The accumulation of CO\textsubscript{2} in the atmosphere is considered to be the main reason for the global warming effect. The emissions can be reduced substantially by capturing and storing the CO\textsubscript{2}. The CO\textsubscript{2}SINK project was Europe’s first onshore project for the geological storage and monitoring of CO\textsubscript{2}. This project started operation near the town of Ketzin, Germany in the North East German basin in April 2004 and has continued as the CO\textsubscript{2} MAN project since April 2010. The main focus of the project was to develop the basis for Carbon Capture and Storage techniques by injecting CO\textsubscript{2} and monitoring of CO\textsubscript{2} in a saline aquifer in order to develop confidence for future geological storage of CO\textsubscript{2} in Europe.

In September 2004, a pilot seismic survey was performed in order to determine the necessary parameters for the conduction of a later 3D baseline seismic survey. The pilot survey was performed along two perpendicular profiles near to the CO\textsubscript{2} injection site. Pseudo 3D and 2D reflection seismic data were acquired. The results from 2D processing of the data contributed to planning of the 3D baseline survey. In this study the pseudo 3D data from the pilot seismic reflection survey is used to perform 3D processing for the first time. A significant part of the study is the correlation of results with the 3D baseline seismic survey and borehole data. All significant horizons, possible faults and traces of remnant gas were identified. Correlation with the 3D baseline, integration with the borehole data and time/depth contour maps showed good agreement with the 3D baseline survey and well log data.

Low fold data, acquisition geometry, time shifts and source generated noise produces severe distortion in the data. Due to these limitations it was difficult to obtain good quality images. Careful processing that involved static corrections and more accurate velocity analysis were the key steps for successful imaging. These results were combined with bore-hole information for an integrated interpretation.
3D Processing of Seismic Data from the Ketzin CO$_2$ Storage Site, Germany

Jawwad Ashraf Qureshi

Handledare: Christopher Juhlin
Abstract

The accumulation of CO₂ in the atmosphere is considered to be the main reason for the global warming effect. The emissions can be reduced substantially by capturing and storing the CO₂. The CO₂SINK project was Europe’s first onshore project for the geological storage and monitoring of CO₂. This project started operation near the town of Ketzin, Germany in the North East German basin in April 2004 and has continued as the CO₂MAN project since April 2010. The main focus of the project was to develop the basis for Carbon Capture and Storage techniques by injecting CO₂ and monitoring of CO₂ in a saline aquifer in order to develop confidence for future geological storage of CO₂ in Europe.

In September 2004, a pilot seismic survey was performed in order to determine the necessary parameters for the conduction of a later 3D baseline seismic survey. The pilot survey was performed along two perpendicular profiles near to the CO₂ injection site. Pseudo 3D and 2D reflection seismic data were acquired. The results from 2D processing of the data contributed to planning of the 3D baseline survey. In this study the pseudo 3D data from the pilot seismic reflection survey is used to perform 3D processing for the first time. A significant part of the study is the correlation of results with the 3D baseline seismic survey and borehole data. All significant horizons, possible faults and traces of remnant gas were identified. Correlation with the 3D baseline, integration with the borehole data and time/depth contour maps showed good agreement with the 3D baseline survey and well log data.

Low fold data, acquisition geometry, time shifts and source generated noise produces severe distortion in the data. Due to these limitations it was difficult to obtain good quality images. Careful processing that involved static corrections and more accurate velocity analysis were the key steps for successful imaging. These results were combined with bore-hole information for an integrated interpretation.
Most of the fundamental ideas of science are essentially simple, and may, as a rule, be expressed in a language comprehensible to everyone”

(Albert Einstein)

Dedicated to my Wife Amna, daughter Zoya and my family
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<td>CO$_2$ Storage by Injection into a saline aquifer at Ketzin</td>
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<td>CMP</td>
<td>Common Mid-Point</td>
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<td>3D</td>
<td>Three-dimensional</td>
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Introduction

The world is facing many challenges due to global warming and the emission of CO₂ into the atmosphere is believed to be one of the main reasons. During the industrial era, fossil fuel has been the major energy source. The burning of fossil fuel results in emission of CO₂ gas. The concentration of CO₂ reached a level of 389 ppm in September 2011. [iii] A figure of 350 ppm or less is considered to be necessary to limit temperature increases. Until the availability of alternate energy sources, Carbon Capture and Storage (CCS) may contribute significantly to reduce CO₂ in the near future. [iv] There are many ways of reducing CO₂ emission, but geological sequestration is likely to prevent emission of a large quantity of CO₂ over a short time. The capture and geological storage of CO₂ has opened new venues to mitigate the effects of CO₂ emission. At the same time this idea faces many different challenges, including characterization of the target reservoir, developing a trained workforce and the most critical aspect is to get the confidence of regulators and the public. [v]

The geological storage of different gases and injection of CO₂ to enhance the recovery of hydrocarbons has been in practice for decades and these have paved the way to CO₂ sequestration.

CO₂ is captured from the main emission sources, transported and then injected at high pressure into geological formations (Figure 1.1).

At high pressure CO₂ behaves like a liquid. Some CO₂ reacts with rock materials to form carbonate minerals and hence provides a permanent storage. Non-reactive CO₂ is permanently stored in the reservoir formation that is covered by an impervious cap rock. Major geological formations suitable for storage have been identified deep under the earth's surface. These are depleted oil and gas reservoirs, coal beds and saline aquifers that are found in the sedimentary basins all over the world. [vi]
The depleted oil and gas fields and deep saline formations are believed to be the best storage rock for CO₂. Deep saline aquifers have higher potential volume for CO₂ storage than depleted oil and gas fields. The fact that CO₂ occurs naturally in the earth and has been stored over geological time scales, improves the credibility of deep underground storage of carbon dioxide. The geological reservoir for CO₂ storage must have the ability to hold CO₂ and there should be no possible lateral migration or leakage. More than 10 small and large projects have been serving this purpose for the last ten years. On the basis of gained experience, new techniques have been developed and improvements in operations for injection and monitoring have been achieved. The main concern about CO₂ sequestration is to establish its acceptability as a safe and reliable method.

Injection monitoring is necessary to evaluate the feasibility and reliability of CO₂ storage in subsurface formations. There are various direct and indirect ways for monitoring. In direct methods, monitoring wells provide the necessary information while indirect methods involve imaging of the subsurface using different geophysical techniques like 3D and Pseudo 3D seismic imaging, Vertical Seismic Profiling and time lapse seismic analysis. These available methods have proven useful for tracking CO₂ and building confidence for large scale CO₂ sequestration with public acceptance.
1.1. CO$_2$SINK project: A climate change mitigation study

Statistical analysis shows a temperature increase of 0.76 °C in the average global annual temperatures in the last 150 years. [iii] The accumulation of the greenhouse gases in the atmosphere is the accepted reason. CO$_2$ is principally the major gas responsible for the greenhouse effect. More consumption of fossil fuels contributes primarily to the increase of CO$_2$ emissions. The concept of CO$_2$ capture and storage has become an effective potential response to global warming.

CO$_2$ SINK was the first European onshore project and was launched in April 2004. [viii] This project involves both applied and theoretical studies related to subsurface storage of CO$_2$.

Following were the main objectives of the project:

a) To enhance the knowledge of science and different practical processes related to underground storage of CO$_2$.

b) To develop trust towards future European geological storage of CO$_2$.

c) To get first-hand knowledge, experience and expertise that can be utilized in developing work-flows and standards for future geological storage of CO$_2$.

To achieve the above objectives a study site was selected near the city of Ketzin, west of Berlin, Germany (Figure 1.2)

![Figure: 1.2 Location map of Ketzin site (from S.H Kazemeini et al., 2008).](image-url)
The site had been in use for natural gas storage from 1970 until 2000. The existence of infrastructure of the abandoned gas storage operation was an important consideration in selecting the site.

Saline aquifers are the target reservoirs. Saline aquifers have no commercial importance so they are generally less characterized. A comprehensive risk evaluation was part of this project.

A 3D baseline seismic survey was an important element in the pre-drilling phase. The 3D baseline reflection seismic survey was conducted in September 2005 with the following key objectives:

a) Provide a baseline for comparison before and after injection.

b) Determine the structural geometry for flow pathways within the reservoir.

c) Provide detailed subsurface images near the injection borehole for the drilling operations.

During and after injection of CO\textsubscript{2}, a broad monitoring was performed with the help of wide range geophysical and geochemical techniques.

1.2. Previous Work

A pilot seismic reflection survey was conducted in September 2004 as a preparatory work for the conduction of the 3D baseline seismic reflection survey at the site. The involved partners were Uppsala University, GFZ Potsdam, Vibrometric and source contractors.

The aims of the pilot study included:

a) Test different acquisition parameters.

b) Evaluate the seismic response of the Ketzin site.

c) Acquisition of 2D and pseudo 3D seismic reflection data.

d) Create a data base to guide the planning of the 3D baseline seismic survey.

The results from the 2D seismic data processing of the pilot survey contributed in planning the 3D baseline survey. The injection of CO\textsubscript{2} started in June 2008 and until February 2011 around 45,000 t of CO\textsubscript{2} had been injected into the saline aquifer.
1.3. **Motivation and objectives of the Thesis**

3D processing of the pilot reflection seismic data for the first time and its integration with well log data are the main motivation for this thesis.

The principle objectives of the thesis study were as follows:

a) 3D processing of the seismic reflection data that was acquired during the pilot survey.

b) Site characterization.

c) Tie Seismic data and well.

d) Marking of the key horizons.

e) Generate time and depth contour maps.

f) Correlation with a synthetic seismogram.

g) Correlation with results from the 3D baseline seismic survey.
Site Geology

The Ketzin site is partly located in the Northeast German Basin (NEGB) which is part of the Permian basin system (Figure 2.1) that stretches from the southern North Sea across Denmark to the Netherlands and northern Germany to Poland. In early Permian, the basin developed by rifting and then subsidence with deposition of Permian clastic sediments and Upper Permian Zechstein salt. Since the early Triassic there were several deformation phases, but the NEGB stayed meta-stable with some development of pillows, walls and diapirs, causing the deformation of the Mesozoic overburden into a system of anticlines and synclines.

Figure: 2.1 The location map of the Ketzin site (http://www.eg.geoscienceworld.org).
The Ketzin site is located in the eastern part of the Roskow-Ketzin double anticline which formed above an elongated salt pillow which is present at a depth of 1500-2000 m (Figure 2.2).

Figure: 2.2 The location of the Ketzin and Roskow Anticlines (http://dc110.gfz-potsdam.de).

The axis of the anticline strikes NNE-SSW with a 15° gentle dip of its flanks. The structurally deformed formations of Triassic and Lower Jurassic are present directly above the salt. It is evident from stratigraphic successions that gentle uplift of the Ketzin anticline was started in the Triassic and a major phase of uplift were at 140 Ma that resulted in erosion of the Lower Jurassic, the Middle and the Upper Jurassic formations (Figure 2.3).
The second major uplift phase was at 106 Ma that caused erosion of the Lower Cretaceous rocks. As the area is part of the structural high, no deposition took place during Upper Cretaceous era. \[vii\] The presence of Oligocene transgressive sediments above the Jurassic sediments remained the same during anticlinal uplift. These are the clear first evidence of regional wrapping of the central parts of the Northeast German Basin and this trend is continuing till present. \[xii\]

The site has a sedimentary environment and it has a system of reservoirs and caprock similar to hydrocarbon geology.

Figure: 2.3 Geological formations inferred from borehole Ktzi 163/69 with main possible horizon are marked.  \(\text{(http://eg.geoscienceworld.org)}\)
The Ketzin area has almost flat topography with some isolated hills of Quaternary sands at local hills with an average relief of 30 m except for one place along profile 1 at approximately Inline 1300 there is one hill with an elevation of 59 m. These quaternary sediments have an average thickness of 50 to 80 m. The Quaternary and sandy Tertiary units are the main fresh water aquifers. The target reservoir at Ketzin is lithologically heterogeneous upper Triassic Stuttgart Formation. It is on average 80 m thick and it lies at a depth of 500-700 m (Figure 2.3).

The Stuttgart Formation has sandy channel facies rocks of good reservoir properties and muddy-flood-plain-facies rocks of poor reservoir quality. It has a system of incised-valley deposits, where amalgamations of individual fluvial channels have created sandy channel belts. The channels have flood-plain-facies or playa-type facies sediments. The thickness of sandstones for the Stuttgart Formation lies between 1 m to 30 m where sub-channels are stacked with widths up to several hundreds of meters. The Weser and Arnstadt formations form an approximately 210 m thick caprock section above the Stuttgart Formation (Figure 2.3). They mostly comprise claystone, silty claystone and anhydrite. At the depth of 500 to 700m, the top of the Weser Formation has a 10-20 m thick anhydrite layer which is known as the Heldburg-Gips. This high impedance anhydrite layer is imaged as a clear reflection on the vintage regional seismic surveys and is known as the K2 (Keuper) reflector (Figure 2.3). K2 is an important marker horizon for the CO₂SINK project since it lies almost 80 m above the top of the target Stuttgart Formation. This reflector has been clearly marked in vintage seismic surveys and the baseline 3D seismic data. Other important reflection horizons (Figure 2.3) are: 1) the T1 horizon, the transgressive phase of the Cenozoic or Base Tertiary; 2) the L4 horizon at the base of the Hettangian, near the top Triassic); 3) the K3 horizon, the top of the Grabfeld Formation that is close to the base of the Stuttgart Formation.

Jurassic sandstones in the form of a multi aquifer system interbedded with mudstone, claystone and siltstone are present above the Arnstadt Formation, at a depth of 250-400 m. These were used for industrial storage of natural gas until the year 2000. This multi aquifer system is covered by 80-90 m thick Tertiary clay (Rupelton). This block of clay acts as an effective caprock for the underlying Jurassic sediments. This clay separates the saline waters in the deeper aquifers from the non-saline groundwater in shallow Quaternary aquifers. Local erosion of the Rupelton aquitard at some locations causes saline water to ascend and get mixed with the fresh waters of the shallow aquifers.
Wells and production data from the former gas storage facility inferred a W-SW-E-NE to E-W trending fault over the Ketzin anticline and later the comprehensive results of the 3D baseline survey confirmed the presence of a fault system, CGFZ. The Central Graben Fault Zone (CGFZ) of discrete normal faults is present in the northern part of Ketzin. This fault zone was created by the extensional faulting across the central part of Ketzin during 106-140 Ma. There are some indications of a strike-slip component in the faulting. The edge detection maps from the 3D baseline seismic survey clearly mark (Figure 2.4) the location and extent of these faults in the Jurassic formation with throws of 20-30 ms. At a few places these faults were traced to the Stuttgart formation as well as underneath it.

![Figure 2.4 Time horizon maps of the K2 (on the left) and near base Tertiary T1 (on the right) with white lines marking the mapped faults.](image)

(Figure from [viii])
Theory

3.1 Seismic Methods

In the early 20th century, the seismic reflection method was introduced by the Geophysical Research Corporation, U.S. Since then, a lot of progress has been made in improving the efficiency of seismic methods and equipment. The Common Mid Point method was introduced and at the same time the performance of source and receivers was upgraded. In the 1970's the development of the 3D seismic method made a breakthrough in improving interpretations. The attributes of seismic methods make them a chosen tool for reservoir characterization and monitoring. [xvi] The reflection seismic method is the most extensively used geophysical exploration method. This method involves the analysis of the time and amplitude of acoustic waves which are generated by a seismic source and recorded after reflection from an acoustic interface.

A conventional data processing sequence is [xvii]:

- Preprocessing
- Deconvolution
- CMP sorting
- Velocity analysis
- Residual Static corrections
- NMO correction and Stacking
- Post stack processing
3.1.1. Preprocessing

Initially raw data are demultiplexed and converted into a convenient format that can be used throughout for processing. Traces are edited which involves removal of noisy traces and polarity reversal of traces where required.

To compensate for the effect of spherical divergence, a gain recovery function is applied to recover the amplitude. To reduce noise sometimes a wide band pass filter is applied before deconvolution. Field geometry is created on the basis of survey information. The coordinates of shot and receiver locations are stored in trace headers. As geometry is the basis of future processing so everything is carefully done and the observer’s log is also considered for making any corrections or changes. Elevation statics are applied to bring all traces to a common datum.

3.1.1. Deconvolution

The earth has rock layers with different physical properties and lithologies. Each rock layer is characterized by its density and velocity which a seismic signal propagates through. The product of density and velocity is called impedance. The difference in impedance values for adjacent layers causes the reflection of seismic waves. These reflected waves carry with them, the earth response convolved with the seismic wavelet. Deconvolution compresses the wavelet components of the source, recording filter, surface reflection and receiver, thus, leaving behind an impulse response of the earth.

Optimum Wiener filtering based deconvolution separates the seismic wavelet from the recorded seismic trace by compressing the wavelet and, hence, increases the temporal resolution of seismic data. Assumption for Deconvolution: Vertically incident, stationary, minimum-phase source wavelet and free of noise white reflectivity series.

After deconvolution, the data often need filtering with a wide band pass filter as deconvolution enhances both the high frequency noise and signal. It is desirable to do some trace balancing after deconvolution as well.
### 3.1.2. CMP sorting

Before further data processing, the data are transformed from shot-receiver domain to Common Mid Point/Common Depth Point domain. For horizontal reflectors with no lateral variations in velocity, CMP and CDP have the same meanings. Every trace is assigned to a relevant midpoint. The traces associated to a particular midpoint are stacked together, making a CMP gather.

Different types of gathers that can be performed:

a) Common-Shot gather

b) Common-Receiver gather

c) Common Midpoint/Depth gather

d) Common-Offset gather

![Diagram](attachment:image.png)

Figure: 3.1 (a) Stack chart, s- shot, g-geophone, (y, h) are midpoints offset coordinates and every dot represents a seismic trace. (b): (1) Common shot-gather, (2) Common-receiver gather, (3) Common-mid-point gather and (4) Common-offset gather, E represents midpoint, E’ shows depth point and x is the cable length. *(From Yilmaz, *Seismic Data Processing, Volume 2).*

Reflected signal and coherent noise like multiples, guided waves and ground roll have different stacking velocities. Coherent noise is generally removed as a result of CMP stacking.
3.1.3. Velocity Analysis

By performing velocity analysis we seek for a velocity that makes the events horizontal with reflections aligned. For a single correct value of velocity, we get flat reflections. For low estimated velocity, the reflections curve upwards; over-corrected. For too high a velocity, reflection curves are downward; under-corrected.

Figure: 3.2 (a) Without velocity correction; (b) with correct velocity; (c) over-corrected; (d) under-corrected (http://www.bairdpetro.com/pdf_files/p58-62.pdf).

For selected CMP gathers, velocity analysis is performed in terms of a velocity spectrum. This velocity spectrum is a function of two-way zero offset time and velocity. Using this velocity spectrum, specific values for velocity and time are picked which give the maximum coherence.

Velocity analysis is usually repeated after an application of residual statics corrections to further improve the velocity picks for stacking. [xvi]

3.1.3.1. NMO velocity

It is the velocity of the medium above the reflector divided by the cosine of dip angle. [xvii]
There is a difference between $V_{\text{stack}}$ and $V_{\text{rms}}$.

- $V_{\text{stack}}$: The velocity that gives best stacking results.
- $V_{\text{rms}}$: The real RMS- velocity of the layer.

Both velocities are equivalent for small offset and horizontal layers. For a dipping reflector $V_{\text{stack}}$ is not equal to $V_{\text{rms}}$.

Velocity analysis is the basis of NMO corrections. The calculated velocities are used in NMO corrections to align the reflections of a CMP gather before stacking.

### 3.1.3.2 Velocity determination

Different ways to determine velocity are as follows:

- $(t^2-x^2)$ analysis
- Constant Velocity Panels (CVP)
- Analysis of velocity spectra

#### 3.1.3.2.1 $(t^2-x^2)$ Analysis

This analysis is based on the fact that the outcome of the move-out expression for $t^2$ and $x^2$ is a linear event. $V^2$ can be calculated from the slope of the plotted values of $t$ and $x$. The data quality affects the velocity picking and the precision of this method depends upon the signal to noise ratio.

Figure: 3.3 $(t^2 - x^2)$ velocity analysis (http://www.bairdpetro.com/pdf_files/p58-62.pdf).
3.1.3.2.2 Constant Velocity Panels – CVP

For different constant velocities, NMO corrections are applied to CMP sorted data. After comparison of results, those velocities are picked for which the hyperbolas for a certain reflectors are flat.

3.1.3.2.2.1 Constant Velocity Stack – CVS

This is calculated for several CMP gathers with NMO applied and the data are stacked in a panel for different stacking velocities. A velocity that gives the best stacking response for a selected event is picked directly from the CVS panel. This method is quite functional for areas with complex formations.

3.1.3.2.3 Velocity-Spectrum

This method is based on the cross-correlation of the traces in CMP gathers. Lateral continuity of stacked events has no role in this method. A velocity spectrum is generated by plotting velocity ranges against the two way travel time. This method can sometimes resolve multiple reflection issues.

*Semblance* is one of the different methods for plotting the velocity spectrum.

Factors affecting Velocity analysis:

- Depth of reflector
- Length of spread
- Data bandwidth
- Signal to Noise ratio
- Velocity sampling
- Static correction
- Reflector dip
- Number of traces and stacking fold
3.1.4. NMO Correction

NMO is the travel time difference at a zero offset and at a given offset. The velocity that corrects this time discrepancy is called the Normal Moveout Velocity. NMO velocity for a single horizontal reflector is the velocity of the medium above the reflector. For a dipping reflector, the NMO velocity is the velocity of the medium divided by cosine of dip angle. For short offsets, the rms velocity down to the boundary under consideration is the NMO velocity for horizontally layered earth.\[^{xvi}\]

Near-surface velocity variations cause static time shifts and these cause the reflection travel times to deviate from a perfect hyperbola. This deviation can be serious for large surface elevation changes and when the weathering layer varies laterally.\[^{xvi}\] Stacking velocity depends on dip angle. NMO decreases with depth and then increases with increase in the offset. NMO has small values for large values of velocity.\[^{xvi}\]

To understand the mathematics behind the NMO corrections, consider a single horizontal layer (Figure 3.4)

![Figure: 3.4 NMO geometry for a single horizontal reflector.](image)

For a midpoint M, the travel time \( t(x) \) from shot position S to depth point D and then to receiver G can be calculated using the following travel time equation:

\[
t^2(x) = t^2(0) + \frac{x^2}{v^2}
\]

(1)

The above equation gives a hyperbola in a plane of offset versus two way travel times.
If time for a specific time at a given offset $t(x)$ and time for a zero offset $t(0)$ are known then the velocity can be calculated. After the estimation of the velocity, the effect of the offset can be corrected from the travel times.

$$\Delta t_{NMO} = t(x) - t(0)$$  \hspace{1cm} (2)

$$t(0) \left[ \left( 1 + \left( \frac{x}{c_{NMO}(0)} \right)^2 \right)^{1/2} - 1 \right]$$  \hspace{1cm} (3)

On the basis of velocity analysis, the NMO correction removes the offset effect and leaves the events flat. \[^{[xvi]}\]

![Figure: 3.5 a) Before NMO correction (b) After NMO correction.](image)

Estimation of NMO for a medium with horizontal iso-velocity layers can also be done. Every layer has a specific thickness that can be characterized by two way zero-offset times. For $N$ number of layers, the layers have interval velocities $V_1, V_2, \ldots, V_n$. The travel time from source to depth and then back to receiver can be calculated by the equation. \[^{[xviii]}\]

$$t^2(x) = C_0 + C_1x^2 + C_2x^4 + C_3x^6 + \ldots,$$  \hspace{1cm} (4)

Where $C_0 = t^2(0)$, $C_1 = 1/v_{rms}^2$, and $C_2, C_3, \ldots$, are the functions which depend upon the thickness of the layer and the interval velocity. The rms velocity at depth $D$ for the reflector can be estimated as
For a small spread approximation, equation 4 can be given in a short form as:

\[
\nu_{rms}^2 = \frac{1}{c(0)} \sum_{i=1}^{N} y_i^2 \Delta t_i(0) \quad (5)
\]

It can be seen from (1) and (5) that the root-mean-square velocity is equal to the velocity essential for NMO corrections for horizontally stratified medium. \[xvi\]

NMO corrections result in an artificial increase in wavelength for large offsets. The stretch-mute is used to truncate the stretched part and hence reduce the stretching effect (Figure 3.6.).

![Figure 3.6 At time t, a signal (a) is stretched to a signal (b) at time t' after NMO correction](http://www.bairdpetro.com/pdf_files/p58-62.pdf).

### 3.1.5. Residual static correction

At times the near surface velocity irregularities affect the Normal Move Out corrections and it is difficult to get a perfect hyperbola. The change in the lateral velocity of a complex structure causes static or dynamic shifts. Residual statics variations normally remain part of the data even after the application of corrections for variations in the weathering layer and elevation. If they become part of the stack then it may cause dim spots along the reflection and a misleading structure. \[xvi\]

Residual statics corrections are required as the field statics and datum corrections do not completely compensate for the effects of deviations in near surface velocity. The surface-
consistent solution is a reflection-based statics correction that works on the differences in arrival times between traces and it is useful for short wavelength static components.

Refraction static methods are based on the absolute arrival time of first breaks and it effectively compensates for the long wavelength variations. Therefore residual statics corrections are calculated and applied to CMP before stacking. [xvi]

The Residual Static Correction is applied to NMO corrected CMP gathers. It is performed in a surface consistent way to remove the residual shifts and improve the quality of stack. The calculated residual corrections are applied to CMP gather without NMO corrections. Finally, the CMP gathers is stacked with improved coherence in reflections as well as elimination of false structure. Usually velocity analysis is to be repeated after residual statics correction in order to update the velocity picks. [xvi]

Surface consistent residual statics is based on an assumption that the static shifts are the time delays due to source and receiver location at the surface. A model is created with move-out corrected travel times from a source to reflectors and then back to receiver. [xvii]

The observed travel time is decomposed into different components like the residual static time shift term associated with the source and receiver stations, the difference in two way travel time at a reference CMP location, the structural term and the residual moveout term with a coefficient. The sum of least-squares error energy between the observed and modeled times is reduced using a least-squares approach.

Residual statics corrections have three steps:

1. Time values picking by pilot trace scheme. The picking phase defines the efficiency extent of residual static corrections. The choice of correlation window and signal quality plays a vital role.

2. Least-square decomposition of time into source and receiver statics, residual moveout term and structural term.

3. Source and receiver terms are applied to pre-NMO CMP gathers.

For poor quality data, residual statics corrections are applied twice. The first time is meant to improve the signal so that the second pass should remove the remaining residuals. [xvi]
Data Acquisition

In September 2004, a pilot survey was conducted and reflection seismic data were acquired along two perpendicular profiles of length of 2.4 km each (Figure 4.1). Those two profiles were close to the proposed CO$_2$ injection site. 2D and Pseudo 3D data were acquired. An overview of the acquisition parameters is provided in Table 4.1.

Table: 4.1. The detailed acquisition parameters of Pseudo 3D seismic data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey type</td>
<td>Pseudo 3D</td>
</tr>
<tr>
<td>Sources</td>
<td>Weight drop</td>
</tr>
<tr>
<td>Type</td>
<td>Impact EWG III</td>
</tr>
<tr>
<td>Profile length</td>
<td>2.4 km</td>
</tr>
<tr>
<td>Number of stations/line</td>
<td>113-115</td>
</tr>
<tr>
<td>Number of shots/station</td>
<td>5-8</td>
</tr>
<tr>
<td>Geophones</td>
<td>28 Hz single</td>
</tr>
<tr>
<td>Number of receiver</td>
<td>239</td>
</tr>
<tr>
<td>Receivers spacing/channel</td>
<td>20 m</td>
</tr>
<tr>
<td>Recording system</td>
<td>SERCEL 408 system</td>
</tr>
<tr>
<td>Recording length</td>
<td>3 s</td>
</tr>
<tr>
<td>Sampling interval</td>
<td>1 ms</td>
</tr>
</tbody>
</table>
Figure: 4.1 Base map shows Pilot survey by black dashed lines and 3D baseline survey by red solid lines. The deep well Ktzi 163/69 can also be seen at Line 1 of Pilot survey. Based on vintage seismic lines, isodepth lines to near top of the Stuttgart Formation are marked by contours.

Line 1 (N-S) was an agricultural road and Line 2 (E-W) had hard soil compressed by heavy equipment. For the Pseudo 3D seismic data acquisition, seismic responses on both perpendicular profiles were measured at the same time. Sources activated on Line 1 and responses were recorded on Line 1 and Line 2 as well and vice versa.
Shooting was performed at all stations and 239 channels (fixed spread) were used for recording. Geophones of 28 Hz were planted 0.2 m deep holes. True coordinates for source and receiver points were stored on raw SEG files then recorded onto disks. Only some locations were skipped due to the presence of buried cables. It should be mentioned that partly heavy rain, wind and traffic on the roads close to the profiles affected the recording and data quality.

The results from vintage seismic reflection surveys and the 3D baseline seismic survey were really helpful to delineate the generic subsurface of the area. Many boreholes had been drilled in the area from 1960 to 1970 for the former natural gas storage. Ktzi 163/69 was one of those boreholes and it is located on the eastern part of Ketzin Anticline over profile 1 and can be seen in figure 4.2.

Figure: 4.2 The location of Ketzin and Roskow Anticlines, Deep borehole well Ktzi 163/69 is marked at Ketzin anticline. (http://eg.geoscienceworld.org).
Data processing

The Processing sequence was almost the same as the one used for the 3D baseline seismic survey. Simple processing steps were followed to avoid any artifacts. Processing was carried out using Globe Claritas™. As the target horizon for the CO₂ SINK project was at a depth of 700m so the focus was kept on the upper 1.5 s.

Figure: 5.1 The fold coverage for the Pilot survey. Generally good fold along Line 1 & 2 and very low fold elsewhere.
Firstly the SEGD data were converted into SEG-Y format. Header values were adjusted and survey information was added. Vertical diversity stacking was performed as there were multiple shootings at the same location. It helped to increase the signal quality and later geometry was extracted. The extracted geometry was binned (12 m × 12 m) into a grid of Inlines and Crosslines. The rectangular grid covered the 3D baseline survey and the Pilot seismic reflection survey so that correlation could be performed later. The fold was generally variable throughout the profiles. Along the profiles the fold was good while elsewhere it was very low (Figure 5.1). Such fold variations negatively affected the first break picking, calculations of refraction statics, velocity analysis and finally the stacked results. So processing was done with great care. After binning, the geometry was added to the SEG-Y data with CDP information.

The overall signal to noise ratio for Line 1 was lower than Line 2 (Figure 5.3) particularly at the northern part of the line. The signal quality dropped due to attenuation of seismic waves by a thick build up of Quaternary sand. Reflections with direct P-wave, ground rolls and source-generated noise can be easily seen in shot gathers (Figure 5.3).

![Figure: 5.2 Base map on Pilot survey. Shot locations along Line 1 & 2.](image)
Figure: 5.3 Noise affected raw shots with visible reflections. Seismogram of Line1 is on left side and seismic response of Line2 is on right side.
A summary of processing steps is given in table 5.1.

Table: 5.1. Processing work flow

<table>
<thead>
<tr>
<th>Step</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Read raw SEGD data</td>
</tr>
<tr>
<td>2</td>
<td>Vertical diversity stack</td>
</tr>
<tr>
<td>3</td>
<td>Extract and apply geometry</td>
</tr>
<tr>
<td>4</td>
<td>Delete bad traces and reverse trace polarity</td>
</tr>
<tr>
<td>5</td>
<td>Pick first arrivals for offset range: 300-500 m</td>
</tr>
<tr>
<td>6</td>
<td>Band-pass filter: Butterworth 7-14-120-200 Hz</td>
</tr>
<tr>
<td>7</td>
<td>Air wave mute</td>
</tr>
<tr>
<td>8</td>
<td>Surface consistent deconvolution: filter 120 ms, gap 16 ms, white noise 0.1%</td>
</tr>
<tr>
<td>9</td>
<td>Ground roll mute</td>
</tr>
<tr>
<td>10</td>
<td>Deconvolution: Filter length 150 ms, Gap length 16 ms and white noise 0.1%</td>
</tr>
<tr>
<td>11</td>
<td>Spectral equalization 20-40-90-120 Hz</td>
</tr>
</tbody>
</table>
| 12   | Band-pass filter:  
0-300 ms: 15-30-85-125 Hz  
350-570 ms: 14-28-80-120 Hz  
620-2000 ms: 12-25-70-105 Hz |
| 13   | Zero-phase filter |
| 14   | Refraction statics: datum 30 m, replacement velocity 1800 m/s, \( V_o \) 1000 m/s |
| 15   | Trace balancing using data window |
| 16   | Velocity analysis. Every 20th CDP in the inline and cross line direction |
| 17   | Residual statics |
| 18   | NMO corrections: 60% stretch mute |
| 19   | Trace balance: 0-1000 ms |
| 20   | FX-Deconvolution: Inline and Crossline directions |
| 21   | Final Stack |
It can be seen in figure 5.3 that the near offset traces were affected by noise and signal quality for far offset was not good. For the calculation of refraction statics and the estimation of near surface structure first breaks were picked for the offset range 300-500 m. Source generated noise and shallow reflections, complex near surface effects and time shifts were the faced challenges. Some first arrivals were masked with noise. Picking was done manually and wrong picks were corrected with the help of LMO and the flattening utility of the software was used as well. Wrong picking could reduce the effectiveness of refraction statics drastically so every possible care was made while picking the first arrivals.

Refraction statics plays a vital role in processing. It improves the signal to noise ratio and it always contributes to a good final stack. 3D refraction statics were calculated using a two layer model. The velocity for the upper layer was 1000 m/s and 1800 m/s for the lower half space. The rms value for the refraction statics was under 2. The improvement in coherence of source gathers and receiver gathers was visible by applying the refraction statics.

To improve the resolution and to balance the spectrum, surface consistent deconvolution was performed on shot gathers and receiver gathers. Common-shot gathers and common-receiver gathers showed relative static shifts from one shot to another and from one receiver to another. It was helpful in estimating the amount of shift while determining the residual statics. Later Bandpass filtering truncated some of the ground roll and air wave removal further improved data quality (Figure 5.4).
Figure: 5.4 Same shot gathers after deconvolution, band pass filtering, noise and mute.
Deconvolution was carried out in order to make reflections more prominent and increase resolution. Ground roll was muted. Ground roll was not muted to zero time in order to avoid further decreases in fold. Some ground roll got stacked into the final volume at some places. After preliminary processing, the data were sorted into the CDP domain. All these efforts were made to condition the data for further processing. Stacked and un-stacked files were generated for velocity analysis.

The velocity analysis was performed before and after the calculation of residual statics. Velocity analysis was performed by picking velocities in constant velocity stack panels. Low fold coverage made it very difficult to perform an effective velocity analysis. For velocity analysis many Inlines were skipped due to no fold coverage. To perform velocity analysis, only 7 Inlines were available out of 61 Inlines. The CDP coverage for available Inlines was less than 20 and none of it was covering the entire time scale. It was impossible to mark out the continuity of any reflector throughout the seismic section. For that reason I had to do extrapolation for the part where I had no coverage. That situation created an immense chance of error. To reduce inaccuracy in velocity estimation, velocity analysis was revised and then improved more than 12 times. To avoid any jumps in the final velocity field, it was all carefully inspected using Constant Velocity Gather and Semblance. There was a smooth variation in the NMO velocity field later. To improve the effectiveness of velocity analysis, an average zero phasing filter was then applied to the initial stacked section. The 60% stretch mute truncated the first arrivals effectively. Later the residual reflection statics brought good coherency in reflections (Figure 5.5).

Figure 5.5 (a) Stack before residual statics, R1, R2, R3, R4 and R5 are the main five reflections from Tertiary, Sinemurian, Exter, Arnstadt and K2, respectively.
Figure: 5.5 (b) Stack after residual statics, all reflections became coherent and consistent.

Finally FX deconvolution was performed on the final cube in the time domain (Figure 5.6).

Figure: 5.6 One portion of the final stack with all possible reflections.
Results & Discussion

6.1 Interpretation

The subsurface is generally well imaged down to 700 ms. Poor images of the subsurface are present where the fold is low. At a few places there are visible reflections from the top Tertiary, from near top Triassic and from the near top Stuttgart formation.

Figure: 6.1.1 Map of Pilot survey. Crossline 1324 has been marked as CC.

Figure: 6.1.2 Interpreted seismic section of CC’ with all possible horizons marked.
A crossline 1324 has been selected near the junction of the two profiles. This part of the seismic survey is relatively better imaged due to good fold (Figure 6.1.1 and 6.1.2). On the basis of information from the borehole data (Figure 2.3) and correlation with the Baseline seismic data, the following reflection horizons were imaged in an un-migrated volume (Figure 6.1.2):

(1) Top/base Tertiary (2) Top Sinemurian (3) Top Exter (4) Top Arnstadt (5) K2.

A strong double reflection (trough-peak-trough) is a characteristic seismic response for the K2 horizon at the Top Weser formation and the near top Tertiary horizon. These horizons are widely and clearly imaged over the entire area with certainty. These formations are normally present throughout the North East German Basin. \[xvi\]

6.2 Remnant Gas

Ketzen site has been used for geological storage for town gas and later natural gas in the lower Jurassic formations from 1970 up until 2000. \[viii\] It is well understood that porous rock with even a small concentration of gas can effectively reduce the velocity of P-waves. \[xvii\] The seismic response of an aquifer with water is essentially different form an aquifer with an accumulation of gas. The results from the Baseline survey have shown the presence of residual gas below the Base Tertiary horizon. While keeping this information in mind, the seismic section is carefully investigated and along crosslines 1250, 1251 and 1252 possible signs of remnant gas are found in the form of bright spot in sandstones of upper Sinemurian age (Figure 6.2.1).

![Figure: 6.2.1 Seismic section of Crossline 1252 with bright spot in the top Sinemurian.](image-url)
A bright spot is evident from the seismic section of selected Crossline 1252 (Figure 6.2.1). This possibly is the indication of remnant gas accumulation as it is in good accordance with the wellbore-based gas distribution map from UGS (Figure 6.2.2). Seismic reflections are stronger with amplitude brightening. The gas-bearing layer can be seen in the Sinemurian sandstones under the base Tertiary (Figure 6.2.1). The degree of residual gas accumulation and its flow is unknown, but its presence is visible.

Figure: 6.2.2 Base map of Pilot survey (Left) with selected Crossline 1252 and possible sign of residual gas in terms of bright spot. The gas distribution map from UGS based on wellbore (Right) for the year 1999 (blue dotted lines) and maximum gas distribution (blue permanent lines) for the year 2004.

This region lies within the maximum gas distribution map provided by UGS for the year 1999 (Figure 6.2.2). The presence of bright spots adds confidence in marking the extent of the residual gas accumulation. Unfortunately it is not possible to track this gas or image the gas to other parts of the survey due to fold limitations.
6.3 Correlation with the Baseline survey

A correlation of the Baseline survey with the Pilot survey is one of the main objectives of the project. This helps to identify the similarities and differences between two regions. For this purpose an arbitrary line GG’ is selected along both surveys (Figure 6.3.1).

Figure: 6.3.1 Base maps for correlation of results from the Baseline survey and Pilot survey. An arbitrary line GG’ has been picked for possible correlation between two surveys.

The seismic section for the line GG’ displays the main horizons across the two surveys. The correlation of seismic sections from both surveys reveals a significant similarity and all the main horizons correlate very well and the results are consistent (Figure 6.3.2).

Figure: 6.3.2 Seismic sections for an arbitrary line GG’ displays main horizons across the two surveys.
6.4 Correlation with the Synthetic seismogram

A deep borehole Ktzi 163/69 lies along line 2 of the Pilot survey. It is one of the objectives of this thesis to tie this well with the seismic data. Due to the unavailability of the Density log and the Sonic log for shallow depths (from surface to depth of 680m), the Gamma ray log was used to generate the partly synthetic Sonic log extending from surface to total depth [xxiv]. This synthetic Sonic log matches with the lithology of the area (Figure 6.4.1).

Figure: 6.4.1 Stratigraphy of the borehole Ktzi 163/69 on left, the partly synthetic Sonic log with the Density log in middle and magnified part of the Sonic log that shows peak for the K2 horizon on right side.

Sonic log marks the top of K2 at depth of 570 m a.s.l and base at 582 m a.s.l. Seismic data also confirms the presence of K2 in terms of clear reflection. The Sonic log gives a relatively higher value for Anhydrite/Gypsum (70 μs/ft) than expected. This may be due to amalgamated Anhydrite or the limitations of the synthetic sonic log for that depth.

A synthetic seismogram was generated on the basis of the partly synthetic sonic log using the following parameters as given in table 6.4. The partly synthetic sonic log justifies the lithology of the area (Figure 6.4.1).
Table: 6.4 List of parameters used for the generation of synthetic seismogram.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelet</td>
<td>Ricker</td>
</tr>
<tr>
<td>AGC length (ms)</td>
<td>0.00</td>
</tr>
<tr>
<td>Frequency</td>
<td>30.00 Hz</td>
</tr>
<tr>
<td>Amplitude Scalar</td>
<td>1.00</td>
</tr>
<tr>
<td>Period</td>
<td>26.00</td>
</tr>
<tr>
<td>Number of Traces</td>
<td>10</td>
</tr>
<tr>
<td>Phase Rotation</td>
<td>0.00 degree</td>
</tr>
<tr>
<td>Multiples</td>
<td>None</td>
</tr>
</tbody>
</table>

For integration of seismic data with the synthetic seismogram, a line CC’ is picked along profile 2 of the Pilot survey and it is extended to the Baseline survey. This gives an opportunity to correlate the Pilot survey with the Baseline survey and integrate synthetic seismogram along the same line at the same time (Figure 6.4.2).

Figure: 6.4.2 Base map of both surveys with line CC’ along Line 2 of the Pilot survey and its continuation to the Baseline survey. The length of CC’ is almost 3.5 km. (i), (ii), (iii), (iv) are the four slices of seismic section for CC’.
The seismic section CC’ is from the west to east direction along CC’. Due to fold limitations some horizons are not imaged continuously. The image is sliced into four figures so as to present results in detail (Figure 6.4.3).

![Seismic Section CC'](image)

Figure 6.4.3 Seismic section of arbitrary line CC’, shows correlations between two seismic sections and integration of synthetic seismogram with seismic data.

Slice (i) of figure 6.4.2 shares the seismic section from both surveys and once again all horizons are in good agreement with each other. K2 horizon is picked with green marker. The K2 horizon shows a dipping trend in slices (ii), (iii) and (iv) of figure 6.4.2. The synthetic seismogram correlates well with the K2 horizon in slice (iv) of figure 6.4.2 and to some extent it justifies other horizons if the continuity of other horizons are extrapolated.
6.5 Time and depth contour mapping of the K2 horizon

The Stuttgart formation is the target formation for the geological storage of CO₂. K2 lies almost 80 m above the Stuttgart formation; it means that identifying the K2 horizon significantly marks the Stuttgart formation indirectly. Time and depth contouring of K2 demonstrates the Ketzin anticline. This can help to understand the subsurface geology of the area for future injection and monitoring at the site.

The time contouring of the K2 horizon (Figure 6.5.1) verifies the location of K2 in the time domain as marked in figure: 6.4.3. It is evident from the time and depth contour maps of K2 that the depth of K2 increases eastwards and southwards along the two surveys.

The depth of the K2 horizon inferred from the study of borehole Ktzi 163/69 (Figure 6.5.2/right) is in accordance with the depth contouring of the K2 horizon (figure 6.5.2/left). The depth of the K2 horizon is about - 570 m a.s.l.
Figure: 6.5.2 Depth contours of the K2 horizon (without Kelly bushing) on left and Stratigraphy of the borehole Ktzi 163/69 on right.

The depth contours mark the depth of K2 horizon around – 533 m a.s.l and when 37.4 m kb is added to this figure, we get depth of K2 at – 570 m a.s.l.
Conclusion

Data quality from the Pseudo 3D data is generally good for the high fold area and most of the 3D volume is imaged to 0.7 s. Traces of remnant gas, cushion, residual gas from the natural gas storage facility are found in the near top of the anticline in the depth interval of about 200 - 400 ms in the form of bright spots and amplitude brightening. It is not clear from the seismic data that the gas is still migrating or static. The K2 horizon shows a dipping trend. Time and depth contour maps of the K2 infer that the depth of K2 increases eastwards and southwards.

The Pilot survey imaged the main horizons to a reasonable degree and the results presented here are consistent with the 3D baseline survey and borehole data. Besides all the limitations and constraints of the survey, all the main reflections of both surveys and borehole data are well correlated. The comparison of both surveys reveals a significant similarity. The correlation with borehole data filled the information gap between the baseline 3D and the borehole Ktzi 163/69.

The result of 3D processing of the Pseudo 3D survey has shown its potential to delineate the subsurface to a reasonable degree. The study has given an understanding of the sub-surface geology of the site and this may be used as a data base for the future monitoring programme or a possible extension at the site or any other project of such type.

The gained experience and information from the CO₂SINK project together with the results of this project study will reduce uncertainty in secure geological sequestration of CO₂ in the future.
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Monika helped me to get started with the data processing. My familiarity with Claritas was due to her kindness, guidance and patience. She was never bothered by my endless questions. I learnt problem solving approach from her as well. I was lucky to have her.

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