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Depositional processes and shallow diagenesis effect on caprock elastic properties in Horda Platform area, northern North Sea

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Summary

Mineralogical composition and initial pore water chemistry affect the caprock properties significantly, which are critical factors to evaluate caprock quality. In this study, five exploration wells (31/3-1, 31/2-8, 32/2-1, 32/4-1, and 35/11-4) from the Horda Platform, northern North Sea, are analyzed to assess the Late Jurassic Draupne Formation organic-rich shale caprock properties. The Draupne Formation caprock is in the mechanical compaction zone with a varying thickness within the studied wells. We evaluated elastic properties using a rock physics template (Vp-density) while log shape pattern, mineralogical and petrographical analyses (XRD, SEM & thin section) were used to assess the depositional variations that controlled changes in rock compositions and grain size distributions. The difference in log pattern with different grain size and mineralogy reflected the depositional environment changes and shallow diagenesis (pyrite framboids abundance and distribution) confirmed the variations of initial pore water chemistry within the studied wells. These factors affect the elastic parameters analyzed in the rock physics cross-plots. The results show that the Draupne Formation shales, which have higher clay content and experienced low-intensity shallow diagenesis, are soft and more ductile compared to the zones with higher brittle mineral contents exposed to relatively severe shallow diagenesis.

Introduction

Mechanical and chemical compaction/cementation convert the clay particles into shales (Taylor and Macquaker, 2011), which are strongly influenced by the mineral composition and the sediment pore water chemistry (Hart et al., 2013). The mineralogical composition of shales (caprocks) vary significantly (both vertically and laterally) within a basin because of the changes of sediment sources (e.g., weathering intensity, climate, particle size) and depositional processes (e.g., seal level changes, tectonic subsidence, oceanic circulation patterns) throughout the geological time (Hart et al., 2013). These processes are leading to significant changes in mineralogy and texture of caprocks, which affect the elastic properties. The study area (Horda Platform) is located in the northern North Sea and bounded by Øygarden Fault Complex (ØFC) in the east, Lomre Terrace (LT) in the west, Uer Terrace (UT) in the north and Stord Basin (SB) in the south (Fig. 1). Several major deep-seated north-south trending normal faults (Vette, Tusse, Svartalv & Troll) and many other minor faults are present in the area. The Horda Platform area is tectonically complex, which influences the overall rock composition and fabric and affects the caprock effectiveness, which is essential for a successful and reliable CO_2 storage project as well as hydrocarbon exploration. Therefore, a careful investigation of caprock elastic properties is necessary to prevent any CO_2 leakage, or for a better understanding of the petroleum system in the area. In this study, we characterize the effect of mineralogical variation due to depositional changes and shallow diagenetic processes on the caprock elastic properties in the Horda Platform, northern North Sea.

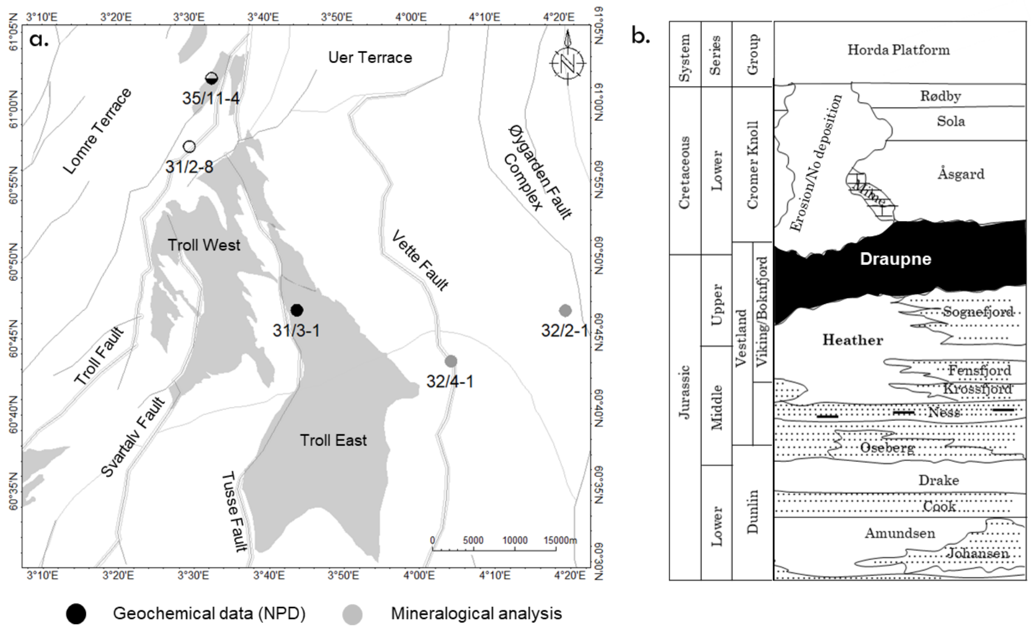

Figure 1: a) The study area showing the structural elements, major faults, and oil/gas discoveries within the studied wells, b) Jurassic and Cretaceous stratigraphic succession in the Horda Platform (modified from NPD CO_2 Atlas, 2014).

The Draupne Formation (the main caprock in the area) is a part of the Viking Group, deposited in Late Jurassic time within the Horda Platform area (Fig. 1b). This formation consists of dark grey-brown to black, usually non-calcareous, carbonaceous, occasionally fissile claystone, which was deposited in an open marine environment with restricted bottom circulation and often with anaerobic conditions (NPD, 2019). It is characterized by high gamma-ray values (usually above 100 API units) because of its Uranium content. Interbedded sandstone and siltstone, as well as minor limestone streaks and concretions, are also present throughout the formation.

Based on the well location, geochemical data and availability of rock samples (both cores and cuttings), five wells from the Horda Platform area are selected for this study (Fig. 1a), out of which wells 31/3-1 and 35/11-4 have geochemical data (retrieved from NPD database, 2020). The Draupne Formation in wells 32/2-1, 32/4-1, and 35/11-4 are sampled and analyzed in this study. The reservoir sandstone (Sognefjord Formation) contains a thick gas column in well 31/3-1 (Troll East), and gas and oil columns in well 35/11-4 (Fram). Oil shows were recorded in well 31/2-8, whereas the other wells are dry (water wet). The caprock thickness varied significantly within the studied wells, ranging from 16 to 106 m in the wells 31/2-8 and 32/4-1, respectively. The Draupne Formation experienced a maximum temperature (exhumation corrected) ranging from 38^0C to 53^0C (assuming a 30^0C/Km geothermal/temperature gradient). The temperature ranges indicate that the studied Draupne Formation in all five wells is within the mechanical compaction zone with various levels of compaction. Moreover, geochemical data from wells 31/3-1 and 35/11-4 (NPD, 2019) suggests that the average TOC content in Draupne Formation is only 2-3%, reflecting an immature (average R_0 = 0.43 and Tmax = 425^0C) source rocks. The deep resistivity (R_D) logs also support the immature Draupne Formation (< 2.5 ohm-m) in all wells except well 31/2-8, which has comparatively high deep resistivity values (~4 ohm-m).

Theory and Method

The log-derived elastic properties can be linked to the compaction history of a caprock. However, the compaction processes are too complicated, and many different factors are involved. In this study, we attempt to relate elastic properties with the depositional and diagenetic processes using bore-hole log data in addition to the petrographic analysis of cutting samples. The gamma-ray log shape helped identify the sea-level fluctuations and paleo-depositional variations within the local sub-basins (Emery and Myers, 1996). All the studied wells have standard wireline log measurements (i.e., gamma-ray, density, P-sonic, resistivity, neutron porosity and caliper etc.) out of which three of them have sampled for petrographic analysis. The volume of shale (Vsh) was calculated from the gamma-ray log using Larionov's (1969) younger rock equation. A rock physics template (e.g., Vp-Density) is employed to evaluate the elastic properties of the Draupne shale caprock. Mineralogy and petrographic analyses (i.e., XRD, SEM, and thin section study) are carried out to interpret the bulk mineral fractions, grain size differences and textural variations.

Results and discussion

The gamma-ray pattern has varied within the studied wells (Fig. 2). The wells 32/2-1 and 32/4-1 of thick Draupne Formation exhibit multiple funnel and bell-shaped cycles, while other wells have a common trend where wells 31/3-1 and 35/11-4 have cylindrical trend and well 32/2-8 has a bell-shaped pattern. Scanning Electron Microscope (SEM) images also show differences in mineralogy and texture. The northernmost well 35/11-4 has coarser detrital grains with kaolinitic clay mineral, while wells 32/2-1 and 32/4-1 have Illite dominated clays. The pyrite framboids are abundant and observed throughout the studied samples in well 35/11-4; in contrast, these are less plentiful, somewhat localized in wells 32/2-1 and 32/4-1. The Vp-density cross-plots of Draupne Formation also show a presence of stiff caprock (higher Vp and density) in the northern wells (35/11-4 & 31/2-8). The soft caprocks (exhibiting low Vp and density) found in wells 31/3-1 and 32/2-1. The data points from well 32/4-1 and few points from well 32/2-1 fall in intermediate-range (Fig. 3). Comparing with the reference curves and Vsh, wells 32/2-1 and 31/2-8 have a better match and follow the reference trend (higher Vsh well follow the higher clay percentage line and vice versa). The well 31/3-1 is roughly following the 100% clay line; however, the Vsh values range between 40% and 60% while wells 32/4-1 and 35/11-4 are following 40% line with measured Vsh values from 80 to 100% (Fig. 3b).

Shales in a basin typically follow systematic vertical stacking patterns with the relative sea-level changes. However, tectonic, climate, and relative factors affect the ultimate character of that basin fill (Slatt, 2011). During Late Jurassic time, the major faults in the study area rotated as a result of the basement blocks rotation, producing numerous local basins (Faleide et al., 2015), which leads to forming a high energy ribbon trending NNE-SSW along the present Troll West area following the main fault trend (Stewart et al., 1995). The Draupne Formation zero thickness trend also follows the existing NNE-SSW pattern, which reveals that during transgression, the erosional/non-depositional structural high still existed. Therefore, the paleo-depositional setup on both sides of the zero thickness has variation, which is explained by the stacking pattern, mineralogy, and grain size differences within the studied wells. Moreover, the variation of pyrite framboids abundance and distribution within the wells indicate changes in pore water chemistry (Taylor and Macquaker, 2011). These depositional variations also affect the elastic properties. The less ductile caprock in the northern depositional setup compared to the southern wells. The high values of Vp and density in well 35/11-4 are explained by shallow diagenesis (where bacterial iron reduction formed pyrite framboids) while a higher level of compaction occurred due to a higher percentage of silt within the clays in well 31/2-8. On the contrary, the presence of a higher percentage of clay content in well 32/2-1 is reflected by soft, ductile nature (low magnitude elastic properties). However, the elastic properties of well 31/3-1 are softer than well 32/2-1 despite exhibiting high Vsh due to the presence of a thick gas column. The gas column within Sognefjord Formation possibly increased pore pressure hence decreased the effective vertical stress and mechanical compaction (Bjørlykke and Jahren, 2015) within the reservoir, which may also affect the above caprock. Moreover, a slight increase in velocity in well 32/4-1 is explained by the presence of carbonate in the Draupne Formation (Fig. 2). Therefore, the differences in caprock properties within the studied wells are dependent on the composition and shallow diagenetic variations, which are functions of the depositional processes.

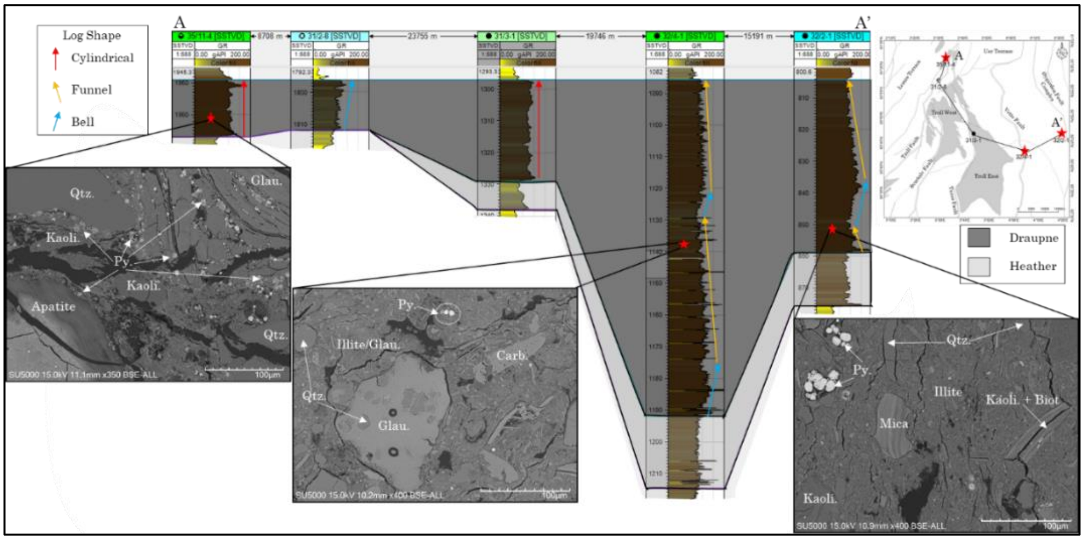

Figure 2: Stratigraphic correlation along AA’, flattened on top Draupne Formation showing the thickness variation with variable gamma-ray log patterns (cylindrical, funnel, and bell), which reveal the paleo-depositional differences. Also, the SEM images from the corresponding depth show the changes in composition and texture in a single caprock unit. All the white dots are the pyrite (Py.) framboids, which have a significant variation in volume and distribution within the studied wells. The abbreviations of Qtz. (Quartz), Glau. (Glauconite), Kaoli. (Kaolinite), Biot. (Biotite) and Carb. (Carbonate) are used for simplicity.

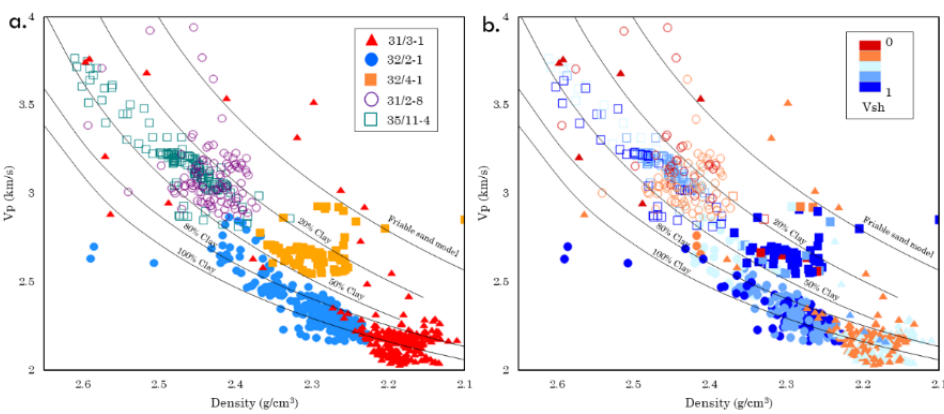

Figure 3: Density vs. Vp cross-plot of Draupne Formation data from the studied wells color-coded by well names (a), and Vsh (b), with reference curves adapted from Avseth et al., 2005.

Two northern wells show similar elastic properties even though well 35/11-4 is a gas/oil discovery, and well 31/2-8 has oil shows. The oil shows possibly indicate that the hydrocarbon migrated into the trap but escaped due to a possible caprock or fault-seal failures. Moreover, the higher deep resistivity (R_D) within the Draupne Formation in well 31/2-8 indicates fluid migration through it (TOC immature in that area). If we assume the bounding fault to be sealed, then mineralogy (mainly clay particles) possibly played a vital role in the caprock breach. In that case, the seal integrity may be difficult to predict only from elastic properties. Caprock properties also depend on many other factors i.e. temperature, stress regime, and diagenesis, etc. (Sone and Zoback, 2014) but heavily depend on the ductile minerals (i.e., clay). Therefore, an integrated approach is needed for a better understanding of caprock effectiveness.

Conclusions

Caprock geomechanical behaviors are the most critical parameters for successful CO_2 storage, and hydrocarbon exploration, which depends on various factors. This study assesses the effect of mineralogical composition and shallow diagenesis of Draupne shale caprock properties in the Horda Platform in the northern North Sea. The changes of the paleo-depositional setup can control the grain size distribution, mineralogy, and pore water chemistry that ultimately influence the compaction processes and caprock properties. However, the elastic property based ductility measurements can be misleading as zones showing similar elastic properties have good sealing potential (oil discovery in well 35/11-4) and a failure (oil shows in well 31/2-8).

Acknowledgments

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