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## A Rock Physics Feasibility Study of the Geothermal Gassum Reservoir, Copenhagen Area, Denmark

K. Bredesen\* (Aarhus University), E. Dalgaard (Qeye), A. Mathiesen (Geological Survey of Denmark and Greenland), N. Balling (Aarhus University)

### Summary

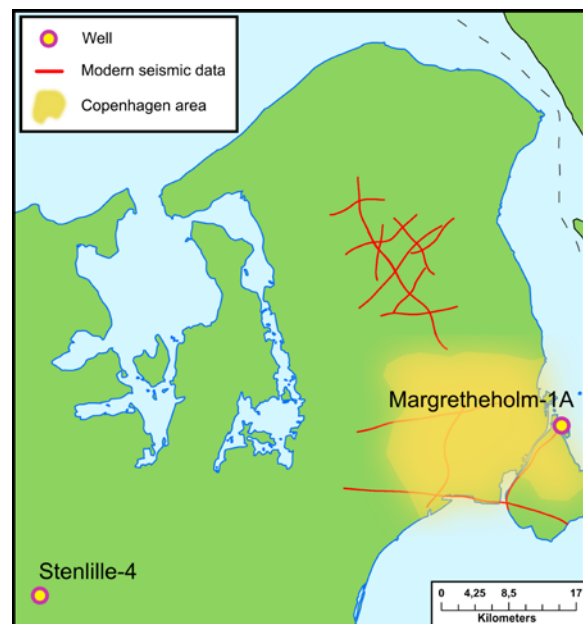
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The subsurface of Denmark stores significant amounts of renewable geothermal energy which may contribute to domestic heating for centuries. However, establishing a successful geothermal plant with robust production capacity require reservoirs with sufficient high porosity and permeability. Modern quantitative seismic interpretation is a good approach to de-risk prospects and gain reservoir insight, but is so far not widely used for geothermal applications. In this study we perform a rock physics feasibility study as a pre-step towards quantitative seismic interpretation of geothermal reservoirs, primarily in areas around Copenhagen. The results argue that it may be possible to use AVO and seismic inversion data to distinguish geothermal sandstone reservoirs from surrounding shales and to estimate porosity and permeability. Moreover, this study may represent new possibilities for future rock physics analysis serving as a tool in exploration and characterization of green geothermal reservoirs.

## Introduction

Geothermal exploitation aims at extracting heat from the subsurface and has received increasing interest worldwide as it can serve as a green and renewable energy source. Establishing a successful geothermal plant however requires locating high porosity and permeability reservoirs for sufficient production capacity. Identification and characterization of geothermal prospects are commonly based on seismic data due to higher resolution compared to other remote sensing measurements, such as electromagnetic and gravity data. Moreover, the potential of seismic modelling and inversion to estimate elastic properties can improve reservoir quality predictions when it is appropriately combined with rock physics modelling. Hence, this workflow, referred to as quantitative seismic interpretation (QSI), enables extracting more valuable information from seismic observables to constrain risks during exploration and reservoir characterization. The QSI techniques has so far not been commonly used for geothermal applications.

Prior to QSI it is important to obtain some initial understanding of the basic relationships between reservoir properties and seismic properties based on well log data (Waters and Kemper, 2014). In this paper we present a rock physics feasibility study of the Upper Triassic – Lower Jurassic Gassum Formation in Denmark based on well log data mainly from the Margretheholm geothermal plant in Copenhagen and one example from the Stenlille gas storage site (see Figure 1). The study demonstrates the initial steps towards QSI in a prospective area north of Copenhagen (see Figure 1) with promising geothermal potential (Vosgerau et al., 2017). The feasibility workflow contains the following key steps; (1) facies discriminability, (2) rock physics model calibration, and (3) Bayesian litho-facies classification based on stochastic rock physics modelling. This workflow has previously been used in hydrocarbon exploration (e.g. Buland et al., 2008) and CO<sub>2</sub> storage (e.g. Grana et al., 2017) and is hereby introduced to geothermal projects.

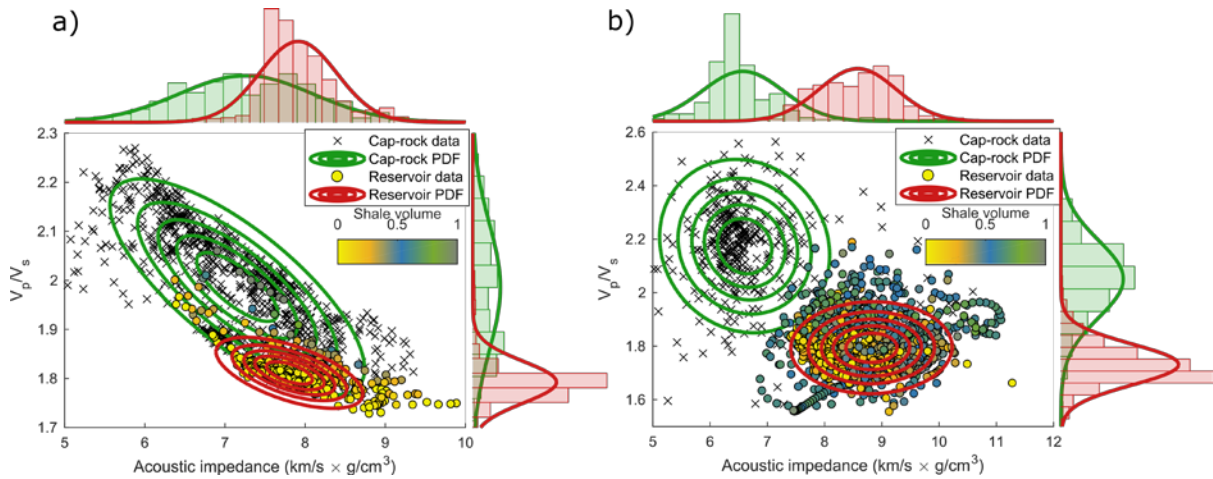


**Figure 1** Map of Northern Zealand showing the wells used in this study and seismic data coverage.

## Rock physics analysis

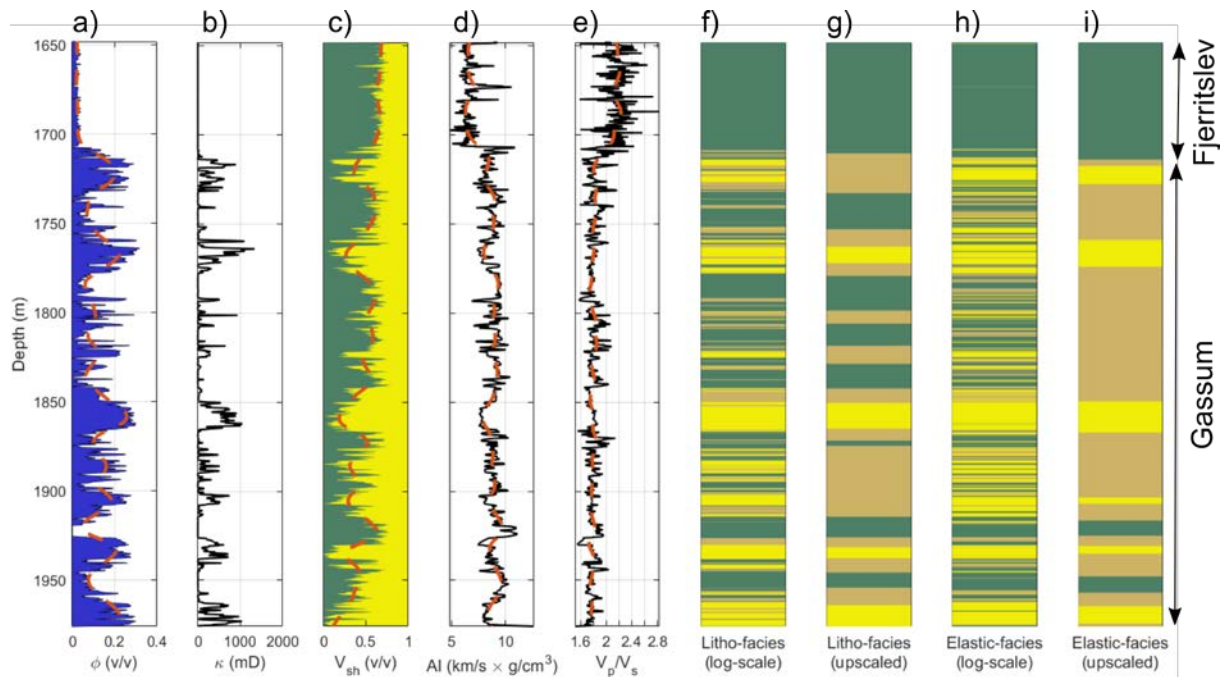
The Gassum Formation is recognized as a sandstone reservoir with excellent reservoir properties and is already being used for geothermal production as well as gas storage. In eastern parts, such as encountered in the Margretheholm-1A well, the reservoir unit is equivalent to the Gassum Formation, but with a more heterogeneous upper part of shaly sandstones. The regional Fjerritslev Formation cap-rock is dominated by impermeable mudstones and claystones.

Figure 2 shows cross-plots of acoustic impedance (AI) vs. P-to-S velocity ratio ( $V_P/V_S$ ) data derived from Stenlille-4 and Margretheholm-1A covering the target reservoirs and the cap-rock. Multivariate normal probability density functions (PDFs) of the data clusters represent the reservoir unit (red contours) and the cap-rock (green contours). The univariate normal distributions are also projected onto each axis and fits well to the backdrop data histograms. The elastic properties of the reservoir is discriminated from the cap-rock facies by larger AI and lower  $V_P/V_S$ . There is also a considerable elastic overlap of the two facies, particularly in Stenlille-4 which is mainly related to lithology and porosity variations within the cap-rock facies. Nonetheless, the similar elastic contrasts in the two wells imply that the seismic response across the interface between the cap-rock and reservoir should exhibit similar seismic characteristics at the Stenlille and Copenhagen areas.



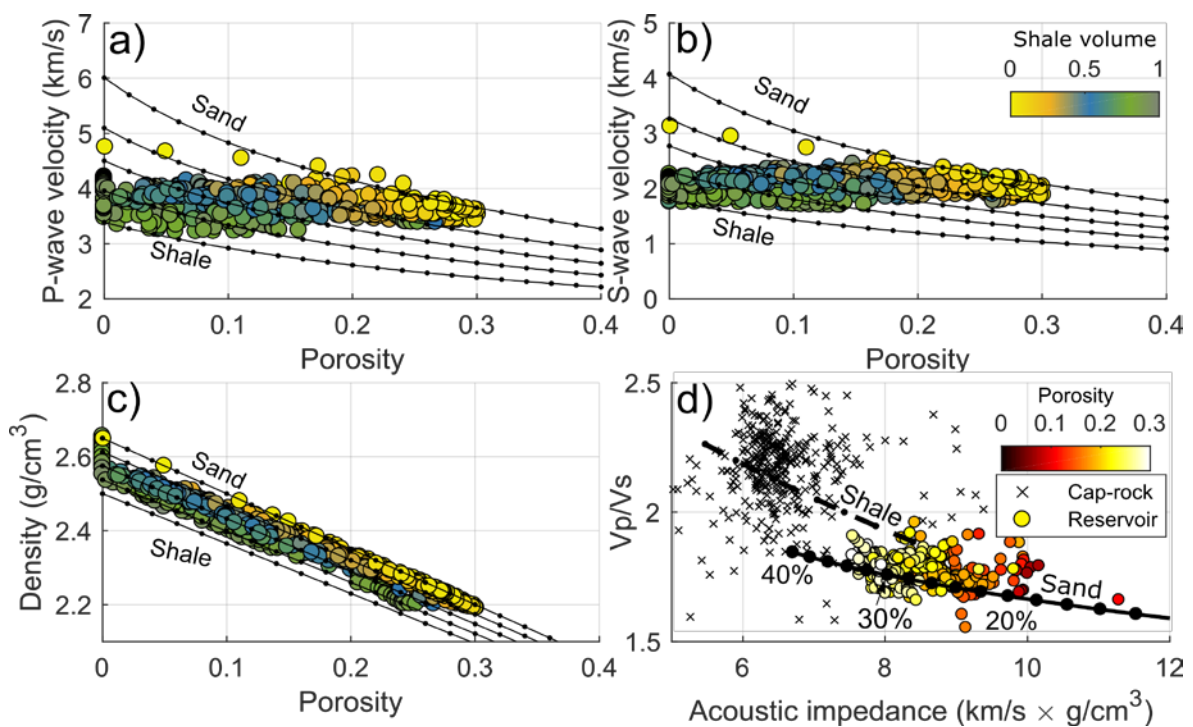
**Figure 2** Cross plot of acoustic impedance vs.  $V_p/V_s$  elastic properties from (a) Stenlille-4 and (b) Margrethelholm-1A. The reservoir data is coloured according to the shale volume.

The following analysis presented are only demonstrated on the Margrethelholm-1A data. To further investigate the seismic discriminability of the reservoir units, Figure 3a-e show a suite of petrophysical and elastic logs next to Figure 3f-i which show profiles of litho-facies and elastic-facies at log-scale and seismic scale (or upscale). The litho-facies profile is obtained from linear discriminant analysis of the porosity and lithology logs where three litho-facies classes are defined: green, brown and yellow colours represent shale, shaly sandstone and clean sandstone, respectively. The elastic-facies profile is estimated from a Bayesian classification model (Doyen, 2007; Grana et al., 2017) with the class-conditional PDFs as shown in Figure 2b but with the reservoir PDF subdivided into clean and shaly sandstone litho-classes due to the reservoir heterogeneity in the Margrethelholm-1A well. The a-priori distributions in the Bayesian classification model are defined from the reservoir net-to-gross ratios. The litho-facies profile shows a fairly good agreement with the elastic-facies profile at both scales. The elastic-facies do however infer a higher reservoir proportion and less shale because most of the reservoir data falls under the clean and shaly sandstone PDFs.



**Figure 3** Porosity  $\phi$ , permeability  $\kappa$ , shale volume  $V_{sh}$ , AI and  $V_p/V_s$  well logs from Margrethelholm-1A together with estimated litho-facies and elastic-facies profiles. Upscaled logs are denoted by stippled red curves.

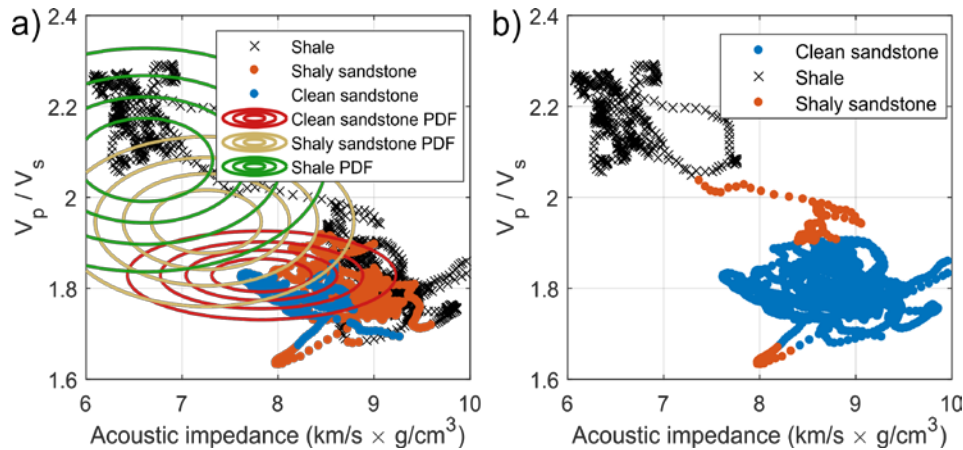
Various litho-facies require tailored rock physics models to link the desirable geological properties with seismically derived parameters. In this study we have calibrated two different rock physics models for the reservoir unit and cap-rock. The Gassum Formation at the Stenlille gas storage site is modelled with a patchy cement model (Avseth et al., 2016), whereas at Margrethholm the reservoir have experienced a larger maximum burial depth resulting in more quartz overgrowth; reducing porosity and stiffening the rock framework. Consequently, we increased the reservoir cementation effect for the Margrethholm data. Figure 4a-4c show cross-plots of seismic properties vs. porosity with rock physics models plotted on top for various shale volumes. The model describes the data fairly well and yields consistent results in neighbour wells. The elastic properties of the cap-rock are modelled with a friable sand model using the coordination number as a fitting parameter. Figure 4d shows a corresponding AI vs.  $V_p/V_s$  data cross-plot with the calibrated rock physics models for the reservoir (only the clean sands are considered) and cap-rock for varying porosity. The models show a good match with the data and the reservoir porosity trend is consistent with the modelled porosity. This implies that in this particular geological setting it may be possible with AVO data and a seismic inversion to distinguish shales from sandstones and to estimate porosities within the sandstone units.



**Figure 4** Rock physics models projected on top of cross-plots of seismic and petrophysical well data.

### Stochastic rock physics modelling and Bayesian litho-facies classification

The calibrated rock physics models can be used in a Monte Carlo simulation to model PDFs for various litho-facies classes to compute Bayesian litho-probability profiles from seismic inversion data. This approach can be useful in exploration settings with poor well control to model various geological scenarios. Figure 5a shows an example of stochastic rock physics modelling using upscaled AI and  $V_p/V_s$  well log data as input. The litho-facies classification in this plot correlates with the profile in Figure 3g. Figure 5b shows the corresponding Bayesian litho-facies classification with the reservoir net-to-gross ratios defining the a-priori distributions. Whereas a great portion of the shale data is correctly classified, much of the shale is misclassified as clean sandstones, while the shaly sandstones appear as clean sandstones. These results are not surprising because (1) the pure shales have more unique elastic properties that are not so easily confused with other litho-facies, (2) the clean and shaly sandstone exhibits overlapping elastic properties that yields lower prediction accuracy, and (3) the a-priori information are in favour of clean sandstones more than the underpredicted shaly sandstone. Moreover, using two instead of three litho-facies classes will increase the classification success rates, but will reduce the detail of the reservoir unit due to fewer litho-facies.



**Figure 5** (a) PDFs are modelled via stochastic rock physics for three different litho-facies classes and (b) subsequently used in a Bayesian litho-facies classification.

## Conclusions

We have conducted a rock physics feasibility study based on well log data covering the geothermal Gassum Formation at the Margrethholm geothermal plant and Stenlille gas storage site, onshore Denmark. The analysis can serve as a basis for successive QSI to constrain geothermal reservoir prognosis when seismic inversion and AVO data are available. The results demonstrate that the Gassum Formation can be discriminated from the regional cap-rock, and, a calibrated rock physics model can be used to predict reservoir properties and perform Bayesian litho-facies classification.

## Acknowledgements

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