A Novel Model of Brittleness Index for Shale Gas Reservoirs: Confining Pressure and Pore Pressure Effect*

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Abstract

Brittleness indices (BI) commonly used in the petroleum industry are based on elastic modulus or mineralogy that can be calculated from well logs. However, they both ignore the effect of confining pressure and pore pressure. Shale is usually distributed at various conditions with different confining pressure and pore pressure. Models without considering the influence of confining pressure and pore pressure will directly lead to inaccuracy in BI calculation, thus resulting in the failure of hydraulic fracturing. In this study, first a model considering the effect of confining pressure in BI calculation has been built by introducing “fracture toughness”. Considering the ratio k of the minimum horizontal effective stress to vertical effective stress and its relation with Poisson's ratio, a relationship between confining pressure and pore pressure has been obtained. Then, a BI model considering pore pressure has been built by replacing confining pressure in the first model with pore pressure. X-ray diffraction analyses, triaxial and Brazil disk split tests have been done to get mineral content and rock mechanics parameters of samples, respectively. Also, Kaiser acoustic emission probe has been used to monitor the generation and expansion of cracks in triaxial texts. Our study shows that BI is usually larger at low confining pressure than at high pressure. Also, BI gets improved with the consideration of pore pressure. The effective stresses in the reservoir decrease at elevated pore pressure, which is equivalent to reducing the influence of confining pressure and thus increases the brittleness of rocks. The results calculated by the new model, which considers the influence of Young's modulus, Poisson's ratio, tensile strength, confining pressure, pore pressure, and fracture toughness in BI calculation, match well with experimental results. This new model can be used to quantitatively calculate BI of rocks at different confining pressures and pore pressures, which is essential in analyzing rock mechanics and selecting fracturing section.

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A Novel Model of Brittleness Index for Shale Gas Reservoirs: Confining Pressure and Pore Pressure Effect

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OUTLINE

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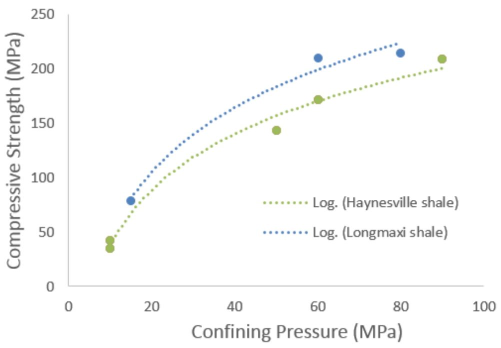
Introduction

- Brittleness is a parameter influenced by many factors, including rock mineralogy, rock mechanics characteristics, in situ stress, confining pressure and strain rate, which results in a plenty of descriptions and characterizations on brittleness.
- Brittleness indices (BI) commonly used in the petroleum industry are based on elastic modulus or mineralogy that can be calculated from well logs.
- Parameters like pressure, temperature and rock texture do have influence on BI, which should be considered in BI evaluation.

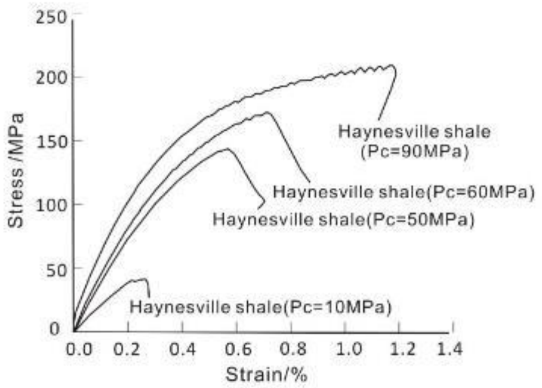
Brittleness Indices		Reference
$B_1 = \frac{\varepsilon_{el}}{\varepsilon_{tot}}$	ε_{el} : elastic strain ε_{tot} : total strain	Coates
$B_2 = \frac{W_{el}}{W_{tot}}$	W_{el} : elastic energy W_{tot} : total energy	Baron
$B_3 = \frac{C_0 - T_0}{C_0 + T_0}$	C_0 : compressive strength T_0 : tensile strength	Hucka and Das
$B_4 = \sin\varphi$	φ : friction angle	Hucka and Das
$B_5 = \frac{\tau_{\max} - \tau_{res}}{\tau_{\max}}$	$\tau_{\max}$: peak strength τ_{res} : residual strength	Bishop
$B_6 = \left\lvert \frac{\varepsilon_f^p - \varepsilon_c^p}{\varepsilon_c^p} \right\rvert$	ε_f^p : plastic strain at failure ε_c^p : specific strain beyond failure	Hajiabdolmajid and Kaiser
$B_7 = \left(\frac{\sigma_{v,\max}}{\sigma_v}\right)^b$	$\sigma_{v,\max}$: max previous experienced effective vertical stress σ_v : current effective vertical stress b : empirical value ~0.89	Ingram and Urai
$B_8 = \frac{1}{2}\left(\frac{E_{dyn}(0.8-\phi)}{8-1} + \frac{\upsilon_{dyn} - 0.4}{0.15-0.4}\right)\cdot 100$	E_{dyn} : dynamic Young's modulus υ_{dyn} : dynamic Poisson's ratio ϕ : porosity	Rickman et al.
$B_Q = \frac{Q}{Q+C+Cl}$	Q : quartz weight % C : carbon weight % Cl : clay weight %	Jarvie et al.

Introduction



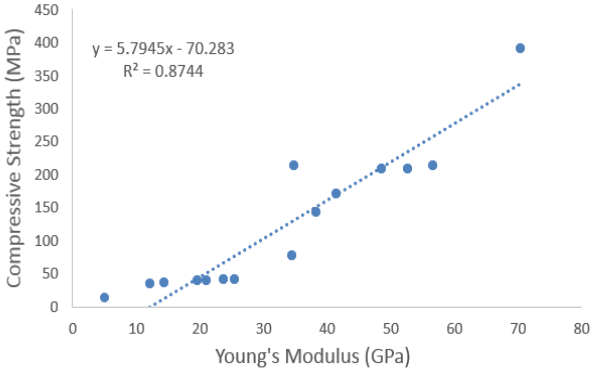
Compressive strength versus confining pressure, data 1

(a)



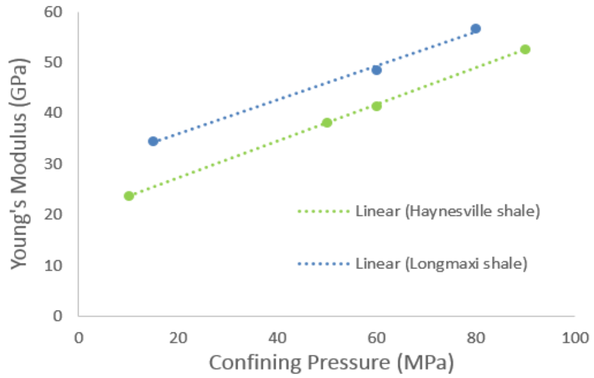
Influence of confining pressure on shale strength (Li et al., 2012)

(b)



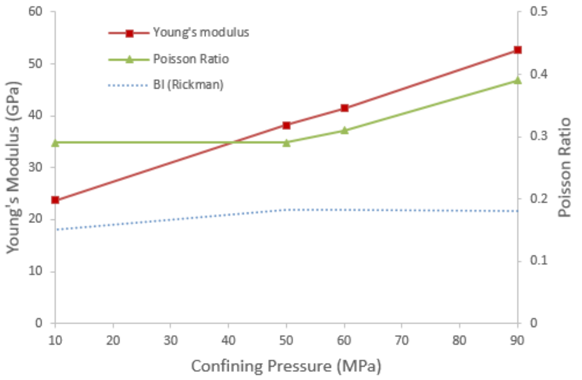
Compressive strength versus Young's modulus, data 2

(c)



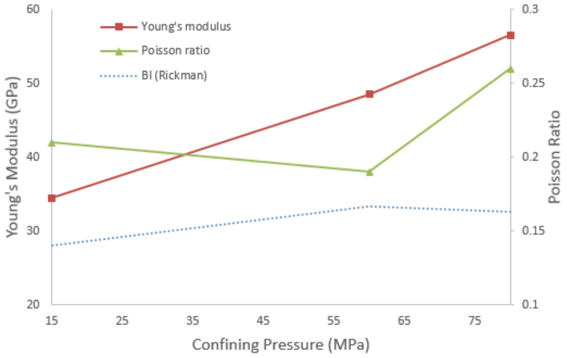
Young's modulus versus confining pressure, data 1

(d)



Haynesville shale samples

(e)



Longmaxi shale samples

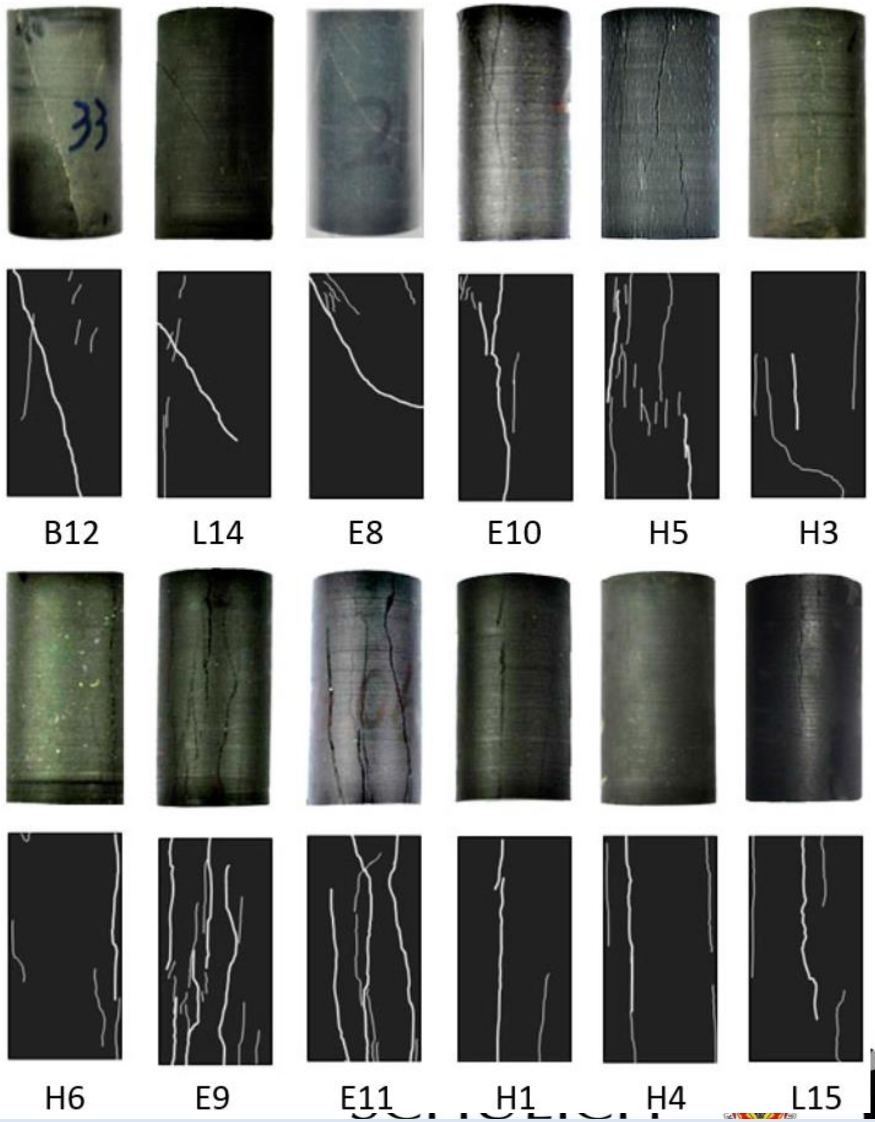
(f)

- Compressive strength increases with an increase in confining pressure.
- Compressive strength increases with an increase in Young's modulus.
- Young's modulus increases with an increase in confining pressure.
- It seems that the Poisson's ratio increases with confining pressure slightly, but it is not obvious, especially for Longmaxi shale samples.

Introduction

Sample Number	Depth (m)	Confining Pressure (MPa)	Young's Modulus (GPa)	Poisson Ratio	Compressive Strength (MPa)
H1	3359	90	52.61	0.39	209.19
H2	3393.7	60	41.4	0.31	171.92
H3	3393.7	50	38.15	0.29	143.73
H4	3233	10	23.73	0.29	42.3
H5	3362.2	10	12.13	0.29	35
H6	3359	10	25.43	0.35	42.49
H7	3219.5	10	4.92	0.62	14.78
E8	4163.1	50	34.74	0.27	214.09
E9	4164	30	20.91	0.21	40.57
E10	4164	20	19.56	0.48	40.56
E11	4164	30	14.33	0.21	37.75
B12	2171.6	60	70.4	0.41	391.25
L13	2071.1	80	56.58	0.26	215.13
L14	2123.4	60	48.54	0.19	210.17
L15	2229.7	15	34.48	0.21	78.5

A microcrack number of samples decreases with an increase in confining pressure.



Typical failure modes of shale specimens under different *Pc* (data from Li et al.)

Pc ↑ → Young's modulus ↑ / Poisson's ratio – ? / Mineral composition and content –

→ $BI_{Rickmen}$ ↑

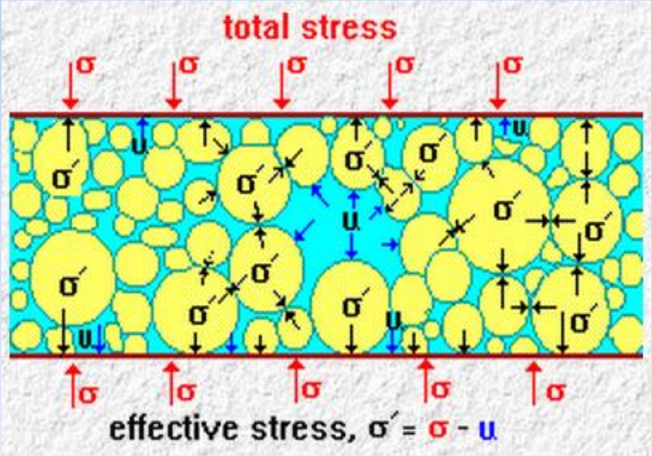
→ BI_{Jarvie}, BI_{Wang} –

↑ : increasing

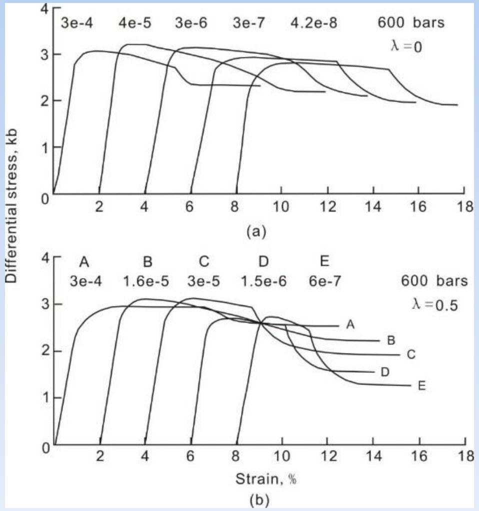
– : unchange

However, previous studies (N.A. Al-Shayea et al., 2000; Sone et al, 2013; Hu et al., 2015) show that rock is commonly more brittle at low confining pressure and will show a tendency toward ductility when the confining pressure increases. Also, microcrack decreases with an increase in confining pressure.

P_p



u: pore pressure, P_p



(Rutter et al., 1972)

$$\lambda = \frac{P_p}{P_c}$$

Unconventional reservoirs underground are usually full of oil, gas or water, which leads to significant pore pressure, especially under high temperature and pressure. Therefore, pore pressure should not be ignored.

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Existing models do not consider the influence of confining pressure and pore pressure.

Methodologies and Objectives

In this study, the following factors have been considered in our model:

- confining pressure
- pore pressure

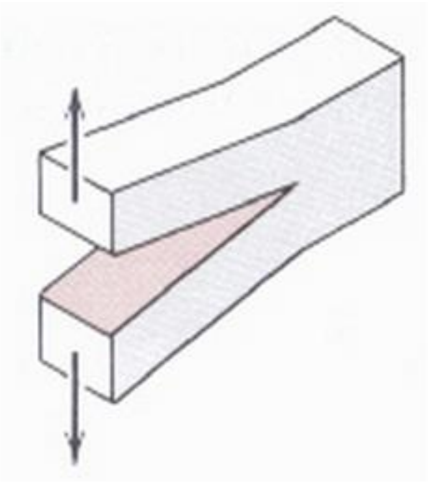
- ➢ The influence factors ignored by other models in brittleness evaluation, such as confining pressure and pore pressure can be addressed.
- ➢ A model of brittleness evaluation that could be built by using conventional data like well logs or seismic data will be created.

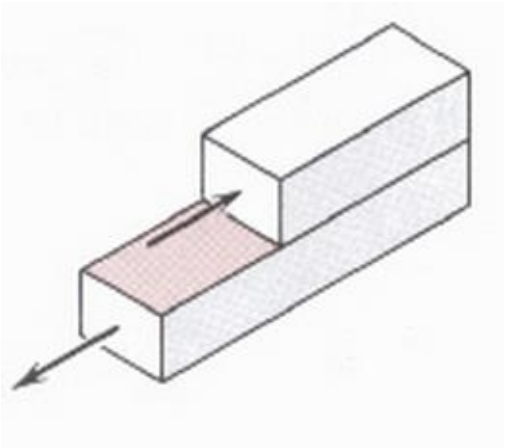
Fracture Toughness

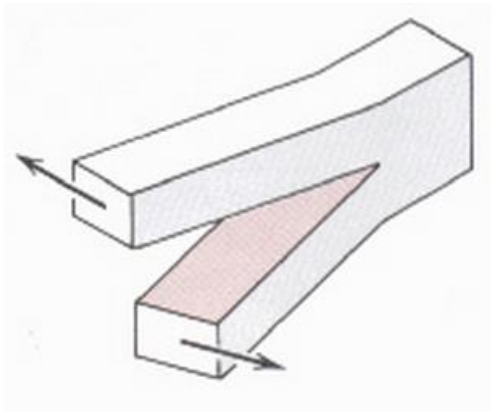
- Fracture toughness is a parameter expressing rock's resistance to a brittle fracture. It is more likely to have a ductile fracture, if the fracture toughness of a rock is high. On the contrary, a rock with low fracture toughness is more likely to have a brittle fracture.

- There are three fracture toughness numbers K_{IC}, K_{IIC}, and K_{IIIC} corresponding to three cracking modes (mode I, II, III).

- Nagel et al. (2011) showed that tensile failure mainly happens in hydraulic fracturing, and shear failure mainly happens in nature fractures by using numerical simulation.


Mode I


Mode II


Mode III

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Effective Stress

Terzaghi defines effective stress as follow :

$$\sigma_{ij}' = \sigma_{ij} - \delta_{ij} P_p \qquad (1)$$

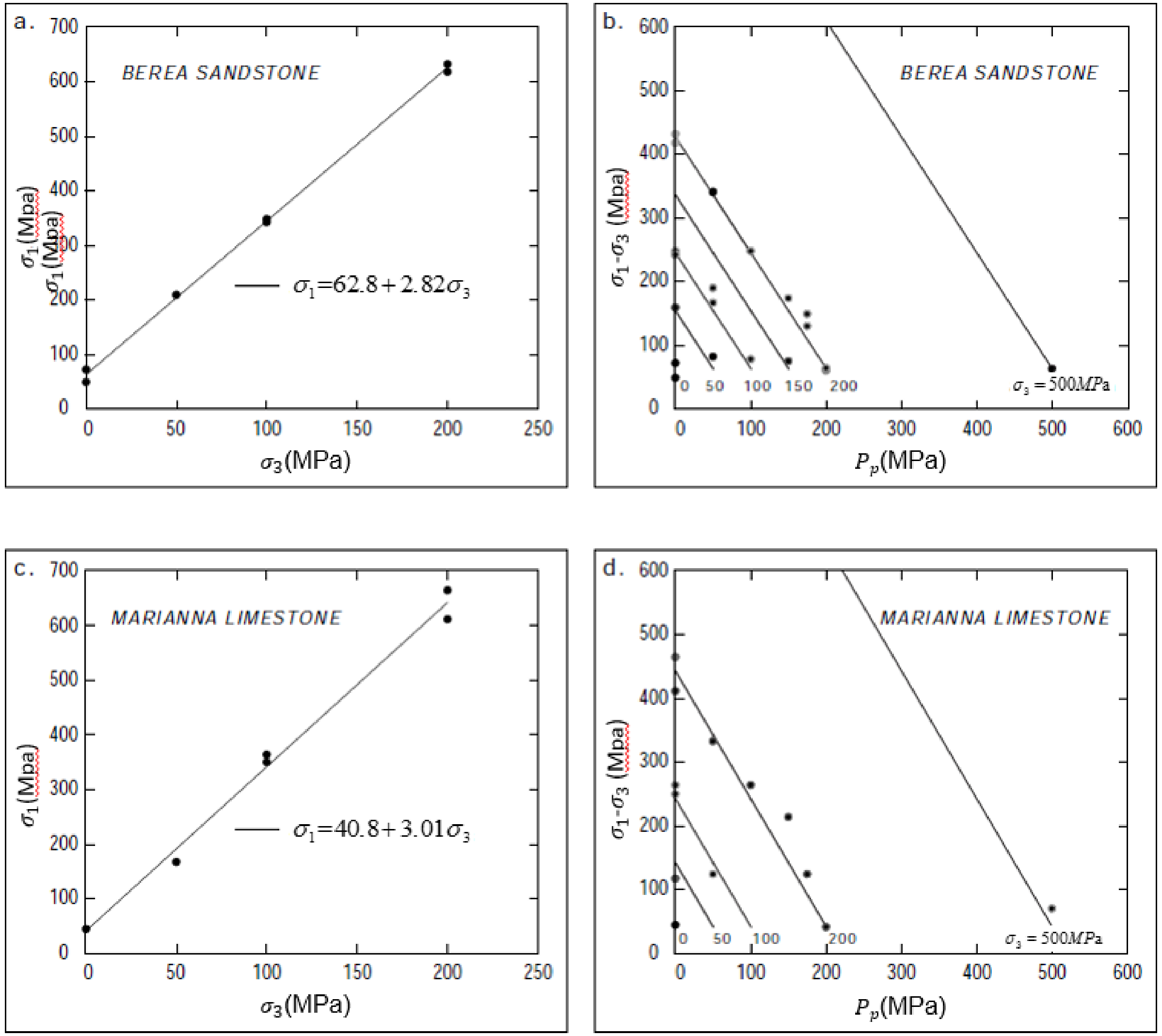
In Fig a&c, the strength tests are shown without pore pressure. σ_1 is shown as a function of confining pressure, σ_3.

$$\sigma_1 = c_0 + n\sigma_3 \qquad (2)$$

Assuming that it is valid to replace σ_1 with $(\sigma_1 - P_p)$ and σ_3 with $(\sigma_3 - P_p)$ in Eq (2):

$$\sigma_1 - \sigma_3 = c_0 + (1-n)P_p - (1-n)\sigma_3 \qquad (3)$$

Fig b&d show that the straight lines predicted by Eq (3) fit the data exactly for the various combinations of confining pressures and pore pressures at which the tests were conducted.



(From Zoback, 2007)

In other words, the effect of pore pressure on rock strength is described very well by the simple (or Terzaghi) form of the effective stress law in most rocks.

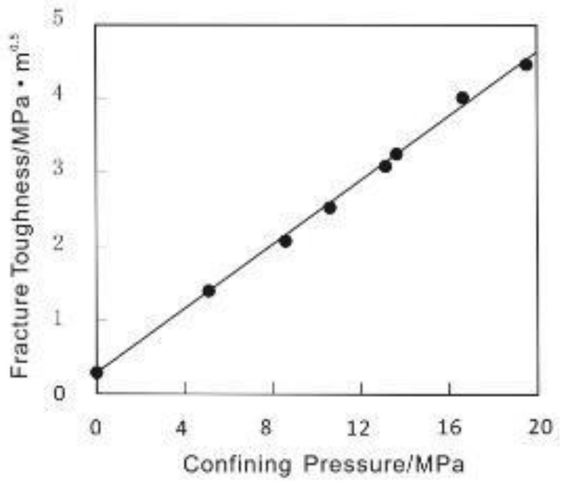
Fracture Toughness vs Effective Pressure

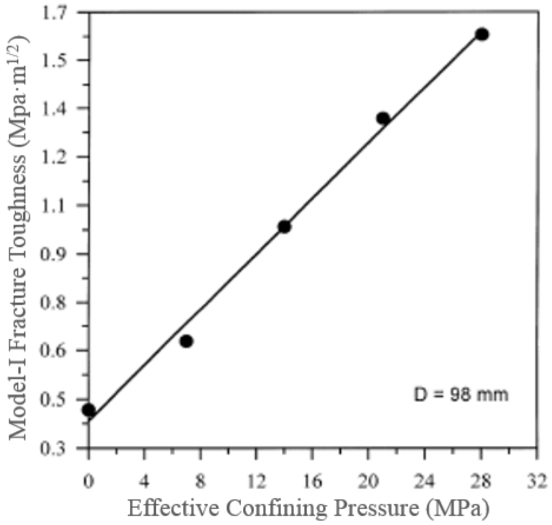
It has been proved that fracture toughness and confining pressure meet a linear relationship (F.Biret et al., 1989; Jin Yan et al., 2001).

$$K_{IC} = 0.052 P_c + 0.536 (R = 0.99) \quad (4)$$

N.A. Al-Shayea et al. (2000) further proves that fracture toughness and effective pressure meet a linear relationship.

$$K_{IC} = 0.043 \sigma_3 ' + K_{IC}{}^0 (R = 0.99) \quad (5)$$

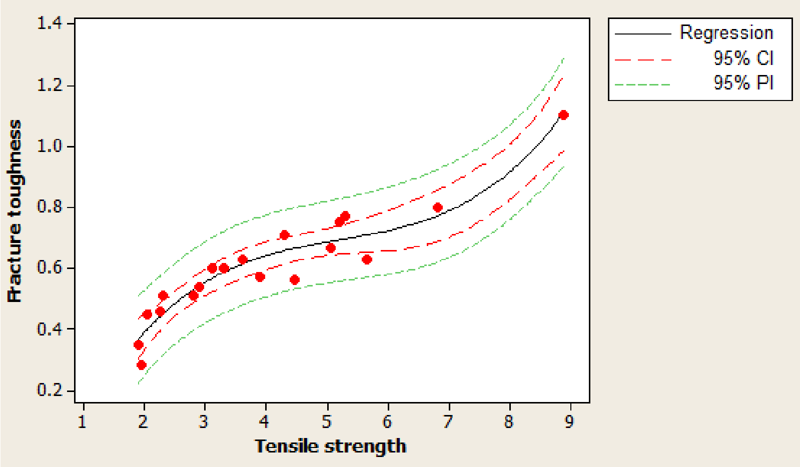




Fracture Toughness vs Effective Pressure from Well Logs

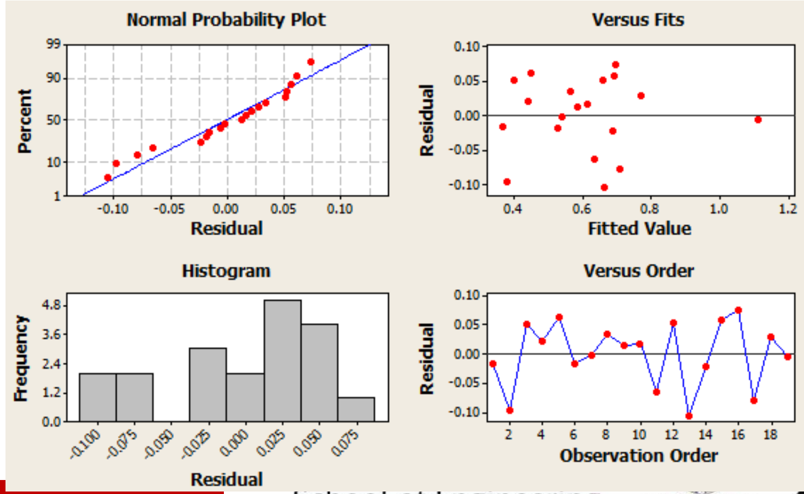
By using the data from Chen (1997), the relationship of fracture toughness and tensile strength has been built:

$$K_{Ic}{}^{0} = 0.0059\sigma_t{}^{3} - 0.0922\sigma_t{}^{2} + 0.5145\sigma_t - 0.3494 \qquad (6)$$



Therefore, fracture toughness can be expressed in effective/confining pressure and tensile strength:

$$K_{Ic} = 0.043\sigma_3{}' + 0.0059\sigma_t{}^{3} - 0.0922\sigma_t{}^{2} + 0.5145\sigma_t - 0.3494 \qquad (7)$$



Fracture Toughness vs Effective Pressure from Well Logs

A relationships between fracture toughness and P-wave velocity/S-wave velocity for shale formation (Chen et al, 1997) has been introduced:

$$K_{IC} = 0.0541 V_p + 0.3876 (R^2 = 0.75) \quad (8)$$

$$K_{IC} = 0.1021 V_s + 0.3876 (R^2 = 0.80) \quad (9)$$

$$K_{IC} = 3.672 \times 10^{-3} E + 0.45034 (R^2 = 0.84) \quad (10)$$

D. Eberhart, et al (2002) also built a relationship between effective pressure and P-wave velocity / S-wave velocity .

$$V_p = 5.77 - 6.94\phi - 1.73\sqrt{V_{sh}} + 0.446(\sigma_3' - e^{-16.7\sigma_3'}) \quad (11)$$

$$V_s = 3.70 - 4.94\phi - 1.57\sqrt{V_{sh}} + 0.361(\sigma_3' - e^{-16.7\sigma_3'}) \quad (12)$$

$$\sigma_3' = P_c - P_p \quad (13)$$

σ_3' effective pressure, MPa
P_c confining pressure, MPa
P_p pore pressure, %
V_{sh} clay content, %
V_p P-wave velocity, km/s
V_s S-wave velocity, km/s
E young's modulus, GPa

New Model Establishment in BI Calculation

When confining pressure increases, the ultimate tensile strength and intermolecular force of rock increase with it. The rock then has larger resistance and needs more energy to be fractured, which can be reflected by fracture toughness.

$$BI = \frac{\frac{BI_R}{K_{IC}} - (\frac{BI_R}{K_{IC}})_{\min}}{(\frac{BI_R}{K_{IC}})_{\max} - (\frac{BI_R}{K_{IC}})_{\min}} \quad (14)$$

→

$$BI = \frac{\frac{BI_R}{0.2176P_c + K_{Ic}{}^0} - (\frac{BI_R}{0.2176P_c + K_{Ic}{}^0})_{\min}}{(\frac{BI_R}{0.2176P_c + K_{Ic}{}^0})_{\max} - (\frac{BI_R}{0.2176P_c + K_{Ic}{}^0})_{\min}} \quad (15)$$

$$BI = \frac{\frac{BI_R}{0.043(P_c - P_P) + K_{Ic}{}^0} - (\frac{BI_R}{0.043(P_c - P_P) + K_{Ic}{}^0})_{\min}}{(\frac{BI_R}{0.043(P_c - P_P) + K_{Ic}{}^0})_{\max} - (\frac{BI_R}{0.043(P_c - P_P) + K_{Ic}{}^0})_{\min}} \quad (16)$$

With $K_{Ic}{}^0 = 0.0059\sigma_t{}^3 - 0.0922\sigma_t{}^2 + 0.5145\sigma_t - 0.3494$

This model considers the influence of Young's modulus, Poisson's ratio, tensile strength, confining/effective pressure and fracture toughness when calculating BI.

New Model Establishment in BI Calculation

Also, by using Eq (8) -Eq (13) BI can be calculated from well log data.

$$BI = \frac{\frac{BI_R}{K_{IC}} - (\frac{BI_R}{K_{IC}})_{\min}}{(\frac{BI_R}{K_{IC}})_{\max} - (\frac{BI_R}{K_{IC}})_{\min}} \quad (14)$$

$$BI = \frac{\frac{BI_R}{0.0541V_p + 0.3876} - (\frac{BI_R}{0.0541V_p + 0.3876})_{\min}}{(\frac{BI_R}{0.0541V_p + 0.3876})_{\max} - (\frac{BI_R}{0.0541V_p + 0.3876})_{\min}} \quad (17)$$

$$BI = \frac{\frac{BI_R}{0.1021V_s + 0.3876} - (\frac{BI_R}{0.1021V_s + 0.3876})_{\min}}{(\frac{BI_R}{0.1021V_s + 0.3876})_{\max} - (\frac{BI_R}{0.1021V_s + 0.3876})_{\min}} \quad (18)$$

With $V_p = 5.77 - 6.94\phi - 1.73\sqrt{V_{sh}} + 0.446(\sigma_3' - e^{-16.7\sigma_3'})$

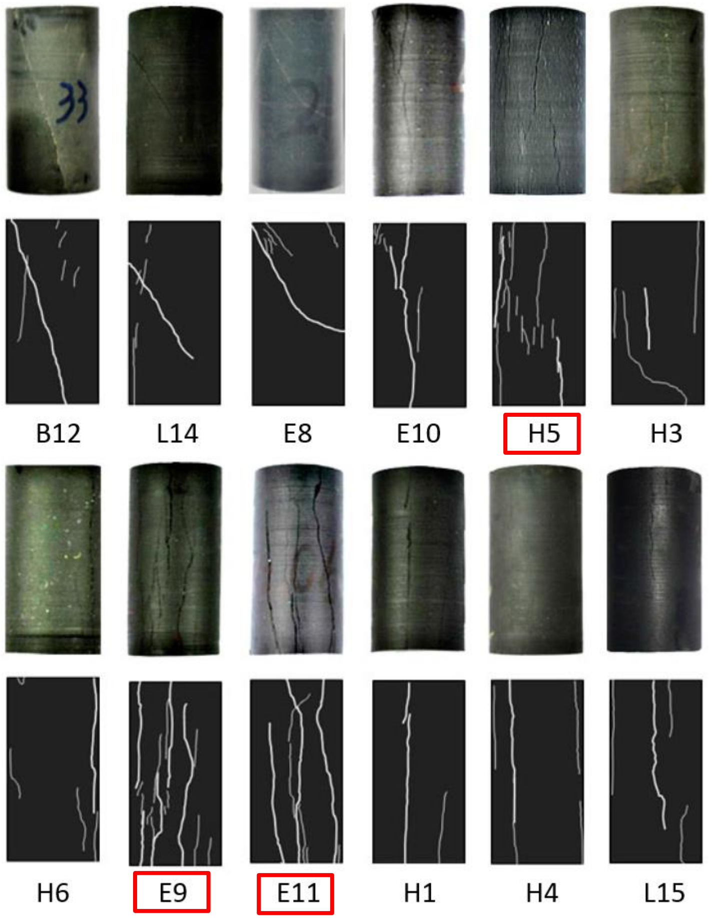
$V_s = 3.70 - 4.94\phi - 1.57\sqrt{V_{sh}} + 0.361(\sigma_3' - e^{-16.7\sigma_3'})$

Case Analysis and Verification

Sample Number	Depth (m)	Confining Pressure (MPa)	Young's Modulus (GPa)	Poisson Ratio	Compressive Strength (MPa)	Peak Strain (%)	Residual Strain (%)	BI_R	BI_{new}
H1	3359	90	52.61	0.39	209.19	1.16	1.26	0.624	0.285
H2	3393.7	60	41.4	0.31	171.92	0.72	0.85	0.618	0.382
H3	3393.7	50	38.15	0.29	143.73	0.53	0.67	0.613	0.416
H4	3233	10	23.73	0.29	42.3	0.3	0.35	0.512	0.524
H5	3362.2	10	12.13	0.29	35	0.3	0.33	0.430	0.707
H6	3359	10	25.43	0.35	42.49	0.21	0.27	0.469	0.433
H7	3219.5	10	4.92	0.62	14.78	0.42	0.43	0.079	0.040
E8	4163.1	50	34.74	0.27	214.09	1.01	1.28	0.607	0.455
E9	4164	30	20.91	0.21	40.57	0.34	0.36	0.565	0.668
E10	4164	20	19.56	0.48	40.56	0.19	0.21	0.310	0.297
E11	4164	30	14.33	0.21	37.75	0.51	0.65	0.518	0.801
B12	2171.6	60	70.4	0.41	391.25	1	1.31	0.731	0.245
L13	2071.1	80	56.58	0.26	215.13	0.38	0.46	0.770	0.364
L14	2123.4	60	48.54	0.19	210.17	0.43	0.51	0.777	0.445
L15	2229.7	15	34.48	0.21	78.5	0.21	0.3	0.660	0.516

H-Haynesville shale, E-Eagle ford shale, B-Barnett shale, L-Longmaxi shale in Sample Number
H-horizontal core, V-vertical core, number behind means the angle between core direction and magnetic north in orientation

Data 1



- The microcrack numbers of samples H5, E9 and E11 are three of the largest, which corresponds to the result of the equations with B_{new} being 0.707, 0.668 and 0.801, respectively.
- The microcrack numbers of samples H4 and L15 are in the second place with B_{new} being 0.524 and 0.516, respectively.

Case Analysis and Verification

Data 2

Sample Number	Qtz (%)	Brittle Mineral (%)	Clay (%)	Confining Pressure (MPa)	Compressive Strength (MPa)	Tensile Strength (MPa)	Young's Modulus (GPa)	K_{IC_16} ($MPa{\cdot}m^{1/2}$)	K_{IC_17P} ($MPa{\cdot}m^{1/2}$)	K_{IC_18S} ($MPa{\cdot}m^{1/2}$)	B_J	BI_R	BI_{16}	BI_{17_P}	BI_{18_S}
1-1	71.4	78.2	16.17	15	261.77	6.14	31.6	1.3444	1.0090	1.2338	0.782	0.789	0.868	0.898	0.890
1-2	71.4	78.2	16.17	30	337.87	6.14	31.5	1.9894	1.3710	1.7866	0.782	0.791	0.546	0.592	0.532
2-1	52.9	62.6	35.35	15	105.95	2.04	6.6	1.0116	0.9948	1.2079	0.626	0.403	0.459	0.336	0.334
2-2	52.9	62.6	35.35	30	140.71	2.04	7.5	1.6566	1.3567	1.7608	0.626	0.409	0.284	0.181	0.150
3-1	38.7	50.55	43.41	15	109.535	4.50	21.8	1.2813	0.9888	1.1976	0.506	0.517	0.558	0.512	0.512
3-2	38.7	50.55	43.41	30	160.815	4.50	23.8	1.9263	1.3507	1.7505	0.506	0.572	0.376	0.363	0.321
4-1	38.2	52.75	39.86	15	81.73	4.29	4.9	1.2720	0.9876	1.1970	0.528	0.286	0.252	0.164	0.162
4-2	38.2	52.75	39.86	30	160.215	4.29	12.5	1.9170	1.3495	1.7499	0.528	0.385	0.212	0.157	0.127
5-1	37.1	37.1	42.8	15	76.86	3.07	12.78	1.2478	0.9893	1.1971	0.371	0.422	0.223	0.368	0.368
5-2	36.8	36.8	46.9	30	162.33	4.70	16.73	1.8657	1.3511	1.7498	0.368	0.456	0.110	0.235	0.201

Data from Sichuan Basin, China

- $BI_{S1} > BI_{S3} > BI_{S2} > BI_{S5} > BI_{S4}$, which is the same for BI_R, BI_{16}, BI_{17_P} and BI_{18_S}.
- The results of BI_{16}, BI_{17_P} and BI_{18_S} also show that BI of the same sample is usually larger at low confining pressure than that at high confining pressure.

Conclusions & Future Work

- Conclusion

  - Rock is usually more brittle at low confining pressure and shows tendency toward ductility when the confining pressure increases, which is conflictive with the existing models in BI calculation.

  - The effective stresses in the reservoir decrease at elevated pore pressure, which is equivalent to reducing the influence of confining pressure and thus increases the brittleness of rocks.

  - The new models which considers the influence of Young’s modulus, Poisson’s ratio, tensile strength, confining pressure and fracture toughness in BI calculation matches well with experimental data and could be built by using conventional data like well logs.

- Future Work

  - Energy consumption has be taken into account to further explain the influence of pressure and temperature on BI. How to calculate the energy consumption of plastic deformation?

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