Compositional control on frictional properties of Goldwyer shale reservoir rocks

Partha Pratim Mandal
Curtin University
Perth, WA
p.mandal@postgrad.curtin.edu.au

Reza Rezaee
Curtin University
Perth, WA
R.Rezaee@curtin.edu.au

Mustafa Sari
CSIRO Minerals
Perth, WA
Mustafa.sari@csiro.au

Joel Sarout
CSIRO Energy
Perth, WA
joel.sarout@csiro.au

SUMMARY

Production from ultra-low permeable gas shale reservoirs is feasible only through hydraulic fracturing stimulation. Slip along a pre-existing natural network of fractures/faults with the injection of hydraulic fluid is mostly controlled by the frictional properties of the shale. We studied the deformation characteristics of the Goldwyer shale formation at in-situ stress conditions by performing a series of multistage triaxial tests to understand compositional controls on fault slip accompanying hydraulic fracturing. The Coulomb friction coefficient is derived from the post-failure axial displacement and the angle of the final failure plane. When the clay and total organic content (TOC) of the studied shale samples are above ~40% by volume, the friction coefficient approaches a value of 0.6, while below this threshold it is higher. This change suggests a transition from a grain-bearing to a clay-bearing structure. Therefore, we can directly estimate the slip tendency of natural faults and fractures in gas shale reservoirs from their clay and TOC content.

Key words: frictional coefficient, deformation, clay, TOC, fault slip, Goldwyer shale

INTRODUCTION

Frictional strength of faults and their stability depends upon several constitutive factors such as mineral composition, depositional history, fault morphology, hydrogeology, and in-situ stress state (Kohli and Zoback 2013; Sarout et al. 2017). Hydraulic fracturing is the most prevalent mechanism responsible for the extraction of liquid hydrocarbon from organic-rich gas shale reservoirs. Researchers (Das and Zoback 2011; Kohli and Zoback 2013) have shown that production from ultra-low permeable gas shale is possible by inducing slip along pre-existing natural faults and fractures network through fluid injected pressure at around least principal stress magnitude. Slip emanating during the process of hydraulic fracturing could be explained in the form of instantaneous slip originated from favorability orientated natural fractures while slow slip occurred from long-period and long-duration slip events on large-scale regional preexisting faults. However, it necessitates further work to understand the fundamental mechanical properties of gas shale formations on factors such as composition and microstructure which primarily control the slip mechanism.

Middle Ordovician Goldwyer shale in the onshore Canning Basin is the most prospective gas shale formation meeting the geological characteristics of a standard gas reservoir (Mandal et al. 2020). Multistage triaxial tests are performed at in-situ stress conditions to analyze the deformation characteristic of Goldwyer shales (Mandal et al. 2021). The samples span a broad range of textural and mineralogical fabric such as detrital clay matrix, siliceous and calcareous mudstone, and mixed shale interpreted from visual core inspection, thin section, and X-ray diffraction analysis. Studied samples were recovered from three Goldwyer units namely G-I, and G-III respectively where most organic-rich and clay dominated G-III formation is sandwiched between two carbonate rich formations, G-II and Willara. Sone and Zoback (2013b) successfully able to describe mechanical behavior by grouping the various gas shale reservoirs by two distinct compliant (clay and total organic carbon content defined as ClayTOC) and clastic (quartz, calcite, feldspar, pyrite components. They further observed a strong correlation between clay and organic content with their elastic, intact rock strength and creep properties. Kohli and Zoback (2013) demonstrated the strong influence of a compliant framework on the slip tendency of various organic-rich shales. Henceforth, to improve our understanding further on potential fault slip, in this work, we studied the effects of mineral composition and microstructure on the failure frictional properties (sliding friction coefficient (μ_s) and peak stress, residual strength) of organic-rich Goldwyer gas shale reservoirs.

METHODOLOGY

The workflow is broadly divided into three sections: (i) Sample characterization (ii) Deformation experiment (iii) Frictional properties.

Sample characterization

Studies samples are received from Western Australia's Department of Mines, Industry Regulations and Safety (DMIRS 2019) database in room temperature and dry state. Mineralogy and total organic content (TOC) of these samples were determined by X-ray diffraction (XRD) and geochemical pyrolysis methods of powdered off-cuts of plugs, respectively. Low-pressure nitrogen gas adsorption (LPNA) at 77 ºK was performed to analyze the pore size distribution mostly mesopores (2-100 nm), pore volume and specific surface area of shale. Crushed sample with a mesh size range of 100 to 60 (150 -250 µm) and degassing over 12 hours for pore surface cleaning are done before the LPNA test. Thin sections were analyzed using standard petrographic techniques to observe microstructural behavior. Due to the complex mineralogical distribution of the Goldwyer gas shale, two dominant clusters are developed to explain the shale's composition into the major compliant and clastic components. Since the clastic quartz and calcite components have similar frictional strength ~0.7-0.8 (Tembe et al. 2010), this study directly allows evaluating the effects of clay and organic content on the shale's microstructure and resultant mechanical characteristics.

Deformation experiment

A total of ten cylindrical core plugs were prepared with flat end surfaces and a standard length to diameter ratio of 2:1 for the experiment. Multistage triaxial tests (Figure 1) were conducted with an autonomous triaxial cell (ATC) at varying confining pressure (Dewhurst and Siggins 2006; Dewhurst et al. 2011) including in-situ stress conditions over five stages on samples parallel and perpendicular to the bedding planes (Mandal et al. 2021). At the last stage, the axial load was applied at a constant strain rate (10^{-5} s^{-1}) until reaching the failure point and further post deformation continued until axial strain reaches up to ~4%.

Frictional properties

Triaxial deformation data from the failure stage allowed us to derive sliding friction coefficient, μ_s, as the ratio of shear stress resolved onto the sliding plane, τ, and applied effective normal stress on the sliding plane, σ_n:

$$\mu_s = \frac{\tau}{\sigma_n} \quad (1)$$

$$\tau = (\sigma_A - C_p)\sin 2\beta \quad (2)$$

$$\sigma_n = \frac{1}{2}[(\sigma_A + C_p)\sin 2\beta + (\sigma_A - C_p)\cos 2\beta] \quad (3)$$

Where σ_A and Cp refer to the applied axial stress and confining pressure, respectively. β is the angle between the fault plane normal and the axial stress direction. The measured β value via a protractor matched the Mohr-Coulomb failure envelope method i.e.,

$$\beta = 45° + \frac{1}{2}\varphi \quad (4)$$

in which ϕ is the angle of internal friction.

RESULTS AND DISCUSSION

Mineral compositions from XRD analysis are expressed in volumetric percentage (vol %) since mechanical properties mostly depend upon rock's volume fraction. Shale samples span a range of ClayTOC from ~10 to 80 vol% representing siliceous, calcareous, and mixed lithofacies. Petrographic images in Figure.2 represent a few of the studied samples. The overall microstructure of Goldwyer gas shales is composed of fine-grained (< 5 µm) illite & mica dominated detrital clay matrix, calcitic matrix (CM), thin lenses to the angular shape of organic matter, and elongated, lenticular to rounded clasts of quartz, feldspar, calcite (10 – 100 µm). Top and bottom rows in Figure.2 present high and low clay and organic content sample groups. Textural fabric development due to preferred orientation of clay, elongated organic matter, detrital fossils depict the bedding plane is seen in Figure.2 top optical microgram. This texture in shale is reflected only when ClayTOC exceeds 30% in volume (Sone and Zoback 2013a). Due to this, we are primarily interested to investigate the dependency of combined effects of clay and TOC on frictional strength and fault stability in an overall gas shale formation.

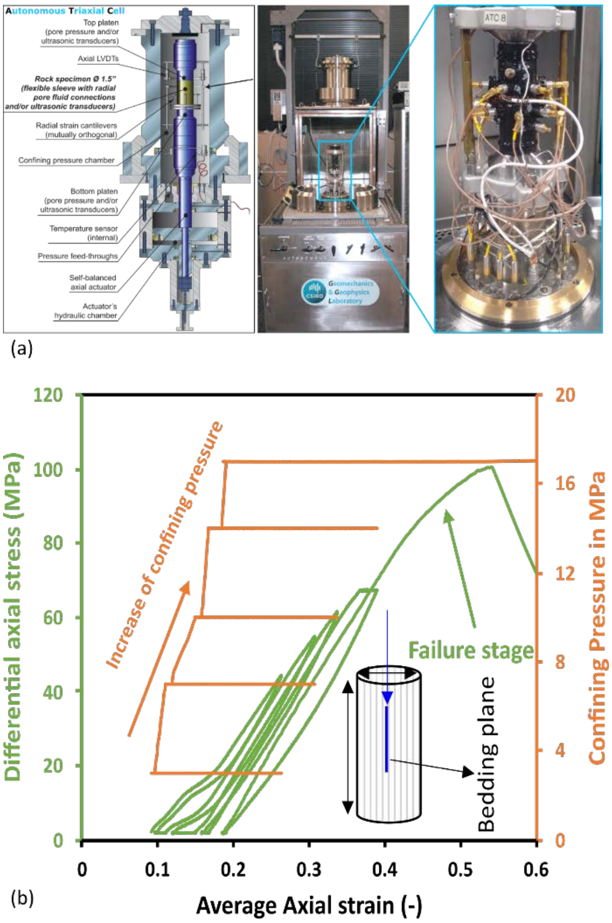

Figure 1. (a) Autonomous triaxial cell used to conduct deformation experiment. (b) A multistage triaxial experimental setup where stress-strain data are plotted for every loading and unloading cycle including the failure stage.

The sliding plane makes an angle with axial stress direction over a range from 55 to 70 degrees irrespective of bedding plane orientation when Eqn.4 is implemented from Mohr-Coulomb failure analysis. Direct measurement of β achieves an ±5-degree uncertainty from the mathematical approach. A decreasing trend of frictional strength is observed with ClayTOC content in Figure.3. All sliding friction coefficients are within ~ 0.55 to 0.85 again reflecting independence of the sample's bedding plane orientation, which matches with an end members system either composed of quartz-illite or calcite-clay. A general linear trend of decrease in sliding friction coefficient with an increase in an organic component is also visible in Figure.4 which confirms the weaker strength of shale dominated by clay and organic matter. When ClayTOC is lower than ~ 40 vol%, an increase in strength behaviour is noted. Degradation of rock strength demonstrated the overall change in the framework from grain to clay supported matrix. This approximate linear tendency of friction strength as a function of ClayTOC fraction reflects an obvious way to classify gas shale composition which normalizes structural matrix framework and varying proportions of clay and TOC.

LPNA data provides specific surface area (SSA) which shows a positive correlation with clay and organic matter content. Henceforth, a large proportion of reservoir intervals are compliant to shear fracturing through fluid injection. The observed transition from dominant clastic to compliant components allows stable sliding in gas shale reservoirs when ClayTOC is approximated to ~35 to 40 vol% (Kohli and Zoback 2013). Volumetric percentage of ClayTOC has significant implication for shear faulting, therefore prone to shear slip. Therefore, the presence of a natural network of fractures and faults within most clay and organic matter dominated gas shale reservoirs interval higher than 40 vol% are induced to shear slip would allow slipping in a stable way when they are favourably oriented in a particular stress regime at depth.

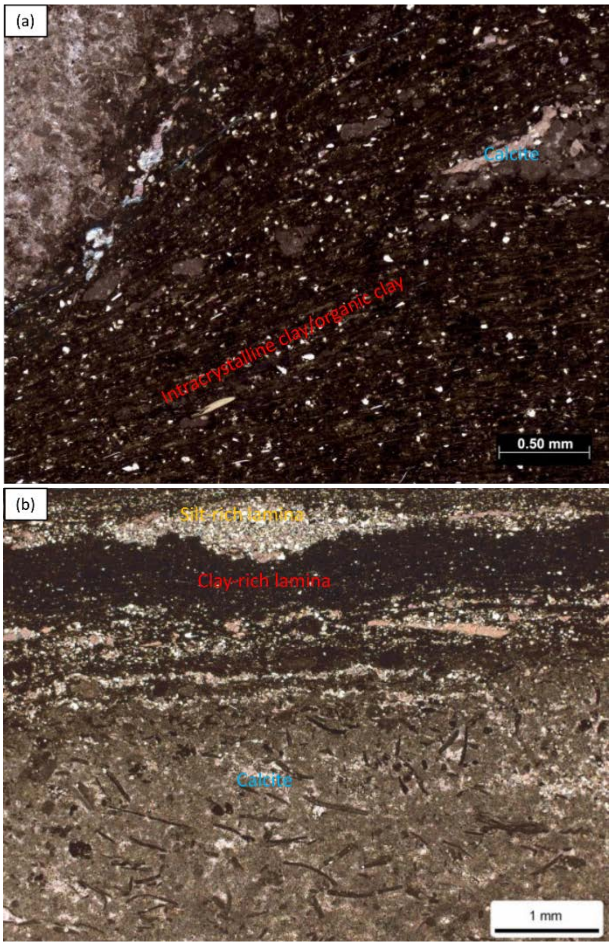

Figure 2. Thin section petrographic image of two representative samples (a) Siliceous mudstone (b) Argillaceous mudstone. Lamination of clay fabric is visible in the top image while the bottom image shows alternating silt and clay-rich lamina.

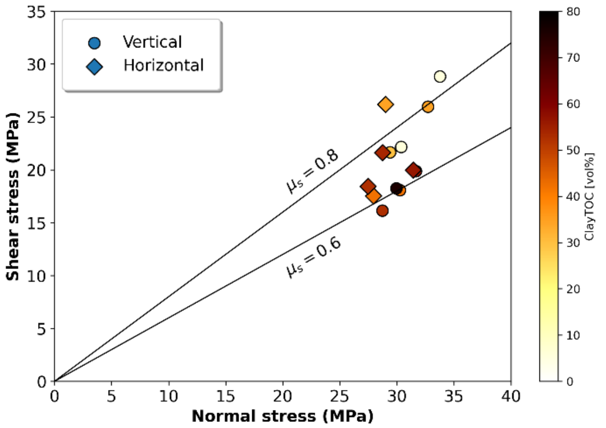

Figure 3. Derived shear stress and normal stress on the sliding plane of all samples from failure stage data by implementing the Coulomb failure function. The colour bar presents the volumetric percentage of clay and TOC for each sample. Two black lines describe the sliding failure plane with a friction coefficient of 0.6 and 0.8, respectively.

CONCLUSIONS

In this work we have shown that frictional strength properties of Goldwyer gas shale reservoirs are dependent upon: (i) microstructure and (ii) compliant clay and organic matter content. When clay and TOC content reaches ~ 40 vol%, sliding friction coefficient values are near to 0.6 whereas below this threshold a strengthening effect is observed. This change of frictional properties of complex gas shale lithologies with the combination of clay and organic matter content is described by a transition from clastic to compliant clay-dominated framework. The study further emphasized the role of clay and organic matter in classifying gas shale formation in a simplified way irrespective of complex microstructure and varying proportions of compliant materials. Finally, the frictional strength properties of gas shale beyond ClayTOC volume percentage of 40, has significant contribution to shear faulting and stable slip of existing fractures and faults network.

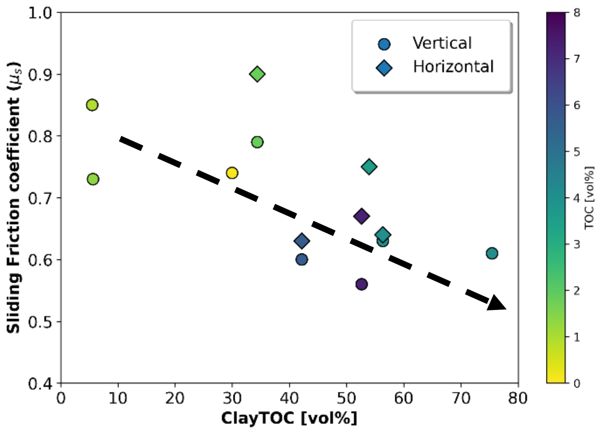

Figure 4. Sliding friction coefficient (μ_s) as a function of clay and organic content (ClayTOC in vol%) for all studied samples of Goldwyer gas shale formation. Samples are colour coded with their TOC values. The black dashed

line indicates an approximately linear trend of decrease in μ_s with ClayTOC.

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