A seismic line from the 2007 Dalders survey, Baltic Sea, has been re-processed and used along with well data as a basis for an investigation into the AVO behavior of the Faludden Cambrian sandstone reservoir. Line OP0701-260 is located in the southern part of the Baltic Sea with an approximate length of 52 km. The study profile lies within the Baltic Syncline which is host to a significant thickness of the Paleozoic sediments. The area has been investigated for years for petroleum exploration and production. The Middle Cambrian sandstones are the most important reservoir rocks for hydrocarbon potential and CO2 storage potential in the Basin. 2D marine seismic data were acquired by Svenska Petroleum in 2007 and processed, but the existence of strong multiples, lack of good seismic image at depth and limited frequencies within the target zone were the significant reasons for reprocessing the data. In this study the seismic data are processed using processing software, Global Claritas, to create a new processing workflow by testing different processes and parameters to improve the processing workflow for a better stacked image. The final stacked image shows improvement in the signal to noise ratio and multiple removals. The improved stacked image shows strong reflections over the Cambrian interval which gives more confidence in the geological interpretation of the data. The B-9 well, which is located 82 km south of Gotland in the Baltic Sea, sampled the Middle Cambrian interval, where P-wave velocity and density logs were recorded. Based on the good correlation between the seismic profile and the synthetic log especially for the Faludden sandstone, AVO modeling was performed based on the B-9 well. The response to changes in gas saturation and porosity within the reservoir sands are investigated. Hampson Russell AVO program was used to study the amplitude variation with offset at the Faludden sandstone interface in the seismic data. The results show a strong AVO anomaly is not anticipated associated with the Faludden interface. Different synthetic models were run for different petrophysical parameters to investigate how they can affect the AVO and stacked amplitude behavior of the data.
Reprocessing of 2D Reflection Seismic Marine Data and Investigation into the AVO behavior of Cambrian Sandstones, Southern Baltic Sea, Sweden

Mahboubeh Montazeri

Supervisor: Christopher Juhlin
Abstract

A seismic line from the 2007 Dalders survey, Baltic Sea, has been re-processed and used along with well data as a basis for an investigation into the AVO behavior of the Faludden Cambrian sandstone reservoir. Line OP0701-260 is located in the southern part of the Baltic Sea with an approximate length of 52 km. The study profile lies within the Baltic Syneclise which is host to a significant thickness of the Paleozoic sediments. The area has been investigated for years for petroleum exploration and production. The Middle Cambrian sandstones are the most important reservoir rocks for hydrocarbon potential and CO2 storage potential in the Basin. 2D marine seismic data were acquired by Svenska Petroleum in 2007 and processed, but the existence of strong multiples, lack of good seismic image at depth and limited frequencies within the target zone were the significant reasons for reprocessing the data. In this study the seismic data are processed using processing software, Global Claritas, to create a new processing work flow by testing different processes and parameters to improve the processing workflow for a better stacked image. The final stacked image shows improvement in the signal to noise ratio and multiple removals. The improved stacked image shows strong reflections over the Cambrian interval which gives more confidence in the geological interpretation of the data. The B-9 well, which is located 82km south of Gotland in the Baltic Sea, sampled the Middle Cambrian interval, where P-wave velocity and density logs were recorded. Based on the good correlation between the seismic profile and the synthetic log especially for the Faludden sandstone, AVO modeling was performed based on the B-9 well. The response to changes in gas saturation and porosity within the reservoir sands are investigated. Hampson Russell AVO program was used to study the amplitude variation with offset at the Faludden sandstone interface in the seismic data. The results show a strong AVO anomaly is not anticipated associated with the Faludden interface. Different synthetic models were run for different petrophysical parameters to investigate how they can affect the AVO and stacked amplitude behavior of the data.
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Chapter 1: Introduction

The Baltic Sea is considered as a bridge between West and East in Europe provides valuable resources such as hydrocarbon fields and saline aquifers, sand, gravel and amber deposits. The main structural feature is a large synclinal depression known as the Baltic Syneclise.

The Baltic Syneclise, which contains several formations and organic-rich source rocks, is the target for petroleum explorations and production especially in the SE onshore area. The major hydrocarbon reservoirs are sandstones in the Middle Cambrian layer which are producing in some areas such as offshore Poland. The studied profile is located within the Baltic Syneclise and the zone of interest is within the Cambrian sediments.

1.1. Research Objectives

The objectives and aims of this master thesis were:

- Processing the marine data by using original workflow in order to establish a baseline for further testing
- Performing velocity analysis method for getting better result
- Improving processing workflow for getting the best result
- Investigate feasibility of AVO analysis based on nearest well data in the area and the result from seismic data and also use the AVO effect to quantitatively and qualitatively assess petrophysical properties
- Perform a Geological interpretation of the final seismic section

1.2. Previous Study Result

An unpublished report details the processing of 2D seismic marine data located in the southern part of Baltic Sea (Østersjøen) for Oljeprospektering AB or OPAB, now Svenska Petroleum. The whole data set covered 72 lines with almost 1800 km.

The aim was production of near, mid, far offset stacks for all lines and the whole data set was collected between October and December 2007 by Gardline Geosurvey. They used ProMAX 2D (version 2003.19.1) for seismic processing and 3DGeo software for migration. The processing steps that they followed are shown in Table 1.1. After processing the data, they encountered and mentioned some problems in the report including:

- Running Statics
- Strong aliased multiples which limited the incident angle of stacks
- Missing of frequency at target area
- Numerous multiples are present 300ms below the Top Ordovician.
1. Segd Input
2. Geometry Assignment (using information from obslogs + field tapes)
3. Recording Delay Statics
4. Bandpass Filter, 1-2-110-125
5. Resampling for 1ms to 4ms
6. Noise Trace Editing in Frequency Domain: Despike by Standard Deviation Parameters
7. True Amplitude Recovery
8. Surface Wave Noise Attenuation in Shot and Receiver Domains
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Table. 1.1. Previous workflow which was run to process the Seismic line OP0701-260.

This research is based on OP0701-260, one of the lines from those mentioned above. One of the objectives of this study is to try to improve the processing work flow for getting an improved result.

1.3. Materials and Methods

1.3.1. Database:
- **Seismic Data**: Seismic marine data, line OP0701-260, were acquired within the 2D Dalder Survey with around 52km coverage in the southern part of the Baltic Sea.
- **Well logs**: Petrophysical logs from B-9 well which were drilled in the Baltic Sea are used. These logs include P-wave velocity (m/s) and Bulk Density (g/cc) (Grossi, B., 1975: Unpublished B-9 Completion report).

1.3.2. Software:
- **Globe Claritas v5-5** used for processing of seismic data in this project.
- **Hampson-Russell** software products for AVO analysis.

1.3.3. Methods:
- The processing of 2D reflection seismic marine data and geological interpretation
- AVO modeling and some investigation into the AVO behavior for the petrophysical parameters
1.4. 2D Reflection Seismic Method

The Seismic technique is applied for:
- Description of near surface geology which means up to 1km, which is known as “Engineering Seismology”
- Exploration and development of hydrocarbons, within the depth up to 10km, and it’s called “Exploration Seismology”
- Investigation of earth’s crustal structure, up to 100 km, which is named “Earthquake Seismology”.

(Yilmaz, 1988)

Since 1920’s, the seismic reflection method has been used as an exploration geophysics method, particularly for oil and gas industry, which records earth’s motion with time (seismogram) and then could be interpreted by modeling or imaging techniques and it is mainly based on the acoustic wave assumption.

The fundamental needs are considered as:
- Seismic source for generating seismic pulse
- Seismic transducer for detecting the wave in the earth
- Seismograph for recording and displaying the waveforms

Seismic sources can have a wide range of frequencies from 1Hz to few hundred Hz. Commonly used source for land acquisition may include explosive sources (dynamites) or non-explosive sources (vibrosis, mini-Sosie, weight drops and hammers, shot guns, buffalo guns and rifles). Popular seismic sources for marine environment are air guns, water guns, marine vibrosis, sparkers, boomers, pingers and chirp.

The transducers which are used on the land surveys are known as geophones and on the marine are called hydrophones.

The recording seismogram is time dependant and the waveform must be recorded and simultaneously stored for future use. This seismic trace shows the combination of earth response and recording system which after removing the noise, the signal can be interpreted in terms of ground structure.

Like most geophysical techniques, seismic method also has some limitation included the vertical and horizontal limits of resolution, wavelength and frequency of data, the environmental noise and velocity variations near the surface.

The whole seismic exploration can be broadly classified into three parts, data acquisition, data processing and data interpretation. In this project we almost cover all parts to get optimum and more holistic image of geological structure of the study area.

1.5. Amplitude versus Offset (AVO) Method

Amplitude Versus Offset (AVO), which first proposed by Bill Ostrander, 1984, is commonly used to determine density, P-wave and S-wave velocities first and then define lithology and fluid content by using these parameters, but the main concern is what those parameters are and how the lithology could be derived by them (Hampson-Russell AVO Tutorial).

AVO has been used initially as a recognition method of seismic amplitude anomalies associated with gas sands (Ostrander, 1984). However it was not that much successful especially when the gas sands obtained amplitudes with lower impedance than the surrounding Shale and also showed increasing reflection coefficients with increasing the offset.

AVO analysis is a successful technique which has been used in reservoir characterization and getting good results from that is surely dependent to the seismic processing result and also rock physics. AVO modeling could help the data processing by making link between rock properties and offset-dependant amplitude response. Seismic wave propagation and seismic responses could define the rock properties. The amplitude of seismic reflection varies with offset, based on changes in incident angle.

Hampson-Russell software products especially the version which is used in this research, HR9, has been providing the innovative tools since 1987 in geophysical field. Three types of analysis can be run by the AVO program including:
- forward modeling
- AVO reconnaissance analysis
- Inversion
and forward modeling applied during this study to test the effect of rock properties and pore fluids on the synthetic model (Hampson Russell AVO Tutorial). The input data for doing this analysis are pre-stack seismic data plus rock parameters measurements. One of the main application of AVO is generating a synthetic seismogram from given earth model, then comparing that by real data and making proper conclusion based on seismic trace behavior. Complication of the model is dependent to the earth model details and calculation methods. The main goal of studying this method is to evaluate the reflectivity at the top and the bottom of the Faludden sandstone as a function of offset/angle.

1.6. Geological Background

The study area in the Baltic Sea which is located on the Baltic Syncline structure is here discussed in more detail. The Baltic Syncline accumulation, which is located in the NW of East European and SE of the Baltic Sea, with 700 km length and 500 km width stretches in the SW-NE direction. The Baltic Syncline has more than 35 years of oil exploration history, especially in its southeastern onshore part. However hydrocarbon potentials are mostly known in Sweden, Poland, Lithuania, Latvia, Estonia, the Kaliningrad region of Russia and Poland. The Baltic Syncline is limited by the Teisseyre-Tornquist Zone (TTZ) in the southwest, the Baltic Shield in the north (Ziegler, 1990; Katzung et al., 1993; Dadlez et al., 1995), the Latvian Saddle in the east and the Belarus-Mazurian Anticline in the southeastern part (Paskevieius, 1997) (Fig.1.1.).

Fig.1.1. The map shows structures and subdivision in the Baltic area (Usaityte, D., 2000).
The Baltic Synclise has been subjected to petroleum exploration and production, especially in the SE onshore area. It is divided into three sections based on geological structures, namely (i) Crystalline basement, (ii) Sedimentary cover and (iii) Quaternary deposits (Usaityte, D., 2000).

- **Crystalline Basement**
  The depth to the crystalline basement ranges from 800-1000 m in the east to 2000-4500 m in the SW of the Baltic Sea.

- **Sedimentary Cover**
  The Baltic Synclise covers four geological structural complexes: the Baikalian, the Caledonian, the Hercynian and the Alpine.
  From a stratigraphical point of view, the sedimentary cover comprises a complete depositional sequence (Usaityte, D., 2000), and its thickness varies from 2000-3000 m to 300-1000 m on the slope of the Synclise (Suveizdis, 1994). The Baikalian complex generally known as the oldest sedimentary sequence are absent in the southern Baltic Sea (Pirrus, 1986).
  The Caledonian complex is the most complete with a total thickness of 1000-1500 m in the SE Baltic Sea and based on geological succession they are subdivided into the Cambrian, Ordovician, Silurian and Lower Devonian structural stages (Paskevicius, 1994). The Cambrian stage includes deposits of sandstones (När, Faludden and Viklau), clays and Gravelites and is predominantly covered by clayey and carbonaceous Ordovician deposits with thicknesses ranging from 180 to 300m in the SE of the Baltic sea (from Isopach map, Usaityte, D., 2000). The Upper Cambrian rocks (Alum Shale) are composed of up to 20 m dark shale’s in the central and western part which have been eroded towards the Kaliningrad region (Kanev et al., 1994). On the east side, black shale and siltstone are represented in the upper and middle Cambrian sequence (Usaityte, D., 2000). In the Baltic Synclise region, the Cambrian offshore layers are oil-bearing, especially near Poland (Laskova, 1979).
  The Viklau member, with late early Cambrian age, is characterized by quartz sandstone in the lower and upper parts, and by siltstone or laminated darkish green shale in the middle part. It overlies the crystalline basement with conglomerate at the base (Hagenfeldt & Bjerkeus 1991; Hagenfeldt 1994).
  From a lithological point of view, the När shale member is distinguishable by a greenish grey to somewhat reddish siltstone/shale which is partly laminated, with sporadic occurrences of thin sandstone beds (Usaityte, D., 2000). It is superimposed to the Viklau member and subjacent to the När sandstone member with well-defined boundaries. Its thickness is around 36 m in offshore well B-9 (OPAB unpublished completion report).
  The När sandstone member reaches up to 52 m of thickness in the offshore well’s east and south of Gotland (OPAB unpublished completion report). It is distinguished by fine to medium-grained sandstone with mud and siltstone irregularly interbedded.
  The Faludden member is predominantly consists of sandstone with minor intercalations of mudstone (Hagenfeldt, 1994) which reaches a thickness of 48 m in the offshore B-9 well. It was finally ranked as a member of the Borgholm Formation by Hagenfeldt (1994).
  The Alum shale formation consists of kerogeneous, black, more or less fissile shale with beds of limestone/stinkstone. It is typically dark brown to black because of high organic carbon content with blackish mudstones/mudshales. It occurs almost everywhere in Scandinavia where lower Paleozoic rocks are preserved, except for in the Siljan area. From the south central Sweden towards the east it usually becomes thinner. This formation belongs to the Mid Cambrian-Early Ordovician and by moving eastwards it is becoming younger and younger.
  The Ordovician rocks are seen almost everywhere in the Baltic Sea and the thickness reaches up to 140 m (Usaityte, D., 2000). In the central, southern and SE of the Baltic Sea, the Ordovician layers are superimposed by the Silurian and Devonian deposits. The complete Ordovician coverage is observed in the latitude of Latvia which is part of the Swedish-Latvian facial type – the Livonian facial zone (Paskevicius, 1972, 1994).
  The Baltic Ordovician member is categorized into Lower, Middle and Upper and are represented by marls, limestone, clays and argillites (Mannil, 1997). Based on lithological or seismo-acoustic features, no clear boundaries can be observed between the Cambrian and Ordovician formations in that area. The thickness of the Upper...
Ordovician formation alters from 800 m to 2800 m in the SE Baltic Sea and from 80 m to 250 m in the central Baltic Sea (Grigelis, 1991).

The Silurian deposits are in general embedded by the Baltic Sea floor and transgressively covered the Ordovician sediments. The depth changes from 600-1200 m in the SE of Baltic Sea. The Silurian layers are characterized by carbonaceous and clayey deposits with high contents of fossils. Towards the east the content of carbonates increases but towards the south the clay is more dominant. In the southern part, the carbonaceous facies are represented by graptolitic shales and argillites (Paskevicius, 1972; Brangulis et al. 1982, Grigelis, 1991). The Lower Silurian strata are widespread in the Baltic Sea floor but the Upper Silurian is dominant in the central and SE region of the Baltic Sea.

The Lower Devonian which is a part of lagoonal, continental and marine sediments is represented by different colored clays with interlayers of argilites, sandstone in the SE Baltic Sea which the depth differs from 250 m to 700 m (Grigelis, 1991).

The Hercynian complex, which from a paleotectonical point of view has the most tectonic structures, has a different depth ranging from 200 m to 800 m in the Baltic Sea. (Usaityte, D., 2000). No carboniferous deposits are distributed around the area and the Alpine complex, with varying composition and structure, is not present in the study area (from Isopach maps, Usaityte, D., 2000).
Fig. 1.2. Geological map with cross section of the Baltic Sea (S.G.U report, Lagring av Koldioxid i berggrunden, 2011). Based on the approximate depth of the bedrock traversed by the cross section OP0701-260 the geological sequence can be found there as well.
1.7. B-9 Well Data

Well logging measurement records different properties of rock formation with depth and are commonly used in geological interpretation, especially in hydrocarbon investigations. During this study, B-9 well data, the nearest well were used.

The B-9 well is located in the Baltic Sea, 82km south of Gotland, with coordinates of $18^\circ 16' 08'' .627^E = 6,227,131 \ m , \ 56^\circ 10' 53'' .627^N = 78,779 \ m$ and was initially drilled to test the north-south middle Cambrian structure, but then it reached down to the Precambrian basement, including the lower När and Viklau sandstone. The drilling was started 27/9/1974 and completed at 15/10/1974, with total reachable depth about of 1267m (Schlumberger depth). Later, it was classified as an abandoned one with gas shows.

![Well map location of the Baltic Sea which shows the location of B-9 which is used in this study (Unpublished report, B-9, the Baltic Sea).]
The stratigraphy results from electronic logs investigate the Silurian (75-954.6m BKB), the Ordovician (954.6-1021m BKB) and the Cambrian (1021-1266m BKB). The only core record was collected in the boundary between the upper and middle Cambrian interface aside from 40 sidewall cores. From the geological point of view during drilling, at 1175m (När sandstone) the methane gas value maximized to 50,000 ppm with 200 ppm of Ethane. There was also gas in the upper part of the Faludden sandstone with water saturation less than 50%, but in the När sandstone the gas saturation was around 80%. However, the loss of the rig caused plugging and abandoning the B-9 well without testing the Faludden sandstone. However the presence of free gas in the När sandstone is interesting result (Unpublished Report, B-9, Baltic Sea).

The starting and ending position of the marine seismic profile are:

\[ 19.3322^\circ E \ 56.4871^\circ N \text{ and } 19.0380^\circ E \ 56.0443^\circ N \]

It is located around 50 km far away from the well position. The only available information from this well includes P-wave velocity and density logs.
Chapter 2. Seismic Processing Method

2.1. Introduction

The main goal of doing seismic processing is to image the earth structure in the seismic time domain based on the recorded field data at different receiver locations. Processing aims to compensate for acquisition effects, remove the coherent and random noise, indemnify the signal distortion and concentrate the recorded wave-field data.

Marine data processing differs from land processing by typically having higher folds, more regular geometries, larger data sets, stronger coherent noise and a more consistent near surface. The coherent noise in recorded marine data can be grouped into different categories (Yilmaz, 1988):

- Guided waves which are mostly seen in shallow recordings in the presence of a hard water bottom and can be distinguished by their early arrival time and scattered nature
- Side-scattered noise, which often occurs with a water bottom with pronounced topography or different irregularities
- Cable noise with low amplitude and low frequency which looks linear
- Multiples known as secondary/fake reflections, which happen whenever seismic energy reverberates in the shallow subsurface. Multiple suppression techniques are usually based on the periodicity of the multiples and the difference between primaries’ move-out and multiple’s move-out.
  Multiples in marine data are mostly categorized as water bottom, peg-leg and intra-bed.

Random noise can be caused by different sources such as wind motion, vibration of the cables below the water and electrical noise from recording instruments (Yilmaz, 1988).

In all the processing sequences, each step is performed in the workflow sequentially; where at each step, all possible parameters are tested in order to obtain the optimum result. All the processing steps are done in Globe Claritas software. The final result and the preliminary interpretation are explained in this chapter.
2.2. Data Acquisition of project

The data for this project were provided by Svenska Petroleum, line OP0701-260 which is part of a grid of 2D lines acquired over the Dalders prospect in the Baltic Sea. The data were acquired in 2007 and the line was 52 km long.

Fig. 2.1. Marine bedrock geological map of the area including the position of the study profile (red line). The location of the B-9 well is highlighted. The blue lines indicate the positions of vintage 2D seismic lines acquired between 1970 and 1990 by Oljeprospektering AB (OPAB) currently Svenska Petroleum (Unpublished report, Sopher, D., 2013).

The marine acquisition parameters of the line OP0701-260 are summarized in the following table (Table 2.1. and Fig.2.2.)
<table>
<thead>
<tr>
<th>Line Name</th>
<th>OP0701-260</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td>OPAB</td>
</tr>
<tr>
<td>Project</td>
<td>Dalders 2D Survey</td>
</tr>
<tr>
<td>Vessel</td>
<td>Sea Surveyor by Gardline Geosurvey</td>
</tr>
<tr>
<td>Date</td>
<td>December 2007</td>
</tr>
<tr>
<td>Source</td>
<td>470 cu in Bolt Gun Array</td>
</tr>
<tr>
<td>Receiver</td>
<td>NTRS 2</td>
</tr>
<tr>
<td>Mean Water Velocity</td>
<td>1454 m/s</td>
</tr>
<tr>
<td>Ref. Point-Stern</td>
<td>29.29 m</td>
</tr>
<tr>
<td>Stern-Centre of Source</td>
<td>73.4 m</td>
</tr>
<tr>
<td>Centre of Source-Centre of Channel 1</td>
<td>50 m</td>
</tr>
<tr>
<td>Sample rate</td>
<td>4 ms</td>
</tr>
<tr>
<td>Channels</td>
<td>240</td>
</tr>
<tr>
<td>Record Length</td>
<td>3 ms</td>
</tr>
<tr>
<td>Shot Numbers</td>
<td>4200</td>
</tr>
<tr>
<td>CDP Numbers</td>
<td>8824</td>
</tr>
<tr>
<td>Profile Length</td>
<td>52500 m</td>
</tr>
<tr>
<td>Nearest Offset</td>
<td>50 m</td>
</tr>
<tr>
<td>Furthest Offset</td>
<td>3037.5 m</td>
</tr>
<tr>
<td>Offset Direction</td>
<td>South</td>
</tr>
</tbody>
</table>

**Table 2.1.** Acquisition parameters for the line OP0701-260.

![Fig. 2.2. Schematic view of a marine seismic Survey](image)

*Fig. 2.2. Schematic view of a marine seismic Survey*


2.3. Data Processing Steps

The workflow for the processing of the 2D seismic line is shown in Table 2.2. More detailed information about the individual steps can be found below.

<table>
<thead>
<tr>
<th>DATA PROCESSING STEPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Adding Navigation to the Raw Data</td>
</tr>
<tr>
<td>2. Geometry Assignment</td>
</tr>
<tr>
<td>3. Adding Geometry</td>
</tr>
<tr>
<td>4. Apply Bulk Shifting</td>
</tr>
<tr>
<td>5. Re-sampling</td>
</tr>
<tr>
<td>6. Auto-muting</td>
</tr>
<tr>
<td>7. Spherical Divergence</td>
</tr>
<tr>
<td>8. FK Filtering on Shot and Receiver Gathers</td>
</tr>
<tr>
<td>9. Deconvolution in Tau-P Domain</td>
</tr>
<tr>
<td>10. Bandpass Filtering</td>
</tr>
<tr>
<td>11. Deconvolution in Time Domain</td>
</tr>
<tr>
<td>12. Velocity Analysis</td>
</tr>
<tr>
<td>13. Parabolic Radon Transform</td>
</tr>
<tr>
<td>14. FK Filtering</td>
</tr>
<tr>
<td>15. Surgical Mute</td>
</tr>
<tr>
<td>16. Stack</td>
</tr>
<tr>
<td>17. Bandpass Filtering</td>
</tr>
<tr>
<td>18. Post Stack Deconvolution in Time Domain</td>
</tr>
<tr>
<td>19. Phase Shift Migration</td>
</tr>
<tr>
<td>20. FXDECON</td>
</tr>
<tr>
<td>21. Post Stack FK Filtering</td>
</tr>
<tr>
<td>22. Bandpass Filtering</td>
</tr>
</tbody>
</table>

*Table 2.2. Processing workflow of the 2D reflection seismic data, line OP0701-260*
2.3.1. Preprocessing

The processing of marine data starts with preprocessing steps. Most of the data are stored in the standard SEG-Y format which is defined by the Society of Exploration Geophysicists (SEG). The first step is to merge the field geometry with the seismic data; this allows the shot and receiver coordinates to be added and stored in the trace headers. This step is divided into different jobs:

2.3.1.1. Making and adding geometry

The marine 2D geometry file was added to the trace headers and CDP & Offset calculated based on shot point and Channel. In this project, all the data from the tapes and the observation logs which include the x and y positions of source and also offset were used to calculate the receiver positions, which are assumed to lie on a linear trend path behind the vessel. The receiver locations were then added to the trace headers. A linear binning line was used where CDPs range from 100 to 8924 with an increment of 2. The CDP bin size was 12.5 m, which reduced the effect of aliasing. The maximum CDP fold was 240.

2.3.1.2. A constant bulk shift was applied to the traces of +38ms (based on the previous processing report).

2.3.1.3. Bandpass filtering was applied. This works by transforming the traces into the frequency domain and only allows specific frequencies to remain. The corner frequencies which were used are F1=1, F2=2, F3=110, F4=125 Hz

2.3.1.4. The traces were then re-sampled to a new rate (based on previous processing report). Anomalously high and low-amplitude traces were muted automatically.

2.3.1.5. Spherical divergence

The geometrical spreading correction corrects for the decrease in amplitude over time due to the spreading of the wavefront. The scalar function which is applied is a multiplication of three factors two-way travel time, velocity and offset. The velocity time function used for the correction is defined between 0-2600 ms for time and 1450-3850 m/s for velocity (Fig.2.3.).

![Shot gather](image)

**Fig. 2.3** Example shot gathers for shot-ID 500 and 1200 in processing workflow a) before b) after applying preprocessing step.
2.3.1.6. Applying F-K filtering on receiver/shot gathers

After looking through different shot gathers, groups of linear noise can be observed on the gathers. These were identified as side scattered noise and are most noticeable in the near surface. The used method to remove this noise is to sort to receiver gathers: i.e. a gather where all the traces are recorded for the same receiver location, but a different shot location. In order to do this, traces were binned into common receiver bins at 12.5m intervals. It was then possible to sort the data via these receiver bins.

The maximum fold in any receiver bin was equal to 316. In the FK domain the side scattered energy is manifest as events with a negative dip in both shot and receiver gathers. These negative dips can easily be filtered out using an FK filter. The FKMUTE processor was used in the workflow which performs a 2D FK forward and inverse transform. After filtering out negative dips on receiver gathers, they sorted back to shot gathers and applied again to remove the remaining negative dips on the shot gathers. (Larner, K., Chambers, R., Yang, M., Lynn, W., Wai, W., 1983)(Fig.2.4.).

![Fig.2.4.](image)

**Fig. 2.4.** The plots show part of the stack along CDP 6500-6800 a) before and b) after applying shot and receiver gather filtering. The noise which removed after filtering annotated in the plot.

### 2.3.2. Deconvolution

Deconvolution is one of the periodic based multiple removal techniques. It compresses the wavelet and attenuates reverberations, short-period multiples and increases the temporal resolution. In general, this method is less efficient when the multiples have a quite long period in comparison with the record length. The reason is that the recording length does not adequately capture the periodicity of the multiples and also that the long operators required for
targeting these long period multiples which might start to attenuate the primaries over long time windows (Fisher, 2004, Applied Seismology).

This removal technique works in the opposite way to the convolution process. The received seismic response is the convolution of the seismic source wavelet with the earth response, the response from the seismic detector and the seismic recording system. An important point is removing the seismic source response and getting the desired wavelet, this requires the selection of appropriate Operator and Gap lengths.

Predictive Deconvolution applied in the $\tau$-$p$ (Time intercept-Slowness) domain with a velocity range of -1000 to 5000[m/s], filter length equal to 800 [ms] and a maximum gap length of 10 ms. $\tau$-$p$ deconvolution is more effective when the interfaces have no lateral variation and horizontal. Then deconvolution is applied for the second time in the time domain with maximum filter length equal to 800 ms and maximum gap length of 220 ms. (Matson, K. H., Paschal, D., Weglein, A. B., 1999, A comparison of the three multiple-attenuation methods applied to a hard water-bottom data set).

Applying deconvolution introduces very low frequencies which are removed by high-pass filtering (Fig.2.5).

---

**Fig.2.5.** The plots show part of stack along CDP 6100-6800. a) before and b) after applying deconvolution. The type of coherent noise which was removed is annotated in the plots.
2.3.3. Velocity Analysis and Normal Move-out (NMO) Corrections

Passing wave through different layers especially for deeper ones, makes the reflections from these deeper layers weaker. Imaging the same subsurface point several times, while considering a process which is known as multifold data (Gellius, 2010) can improve that the signal to noise ratio at depth. A collection of different pairs of shot and receiver positions which image the same subsurface position is called a Common Midpoint (CMP) and can be input for NMO corrections (Robinson, 1988; Gellius, 2010) (Fig.2.6.).

Velocity analysis is performed in order to define a velocity field for all times and CDP positions along the profile. After applying the NMO correction to the data, using the correct velocity field once can stack the data to improve the signal-to-noise ratio for each CDP position and decrease the amount of processed data for next steps. Different factors like porosity, temperature, pressure and composition control the velocity. Velocity analysis is done to get the best stacking velocity model called velocity function.

For a single constant horizontal velocity layer, the reflection travel time curve, as a function of offset is a hyperbola. The travel time difference between a specified time on the reflection and the zero-offset time is named the “Normal Move-Out (NMO)”. The required velocity for correcting the NMO is called the NMO-velocity. NMO velocities are the best velocities that could make the events flat as a function of offset (Fig.2.6.).

The reflection travel time of a single horizontal layer with constant velocity for different offsets is calculated by:

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

where
- \( t(x) \): two-way travel time at offset \( x \)
- \( t(0) \): the time for \( x=0 \)
- \( x \): offset distance between source and receiver
- \( v \): medium velocity above the interface

For a scenario involving multiple layers, the velocity of the overlying medium is averaged to give what is known as the root-mean-square velocity (\( V_{rms} \)). For \( n \) horizontal layers the \( V_{rms} \) can be expressed below as:

\[
V_{rms} = \frac{\sum_{i=1}^{n} V_i^2 \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}
\]
\[ V_{int,i} = \sqrt{\frac{V_{ms,i}^2 t_j - V_{ms,i-1}^2 t_{j-1}}{(t_j - t_{j-1})}} \]

where \( \Delta t_i \): travel time through \( i \)th layer
\( t_j \): Two-way travel time
\( V_j \): velocity of \( i \)th layer

The expressions for RMS velocity and the NMO correction assume a case where the layers in the subsurface are horizontal or gently dipping reflectors and trace offsets are less than or equal to the reflection depth.

\[ \text{Fig. 2.7.} \] The plot shows the water depth variation along the line after converting to time domain which is almost constant.

The shot gathers require transferring to CMP/CDP gathers before doing any velocity analysis. The Velocity model was picked by combining two methods; Semblance Spectrum and Constant velocity stacks (CVS). Semblance Spectra give the cross-correlation within a CDP calculated along a given velocity curve at a given zero offset time. Constant Velocity Stacks (CVS), as an alternative method for velocity analysis, uses constant velocity values specified within a range; stacked sections are generated using these constant velocities – which can be used to choose appropriate velocities at a given time/CDP. The final velocity model which was picked is shown in Figure 2.8.
2.3.4. Parabolic Radon Demultiple

This is a multiple removal technique which is based on the different move-out between primaries and multiples, as at a given time multiples tend to have more move-out in comparison with primaries. This method is less sensitive to the missing near surface offsets and out of plane reflections. After applying an NMO correction to the data using the picked velocities, the primaries are flattened; however, the multiples are not, and exhibit residual move-out. The corrected gathers are then transformed to the hyperbolic radon domain, where certain parts containing the multiples are muted. The data is then transformed back.

The generalized radon transform \(u(q, \tau)\) is described as (Foster and Mosher, 1992)

\[
u(q, \tau) = \int_{-\infty}^{\infty} (d(x,t) = \tau + q\phi(x))dx
\]

where

- \(d(x,t)\) : original seismogram
- \(\tau\) : intercept time
- \(x\) : spatial variation (offset)
- \(\phi(x)\) : curvature
- \(q\) : slope of curvature

Which can be described on velocity model as well (Yilmaz, 2001). The cost of running hyperbolic transform on CDP/CMP gathers concerning about seismic events and also errors in move-out corrections leads the technique to parabolas. The forward and inverse radon transform in NMO-corrected is written as:

\[
u(q, \tau) = \sum_{x} d(x, t_{x} = \tau + qx^2)
\]
\[ d'(x,t) = \sum_q u(q, \tau = t_a - qx^2) \]

Those formula were transformed later by Yilmaz(2001) after applying \( t^2 \) stretching to get exact parabola.

The Parabolic Radon Demultiple processor models the multiple reflections and then subtracts them from data. The main inputs which are required are two move-out ranges: MODEL-MS and NOISE-MS. The limitations of this method are a) If the tails of the multiples cross into the primary area, the residual multiples will be improved. b) Differentiation between primary and multiple will be difficult for the near surface if the move-out values are large and reflections are only visible on near offsets and c) If the amplitudes of near-offset primaries are distorted (Claritas Tutorial).

The input seismic data is NMO corrected, and the defined Model-moveout and Noise-moveout windows used in the Parabolic Radon Demultiple process are -500:3000 and 300:2200 m/s (Fig.2.9.).

2.3.5. Stacking

The most important reason to get the correct velocity function is to achieve the best stacked data. Stacking is one of the three main steps in seismic data processing (besides Deconvolution and Migration) which play important roles in improving the signal-to-noise ratio (Yilmaz, 1988).

The basic concept behind stacking is NMO corrected traces within a CDP are summed together. This approach decreases the noise and enhances the seismic signal in the data, and then it reduces the data volume (Fig.2.10.).
Fig. 2.10. Single trace after stacking on the interface

Besides the great merits of stacking, NMO stretch occurs which distorts the frequency and it is most severe for the shallow events and large offsets. Therefore effected parts of the data are shifted to the lower frequencies. Automatic or manually muting solves this problem.

To achieve a better stack, some noise removal techniques were tested and applied before running stack as follows:
- F-K filtering to remove multiples based on the move-out values in F-K domain
- Scaling the trace in time domain
- Surgical Muting applied to the seismic trace to remove the effect of NMO stretch and noises with extremely wide angles on NMO corrected data.

### 2.3.6. Post stack processing

2.3.6.1. Stacking introduced noise, then Bandpass frequency filtering was used to remove those effects. The applied frequencies are ranged F1: 10 Hz; F2: 25 Hz; F3: 60 Hz; F4: 100 Hz (Fig.2.11.).
2.3.6.2. Post Stack Deconvolution
Time domain Deconvolution was applied on the stacked data to reduce the remaining multiples and make the wavelet sharper. The maximum filter length and maximum gap length for three time windows were 800 and 220ms.

2.3.6.3. Post Stack Migration
Migration of the seismic data creates a focused stacked image through a mathematical reconstruction achieved by moving the dipping events to their true subsurface positions and collapsing the diffractions. Having the proper velocity model improves the migration process. The migrated reflector is seen deeper, shorter and updip from the unmigrated one.

Phase-Shift Migration; which can just handle vertical velocity variation, gives the better result on stacked section between other algorithm types.

2.3.6.4. Post Stack Filtering
Finally, various noise removal processes were applied to the stacked image. These include applying FXDeconvolution which makes the stacks less wormy, 2D FFT and Bandpass filtering (Time: 0-1000 ms F1=12; F2=32; F3=60; F4=100 Hz; Time: 1000-3000 ms F1=8; F2=22; F3=70; F4=110 Hz) at the end (Fig.2.12. and Fig.2.13.).

Fig.2.11. The plot shows the processing stacked image after applying Bandpass filtering.
Fig. 2.12. Final stacked section, line OP0701-260 (Grey-scale)
Fig. 2.13. Final stacked section, line OP0701-260 (Blue Red)
2.4. Comparison of New Result with Previous Processing

The processing workflow developed as part of this study based on testing different modules and processes was applied to the profile. The final stacked section is compared with the previous study result (appendix I), these goals have been achieved:

- The wavelet has been sharpened and strong reflecting events especially those around 1000ms for the Cambrian reservoirs are enhanced.
- Better noise removal technique applied, especially around 500ms, and multiples in this part are strongly attenuated.
- A better near surface image has been achieved.
- The improved stacked section shows structural features more clearly. This can therefore be used to better understand the structure and geology of the area.
- The Mid-Silurian reflection, around 800 ms on the southern end of the profile, is better imaged on the previous processing image.
2.5. Preliminary Interpretation

In conventional seismic interpretation, changes in acoustic impedance can occur at the boundary between different media and these contrasts give rise to seismic reflections. Plotting the arrival times of reflectors in a stacked section therefore gives a deep insight into the structure of the area. Having improved processing results can give us more details about the geological structures.

The aim in this section is to do a preliminary interpretation of the seismic reflection image. The B-9 well and the background geology can be used to understand the strong reflectors which are seen in the section. The B-9 well lies around 50km out of the seismic profile, and it might not show good correlation with the seismic stack for some events.

The B-9 well is the closest well to the seismic profile located in the Baltic Sea (82km south of Gotland) and it was drilled on September 27, 1974 with total drilled depth of 1265 meters. The primary goal of drilling this well was to penetrate the Middle Cambrian sandstone.

In order to interpret the data the following steps were followed:

2.5.1. Reading the data
- **Well data**
  Hampson-Russell software was chosen for importing the P-wave velocity and density log data for the B-9 well and also for subsequent modeling. GEOVIEW works as a database for the whole HR package and the available logs were imported as ASCII format which was used for creating the AVO synthetics.
  The AVO program reads the well data from the database including defined x and y positions coordinates, as well as other data such as tops in the well.

- **Seismic data**
  In order to tie the synthetic seismogram to the seismic data, the seismic SEG-Y file needs to be read in. In this project the well is not located along the profile instead it lies almost 50km away from the seismic profile. A range of different CDP locations were tested for the location of the B-9 well, in the end a location with a good correlation coefficient between the synthetic and seismic stack was chosen.

2.5.2. Correlating the log and making a Zero-offset synthetic seismogram

The AVO modeling option in the AVO program requires the user to define the required well log information. Since only P-wave velocity and density logs are available for this study, S-wave velocity was calculated by using Castagna’s equation.

The sonic logs do not tie the seismic profile initially and needs to be corrected. The wavelet is assumed to be a Ricker wavelet with a dominant frequency of 45Hz. The Zero-offset synthetic (blue seismograms) resulted after well to seismic tie (Fig.2.14).
2.5.3. Defining the reflectors
By detailed comparison of the Zero-offset synthetic response and the seismic stack data, it was possible to interpret different geological structures as well as seismic horizons across the stacked section and strong amplitude reflection can be seen for the Cambrian-Faludden sandstone.

2.6. Seismic Processing Results
The stacked seismic data file and the interpreted geological horizons were plotted in GMT (Fig.2.15. and Fig.2.16.).
Fig. 2.15. Stacked image after the processing and applying the preliminary interpretation of line OP0701-260
Fig 2.16. Geological section after the processing and applying the preliminary interpretation of line OP0701-260.
2.7. Seismic Processing Conclusions

This chapter showed the detailed processing workflow which was designed to obtain a significant improvement in the signal to noise ratio, especially in the final stacked image, as well as a preliminary interpretation based on the geology of the area.

- After testing new modules and processes and creating a new workflow, the quality of the final stacked section has been improved.
- Choosing the appropriate CDP bin size had an important role in removing aliasing affects for this dataset.
- Multiple energy is a big issue for the processing of this marine dataset. Deconvolution in the Tau-p domain and Deconvolution in the Time domain (with proper parameters) worked effectively as noise removal techniques and improved the stacked data, especially around 500 ms.
- The new processing workflow improved the amplitude of reflections which resulted in a better image of the seismic events, especially around 1000 ms, interpreted in this study as the Cambrian layers.
- The improved stacked image gives greater interpretational confidence and better understanding of the geological structures, such as faults in the area. In the final stacked section, the high amplitude events, interpreted as the Faludden sandstones, can be interesting as potentials for further hydrocarbon investigations.
Chapter 3: AVO Modeling

3.1. Introduction

The aim of this chapter is to look at the amplitude variation with offset (AVO) in seismic data and to investigate the changes in AVO along the profile in the real data. A suite of different models have been generated to investigate changes in several different petrophysical properties. Seismic forward modeling is used to investigate the AVO behavior associated with the petrophysical changes.

The Hampson Russell AVO program used two kinds of input data:
- Pre-stack 2D Seismic data which is already CDP sorted
- Well log data

In the AVO program the well log data can be edited for different fluid substitutions and petrophysical parameters, porosity and saturation were considered in this study. Different synthetic seismograms were calculated, using the Zoeppritz, Zero-offset and Finite Difference methods, the models were compared and the AVO variation within the target zone were investigated. Key differences, assumptions and limitations of the methods are also discussed.

Finally the real seismic data are analyzed to study the AVO variation along the profile. This section will begin with a brief theoretical overview before the methodology and the results of the forward modeling and real data analysis are discussed.

3.2. Theoretical Background

The normal incident reflection coefficient and the difference in Poisson’s ratio at the interface between two rock layers influence the Amplitude Versus Offset (AVO) behavior (Rutherford and William, 1989). The P-wave reflection coefficient is quite dependent on the incident angle, and when the contrast in Poisson’s ratio of the interface is large, small changes on angle will make a large difference in reflection coefficient (Ostrander, 1984).

3.2.1. Reflection Coefficient (R)

The recorded seismic signal at a given geophone can be calculated by convolution between the zero offset reflectivity series and a seismic wavelet (plus noise). The ability which allows passage of a wave through the rock is called acoustic impedance. When there is a change in acoustic impedance at an interface this will lead to a reflection. This simple convolutional model and the equation shown below are only valid for a simple zero-offset or normal incidence case.

\[
R_i = \frac{Z_i - Z_{i-1}}{Z_i + Z_{i-1}}; \quad Z_i = \rho_i V_i
\]

where
- \( R_i \): Reflection coefficient of \( i \)th layer
- \( \rho_i \): Bulk density
- \( V_i \): velocity of medium

3.2.2. Poisson’s Ratio (\( \sigma \))

Poisson’s relation expresses the ratio between the strain parallel to a compressional or tensile stress, and the strain perpendicular to that stress. Changes in the Poisson’s ratio can occur due to pore fluid changes and it can be calculated as follows:

\[
\sigma = \frac{\gamma - 2}{2(\gamma - 1)}
\]

where
- \( \gamma = \left( \frac{V_p}{V_S} \right)^2 \)
- \( V_p \): Compressional wave velocity
- \( V_S \): Shear wave velocity
3.2.3. Shear Wave Velocity (Vs)
This estimation is the application of Log Transform function which defines the relationship between different physical
parameters of rocks and the simple empirical relationship between P-wave and S-wave velocities used in the following
calculations (Castagna et al., 1985).

\[ V_s = 0.862 V_p - 1.172 \]

This equation shows the straight forward relationship between \( V_p \) and \( V_s \) and the line \( V_p / V_s \) plot is called as Mudrock Line.

3.2.4. Water Saturation (S\(_w\))
Water Saturation which directly is related to rock properties, is the volume ratio filled with the fluid to the total pore volume
and it is dimensionless quantity. In different cases;
- If available fluid in the rock pores is water, then \( S_w = \frac{V_w}{V_p} \)
- If the whole rock pores are just filled with water, then \( V_w = V_p; S_w = 1 \)
- If hydrocarbon and water are available in the rock pores, then \( V_{hy} = V_p - V_w; S_w = (V_p - V_{hy}) / V_p \)

3.2.5. Porosity (\( \phi \))
Porosity which also is related to rock properties, is defined as pore volume divided by bulk volume. The value is usually
shown as a fraction between 0 and 1 or a percentage varying between 0% and 100%.

\[
\phi = \frac{V_{pore}}{V_{bulk}} = \left( \frac{V_{bulk} - V_{matrix}}{V_{bulk}} \right) = \left( \frac{V_{bulk} - \frac{W_{dry}}{\rho_{matrix}}}{V_{bulk}} \right)
\]

where
- \( V_{pore} \) : pore volume
- \( V_{bulk} \) : bulk rock volume
- \( V_{matrix} \) : volume of solid particles composing the matrix
- \( W_{dry} \) : total dry weight of rock
- \( \rho_{matrix} \) : mean density of mineral matrix

It should be considered that the porosity does not give any information about the size and distribution of pores or its
connection.

3.2.6. The Biot-Gassmann Theory
The Biot-Gassmann modeling theory (Gregory 1977) is used in AVO program. By importing the P-wave velocities and
densities of rocks with the known porosity and water saturation, new P and S-wave velocities and densities based on new
porosity or water saturation values could be derived. In this calculation some parameters such as bulk modulus of the water,
hydrocarbon and matrix are known.
\[ K_{\text{sat}} = K_{\text{dry}} + \left( \frac{\beta^2}{\phi + \left( \frac{\beta - \phi}{K_{m}} \right)} \right) \]

where \[ \beta = 1 - \left( \frac{K_{\text{dry}}}{K_{m}} \right) \]

\[ \beta = \text{Biot coefficient} \]

\( K_{\text{sat}} \): Bulk modulus of saturated rock
\( K_{f} \): Bulk modulus of the fluid; known
\( K_{\text{bulk}} \): Bulk modulus of dry rock
\( K_{m} \): Bulk modulus of mineral components; known

By using \( V_{P} - V_{S} \) values, this formula could be re-written as follows:

\[ K_{\text{sat}} = \rho_{\text{sat}} V_{P}^2 - \left( \frac{4}{3} \rho_{\text{sat}} V_{S}^2 \right) \]

### 3.2.7. AVO Reservoir Sand Classification

**AVO Attribute Theory**

Another approach in AVO program is known as Intercept/Gradients quantities, which are analyzed for AVO anomalies. The isotropic homogeneous elastic media is assumed at the interface and by plotting reflecting amplitude versus offset (angle), the point where the best fit line meets the zero-offset axis is called Intercept and the slope of that is known as Gradient (Fig 3.1).

Aki-Richards’ approximation of Zoeppritz equations (1980) is written in the formula as below:

\[ R(\Theta) \approx A + B \sin^2(\Theta) + C \sin^2(\Theta) \tan^2(\Theta) \]

where \[ R: \text{Reflection coefficient as a function of average angle } \Theta, \]

\[ A = \frac{1}{2} \left( \frac{\Delta V_{P}}{V_{P}} + \frac{\Delta \rho}{\rho} \right) \]

\[ B = \frac{1}{2} \left( \frac{\Delta V_{P}}{V_{P}} - 2 \left( \frac{\rho_{s}}{\rho_{P}} \right)^2 \left( 2 \Delta \frac{\rho_{S}}{\rho} + \Delta \rho \right) \right) \]

\[ C = \frac{1}{2} \left( \Delta \frac{V_{P}}{V_{P}} \right) \]

where \[ \Delta V_{P} = \left( V_{P2} - V_{P1} \right); \text{ the change of P-wave velocities across the interface} \]

\[ V_{P} = \left( \frac{V_{P2} + V_{P1}}{2} \right); \text{ the average P-wave velocities across the interface} \]

\[ \Delta V_{S} = \left( V_{S2} - V_{S1} \right); \text{ the change of S-wave velocities across the interface} \]
\[ V_s = \left( \frac{V_{s1} + V_{s2}}{2} \right) \]; the average S-wave velocity across the interface
\[ \Delta \rho = (\rho_2 - \rho_1) \]; the change of density across the interface
\[ \rho = \left( \frac{\rho_2 + \rho_1}{2} \right) \]; the average density across the interface

Fig. 3.1. Definition of Intercept and Gradient (AVO Hampson Russell software)

Shuey (1985) accounted a polynomial fit for reflection coefficient, density and Poisson’s ratio calculations and the simplification of Zoeppritz equations described the angular dependence of P-wave reflection coefficients with Intercept/Gradient values. And the results are accurate for angles up to 35 degree (Hampson Russell AVO Tutorial).

\[ R(\theta) \approx A + B \sin^2(\theta) \]

where
- A: AVO intercept
- B: AVO gradient

AVO analysis on CDP gathers provide information about the lithology and pore fluid of rocks, therefore four AVO classes are investigated based on seismic response at top reservoir and also acoustic impedance contrast over interfaces. AVO characteristics of gas-sand reflections were classified by Rutterford and William (1989), Ross and Kinman (1995) and Castagna (1997) (Fig. 3.2.).
3.2.8. FRM (Fluid Replacement Modeling)
FRM modules allow you to see how changing certain properties within different fluid could vary the logs values and explain the petrophysical concepts. The different rock properties are investigated in the synthetic and the real models to interpret variations.

3.2.9. Seismic Wavelet
The wave form is changed through a linear filter such as earth layers which is known as Convolution. If the wavelet convolves with reflectivity and plus noises, then the result of this basic convolutional model would be known as Seismic trace.

\[ S_j = \sum_{j} (R_jW_{j+1} + n_j) \]

where
- \( R_j \): the Zero-offset reflectivity of the earth expressed as a time series, up to top of \( j \)
- \( W_j \): Seismic wavelet constant
- \( n_j \): Additive measurement noise for \( n \) layers

Wavelet is the generation of seismic source signature by using mathematics and defines by amplitude spectrum (amplitude Vs frequency) and phase spectrum (phase Vs frequency). Different factors could change the wavelets such as near surface effects, multiples, NMO stretch and processing artifacts.

**Ricker wavelet**, which is used for generating synthetic seismograms, can be changed by time, phase and frequency. The dominant frequency is the frequency response of the wavelet, corresponding to maximum amplitude and also close to the Cambrian reservoir. The phase also assumes as a linear phase with phase rotation equals to zero, sample rate 4ms and wavelet length 200ms (Fig 3.3).
Fig. 3.3. Ricker wavelet which is used in synthetic modeling in time and frequency domains.

3.2.10. Synthetic Models

The applied Synthetics options for the modeling are:

- Zoeppritz equations
- Aki-Richards equations
- Elastic wave equations
- Finite Difference equations

**Zoeppritz Equation**

In Zoeppritz calculations (1919) the amplitude of reflected and transmitted waves at interface are based on conservation of stress and displacement along the boundary of media. It shows how the incident, reflected and transmitted compressional and shear waves are related together at an interface of isotropic media.

The Zoeppritz equation can be written in matrix form of angles (incident, reflected and transmitted) for P and S-waves, velocities and densities. It is simplified in three forms; the first one gives the amplitude at normal incident, the second one works for intermediate angles and the last term is the combination of elastic properties (Shuey, R. T., 1985; A simplification of the Zoeppritz equations). This linearized version, which usually is applied in AVO calculations, uses the averages and differences of those parameters. In AVO program, the Zoeppritz calculations are based on the plane P-wave propagation, and different approximations are made afterward such as Bortfield approximations (1961).

**Aki-Richards Approximation**

Aki-Richards (1979) gave the simplified forms of Zoeppritz equations, and when the Zero-offset reflectivity value << 1, the difference would be quite small.

Aki-Richards equation in full format is written in three terms by using average properties of P, S-wave velocities and densities between two layers.

\[
\begin{aligned}
    r_\theta &= \frac{1}{2} \sin^2 \theta \left( \frac{\Delta V_p}{V_p} \right) - 4 \left( \frac{V_S}{V_p} \right)^2 \sin^2 (\theta) \left( \frac{\Delta V_s}{V_s} \right) + \frac{1}{2} \left( \frac{V_S}{V_p} \right)^2 \sin^2 (\theta) \frac{\Delta \rho}{\rho} \\
\end{aligned}
\]

By using different input parameters and resulting different outputs, different number of equations are obtained from the Aki-Richards equation.
Elastic Wave Equation

The Elastic wave equation is based on spherical wave propagation, and internal multiples and mode-converted events are calculated by using reflectivity modeling. It is more accurate for complex models such as thin target layer with large impedance contrasts. In the isotropic media, the plane and spherical waves usually have the same travel time and also the same incident angles (Li, Y., Downton, J., Xu, Y., 2004; AVO modeling in seismic processing and Interpretation II: Methodologies).

The Zoeppritz and Full Elastic equations are two commonly used techniques in the AVO modeling. Even though the Zoeppritz modeling is known as a fast and easy method for identifying primary reflections, and the Elastic wave modeling accounts for direct waves, reflection waves, converted waves, head waves and also diffracted waves (Li, Y., Downton, J., Xu, Y., 2004; AVO modeling in seismic processing and Interpretation II: Methodologies).

Finite Difference

Finite Difference method (FDM) uses the numerical solution for the partial differential equations and is widely applied in the 2D and 3D seismic modeling. In FD methods, the velocity-stress formulation is basically used on the staggered grids to model seismic wave, which represents the wave field function in different numerical derivatives (Juhlin, C., 1995; Finite Difference Elastic wave propagation in 2D heterogeneous transversely isotropic media). For dense grids, the calculation of direct method is more accurate without any restriction about material changes, but it will increase the memorial volume and the modeling cost of the complex geological structures in seismic frequency range. This method does not encounter any restriction on modeling of the complex geology and different wave modes.

3.3. Methodologies

Different fluid substitutions alter well logs properties and these can be used to create Zero-offset or offset synthetic seismograms in the AVO modeling software. Two parameters saturation and porosity are investigated and the resulting synthetic seismograms analyzed. All the models are based on the B-9 well data which is long distance away from the seismic profile.

3.3.1. Fluid Substitutions

In the Fluid Replacement Modeling (FRM) module in the AVO program, the Gassmann theory is applied which calculates the log response to the variation of various petrophysical parameters. Saturation and porosity are parameters which are considered in this part.

• Saturation parameter

In this first scenario the impact of substituting CO\textsubscript{2} gas was investigated. Using the FRM module brine (assumed to be present in the B-9 well) is replaced by variable amounts of CO\textsubscript{2}.

In this first scenario P-wave and density logs are known, porosity can be calculated using density log values and S-wave log values are assumed based on Castagna’s equation. Fluid composition is considered in 2 phases: Brine + Gas and the water saturation value is considered to be 100%. The depth of interest is defined between the top and base of the Faludden sandstone, from 998.400 m to 1046m below sea level. For the petrophysical parameters: Matrix and Fluid parameters are specified, matrix type defaults as sandstone, plus default Brine and Gas values. For the output parameters, porosity values are assumed to be equal to the input, and the gas saturation value (CO\textsubscript{2}) changes between 0 to 75 %.

• Porosity parameter

In the second scenario, the porosity values are changed from 5% to 15% in the target zone to see how it effects the AVO variations in the synthetic models. The fluid saturation for the models was kept constant at 100% brine. This was done using the Fluid Replacement Modeling (FRM) module. The input values are as follows:

P-wave and density logs are known, porosity can be calculated by density log value, S-wave log will be assumed based on Castagna’s equation, Fluid composition is considered 2 phases: Brine + Gas and water saturation value is equal to 100%. The depth of interest is the same as before, the Faludden sandstone, from 998.400 m to 1046m below sea level. For the petrophysical parameters: Matrix type defaults as sandstone, plus default values for Brine and Gas. For the output results a constant saturation was assumed equal to the input (i.e. 100% brine) and only the porosity was varied.
3.3.2. Synthetic Modeling Options

3.3.2.1. Test Modeling
For the initial modeling exercise, a simple earth model with single interface (which is free from tuning effects) was assumed, with known P-wave velocity and density logs. Castagna’s equation was used to calculate the S-wave velocities. The following model A shows the interface of the Ordovician (Kvarne – shale/mudstone) layer on top and the Ordovician (Bentonitic Limestone - Limestone) below and the model B, the Ordovician (Bentonitic Limestone - Limestone) layer on top and the Cambrian (Faludden - Sand) below (Fig 3.4).

Model A

**Kvarne**

$V_p = 4700 \text{ m/s } \rho = 2.49 \frac{\text{g}}{\text{cc}} h = 500\text{m}$

**Limestone**

$V_p = 5065.8 \text{ m/s } \rho = 2.67 \frac{\text{g}}{\text{cc}} h = 700\text{m}$

Model B

**Limestone**

$v_p = 5065.8 \text{ m/s } \rho = 2.67 \frac{\text{g}}{\text{cc}} h = 500\text{m}$

**Faludden Sandstone**

$v_p = 4258.8 \text{ m/s } \rho = 2.43 \frac{\text{g}}{\text{cc}} h = 700\text{m}$

*Fig 3.4. A) and B) shows the testing models parameters and the logs at interface*

In the AVO program, different AVO synthetic models were generated using the simple logs shown above, as well as those generated using the FRM module. The following parameters were used:

**Used Wavelet:** Ricker wavelet

**Uniform Offset Range:** selected 60 offsets, from 50-3037 m (similar to real data)

**Target Zone for Detail Modeling:** Detailed modeling uses ray tracing technique over all layers within this zone and computes the reflection coefficient. But for the layers outside the zone, the reflection amplitude is assumed to correspond to the Zero-offset which decreases the calculation time. It could be calculated in the time or depth domain: 900-1300 ms
Modeling Option:

- **Processing Sample Rate**: It sets the sample rate in synthetic calculation and it is not required to be equal to real processed data: 4ms
- **Output Domain**: Time
- **Output Sample Rate**: It controls the sample rate of the actual synthetic SEG-Y file and was set to 4ms.
- **Synthetic Type**: It defines what type of synthetic and NMO corrected chosen because it will be estimated around NMO-corrected seismic data.
- **Modeling Options**: The different options are; “Geometrical spreading” which corrects for the 3D spread of energy from the source, “Transmission losses” which calculates the loss of incident angle’s energy through the earth layers, “Anisotropy” which is applicable for weak anisotropic lithology, “Array effect” that calculates for the effect of source and receiver arrays and “Mute post-critical events” which was applied for the incident angles greater than the critical angle and sets the reflection amplitude to zero.

The synthetic results of the test models are shown for the Zoeppritz, Aki-Richards and Elastic wave equations.

For a better understanding of synthetic seismograms, the “CREWS Zoeppritz Explorer Applet” was also used to calculate the Reflection coefficient for the two models discussed above. The different reflection coefficient values are calculated for different medium parameters such as the density and the P-wave and S-wave velocities. The coefficients are all real for small enough angles, but become complex after passing the critical angle. The results show both magnitude and phase variation with the incident angle. The synthetic offset gathers which are generated by using the AVO software shown in figures 3.5 and 3.6.
Fig 3.5. AVO Synthetic results for the first test model (Top-Kvarne +Limestone) after applying different equations a) Aki-Richards b) Elastic wave c) Zoeppritz without applying mute d) Zoeppritz with applying mute. The most reasonable seismogram is obtained with the Zoeppritz equation.

Fig 3.6. AVO Synthetic results for the second test model (Limestone+ Faludden Sandstone) after applying different equations a) Aki-Richards b) Elastic wave c) Zoeppritz without applying mute. The Zoeppritz seismogram is chosen for the rest of calculation.
Fig 3.7. The CREWS Zoeppritz Explorer 2.2 plots which show the Reflection coefficient variation for different incident angles a) the interface on top of the limestone and b) below the limestone layer (www.crews.org).

By comparing these results, if we consider reflection at the boundary between the Limestone and the Faludden sandstone, they support a change in Reflection coefficient with incident angle. The large increase in amplitude that happened at large offsets, which is seen in the Zoeppritz applet with changing the phase, could be muted in AVO modeling options. For the angles more than the critical angle, it can remove the large amplitude events as an option in the seismogram, which is not available in the Elastic wave method. With considering the theories of different equations and methods, the Zoeppritz equation is selected for our real data modeling investigation which uses simple ray-tracing in the interfaces and shows more reasonable amplitude variation with the offset for P-wave.

3.3.2.2. Detailed Modeling – B-9 well

- Saturation

The input data for making synthetic seismograms include the P-wave, S-wave and density logs before and after fluid substitution at target zone with CO2 gas (Fig. 3.8.). The calculation is based on three different equations (which were explained before), the Zoeppritz, Finite Difference and Zero-offset. For getting rid of high frequency noise such as spikes and having better results in comparison with the real data, the logs were edited using a Median Filter; Operator length: 11 (applied zone: the whole logs) Block size: 20m (applied zone: up to the Faludden sandstone layer)

The Finite Difference equation which is run through the Seismic Unix code (Juhlin C. 1995. Finite Difference Elastic wave propagation in 2D heterogeneous transversely isotropic media, Uppsala University) was used to generate offset synthetics for this study as well. The necessary inputs are the P-wave, S-wave velocities and density log values plus geometry data which describe the depth model for different layers. The Finite Difference synthetic seismograms were obtained for different values of gas saturation as well as the original brine saturated logs. The logs were edited using a blocking size of 3m.
Fig. 3.8. Density, P-wave and S-wave logs before and after fluid substitutions at the target zone. Blue color shows 0% gas (CO2) saturation, purple color 5% gas (CO2) saturation and orange color 50% gas (CO2) saturation.

The different modeling outputs are sorted to CDP gathers and displayed together so they can be compared. (Fig. 3.9. shows results for the Zero-offset equation, Fig.3.10. for the Zoeppritz equation and Fig.3.11. for the Finite Difference equation).

Fig. 3.9. Zero-offset synthetic result which shows how amplitude varies with increasing gas saturation at the top and base of the Faludden sandstone.
Fig. 3.10. Plots a) and b) show amplitude variations with offset for the Zoeppritz equation at top and base of the Faludden sandstone after replacing with certain amounts of gas. The CDP gathers data are picked before critical angle.
Fig. 3.11. Plots a) and b) show amplitude variations for whole offset after running the Finite Difference equation. The gathers for three amounts of gas saturations for top and base of the Faludden sandstone are plotted.

At the top of the Faludden Sandstone, the Zoeppritz equations plot for the limited offset range shows that while the greatest AVO variation occurs between 0 and 5% gas, adding more gas after this point does not change the response much. The amount of variation at the base of the Faludden sandstone is quite small in comparison with the top of the Faludden sandstone (Fig.3.10.).

The Finite Difference plots also show the same AVO variation trend as the Zoeppritz models, with the greatest variation in amplitude observed with the addition of a small amount of gas (5%) (Fig.3.11.).
In order to assess the response in the stacked section the results from the three models were NMO corrected and stacked. The stacked traces from the various offset synthetics with the different gas saturations of 0%, 5%, 50% are plotted together (Fig. 3.12).

*Fig. 3.12. Variation of amplitude with gas saturation of the stacked offset synthetics, a) top of the Faludden sandstone and b) base of the Faludden sandstone interface. Results have been normalized to 0% gas saturation.*
In the synthetic seismograms, at the interface of the top Faludden sandstone, it is seen that in all the models the amplitude increases after adding 5% gas. There is little change in the amplitude between 5% and 50% gas. The general trend of amplitude with offset is the same for all models, albeit with different values. At the base of the Faludden sandstone the amplitude decreases after adding 5% gas, a gradual change is observed after adding more gas, up to 50% in the Zoeppritz and the Zero-offset. Therefore a strong AVO anomaly associated with these interfaces as a result of the presence of gas is not anticipated. A change in the stacked amplitude as a result of small quantities of gas is suggested by these results.

- **Porosity**

  The new P-wave, S-wave and density logs acquired after changing the porosity in the FRM module for the Faludden sandstone were used as input for further seismic modeling and the results are described below (Fig.3.13.). Before generating offset synthetics with the logs, they were edited by applying a Median Filter with an operator length of 11 samples over the whole logs and blocking with a size of 20m up to the target zone. The Zoeppritz and the Zero-offset algorithms were used to generate synthetics in order to observe the effects of varying porosity.

*Fig.3.13. Density, P-wave and S-wave logs with different fluid substitution values at the target zone. Blue color represents for the 5% porosity, orange color 7.5% porosity, red color 13% and purple color 15% porosity.*
The offset synthetics, which are not displayed here, clearly indicate very little change in amplitude along offset for the different porosities in the target sand. Only the amplitudes of the stacked offset synthetics are shown below (Fig. 3.14.).

Fig. 3.14. Plots show stack amplitude variation with changing porosity for a) the top and b) the base of Faludden sandstone calculated using the Zoeppritz and the Zero-offset equations.
It can be seen that the stack amplitude variation with the different porosities has the same general trend with both the Zoeppritz and Zero-offset models for the base of the Faludden sandstone. At the interface of the Faludden sandstone and Limestone, the amplitude increases with increasing porosity but at the base of the Faludden sandstone the opposite is observed.

3.4. AVO Investigation in Real Data

3.4.1. AVO Attributes

Despite the modeling results, which indicate that a strong AVO anomaly is not anticipated as a result of variations in gas saturation or porosity, efforts were made to investigate the AVO characteristics of the real data. In order to do this, the processed CDP gathers and the stacked data were imported into the Hampson Russell AVO program for analysis. There are different methods for the detection of gas, especially in sandstone reservoirs, among them AVO attributes and Intercept/Gradient Crossplots have been used to identify and characterize AVO anomalies. On the figures below, several AVO attributes which are extracted from generated super gathers of the real data, shown as color plots. The wiggle shows the Intercept, and the color indicates a product of the Intercept and Gradient.

In the first plot, the color data volume which is the product of (A*B) was analyzed for the specified CDP ranges. The color data range is between -1e-22 to 1e22. Around some CDPs bright spots can be seen, these have been targeted for closer investigation. The Crossplot of Intercept and Gradient have been prepared for all the traces for the intervals stated below.

In another plot, the Scaled Poisson’s Ratio (aA+Bb) is also prepared with the color data range between -0.09 to +0.09 m and shows the AVO variations. The other parameters are as follows:

**CDP ranges:** 3700-3800; 6252-6340; 6740-6804

**X Axis Attribute:** Intercept (A)

**Y Axis Attribute:** Gradient (B)

**Scale Factor:** \( a=0.5 \); \( b=0.5 \); \( k=\left(\frac{V_S}{V_P}\right)^2 = 0.25 \)

**Data Slice:** Constant time over target zone {Faludden sandstone}

**Color Key Option:** Time

**Initial Filter Option:** Peaks and Troughs

*Fig.3.15.* AVO attribute analysis along the CDP 3700-3800, which is shown in a) Crossplot b) A*B product c) Scaled Poisson’s Ratio for the Intercept and Gradient values.
No obvious anomaly is seen in the A*B product, and based on the fact that A<0 in the data, no obvious cloud, related to the target zone time, is distinguished away from the wet trend in the Crossplot. In the SPR image, no distinguished low amplitude is seen on top of the layer (Fig. 3.15.).

Fig. 3.16. AVO attribute analysis along the CDP 6150-6250 which is shown in a) Crossplot b) A*B product c) Scaled Poisson’s Ratio for the Intercept and Gradient values.

The bright spot is seen in the A*B product, and also the cross plot shows that there is a cloud away from the trend line in the quadrant III, which indicates it could come from an event within our target zone, the Faludden sands, A<0, B<0 (Fig. 3.16.)

Fig. 3.17. AVO attribute analysis along the CDP 6740-6840 which is shown in a) Crossplot b) A*B product c) Scaled Poisson’s Ratio for the Intercept and Gradient values.
A wider anomaly is seen in the A*B product which should not be confused with the Limestone effects. Several clouds corresponding to the top of the Faludden layer in quadrant III (A<0 and B<0) can be observed. Yet there is no obvious low amplitude value at the top of the layer (Fig. 3.17.). Based on the results through different plots and the classification of sandstone (class I, II, III and IV), in figures 3.16., the results show an AVO anomaly which might be due to hydrocarbon, lithological effects or noise in the data. If it is considered as the presence of hydrocarbons, the behavior could follow that of the Class III sandstone, the SPR result plots do not support or deny the assumption.

3.4.2. AVO Changes in Seismic Data
Amplitude variations with offset at the top of the Faludden sandstone for different CDP gathers of the processed line data, are averaged and plotted below. In general the pre-stack data look quite noisy, there is a change in mean amplitude with offset, but this is not pronounced relative to the noise in the data. In figure 3.18., plot a) there is a change in amplitude for the near and far offsets. The maximum amplitude variation in this plot is less than other CDP gathers. The plots b), c) and d) show similar trends for AVO variation. Toward higher CDP numbers (plot b and c) the amplitude variation increases for the near and mid offsets. Some of these trends could be potential targets for further investigation.
Fig. 3.18. Average AVO variation for the different CDP gather along the profile, a) CDP 3700-3748, b) CDP 6196-6244, c) CDP 6252-6340, d) CDP 6740-6804 for every 8th CDP are plotted. The results have been normalized to the near offset amplitude.

The whole observations of AVO changes for the real pre-stacked data, and also the Intercept and Gradient results can lead to the point that we do not have strong tools to prove the presence of gas sands in the target zone. Our preliminary guess of the presence of class III gas sands cannot be supported by the detailed analysis of the real data from the study area. Since it is potentially classified as class III sandstone, the magnitude of amplitude should increase with offset, but we cannot see this in the real data which looks quite noisy.
3.5. AVO Discussion

- Testing several synthetic modeling methods, using the well-log data, provided similar AVO results.
- In the modeled seismograms, increasing the Gas (CO₂) saturation up to 5% in our target zone (the Faludden sandstone) results in a large change in amplitude in stack/gathers, adding more gas does not make a large difference.
- In the modeled seismograms, increasing the porosity inside the target zone (the Faludden sandstone) leads to a change in the amplitude in the stack/gathers.
- AVO Intercept-Gradient attribute analysis shows anomalies in Crossplots, in some parts of the line, especially around CDP 6150-6250 that could be interpreted as AVO anomalies, lithology effects or noise.
- Amplitude variation of the pre-stack seismic data looks quite noisy and does not show significant variations in different parts of the line when compared with the noise level. However, the general trend is the same for the whole CDP range.
- Amplitude variations at top of the Faludden sandstone in the pre-stack seismic data show that the maximum amplitude change happens towards the larger CDP numbers, which makes this area more interesting to study for any potential AVO anomaly in the future.
- Having better well log data (at least S-wave velocity) can be helpful for improving the interpretation and modeling.
Chapter 4: Conclusion

Based on the results associated with the methods and studies applied in this project, the following conclusions can be made:

- Processing of the marine seismic data, with testing new modules and processes and creating a new workflow, improves the quality of the final stacked section. This new processing workflow improved the signal to noise ratio of the data resulting better image, especially around 1000 ms related to the Cambrian formation. Multiples were removed efficiently, by applying Deconvolution in the Tau-p domain and Deconvolution in the Time domain with proper parameters, thus resulting in significant improvement around 500 ms. The final stacked image gave high confidence for doing geological interpretation and understanding the structures of the area. The high amplitude reflections in the stacked section, interpreted as the Faludden sandstone, may have potential for future hydrocarbon investigations.

- In AVO analysis, different synthetic modeling methods were tested to study the AVO behavior and the results showed similar amplitude variation for the tested methods. In the modeled seismograms, increasing the Gas (CO2) saturation up to 5% and also increasing the porosity inside the target zone (the Faludden sandstone) can change the amplitude in stack/ gathers. Amplitude variations of pre-stack seismic data do not show significant changes along the line, in comparison with the noise level in the data. However the maximum amplitude changes happen towards the larger CDP numbers, which makes this area more interesting to investigate for any potential AVO anomaly in the future. AVO attribute analysis along the profile shows anomalies in some parts, especially around CDP 6150-6250 in the Intercept-Gradient Crossplot which could be interpreted as hydrocarbon anomalies, lithology effects or noise.
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Appendix I

Previous processing stacked result (Line OP0701-260, prepared by OPAB).
Nr 1 Geomorphological mapping and hazard assessment of alpine areas in Vorarlberg, Austria, Marcus Gustavsson

Nr 2 Verification of the Turbulence Index used at SMHI, Stefan Bergman

Nr 3 Forecasting the next day’s maximum and minimum temperature in Vancouver, Canada by using artificial neural network models, Magnus Nilsson

Nr 4 The tectonic history of the Skyttorp-Vattholma fault zone, south-central Sweden, Anna Victoria Engström

Nr 5 Investigation on Surface energy fluxes and their relationship to synoptic weather patterns on Storglaciären, northern Sweden, Yvonne Kramer


Nr 262 Meteorological Investigation of Preconditions for Extreme-Scale Wind Turbines in Scandinavia. Christoffer Hallgren, May 2013


Nr 264 A climatological study of Clear Air Turbulence over the North Atlantic. Leon Lee, June 2013

Nr 265 Elastic Anisotropy of Deformation Zones in both Seismic and Ultrasonic Frequencies: An Example from the Bergslagen Region, Eastern Sweden. Pouya Ahmadi, June 2013

Nr 266 Investigation on the Character of the Subglacial Drainage System in the Lower Part of the Ablation Area of Storglaciären, Northern Sweden. Fanny Ekblom Johansson, July 2013

Nr 267 Basalt and Andesite Magma Storage and Evolution in Puyehue Volcano (40.5 °S), Chile. Joaquim Otero, September 2013


Nr 269 Changes in Arsenic Levels in the Precambrian Oceans in Relation to the Upcome of Free Oxygen. Emma H.M. Arvestål, November 2013

Nr 270 Environmental and Climate Change During Holocene in Hjaltadalur, Skagafjörður, North Iceland - Peat core analysis and pollen identification. Jenny N. Johansson, November 2013