A 3D Sub-Surface Characterisation of the Arnager Greensand, South-west Skåne

En 3D ytkarakterisering av Arnager Greensand, södra Sverige

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Abstract

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A surface characterisation of the Arnager Greensand in south Sweden, a deep saline aquifer found to be suitable for geological storage of CO₂ or energy storage, was undertaken in this thesis. Vintage seismic reflection data only available as scanned tiff images of the final stacked sections were digitized and processed using modern interpretation software to provide new insights into the morphology of the Arnager Greensand and to analyse the reservoir’s potential as an energy storage unit. The primary energy storage method discussed and evaluated was Compressed Air Energy Storage (CAES). This is a modern energy storage method developed as a tool for regulating inherently intermittent renewable energy sources. Such methods are key to the growth of the renewable sector and for providing a competitive alternative to fossil fuels. Moreover, in comparison with other energy storage methods such as battery storage, CAES is known to have strong potential to deliver high-performance energy storage at large scales for relatively low costs compared with any other solution. Previous studies conducted in the 1980’s by Swedegas produced a 2D isochrone surface map of the Arnager Greensand by hand interpolation methods utilizing analogue data collected by Oljeprospektering AB (OPAB, currently Svenska Petroleum). The Geological Survey of Sweden (SGU) has now transferred a vast amount of the historical OPAB dataset to modern digital format. This thesis contributes to those efforts and seeks to find new interpretations from the vintage data. A more comprehensive 3D model of the top of the Arnager Greensand employing the application of modern interpretation software was produced in this study. Strong similarities between morphology and dip-trend have been observed between the surface model generated in this report and the historical Swedegas isochrone surface map. Reservoir properties such as thickness, porosity and permeability gleaned from the earlier reports show the Arnager Greensand to exhibit excellent potential as a storage unit. Preliminary effective capacity estimates by Nordic CCS Competence centre show the Aranger Greensand to be one of the top three storage aquifers in Sweden. These positive appraisals highlight the need for a better characterization of the Aranger Greensand through data digitization and modern interpretation means. This thesis contributes to that endeavour.

Keywords: Arnager Greensand, digitization, depth conversion, reservoir, storage potential

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Gregory Marcel Davies Jones


Nyckelord: Arnager Greensand, digitalisering, djupkonvertering, reservoar, lagringspotential

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1. Background

1.1 Renewable Energy and Energy Storage

The United Nation’s primary body for assessing and reporting on current climate science is the Intergovernmental Panel on Climate Change (IPCC). The IPCC initially made mention of human activity being linked to rises in global carbon dioxide (CO₂) emissions in its first report in 1990 (IPCC, 1990). Today, global CO₂ emissions from human activity continue their upward trajectory. The year 2018 saw an unprecedented rise in global carbon emissions, with a sustained increase in uses of fossil fuels worldwide (Le Quéré et al., 2018).

Despite the imprudent persistence in fossil fuel usage, developments in and recourse to renewable energy technologies are also making ground. 2017 was a record-breaking year for global renewable energy usage. The largest increase in global renewable energy power capacity combined with falling costs and increases in investment ensured that the renewable transition is underway (REN 21, 2017). Given the 2018 Global Carbon Budget outcome (Le Quéré et al., 2018) this evidently does not necessarily mean a decrease in fossil fuel usage but at least it paves the way for further development of the renewable sector and, in so doing, provides cost-effective energy alternatives to fossil fuels.

A significant caveat in the estimation of renewable energy production is the intermittent nature of renewable energy sources. In the example of wind energy - a prominent source of renewable energy in Sweden, the intermittence in supply arises from the inherent variability characteristics associated with wind conditions over time. For a future energy supply based on renewables, energy storage will become a crucial component to compensate for producer fluctuations and seasonal variability. Locally, it can improve the management of distribution networks whilst reducing costs and improving efficiency. In this way, it can ease the introduction of renewables into the energy market, accelerate the decarbonization of the electricity grid, improve the security, efficiency and distribution of electricity transmission, stabilize market prices for electricity, whilst simultaneously ensuring a higher security of energy supply.

Energy storage technologies involving the use of underground geological reservoirs offer large capacities, discharge rates and storage times ranging from hours to years (GeoEnergy, 2014), thereby bringing all the advantages of a large-scale seasonal energy storage system whilst minimising environmental and social impacts. Such a system will be vital for northern
countries like Sweden where increased lighting and heating demands, coupled with higher average economic activity in winter periods, result in winter energy consumption that is twice that of summer periods (Hekkenberg et al., 2009; Figure 1).

Figure 1. Seasonal variation in daily electricity demand in several EU countries over the period 1986–2006 (Hekkenberg et al., 2009).

There are myriad energy storage methods currently in operation or in development, ranging from conventional battery systems to super-conducting magnetic energy storage and thermal energy storage. Compressed Air Energy Storage (CAES), the predominant method discussed in this report and which is often used in conjunction with wind-energy, is one such technology that could provide an effective approach to stabilising wind-energy generation.

1.2 Compressed Air Energy Storage

The mechanism of CAES works by using remnant electrical energy generated from wind to compress air which is then stored within a reservoir (Figure 2). During periods of minimal wind or high electrical demand, electricity is regenerated by recovering and expanding the
compressed air through turbines (Levendal et al., 2018). Gas can be added during this phase to aid the expansion; geo-thermal energy, more environmentally friendly, can likewise be stored during compression and this can then be used in the expansion. This method is known as Advanced Adiabatic (no heat transfer) CAES (AA-CAES), wherein no fuel is required at the expansion phase, thus resulting in a more carbon friendly approach (RWE Energy, 2010). In conventional CAES, the excess electricity from wind energy is used to power a chain of compressors which draw in and compress air. The compressed air is then stored at high pressure within a suitable storage medium; the medium investigated in this report is a geological formation known as a natural subsurface reservoir, in this case a porous rock formation. As described above, when required, the compressed air can then be extracted from the reservoir and subsequently expanded to turn turbines at the surface and hence generate electrical energy (Levendal et al., 2018).

![Diagram of Diabatic CAES](image)

**Figure 2.** Diabatic CAES (conventional) – schematic showing a salt dome used as the storage medium and natural gas as fuel in the expansion process (Energy Storage Sense, 2017)

### 1.2.1 The Ideal Storage Media

There are three main geological formations that are considered suitable for CAES energy storage: Underground salt caverns; hard and porous rocks. Of these main classifications, salt-dome formations are the most straightforward in terms of developing and then operating at a relatively low cost. A desirable characteristic of salt caverns when considering their suitability for CAES are their inherent elasto-plastic properties. Therefore, salt caverns are less brittle by
nature and hence exhibit more malleable characteristics when subject to stress. CAES storage reservoirs formed from salt caverns are accordingly less susceptible to air leakage (Succar and Williams, 2008).

The geological formation discussed in this thesis is the Arnager Greensand aquifer – a saline aquifer located in Southwest Scania (see section 1.4). This comes under the third category outlined above - the porous rock geological formation such as sandstone or carbonate rock.

Porous reservoirs have the potential to be the least costly of all the CAES options when considering large-scale CAES plants. The estimated development cost for a saline aquifer CAES plant with incremental storage volume expansion is 0.11 dollars/kWh (Succar and Williams, 2008). A limitation of employing saline aquifers as CAES sites is the extensive characterisation of the target site that needs to be carried out prior to the storage. In this regard it is useful to note that knowledge can be gleaned from existing studies undertaken for other underground fluid storage applications such as natural gas.

An advantage particular to the area examined in this report is that pre-existing hydrocarbon exploration data can be utilized for such assessment. These data are extremely beneficial insofar as they enable the building of a geological map of the target site without the need to carry out a costly, time consuming seismic study (see section 1.3).
1.3 Seismic Reflection Data Set from SW Skåne

The data utilized in this study to more accurately determine the top of the Arnager Greensand were accrued from reflection seismic investigations conducted in the 1970s by Oljeprospektning AB (OPAB) (Figure 3).

Figure 3. Example of vintage data (.tiff) from reflection seismic investigations conducted by OPAB (please see appendix for further examples).

The reflection seismic method is the most widely used geophysical technique. It involves an examination of the Earth’s internal structure by measuring subsurface reflections generated by a surface energy source. This technique has been widely employed in the mining and hydro-carbon industries to study near-surface characteristics (Malehmir et al., 2016). Similar methods can be harnessed to probe deep earth structures using recordings from earthquakes or very large explosions. Reflected seismic waves are particularly sensitive to velocity and density variations and consequently tend to provide greater clarity on vertical and horizontal resolutions than can be acquired from refraction seismology (study of direct seismic phases such as Primary and Secondary) (Shearer, 2009). This clarity in resolution in near-surface investigations is a major
asset when carrying out characterisation of CAES target sites. The attributes of reflection seismology ensure that it is the predominant tool for reservoir-characterisation and monitoring (Ashraf, 2013).

There is a large amount of 2D-reflection seismic data available covering vast areas of the Swedish Baltic Sea region including Gotland and Skåne. The majority of the data were collected between 1970 and 1990. These data, procured for petroleum exploration, consist of both marine and land surveys from a variety of different sources (OPAB, Shell), with by far the greatest amount coming out of the Oljeprospektering AB (OPAB) dataset. These data were later handed to the Geological Survey of Sweden (SGU) who undertook the task to transfer them to a more suitable and accessible format. Despite these efforts by SGU to modernize the OPAB dataset, much of the data still exist only in a form where the geological information cannot easily be extracted. For example, much of the data are present only in the form of scanned tiff images (Figure 3) hence requiring digitization before they can be imported into modern visualization or interpretation software.

This study utilizes two-dimensional (2D) reflection land seismic data from Skåne with the aim of more accurately determining the top of the Arnager Greensand, one of the three most promising storage units in Sweden (Bergmo, 2014), in comparison with the estimate obtained in the mid-1970s (Juhlin et al., 2013).

1.4 Geological Overview – The Arnager Greensand

The focus of this study is in the south of Sweden (Skåne), in particular SW Skåne where the Arnager Greensand aquifer is located. According to reservoir properties, the Arnager Greensand represents one of the most attractive storage units in the area of Skåne (Aagaard et al., 2014, Anthonsen et al., 2014). The Arnager Greensand is part of a regional Lower Cretaceous sequence that overlies a mid-Jurassic unconformity and is located in SW Skåne and in the Kristianstad and Hanö Bay basins. A Lower Cretaceous boundary sandstone is also present as the second main sandstone unit within the Lower Cretaceous sequence. The Arnager Greensand is a partially fault-confined open saline aquifer covering approx. 5200 km² in the Swedish Economic Zone. It is exposed at one location only on the Danish island of Bornholm – at its namesake Arnager bay (Mortensen et al., 2016). Borholm lies in the Baltic Sea and is located in the southernmost region of the Arnager Greensand. The Greensand gently dips towards the North East by between 1 and 2 degrees. It is cut off in the North East by the
Romeleasen fault zone. Dating records put the Aranger Greensand in the Albian - Cenomanian Boundary (100.8 Ma [with ±1.4 Myr uncertainty (analytical precision)]) (Ando, 2016) – the middle of the Cretaceous (Mortensen et al., 2016). The Lower Cretaceous sequence is between 100-150 m thick. This includes its two main sandstone units: The Lower Cretaceous Sandstone (4-27 m) and the Arnager Greensand (17-55 m). The Arnager Greensand is well-mapped in South West Skåne due to oil prospecting initiatives undertaken in the late 20th century. The sizeable acoustic impedance between the Greensand and the overlying limestone gives one of the strongest seismic reflection markers of its kind in Skåne (Figure 4).

The aquifer has good potential as a storage unit in the central and southern parts but the northern region of the Greensand is less suitable (Juhlin et al., 2013). In this region there is a shift to finer-grain size and increased quartz cementation. The storage unit itself does not contain any large structural traps or closures. Comprehensive descriptions of vertical and horizontal anisotropy are not well understood, although the sedimentary facies and well-log responses in the southern regions of the reservoir suggest that there is less anisotropy and more homogeneity (Juhlin et al., 2013).

The Arnager Greensand is characterized by poorly consolidated, fine-to-medium-grained glauconitic quartz arenite. A series of other associated minerals also occurs in the sandstone including micas, pyrite, feldspars and zircon. There is an abundance of glauconite in the sequence, mostly occurring in grain but also in the form of mineralization on other disparate grains (Figure 5).
The Greensand also contains clay in matrix form as well as small deposits of carbonates restricted to primarily the northern region of the sequence. The abundance of galuconoite, carbonates and scattered fossil remnants all suggest a shallow marine deposition setting for the Arnager Greensand (Hajny, 2016).

A Late Cretaceous to Paleocene clayey limestone and chalk caps the Arnager Greensand. This limestone cap varies in thickness between 900 and 1600 m (Mortensen et al., 2016).
Figure 5. Stratigraphic log illustrating defined units and their depositional environment (Hajny, 2016).
2. Methodology

2.1 Digitizing Data

Whilst seismic reflection data is the “standout tool” for probing the structure of the Earth at near surface depths, seismic reflection surveys are costly endeavours, especially when collecting land data. Advancements over the past half-century in computer power and memory mean that digital data storage is now a fraction of the cost it was just a decade or two ago (Griffin, 2015). As a direct result of these computational advancements, large amounts of legacy seismic data, once too costly to process due to their large storage media, can now be utilized. Aside from considerations of cost, there are numerous advantages in studying legacy data using modern tools. Reprocessing of historical data can lead to improved interpretations along with better image constructions. Historical industry data are often de-classified and can be used for academic research purposes. Despite the obvious benefits, there are a number of drawbacks in the processing of such data. A great deal of vintage data is available in only certain formats, such as tapes and scanned images with no record of the original digital data or adequate acquisition and processing documentations. In order to combat this hindrance, a method of vectorizing or digitizing stacked reflection seismic data (available only as printed images) has to be undertaken. Vectorization is defined as the process of digitizing the time and amplitude information characteristics of each trace in the stacked seismic reflection section and subsequently outputting this data in conventional digital format (SEG-Y) (Sopher, 2017).

The algorithm used in this work was written in MATLAB by (Sopher, 2017) (Figure 6). In order to produce the best digitization quality from tiff scans to SEG-Y (Society of Exploration Geophysicists – data processing extension), there were two crucial steps in the processing sequence that needed to be correctly executed. Firstly, once the chosen tiff file was imported into the program, the user was asked to input a number of vectorization parameters. These parameters had an initial default value which the majority of them retained. Exceptions were the output time-sampling frequency and the bandpass corner frequencies, which had to be adjusted to provide better quality digitized SEG-Ys. Most of the scans included information on the processing parameters used which enabled these to be simply put into the MATLAB parameter window. Occasionally, the scans were lacking the output time-sampling frequency and in this instance a standard higher seismic sampling frequency of 2ms was chosen. The general method is outlined below.
### Table 1. Process of Digitization/Vectorization algorithm

<table>
<thead>
<tr>
<th>Step</th>
<th>Action initiated by algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Binary (in this case, tiff format) image is read-in by generating a scan of the original hard copy</td>
</tr>
<tr>
<td>2</td>
<td>Geometry (coordinates of cdp points) file for selected image is loaded from server</td>
</tr>
<tr>
<td>3</td>
<td>Area of image is defined and trace numbers assigned</td>
</tr>
<tr>
<td>4</td>
<td>Timelines and baselines of stacked section are detected</td>
</tr>
<tr>
<td>5</td>
<td>Geometry information is related to detected traces</td>
</tr>
<tr>
<td>6</td>
<td>Waveform of each trace is then extracted and stacked seismic data outputted in SEG-Y format</td>
</tr>
<tr>
<td>7</td>
<td>Quality control options are then offered</td>
</tr>
</tbody>
</table>

A further more extensive processing sequence flowchart is shown on the following page (Figure 6).
Figure 6. Flowchart describing the morphological image processing steps taken for timeline and baseline detection from original input image (Sopher, 2017).
2.2 Map Plotting with Quantum Geographic Information Systems (QGIS)

Plotting and visualizing accurate geospatial information is an important step when characterizing a survey area. Accurate inference of the subsurface becomes more challenging without a comprehensive understanding of the geospatial positioning of the various components within the survey area. QGIS is an open-source geographic information system, where geographical land models to-scale can be plotted with associated coastlines and other characteristics of the terrain. Seismic lines and well-locations amongst other components pertinent to reflection seismic or various other scientific surveys can be created, visualised and analysed using QGIS software (Figure 7). Shape files are the most common file format used for storing vector QGIS data. Shape files contain non-topological vector data alongside corresponding attribute data. Shape files are comprised of three fundamental files types, namely .shp, .shx and .ddf. These three file formats must be present and accessible in the same directory for the mother file to be manipulated (GIS lounge, 2015).

All reflection seismic survey areas investigated within this study were located in south-west Sweden, encompassing three separate regional locations. Swedish territory and coastline were first plotted and subsequently shape files were created corresponding to the existing reflection seismic lines and well-locations for the purpose of geospatial visualisation and analysis.
2.3 Time-to-Depth Conversion

The processing of reflection seismic data is a crucial step in developing accurate interpretations and characterizations. An important feature in that process applied within this study is time-to-depth conversion. Time-to-depth conversion must be carried out in order to build an effective structural model consistent with the geospatial characteristics of the target area. The salient events (reflections) need to be translated from “time” to “depth” (Figure 8). This information is normally best acquired from results obtained independently from seismic reflection data, such as those from velocity logs relating to wells. The conversion was performed using a time to depth conversion module TDCONV1 in GLOBE Claritas (www.globeclaritas.com), which is a software package for 2D and 3D-land and marine seismic data processing. The process required a velocity model, which was obtained from the velocity information provided in the scanned images. Converted seismic data were then checked against Arnager Greensand depth information obtained from boreholes in the area (shown later in thesis).

**Figure 8.** Graphic showing the time-to-depth conversion by assigning velocity models (www.eliis.fr).
2.4 Horizon-Picking

Horizon-picking was conducted using a seismic interpretation software package OpendTect (www.dgbes.com). The interpretation program allows users to infer geologic information from an input of seismic data (Figure 9). OpendTect was utilized in this investigation in order to pick horizons from the digitized seismic data. Horizons are defined as reflection events present within the seismic data which can be tracked along a profile. Horizon-picking allows tracking of a stratigraphic surface and is an essential part of reflection seismic interpretation. Detecting and picking horizons allows the principal reflections to be highlighted and modelled into the geological features of interest. In this study, horizon-tracking was used to detect and model the top of the Arnager Greensand unit.

![Figure 9. OpendTect user interface showing horizon-picking element tool. The picked horizon is shown as a light blue feature (dGB Earth Sciences, 2015).](image-url)
2.5 Interpolation and Plotting

The dataset studied in this report consists of over seventy 2D seismic lines acquired over the southernmost part of Sweden (discussed in section 3.1).

In order to fill in the missing geophysical information in the area of interest and obtain a 3D-map of the top of the Arnager Greensand layer, interpolation is performed within Matlab using a natural neighbour interpolation algorithm. Specifically, the interpolation technique was used here to estimate the surface depth of the Arnager Greensand in areas where acquisition lines were absent but within the wider survey area. The result of the interpolation, i.e the 3D-surface model of the Arnager Greensand was then plotted using Generic Mapping Tools (GMT).
3. Results

3.1 Digitized Tiff Files

Over 120 separate scans (.tiff format) were successfully digitized into the conventional SEG-Y format. These scans were compiled from over 70 profiles in the Swedish south-west region. The majority of these profiles were located within three main profile areas (D69, C71, CV73 – see section 3.2, QGIS map plot). For a full breakdown of the digitization process see Methodology section 2.1.

To ensure effective quality control, a comparison between the original scan and SEG-Y was made during the digitization process (Figures 10 and 11).

Figure 10. Graphic of quality control plot line C71_13 (location discussed in section 3.2). Both input and output are shown for visual comparison purposes. Plotted in Matlab.
3.2 Map-Plotting of Survey Area

QGIS was used to geographically map out the southern Swedish coastline territories as well as the seismic profiles and wells. Three main regions of seismic profiles were plotted. These regions were named D69 (26 profiles), C71 (14 profiles), CV73 (25 profiles) and MV73 (one further, smaller region comprising 4 profiles) (see Figure 12 for the location). In total 14 wells were plotted across the survey area. All profiles included in the survey map were digitized. Of the profiles digitized only a selection (Figure 13) was then depth-converted and used to model...
the Arnager Greensand (see section 3.3). Some profiles could not be depth-converted due to the lack of velocity information or well-logs in certain areas.

**Figure 12.** Geographic map of all survey parameters. Seismic acquisition profiles (lines) and wells (dots) stated in legend. All profiles shown here were digitized.
Figure 13. Geographic map of all profiles and wells used in obtaining the final Arnager Greensand model. Identical plotting parameters used as in Figure 12.

3.3 Depth Converted Seismic Sections

GlobeClaritas was used to formulate normal move-out velocity (NMO) files (Figure 14). These NMO files were then used to convert the seismic sections from the time-domain (Figure 15) to the depth-domain (Figure 16).
Figure 14. NMO file from C71 area.

Figure 15. Initial time-domain SEG-Y from D69, line 4.
3.4 Modelling and Horizon Interpretation in Opendtect

Depth converted SEG-Ys were inserted into Opendtect and a specific survey area was created. Positions and markers of wells were then entered into the existing model. Well-markers were used to substantiate the position of the top of the Arnager Greensand unit. Once all lines and markers were added to the model, horizon-picking was performed. Figures 17 and 18 show Opendtect models of acquisition lines and corresponding seismic attributes within chosen survey parameters and the model which includes all well-markers and picked horizons respectively.

Figure 16. Depth converted SEG-Y from D69, line 4.
Figure 17. Opendtect model of acquisition lines and corresponding seismic attributes within chosen survey parameters.
Figure 18. Opendtect model including all well-markers and picked horizons.
3.5 Top of the Arnager Greensand Model

Horizons and profile coordinates (x, y, z) were exported from Opendtect to MATLAB for interpolation. Once interpolation had been carried out, results were plotted geographically using Generic Map Tools (GMT) for observational assessment and comparison (Figure 19).

Figure 19. Final surface model of the top of the Arnager Greensand. Contour lines show depth values. Well-locations and respective depths (m) in relation to the reservoir unit are also presented.
4. Discussion

4.1 Digitization

Recording and processing parameters were usually displayed on the scans. The sampling frequencies used during the seismic acquisition were either 2 ms or 4 ms. In those instances when that information was missing, then 2 ms rate was chosen. Higher sampling rates are more effective at capturing peaks in the analogue signal. This method of choosing the higher sample-rate results in a more accurate digitization conversion. The drawback of choosing a high sampling rate is that the amount of data increases and this lengthens the processing sequence.

Adjustments of the default setting of the bandpass corner frequencies were important in achieving higher resolution in the output SEG-Y. Cutting off or allowing the wrong frequency range through gave rise to poor quality SEG-Ys. Default bandpass corner frequencies were adjusted to [12 30 100 124] Hz or [12 40 90 124] Hz. These corner frequencies were found to produce the highest resolution quality when acquiring SEG-Y outputs during vectorization.

![Figure 20](image)

**Figure 20.** Graphic of quality control plot for C71 line 13. Output SEG-Y quality is poor due to incorrect bandpass corner frequency choice. Default corner frequencies used here.
In the Figure 20, the bandpass corner frequencies were maintained at the default value. In comparison to Figure 10, the quality of the SEG-Y output was far poorer. The seismic attributes contained within the original tiff scan were largely lost during the digitization process. This highlights the importance of selecting the right bandpass corner frequencies when applying the digitization method.

### 4.2 Velocity Models for Time-to-depth Conversion

A limiting factor during the time-to-depth conversion process was the sparsity of velocity information for certain lines. Some areas, such as CV73 (see Figure 12), contained no velocity information at all in the dataset. The seismic acquisition region D69 contained velocity information for only seven out of twenty profiles. Well-log data (sonic logs/velocity logs) from central and easterly sections of the Arnager Greensand region were also sparse. To execute the time-to-depth conversion of the SEG-Ys, these velocities had to be known. Therefore, only a selection accordingly of the initial profiles digitized were depth-converted (Figure 13.). The majority of the SEG-Ys time sections contained a considerable amount of velocity information, with the proviso that a small number contained far less velocity information but enough to create the NMO files (Figure 21).

Figure 21. NMO file for D69, Line 26.
Less velocity information for certain profiles meant that the depth-converted SEG-Ys belonging to these profiles had a higher degree of error in the constructed models.

### 4.3 Interpreting and Modelling the Arnager Greensand

Wells located geographically close to the profiles were used for depth comparisons of the Arnager Greensand unit (Table 1). The well-markers provided further clarity on the depth of the top of the Greensand when compared with the seismic data.

**Table 2.** Elevation corrected well markers for Arnager Greensand (gl used instead of msl metric).

<table>
<thead>
<tr>
<th>Well</th>
<th>Top of Arnager Greensand (gl,m)</th>
<th>Bottom of Arnager Greensand (gl,m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mosh-1</td>
<td>1708</td>
<td>1764</td>
</tr>
<tr>
<td>Ku-1</td>
<td>1278</td>
<td>1325</td>
</tr>
<tr>
<td>Ba-1</td>
<td>1731</td>
<td>1748</td>
</tr>
<tr>
<td>Es-1</td>
<td>1378</td>
<td>1413</td>
</tr>
<tr>
<td>Ma-1</td>
<td>1245</td>
<td>1277</td>
</tr>
<tr>
<td>Nv-1</td>
<td>1783</td>
<td>1819</td>
</tr>
<tr>
<td>Hå-1</td>
<td>1329</td>
<td>1366</td>
</tr>
<tr>
<td>Hô-1</td>
<td>1193</td>
<td>1245</td>
</tr>
<tr>
<td>Ha-1</td>
<td>1209</td>
<td>1251</td>
</tr>
<tr>
<td>Lj-1</td>
<td>1180</td>
<td>1228</td>
</tr>
</tbody>
</table>
When modelling and comparing seismic sections with the well-markers, choosing the right reference datum-level was crucial. The well-markers picked from the SwedSTORE report (Juhlin et al., 2013) were obtained using the metric meters below the sea level (mbsl) but the seismic sections were measured from the ground level metric (gl). To account for this discrepancy in the datum-level, the topography height above the sea-level for each of the well-positions was added to the msl value before interpretation in Opendtect – thus holding constant the reference datum-level as gl (Table 1).

Once all wells and profiles had been correctly imported, an adjustment phase began wherein comparisons were made between the well-markers of the Greensand against the seismic events. Likewise comparisons were made at the crossing points between the seismic sections to observe and note matching events.

Some parts of the survey area (C71 primarily) lacked wells and therefore well-marker and SEG-Y tying was difficult to make. A smaller number of comparisons resulted in less clarity and therefore a higher degree of error when interpreting. To provide more accuracy in the surface characterization of the Arnager Greensand in this region, new well-log data would be needed.

Surface horizons were picked using the function ‘seed tracing’ in Opendtect which allowed for point-picking along the horizon with the option for extrapolation between the picked points. Ensuring the same horizon is picked along each of the seismic sections was the key. By virtue of the Arnager Greensand being the strongest seismic marker in the region, horizon-picking of the surface was straightforward (Figure 22).
Figure 22. Close-up of Horizon-picking and well-markers on C71, line 13.
4.4 Surface Characterization of Arnager Greensand Across South-West Sweden

Interpolation of the picked horizon of the top Arnager Greensand provided a surface characterization model of the unit across south-west Sweden. This surface model was then compared with the SwedSTORE characterization (Juhlin et al., 2013; Figure 23) in order to visually assess and compare the two interpretations. The SwedSTORE isochrone map was obtained from seismics and well-tying during a project in the late 1970s undertaken by Swedegas and OPA whilst, investigating the possibility of gas storage in the region. The SwedSTORE isochrone map includes both land and marine data.

Figure 23. Isochrone map of Arnager Greensand surface (SwedSTORE) (left) and surface characterisation of Arnager Greensand obtained in this study (right).

Comparisons in depth ranges between the two interpretations show a sound degree of compatibility. The general morphology of the surface is consistent across both models. The Arnager Greensand is shallowest in the south west (1200 m) and dips gradually towards the north east (1900 m) before being cut off at the Romeleåsen Fault Zone. However, the
digitization method employed in this study produced a 3D-surface interpretation of the Arnager Greensand using up-to-date software and thus providing better accuracy.

### 4.5 Reservoir properties of the Arnager Greensand

The southwestern region of the Arnager Greensand is found to exhibit excellent reservoir potential. The thickness of the reservoir in this area is in excess of 50 m in places (Table 2). Höllviken-1 is located in this southwestern area and the respective well-markers show a thickness of 55 m (Table 2). Porosity values in the south-west range between 25-30% and gas permeability measurements taken during hydraulic testing show values of up to a couple of darcies (Juhlin et al., 2013). The northern section (above Malmö) offers less suitable conditions, with reservoir thickness dropping down to below 30 m and permeability readings not exceeding 100 mD; the well FFC-1 is representative of this area (Table 2). In the northern areas the Greensand becomes fine-grained and less continuous with interbeds of silt and clay present. Transmissivity values from this region (FFC-1) show low values (Erlström and Sivhed, 2012; SwedSTORE, 2013)

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth (m)</th>
<th>Gas permeability (mD)</th>
<th>Porosity (%)</th>
<th>Reservoir thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svedala-1</td>
<td>1505.87</td>
<td>85</td>
<td>28.7</td>
<td>43</td>
</tr>
<tr>
<td>Maglarp – 1</td>
<td>1251.79</td>
<td>1604</td>
<td>26.6</td>
<td>32</td>
</tr>
<tr>
<td>Höllviken-1</td>
<td>1259.60</td>
<td>1275</td>
<td>~28</td>
<td>55</td>
</tr>
<tr>
<td>FFC-1</td>
<td>1627</td>
<td>56.1</td>
<td>23.0</td>
<td>27</td>
</tr>
</tbody>
</table>
An assessment of the storage potential of Swedish reservoirs was carried out in 2014 by Nordics CCS Competence Centre. The Arnager Greensand was picked as one of the top three potential storage units (Bergmo, 2014). Preliminary estimations on storage capacities are listed in Table 3. The effective capacity estimate for the Arnager Greensand is 521 Mt and is based on a storage efficiency factor of 2% (Aagaard, 2014). With a view to attaining a more comprehensive characterization of the reservoir, further study is needed to provide an accurate interpretation of the base of the Greensand across its full extent. Certain regions of the reservoir, such as in the east, lack velocity information due to a sparsity of wells. A better understanding of the velocities would enable a more precise understanding of the reservoir parameters. Once a fuller characterisation is achieved, a meaningful energy-storage estimate can be made.

Table 4. Averaged physical parameters and first storage capacity estimates for aquifers (Aagaard, 2014).

<table>
<thead>
<tr>
<th>Name</th>
<th>Depth mbsl</th>
<th>Thickness m</th>
<th>Porosity %</th>
<th>Permeability mD</th>
<th>Theoretical capacity Mt</th>
<th>Effective capacity Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faludden Sandstone</td>
<td>830</td>
<td>45</td>
<td>14</td>
<td>147</td>
<td>37271</td>
<td>745</td>
</tr>
<tr>
<td>Arnager Greensand</td>
<td>946</td>
<td>39</td>
<td>26</td>
<td>400</td>
<td>26050</td>
<td>521</td>
</tr>
<tr>
<td>Höganäs-Rya seq.</td>
<td>976</td>
<td>180</td>
<td>23</td>
<td>200</td>
<td>27127</td>
<td>543</td>
</tr>
</tbody>
</table>
5. Conclusions

The work undertaken in this thesis aimed to provide a new sub-surface topography characterization of the Arnager Greensand (a Late Cretaceous sandstone sequence) and, in so doing, to examine the storage potential of the reservoir unit.

Vintage seismic data acquired in the mid-1970s by OPAB and presently made available for research purposes was subjected to a digitization process. Digitizing historical data provides opportunities for new interpretations using up-to-date seismic processing software.

Analogue data from over 70 different profiles in the Swedish south-west region were digitized. During the digitization method it was crucial to observe and adjust relevant vectorization parameters in order to produce the best quality output. Sampling rates and corner frequencies were found to exert the largest influences on the digitization method. It was key to ensure these two salient parameters were manipulated and then assessed during quality-control checks. Digitized seismic sections were then imported into Globe Claritas seismic processing software for depth-conversion. Depth converting in Claritas involved formulating NMO files from velocity information present on the original scans. A sparsity of wells and/or velocity information in certain regions meant that certain time-constrained seismic sections were unable to be depth-converted or the converted sections had a higher degree of error in the constructed velocity models. This limited the coverage of the Arnager Greensand to primarily the western and northern regions of the studied area.

Modelling of the depth converted SEG-Ys, and well-markers was carried out in Opendtect. Choosing a consistent data reference level was key and well-markers and seismic sections were adjusted to match the same metric (gl). By virtue of the Arnager Greensand being the strongest seismic marker in the region, picking surface-horizons was comparatively straightforward. Latitude, longitude and depth-coordinates of the modelled profiles were then exported into Matlab for natural neighbour interpolation. Surface horizons of the Greensand were interpolated to provide a fuller 3D-characterization of the top of the reservoir. This result was then plotted in GMT and compared to a previous interpretation produced in the early 1980s during an aquifer storage appraisal conducted by Swedegas and presented in the SwedSTORE report. Comparisons between the two interpretations showed strong similarities in both morphology and general dip trend. It is to be noted that the Arnager Greensand surface model
developed in this thesis produced a 3D-characterization by employing modern seismic processing and interpretation software.

Reservoir storage properties such as permeability, porosity and thickness illustrate excellent reservoir properties in the central and particularly southern regions of the Greensand in the studied area. Additional seismic data are required to characterize both the base of the reservoir and the thicknesses in the eastern sections (south Sweden) to facilitate a 3D image suitable for improved estimation of the reservoir storage capacity.
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Appendix

Vintage data examples in the form of scans

Scan from D69_Line 4