DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/52**

Capture, Storage and Use of CO_2 (CCUS)

Quantitative seismic interpretation (rock physics models, seismic inversion, AVO and attribute analysis) (Part of work package 5 in the CCUS project)

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Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO2 capture technologies, (2) the potentials for both temporary and permanent storage of CO2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO2 usage potentials, including business case for converting CO2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plants in Denmark.

The present report forms part of Work package 5 (Validation of storage complexes) and focuses on assessing the rock physics and seismic properties of the Gassum Formation using the Stenlille aquifer gas storage as a reservoir analogue for the Havnsø CO_2 storage prospect.

Contents

Dansk opsummering

De bjergartsfysiske og seismiske egenskaber af Gassum Formationen ved Stenlille gaslagringsanlægget er studeret, idet det antages at reservoiret er en analog for CO_2 lagring i Havnsø strukturen. De tilgængelige data ved Stenlille består af 3D seismiske data og log data fra 20 boringer, og repræsenterer de mest omfattende geofysiske datasæt onshore Danmark. Alligevel indeholder datasættet ikke tilstrækkelig information til at lave mere avancerede kvantitative tolkninger. I studiet bruges derfor alternative metoder hvor formålet er at (1) evaluere hvorvidt de geofysiske data ved Stenlille er brugbare til at prædikere den seismiske respons idet resultatet antages at være analoge for CO_2 lagring i Havnsø strukturen, og (2) vurdere fordelingen af gas injektion i de forskellige reservoirzoner ved Stenlille.

Resultaterne i denne rapport har dannet grundlag for et manuskript som er indsendt til *International Journal of Greenhouse Gas Control* i juli 2020.

Summary

Rock physics and seismic properties of the Gassum Formation at the Stenlille aquifer gas storage is assessed as a reservoir analog for the Havnsø CO_2 storage prospect. The dataset at Stenlille compose of a 3D seismic survey and 20 wells, and represents the most comprehensive onshore dataset in Denmark, but still lacks some essential data in a format required for more sophisticated quantitative seismic interpretations. Hence, the work adopts some alternative approaches where the main objectives are to (1) evaluate whether geophysical data at Stenlille are suitable for predicting the seismic response of a CO_2 storage scenario at Havnsø, and (2) interpret the injected natural gas distributions within various reservoir zones at Stenlille.

The results shown in this report was prepared in a manuscript and submitted to the *International Journal of Greenhouse Gas Control* in July 2020.

Introduction

One of the most prospective CO_2 storage sites in Denmark is the Havnsø anticline structure in Sjælland with the Gassum Formation used as a reservoir. The lack of modern remote geophysical data and nearby wells of this prospect is a problem for doing reservoir characterization. Previous assessments of the Havnsø CO_2 prospect are mainly based on extrapolating data from the Stenlille saline aquifer gas storage facility, located approximately 30 km southeast of the Havnsø structure (Fig. 1). At Stenlille, natural gas has been injected into and stored in the Gassum sandstone reservoir since the 80's. The geological setting at Stenlille is assumed to represent a good analog to the Havnsø structure since similar lithologies and burial depths for the Gassum Formation are expected.

In this study, rock physics and seismic data analysis are presented using available well log and post-stack 3D seismic data covering the Stenlille aquifer gas storage.

The dataset used is shown in Fig. 1 and contains:

- Seismic: 3D post-stack seismic volume
- Wells: 20 wells in the Stenlille area, although only a few were actually used in this study

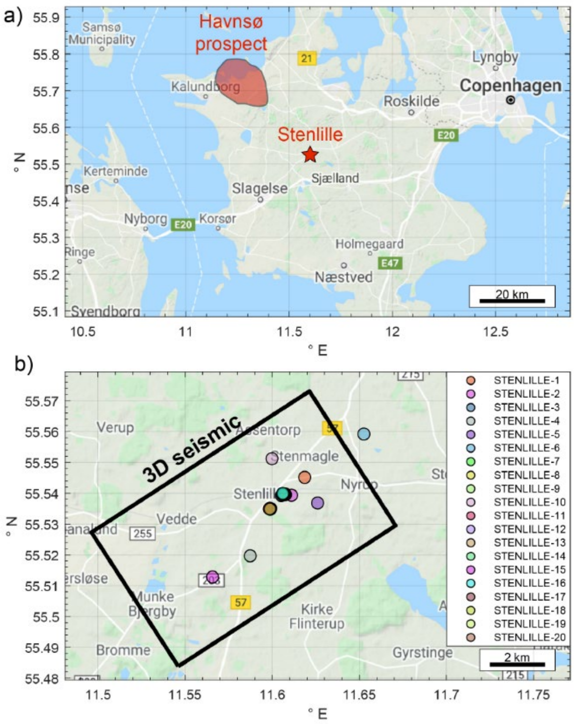

Fig. 1: Location maps of (a) Sjælland and (b) zoom in at Stenlille area showing the dataset used.

Rock physics analysis

To better understand how reservoir variations in the Gassum Formation influence the seismic characteristics, rock physics analysis was performed using the Stenlille-19 log data, which was the only well containing check shot data for establishing a time-depth relationship. Stenlille-19 is therefore used as a key reference well. Fig. 2 shows so-called Fluid Replacement Modeling (FRM), where the injected natural gas injected primarily into zone 5, are replaced by CO_2 and water. Subsequently, synthetic seismic traces are generated for near and far offsets represented by $\Theta = 0$ and theta $\Theta = 30°$. The synthetic traces for the 100% water scenario (blue curves) deviates significantly from the in situ natural gas and CO_2 scenarios. This indicates that the Gassum sandstones are sensitive to the different modeled pore fluids. Furthermore, there are no significant differences between the natural gas and CO_2 storage scenarios. This indicates that the natural gas storage at Stenlille represents a good case analog for studying how the variable CO_2 saturation affects the seismic response in the Gassum Formation with a similar lithology and burial depth, which is an underlying assumption for the Havnsø prospect. In addition, larger amplitudes are observed for the far offset trace compared to the zero-offset trace, which indicates that amplitude vs. offset (AVO) analysis from pre-stack data are feasible to interpret pore fluid content when sufficient high offsets and seismic data quality are available.

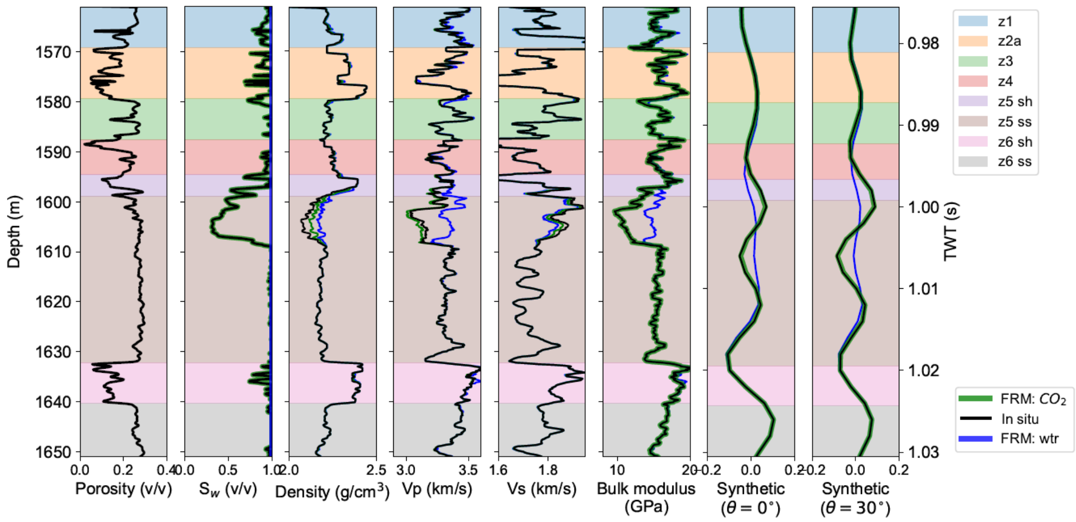

Fig. 2: Rock physics modeling where insitu natural gas is replaced with CO_2 and 100% water fluid scenarios.

Seismic interpretation and analysis

Fig. 3 shows a 2D cross-section intersecting the Stenlille-19 well through the Gassum Formation, with water saturation superimposed. A trough event (white shading in Fig. 3) was picked to represent an increase in AI, which is consistent with the AI measurements in Stenlille-19 from the lower part of the Fjerritslev Formation to the upper part of the Gassum Formation.

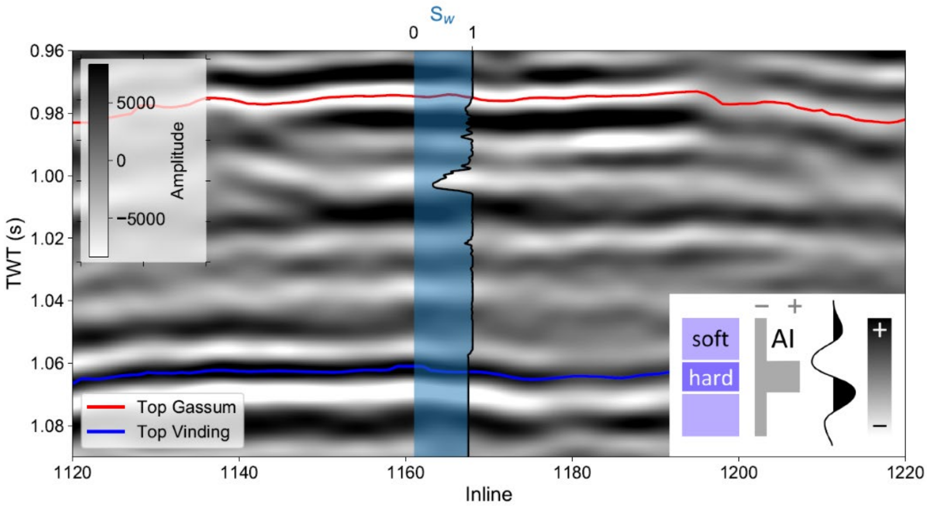

Fig. 3: Seismic crossline section with water saturation log from Stenlille-19 plotted on top. The seismic data has reverse polarity.

Some clear amplitude discontinuities are observed when moving laterally away from the top of the anticline structure. This can partly be due to faults and varying signal-to-noise ratio, which is problematic for the Stenlille 3D survey according to the processing report. More generally, the seismic image beneath the Base Chalk interface suffers from multiples and converted waves interfering with the primary reflections. To study some possible fractures around the top of the reservoir, Fig. 4 shows a minimum curvature attribute map of the complete survey with faults highlighted in blue, particularly to the south side of the dome structure, as outlined by the iso-line contours. The zoom in at the top of the dome structure shows two key faults identified in the area where gas is injected via the plotted wells. These faults are possibly segregating the Gassum reservoir into different compartments (marked with green hatched lines).

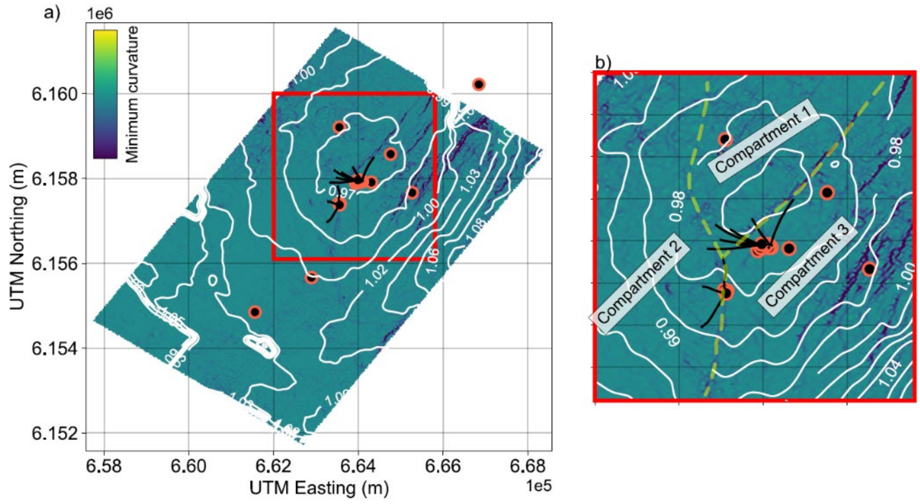

Fig. 4: Minimum curvature geometric attribute for mapping faults representing the Top Gassum horizon. Well paths are plotted as black lines with the well head plotted as orange circles.

Regarding seismic mapping of the gas storage distribution, we expect to see a fluid response for the gas injected prior to the seismic acquisition in 1997. At the time of the survey, approximately 520 million Nm^3 of natural gas was injected into zone 1-3, whereas approximately 340 million Nm^3 was injected into zone 5 from 1995. Fig. 5 shows an amplitude root-mean-square (RMS) map extracted within a 6 ms window with center 10 ms beneath the Top Gassum horizon. This map seems to delineate the gas distribution within zone 1-3. The gas front is abruptly cut off by the fault lines south of the dome as interpreted in Fig. 4, and conforms to the depth contours to some extent.

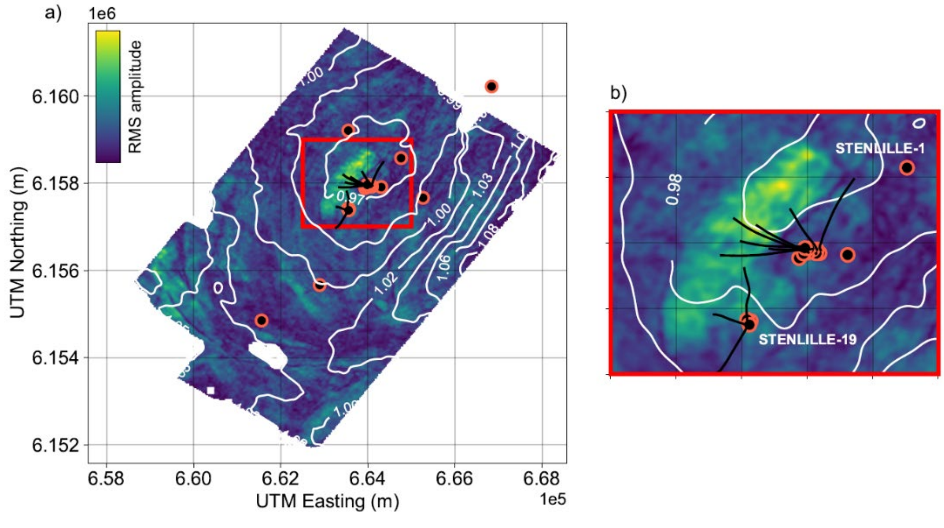

Fig. 5: RMS amplitude map revealing the gas distribution in reservoir zone 1-3.

In reservoir zone 5, a corresponding clear fluid anomaly is not observed. Presumably, the gas column must have been thinner than the gas column observed in Stenlille-19 from 2001, and may be below the vertical seismic resolution. To better reveal the injected gas in reservoir zone 5 at the time of the seismic survey, a so-called colored inversion approach was performed. This procedure transforms the reflectivity data from the layer boundaries in to the relative AI changes within each layers, which is subsequently linked to changes in reservoir properties. Fig. 6 shows the color inversion results along the same cross-section as in Fig. 3, with water saturation log from Stenlille-19 superimposed.

A flat anomaly (brown-white color) represents a relative decrease in AI and correlates with the gas column in Stenlille-19.

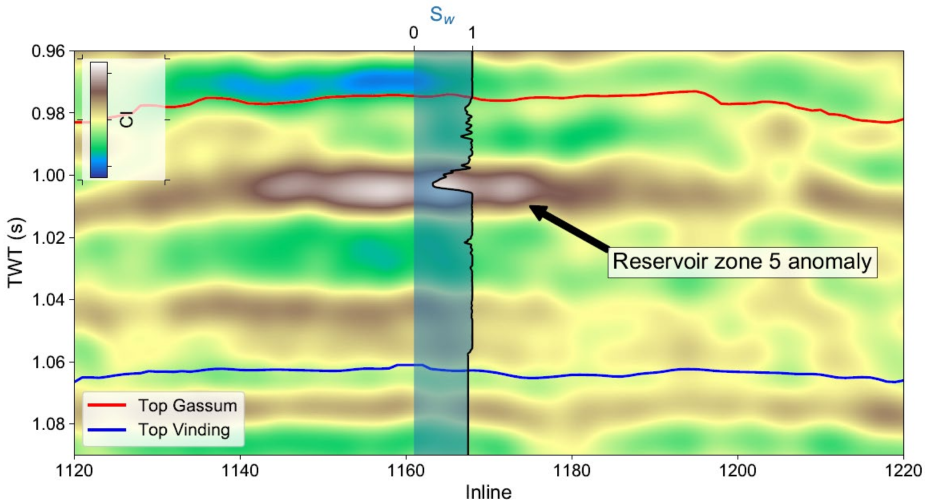

Fig. 6: Color inversion results from a crossline section intersecting the Stenlille-19 well.

Fig. 7 shows the colored inversion results extracted from an interpreted horizon of the reservoir zone 5. The map indicates two distinctive gas anomalies in the injection area covering approximately 200-250 m^2 each within the reservoir compartments 1 and 2, possibly separated by faults (dashed lines). It is possible that the gas injected into Stenlille migrated into the top structure, whereas some of the gas injected further southwest was prevented from migrating into the top structure due to the north-south striking fault.

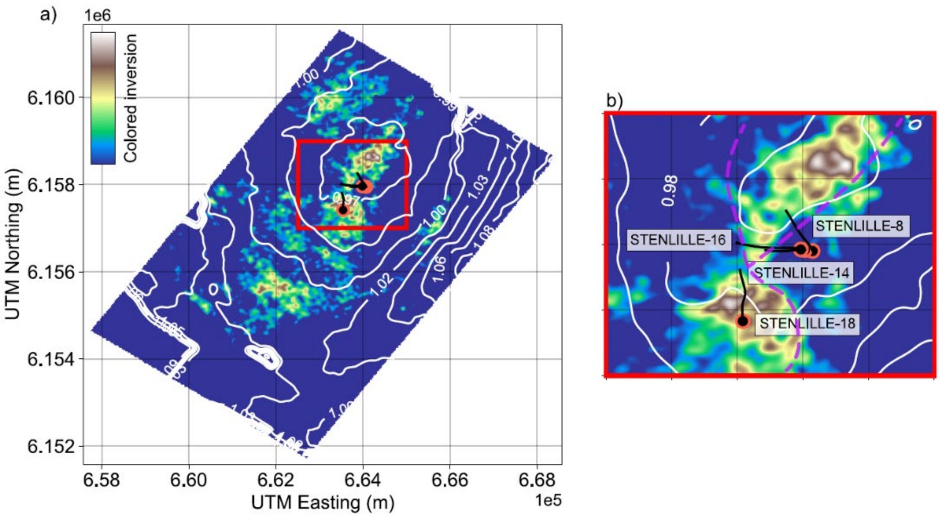

Fig. 7: Colored inversion in map view extracted from reservoir zone 5.

Also notice that some anomalies are present outside the injection area at the top of the structure, which is likely caused by noise in the seismic data.

Conclusions

- The rock physics analysis presented indicates that seismic properties are sensitive to variations in reservoir properties and pore fluid content in the Gassum Formation at Stenlille.
- The in situ natural gas stored at Stenlille exhibit similar seismic characteristics to CO_2 stored at similar burial depth. Hence, the dataset at Stenlille is suitable for investigating and predicting the seismic response of a growing CO_2 plume within the Havnsø prospect.
- Seismic attributes were used to delineate faults within the reservoir in the gas injection area at Stenlille.
- A relative colored inversion indicated gas concentrations within the lower gas storage reservoir zone 5, located in two reservoir compartments separated by possible faults that act as flow barriers.

Suggestions for supplementary investigations and research

The initial objective of this study was to perform quantitative seismic interpretation based on a pre-stack seismic inversion using the 3D seismic survey at Stenlille. However, because the seismic data was only available in a post-stack format, it was not feasible to perform a pre-stack seismic inversion. Moreover, because the 3D post-stack data was influenced by substantial noise, a roust post-stack inversion result was also difficult to obtain.

In addition, the well log content varies between the different wells in Stenlille, and in most cases, there were some essential log measurements missing that were required for a rigorous quantitative seismic interpretation. In particular, the shear wave velocities were only available in a few wells through the target depth interval.

Some possible actions for optimizing the data foundation at Stenlille for quantitative seismic interpretation could be to (1) perform a full reprocessing of the Stenlille 3D seismic survey to improve the seismic signal-to-noise ratio, and retrieve the recorded pre-stack seismic data in a CDP gather format, and (2) measure a complete suite of log measurements in all the Stenlille wells. These are important implications for collecting data in the future for quantitative seismic interpretation of CO_2 storage operations.

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