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The Feasibility Study of Reservoir Geomechanics from Brittleness Evaluation

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ABSTRACT - A detailed understanding regarding the rocks Brittleness Index is helpful in oil and gas exploration as upfront information to determine the rock fracture gradient. Researchers have proposed several methods to estimate the rock Brittleness Index. However, different ways may yield different results and lead to varying interpretations regarding the Brittleness Index classification. This paper evaluates the Brittleness Index of an Indonesian gas well using three approaches based on the elastic properties log data, elastic properties rock physics modeling, and mineralogical rock physics modeling to assess the consistency of the methods. The results obtained in this study suggest that elastic properties-based and mineralogical methods produced a consistent Brittleness Index. However, the vertical resolution is different. It indicates that the Brittleness Index estimated from the actual log data showed higher resolution than the Brittleness Index calculated from the rock physics modeling. Combining TOC data with the Brittleness Index is recommended to optimize hydraulic fracturing design and planning. For further investigation, the authors will be suggesting direct sampling from cores and laboratory measurements to obtain the in-situ mechanical properties of shale rocks.

Keywords: brittleness index, mineralogy, elastic properties, rock physics modeling.

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INTRODUCTION

A detailed understanding regarding the rock Brittleness Index is significant in oil and gas exploration as upfront information to estimate the rock fracture gradient. The Brittleness of the shale formation plays a vital role in evaluating the potential interval area for hydraulic fracturing. Brittleness, a measure of rock's ability to fracture, is a complex function of mineral composition, the amount of Total Organic Carbon (TOC), effective stress, reservoir temperature, diagenesis process, thermal maturity, porosity, and type of fluid (Wang & Gale, 2009) Therefore, Brittleness is one of the critical mechanical properties of rocks and is included in most of the petrophysical reports of unconventional shale reservoirs (Hucka & Das, 1974) However, the absence of a universally accepted definition and measurement of Brittleness has led to various methods or models for its quantification (Göktan, 1991).

One of the critical parameters in shale gas exploration is that the interval should be brittle and contain fractures. The shale should have composed more quartz than clay minerals to keep the fractures open during production. We quantified the Brittleness indicator of gas-saturated shale interval using two parameters of Poisson's Ratio and Young's Modulus. Both are affected by the kerogen content (high TOC), the maturity of kerogen, and the fluid type saturated within the pore space.

Rock-Eval and Vitrinite Reflectance (R_o%) plot analysis indicated that the amount of Total Organic Carbon (TOC) in the studied area was about 2-3% and within the maturity level of immature and early mature. This work aimed to be the feasibility study for evaluating the sweet spot of the gas shale layers using the integrated analysis of petrophysical and estimated elastic properties from Rock Physics Modeling of shale intervals by utilizing the dataset available at a certain limited depth.

DATA AND METHODS

We quantified the Brittleness Index of shale intervals by utilizing at least three approaches of rock mineral compositions, elastic properties from well logs analysis, and elastic properties from the rock physics modeling to obtain the optimum brittleness information of fully gas saturated.

According to their interval values of mechanical rock properties, mineral composition, TOC, and others (Altamar & Marfurt, 2014); we classified these values into several groups as below:

Ductile	= <0.16
Less Ductile	= 0.16 – 0.32
Less Brittle	= 0.32 – 0.48
Brittle	= > 0.48

Mineral composites of rocks were the crucial factor determining the mechanical behavior of rocks (Ye , et al., 2020). The most brittle area has abundant quartz, and the least dominantly consists of clay minerals (Jarvie, et al., 2007). First, we estimated the brittle intervals of shale rocks by utilizing the information of mineral variability and TOC of rocks using the equation (1).

$$BI_{modification} = \frac{F_{Quartz}}{F_{Quartz}+F_{Clay}+F_{TOC}+F_{Composite}} \quad (1)$$

Next, evaluating the average value brittleness using the combination of Poisson's Ratio and Young's Modulus calculated from well logs data, as the controlling mechanical properties (Grieser & Bray, 2007) using the following equation (2)-(4).

$$E_{brittleness} = \frac{E-E_{min}}{E_{max}-E_{min}} \quad (2)$$

$$v_{brittleness} = \frac{v-v_{max}}{v_{min}-v_{max}} \quad (3)$$

$$BI_{average} = \frac{E_{brittleness}-v_{brittleness}}{2} \quad (4)$$

Finally, we incorporated the combined porosity, mineral composition, TOC, and fluid type into the rock physics model to estimate the Brittleness Index. The modification of our rock physics schemes (Figure 1) aims to discriminate the ductile and brittle interval layers using the information of elastic properties of rocks, which then transformed into mechanical properties of Poisson's Ratio and Young's Modulus.

Due to limited data in modeling our gas-saturated shale rock, we had carefully done several steps to get the best model in delineating the sweet spot according to Brittleness Index from the targeted well as the following:

- estimating the bulk modulus of matrix mineral (K_{ma}) using the Voigt-Reuss-Hill Bounding Average (5)-(7), which is mainly composed of quartz, clay, and several minor minerals from the X-ray Diffraction (XRD) dataset. K_{ma} plays a significant role in calculating shale gas-saturated bulk modulus. For depicting the actual condition of rocks, we expected an adequate solid shale model.
- combining the information of aspect ratio for computing bulk modulus of dry rock (K_{dry}) using the Kuster-Toksöz approach (8)-(9) by using the type of inclusion of the penny cracks (Table 1).

$$M_V = \sum_{i=1}^{N} fiMi \quad (5)$$

$$\frac{1}{M_R} = \sum_{i=1}^{N} \frac{fi}{Mi} \quad (6)$$

$$M_H = \frac{M_V+M_R}{2} \quad (7)$$

$$(K_{KT}^* - K_{ma})\frac{\left(K_m+\frac{4}{3}\mu_m\right)}{\left(K_{KT}^*+\frac{4}{3}\mu_m\right)} = \sum_{i=1}^{N} xi(K_i - K_{ma})P^{mi} \quad (8)$$

$$(\mu_{KT}^* - \mu_{ma})\frac{\left(\mu_m+\frac{4}{3}\xi_m\right)}{\left(\mu_{KT}^*+\frac{4}{3}\xi_m\right)} = \sum_{i=1}^{N} xi(\mu_i - \mu_{ma})Q^{mi} \quad (9)$$

- finally, estimating the best V_p and V_s (11)-(12) of shale gas saturated from Biot-Gassmann equations (10) where the aspect ratio distribution is obtained from the use of the constant Pore Space Stiffness Zimmerman Equation (13)-(16), and transformed these parameters into Poisson's ratio and Young's Modulus.

$$\left(\frac{K_{sat}}{K_{ma}-K_{sat}} = \frac{K_{dry}}{K_{ma}-K_{dry}} + \frac{K_{fl}}{\Phi(K_{ma}-K_{fl})}\right) \quad (10)$$

$$V_p = \sqrt{\frac{K+\frac{4}{3}\mu}{\rho}} \quad (11)$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (12)$$

Table 1
Pmi and Qmi coefficients for the form of inclusion of penny cracks modification: (Berryman, 1995)

Inclusion Shape	PMI	Q
Penny Crack	$= \dfrac{\left(K_m + \frac{3}{4}\mu_i\right)}{\left(K_i + \frac{3}{4}\mu_i + \pi\alpha\beta_m\right)}$	$\frac{1}{5} = \left(1 + \dfrac{8\mu_m}{4\mu_i + \pi\alpha\,(\mu_m + 2\beta_m)} + 2\,\dfrac{K_i + \frac{2}{3}(\mu_i + \mu_m)}{K_i + \frac{4}{3}\mu_i + \pi\alpha\beta_m}\right)$
Notes:	$\beta = \mu\,\dfrac{(3K+\mu)}{(3K+4\mu)}$	, α = crack aspect ratio, a disk is a crack of zero thickness.

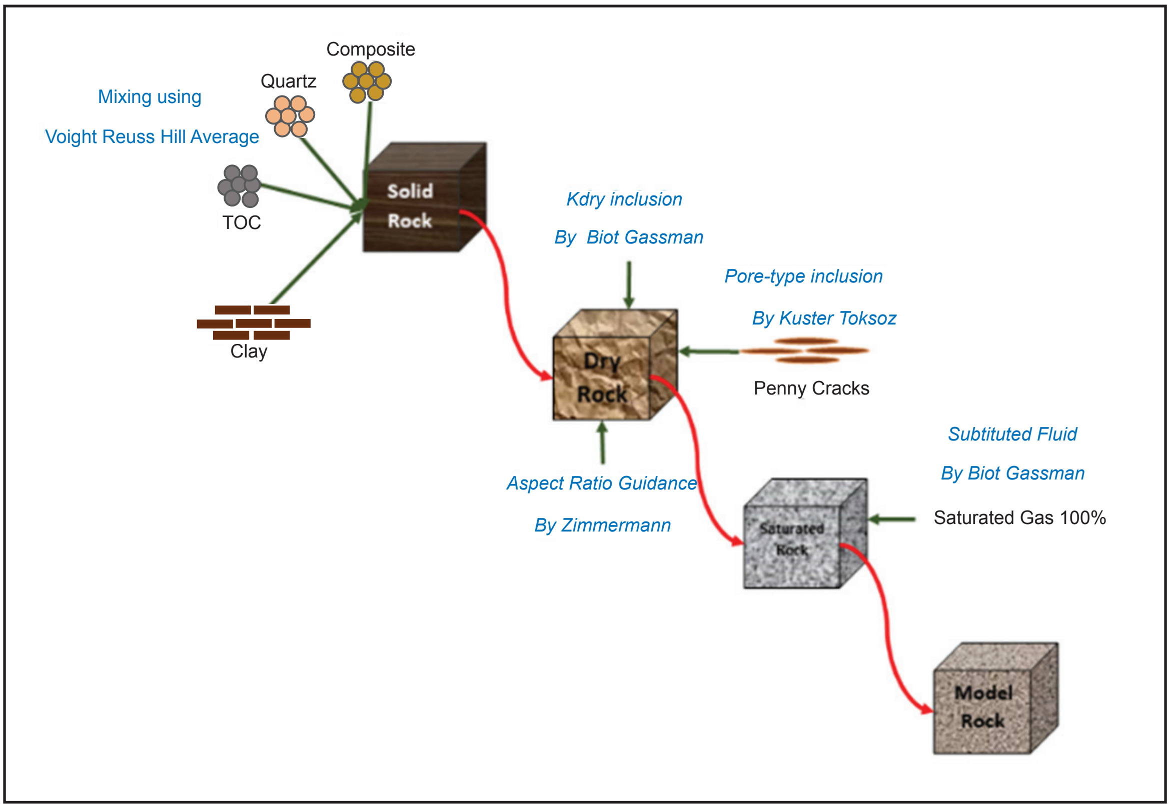


Figure 1
A modified rock physics modeling scheme modified (Zhu, et al., 2012).

$$\frac{1}{K_{dry}} = \frac{1}{K_m} + \frac{\Phi}{K_\Phi} \quad (13)$$

$$K_\Phi = \frac{\Phi}{\frac{1}{K_{dry}} - \frac{1}{K_m}} \quad (14)$$

$$\frac{k_{dry}}{K_m} = \frac{1}{1+\frac{\Phi}{k}} \quad (15)$$

$$k = \frac{K_\Phi}{Km} \quad (16)$$

Both properties obtained were assumed to be the best-fit parameters in the model, representing the condition of minerals composing rock, fully gas-saturated rock, and pore space of rock.

RESULTS AND DISCUSSION

A. Brittleness Index Based on Elastic Property Data Log

Based on the modulus of elasticity information from the log data, the corrected Brittleness Index value is in the range of 0.001 - 0.795 (Table 2), where the Brittleness of the rock in the research well has a ductile to brittle type. Rock Brittleness is dominated by less ductile rocks to less brittle, with an average Brittleness Index value of 0.294 (Figure 2). The higher fracture layers potential, the average value of Brittleness index of 0.425 within seven depth points at each thickness. These intervals tend

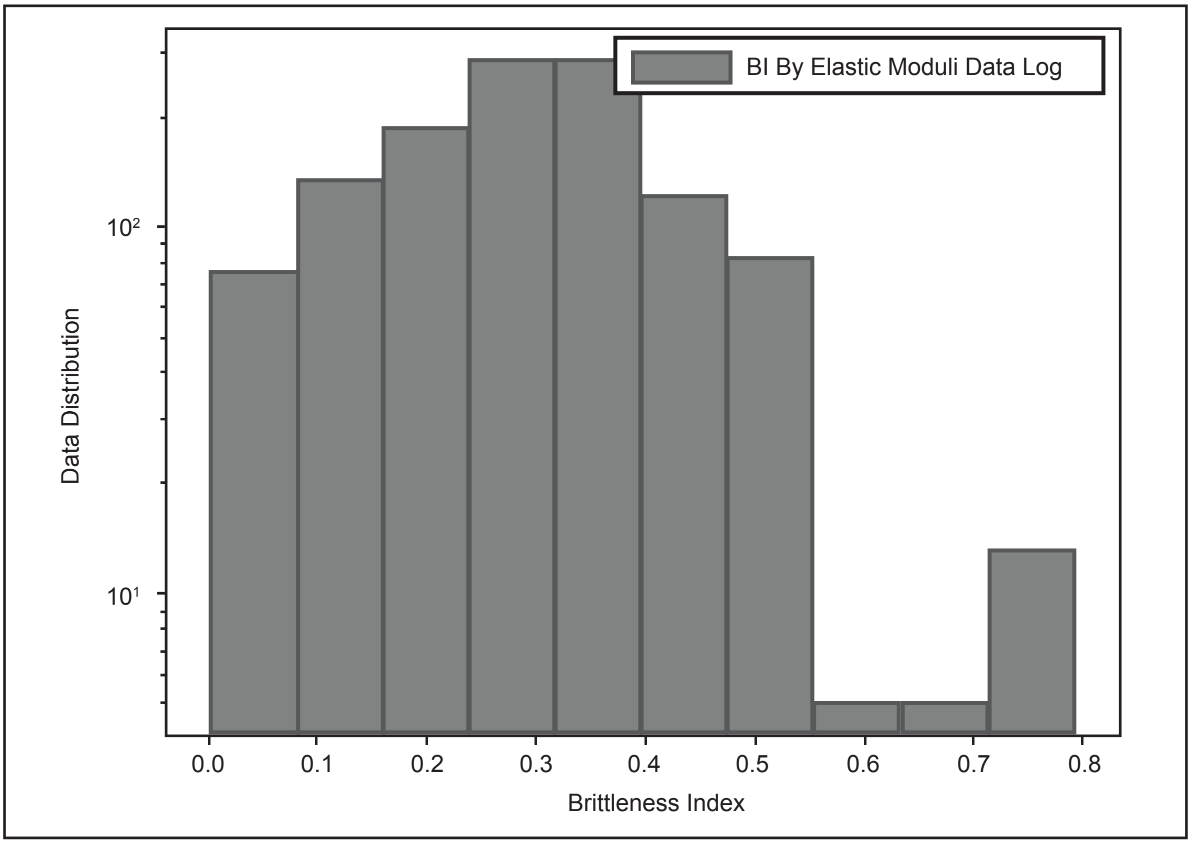


Figure 2
Histogram of brittleness Index data log.

Table 2
Brittleness index based on elastic property data log

Britleness Index Based on Log Data					
No	Depth Interval (ft)	Range of BI	Average BI	Potential to be Cracked	
				Yes	No
1	5400-5417.5	0.307-0.387	0.349		✓
2	5418-5491	0.311-0.554	0.435	✓	
3	5491.5-5607.5	0.087-0.421	0.199		✓
4	5608-5620	0.334-0.534	0.446	✓	
5	5620.5-5628.5	0.323-0.329	0.327		✓
6	5629-5640.5	0.334-0.482	0.415	✓	
7	5641-5700	0.243-0.417	0.33		✓
8	5700.5-5709	0.341-0.509	0.445	✓	
9	5709.5-5808	0.002-0.297	0.156		✓
10	5808.5-5818.5	0.336-0.459	0.42	✓	
11	5819-5935.5	0.171-0.358	0.249		✓
12	5936-5973.5	0.323-0.795	0.48	✓	
13	5974-5988.5	0.126-0.317	0.227		✓
14	5989-6000	0.322-0.771	0.498	✓	

to have higher V_p and V_s, higher Young's modulus, and lower Poisson Ratio (Figure 3), indicating the excellent ability to flow the fluid.

B. Brittleness Index Based on Elastic Properties from Rock Physics Modeling

Rock physics analysis is the proper tool for estimating the change of mineral composite of solid rock with various fluid content within pore types. This study aimed to delineate the gas saturated layers of shale formation to account for their Brittleness Index.

Figure 4(a) indicates a relatively softer solid matrix of shale. This is due to the clay mineral fraction and lowering the K_m into Reuss's lower bound. We estimated the pore size within the shale model using the Zimmerman theory (Russell & Lines, 2011) of aspect ratio shown in Figure 4(b). The aspect ratio ranges from 0.05 to 0.1. In that case, utilizing the penny cracks model to calculate the dry rock modulus may lead to the closest condition of the actual pore space in the shale matrix.

We have successfully obtained the best fit of P-wave velocity as the representation of K_m, K_{dry},

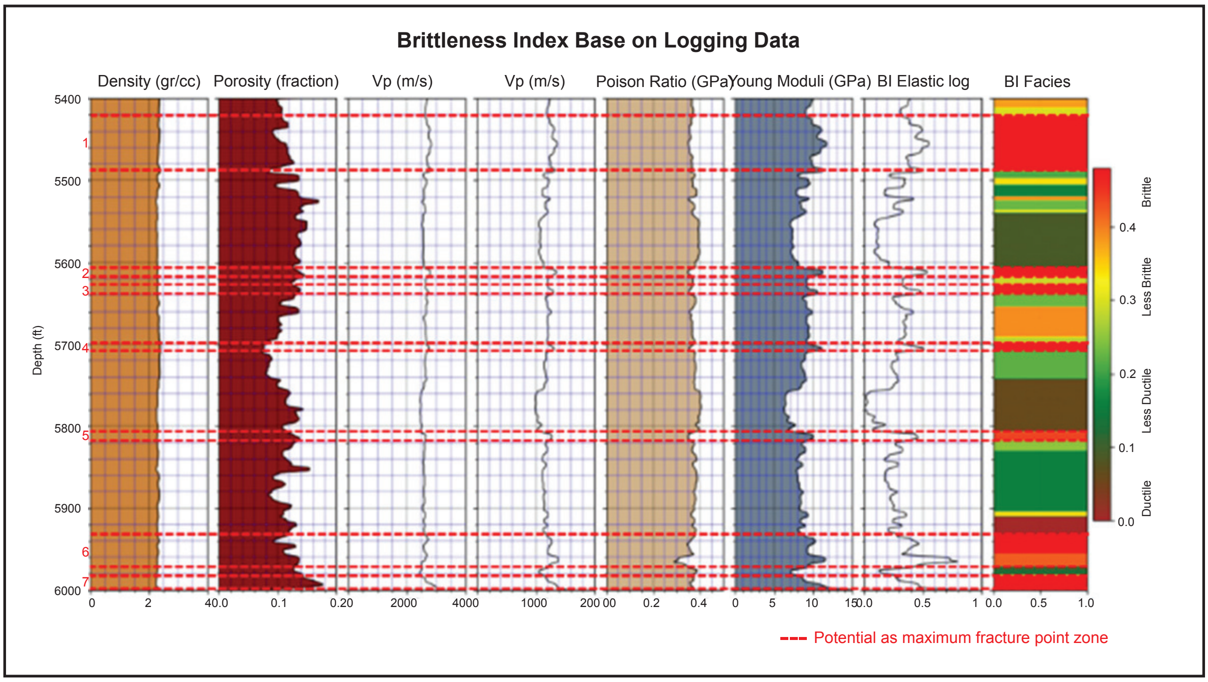


Figure 3
Brittleness Index interpretation based on elastic properties of data logs with maximum fracturing point location.

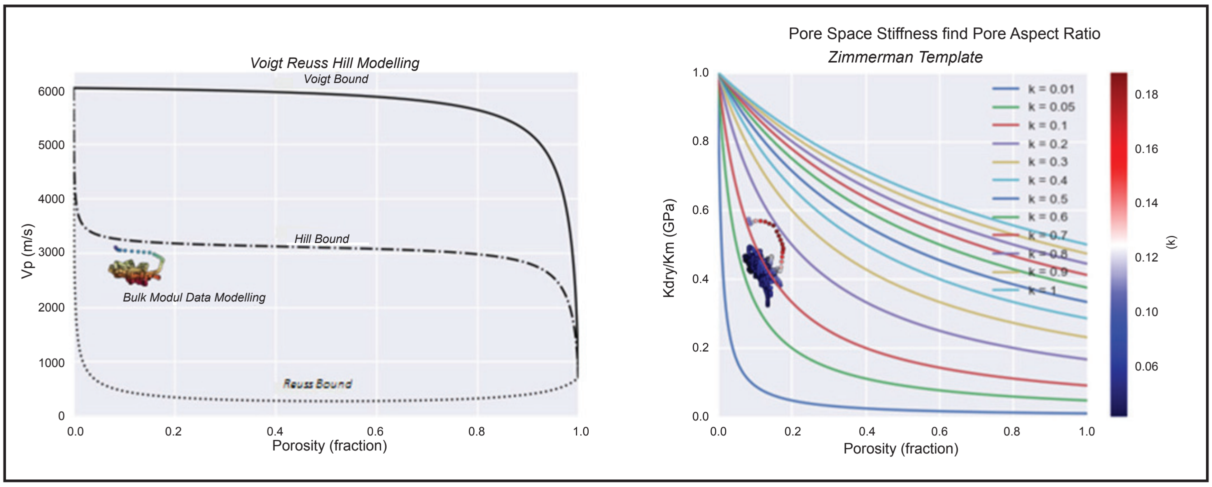


Figure 4
Voigt Reuss Hill modeling (Mavko, Mukerji, & Dvorkin, 2020), (b) Pore aspect ratio distribution using Zimmerman's constant pore space stiffness (Russell & Smith, 2007).

K_{sat}, and the porosity of the shale model, as shown in Figure 5. Next, calculated the Poisson's Ratio and Young's Modulus and estimated Brittleness Index. In this case, we expected a considerable difference in S-wave velocity due to the limited information of mineral and TOC contents at all depths.

A ductile to brittle layers with the estimated ranges of 0.241-0.502 distributed through the depth (Table 3). The average Brittleness Index value of 0.294 is grouped as less ductile (Figure 6). The potential location of the maximum fracture zone is localized at four depth points with different thicknesses with the level of rock Brittleness from less brittle to brittle with an average Brittleness Index of 0.384. The maximum Brittleness of rocks tends to have high seismic wave velocities, high Young's modulus, and low Poisson Ratio (Figure 7). This shows that the potential zone as the maximum fracture point tends to have high seismic wave velocities associated with its excellent ability to penetrate rock layers with maximum Brittleness.

C. Brittleness Index Based on Mineralogical Rock Physics Modeling

Based on mineralogy information from Rock Physics Modeling, the corrected Brittleness Index value is in the range 0.140 - 0.354 (Table 4), where the rock Brittleness in the research well has a ductile type to less brittle. Less ductile rocks dominate rock brittleness with an average Brittleness Index value of 0.191 (Figure 8). The potential location of the maximum fracture zone is localized at three depth points with different thicknesses, and the level of Brittleness of the rock is less brittle 0.230 (Figure 9). The maximum Brittleness of rocks tends to have a relatively high distribution of non-clay minerals (Quartz + Composite) (23.3 - 23.6 %), relatively low clay minerals (73.0 - 74.6 %), and relatively high Total Organic Carbon content (2.2 - 3.4%) as a determining factor for the optimum and economic fracturing potential zone (Figure 10). Localized zones 1 and 2 which have the potential to be fractured

Table 3
Brittleness index based on elastic properties from rock physics modeling

Britleness Index Based on Elastic Property Rock Physics Modeling Data					
No	Depth Interval (ft)	Range of BI	Average BI	Potential to be Cracked	
				Yes	No
1	5400-5429	0.278-0.319	0.293		✓
2	5429.4-5469.5	0.306-0.371	0.332	✓	
3	5470-5608	0.255-0.352	0.293		✓
4	5608.5-5618	0.322-0.371	0.346	✓	
5	5618.5-5959.5	0.242-0.345	0.282		✓
6	5960-5973	0.312-0.5	0.365	✓	
7	5973.5-5990	0.285-0.381	0.313		✓
8	5990.5-6000	0.311-0.502	0.419	✓	

Table 4
Brittleness index based on mineralogical rock physics modeling

Britleness Index Based on Mineralogy Rock Physics Modeling Data								
No	Depth Interval (ft)	Range of BI	Average BI	Potential to be Cracked		Mineral Composition (%)		
				Yes	No	Quartz	Clay	TOC
1	5400-5432.5	0.176-0.236	0.196		✓			
2	5433-5476	0.180-0.271	0.232	✓		23,2	74,6	2,2
3	5476.5-5602.5	0.155-0.254	0.194		✓			
4	5603-5620	0.184-0.275	0.232	✓		23,2	74,4	2,4
5	5620.5-5975.5	0.140-0.250	0.181		✓			
6	5976-6000	0.162-0.355	0.236	✓		23,6	73,0	3,4

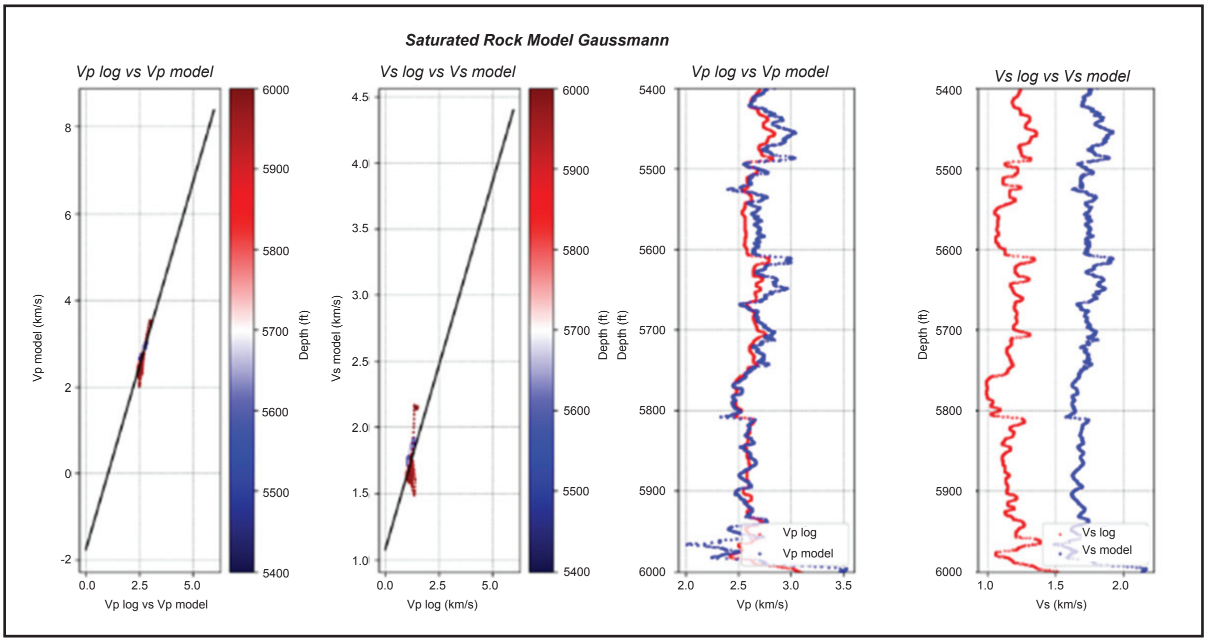


Figure 5
Seismic velocity modeling results with Biot Gassmann Modeling.

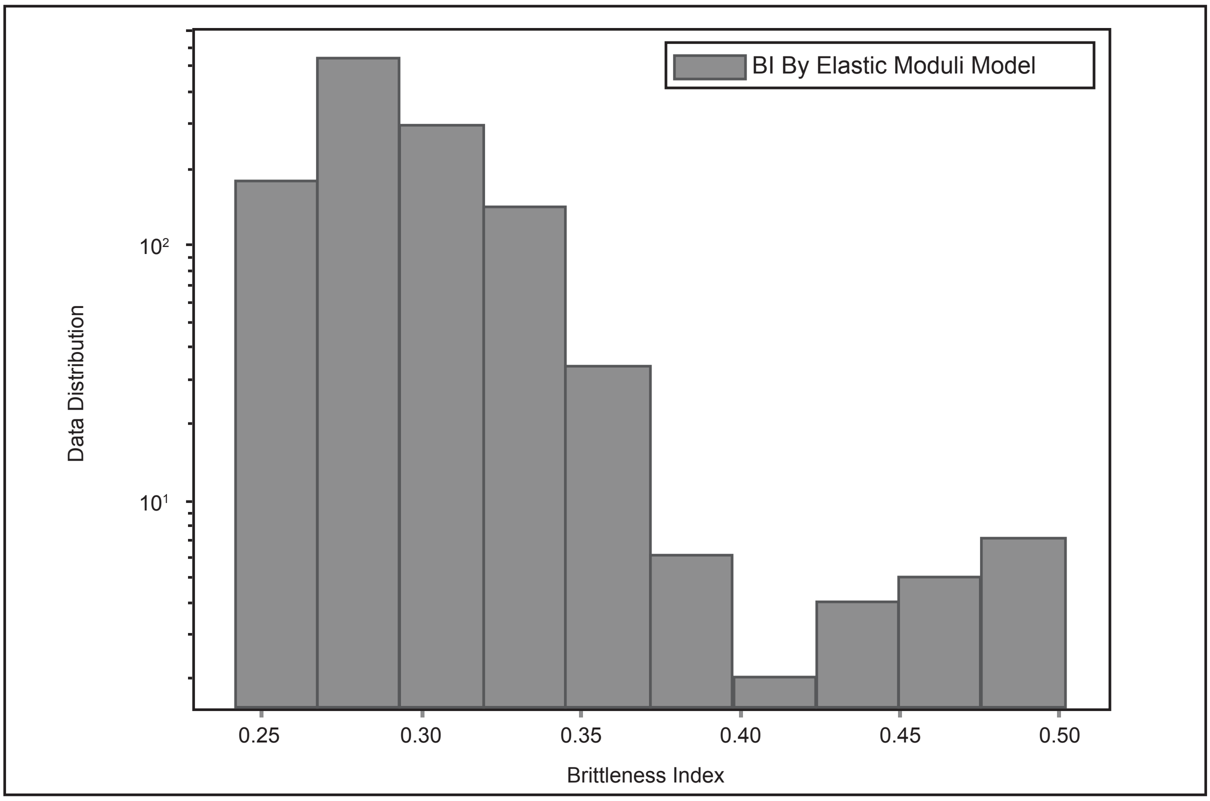


Figure 6
Histogram of brittleness index rock physics modeling.

have low TOC levels so that it becomes less economical to be used as a hydraulic fracturing point as a non-conventional oil and gas source, while zone 3 has considerable potential as a non-conventional oil and gas source for hydraulic fracturing.

The results of applying the Brittleness Index using the elastic properties of rocks with log data provide more complex and dynamic results than the Brittleness Index modeling results, which is limited to several data on the constituent minerals

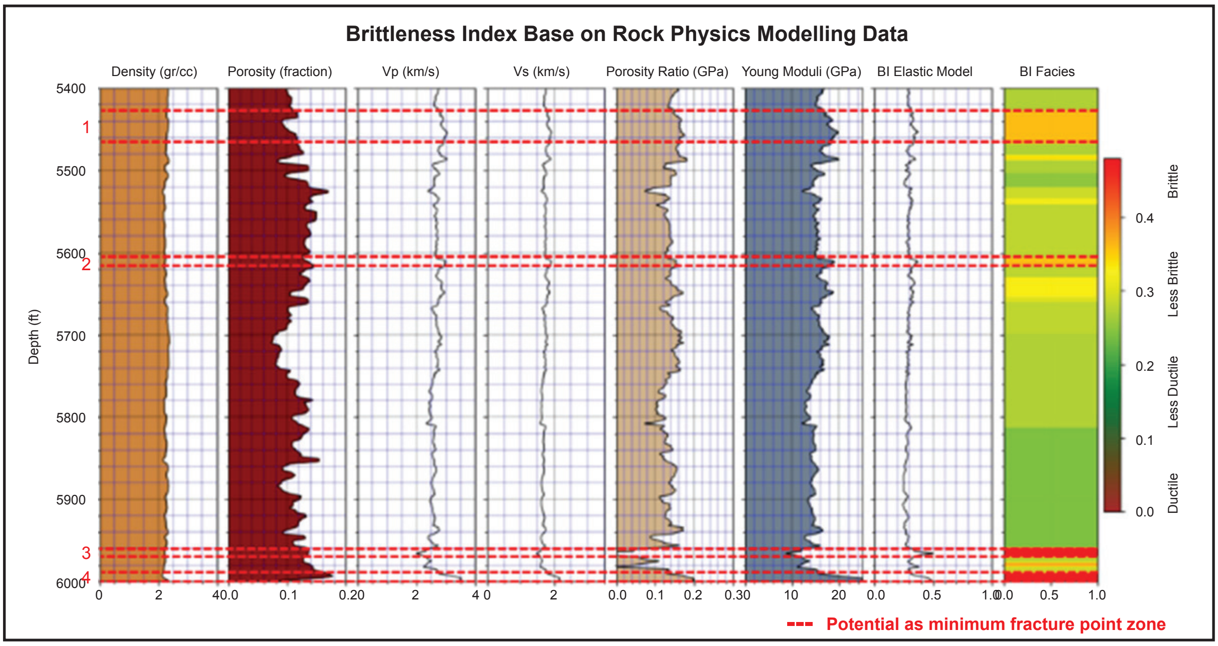


Figure 7
Brittleness index interpretation based on elastic properties of rock physics modeling with maximum fracturing point location.

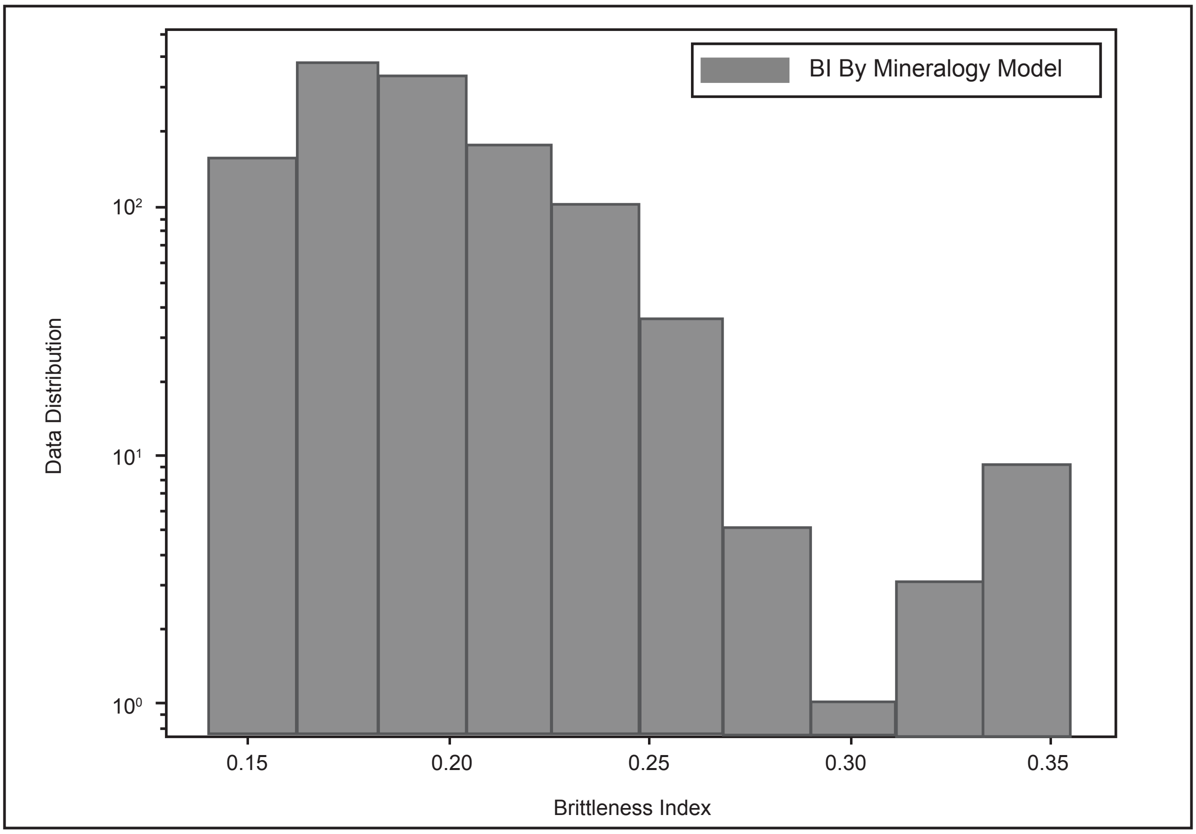


Figure 8
Histogram of brittleness index mineralogy.

and related physical properties (11b). This affects the vertical resolution of the Brittleness of the rock facies in the study area, where the vertical resolution of the Brittleness Index using the elastic properties of log data is better than the vertical resolution of the Brittleness Index using the elastic properties and mineralogy of Rock Physics Modeling (Figure 11a).

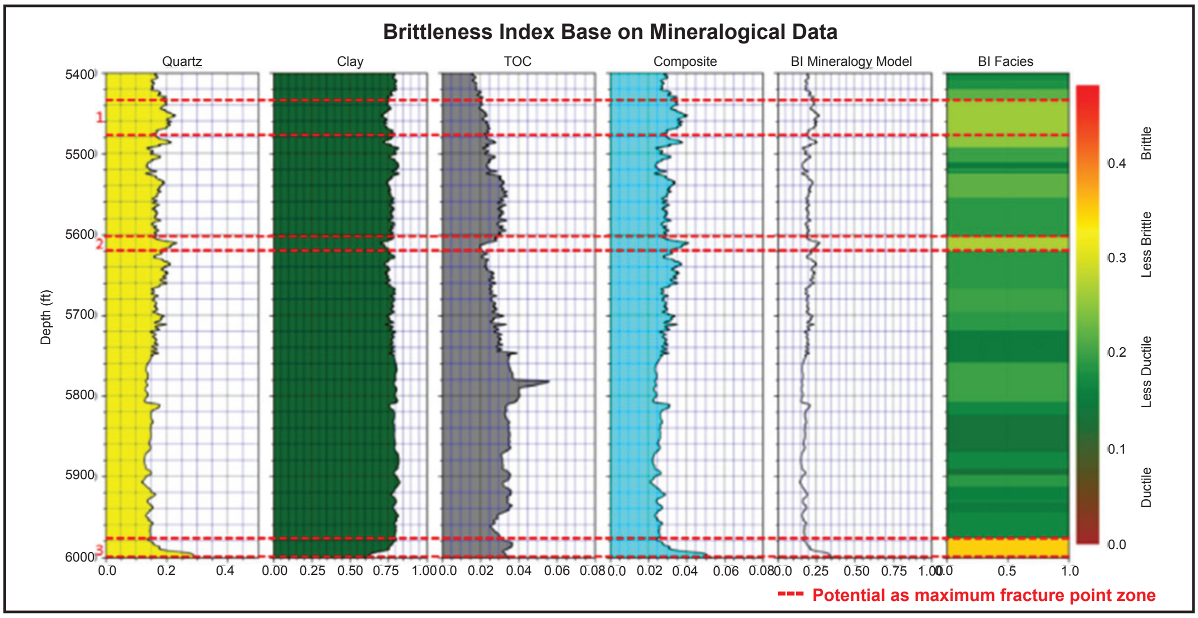


Figure 9
Brittleness index interpretation based on mineralogical properties
of rock physics modeling with maximum fracturing point location.

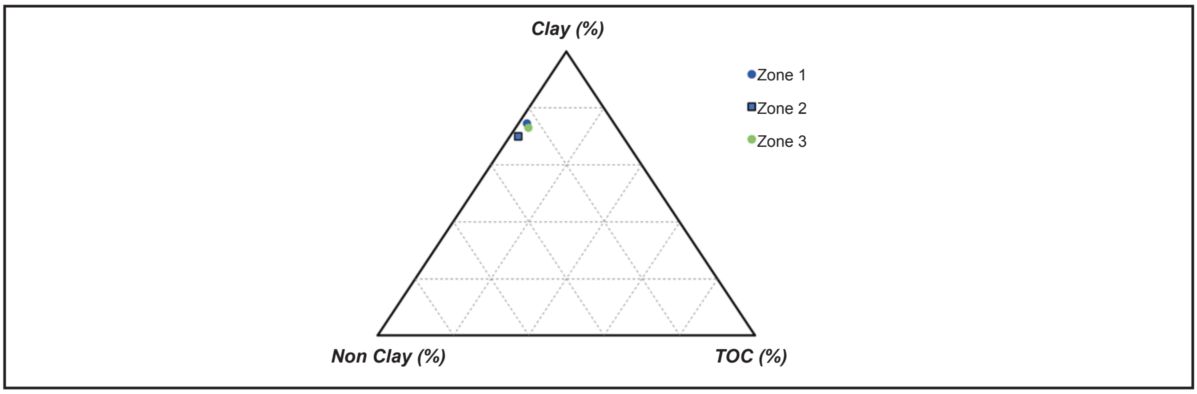
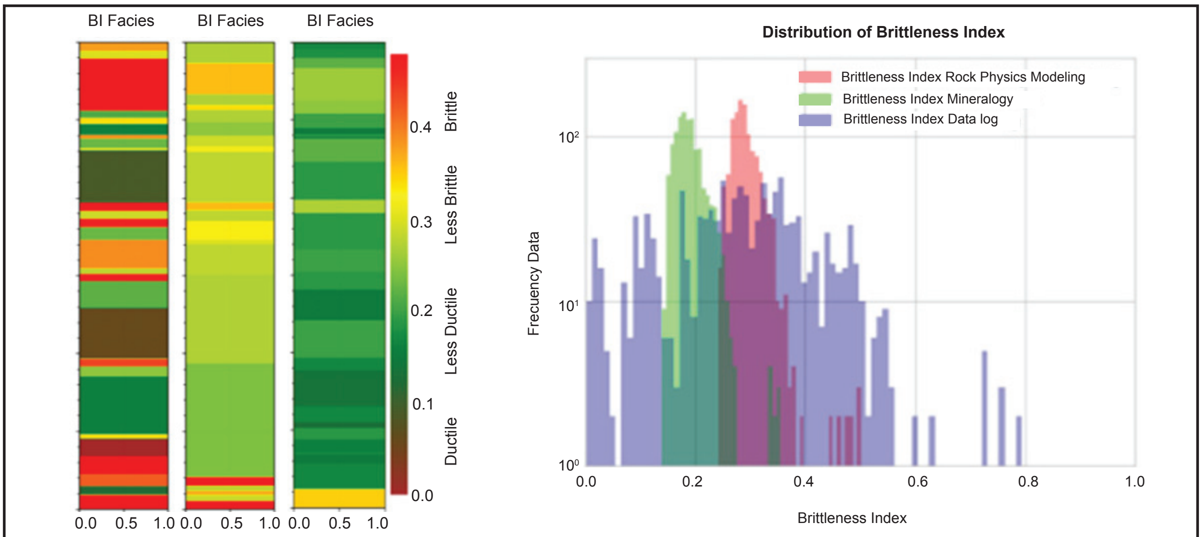


Figure 10
Mineral composition at maximum fracture point based on mineralogical modeling.



(a) BI Elastic Properties Data Log, BI Elastic Properties RPM, BI Mineralogy RPM

(b) BI Elastic Properties Data Log, BI Elastic Properties RPM, BI Mineralogy RPM

Figure 11
Brittleness index interpretation.

CONCLUSIONS

We proposed three approaches for estimating the Brittleness Index in the case of shale gas saturated. The results show consistency in the in-situ logs. It is critical to incorporate the information of mineral composites and TOC amount within pore space to optimize the hydraulic fracturing design and planning. This study may be implemented in the actual field as the quick look of fracturing schemes analysis when the core data is not available. For further investigation in the future, we suggest measuring the in-situ mechanical properties of shale rocks in the laboratory from the sample/core to the study area.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
F_{Quartz}	Quartz mineral fraction	fraction
F_{Clay}	Clay mineral fraction	fraction
F_{TOC}	Total Organic Carbon mineral fraction	fraction
$F_{Composite}$	Composite mineral fraction	fraction
E	Modulus Young	Gpa
v	Poisson ratio	Gpa
$E_{brittleness}$	Modulus Young brittleness	Gpa
E_{max}	Modulus Young maximum	Gpa
E_{min}	Modulus Young minimum	Gpa
$v_{brittleness}$	Poisson ratio brittleness	Gpa
v_{max}	Poisson ratio maximum	Gpa
v_{min}	Poisson ratio minimum	Gpa
$BI_{average}$	Brittleness Index average	
fi	Rock mineral elastic modulus fraction (fraction)	

Symbol	Definition	Unit
Mi	The elastic modulus of rock minerals	Gpa
M_V	Voigt elastic modulus of rock minerals	Gpa
M_R	Reuss elastic modulus of rock minerals	Gpa
M_H	Hill elastic modulus of rock minerals	Gpa
Xi	Volume fraction of rock pore shape	
Km	Rock mineral bulk modulus	
μm	Rock mineral shear modulus	
Ki	Rock fluid bulk modulus	
μi	Rock fluid shear modulus	
K^*_{KT}	Bulk modulus of minerals Kuster Toksoz model rock	
μ^*_{KT}	Shear modulus of the Kuster Toksoz mineral model rock	
Q^{mi} dan P^{mi}	The coefficient describing the effect of fluid inclusion in rock minerals	
α	Aspect ratio	
Ksat	Bulk modulus of fluid-saturated rock	Gpa
Kf	Fluid bulk modulus	Gpa
Kdry	Bulk modulus of dry rock	Gpa
Φ	Rock porosity	%
μdry	Shear modulus of dry rock	Gpa
μsat	Shear modulus of fluid-saturated rock	Gpa
V_p	Primary wave velocity	m/s
V_s	Secondary wave velocity	m/s
K	Modulus bulk	Gpa
ρ	Density	gr/cc
μ	Modulus shear	Gpa

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