Introduction

The Danish subsurface has significant potential for CO_2 storage, with multiple structures under investigation following recent CO_2 licensing rounds. The key reservoir–seal pair being studied in the North Sea and onshore Denmark is the Triassic to Lower Jurassic Gassum Formation sealed by the Lower Jurassic Fjerritslev Formation (Springer et al. 2020). Evaluating seal integrity requires direct measurements and rock property tests (cf. Mbia et al., 2014). However, many wells relevant for evaluating the Gassum–Fjerritslev reservoir–seal pair in eth western North Sea and onshore Denmark, drilled between the 1950s and 1980s, lack comprehensive or modern wire-line log data, and cores from the seal sections are rare. Consequently, cuttings samples are often the primary source for formation evaluation and to provide intra well calibration of key petrophysical parameters. This study aims to evaluate the mineralogical composition of the Fjerritslev Formation and provide a harmonized wire-line log interpretation. These findings are crucial for understanding of the geomechanical strength and seal integrity and capacity, essential for CO_2 storage.

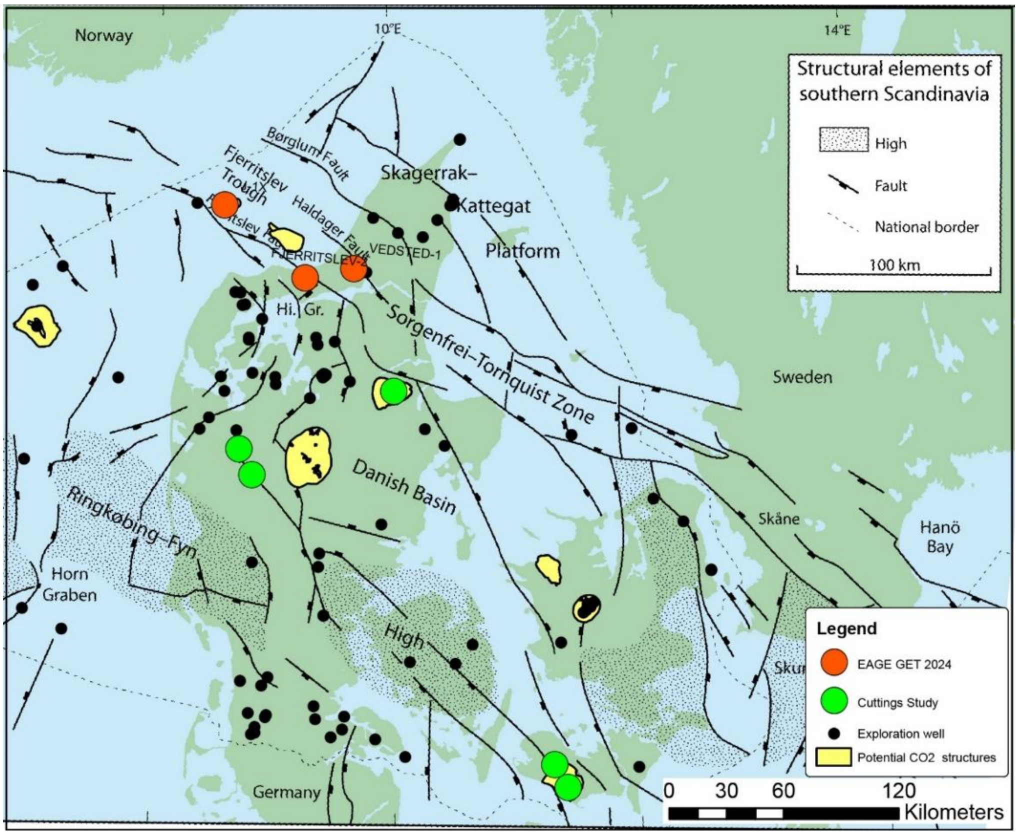

Figure 1 *Studied wells in western North Sea and onshore Denmark. Structural map from Nielsen (2003).*

Methodology

Screening of cuttings using hand-held XRF (HH-XRF) was conducted regionally on the main Cenozoic seals in Denmark (see Schovsbo and Petersen 2024 for the full study). The HH-XRF data are measured on the 1-4 mm size fraction of cuttings, hence weakly or un-consolidated fine sands beds was not captured. For this study, we used data from the J-1X, Fjerritslev-2, and Vedsted-1 wells to focus on the North Sea and the northwestern part of onshore Denmark (Figure 1). HH-XRF data was subsequently corrected using high quality ICP-MS/OES determined major and trace elements to ensure data consistency and reproducibility, following the approach of Schovsbo et al. (2018). Advanced multilinear regression analysis using the partial least squares regression (PLS) method was applied using the extensively studied dataset regarding seal capacity measures from the Eocene–Miocene Lark

Formation in the Danish North Sea (cf. Schovsbo et al., 2022) as training set. All presented PLS correlations (HH-XRF to XRD-determined total clay minerals (Vclay), sum of quartz and feldspar (QF), and total carbonate) each have a goodness-of-fit, r^2, higher than 0.9 based on a test and validation data set, following the approach of Esbensen and Swarbrick (2018). Mineralogical volumes are reported on porosity free basis and summed to 100% ignoring other trace mineral phases present. The resulting algorithms are here collectively termed *"SHARP_PLS_XRD algorithm"*.

Establishing wire-line based Vclay measurements was done by comparing down-hole variation of SHARP_PLS_XRD total clay with the gamma-ray curve in the J-1X well and with the SP curves in the Vedsted-1 and in Fjerritslev-2 wells, as no gamma ray logs are available from these, and then applying linear shifts to establish the correlation. For the Vedsted-1 well the SP log was measured in two runs and the Vclay log presented here has been edited between 1000–1626 m to merge the upper run to eth lower run. This correction is consistent with the resistivity log in the well and with the sequence stratigraphy interpretation presented by Nielsen (2003). For the J-1X well, total porosity was calculated from density wireline log, assuming a brine density of 1.1 g/cm^3, a clay grain density of 2.4 g/cm^3 and a quartz density of 2.65 g/cm^3. As mineralogical brittleness index (MBI), we used the percentage of quarts and feldspar (QF) in the mineral matrix, following Jarvie et al. (2007).

Results

Cuttings are influenced by various factors that can limit their reliability as a source of direct information. Generally, the cuttings are a reliable source of information, however, in the current dataset, several instances were observed where cuttings appeared biased or contaminated (c.f. Schovsbo and Petersen 2024). In this study, the averaging of rock properties significantly affects the results whereas cavings and down fall in generally played a minor role. In the Gassum Formation, which is a heterogeneous sandstone interbedded with muddy beds, the cuttings cannot accurately depict lithological variations due to the facies variation and due to the studied cutting fraction. Conversely, the Fjerritslev Formation has less lithological variability, allowing cuttings to effectively represent long-term variations and inter-well differences.

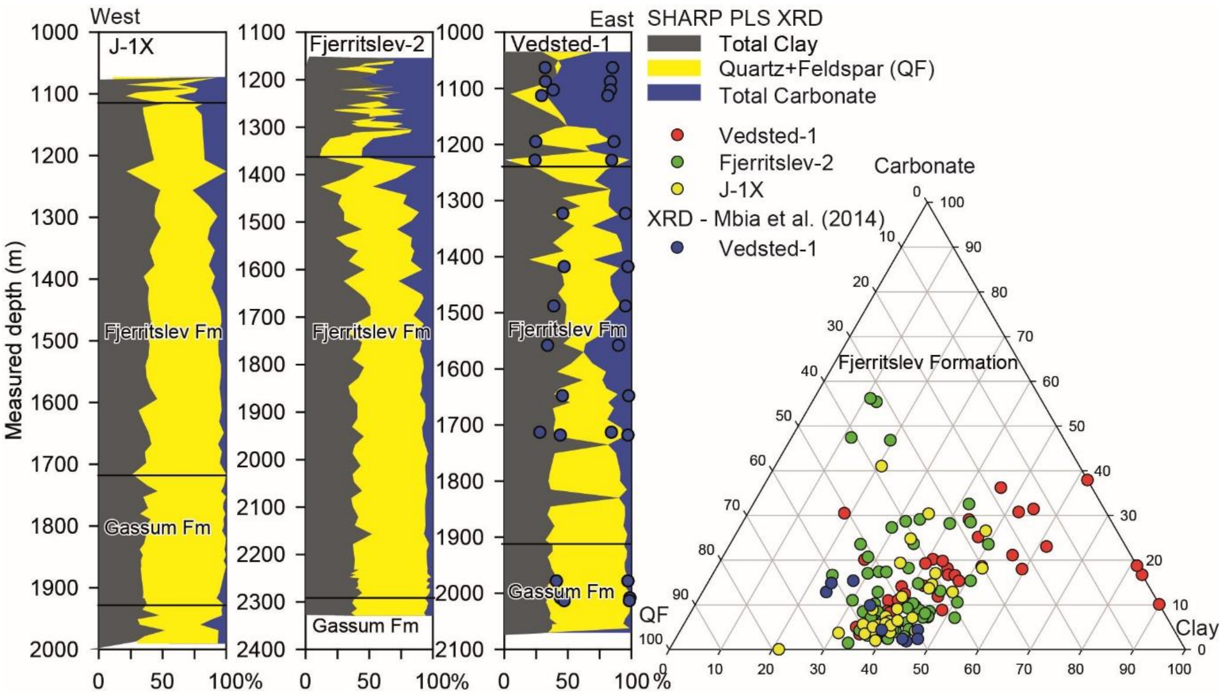

***Figure 2** Mineralogical evaluation of the J-1X (west), Fjerrislev-2 and Vedsted-1 (east) wells, and triangle diagram showing the mineral composition of the Fjerritslev Formation. Composition calculated based on HH-XRF data applying the SHARP_PLS_XRD algorithm.*

The clay content of the Fjerritslev Formation is 30–50% and total porosities vary between 10–25% suggesting that it possesses acceptable seal properties for CO_2 storage (Figures 2, 3). We note that the SHARP_PLS_XRD Vclay, QF and carbonate predicted concentrations is in line with those measured by XRD methods presented by Mbia et al. (2014) for the Vedsted-1 well.

The mineralogical brittleness index of 0.4–0.5 (Figure 3) indicates a composition, which is favourable for maintaining seal integrity under the stresses associated with CO_2 injection and storage albeit laboratory measurements still needs to be conducted to draw safe conclusions. The presence of porous and potentially permeable beds that are verified by petrophysical interpretations about 100 m from the base of the formation in the J-1X and Vedsted-1 wells, underscores the need for detailed site-specific evaluations to ensure the effectiveness of the seal (Figure 3).

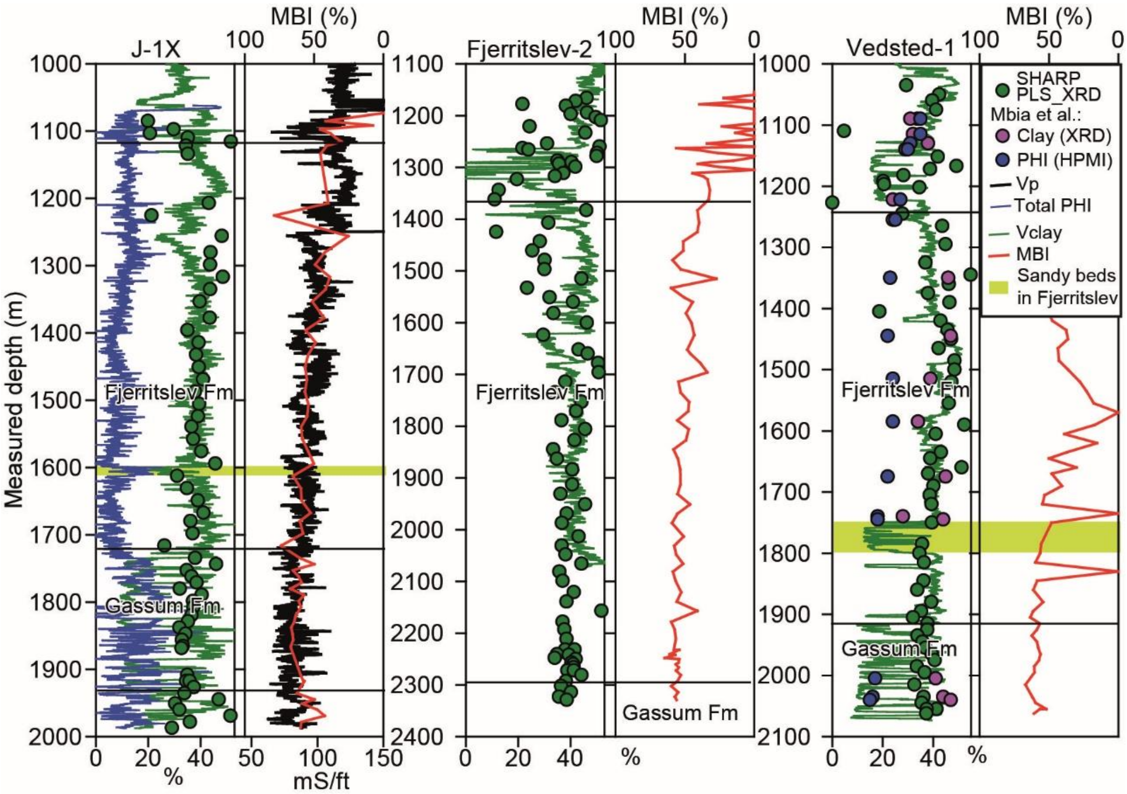

Figure 3 *Log panel of J-1X, Fjerritslev-2 and Vedsted-1: Vclay, total porosity, MBI (Mineralogical Brittleness Index, Jarvie 2007) composition are calculated based on HH-XRF data applying the SHARP_PLS_XRD algorithm. Cuttings total clay content and phi are from Mbia et al. (2014).*

Discussion

The Lower Jurassic Fjerritslev Formation range in thickness from 600–1000 m in the studied wells (Figure 3). The Vclay profiles though the Fjerritslev Formation established here indicate an average clay content of about 40% throughout the formation which combined with the thickness makes it an excellent cap rock. Vclay lows representing sandy and carbonaceous beds and notably beds present in the J-1X and in the Vedsted-1 about 100 m from the base draw attention (Figure 3). In the J-1X well the total porosities of 15–25% have been calculated and these sandy beds may represent a divide between a primary and a secondary seal unit within the Fjerritslev Formation seal complex.

In the studied wells, no geomechanical tests have been conducted, and full wave sonic logs are absent. In such cases, mineralogical indices, such as the mineral brittleness index of Jarvie et al. (2007), can be cautiously used as proxies for lithology and composition and thereby to mechanical properties as the mineralogical brittleness index is a proxy of the rock's tendency to fracture rather than deform plastically and is particularly important in understanding the behaviour of seals in CO_2 storage, as brittle rocks are more likely to fracture under stress, potentially compromising the seal integrity. Our data suggest that the Fjerritslev Formation do not include specific zones with higher than expected brittleness such as zones rich in biogenic silica, but further studies are needed to substantiate this interpretation.

Conclusions

This study provides a first full assessment of the rock properties in the Fjerritslev Formation from three wells in the western North Sea and north-western Denmark using advanced multi-regression analysis. Our findings contribute to the understanding of the Fjerritslev formation's suitability as a CO_2 storage seal, offering insights for future exploration and development in the area. The presented workflow provides calibrated measures of Vclay from wireline logs, overcoming traditional pitfalls in defining low and high values and harmonizing between different well log types. The results indicate that the Fjerritslev Formation is a thick mudstone with a typical clay content of 30–50% and average total porosities of ca. 15%. The rock has a mineralogical brittleness index of 0.4–0.5. Porous sandy beds occur within the shales, highlighting its spatial and temporal complexity.

Acknowledgements

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