Rock-Physics–Based Caprock Evaluation of Rogaland Group Shales for CO_2 Storage in the Central North Sea

Introduction

Shales account for 70% of the world's sedimentary basins, making them imperative for subsurface characterization studies. Shales serve as source rocks (if organic-rich), caprocks, and even unconventional reservoirs if prone to hydraulic fracturing across different geologic settings. Hence, these characteristics of shales make them a good candidate as a sealing caprock in potential CO_2 storage sites. To evaluate sealing capacity, it is crucial to establish the link between petrophysical, elastic, and mechanical rock properties. Before storing CO_2 in potential reservoirs, a caprock feasibility study is needed to assess the rock's brittleness and its mechanical behavior during and after CO_2 injection. Many studies from microscale (thin sections, cores) to mesoscale (well logs) to macroscale (seismic) have been conducted to evaluate the mechanical behaviour of shales in terms of brittleness (Jarvie et al., 2007; Perez-Altamar and Marfurt, 2014; Rahman et al., 2020). Analysis to differentiate ductile from brittle rocks in the seals is critical for safe and sustainable CO_2 storage projects. In this study, we evaluate the elastic and geomechanical properties of the Paleogene shales in the central North Sea, Norway. To integrate geologic information into geomechanical assessment, we present a rock-physics-based workflow that uses crossplots of processed well logs and theoretical modelling.

Background and Dataset

This study focuses on three shale formations within the Rogaland Group in the central North Sea, where we evaluate the potential CO_2 storage sites in exploration licenses EXL010 and EXL011 (Figure 1a). From younger (early Eocene) to older (late Paleocene), the Rogaland Group has three shale formations of Sele, Lista, and Vale, which are potential caprocks for their underlying sandstones (Figure 1b). We use 8 wells with a full suite of logs, including caliper, gamma ray, resistivity, density, P-wave (Vp), and S-wave (Vs) velocities. The mineralogical analysis of Sele, Lista, and Vale formations is obtained from the cuttings of well 25/2-18A, and the measurements are sampled at 10-meter intervals (Figure 2). The elastic and petrophysical logs, combined with mineralogical information, help us constrain rock physics modelling and estimate the geomechanical properties required for the caprock evaluation.

Theory

To correlate geologic background with shale elasticity, the Hertz-Mindlin model (Mindlin, 1949) for friable sediments and the contact cement model (Dvorkin and Nur, 1996) for cemented sediments are used. Dry elastic properties estimated from these theoretical models serve as a background for interpreting and understanding the behaviour of three different shales. Gassmann fluid substitution is then applied to estimate brine-saturated velocities. Since the mineralogical analysis, based on quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) and X-ray diffraction (XRD), predominantly shows clay minerals and, secondarily, quartz. We utilise this information in the theoretical modelling. QEMSCAN also indicates that clay minerals mainly consist of illite and illite/smectite (I/S) mixed layer, and smectite. Elastic moduli and density of

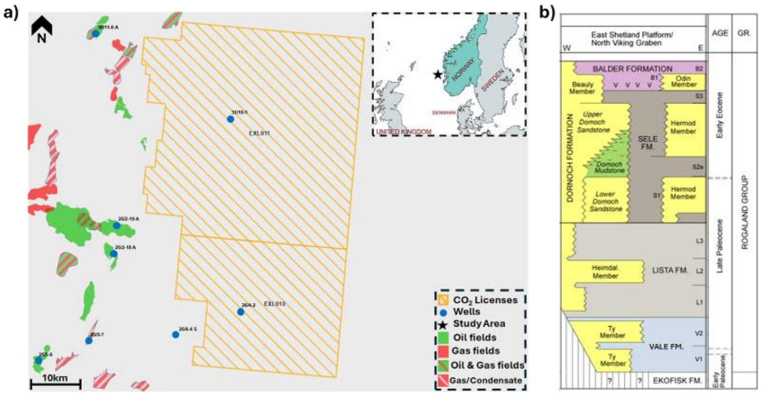

Figure 1 a) map illustrating the study area, b) generalized stratigraphic column of the Rogaland Group quartz (Carmichael, 1989) and clay minerals (Wang et al., 2001) are used here for modelling purposes.

Rock physics crossplots such as λρ versus μρ (lambda-rho versus mu-rho) and E versus ν (Young's modulus versus Poisson ratio) are commonly used for litho-fluid discrimination and geomechanical analysis (Goodway et al., 1997; Perez-Altamar and Marfurt, 2014; Rahman et al., 2020). We also use these well-known crossplots to analyze the mechanical behaviour of the studied shale caprocks. Elastic brittleness index is estimated by combining Young's modulus and Poisson ratio as suggested by Grieser and Bray (2007). Since the shale burial history varies from the mechanical compaction domain to the chemical compaction domain, the empirical approximation of Marcussen et al. (2010) is used to estimate cement volume. The temperatures are calculated from the thermal gradient of each well, based on bottom-hole temperature measurements.

Results and Discussion

First, P- and S-wave velocities are modelled to determine how the measured data are distributed across theoretical curves based on deposition and diagenesis (Figure 3). Shales with high clay content exhibit variation among clay mineral types, especially in S-wave velocity. It is also clear that some of the facies are chemically compacted with high porosity reduction.

Following that, we compute Young's modulus and Poisson ratio to analyze how ductile the Sele, Lista, and Vale formations are. These estimated elastic parameters are evaluated based on different geologic effects, including burial temperature, cementation, and the brittleness index (Figure 4). Based on the brittleness template of Perez-Altamar and Marfurt (2014), temperature slightly increases the brittleness of shales, especially for the Sele and Lista formations. Additionally, even though cementation is observed in higher Young's modulus values, these intervals mostly lie within the ductile and less-ductile zone based on the aforementioned template. However, when the elastic brittleness index is considered, this commonly used background template does not align with the data's brittleness trend.

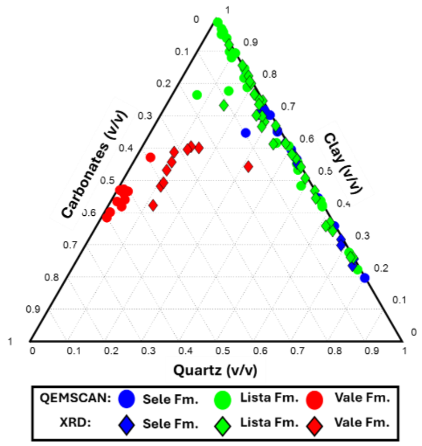

***Figure 2** Mineralogy of the Rogaland Group shales.*

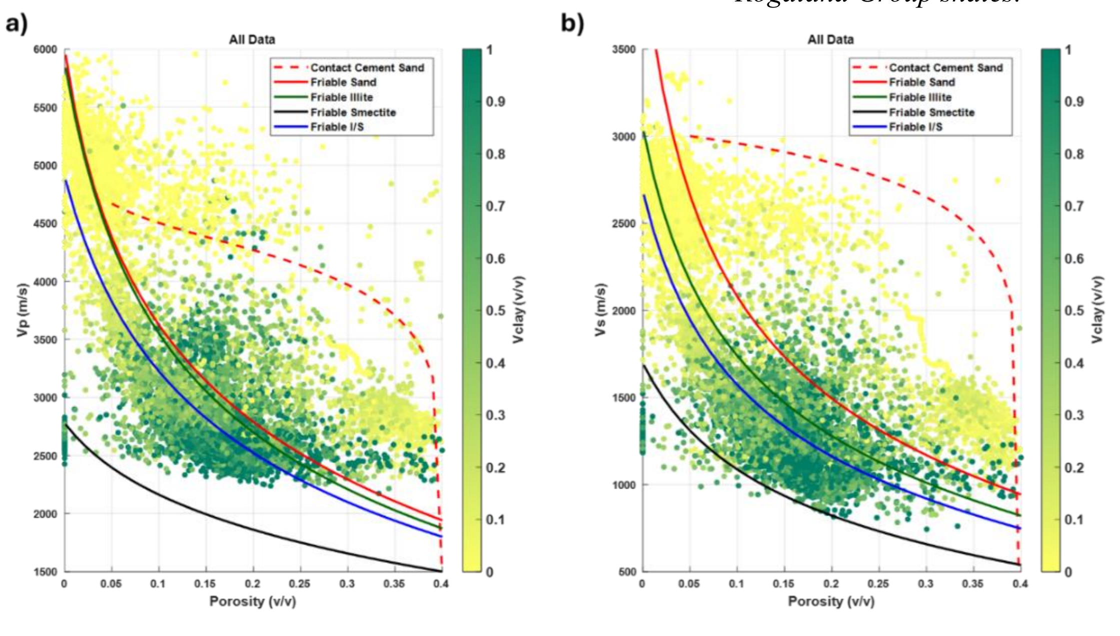

Figure 3 *Data from 8 wells covering shale formations superimposed with theoretical curves a) Vp – porosity b) Vs-porosity color-coded by clay volume.*

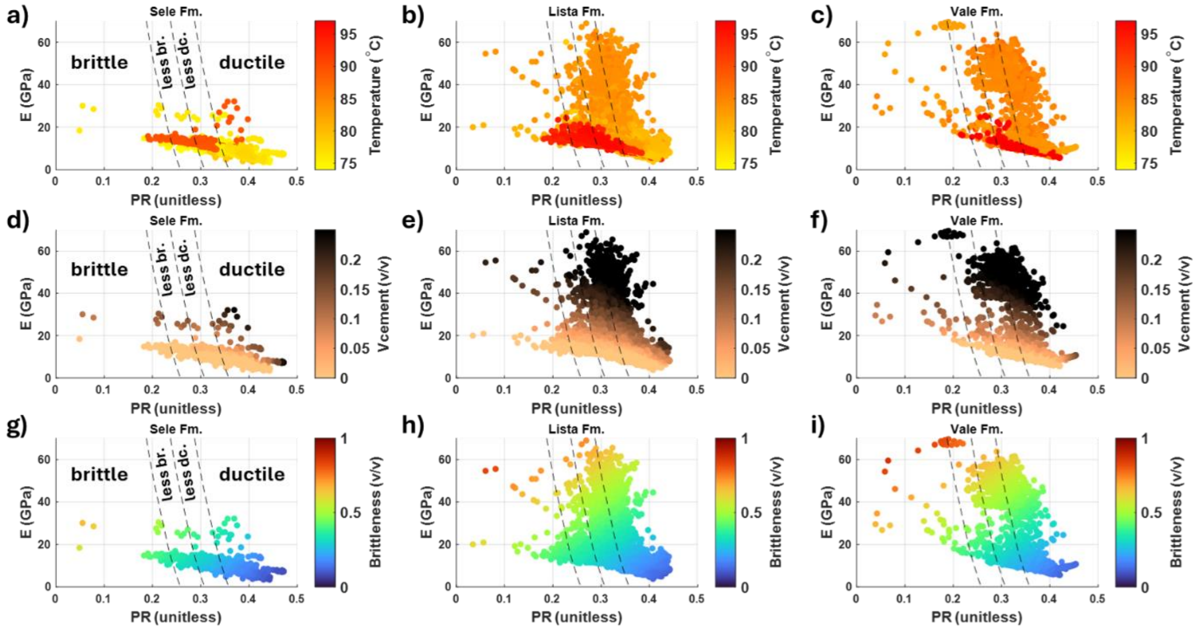

Figure 4 *Young's modulus versus Poisson ratio crossplots for each shale formation, colour-coded by: (a,b,c) temperature, (d,e,f) cement volume, and (g,h,i) brittleness index. Note that the brittleness classification of Perez-Altamar and Marfurt (2014) is superimposed.*

We then established our customised template based on the local mineralogy, following a similar approach to Perez et al. (2011). The four main minerals in this study (quartz, illite, I/S, and smectite) are considered for rock physics modelling using solid mineral endmembers with increasing porosity (Figure 5). This aids the interpretation of the λρ versus μρ crossplot, enabling the effects of porosity and brittle (quartz) versus ductile minerals (clays) to be distinguished. It is clear that the elastic brittleness of the data follows a similar trend and shows high compatibility from brittle to ductile minerals.

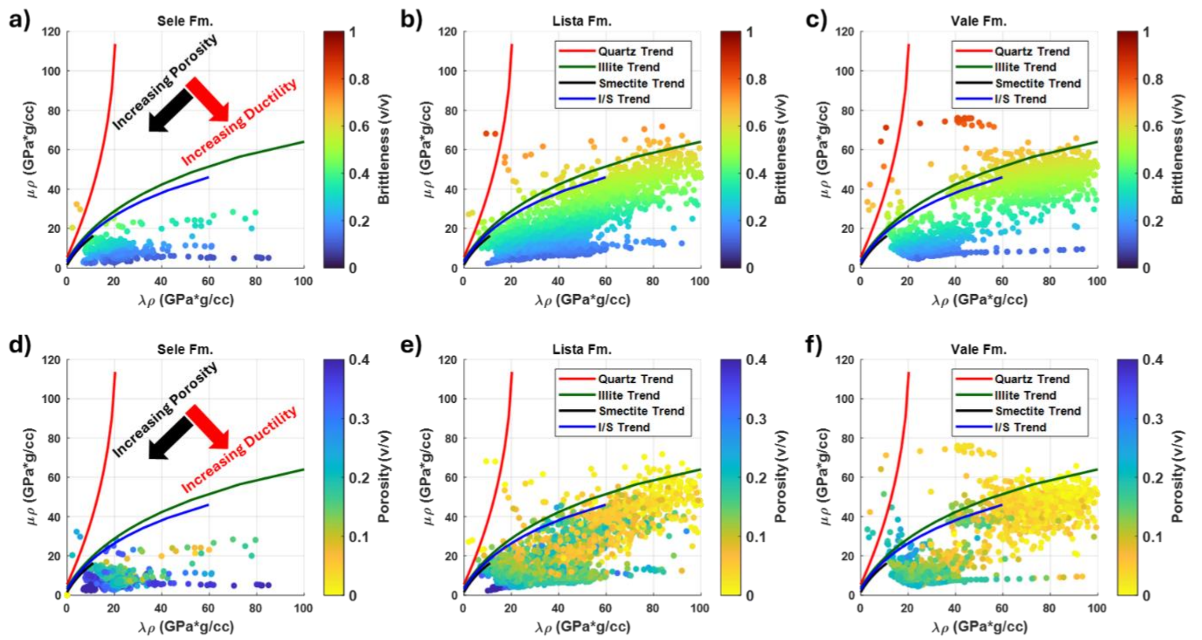

Figure 5 *λρ versus μρ crossplots for each shale formation, color-coded by: (a,b,c) brittleness index, and (d,e,f) porosity. Note that theoretical rock physics curves are superimposed, with each mineral's endmembers plotted at increasing porosity.*

Jarvie et al. (2007) demonstrated from a mineralogical perspective that quartz and carbonate minerals tend to be more brittle than clay minerals, and the λρ-μρ crossplot with rock physical background also confirms this in elastic space in our study area. Most of the data for the three shales have a reasonably low brittleness index (BI < 0.5). Furthermore, the porosity reduction also follows a similar trend with theoretical approaches.

Conclusions

Our rock-physics–based evaluation demonstrates that the Paleogene shales of the Rogaland Group generally exhibit low to moderate elastic brittleness, indicating favourable sealing potential for CO_2 storage in the central North Sea. By integrating mineralogy, theoretical rock-physics modelling, and elastic parameters, we show that temperature and cementation influence stiffness but do not necessarily shift these shales into a mechanically brittle regime. The customised λρ-μρ template, calibrated to local quartz and clay endmembers, provides a more reliable framework for brittleness than generic templates.

Acknowledgements

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