Seal quality prediction using E-Poisson's ratio rock physics templet- A case study from the Norwegian Barents Sea

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Summary

This study predicts seal quality of Lower Cretaceous Kolmule Formation from well log data of two exploration wells Skalle (gas discovery) and Juksa (dry well) in the uplifted and tectonically complexed Norwegian Barents Sea using the Young's modulus-Poisson's ratio (E-ν) rock physics templet. Among other causes (e.g. pressure release and gas expulsion, tilting and spillage from pre-uplift hydrocarbon accumulation, cooling of source rock etc.) failure of seals linked to the uplift have been proposed the main cause for the lack of success in finding commercial petroleum accumulation in the Norwegian Barents Sea. A simple rock physics model which allowed to compute theoretical values of dynamic elastic parameters for common constituents of shales are utalized to constructe the E-ν templet. The template shows the variation in E-ν for a combination of mineralogical mixtures (quartz, calcite, clay and organic matter) versus porosity or depth/effective stress. Results show that the Kolmule formation in both wells has significant variations of brittleness values where sand dominated sections show high brittleness compared to shale dominated sections (more ductile). The top seal of gas bearing Kolmule Formation in Skalle well has low BI and fall on the ductile region agreeing well with brittleness definition. Brittleness indices estimates based on elastic parameters are easy to use but require calibration of lab observation.

Introduction

Petroleum exploration in the Norwegian Barents Sea (NBS) began early in the 1980s. Since then 150 exploration wells were drilled in the NBS but the success rate of commercial discovery is very low. Many of the exploration wells show only residual hydrocarbon. It is generally agreed that several episodes of Cenozoic uplift and erosion have caused the depletion of hydrocarbon accumulations in the region (Ohm et al. 2008). Among the possible reasons for leakage of hydrocarbon from reservoirs are spill due to tilting, expulsion caused by gas expansion and seal failure. Seal quality assessment is thus embarked upon to enhance the knowledge needed for future exploration and exploration success of the NBS. This study evaluates seal quality of lower Cretaceous Kolmule shale of two exploration wells 7120/2-3 S (Skalle, gas discovery) and 7120/6-3 S (Juksa, dry well) in the NBS (Fig. 1) using a rock physics templet (RPT) E-ν. Low Poisson's ratio and high Young's modulus indicate more brittle shales whereas ductile shales exhibit a high ν and low E (Grieser and Bray, 2007).

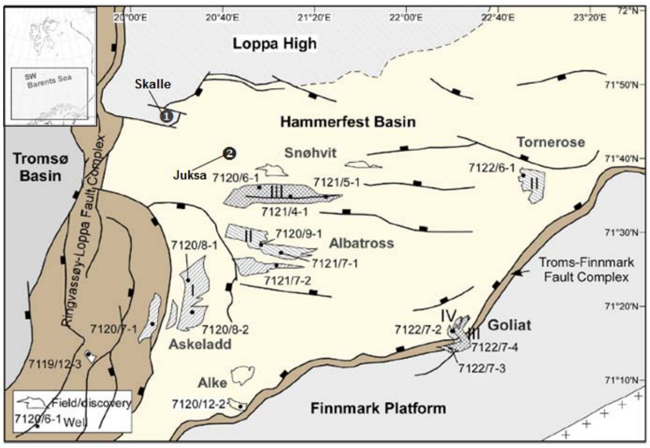

Figure 1: Index map overlayed with major structural elements of south-western part of the Norwegian Barents Sea. Location of the studied wells of Skalle gas discovery (1) in the south-western tip of the Loppa High and Juksa dry well (2) in the north-western part of the Hammerfest Basin. Map modified from Murillo et al. (2016) and NPD FactPages (2018).

The well 7120/2-3 S was drilled on the Skalle prospect north-west of the Snøhvit Field at a location between the Loppa High to the north and the Hammerfest Basin to south (Fig. 1). The primary objective was to explore sandstones of the lower Cretaceous Kolmule Formation as well as reservoir potential of Lower-Middle Jurassic Stø, Nordmela and Tubåen Formations (Fig. 2a) (source: NPD FactPages, 2018). The well encountered two gas columns from 1576-1639.4 m (RKB) in the Kolmule Formation and 2071-2095.9 m (RKB) in the Stø Formation (Fig. 2b). The Kolmule reservoir had a gross thickness of 150 m, consisting of several sandstone bodies with reservoir facies ranging from shallow marine sandstones to conglomerates and homogenous slope turbidities. The Stø reservoir consisted of 149 m thick, clean sandstone. The other exploration well 7120/6-3 S was drilled on the Juksa prospect in the north-western part of the Hammerfest Basin, in a sub-basin north of the Snøhvit field (Fig. 1). The primary objective was to test the lower part of the Kolmule Formation (Fig. 2c). The secondary target was wedges of intra-formational sandstones in the uppermost Hekkingen/lowermost Knurr Formations and the tertiary target was sandstones in the Lower-Middle Jurassic Nordmela and Stø Formations (source: NPD FactPages, 2018). The well encountered sandstones with hydrocarbon shows in the lower Kolmule Formation. No sands or hydrocarbon shows were seen in the Knurr Formation. The well penetrated a 2-meter thick organic-rich shale (oil prone source rock) at 2416 m (RKB) in the Kolje Formation. The lower part of the Hekkingen Formation had a high organic content (Fig. 2c). Sandstones in the Lower-Middle Jurassic Stø and Nordmela Formations were water bearing with shows in side wall cores.

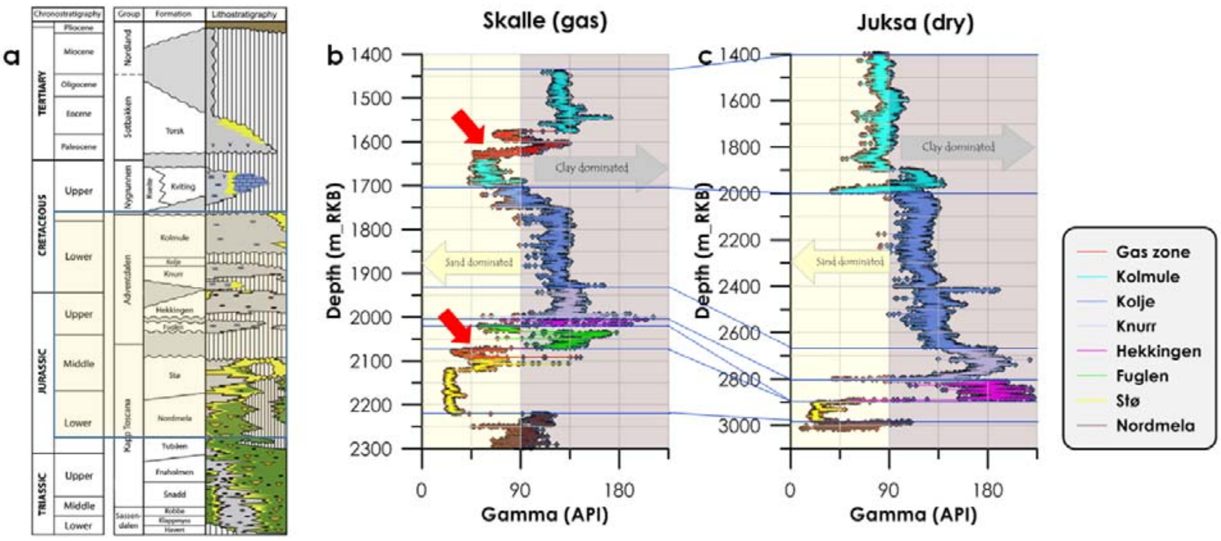

Figure 2: a) Generalized lithostratigraphic section of the Norwegian Barents Sea, b-c) well-to-well correlation of Skalle (7120/2-3 S, gas discovery) and Juksa (7120/6-3 S, dry well). Two gas zones (within Kolmule and Stø Formations) in Skalle well are marked by red arrows. The lithostratigraphy is modified after Glørstad-Clark et al. (2010) and NPD FactPages (2018).

Theory and Method

Poisson's ratio (ν) is believed to reflect rock's ability to fail under stress, and Young's modulus (E) reflects the ability to maintain a fracture once the rock fractures (Perez, 2014). Therefore using a RPT of E-ν one can predict quality of caprock shales (e.g. brittle versus ductile). A simple rock physics model which allowed to compute theoretical values of dynamic elastic parameters for common constituents of shales are utalized to constructe the templet (Fig. 3a). The average Vp, Vs and density values of common constituents published in the literature form the base for the templet that are used to compute E, v and equivalent K (bulk modulus) and μ (shear modulus) values for each of the mineral members. Based on the mineralogy content, ductility (the opposite of brittleness) is controlled by clay, calcite, and organic content (Perez and Marfurt, 2014). The next step is to apply the RPT to well log data of target zones to interpret/classify the observed trends and characteristic populations in the data (Fig. 3b). The measured well log data of Vp, Vs and density are used to calculate elastic parameters E, ν, K and μ. To classify shale caprocks based on their ability to undergo brittle failure, or conversely, showing varied degree of ductility, a series of brittleness indices (BI^1-BI^8) are computed (Table 1). The computations are based on emperical relations suggested by Grieser and Bray (2007), Rickman et al. (2008), Guo et al. (2012), and Chen et al. (2014) where Young's modulus (E), Poisson's ratio (ν), Lamé constant (λ), and shear modulus (μ) are utilized.

Table 1: Brittleness indices (BI^1-BI^8) definitions based on elastic properties.

Grieser and Bray (2007) $BI^1=[(E-E_{min})/(E_{max}-E_{min})]/2$ ………… (1) $BI^2=[(\nu-\nu_{max})/(\nu_{min}-\nu_{max})]/2$ ………… (2) $BI^3=(BI^1+BI^2)/2$ ………………………… (3) where E_{max}=~69 GPa, E_{min}=0 Gpa and ν_{max}=0.5 and ν_{min}=0	Rickman et al. (2008) $BI^4=[(E-E_{min})/(E_{max}-E_{min})]/2$ .... (4) $BI^5=[(\nu-\nu_{max})/(\nu_{min}-\nu_{max})]/2$ ....(5) $BI^6=(BI^4+BI^5)/2$ ....(6) where E_{max}=55 GPa, E_{min}=7 Gpa and ν_{max}=0.4 and ν_{min}=0.15	Guo et al. 2012 $BI^7=(\lambda+2\mu)/\lambda$ ………….. (7) Chen et al. 2014 $BI^8=E/\lambda$ ....(8)

Results and discussion

The Kolmule formation of both Skalle and Juksa wells shows a wide variations of brittle-ductile behavior (Fig. 3b). The top seal of Kolmule Formation in Skalle well shows ductile behavior compared to water and gas bearing zones (Fig. 3c). Notice that a cloud of high-BI points (color coded in magenta) of Skalle well falls into the brittle region that generating a conflict (Fig. 3c). Figure 3d compares the elastic parameter based brittleness index of Kolmule Formation in Juksa well superimposed on the E-ν plot. Brittleness of Komule Formation of Juksa well shows significant differences where lower sandy unit shows brittle behavior compared to clay (ductile) and mixed sand-clay (less brittle-less ductile) units.

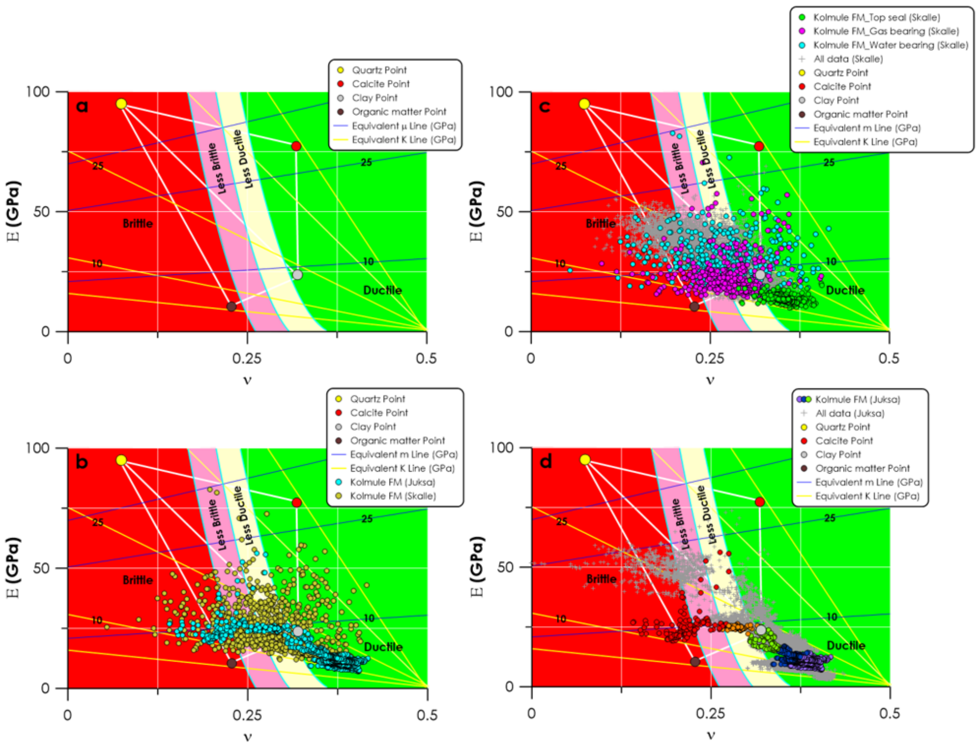

Figure 3: a) Constructed RPT of E and ν. Young's modulus and Poisson's ratio values of quartz, calcite, clay and organic matter are superimposed on the lines of constant bulk (yellow lines) and shear (blue lines) moduli. The background classifications of brittle versus ductile zones are adapted from Perez and Marfurt (2014). b) Data of Kolmule Formation from Skalle and Juksa wells are plotted on top of the RPT. c) Data of Kolmule formation of Skalle well classified by water (blue), gas (magenta) and top seal (green) are plotted on top of the RPT. d) Data of Kolmule Formation of Juksa well classified by brittleness index BI^6 (Rickman et al. 2008) are plotted on top of the RPT.

BI definition assumes that quartz and dolomite are the most brittle minerals in the rock (Wang and Gale, 2009). Those rocks with low negligible amounts of these two minerals, such as limestone or shaly limestones, will be considered to be ductile. Figure 4a shows a sharply decreasing brittleness at the very top of the Kolmule Formation which reflects the lowest brittleness and lies in the ductile region (Fig. 3c). The decreased brittleness correlates well with the high clay content observed in gamma ray log at top of the section (Fig. 3c). In general, most of the Komule Formation in Juksa well has lower brittleness (ductitle to less ductile) whereas a sudden increasing trend in brittleness indices is observable in the bottom 20 m of the formation (Fig. 4b).

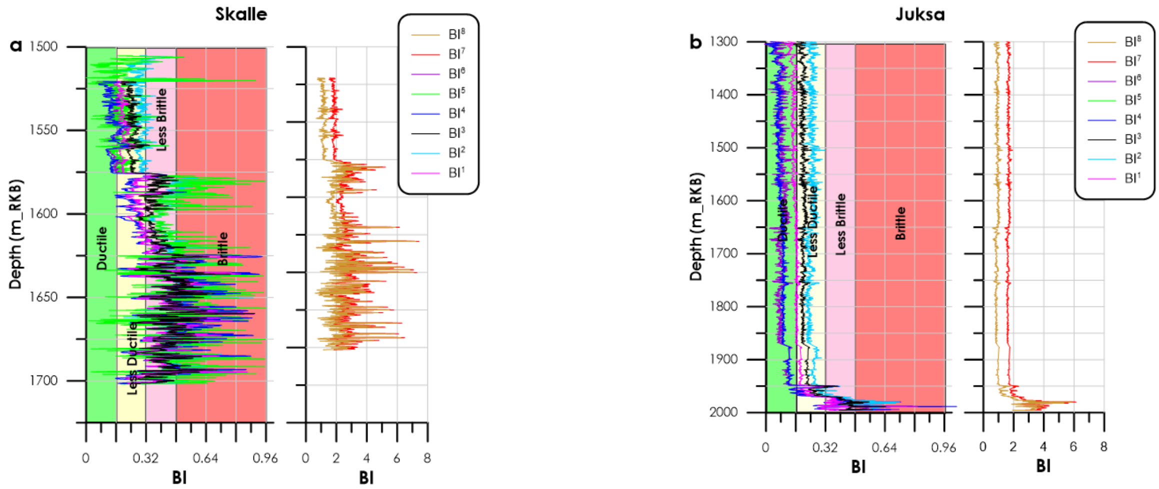

Figure 4: Elastic parameter based brittleness indices (BI^1-BI^8) estimations of Kolmule formation of a) Skalle and b) Juksa wells .The background classifications of brittle-ductile zones are adapted from Perez and Marfurt (2014).

Considering absolute differences between various brittleness indices tested in this study, the average value of BI increases in the order BI^2>BI^3>BI^1>BI^5>BI^6>BI^4 for Kolmule Formation for both wells (Fig.4a-b). BI^7 is higher than BI^8. The increased brittleness correlates well with the section of high sand content of the formation that observed in Gamma Ray Logs (Figs. 2 and 4). In Skalle wells, the high risk zone (refers to the more fracture-prone) is a thick lower part of the formation whereas in Juksa well only a thin lower section shows highly brittle. The elastic parameter based brittleness estimation based on the assumption of the liner relationship between rocks brittleness and elastic parameters, and their control on rocks failure behaviour. However, this assumption is somewhat invalid since brittle rocks can have low Young's moduli, or conversely, ductile rocks have high Young's Moduli (Perez and Marfurt, 2014). Therefore, brittleness can be treated as a behavior rather then a rock property that dependent on a complex function of rock strength, lithology, texture, temperature, fluid type (Handin and Hager, 1957; Handin et al., 1963; Davis and Reynolds, 1996), stress regime (Hu et al., 2015), stress relaxation (Sone and Zoback, 2014), diagenesis, and TOC (Wells, 2004).

Conclusions

This study assesses seal integrity of Lower Cretaceous Kolmule formation of two wells 7120-2-3 S (Skalle, gas discovery) and 7120/6-3 S (Joksa dry well) from the Norwegian Barents Sea using the rock physics templet E-ν. Brittleness indices of Kolmule Formation obtained from different methods are compared between the two wells. A wide range of brittleness variations are obsrved for Komule Formation of two studied wells. The top seal in Komule Formation of Skalle well shows ductile and be able to hold gas in the formation. Apart from a lower sandy unit, overall the Kolmule Formation in Juksa well is ductile means good seal though the well is dry. Due to dependanc of many factors (e.g. mineralogy, diagenesis, stress regine, stress gradient, stress relaxation), brittleness should be treated as a behavior rather then a rock property. The elastic parameter based brittleness estimations can be useful to evaluate seals only when calibrated to the conditions in the formation of interest and supported further by evidence from the lab.

References

Chen, J.J., Zhang, G.Z., Chen, H.Z. and Yin, X.Y. 2014. The construction of Shale rock physics effective model and prediction of rock brittleness. SEG Technical Program Expanded Abstracts 2014, 2861-2865.

Davis, D. and Reynolds, S. J. 1996. Structural geology of rocks and regions, 2nd ed.: Wiley.

Glørstad-Clark, E., Faleide, J.I., Lundschien, B.A. and Nystuen, J.P. 2010. Triassic seismic sequence stratigraphy and paleogeography of the western Barents Sea area. Marine and Petroleum Geology, 27, 1448-1475.

Grieser, B. and Bray, J. 2007. Identification of production potential in unconventional reservoirs. SPE paper 106623,6.

Guo, Z., Li, X. and Chapman, M. 2012. Exploring the effect of fractures and micro- structure on brittleness index in the Barnett shale, SEG Technical Program Expanded Abstracts 2012, 1-5.

Handin, J., and Hager, R. V. 1957**.** Experimental deformation of sedimentary rocks under confining pressure: Tests at room temperature on dry samples: AAPG Bulletin, 41, 1–50.

Handin, J., R. V. Hager, M. Friedman, and Feather, J. N. 1963. Experimental deformation of sedimentary rocks under confining pressure: Pore pressure tests: AAPG Bulletin, 47, 717–755.

Hu, Y., Perdomo, G., Wu, K., Chen, Z., Zhang, K., Ji, D., Zhong, H. 2015. A novel model of brittleness index for shale gas reservoirs: Confining pressure effect. Paper SPE 176886 presented at the SPE Asia Pacific Unconventional Resources Conference and Exhibition, Brisbane, Australia, 9–11 November 2015.

Murillo,W.A., Vieth-Hillebrand, A., Horsfield, B. and Wilkes, H. 2016. Petroleum source, maturity, alteration and mixing in the southwestern Barents Sea: New insights from geochemical and isotope data. Marine and Petroleum Geology, 70, 119-143.

NPD, FactPages 2018. Norwegian Petroleum Directorate FactPages. Available at: http://factpages.npd.no/factpages/

Ohm, S.E., Karlsen, D.A., Austin, T.J.F. 2008. Geochemically driven exploration models in uplifted areas: example from the Norwegian Barents Sea. AAPG Bulletin, 92, 1191-1223.

Perez, A. R., Marfurt, K., 2014. Mineralogy-based brittleness prediction from surface seismic data: application to the Barnett Shale. Interpretation, 2, T255–T271.

Perez, A. R. 2014. Mapping brittleness and stress. Extended Abstract, GeoConvention 2014.

Rickman, R., Mullen, M.J., Petre, J.E., Grieser, W.V., Kundert, D. 2008. A practical use of shale petrophysics for stimulation design optimization: All shale plays are not clones of the Barnett shale. Paper SPE 115258 presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, 21-24 September 2008.

Sone, H., Zoback, M.D. 2014. Viscous relaxation model for predicting least principal stress magnitudes in sedimentary rocks. Journal of Petroleum Science and Engineering, 124, 416-431.

Wang, F.P., Gale, J.F.W., 2009. Screening criteria for shale-gas systems. Gulf Coast Assoc. Geol. Soc. Trans. 59, 779–793.

Wells, F. 2004. A new method to help identify unconventional targets for exploration and development through integrative analysis of clastic rock properties. Houston Geological Society Bulletin, 47, 34–49.