Introduction

Seismic AVO inversion has been an effective procedure for reservoir characterization in the oil and gas industry for several years (Buland et al., 2008). Applying seismic AVO inversion for characterisation of geothermal reservoirs seems obvious as we are aiming at identifying the different lithologies together with a porosity estimate in the target zone. From the seismic it is possible to invert for different elastic properties such as acoustic impedance (AI), Vp/Vs, and density. For sedimentary rocks, AI typically correlates well to the porosity, whereas Vp/Vs combined with AI typically acts as a good lithology discriminator.

A field case is demonstrated to show how 2D seismic AVO inversion together with well log analysis can aid in reservoir characterisation of a geothermal play in the northern Zealand of Denmark (Figure 1). From the seismic inversion it is possible to make interpretations of the different lithologies and estimating porosities via links established at the well logs.

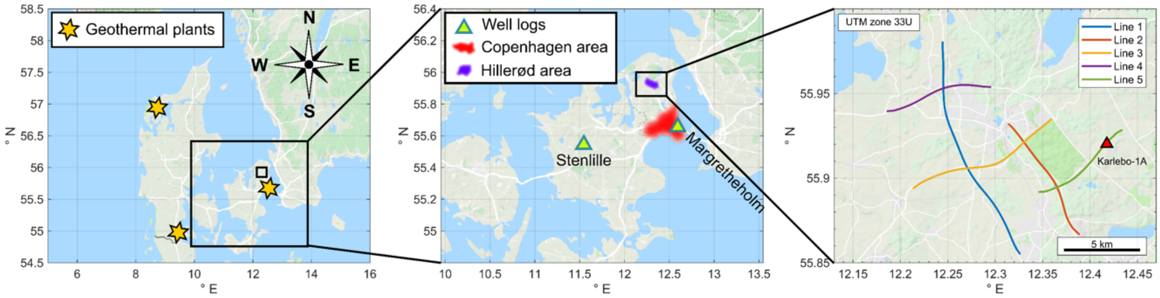

Figure 1 *Location map of the study area in the Northeast of Zealand, Denmark showing seismic and well log data used in this study. Wells at Margretheholm and Stenlille are located approximately 30 and 60km away from the prospect area, respectively. Courtesy to Google Maps. Extracted from Bredesen et al. (2019).*

The target is located within the Lower Jurassic reservoir unit (LJRU) and the Gassum Formation (Figure 2) at a depth of around 2 km below surface. The Gassum Formation has proven very good reservoir quality at several locations and act as a geothermal reservoir for two other geothermal plants in Denmark. The temperature in the Gassum Formation is in this case expected to reach levels around 50°C (Poulsen et al., 2016).

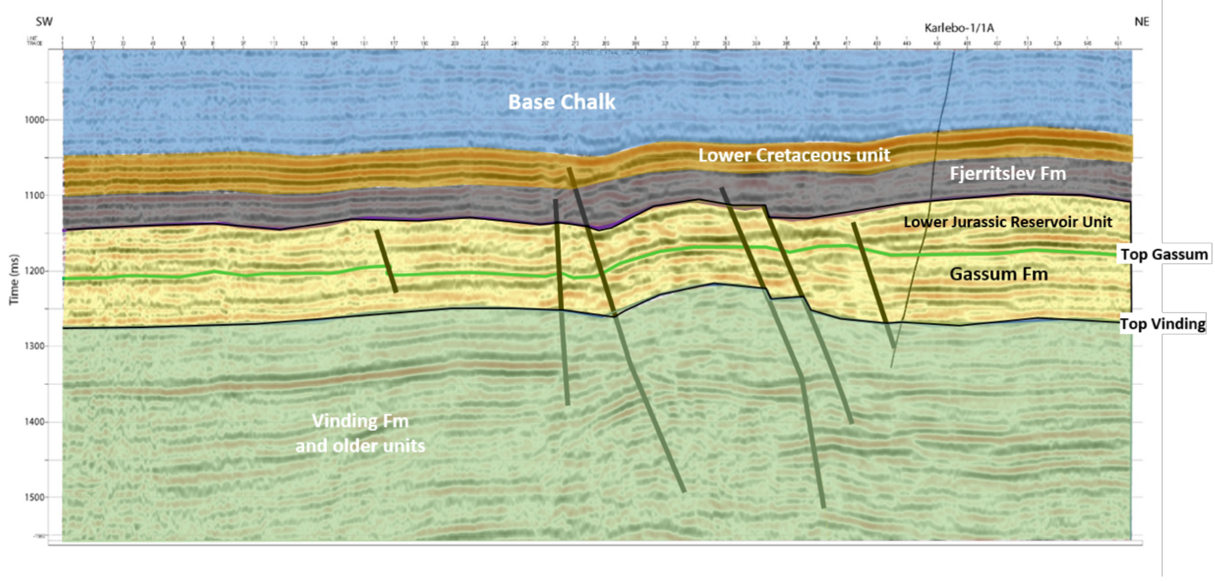

Figure 2 *A geological interpretation in Two-Way-Time (TWT) of the main geological formations based on the seismic line number 5, about 7 km in length. The Karlebo-1A well path is projected on top. Extracted from Bredesen et al. (2019).*

The Karlebo-1A well (Figure 1) was used for establishing the link between the earth properties and the seismic by a wavelet and a background model. This well is the closest and it is located around 77 meters to the nearest point on line number 5. Karlebo-1A has a limited amount of measured logs and therefore the well at Margretheholm (Figure 1) was used to support Karlebo-1A in order to obtain a sufficient amount of well logs.

Seismic AVO inversion

The seismic inversion scheme used in this setting is a global seismic simultaneous AVO inversion algorithm, which inverts partial stacks directly for acoustic impedance, Vp/Vs and density. 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.

As elastic well log data in this case 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 is estimated based on seismic inversion tests. As the seismic data in nature is lacking information from the low frequencies, this is consequently 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.

Well logs

A key challenge for this specific project was linked to the limited amount of logs in the Karlebo-1A well. Therefore, the available logs, including gamma ray, sonic and a porosity, was used to derive additional density, shear sonic and shale volume logs. Margretheholm-1A, which contains a complete set of logs, was used to calibrate empirical relations to be used at Karlebo-1A. Margretheholm-1A represents a good reservoir analogue to the Karlebo-1A well as it penetrates the same formations in the same geological setting and is located nearby. As a porosity log is available in the Karlebo-1A well, this was considered to represent the most appropriate reservoir property to evaluate the seismic inversion results within. Therefore, the seismic inversion was used to predict lithologies and porosities via links established at the well logs from Karlebo-1A (Figure 3) and Margretheholm-1A.

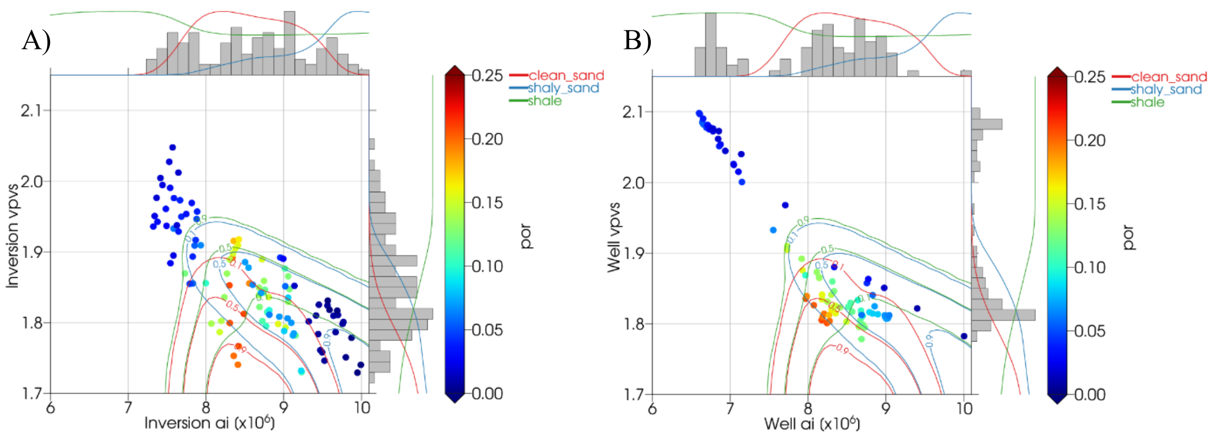

***Figure 3** AI vs Vp/Vs cross-plots colourized with porosity from Karlebo-1A overlain with PDFs for clean sand, shaly sand and shale. A) is showing points from the seismic inversion extracted along the well and B) is showing points extracted from Karlebo-1A.*

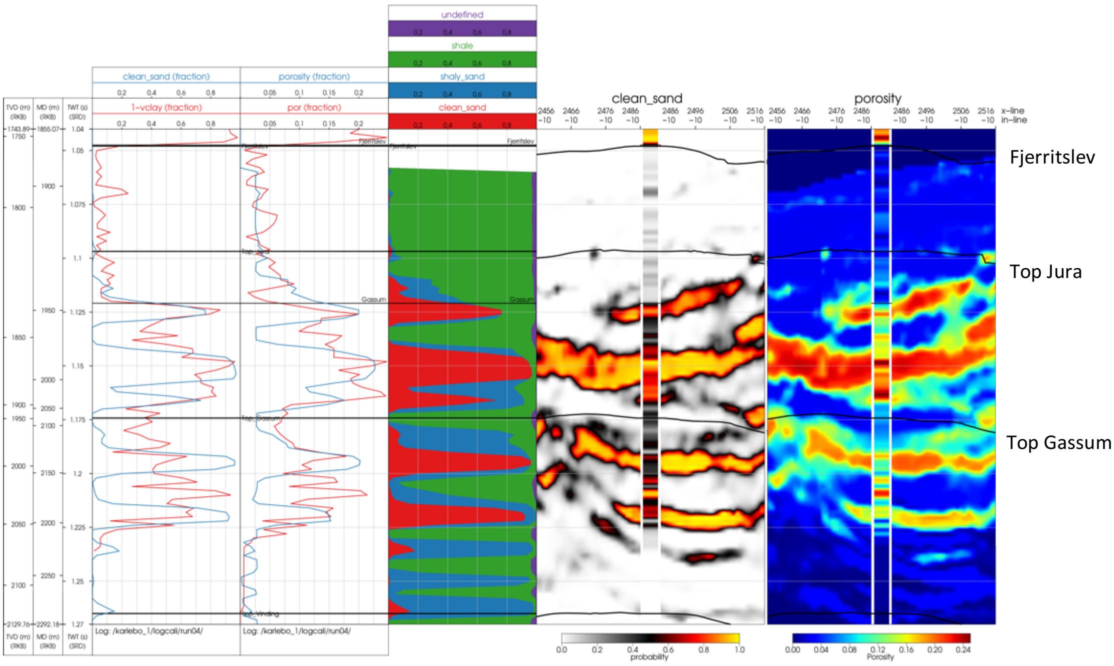

Figure 4 *Lithology and porosity results predicted from the seismic inversion and projected on Karlebo-1A. First panel is showing seismic predicted probability of a clean sand (blue curve) and volume of clay from well log reversed (red curve). Second panel is showing seismic predicted total porosity (blue curve) and porosity from the well log (red curve). Third panel are showing the probability of the different lithologies based on the seismic inversion. 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.*

Lithology classification and porosity estimation

A classification of three facies: 1) clean sandstone, 2) shaly sandstone and 3) shale, are performed based on non-Gaussian probability density functions (PDFs) estimated using a Gaussian kernel-density estimation. These PDFs (Figure 3) are subject to interpretation and honour the well log observations from Karlebo-1A and Margretheholm-1A and the geological model of the area. The PDFs were applied to the inversion results. Figure 4 shows how the seismic lithology classification is matching the Karlebo-1A well, where a pure shale package in the Fjerritslev Formation is classified, and thin sand packages within the Lower Jurassic reservoir unit and the Gassum Formation are classified as well.

The AI vs. Vp/Vs cross-plots from Karlebo-1A in Figure 3 show a strong correlation between AI and porosity ϕ. A simple linear relation $\phi_F = a_F AI + b_F$ is estimated for each facies F, and applied to calculate a facies-dependent porosity. The total porosity is obtained by weighting the facies-dependent porosities with the probability of the given facies.

In Figure 4 the seismically estimated porosity shows a good match to the corresponding porosity log from Karlebo-1A. Figure 5 shows the porosity estimates along line 1, which are consistent with the Karlebo-1A and Margretheholm-1A trends. For example, the porosity predictions approach 20-25% within the Lower Jurassic reservoir unit and the Gassum Formation, whereas 2-4% is the case for the Fjerritslev Formation.

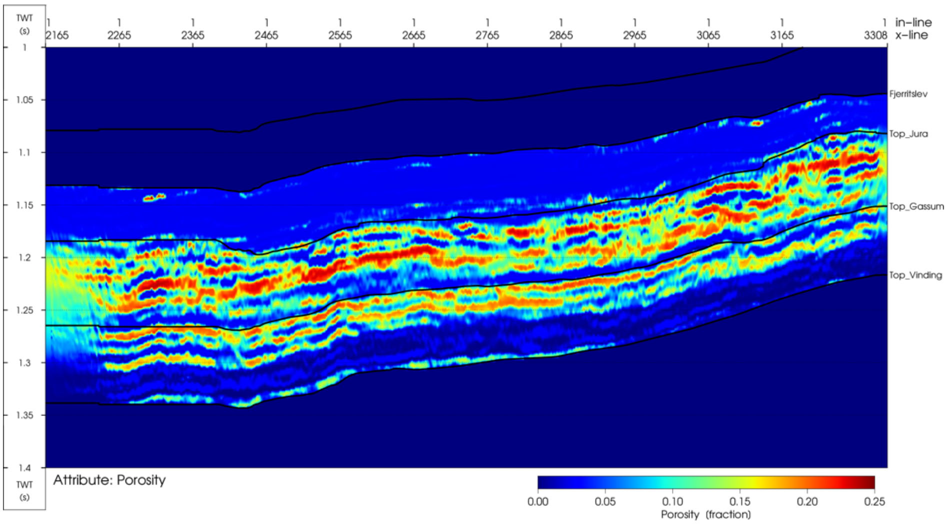

Figure 5 *Total porosity estimated from the inversion and the lithology classification at line number 1.*

Conclusions

It was demonstrated how 2D seismic AVO inversion together with well log analysis can aid geothermal reservoir characterization. From the seismic inversion it was possible to interpret different lithologies and estimate porosities via links established at well logs. With the specific results it is possible to plan future target zones for geothermal energy plants in the area of Hillerød in Northern Zealand, Denmark. Several connected high porosity sands were predicted, and with an expected temperature of around 50°C in the target zone this strengthens the prognosis for a potential good geothermal reservoir.

Despite lack of elastic logs from the Karlebo-1A well, it was possible to evaluate the inversion results. 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 facies specific porosities and the seismic inversion results.

With this specific field case it is demonstrated how seismic AVO inversion can be applied where geothermal reservoir characterisation is needed in order to obtain a better understanding of potential geothermal plays.

Acknowledgements

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