Introduction

Norway is planning to launch a large-scale CO\textsubscript{2} storage project (Northern Light) in the northern North Sea (south of the Troll field). For such offshore CO\textsubscript{2} storage project, geomechanical and geophysical evaluations are essential to ensure safe operation and to avoid unwanted leakage of injected CO\textsubscript{2} to the seabed (i.e., storage conformance and containment). In this study, we evaluate the feasibility of the microseismic monitoring technique of potential CO\textsubscript{2} storage sites in the northern North Sea. Microseismic monitoring is based on measuring seismic signals resulting from abrupt movement, deformation, and re-activation or creation of fractures and faults within the subsurface. We performed advanced laboratory testing in combination with numerical simulations at the field scale, including fracture/fault (re-)activation and/or creation. The laboratory tests include microseismic monitoring of acoustic emission (AE) in laboratory-scale microseismicity.

Generally, AE events in shales are rare due to microseismicity but AE events reported in the literature (e.g., Amann et al., 2011) in the unconfined compressive strength tests of Opalinus Clay. Microseismic monitoring is frequently used in shale gas stimulation (Cipolla et al., 2010, Maxwell et. al, 2011), however, only a few surveys are available for the North Sea related to fields with large depletion and deformations in the reservoir and cuttings reinjection projects. There are currently no published microseismic or AE datasets from the North Sea directly relevant for CO\textsubscript{2} injection. This study focuses on the geomechanical and AE response of caprock shales in the North Sea CO\textsubscript{2} storage sites. Two multistage triaxial tests perform on caprock lithologies, one shallow (700 m) mudstone from Nordland Group overlying Sleipner CO\textsubscript{2} Utsira sand reservoir in the Southern Viking Graben and another one is deeply buried (2581 m) shale of Draupne Formation from well 16/8-3S within the Ling Depression in the central part of the North Sea. The Nordland shale is a caprock of shallow Utsira and Skade sandstones. The Draupne shale is the caprock overlying the Sognefjord sandstone reservoir of relatively deep CO\textsubscript{2} storage sites around in the Troll field area. The elastic properties of tested shales compare with the existing datasets and empirical correlations of shales in the North Sea. Besides, the correlations apply to well log data acquired from the potential CO\textsubscript{2} storage site Smeaheia.

Method

These two shales have previously been described and tested (Mondol et. al., 2010 and Skurtveit et. al., 2015). For the Nordland mudstone, the porosity ranges between 39 - 41%, the permeability is 1.6×10\textsuperscript{-3} mD, and the bulk mineralogy is 68% clay, 19% Quartz, 7% K-feldspar, 5.5% plagioclase, with a minor amount of Calcite and Pyrite (Mondol et. al., 2010). For the Draupne shale, the porosity is 6.5-12.5%, permeability is in the range of 1-6×10\textsuperscript{-7}mD the bulk mineralogy is 48% clay 24% Quartz, 18% Feldspar 3% Pyrite and 2% Carbonates and (Skurtveit et. al., 2015).

The consolidation stresses applied to the two specimens are representative of their in-situ stresses at the depth from where they retrieved. The Nordland sample was consolidated with a fixed ratio between confining stress and effective vertical stress of 0.5. The final effective horizontal consolidation stress was σ\textsubscript{h\prime} = 4 MPa and effective vertical stress σ\textsubscript{v\prime} = 7 MPa. The sample was then unloaded and reloaded by Δσ\textsubscript{v\prime} = 1 MPa while keeping σ\textsubscript{h\prime} constant, to simulate the elastic response due to injection. The sample was then axially loaded to failure (sheared) at a constant strain rate, to create a through-going fracture. Following failure and the continued deformation of the sample at the residual stress, the confining stress was reduced, and the fracture was re-mobilized by increasing σ\textsubscript{v\prime}. Three different confining stresses were used for fracture reactivation (4, 2.5 and 1 MPa). For the Draupne sample, the effective consolidation stress was σ\textsubscript{v\prime} = 25.8 MPa and σ\textsubscript{h\prime} = 17 MPa. There was no unloading/reloading loop in this test. The sample was sheared to failure, and the fracture was re-mobilized at three different confining stresses (8.9, 10.7 and 15.6 MPa). Note that to speed up the test on the lower-permeability Draupne sample, the strain rate during shearing was higher than the normal requirements, and excess pore pressure was therefore likely increased during the shearing of this sample. For both samples, AE and the axial and radial P-wave velocities were measured during all phases of the tests.

We compared the elastic moduli data from these two tests to the results of two empirical correlations between velocity and modulus, and other relevant data from the northern North Sea. We discuss these
results in light of recent 3D field-scale geomechanical modelling of CO$_2$ injection in Smølaheia performed as part of a parallel study (Choi et al., 2019).

**Results and discussion**

The results from the laboratory testing are shown in Figure 1. For both lithologies, no AE events were detected during any test phase—neither during consolidation, unloading/reloading cycle, shearing of intact rock nor during remobilization of the induced fracture. Of the test phases, the effective stress unloading from the in-situ stress, and the remobilization of the fracture at low confining stresses are the most representative of a CO$_2$ injection scenario. The shear stress during shearing of the intact rock is significantly higher than in the expected stress path during CO$_2$ injection—the aim of this test phase was simply to induce a fracture. Although both samples dilated significantly during shearing, there were no AE events detected during this phase. We observed a more abrupt post-peak stress drop in the Draupne sample compared to the Nordland sample. From the fracture re-mobilization phase, the shear strength during at the 3 different confining stresses gave friction angles and cohesion of 20.4° and 0.8 MPa for the Nordland sample, and 19.2° and 1.45 MPa for the Draupne sample.

**Figure 1** Results of the triaxial testing of Nordland mudstone. a) Unloading/reloading loops simulating injection. b) Tangential shear modulus during shearing. c) Shear modulus vs. P-wave velocity from testing, compared with empirical correlations. Data from unloading modulus and 50% shear modulus. d) Shear modulus vs. P-wave velocity from tests compared with empirical correlations. Data from unloading modulus and 50% shear modulus.

The Young's Moduli were determined from the axial unloading and reloading data. For the Nordland sample, $E_{\text{axial}}$ at the in-situ stresses were 1.1 and 1.3 GPa respectively. P-wave velocities were measured at 2258 m/s in the axial (in-situ vertical) direction ($V_{p,\text{ax}}$), and 2213 m/s in the radial direction ($V_{p,\text{rad}}$), showing a near-isotropic velocity. A previous test on the same Nordland mudstone showed more anisotropy, with $V_{p,\text{ax}}/V_{p,\text{rad}}$ of 1.1 (Mondol, et. al, 2010). For Draupne shale, $V_{p,\text{ax}}$ was 2739 m/s and $V_{p,\text{rad}}$ was 3313 m/s at the effective consolidation stress, reflecting a significant velocity anisotropy. The initial shear modulus at the start of shearing is 2.25 GPa, and Shear Modulus $G_{50}$ at 50% shear strain is 1.38 GPa. The initial Young's Modulus at the start of shearing was 5.6 GPa, and Young's Modulus at 50% shear strain was 4.6 GPa. This velocity anisotropy is in agreement with previous observations on
the same shale core, where a dynamic anisotropy of $V_{p,ax}/V_{p,rad}$ of 1.2 and mechanical anisotropy $E_{\text{horizontal}}/E_{\text{vertical}}$ of 2 was found (Skurtveit et al., 2015). In Figure 1, we compare the elastic moduli and velocity data from testing with two empirical correlations. Other relevant datasets from the northern North Sea are included for comparison: these data are for samples from the Horda platform (1100-1400 m), and a deeper shale from northern North Sea (2500-2900m). Although these samples are from different depths and varying lithologies, their trends between velocity and stiffness are rather similar. The data from the Horda Platform is close to the empirical correlation suggested by Horsrud (2001). In both tests unloading phases are not available. The small strain static modulus has been derived from the initial tangential modulus during shearing. The small strain data are closer to the correlation of Grande et al. (2008). Most data points for both 50% shear and initial small strain modulus are within the trendlines from these two correlations, which can be used as a guideline for the large and small strain moduli respectively.

Systematic studies performed on sonic velocity well logs from the North Sea indicate large variability within the same formations, at various locations and depths in the North Sea. This implies that large variations in elastic properties can be expected along with North Sea wells; therefore, local site evaluation is usually required. In this study, correlations were applied to well log velocity data from the Alpha prospect (32/4-2, Figure 2) as well as two other wells 32/2-1 (Beta in Smeaheia) and a well (31/6-6) from the Troll East. Figure 2 shows the Young’s and Shear moduli against depth: the static moduli ($E_s$ and $G_s$) are based on correlations from Horsrud (2001); the dynamic modulus ($E_d$ and $G_d$) are based on dynamic relationships and data for unloading shear modulus (NGI equation, Grande et al., 2008).

Figure 2 Young’s modulus and shear modulus of the overburden lithologies based on empirical correlations and the measured velocity log from well 32/4-1.

From the logs, it appears that the Draupne shale has Young’s Modulus ($E_s$) in the range 1.3 - 1.8 GPa. The tested Draupne shale from the Ling depression has $E_s$ of around 2.4- 2.9 GPa, significantly stiffer than as indicated by logs in the Draupne shale in the Smeaheia area. The velocities and stiffness for lithologies in the Smeaheia area are likely affected by overconsolidation due to significant uplift (800 for Troll East and 1100 m for Smeaheia ). While the present-day in-situ pore pressure is expected to be hydrostatic, the pore pressure and effective stress during geological history are uncertain. In comparison, the Kyrre, Våle and Lista formations have rather high-velocity peaks, and the velocity vs. depth trend may locally reduce with depth. This differs from the normal compaction trends observed in the North Sea, where velocities gradually increase or remain constant with depth. The Lista formation in well 32/4-1 has large local variations in velocities, however, data quality in this section may questionable.
The choice of parameters for geomechanical modelling depends on the type of problem to be analysed. In Smeaheia, the formations are uplifted during Cenozoic time, and a stiff behaviour is expected both in the case of small unloading or loading caused by the injection of CO2 into the reservoir. Hence, the most relevant elastic properties are for small strains during unloading/reloading phases. In the geomechanical model, the choice of stiffness will affect the relationship between horizontal stress and pore pressure (poroelastic effect), influencing stresses in the overburden, and close to the well, where thermal stress reduction from injecting a cooler CO2 (thermal effects). From 3D Finite Element Modelling (FEM) of the Smeaheia Alpha structure, an expected maximum pressure build-up of 1.2 MPa results in an expansion of 5 cm within the reservoir during the injection lifetime (Choi et al., 2019). The maximum change of effective stress in the caprock is a 0.2 MPa increase in the area above the injector. Considering a small strain Young's Modulus of 2.5 GPa for Draupne in Smeaheia, a 0.2 MPa effective stress change results in a strain of less than 0.1 mS. This limited amount of induced strain supports using the small-strain stiffness in the mudstone or shale lithologies surrounding the reservoir. The overall shear stress in the intact or fractured caprocks is low, and the stress path resulting from the injection is not critical with respect to shear failure. The potential for mobilization of shear fractures is therefore low, and we expect low seismic activity within the mudstone layers. Further, any potential critical fracture events in the cap rock may be difficult to detect with microseismic monitoring due to the aseismic (within the observable frequency range) behaviour of the North Sea caprock lithologies as indicated from our AE tests.

**Conclusion**

Triaxial testing of shallow and deep caprock shales showed no microseismic activity during any of the phases, including effective stress unloading corresponding to CO2 injection; shearing of the intact rock; and remobilization of the induced fractures. The small strain elastic response in the two lithologies are in agreement with previously published datasets and empirical trendlines. The small strain modulus (as opposed to large-strain) is the most relevant input parameter for geomechanical studies for evaluating CO2 storage sites.

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**References**


