resolution (Telford et
al., 1996). The popularity of this method is seen by its wide application in petroleum exploration and development.

Other applications of seismic methods are in groundwater, civil engineering, mining and pure scientific studies of subsurface geology. Based on these applications, seismic methods can be categorized in (1) engineering seismology that deals with description of the near-surface geology using seismic methods for engineering purposes, (2) hard rock seismology that deals with application of seismic methods in crystalline rocks and (3) exploration seismology that deals with the application of seismic methods in sedimentary environments and includes, in particular, the reflection technique for exploration and development of oil and gas reserves.

Controlled-source seismology is also a common general term given to seismic methods, which covers all three categories mentioned above and refers to both reflection and refraction techniques. The term exploration in front of seismology is used sometimes to distinguish it from earthquake seismology. In this case, exploration seismology has the same meaning as controlled-source seismology.

This thesis is devoted to application of the seismic reflection technique in a sedimentary area. In this chapter, I briefly review some concepts of exploration seismology in its particular meaning as mentioned in item (3).

3.2 The nature of seismic reflections

Seismic methods in general make use of wave propagation through the earth to obtain subsurface information. The energy released from a seismic source is transmitted down into the ground in the form of an elastic wave and propagates by movement of rock particles. To utilize this motion, the reflection and refraction of seismic waves in an elastic medium, understanding of the elastic wave equation, Huygens’ Principle and Snell’s law is essential. In this section, I briefly explain the elastic wave equation, Huygens’ Principle and Snell’s law. The equations are taken from Shearer (1999).

3.2.1 Elastic wave equation

Seismic wave propagation is governed by the elastic properties of the medium. Seismic waves propagating in a homogeneous isotropic infinite medium satisfy the following equation:

$$\rho \ddot{u} = (\lambda + 2\mu)\nabla \nabla \cdot u - \mu \nabla \times \nabla \times u$$  \hspace{1cm} (3.1)
where \( u \) is the displacement vector \( (\ddot{u} = \frac{\partial^2 u}{\partial t^2}) \), \( \lambda \) and \( \mu \) are Lame’s constants and \( \rho \) is density. This equation can be simplified by separating the wavefield into curl-free and divergence-free components, which leads to the equations for P-wave and S-wave propagation, respectively. By applying the divergence operator to the elastic wave equation, we obtain:

\[
\frac{\partial^2 (\nabla \cdot u)}{\partial t^2} = \frac{\lambda + \mu}{\rho} \nabla^2 (\nabla \cdot u) \tag{3.2}
\]

This is the acoustic wave equation and the P-wave velocity \( (V_P) \) is given by:

\[
V_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad \text{or} \quad V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad \text{or} \quad V_P = \sqrt{\frac{M}{\rho}}, \tag{3.3}
\]

where \( K \) is the bulk modulus and \( M \) is the P-wave modulus. Analogously, by applying the curl operator to equation (3.1), we obtain:

\[
\frac{\partial^2 (\nabla \times u)}{\partial t^2} = \frac{\mu}{\rho} \nabla^2 (\nabla \times u) \tag{3.4}
\]

This is the S-wave equation and the shear wave velocity \( (V_S) \) is given by:

\[
V_S = \sqrt{\frac{\mu}{\rho}} \tag{3.5}
\]

3.2.2 Huygens’ Principle

Huygens’ Principle is important for understanding wave propagation and constructing successive positions of the wavefront (Sheriff and Geldart, 1999). Moreover, this principle can be used to derive Snell’s law. Huygens’ Principle states that every point on a propagating wavefront provides a secondary source of waves and that the surface which is tangential to the secondary waves can be used to construct the future position of the wave.

3.2.3 Snell’s law and interface partitioning

When an elastic wave encounters a boundary of different elastic properties the continuity of stresses and displacements at the interface require that the wave be divided into reflected and refracted waves. In seismology, this
effect is referred to as partitioning at the interface. In partitioning at an interface, part of the wave energy reflects back toward the surface and another part continues to transmit into the second medium with an abrupt change in the propagation direction (*Sheriff and Geldart, 1999*). The relation between incidence angle and reflection and refraction angles is governed by Snell’s law. A P-wave with amplitude $A_0$ and incidence angle $\theta_0$, incident on an interface boundary of two solids (Figure 3.1) will be divided into reflected and refracted P-waves as well as reflected and refracted S-waves. Snell’s law for such waves can be written as:

$$\frac{\sin\theta_0}{V_{P1}} = \frac{\sin\theta_1}{V_{P1}} = \frac{\sin\beta_1}{V_{S1}} = \frac{\sin\theta_2}{V_{P2}} = \frac{\sin\beta_2}{V_{S2}} = p$$ (3.6)

where $\theta_0$, $\theta_1$, $\theta_2$, $\beta_1$, $\beta_2$ are incidence angle, reflected P-wave angle, refracted P-wave angle, reflected S-wave angle, refracted S-wave angle and $V_{P1}$, $V_{P2}$, $V_{S1}$, $V_{S2}$ are the P-wave and S-wave velocities of the two media. $p$ is the ray parameter and remains constant along the ray path.

*Figure 3.1:* Energy partitioning of an incident P-wave at a solid-solid interface.
The relations between amplitudes of the incident P-wave with the reflected and refracted P- and S-waves are given by Zoeppritz’s equations (Sheriff and Geldart, 1999). In normal-incidence cases (including incidence angles up to 20° (Telford et al., 1996) as commonly used in reflection seismic techniques, there is little S-wave conversion. In this simple case, Zoeppritz’s equations state that the ratio of reflected amplitude to incident amplitude is a function of changes in the product of density and velocity, known as acoustic impedance. This ratio is basically reflection strength and is referred to as the reflection coefficient (RC):

\[
RC = \frac{A_1}{A_0} = \frac{Z_2 - Z_1}{Z_2 + Z_1}
\]

(3.7)

where \( Z_1 = \rho_1 V_p \) and \( Z_2 = \rho_2 V_p \) are acoustic impedances of the two media and \( A_1 \) is the reflected wave amplitude. The widely used reflection seismic technique is based on normal and close to normal incidence reflection measurements.

In the non-normal incidence cases, Zoeppritz’s equations account for both wave conversion and amplitude changes, but provide little intuition on how amplitude changes relate to the several factor involved (Sheriff and Geldart, 1999). In practice, approximations are usually made in order to obtain an equation form which gives more insight into changes expected for various situations. Non-normal incidence involves variation of amplitude with angle, which is the basis for AVO (Amplitude Variation with Offset) studies.

3.2.4 Seismic Trace

In the seismic reflection technique, the propagated energy from source through the earth will be recorded in the form of seismic traces. Ideally, these records represent the source signature convolved with the earth’s reflectivity. If this were the case, the complete solution to the seismic problem would be easy to determine. In the simple forward modeling technique for generating synthetic seismograms, each seismic trace \( T(t) \) is assumed as a successive series of source signatures \( S_s(t) \) convolved with reflectivity \( R_c(t) \):

\[
T(t) = S_s(t) * R_c(t)
\]

(3.8)

However in the real world, coherent noise, such as multiples, diffractions, surface waves, scattered waves, as well as random noise, are present in the seismic records. In practice, we can consider a seismic trace as the result of successive convolutions of the non-stationary source signature with a number of impulse responses as (Sheriff and Geldart, 1999):
\[ T(t) = Ss(t) \ast Rc(t) \ast P(t) \ast Q(t) \ast O(t) + N(t) \]  

(3.9)

where \( P(t) \) represents a modifying factor due to multiple, diffraction, reflected refractions and so on, \( Q(t) \) is related to the disproportional modification of the seismic pulse in near surface, \( O(t) \) representing the impulse response of the zone in the vicinity of the source where absorption of energy is extreme and \( N(t) \) is random noise.

This concept that the seismic trace is a series of convolutions is known as the convolutional model and is fundamental for seismic data processing. The convolutional model is commonly presented as:

\[ T(t) = W(t) \ast Rc(t) + N(t) \]  

(3.10)

In this form \( W(t) \), known as the embedded or equivalent wavelet, includes \( Ss(t), P(t), Q(t) \) and \( O(t) \) and is the wavelet that would be reflected from a single isolated interface.

### 3.3 Geometry of reflection path

Determining the position and configuration of a reflector is the basic problem in reflection seismology. Travel time measurements and knowledge of velocity are essential to solve this problem. In the simple case of a horizontal reflection at depth \( h \) and constant velocity \( V \) in the layer above, for source and receiver at the same surface point (vertical ray path) vertical travel time will be (Telford et al., 1996):

\[ T_0 = \frac{2h}{V} \]  

(3.11)

For the source-receiver offset \( x \) shown in Figure 3.2, we can write:

\[ T^2 = \frac{x^2}{V^2} + T_0^2 \]  

(3.12)

This equation indicates that the reflection travel time curve in the t-x domain is a hyperbola, as shown in Figure 3.2. The difference between travel time at offset \( x \) and the vertical travel time is known as normal moveout (NMO) and can be approximated as:

\[ \Delta t_n = T - T_0 = \frac{x^2}{2V^2T_0} \]  

(3.13)
For a non-horizontal reflector, the dip of the reflector with respect to the direction of the profile needs to be taken to account. In the case of vertical velocity variations, when the ray paths are not linear and rays bend at each layer interface, equations 3.12 and 3.13 are not appropriate. A layer with varying velocity can be assumed as a series of $n$ layers with constant velocities ($V_i$). Dix (1955), showed that for such layer, $V$ in the equation (3.13) can be replaced with the root-mean-square velocity ($V_{rms}$) where

$$V_{rms} = \left( \frac{n}{1} \sum V_i^2 t_i / \sum t_i \right)^{1/2}$$

(3.14)
3.4 Common midpoint method

Green (1938) proved the ability of multiple sampling from a common reflection point (also known as a common depth point (CDP)) to eliminate the effect of dip on velocity calculation. Despite this study, prior to the 1960s seismic reflection surveys were collected as single-fold recordings, in which each reflection point was sampled only once (Sheriff and Geldart, 1999). Mayne (1962) proposed a method of multifold surveying. Based on this method, in order to enhance the signal to noise ratio and allow velocity analysis, the information acquired by repeatedly sampling a given reflection point can be combined after applying appropriate corrections. Recording several seismic traces from the same reflection point increases the fold coverage and can be done by moving sources and receivers an equal distance to either side and repeat shooting. The point on the surface half-way between the source and the receiver is called the common midpoint. Therefore, this method is also known as the common-midpoint (CMP) method. In practice, for each shot point, data are recorded for several active receivers in a shot record or shot gather. Later, seismic traces with different source-receiver pairs but the same midpoint can be sorted into a CMP gather. The common midpoint method is summarized in Figure 3.3.

3.5 Disciplines of the 3D seismic studies

Although field methods, processing and interpretation methods of seismic reflection surveys vary considerably depending on the area and objectives of the project, there are common routines for almost all programs. A general technical time line for a 3D seismic reflection program is showed in Figure 3.4 (Cordsen et al., 2000). In marine seismic programs, surveying (navigation) and acquisition are simultaneous. In practice, financial considerations are as important as technical requirements and sometimes may even force changing the procedure.

In the following sections, four main parts of the seismic studies including survey design, acquisition, processing and interpretation are briefly explained. I have focused on 3D seismic studies as it is the case for this research.

3.6 Survey design

After clarifying budget related issues for a 3D seismic program, the 3D survey needs to be designed with respect to the study objectives. Before that, there are some initial considerations. A scouting trip to the area provides important information about the surface condition and obstacles in the area.
In order to have optimum field layout parameters (source and receiver geometry), field and source tests are also necessary.

3D seismic design is based on objectives of the program, costs and budget, subsurface geological information, information obtained from the scouting, field and source test information, as well as seismic considerations. In
addition, there are other factors which may practically influence and change the 3D seismic design. For example, local availability of seismic acquisition crews, possible delays due to weather or any other delays, etc. Therefore, seismic survey design is more than just choosing a source and receiver and shooting away. In fact, 3D acquisition design is compromising between different factors and parameters in order to get the best signal at the lowest cost. Some of the most important technical parameters which need to be determined in a 3D seismic survey design are summarized in Table 3.1.

![Figure 3.4: General time line of a 3D seismic reflection program.](image)

### 3.7 Acquisition

Surface seismic data acquisition is the process of sending artificially generated seismic waves into the earth and recording the wave returning back to the surface (*Sheriff and Geldart, 1999*). Although 3D seismic data acquisition may vary from one area condition to another (i.e. different techniques in land, marine and transition zone areas), the main concept and key equipment are common in all surveys. Four main field components of the surface seismic data acquisition surveys include source, receiver, cable and digital boxes and recording system. Land data acquisition can be more complicated than acquisition in marine environments. In land acquisition, different choices of source, shot and receiver arrays and spreads are available for different
conditions. Usually data are acquired in a template with a certain line layout and then the template is moved successively to cover the entire survey area.

Table 3.1. 3D seismic survey design parameters (modified after Cordsen et al., 2000).

<table>
<thead>
<tr>
<th>Seismic parameters</th>
<th>Definitions and requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fold</td>
<td>Number of samples (field seismic traces) in a bin which are stacked together. Determined based on the required S/N ratio.</td>
</tr>
<tr>
<td>Bin Size</td>
<td>The size of an area where traces are stacked within it. Determined based on the target size, maximum unaliased frequency due to target dip and lateral resolution.</td>
</tr>
<tr>
<td>$X_{\text{min}}$ and $X_{\text{max}}$</td>
<td>Minimum and maximum offset. Determined based on the target depth and other offset-dependent phenomena such as: direct and refracted waves interferences, NMO, Multiple discrimination, AVO analysis and dip measurement.</td>
</tr>
<tr>
<td>Migration apron</td>
<td>The area which needs to be added to the full fold area to allow migration of dipping reflections. Determined based on the value of dip in different directions.</td>
</tr>
<tr>
<td>Fold taper</td>
<td>The area around the full fold area which fold build-up occurs. Determined based on the fold, receiver and source line intervals.</td>
</tr>
<tr>
<td>Record length</td>
<td>The time length of data recording. Must be enough to receive signals from the deepest target and all needed diffraction tails.</td>
</tr>
</tbody>
</table>

In marine data acquisition, there is less possibility for spreading source and receiver lines and also surface conditions usually have less variations. Therefore, offshore acquisition is considered to be somewhat simpler and faster than land data acquisition (Bacon et al., 2007). Two main marine data acquisition methods include Ocean Bottom Cable (OBC) in which three-
component receivers are deployed at the sea bottom and *streamer acquisition* in which one or more receiver cables (streamers) and one or more source arrays are towed by a seismic vessel.

In transition zone areas, where water depth is too shallow for marine data acquisition with a towed streamer and the land source line is approaching the sea, special technique need to be considered. In a developed method, both land and marine sources and receivers are employed to achieve full coverage from both sides of the shoreline. Sea-bottom cables connected to land cables is also a solution for data acquisition in such conditions.

### 3.8 Processing

The goal of this chapter is not to provide a full explanation about each process, but to provide an overview of the main processing steps. For more detailed descriptions, I refer to Yilmaz (2001).

Acquired shot record carries information on the subsurface structure. However, it is very difficult to see a clear subsurface image from a raw record because it is affected by several factors, which can hide or mask subsurface structures. For example, a recorded seismic trace in land data may contain different types of waves such as direct waves, refractions, primary reflections, multiples and surface waves. Only primary reflections are generally considered as signal in the reflection seismic method, the rest are noise. In addition to this type of noise, known as coherent noise, there is always some random noise contaminating seismic data. One of the goals of seismic data processing is to attenuate this noise and to enhance the signal (primary reflections) to noise ratio. Besides noise, there are other factors such as amplitude decay, perturbation of seismic signal, and travel time differences, which affect seismic data and need to be corrected in order to produce a seismic section that looks as close as possible to the subsurface geology (Yilmaz, 2001). Seismic data processing flows may differ depending on the area and objectives of the project. However, considering common necessary corrections, almost all seismic data processing sequences are based on the following basic corrections: 1) Preprocessing, 2) Amplitude correction, 3) Deconvolution (Frequency and phase corrections), 4) Travel time corrections, 5) Noise suppression, 6) Stacking and 7) Imaging. These corrections can be categorized into two categories: primary processes, which aim to improve seismic resolution and enhance S/N ratio, and secondary processes, which aim to improve the performance of primary processes. The primary processes are deconvolution, stacking and imaging (migration) (Yilmaz, 2001). Figure 3.5 shows an example of a conventional processing flow for land seismic data. The number in front of each process corresponds to the seven corrections mentioned above.
3.9 Interpretation

Understanding subsurface geology is the common goal for almost all seismic reflection studies. Ideally, a processed seismic section should look like its corresponding geological section, but there are several factors involved that make it different from real geology. For example, seismic data can see geological boundaries only if they are associated with acoustic impedance boundaries (Badley, 1985). Even in this case, interference of closely spaced interfaces complicates the seismic response. In addition, seismic data record each boundary in two-way time rather than depth. Therefore changes in both velocity and depth will affect seismic images. Velocity pull-ups and push-downs are two well known velocity-related artificial structures on seismic sections which are not related to subsurface geology. All these factors complicate the task of relating seismic sections to the subsurface geology. Seismic interpretation attempts to translate seismic reflections into geological information.

A seismic reflection event can have several descriptive properties which may relate to geology. Among these properties, geometry, amplitude and frequency are better linked to geology (Badley, 1985). To make use of these properties, seismic interpretation assumes that seismic reflections are from acoustic impedance contrasts in the earth and that seismic properties of a reflection correspond to properties of rocks and fluids (Sheriff and Geldart, 1999). Considering these fundamental assumptions, seismic interpretation methods are classified as structural interpretation ones that deals with struc-
tural mapping based on reflection configuration, *stratigraphic interpretation* ones that try to extract the depositional system and facies information from the seismic data, and *quantitative interpretation* ones that deal with extracting reservoir properties such as pore fluid and lithology from seismic attributes (Avseth et al., 2005; Bacon et al., 2007).

Modeling, which is often divided into forward and inverse, helps us to understand how different features might be appear on seismic data (Edwards, 1988; Fagin, 1991; Noah et al., 1992). Since modeling of the CO$_2$ response is part of this research, it will be explained in more detail in chapter 4.

### 3.9.1 Structural interpretation

Structural seismic interpretation is the study of reflection geometry and is the first fundamental step in extracting geological data from seismic sections. This technique is based on picking a seismic reflection corresponding to a certain geologic boundary. The horizons are usually picked in a time section and then converted to depth. Depth conversion can be problematic, especially in areas with complex velocity variations. Different methods of depth conversion are developed based on well-derived or seismic velocities. The final output of this type of interpretation are structural maps for particular horizons, isopach maps for intervals or geological layers and 3D geological models incorporating objective horizons and faults.

To mark geological horizons on seismic sections, well data provide an important aid in structural interpretation. Establishing a relationship between seismic reflections and geological boundaries is known as *well to seismic ties* and these are even more important in detailed interpretations using seismic attributes (Bacon et al., 2007). Generating *synthetic seismograms* is a popular way to tie well and seismic data. Well-generated synthetic seismograms are produced by one dimensional (1D) forward modeling based on the convolutional model (discussed in section 3.2.4) and predict the seismic response of the earth. They are simply generated by convolving an extracted or estimated wavelet with the well-derived reflection coefficients (Figure 3.6). Sonic and density logs are used to calculate the acoustic impedance and reflection coefficients for normal incidence. The calculated reflection coefficient log can be converted to time using a time-depth function usually obtained from check-shot data or from sonic transit time integration (TTI) of a sonic log (Serra, 2008). By comparing synthetic seismograms with real seismic data at the well location reflections corresponding to each geological boundary can be marked if there is a good match. Geological boundaries with no reflection can also be determined.
Figure 3.6: (a) Schematic generation of a synthetic seismogram from an acoustic impedance log and (b) Example of a synthetic seismogram correlated with seismic data, Soroush Oil field-Persian Gulf.

The degree of match between synthetic seismograms and surface seismic data depends on the well log data and the seismic data quality and also on the correspondence between the extracted or estimated wavelet and the real seismic wavelet. In papers II and IV of this research, synthetic seismograms are generated for two wells and matched to the surface seismic data at Ketzin site.
3.9.2 Stratigraphic interpretation

Seismic stratigraphy in general implies interpreting seismic data to obtain non-structural information (Sheriff and Geldart, 1999). In a more specific definition, seismic stratigraphy is the detailed study of seismic event geometries to determine the relation of system tracts within seismic sequences for understanding the depositional system in a sedimentary basin. It can be also referred to as using seismic data in sequence stratigraphy. An advantage of using seismic data in sequence stratigraphy lies in the fact that large-scale seismic data are combined with small-scale well data to predict the distribution and quality of the sedimentary facies (Veeken, 2007).

3.9.3 Seismic attribute analysis

Sheriff (1991) defined seismic attributes as “any measurement derived from seismic data”. In a similar definition, seismic attributes are also considered as a measure based on one or more of the seismic characteristics such as time, amplitude, phase, frequency, attenuation and shape of the waveform (Brown, 1996; Chopra and Marfurt, 2005). Based on this broad definition, many of the seismic analysis techniques including seismic inversion for acoustic impedance, AVO analysis and spectral decomposition can be regarded as seismic attribute analysis. Seismic attribute analysis was first limited to application of tools for displaying and visualization of seismic data, but later they become useful as analytical tools for providing quantitative information on subsurface geology. In fact, the common and basic objective of all attributes is to provide accurate and detailed quantitative information to aid structural and stratigraphic seismic interpretation, as well as rock property estimation and reservoir characterization (Taner, 2001). As countless seismic attributes have been introduced, they are classified in many different ways such as; pre-stack and post-stack attributes, sample-derived or instantaneous and interval-derived or transmissive attributes, geometrical and physical attributes, 1D, 2D and 3D attributes, general and specific attributes, etc (Taner et al., 1994; Brown, 2004; Liner et al., 2004; Chopra and Marfurt, 2005). Figure 3.7 shows a general classification of attributes. Fomel (2007) introduced a new category of attributes called local attributes which are not extracted instantaneously at each sample and not in a certain interval, but locally in the neighborhood of each data point. One of the introduced attributes, local similarity, is useful for registration of time-lapse seismic images. I applied the method of registration based on local similarity as defined by Fomel and Jin (2009) in paper III of this research to isolate amplitude differences caused by injected CO₂ from amplitude changes from time shifts. Other attributes used in this research are decomposed frequency and similarity as well as edge detection.
Spectral decomposition is a widely used method for decomposing a seismic trace into its constituent frequency components in order to obtain more detailed geological information. Different methods of spectral decomposition have been introduced (Castagna and Sun, 2006). The common output of these methods is a frequency spectrum for each time sample. Main applications of this method include determining layer thickness, stratigraphic visualization, and direct hydrocarbon detection (Partyka et al., 1999; Marfurt and Kirlin, 2001; Castagna et al., 2003). In paper II, I used this method to map sandy channels and also to detect the remnant gas distribution at the Ketzin structure.

Edge detection is another attribute and was used in this research to map faults and discontinuities on a horizon slice. Edge detection highlights discontinuities across a horizon. In a simple version of this algorithm, a set of 3x3 samples on either side of each sample are compared and the result gets assigned to the sample point (Gonzalez and Wintz, 1987). Based on Figure 3.8 the equation for calculating the edge detection attribute at point E is:

\[ \text{edge} = \sqrt{x^2 + y^2} \]  
(3.15)

where \( x = (C + 2F + I) - (A + 2D + G) \) and \( y = (A + 2B + C) - (G + 2H + I) \) (Gonzalez and Wintz, 1987).
Figure 3.8: Illustration of a set of $3 \times 3$ samples for calculating the edge detection attribute.

*Similarity* is a measure which expresses how much two or more seismic traces look alike (*Tingdahl and De Groot, 2003*). As with edge detection, this attribute also is calculated over a set of 3x3 traces and considers the vector nature of traces in hyperspace. It is defined as one minus the Euclidean distance between each sample normalized over the vector length. The similarity is measured over a time window which can be just few samples across a horizon or time slice. If all trace segments are identical in waveform and amplitude then similarity will be one and if they are completely dis-similar the similarity measure will be zero. As is shown in paper II, this attribute has proved to have the capability to map faults at the Ketzin structure.
4. CO₂ response modeling

One of the objectives of this research is the CO₂ response modeling on the surface seismic data. There are two steps involved in this study. First, we need to understand how CO₂ may affect rock properties and change the effective seismic velocity and density of the medium. Then we need to model and evaluate the effect of these changes on surface seismic data. To predict magnitude and character of the CO₂ response on seismic data under certain conditions, a rock physics model needs to be generated and incorporated in a seismic forward modeling scheme.

In this chapter, I briefly explain rock physics modeling and two forward modeling techniques. These were used in Paper III.

4.1 Rock physics modeling

Rock physics modeling deals with understanding how effective rock density and seismic velocities are affected as a result of changes in fluid, porosity, pressure, lithofacies, etc (Bacon et al., 2007). Figure 4.1 summarizes the effect of these parameters on seismic velocities.

One of the common rock physics problems, fluid substitution, deals with understanding changes in velocity and impedance due to pore fluid changes (Avseth et al., 2005). Two effects associated with fluid substitution are effective bulk modulus and density changes which result in velocity and impedance changes. The effect of fluid change appears more significant on velocity (Badley, 1985). Nevertheless, both properties should be considered in building a realistic rock physics model. The Biot-Gassmann theory (Gassmann, 1951; Biot, 1956) which relates bulk modulus of rock before and after fluid change is the fundamental basis for rock physics modeling. According to this theory, for an isotropic rock, changes in fluid will change the bulk modulus, but the shear modulus, which is insensitive to pore pressure, will stay constant. In order to apply the Biot-Gassmann theory in a particular case of fluid substitution, bulk modulus with the initial saturation, grain bulk modulus, and fluids bulk moduli, as well as porosity need to be estimated.

In paper III, the Biot-Gassmann theory is applied to generate a rock physics model for the CO₂ injection at the Ketzin site.
Figure 4.1: Effects of rock and fluid property changes on P-wave and S-wave velocities and their ratio (after Tatham and McCormack, 1991).

4.2 Seismic modeling

Seismic modeling is a general term for different techniques which are used to generate synthetic data for better understanding of wave propagation, testing acquisition and processing parameters and supporting interpretation of seismic data (Keiswetter et al., 1996). Seismic modeling involves estimating both travel time and amplitudes of seismic waves propagating through the model (Yilmaz, 2001). Various modeling techniques such as simple and complex convolutions, ray tracing, Kirchhoff modeling and finite-difference modeling can be selected depending upon the objectives of the study and computational cost. Regardless of the very different algorithms, all modeling techniques try to generate synthetic seismic data based on an initial model. The resemblance of generated synthetic data to real seismic data depends on the accuracy of the model and the efficiency of the algorithm. In fluid substitution problems, after predicting velocity and density based on the rock physics model, the next step is to generate synthetic data to see how these changes can affect seismic data.

In Paper III, we use 1D elastic convolutional modeling in order to incorporate both P-wave and S-wave predicted velocities and density and to estimate amplitude changes related to CO₂ injection in a CMP gather. We also use acoustic 2D finite difference modeling in order to evaluate possible interferences from other seismic events (i.e. multiples) rather than only primary reflections on the CO₂ response.
5. Seismic resolution

Resolution of seismic data is an important problem that needs to be properly considered in seismic studies. Improving reflection seismic resolution in order to map thinner features is one of the objectives of this research. In this chapter, I review the resolution concepts and explain the seismic resolution challenge at the Ketzin site.

5.1 Concepts

“The ability of seismic data to resolve two closely spaced features is known as seismic resolution” (Sheriff, 1991). Seismic resolution deals with the following question: How close can two interfaces be in the vertical and lateral directions to be seen as two separate events on seismic data? Both vertical and horizontal resolution impose limitations on seismic data and are controlled by the dominant wavelength, which is velocity divided by the dominant frequency \( \lambda = \frac{V}{f} \) (Yilmaz, 2001).

5.1.1 Vertical resolution

In reflection seismology, vertical resolution is a measure of how close two reflectors need to be in time in order to be distinguished on a seismic section (Sheriff and Geldart, 1999). Vertical resolution is governed by the wavelet length. For an ideal spiky seismic pulse with instantaneous particle motion and infinitesimal wavelength, vertical resolution would be almost perfect (Badley, 1985). However, the seismic pulse in reality has a finite duration, increasing with time due to attenuation of higher frequencies.

Considering such a dilating wavelet, the effect of interference between reflections from closely spaced reflectors is inevitable. Interaction between the wavelet length and spacing of the reflectors controls the interference and defines whether two reflectors are resolvable or not. A generally accepted limit for vertical resolution, known as the Rayleigh criterion, is a quarter of the dominant wavelength \( \lambda/4 \) (Yilmaz, 2001). Reflectors with spacing less than this limit in time are generally not resolvable on seismic data. However, this limit may change depending on the reflection strength and the signal-to-noise ratio.
A common model considered to explain the vertical seismic resolution limit is a wedge-shaped unit of a high velocity rock encased by a lower velocity rock. Moving from higher thickness toward lower thickness over this model, the character of seismic data is changing due to interference between two reflections from top and bottom of the layer with opposite polarity. As long as the thickness of the wedge-shaped unit is equal or greater than half the wavelength ($\lambda/2$) there is no interference and the top and bottom of the unit will be resolved. Where the thickness of the wedge-shaped unit is between half wavelength ($\lambda/2$) and one-quarter wavelength ($\lambda/4$) reflections from the top and bottom of the unit will start to interfere, but still can be distinguished as two reflections. At the point in which the thickness of the wedge reaches one-quarter of the wavelength ($\lambda/4$), the two reflections form one single reflection with maximum amplitude due to constructive interference. After this point, which is called the tuning thickness, the separation of the top and bottom of the unit on the seismic section (apparent thickness) will stay constant. The further decrease in the thickness of the wedge only results in amplitude reduction. Therefore, the top and bottom reflections cannot be resolved, but the reflection from the wedge will be detected until the point that the thickness is reduced to approximately one-twentieth to one-thirtieth of the wavelength ($\lambda/20 - \lambda/30$) (Badley, 1985; Sheriff and Geldart, 1999). This limit, which is considered as the detectability limit, needs to be distinguished from the resolution limit.

Widess (1973) introduced a method to calculate the thickness of thin beds below the tuning limit. He showed that the character of the reflecting wave changes even below the tuning limit ($\lambda/4$) until the thickness reaches $\lambda/8$ and after that stays unchanged. Reflection amplitude ($A_r$) for beds thinner than $\lambda/8$ is given by

$$A_r = 4\pi A_0 b/\lambda$$

where $\lambda$ is the wavelength, $b$ is the thickness of the bed and $A_0$ is the amplitude from the top of the bed in case of an individual reflection with no interference. This equation shows that reflection amplitude below the resolution limit is proportional to the thickness and, thus, can be used to estimate bed thickness (Bacon et al., 2007). Several amplitude-based methods for calculating bed thickness below the resolution limit have been suggested. The assumption associated with all of these methods is that all lateral amplitude changes are caused by thickness changes and not by reflection coefficient changes. Figure 5.1 illustrates a schematic wedge model and the corresponding tuning curve. The amplitude achieves a maximum value at the tuning thickness. The apparent thickness (i.e. thickness from the seismic section) reaches a minimum here and remains constant even though true thickness continues to decrease.
5.1.2 Lateral resolution

In reflection seismology lateral resolution refers to how far apart two points need to be on a reflecting interface in order to be resolved (Yilmaz, 2001). The upgoing wave is reflected not just from a single point located on an interface, but from an area known as the Fresnel zone (Badley, 1985). In the same way that the length of the wavelet is taken as limiting the vertical resolution, the size of the Fresnel zone limits the horizontal resolution. Thus, the horizontal limit for unmigrated seismic data is the size of the Fresnel zone.

When the phase difference of the waveform passing the Fresnel zone is not more than a half-cycle, the wave interference is constructive (Sheriff and Geldart, 1999). A reflector can be considered as a continuum of diffractive points. As illustrated in Figure 5.2, the travel time for reflected energy from
point (O) to the source and receiver at surface point (S) is \( t_0 = 2Z_0/V \), where \( V \) is the average velocity. As the wave continues to propagate in depth by the amount \( \lambda/4 \) (half-cycle in two way time), the reflected energy from points A and A’ will arrive to the point (S) at \( t_1 = 2(Z_0 + \lambda/4)/V \). All points within the reflecting portion OA’ will reflect energy sometime between \( t_0 \) and \( t_1 \). All events arriving within the time interval \((t_1 - t_0)\) have constructive interference (Yilmaz, 2001). The AA’ portion of reflector is the Fresnel zone and two reflecting points within this area are not resolvable. The radius of the Fresnel zone \( (r) \) depends on velocity, frequency and two way time \((TWT)\) \((t)\) and can be approximated as follow:

\[
 r = \frac{1}{2} V \sqrt{\frac{t}{f}}
\]  

(5.2)

All objects with horizontal dimension less than the Fresnel zone diameter \((2r)\) produce a seismic diffraction response which amplitude is dependent on object geometry but traveltimes are same as diffraction point. Therefore, horizontal resolution can be described also as the ability of seismic data to distinguish two adjacent diffractions. Similar to deconvolution, which sharpens the wavelet and increases vertical resolution, seismic migration, which is a process that collapses diffractions, improves horizontal resolution. In fact migration, as downward continuation of the observation plane from the surface to the reflector, decreases the Fresnel zone and increases the horizontal resolution (Yilmaz, 2001). In 3D migration, the diameter of the Fresnel zone will collapse to approximately one-half of the wavelength, but in case of 2D migration the decrease occurs only in the seismic line direction (Lindsey, 1989).

With appropriate spatial and temporal sampling, the size of the Fresnel zone and the length of the seismic wavelet control horizontal and vertical resolution, respectively.

Note that estimating vertical and horizontal limits based on the dominant frequency (or dominant wavelength) gives an overall idea of the resolution for the most of the data, but considering lower and higher frequencies may also be essential. In fact, one should consider that having a sharper seismic wavelet requires a broad bandwidth with both low and high frequencies, and not just high frequencies.

5.2 Seismic resolution challenge at Ketzin

The reservoir for CO\(_2\) injection at the Ketzin site is a sandy interval of the Stuttgart Formation. The thickness of the sandstone interval varies from a few meters up to 30 m (Förster et al., 2006) which is typical for fluvial environments. Mapping this variable reservoir interval at the Ketzin site is one
of the challenging aspects of the CO2SINK project. 3D seismic data acquired over the area are one of the important data sets to be used for this purpose. Using conventional seismic processing and interpretation methods is not possible to map the Stuttgart sandy intervals on the 3D seismic data because the dimensions of the sand bodies are mostly below the seismic resolution. The vertical resolution limit for the Ketzin 3D surface seismic data with a frequency bandwidth from 25 to 60 Hz and average velocity of 2500 (m/s) is from 10 to 25 m. Considering the interference of all frequency components, it is hard to resolve objects which are less than 15 m thick at the Stuttgart depth. Although sand bodies are mostly smaller than this limit, their presence may affect the amplitudes of the surface seismic data and this can be an aid to detecting and mapping sand bodies even below the seismic resolution limit. Hence, amplitude-based analyses which can map the sand bodies based on amplitude changes need to be examined.

As part of this research in papers I and II, the Ketzin sand bodies are mapped using amplitude changes. The result is confirmed and improved by the Continuous Wavelet Transform (CWT) decomposition application. Paper IV also presents a novel technique for enhancing seismic resolution.

![Fresnel zone for a flat reflector.](image-url)

*Figure 5.2: Fresnel zone for a flat reflector.*
6. Seismic and well data

Data used in this research include a 2D seismic pilot line, 3D surface seismic data, VSP data and well data.

6.1 2D seismic data

In September 2004, two pilot 2D reflection profiles were acquired over the Ketzin structure (Yordkayhun et al., 2009). This pilot study was performed to test acquisition parameters for the planned 3D survey. One of the lines with an E-W trend which passed close to the well Ktzi 163/69 and entered in the 3D seismic survey area (Figure 6.1) is used in this study to tie the well and the 3D seismic data. This line is 2.4 km long and was acquired using three different sources. However, we used the processed data which was acquired using the VIBSIST source.

6.2 3D seismic data

A 3D seismic survey with 12 km² subsurface coverage was acquired on the crest of the Ketzin structure from September to November 2005. A total number of 7500 shots were recorded in 72 active acquisition days. The data were acquired using a weight drop source and an overlapping template scheme with the same acquisition geometry for each template. The template geometry consisted of five receiver lines 96 m apart with 48 active channels spaced at 24 m in each line. Twelve source lines 48 m apart with 16 or 17 shot points spaced 24 m apart in each line were shot perpendicular to the receiver lines. The total potential source points for each template were 240, but every 6th shot point was skipped so that 200 theoretical source points and a 25 nominal fold were obtained for each template. However, in some areas where the source points were not accessible or the shot was not possible due to surface obstacles, roads, residence areas and nature reserves the actual fold is smaller. The data were recorded with a 1 ms sampling rate and 3 sec record length using a SERCEL 408 UL system.

The data were processed with a relatively simple flow in order to allow processing to be quick and to minimize introduction of potential artifacts into data. The key processing steps included: geometry application and CMP
binning (12 × 12 m), spherical divergence correction ($V^2t$), surface consistent deconvolution, band-pass filtering, zero phasing, refraction statics, NMO, stack and 3D finite-difference migration.

6.3 VSP data

A Vertical Seismic Profiling (VSP) survey was carried out at the observation well CO2 Ktzi 202/2007 in November 2007. The survey covers approximately a radius of 300 m around the well. The VSP source points were on the same radial lines as for the Pseudo-3D survey. In addition, one zero-offset source point was used. The recorded interval for the zero-offset source point is 11 to 666 m. The VSP acquisition parameters are summarized in the Table 6.1.

In Paper IV we compare the enhanced-resolution 3D seismic cube with the processed zero-offset VSP data.

Table 6.1. VSP acquisition parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receivers</td>
<td></td>
</tr>
<tr>
<td>Geophone Type</td>
<td>3component R8XYZ-cgGeophone Chain</td>
</tr>
<tr>
<td>Spacing</td>
<td>5 m</td>
</tr>
<tr>
<td>Channel</td>
<td>132 (for zero-offset shot)</td>
</tr>
<tr>
<td>Source (Zero-offset)</td>
<td></td>
</tr>
<tr>
<td>Impact energy</td>
<td>VIBSIST-1000</td>
</tr>
<tr>
<td>Impact Frequency</td>
<td>2500 J</td>
</tr>
<tr>
<td>Operating weight</td>
<td>340-680 blows/min</td>
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<tr>
<td></td>
<td>2200 Kg</td>
</tr>
<tr>
<td>Recording</td>
<td></td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>0.25 ms</td>
</tr>
<tr>
<td>Record Length</td>
<td>3 s</td>
</tr>
</tbody>
</table>

6.4 Well data

Besides several available deep and shallow wells at the Ketzin area, during the CO2SINK project, two observation wells (CO2 Ktzi 200/2007 and CO2 Ktzi 202/2007) and one injection well (CO2 Ktzi 201/2007) were drilled at the Ketzin injection site. These wells are located on the southern flank of the structure. The well CO2 Ktzi 200/2007 was originally planned to be the
injection well, but due to some drilling and completion considerations the well CO2 Ktzi 201/2007 was made the injection well. Well log data, including velocity, formation density, gamma ray and porosity logs from the wells Ktzi 163/69, CO2 Ktzi 200/2007 and CO2 Ktzi 202/2007, core analyses results and geological well descriptions are used as complementary data sets in this research (see Figure 6.1 for basemap).

Figure 6.1: 3D seismic survey area with the system of in-lines and cross-lines, the location of the CO2 observation and injection wells and the deep well Ktzi 163/69. 2D seismic pilot lines are shown by black dashed lines. Contours are isodepth lines to the near top of the Stuttgart Formation based on vintage 2D seismic lines in the area.
7. Papers summary

This thesis work is supported by four papers. In this chapter, I briefly summarize objectives, methods, results and conclusions for each paper. The papers are based on team work where my personal contribution for each paper includes:

Paper I: Besides participating in the field work for the 3D seismic data acquisition, I was part of the data processing team and I contributed in the Ketzin 3D data processing. In particular, I did the first break picking for two swaths, ground roll suppression tests, zero-phase filter design and velocity analysis. I have also been involved in the time-depth conversion of the interpretation results.

Paper II: The studies were performed by me while the discussion and conclusions are efforts of all authors. The manuscript was also written by me, with a strong contribution from Christopher Juhlin, and suggestions for improvements from other co-authors.

Paper III: The main part of the studies, including: rock and fluids elastic property estimation, rock physics and seismic modeling were done by me. Christopher Juhlin contributed in the initial model building for different CO₂ geometry extensions and Sergey Fomel contributed in image registration for isolating the reservoir amplitude changes. The conclusions are the result of discussion with all authors. The manuscript was written by me with comments for improvement from co-authors.

Paper IV: The pre-stack spectral blueing operator design, reprocessing of the 3D data set and interpretation of results were done by me. Can Yang processed the VSP data and contributed in the comparison between the blued sections with the VSP data and synthetic seismograms. Christopher Juhlin contributed in reprocessing of the data, Sergey Fomel contributed in the blueing filter design and Calin Cosma was involved in the VSP data acquisition. The manuscript was written by me with comments for improvement from Christopher Juhlin, Sergey Fomel.
7.1 Paper I: 3D baseline seismics at Ketzin, Germany: The CO2SINK project

7.1.1 Summary

3D seismic investigations are one of the important components of the CO2SINK project. Thus a 3D data set with 12 km² of subsurface coverage, was acquired in autumn 2005. The main objectives of this 3D program were to (1) ensure that the structural geometry and reservoir properties in the Ketzin site are suitable for CO₂ injection, (2) provide a baseline for after injection seismic surveys and (3) give detailed images for planning the injection and observation boreholes. This paper presents results from the 3D baseline survey with regard to these three objectives. The paper gives background information on the geological setting of the site, acquisition parameters and processing sequences and then summarizes the interpretation results.

The quality of the 3D data is fairly good and, except for some parts of the survey where the fold is low, the subsurface features are well imaged from 100 ms to 900 ms. Structural interpretation, edge detection attribute mapping, as well as amplitude mapping were the three methods of investigation in this research.

Figure 7.1 shows a crossline with picked reflection horizons corresponding to geological formations. With the present processing, the first clear reflection (T1) is from the near Base Tertiary unconformity and shallower layers (i.e. Quaternary and Tertiary) are not mapped on this data. The near Base Tertiary time structure map and edge detection map (Figure 7.2) reveal a subhorizontal to slightly dome-shaped horizon intersected by an east-west to west-southwest-east-northeast trending fault system. These faults form an approximately 600-800 m wide depression on the crest of the Ketzin structure named the Central Graben Fault Zone (CGFZ). The Top Sinemurian and the near Top Triassic horizons are associated with relatively strong reflections on the seismic data and define the dome-shaped structure. In contrast, there is no particular seismic event related to the near Top Arnstadt formation. The horizon is identified in a peak about 70 ms below the near Top Triassic reflection. The K2 reflection which is one of the strongest seismic events on the 3D seismic data is attributed to a 20-m-thick anhydrite layer in the uppermost part of the Weser Formation. The CGFZ is still recognizable in this horizon.

Since at the time of the 3D interpretation, there was no well-tie control, neither the top nor the base of the Stuttgart Formation could be related to a particular seismic event. With some uncertainty, the top and base of the formation were picked, respectively, in a weak peak about 80-90 ms below the K2 horizon and a weak trough 70 ms later. At least one of the main faults of the CGFZ can be recognized at the Stuttgart level. But there is no fault seen
on the seismic data in the vicinity of the injection site, which is located more than 1.5 km south of the CGFZ. The remnant stored gas in the depth interval about 250-400 m is clearly identified on the 3D seismic data by amplitude brightening and also velocity pull down. Amplitude mapping also suggests the existence of a channel system related to the higher amplitudes close to the injection site.

![Seismic data image](image)

*Figure 7.1: Crossline 1105 crossing nearly over the top of Ketzin anticline. Mapped reflection horizons are (1) near BaseTertiary (T1), (2) near Top Sinemurian (TS), (3) near Top Triassic (TT), (4) near Top Arnstadt Formation (TA), (5) Top Weser Formation (K2), (6) near Top Stuttgart Formation (TSt), and (7) near Base Stuttgart Formation (BSt). CGFZ, G1, G2, and FS indicate the upper gas layer, the lower gas layer, and the flat spot, respectively. Depth in kilometers corresponds roughly to time in seconds since rms velocities vary from about 1700 to 2400 m/s down to the target depth.*

### 7.1.2 Conclusion

The 3D data quality is fairly good and significant seismic events can be seen down to 1 sec. The Ketzin structure interpreted on the 3D seismic data is close to that which is expected from other vintages of seismic data and boreholes. A clear fault system is observed on the crest of the structure, but does not extend towards the south. Therefore, no clear fault is seen close to the injection site on the seismic data.

The mapped remnant gas package on the seismic data extends towards the top of the dome and not towards the injection site in the south. The high amplitude feature near the injection site on the summed absolute amplitude map, generated over a time window covering the Stuttgart formation, indicates a possible sandier channel in the formation at this location.
This study showed that high-quality 3D seismic data required for CO₂ injection monitoring can be acquired using a small crew, single geophones and a simple weight drop source. 

Figure 7.2: (a) Time horizon map of the T1 (near Base Tertiary) reflection and (b) corresponding edge detection map of the horizon. White lines in (a) mark mapped faults. CGFZ-Central graben fault zone.
7.2 Paper II: Application of the continuous wavelet transform on seismic data for mapping of channel deposits and gas detection at the CO2SINK site, Ketzin, Germany

7.2.1 Summary

This paper presents some of the results from a more detailed 3D seismic interpretation which was carried out as complimentary work following the previous conventional interpretation discussed in the paper I.

The paper focuses on some of the objectives of the 3D seismic study such as reservoir heterogeneity, automatic fault mapping and remnant gas detection at the Ketzin site. To achieve these objectives, we applied the Continuous Wavelet Transform (CWT) decomposition method on the seismic data for mapping of the potential channel deposits, as well as remnant natural gas detection by mapping low-frequency shadows associated with the gas. We also used the similarity attribute in order to map faults in the Ketzin structure. In order to have better well control on the Stuttgart top and base reflectors, we tied data from two wells into the 3D seismic data and correlated the top and base horizons based on the synthetic seismograms.

Figure 7.3 illustrates the result of applying the CWT method on a horizon within the Stuttgart Formation. The result is compared with an amplitude map for the same horizon. A possible curved channel feature, which can be hardly seen on the amplitude map, is much clearer on the 25 Hz decomposed map because other frequency components are not interfering with the signal. The features with high amplitude on the 35 Hz decomposed map can be interpreted as thinner sands which continue south of the planned injection site while thicker sand bodies are probably resolvable at this frequency and hence not high amplitude. The 45 Hz map reveals more details of the thinner sands and lower amplitudes since most of the sand bodies are resolvable in this frequency.

The CWT method is also used to map remnant gas in the shallower part of the Ketzin structure. Figure 7.4 shows the decomposed frequency maps for two time slices, one slightly below the top gas (Figure 7.4a and 7.4b) and another one 25 ms below the deepest gas layer (Figure 7.4c and 7.4d). The dotted line shows the maximum distribution of the gas area based on UGS (the operator of the natural gas storage facility at Ketzin) borehole data. The 20 Hz decomposed slice near the top gas slice (Figure 7.4a) is not bright while the 20 Hz slice at 300 ms (Figure 7.4c) shows a strong signal below the gas accumulation zone which is interpreted as a low frequency shadow associated with the gas above it. The 40 Hz decomposed slice near top gas shows clear bright spots that match the UGS-replotted gas area. This bright
amplitude disappears on the 40 Hz slice below the gas. This result confirms the presence of a low frequency shadow beneath the gas zone and also the ability of the CWT method to map it. The distribution pattern of gas is in good accordance with the fault system. The fault system at top of the Ketzin structure is also mapped in this study using the similarity attribute.

Figure 7.3: a) Horizon amplitude map on a selected horizon 45 ms above the base Stuttgart Formation. b), c) and d) Decomposed common frequency maps using Mexican Hat wavelets on a horizon 45 ms above the base Stuttgart Formation. The curved feature (dashed lines on b, c and d) may represent a channel.
7.2.2 Conclusion

The CWT decomposition method has an ability to map thin beds in seismic data. We use this method to extract more information about the internal architecture of the Stuttgart Formation which is important for the reservoir modeling and site characterization phase of the CO2SINK project. The presence of meandering channel beds within the Stuttgart formation, a highly plausible geological situation, is suggested by our CWT analysis.

We also showed that the CWT decomposition method is capable of detecting remnant injected gas and can be used for monitoring of the injected CO₂ during and after injection. The common frequency slices and maps can give valuable information about the frequency-dependent anomalies which may not be obtained from conventional amplitude analysis.

This study confirmed that the low-frequency components of seismic data are higher below gas bearing rocks than above. The low frequencies are not observed in deeper horizons and therefore they cannot be due to simple attenuation in the gas layer. Although many other authors have observed this phenomenon, there is no accepted clear explanation for it.

Figure 7.4: Decomposed common frequency slices using Morlet wavelets for a time slice near the top gas (a and b) and about 25 ms below the deepest gas-water contact (c and d). The maximum gas distribution for the area in 2004 based on UGS report is shown as dotted black lines.
7.3 Paper III: Monitoring CO₂ response on surface seismic data; a rock physics and seismic modeling feasibility study at the CO₂ sequestration site, Ketzin, Germany

7.3.1 Summary

An important means of CO₂ monitoring, seismic monitoring, can be performed using borehole seismic data such as VSP and cross-hole, as well as surface seismic data. The large scale surface seismic is useful for monitoring CO₂ far from boreholes and also for detecting possible leakages from natural pathways on a large scale. However, reservoir conditions, CO₂ quantities and data quality govern whether changes in subsurface physical properties caused by injected CO₂ can be observed on surface seismic data. Hence, for each particular case, a feasibility study based on the specific subsurface conditions needs to be done. Therefore, as one of the concerns of the CO2SINK project is if the injected CO₂ can be monitored using surface seismic data considering the Stuttgart Formation setting, we carried out a modeling study to estimate the CO₂ response on the surface seismic data. This paper presents the results of our study. The methods for this study include (1) rock physics modeling for the Stuttgart Formation in order to estimate changes on elastic properties caused by injected CO₂ and (2) seismic modeling to identify the effect of the elastic changes on surface seismic data.

Considering the pressure and temperature at the target depth at the Ketzin site, the injected CO₂ will be present in a gaseous state rather than a supercritical state. The density and bulk modulus of the CO₂ under such conditions are 0.174 g/cm³ and 0.00832 GPa (Figure 7.5).

Based on the rock physics models for both patchy and uniform saturations for 30% CO₂ in the sandy interval of the Stuttgart Formation, P-wave and S-wave velocities as well as density changes are estimated. As shown in Figure 7.6, P-wave velocity and density changes before and after CO₂ injection are significantly larger than the corresponding S-wave velocity changes. The decrease in P-wave velocity in the uniform saturation case is also larger than in the patchy saturation case.

Based on this velocity model, 1D elastic modeling was performed to evaluate possible amplitude variations in a synthetic CMP gather before and after injection. Figure 7.7 shows the result of the 1D elastic modeling for both patchy and uniform saturations. Although no clear amplitude changes with offset can be observed in each CMP gather, the amplitude changes before and after injection are obvious.
Figure 7.5: Velocity, bulk modulus, and density of CO2 under Stuttgart Formation conditions (T=35.5º C, and P=6.33 MPa). Injected CO2 will be in gaseous form within the reservoir.

We also carried out 2D finite-difference modeling in order to evaluate the CO2 effect on the seismic sections taking into account all acoustic wave geometries rather than only primary reflections. Figure 7.9 shows the results of this modeling based on the 12-layer models shown in Figure 7.8 for both patchy and uniform saturations and for different CO2 extensions. In order to isolate amplitude changes in the reservoir from amplitude changes due to time shifts, we used a local-similarity based image registration technique.

In order to distinguish between CO2 and brine bearing sands, acoustic impedance versus Poisson’s ratio crossplot is examined (Figure 7.10).
Figure 7.6: Velocities, density, and Poisson’s ratio logs for uniform- and patchy-saturation models at 30% CO2 saturation. Last track shows how the shear modulus and dry-rock bulk modulus overlap in the relatively cleaner sandstone interval. Lithological column after Norden et al. (2008).

Figure 7.7: Synthetic seismic CDP gathers before and after CO2 injection for both uniform- and patchy-saturation cases.
Figure 7.8: Velocity models before and after CO2 injection for patchy- and uniform-saturation cases and having different lateral extensions. The CO₂ accumulations are marked with dashed circles.
Figure 7.9: Synthetic seismograms resulting from acoustic 2D finite difference modeling performed on the different models shown in Figure 7.8.
Figure 7.10. Acoustic impedance and Poisson’s ratio cross-plot for the Stuttgart Formation sandy interval. CO₂/brine sands are separated from original brine-saturated sands in both uniform- and patchy-saturation cases.

7.3.2 Conclusion

In this paper we have shown how CO₂, which is in gaseous state, will change the velocities and density of the Stuttgart sandy interval under its specific subsurface conditions. The CO₂ in gaseous phase will produce a stronger seismic response than if the CO₂ were present as a supercritical fluid. We also examined the feasibility of CO₂ monitoring on surface seismic data. As the seismic models show, the CO₂ response is detectable on the surface seismic data in both the patchy and uniform saturation cases. However, it also depends on other conditions related to acquisition, such as signal-to-noise (S/N) ratio, repeatability of acquisition parameters and the effect of changes in the near-surface conditions.
7.4 Paper IV: Enhancing seismic data resolution using the pre-stack blueing technique: An example from the Ketzin CO₂ injection site, Germany

7.4.1 Summary

Considering the stratigraphy of the Ketzin CO₂ injection site, some geological units, in particular the internal architecture of the main target, Stuttgart Formation, cannot directly be resolved on the 3D seismic data. However, using unconventional techniques may improve and push the seismic resolution limit. In this paper, the pre-stack spectral blueing technique (Kazemeini et al., 2008) is used to enhance the Ketzin 3D seismic data resolution. A blueing operator is designed in a suitably small time window using the well-derived reflectivity log spectrum and then applied to pre-stack data.

Application of the blueing operator to pre-stack data shapes the seismic spectrum to match the reflectivity spectrum while producing fewer artifacts in comparison with the routine post-stack blueing technique.

A comparison between the inline sections (Figure 7.11) and crossline sections (Figure 7.12) extracted from the original 3D seismic data with no blueing, post-stack blued and pre-stack blued, show that some tuned reflections on the seismic sections are better resolved on both the post-stack and pre-stack blued sections. In Figure 7.11a a tuned seismic event marked (A) is clearly resolved on both the post-stack and pre-stack blued sections in Figures 7.11b and 7.11c. The area with brightened amplitude around 0.3 sec on the crossline showed in Figure 7.12 between CDP 150 to 250, on the crest of the structure is related to the remnant natural gas in several layers. Amplitude variations in this part of the section are due to both the presence of gas and tuning. For example, in Figure 7.12a the tuned reflection marked (B) just above the gas can be easily misinterpreted as the top of the gas. However, the reflection is resolved in both blued sections in Figures 7.12b and 7.12c, indicating that the high amplitude is due to tuning not the presence of gas.

Overall, the pre-stack sections illustrated in Figures 7.11c and 7.12c have a less ringy appearance associated with them compared with the post-stack blued sections in Figures 7.10b and 7.11b. For instance, the area within the dashed circles in Figures 7.10b and 7.11b shows some ringing artifacts on the post-stack blued inline and crossline which are not as apparent in the pre-stack blued inline and crossline in Figures 7.11c and 7.12c.

The results of pre-stack and post-stack blueing are also compared with high resolution zero-offset VSP data and a synthetic seismogram from the well Ktzi 202/2007. Figure 7.13 illustrates the match between the zero-offset VSP data presented as a corridor stack and with an inline passing across the well from the original 3D seismic data with no blueing (Figure 7.13a), the
post-stack blued section (Figure 7.13b) and the pre-stack blued section (Figure 7.13c). A better match is obtained between the blued sections and the high resolution VSP data. The well to seismic tie (Figure 7.14) is also improved by performing spectral blueing, especially by pre-stack spectral blueing.

7.4.2 Conclusion

It has been shown in this paper that the pre-stack spectral blueing technique has the capability to enhance the resolution of the seismic data within the seismic frequency band and with significantly fewer ringing artifacts than that produced by the post-stack blueing technique. Reduction of the size and number of side lobes during stack is probably due to application of non stationary processes like normal moveout in the pre-stack phase, increases the amplitude integrity and gives more consistent results with a less ringing appearance.

Spectral shaping methods such as spiking deconvolution which are based on the white reflectivity assumption over-amplify the low frequencies of the seismic bandwidth while designing a deconvolution operator based on the blue reflectivity and performing a blue deconvolution instead of a spiking deconvolution may enhance the resolution of the seismic data. The designed blueing operator shapes the low and high frequencies in the seismic spectrum to the level of the reflectivity spectrum defined by the well log data.

Both pre-stack and post-stack techniques improve seismic resolution by enhancing higher frequencies within the seismic frequency band. This is verified by a better match between high resolution VSP data and blued seismic sections and a higher correlation coefficient obtained from tying blued seismic traces to a synthetic seismogram.
Figure 7.11: Comparison between original data with no blueing, post-stack and pre-stack blueing for inline 1220 extracted from the 3D seismic cube (see Figure 6.1 for location map). (a) inline before blueing (b) after post-stack blueing and (c) after pre-stack blueing.
Figure 7.12: Comparison between original data with no blueing, post-stack and pre-stack blueing for crossline 1150 extracted from the 3D seismic cube (see Figure 6.1 for location map). (a) crossline before blueing (b) after post-stack blueing and (c) after pre-stack blueing.
Figure 7.13: Zero-offset VSP is compared with inline 1172 extracted from (a) original 3D seismic data, (b) post-stack blued cube and (c) pre-stack blued cube. Blued sections (b) and (c) show a better match with the VSP data. i.e the two reflections at 580 are resolved on the pre-stack and post-stack blued sections (b) and (c), while tuned on section (a). The first 300 ms of the seismic data between CDP 1100 to 1130 is poorly imaged because of the low fold due to injection infrastructure obstacles.
Figure 7.14: Synthetic traces generated in wells Ktzi 202/2007 are correlated with (a) original 3D seismic traces, (b) post-stack blued seismic traces and (c) pre-stack blued seismic traces of inline 1172 passing over the well (see Figure 6.1 for location map). Events on synthetic traces are better correlated with the pre-stack blued seismic traces shown in (c). A trace selected from the seismic data is repeated and plotted beside the synthetic traces for easier comparison.
8. Conclusions and future work

8.1 General conclusions

3D seismic data interpretation provides a good understanding of subsurface features. In particular, as it is shown in this thesis, 3D geological structures, such as faults, as well as lithological heterogeneities and gas effects can be delineated using 3D seismic data. However, in many cases, detailed subsurface information cannot be obtained from conventional seismic interpretation methods. Valuable detailed information retrieval requires, as shown in this study, that complementary analyses to improve seismic data resolution, to avoid distractive effects of noise, and to reveal subsurface features.

Two principle objectives of this thesis are (1) to obtain more detailed information about the internal architecture of the Stuttgart formation at Ketzin site and (2) to evaluate the CO₂ effect on surface seismic data. These two objectives are in accordance with the concerns of the CO₂SINK project regarding the sands distribution in the Stuttgart Formation as the main target reservoir for CO₂ injection and also the feasibility of tracking CO₂ during and after injection using surface seismic data. In this research, the CWT decomposition method for channel mapping and the spectral blueing technique for seismic resolution enhancement are shown to provide more information in order to achieve the first objective. The decomposed frequency horizon maps show high amplitude reflected energy related to different thicknesses of sands and representing a highly heterogeneous meandering channel system on top and on the flank of the Ketzin structure. The CWT decomposition method also successfully mapped the remnant gas on seismic data and thus can be considered as a means for CO₂ monitoring after initial injection, the second objective.

The resolution of seismic data can be improved by both post-stack and pre-stack spectral blueing techniques. Pre-stack blueing produces more stable results with less ringing artifacts.

Seismic modeling showed that, even in the case of patchy saturation for the heterogeneous Stuttgart reservoir, the seismic response of CO₂ should be observable on surface seismic data.
8.2 Outlook

8.2.1 Sand body mapping and seismic resolution
In this research, I mapped a possible sandy channel system on the seismic data using detailed interpretation techniques. This effort gives the answer to the question of whether there is enough room for CO₂ injection into the Stuttgart formation. It is probable that the channel system developed in the Stuttgart Formation at the Ketzin site, with high porosity and permeability, contains enough capacity to store the injected CO₂. Incorporation of the result of sandy channel mapping into the static modeling of the reservoir will give a better estimation of the reservoir capacity to store CO₂. Therefore, I would suggest revising the reservoir models based on this result. Regardless, the result of this part of the research will be verified during the monitoring phase of the project where the CO₂ migration path toward the crest of the structure should be observed. The technique we used for channel mapping is able to map thin beds to some extent. However, there are probably still thin sands which are not mapped. Therefore there is still a possibility for further improvements. One method is to consider mapping sand bodies using the spectral blueing outputs with higher seismic resolution.

8.2.2 CO₂ response on surface seismic data
In this research, I also showed that the injected CO₂ will be in gaseous state and should have a significant response on surface seismic data. The expectation based on this result is that, even with a small amount of CO₂ distributed as patchy saturation, the changes will become detectable on the surface seismic data. However, other data conditions are also important and need to be considered. As possible further work, performing a 3D CO₂ response modeling covering a larger area, not just the area around the injection site, may give more information about the three-dimensional changes within the reservoir and how they will affect the CO₂ response.

Det europeiska samarbetsprojektet CO2SINK startades i april 2004 och handlar om att studera olika aspekter av koldioxidlagring. Koldioxiden skall lagras i en saltvattenförande reservoar i den sedimentära berggrunden vid Ketzin, en reservoar som tidigare har använts för lagring av naturgas. Projektet syftar huvudsakligen till att: (1) förbättra den vetenskapliga och praktiska förståelsen för de olika processerna involverade i koldioxidlagring; (2) bygga upp förtroende för framtida europeisk koldioxidlagring; och (3) utgöra en erfarenhetsbas för framtagandet av regelverk och normer rörande koldioxidlagring.

Den seismiska undersökningen är en viktig del av projektet CO2SINK. Ett mål är att avbilda strukturer som kan utgöra flödesvägar för gasen i reservoaren. Ett annat viktigt mål är att med hjälp av upprepade seismiska mätningar på samma plats studera utbredningen av gasen med tiden. I den här studien har jag riktat in mig på två centrala aspekter av projektet, den första utgörande en studie av den interna strukturen i den heterogena Stuttgartformationen, vilken utgör reservoar för gasen, och den andra aspekten är möjligheten att upptäcka en seismisk respons av den injekterade koldioxiden, med fokus på 3D-mätningarna (projektet innehåller även andra typer av seismiska mätningar).

De vanliga använda metoderna för att tolka seismiska data är inte tillräckliga för att avbilda den interna strukturen i reservoaren, så jag har istället använt en speciell matematisk transform (Continuous Wavelet Transform) för att med hög upplösning studera laterala variationer i frekvensinnehållet för den reflekterade seismiska signalen. Resultaten visar detaljer av de sandkroppar som uppträder inom Stuttgartformationen. Tekniken har också gjort det möjligt att upptäcka och avgränsa resterande volymer av den naturgas
som tidigare lagrades i formationen, vilket var mycket viktigt ur säkerhets-
synpunkt inför den borrhning som har utförts innan gasinjektionen.

För att avgöra om det är möjligt att upptäcka en seismisk respons av den
injekterade gasen konstruerades en datormodell för de fysikaliska egenska-
per av berggrunden som påverkar den seismiska responsen, d.v.s. de elastis-
ka egenskaperna och densiteten. Därefter simulerades responsen av den in-
jekterade gasen med hjälp av två olika typer av finitdifferensmodellering.
Den första är en s.k. 1-dimensionell elastisk modellering, där berggrundens
egenskaper endast antas variera med djupet, men där modelleringen tillåter
både P- och S-vågor. Den andra typen är en 2-dimensionell akustisk modell-
lering, där även laterala variationer i de fysikaliska egenskaperna är möjliga,
men där endast P-vågor tillåts. Resultaten av de olika modelleringarna visar
att den seismiska responsen från den injekterade gasen bör vara möjlig att
upptäcka trots heterogena förhållanden i reservoaren samt olika former av
bakgrundsbrus som kan förväntas störa de seismiska mätningarna. En kom-
plicerande faktor är att den injekterade gasen inte bara påverkar amplituden
av de reflekterade signalerna, utan även påverkar ankomstsiderna, eftersom
den seismiska hastigheten i berggrunden förändras av gasen. Jag har använt
en metodik som registrerar de lokaliserad-likhets bilderna för att kunna isole-
ra amplitudvariationer i reservoar från amplitudvariationer på grund av tids-
skift under reservoar. Jag har också visat att det är användbart att studera
variationer i den akustiska impedansen (produkten av P-våghastighet och
densiteten) gentemot variationer i Poissons kvot. Ett användningsområde är
att särskilja sand innehållande gas från sand innehållande salthaltigt grund-
vatten.

Sammanfattningsvis anser jag att resultaten som presenteras i avhandling-
en har gett viktig information om hur koldioxiden kan spridas i reservoaren
samt ökat förståelsen för hur spridningen kan följas med hjälp av de seismis-
ka mätningarna.
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I commence with the name of God – in whom all excellences are combined and who is free from all defects. The Compassionate – One whose blessings are extensive and unlimited. The Merciful – One whose blessings are inherent and eternal.

Thanks God for giving me everything I have and thanks God for not giving me what I should not have, thanks God for granting me the opportunity of trying for better understanding, thanks God for blessing me to meet good friends, colleagues and teachers and thanks God for having a lovely, kind and supportive family. I do not believe in fate and chance and I do not think I deserve what God has given me either, but I do believe in God’s endless mercy. I think it is easy to thank God, as soon as you feel you should thank him then he will hear you. You do not need to find appropriate words which worth it; he knows what is in the deepest level of your heart, while I am not sure if my words can express how I am grateful of many great people who have taken part in what I am now.

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