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Geomechanical and Seismic Behaviors of Draupne Shale: A Case Study from the Central North Sea

N.H. Mondol[1]*

[1] University Of Oslo

Summary

Organic-rich shales exhibit a variation in shear strength and anisotropic behavior of seismic wave propagation when the direction of the plane of weakness is varied with respect to the direction of the principal stresses. This study investigats geomechanical and seismic behaviors of a Draupne shale core retrieved from an exploration well from the Central North Sea, offshore Norway. CIU- Isotropically Consolidated Undrained-tests were performed on three core plugs that drilled parallel (0 degree), inclined (45 degree) and perpendicular (90 degree) to the layerings/beddings. The index test results indicate very low permeability of the shale with small pore throats ensuring a high capillary sealing for the intact part, whereas the observed shear fracture is more uncertain with respect to sealing capacity. Anisotropy has been demonstrated to have a marked influence on the strength properties (e.g. shear strength, Young's Modulus, Poisson's Ratio) of the Draupne shale. The minimum shear strength is measured for 45 degree core plug whereas the plug drilled parallel (0 degree) to the layering exhibits the highest shear strength. Post-test sample observation confirms that the strength anisotropy is related to failure with respect to the layerings/beddings.

Introduction

This study investigates geomechanical and acoustic behaviours of a shale core that retrieved from the upper most part of the Draupne Formation (from 2574.5 m to 2584 m) from well 16/8-3 S. The well 16/8-3 S (Lupin prospect) was drilled in the Ling depression in the Central North Sea (Figure 1a). The main objective to acquire Draupne shale was to provide high quality core for mechanical and rock physical studies related to seal integrity evaluation for future CO_2 storage in the North Sea (Skurtveit et al., 2015). The Lupin prospect was defined by a tilted horst block with several small internal rotated fault blocks of Permian age (NPD FactPages, 2019). The objective to drill the well was to prove a commercial accumulation of hydrocarbons in Permian Rotliegendes sandstones. The well penetrated rocks of Nordland, Hordaland, Rogaland, Shetland, Cromer Knoll, Viking, Hegre, Zechstein and Rotliegend Groups from Quaternary, to Permian ages (Figure 1b). The top of the expected main reservoir, the Rotliegendes Group was picked at 3015 m TVD (Total Vertical depth). As many other wells drilled around the Lupin prospect (Figure 1), there was no indication of hydrocarbons in the well (NPD FactPages, 2019).

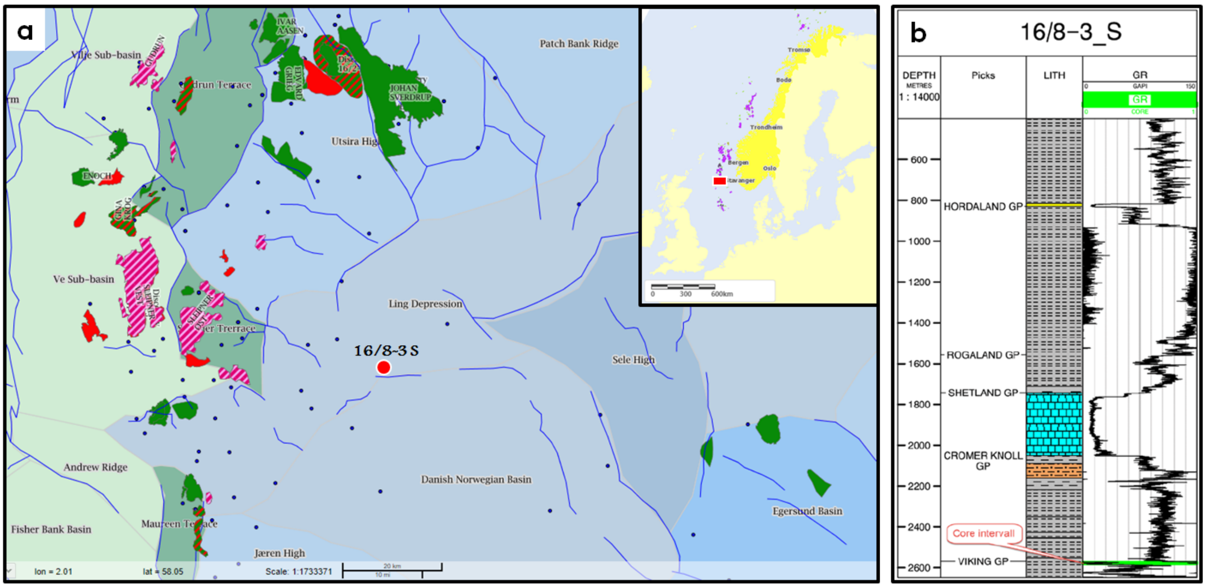

Figure 1 *a) Index map overlaid with major structural elements of the Central North Sea). Location of the studied Lupin well (16/8-3 S, red circle) in the Ling Depression is shown on the map. Map modified from the Norwegian Petroleum Directorate (NPD FactMaps, 2019) and b) Gamma Ray Log of Lupin well showing a genetralized lithostratigraphy and location of the core interval (Skurtveit et al., 2015).*

The Upper Jurassic Draupne Formation (equivalent to the Kimmeridge Formation) found throughout the Norwegian Continental Shelf (NCS) as main source, carrier or seal rock in several oil fields. It is an organic-rich shale deposited in a low-energy intra-shelf marine environment where focusing and ponding of the clayey sediment resulted in thick basinal sections. In the Southern North Sea, the equivalents to the Draupne Formation are the Mandal and Tau Formations, which vary in thickness from 1 to 170 meters (Mandal Formation) and 2-118 meters (Tau Formation) respectively. In the Norwegian Sea and the Barents Sea, the equivalent to the Draupne Formation are Spekk and Hekkingen Formations, which vary in thickness from 1 to 150 meters (Spekk Formation) and 2 to 190 meters (Hekkingen Formation) respectively (NPD FactPages, 2019). In the North Sea, Draupne Formation penetrated by exploration wells in various depth levels (from 800 to 6000 meters). Draupne Formation has been substantially indurated in the North Sea by burial and later uplifted where the maximum uplift documented towards the cost. The thickness of the Draupne Formation in well 16/8-3 S is 86 m (2570-2656 m RKB). The exhumation study performed by Jørgen et al. (2017) suggested no uplift in the well location.

Material and Methods

The Draupne Formation consists of dark grey-brown to black, occasionally fissile claystone (Figure 3). It is characterized by very high radioactivity (often above 100 API units) which is a function of organic carbon content. It has anomalously low velocity, density and high resistivity. Minor limestone streaks and concretions occur throughout the formation. The core naturally split into sub-sections along the bedding parallel fractures. Three cylindrical core plugs (one perpendicular to the layering, one parallel to the layering and one at 45° to the layering) with dimensions of approximately 25 mm in diameter and approximately 55 mm in height were prepared for CIU test. CIU is isotropically consolidated test with undrained shearing. The following operations were performed for the CIU triaxial test:

- The specimen was mounted into the triaxial cell (Figure 2) and subjected to a vacuum of 0.1 MPa.
- A cell pressure of 0.5 MPa was applied. The cell pressure was increased to 20 MPa.
- Release of the vacuum by allowing salt water to go into the filter disks. Swelling was observed for test at 20 MPa. The sample was allowed to swell for some time. Estimated swelling pressure is around 20 MPa.
- The specimen was allowed to stabilize prior to shearing until the octahedral strains stabilized with time.
- Undrained shearing by increasing the vertical stress until failure. Axial strain rate was 0.01-0.1 mS/hr during undrained shearing.
- P- and S-wave velocities in both axial and radial directions were logged continuously for both consolidation and shear phases.

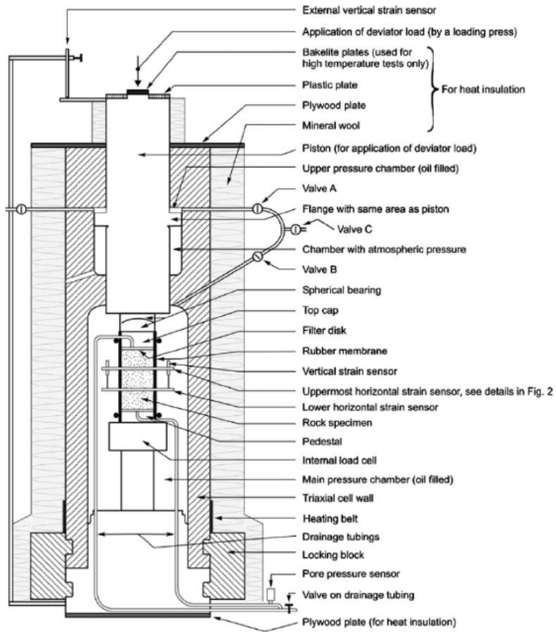

***Figure 2** Schematic illustration of the triaxial cell used in CIU test (Berre, 2011).*

Sample characterization		
	Porosity	7.8 %
	Bulk density	2.24 g/cm^3
	Water content	8 %
	CEC	23 Meq/100g
	SSA	11 m^2/g
	Pore throat	9 nm
Bulk Mineralogy	TOC	6.8 %
	Quartz	22.40 %
	Microcline	17.80 %
	Pyrite	7.7 %
	Calcite	0.7 %
	Dolomite	1.2%
	Total clay	50.7 %
Clay Mineralogy	Kaolinite	62.10 %
	Smectite	18 %
	Chlorite	0.7 %
	Mica/Illite	19.30 %

***Figure 3** Index parameters and mineralogical composition of Draupne Shale (left table). Core photo of black Draupne Shale showing glossy shear surface with scattered striations and rough topography related to asperities (right).*

Bulk and clay mineral analyses (Table in Figure 3) were carried out by preparing randomly oriented powder and oriented clay fraction (<2 μm), respectively, for X-ray diffraction (XRD) analysis with the use of a Bruker D8 ADVANCE machine. A helium pycnometer was used to measure the grain density of the crushed and dried samples. The TOC content was obtained from a pulverized sample analyzed on a LECO SC-632 instrument. A mercury intrusion porosimetry test was used to determine the connected porosity and to obtain information on the pore size distribution. The BET method was used to determine the external SSA (Specific Surface Area) of dried and degassed power sample. CEC (Cation Exchange Capacity) was estimated using the ammonium acetate method with power sample.

Results and Discussion

Figures 4 and 5 show the results for the undrained triaxial shear phase for three Draupne shale core plugs. The studied Draupne shale has a nearly linear stress-strain response before increased ductility occurs in the near-peak region (Figure 4a). Once the peak shear stress is reached, the vertical and horizontal strains reduce rapidly and the post-peak curves become nearly horizontal. The pore pressures increase until peak shear stress is reached, then dropped for the tests (Figure 4b). Figure 4c shows the mobilized friction versus vertical strain. As can be seen, 90^0 plug is much more compressible compared to the two other plugs where plug drilled 45^0 to the layerings/beddings shown minimum compaction (Figure 4c).

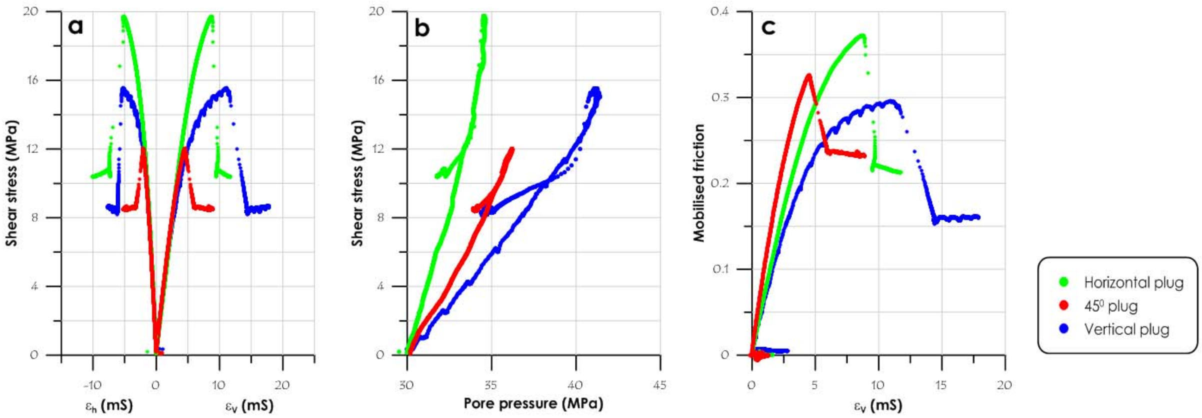

Figure 4 *Relationship between a) shear stress vs. vertical and horizontal strains, b) shear stress vs. pore pressure and c) mobilized friction vs. vertical strain of three Draupne shales core plugs drilled parallel (green), 45^0 (red) and perpendicular (blue) to the layerings/beddings.*

The index test results presented in a table in Figure 3 indicate very low porosity and permeability of the Draupne shale with small pore throats ensuring an effective seal. On the other hand, the observed shear fractures are more uncertain with respect to sealing capacity. The anisotropic behavior of Vp and Vs in the subsurface and in the laboratory is well documented for organic-rich shales (Zadeh et al., 2017). During the shearing phase P- and S-wave velocities are measured. Vp (both horizontal Vph and vertical Vpv) and Vs (both horizontal Vsh and vertical Vsv), are measured for all three samples drilled 0^0, 45^0 and 90^0 respectively to calculate anisotropic parameters. Vp and Vs presented in Figure 5b measured at failure or at maximum shear stress. As seen in Figure 5b, the results indicate a trend towards the P-wave decreasing with increasing β (layering/bedding) from 0 to 90^0. In contrary, the highest Vs (both Vsv and Vsh) measured in 45^0 degree plug. The porosity values presented in Figure 5a measured at the end of consolidation where a trend of decreasing porosity with increasing β (layering/bedding) is observed. Undrained Young's modulus (E) and Poisson's Ratio (ν) are calculated as the secant module at 50% of the peak deviatoric shear stress (Figure 5c). As expected, both E and ν decrease with increasing layering/bedding. The porosity values presented in Figure 5a measured at the end of consolidation where a trend of decreasing porosity with increasing β (layering/bedding) is observed.

Conclusions

Laboratory tests on Draupne shale have shown that strength is anisotropic and the strength anisotropy is related to the layerings/bedding planes. A systematic variation in strength with sample orientation is observed for tests of three core plugs at similar effective isotropic consolidation stress. Post failure inspection of the plugs show that the failure planes are directly affected by the orientation of the applied stress relative to the bedding planes. Results suggesting that the bedding represent weak planes which tend to fail before intrinsic failure occur, whenever the orientation of these planes is suitable.

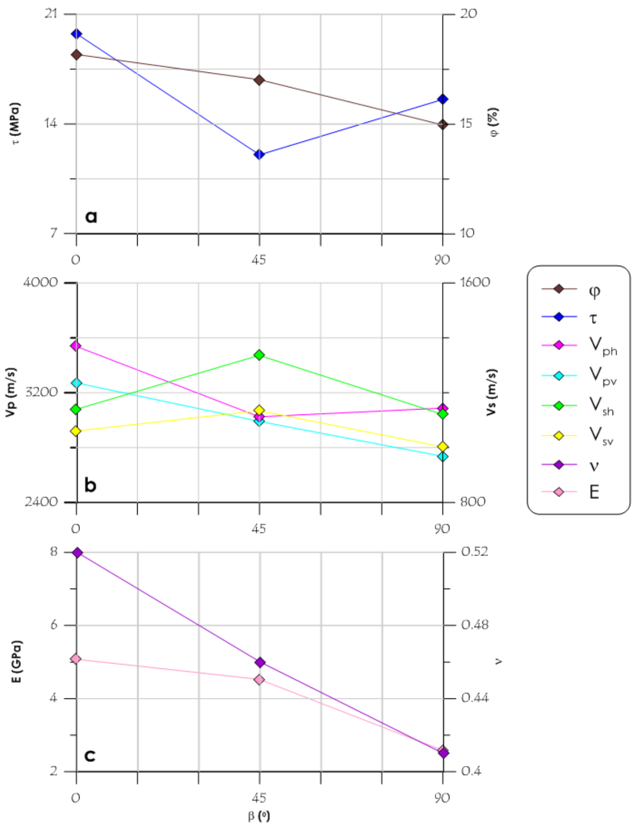

__Figure 5__ Anisotropic behavior of petrophysical (e.g. porosity), geomechanical (e.g. shear stress, Young's Modulus and Poisson's Ratio) and seismic (both Vp and Vs) prarameters of Draupne Ssale core plugs drilled 0^0 (parallel), 45^0 (inclined) and 90^0 (perpendicular) to the layerings/beddings.

Acknowledgements

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References

Berre, T. [2011]. Triaxial testing of soft rocks. Geotechnical Testing Journal, **34**(1), 61-75.

Hansen, J.A., Yenwongfai, H.D., Fawad, M. and Mondol, N. H. [2017]. Estimating exhumation using experimental compaction trends and rock physics relations, with continuation into analysis of source and reservoir rocks: Central North Sea, offshore Norway: 87th Annual International Meeting, SEG, Expanded Abstracts, 3971-3975, https://doi.org/10.1190/segam2017-17783053.1.

NPD FactPages 2019. http://factpages.npd.no/factpages/Default.aspx?culture=en

NPD FactMaps 2019. http://gis.npd.no/factmaps/html_21/

Skurtveit, E. Grande, L., Ogebule, O.Y., Gabrielsen, R.H., Faleide, J.I., Mondol, N.H., Maurer, R. and Horsrud, P. [2015]. Mechanical testing and sealing capacity of the Upper Jurassic Draupne Formation, North Sea. ARMA paper 15-331.

Zadeh, M.K., Mondol, N.H. and Jahren, J. [2017]. Velocity anisotropy of Upper Jurassic organic-rich shales, Norwegian Continental Shelf. Geophysics, **82**(2), C61-C75.