2D seismic AVO inversion for geothermal reservoir characterisation in Zealand Denmark

*Esben Dalgaard[1], Kenneth Bredesen[2], Anders Mathiesen[2], Niels Balling[3], Adriana Gordon[1]**
[1]Qeye; [2]GEUS; [3]Aarhus University

Summary

A 2D seismic AVO inversion and well log analysis was performed to characterise a geothermal reservoir in the northern Zealand of Denmark in 2019. This case study shows how from the seismic inversion results it is possible to interpret different lithologies and estimate porosities through links established with well logs. The results revealed several layers of porous and clean sandstone as potential high-quality reservoirs for geothermal energy development within the Lower Jurassic unit and the Gassum formation. Even though the limited data available for the study caused some challenges, the obtained predictions seem generally reasonable when compared to existing regional well data, seismic interpretations and geological expectations. Ultimately, this study demonstrates the applicability of seismic AVO inversion for reservoir characterisation as a tool for de-risking geothermal resources.

Introduction

Seismic AVO inversion has been a well-known and effective procedure for reservoir characterisation in the oil and gas industry for multiple years (Buland et al., 2008). The use of seismic AVO inversion for the characterisation of geothermal reservoirs seems valid as the aim is to identify different lithologies while estimating the porosity at the zone of interest. From seismic data, it is possible to invert for different elastic properties such as acoustic impedance (AI), P-wave and S-wave velocity ratio (Vp/Vs) and density. Typically for sedimentary rocks, AI is often correlated to the porosity while both Vp/Vs and AI can act as a good lithology discriminator.

This case study demonstrated how a seismic AVO inversion can help de-risk a geothermal play by characterizing the reservoir in the northern Zealand of Denmark. Figure 1 shows the location map of the study area Hillerød, 5 2D seismic lines and the wells available for the study.

The target is located within the Lower Jurassic unit and the Gassum formation at an approximate depth of 2 km below the surface. Figure 2 shows the interpreted seismic section of Line number 5, highlighting the main geological formations with the Karlebo-1A well projected on top. The Gassum formation has proven very good reservoir quality at several locations and is also the geothermal reservoir for two other geothermal plants in Denmark. The temperature in the Gassum formation in this case is expected to reach levels around 50°C (Poulsen et al., 2016).

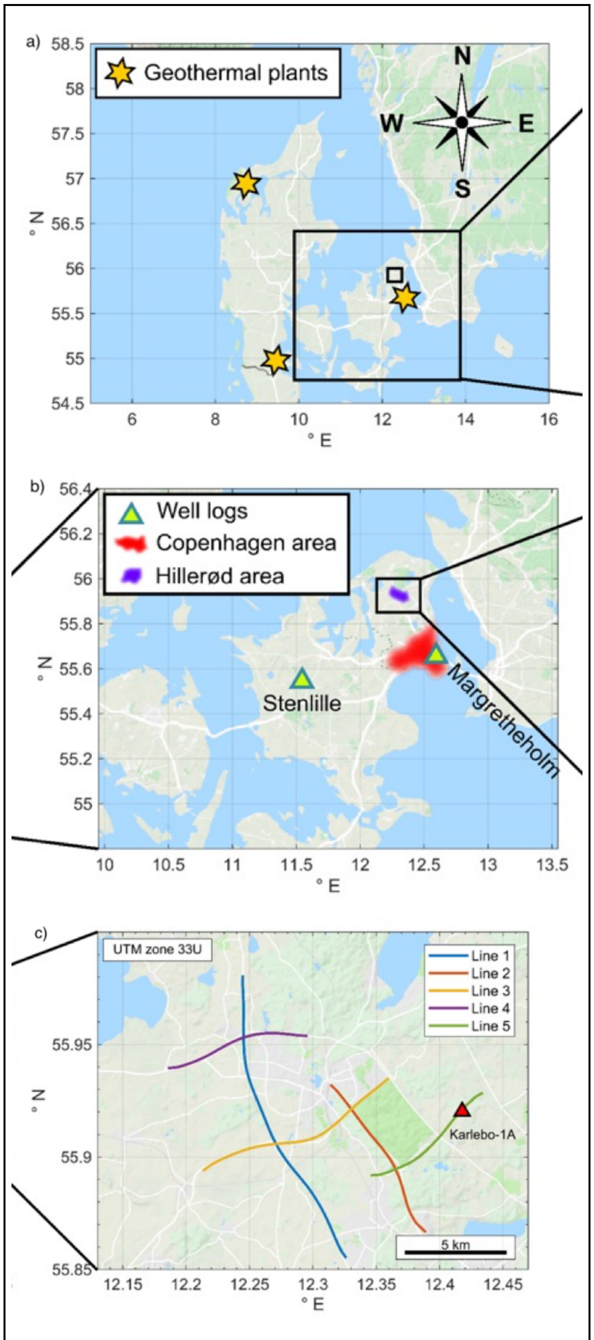

Figure 1: Location map of the study area in the Northeast of Zealand, Denmark highlighting well log and seismic data available for the study. Wells at Margretheholm and Stenlille (b) are located approximately 30 and 60 km from the Hillerød prospect area, respectively. Courtesy of Google Maps.

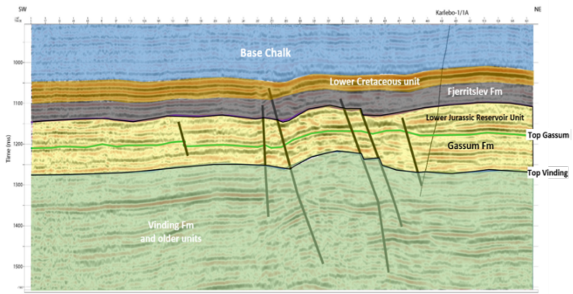

Figure 2: Geological interpretation of the main geological formations based on the 2D seismic line number 5, about 7 km in length. The Karlebo-1A well path is projected on top.

The Karlebo-1A well (Figure 1, c) was used for establishing the link between the earth properties and the seismic through a wavelet extraction and a background model. This well is the closest to the study area and it is located approximately 77 meters to the nearest point on line number 5. Regardless of its proximity to one of the 2D lines, Karlebo-1A has a limited amount of measured logs and therefore the well at Margretheholm (Figure 1, b) was used to support Karlebo-1A in order to obtain a sufficient amount of well logs for the analysis.

Seismic AVO inversion

The seismic inversion scheme used in this setting is a global seismic simultaneous AVO inversion algorithm, which inverts partial stacks (angle-stacks) directly for acoustic impedance (AI), Vp/Vs and density. The input to the simultaneous AVO inversion is a wavelet for each partial stack and a low-frequency model for each property to be inverted for.

Since for this study, the elastic well log data was limited, the wavelets used for the seismic inversion are statistical wavelets based on the seismic data only. The spectral amplitude content is derived directly from the seismic data. The phase and the scaling of the wavelet are estimated based on seismic inversion tests. As the seismic data in nature is lacking information from the low frequencies, this information is extracted from the well logs. The background model is based on the Karlebo-1A well log data. The log information was extrapolated along the horizons using a radial basis interpolation method.

The seismic AVO inversion results at a well location are shown in Figure 3. The first panel corresponds to the porosity log (in red) and the volume of clay (in blue). The second and third panels correspond respectively to the AI and Vp/Vs inversion results (in green) compared to the log curves (in blue) with the background model (in gray). The fourth and fifth panels show the inversion results at a small section near the well location. A fairly good tie is observed for both AI and Vp/Vs inversion results.

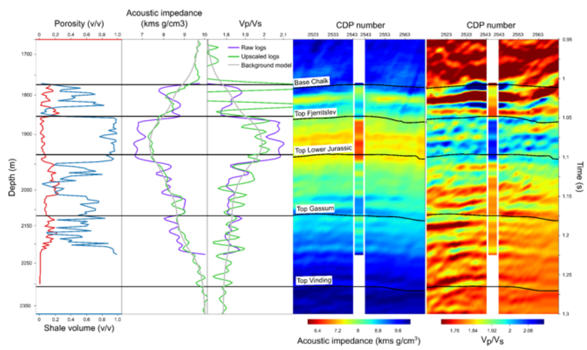

Figure 3: AI and Vp/Vs inversion results for Karlebo-1A. The first panel is showing porosity from the well log (red curve) and volume of shale (blue curve). The second panel shows the AI log (blue curve) and the inversion result (green curve) and the background model (gray curve). The third panel shows Vp/Vs log (blue curve) and inversion result (green curve) and background model (gray curve). The fourth and fifth panels are showing the AI and Vp/Vs results at a mini-section crossing the well log, respectively.

Well logs

A key challenge for this particular project was the limited well log data available, in specific for the Karlebo-1A well. The only logs available for this well were gamma-ray, sonic and a porosity.

Density and shear sonic were predicted by a Gardner relation (Gardner et al., 1974) and a Greenberg Castagna relation (Greenberg and Castagna, 1992), respectively. In addition, a volume of clay log needed for the density and shear prediction was estimated from the gamma-ray (Figure 3). All relations for the various predictions and estimations were established at Margretheholm-1A well, which contains all the logs needed. Margretheholm-1A is a very good analogue to the Karlebo-1A well as it penetrates the same formations and is relatively close by. As porosity is one of the available logs in the Karlebo-1A well, this was found to be the most important domain to evaluate the seismic AVO inversion results within. Consequently, the seismic inversion results were used to predict lithologies and porosities via links established at the well logs from Karlebo-1A (Figure 4) and Margretheholm.

Lithology classification and porosity estimation

A classification of three facies: 1) clean sandstone, 2) shaly sandstone and 3) shale was performed based on non-Gaussian probability density functions (PDFs) estimated using a Gaussian kernel-density estimation. These PDFs (Figure 4) are subject to interpretation and honor the known well log information from Karlebo-1A and Margretheholm-1A and the geological expectation of the area. The PDFs were applied to the inversion results. Figure 5 shows how the seismic lithology classification is matching the Karlebo-1A well, the shale package in the Fjerritslev formation is also classified, and we also observe thin sand packages within the Jurassic formations.

Examining the cross-plots between AI and Vp/Vs color-coded with porosity for Karlebo-1A (Figure 4) a high correlation between AI and porosity is observed. A simple linear relation is estimated for each facies, and applied in order to calculate a facies-specific porosity. The total porosity is obtained by weighting the facies specific porosities with the probability of the given facies.

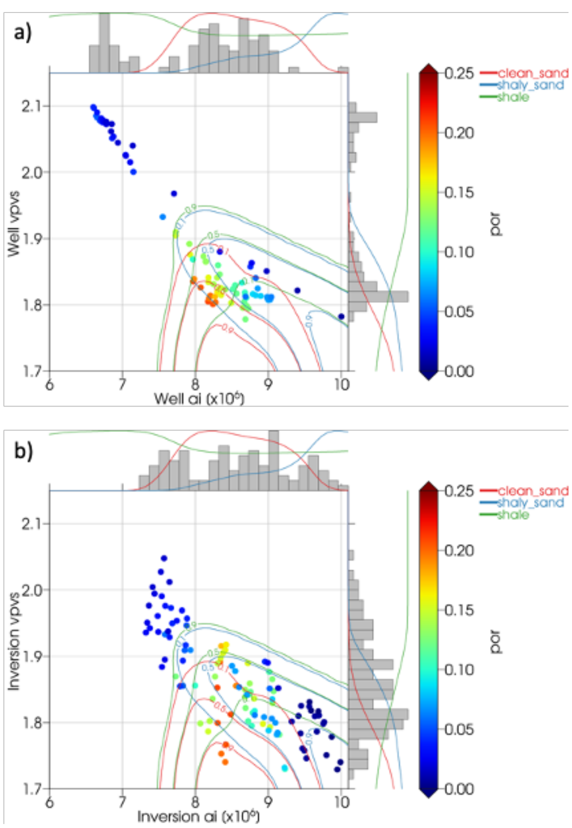

Figure 4: AI vs Vp/Vs cross-plots color-coded with porosity from Karlebo-1A overlain with PDFs for clean sand, shaly sand and shale. a) is showing points extracted from Karlebo-1A well and b) is showing points from the seismic inversion extracted along the well.

Given that the only logs available for Karlebo-1A well were porosity log, gamma-ray log and sonic log, the porosity estimation was in this particular case the best way to evaluate the inversion results. In Figure 5 the seismic estimated porosity is compared with the porosity from the Karlebo-1A well, a very good fit between the two is observed. In Figure 6 we see the porosity estimate across line number 1, and it is observed that the porosity values along this line are in accordance and following the trends which are measured in Karlebo-1A and at Margretheholm. For example, we see a lower porosity with depth and we observe porosities up to 20 and 25% in the Jurassic layers and a porosity around 2 to 4% in the Fjerritslev formation.

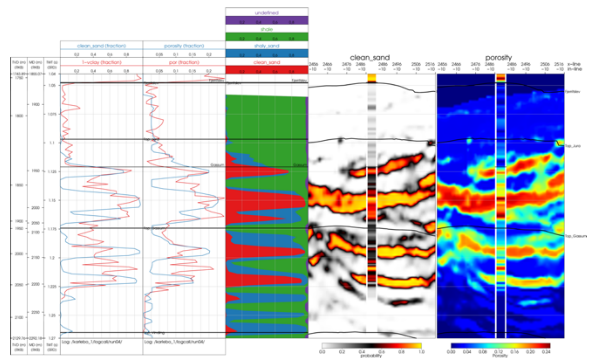

Figure 5: Lithology and porosity results predicted from the seismic inversion and projected on Karlebo-1A. The first panel is showing the seismic predicted probability of a clean sand (blue curve) and volume of clay from well log reversed (red curve). The second panel is showing seismic predicted total porosity (blue curve) and porosity from the well log (red curve). The third panel is showing the probability of the different lithologies based on the seismic inversion. The fourth panel is showing seismic predicted clean sand at a mini-section crossing the well log. The Fifth panel is showing the seismic predicted porosity at a mini-section crossing the well log.

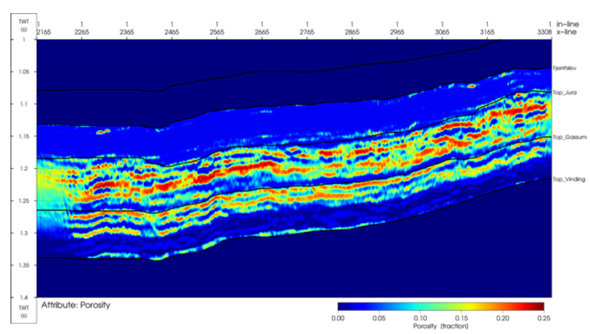

Figure 6: Total porosity estimated from the inversion and the lithology classification at line number 1.

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Conclusions

It was possible to predict lithologies and porosities at several 2D seismic lines by performing a seismic AVO inversion with well log analysis and supported by the geological understanding of the study area. This prediction can help characterize the reservoir in order to plan target zones for future geothermal energy plants in the area of Hillerød in Northern Zealand, Denmark. The results yielded several porous and clean water-bearing sandstone layers as potential high-quality geothermal reservoirs within the Lower Jurassic unit and the Gassum formation.

Despite the lack of elastic information from the Karlebo-1A well it was possible to evaluate the inversion result. An evaluation was performed in the elastic domain between predicted elastic properties in the well and the elastic inversion results. As the porosity log was available in the Karlebo-1A well, the main evaluation of the seismic product was performed in the porosity domain by establishing transforms between lithology-specific porosities and the seismic inversion results.

Although the data limitations encountered posed a significant challenge in our study, the predictions obtained seem fairly reasonable when compared with regional well data, seismic interpretations and geological expectations. Lastly, the study demonstrates the potential of seismic characterization as a tool for de-risking geothermal resources to increase hydrothermal production volumes.

Acknowledgments

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