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Brittleness evaluation of the shale reservoirs in Wufeng and Longmaxi formation in the DS Area, southeast Sichuan, China

Zhenhua Luo[1,2,3] , Qirong Qin[1,2*], Hu Li[4], Cheng Zhong[1,2] & Xiaojun Dai[1,2,3]

[1]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610 500, China
[2]School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610 500, China
[3]School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu 610 500, China
[4]PetroChina Tarim Oilfield Company, Xinjiang Korla 841 000, China
* [E-mail: luocarry@126.com]

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Present study analyzed the brittleness of shales in the Wufeng and Longmaxi Formations based on mineral composition and elasticity parameters, using a combination of core samples, well logging, X-ray diffraction, and mechanical tests. Fracturability of the two formations was then assessed. The results show that, from the perspective of mineral composition, the brittleness of shales in the Wufeng and Longmaxi Formations is affected mainly by brittle minerals like quartz, feldspar, and pyrite. Shale samples ranged from 36.2% to 62.7% in brittleness index (BRIT) based on mineral composition, with an average of 48.6%. Mechanical tests under different confining pressures revealed three failure modes of the shale samples: splitting, bidirectional shear, and unidirectional shear. Their values of BRIT based on elasticity parameters were between 40.7% and 61.6%, averaging 52.6%. Compared to other gas-producing shale formations, the Wufeng-Longmaxi shales in the study area have above-average BRIT levels and high fracturability. There are good correlations between their brittle mineral content, BI, and total organic carbon (TOC). At well DY1, the strata at depths of 2027 to 2054.2m show high brittleness with BRIT values exceeding 50%.

[Keywords: shale reservoirs; brittleness; mineral composition; elasticity parameters; the Wufeng and Longmaxi Formations; DS area]

Introduction

Shale is a typical low-porosity and low-permeability reservoir rock. Fracturing stimulation is an important method for extracting shale gas and increasing production at a later stage [1-5]. Brittleness is a key factor considered in assessing whether a shale formation is fracturable and selecting appropriate fracturing techniques [6-8]. The more brittle a shale is, the more likely fractures will occur in it and form a fracture network. Conversely, for a shale with lower brittleness, the fracture structure created by fracturing is simpler and less effective in improving production efficiency [9]. The high gas production from the Barnett and Haynesville shale gas fields in North America and the Fuling shale gas field in China is found to be closely associated with the brittleness of local shales. Brittleness evaluation can provide a valid basis for selecting proper hydraulic fracturing measures and techniques as well as subsequent evaluation based on fracture parameters [10-14.]

Brittleness is a general property of rocks affected by multiple factors, such as rock's mineral composition and elastic properties, presence of fractures, in-situ stress, burial depth, etc. [15, 16]. At present, brittleness evaluation for shaleis mainly based on shale's mineral composition or mechanical parameters. However, evaluation based on a single criterion usually has some limitations as factors influencing shale brittleness vary from region to region. By drawing on North America's successful experience in shale gas exploration and development in [17-19], the present study evaluated the brittleness of shales in the Wufeng and Longmaxi Formations in the DS area, Southeast Sichuan, based on mineral composition combined with elasticity parameters. Mineral composition analysis and mechanical tests were performed on shale samples from the study area. The study aims to identify a favorable zone for occurrence of shale gas and provide guidance for subsequent application of fracturing to shale gas wells and development.

Materials and Methods

There is no uniform method and criteria for shale brittleness assessment in China. Brittleness indexes based on mineral composition and mechanical parameters are relatively established methods for representing shale brittleness [20-22]. Shales are normally composed of quartz, feldspar, calcite, dolomite, pyrite, and clay minerals. There is still controversy over which minerals contribute to the rock's brittleness (Table 1). For instance, a study of the Barnett Shale by Jarvie D.M. et al. [23]suggests that quartz is the only brittle mineral constituent of this rock. Chen J. and Xiao X.M.[24] from China classify quartz, feldspar, calcite, and dolomite as brittle. Li J.Y. [25] argues that both carbonate minerals and quartz are brittle minerals, but the former are more brittle than the latter. Some scholars use strength parameters to characterize the brittleness of rocks (Table 1). For example, Hucka V. and Das B. [26] calculated rock brittleness from the ratio of compressive strength to tensile strength and strain ratio, based on stress-strain curves. Guo Z. et al. [27]directly used the ratio of elastic modulus to Poisson's ratio to describe brittleness. Through normalizing the two parameters when they were given the same weights, R. Rickman found that rocks with a higher elastic modulus and lower Poisson's ratio were more brittle. Diao H.Y.[28]analyzed the strengths and weaknesses of brittleness evaluations based on mineral composition and elasticity parametersand provided a new method combining elasticity parameters and mineral composition (EP & MC method). Through an experimental and numerical analysis of the relationships of elastic modulus and Poisson's ratio to quartz content, she concludes that quartz is the major brittle mineral contained in shale and its brittleness determines the overall brittleness of the rock.

Based on a review of previous studies, the authors believe that shale's brittleness is the mechanical behavior of the rock and the presence of brittle minerals has a direct bearing on the rock's mechanical properties. The Longmaxi shale in the DS area and other marine shales found in South China are characterized by large amounts of quartz and feldspar, presence of pyrite, high elastic modulus and low Poisson's ratio. Given these characteristics, the present study evaluated the brittleness of shale reservoirs by analyzing mineral composition (quartz, feldspar and pyrite) and elasticity parameters [29]. The equations used to calculate brittleness are as follows:

$$BRIT_1=\frac{v_{quartz}+v_{feldspar}+v_{pyrite}}{v_{quartz+feldspar+pyrite}+v_{carbonate\,minerals}+v_{clay}}\times 100\% \qquad \ldots (1)$$

Table 1 — Common methods for evaluating shale brittleness

Evaluation method	Equation for brittleness determination	Variable description
Mineral composition analysis	$BRIT_1=\frac{v_{quartz}}{v_{total}}\times 100\%$	Quartz is a brittle mineral.
	$BRIT_2=\frac{v_{quartz}+v_{feldspar}+v_{calcite}+v_{dolomite}}{v_{quartz}+v_{feldspar}+v_{calcite}+v_{dolomite}+v_{clay}}\times 100\%$	Quartz, feldspar, calcite, and dolomite are brittle.
	$BRIT_3=\frac{v_{quartz}+v_{carbonate}}{v_{quartz}+v_{calcite}+v_{clay}}\times 100\%$	Quartz and carbonate minerals are brittle, with the latter having greater brittleness.
Elasticity parameter analysis	$BRIT_4=E/\mu$	E is elastic modulus and μ is Poisson's ratio.
	$BRIT_5=\sigma_c/\sigma_t$	σ_c is compressive strength and σ_t is tensile strength.
	$BRIT_6=\varepsilon_r/\varepsilon_t$	ε_r is recoverable strain and ε_t is total strain.
	$BRIT_7=\frac{(E+\mu)}{2}$	E is normalized elastic modulus and μ is reversely normalized elastic modulus.
A combination of elasticity parameter and mineral composition analysis	$BRIT_8=\frac{v_{quartz}\times(\frac{YM_{quartz}}{PR_{quartz}})}{v_{quartz}\times(\frac{YM_{quartz}}{PR_{quartz}})+v_{calcite}\times(\frac{YM_{calcite}}{PR_{calcite}})+v_{clay}\times(\frac{YM_{clay}}{PR_{clay}})}\times 100\%$	Quartz is brittle. YM is Young's modulus and PR is Poisson's ratio.

$$BRIT_2 = \left[\frac{E-1}{8-1} \times 100 + \frac{\mu - 0.40}{0.15-0.40} \times 100 \right] / 2 \qquad \ldots (2)$$

where $BRIT_1$ is the BRIT based on mineral composition; $v_{quartz}, v_{feldspar}, v_{pyrite}$ are the content of the aforementioned three brittle minerals (%); $v_{carbonate\,minerals}$ is the content of carbonate minerals (%); v_{clay} is the content of clay minerals (%); $BRIT_2$ is the BRIT based on mineral composition; E is elastic modulus, measured undera load of 10 GPa; and μ is Poisson's ratio (dimensionless).

Brittle mineral content is considered a major factor influencing shale brittleness, development of fractures and failure mode of the rock [30, 31]. The higher the brittle mineral content, the more brittle the shale is and the more likely fracturing operations will create a group of fractures or a fracture network. Therefore rock brittleness based on mineral composition is a key indicator used in brittleness evaluation for shale reservoirs[32, 33].

Composed primarily of grayish blacksilty mudstone and mudstone, the Wufeng and Longmaxi Formations in the DS area were laid down under reducing conditions at bathyal to abysmal depths. In this study, 22 samples of the Wufeng-Longmaxi shales were collected from wells DY1, DY2, DY3, and DY4 (in descending order of depth) drilled in the DS area and analyzed by X-ray diffraction for their whole-rock mineral composition. The results are presented in Fig. 1 and Table 2. It was found that the shale samples from well DY1 generally had high content of brittle minerals, varying from 35.5% to 57.6% and averaging 45.3%. Their content of clay minerals, the second major mineral constituents, was between 26.2% and 49.2%, with an average of 39.2%. These samples contained relatively small amounts of carbonate minerals, ranging between 14.5% and 16.8% and averaging 15.5%. The concentration of pyrite was 1.1% on average. In the samples from well DY2, the brittle mineral content was relatively high at 31.4%-56.5%, with an average of 43.8%. The content of clay minerals reached 22.9%-48.4%, with an average of 39.7%.The content of carbonate minerals fell within the range of 8.8% to 26.0%, with an average of 16.0%. Pyrite content was 1.2% on average. The shale samples from well DY3 also contained large quantities of brittle minerals, with brittle mineral content ranging from 39.3% to 62.6% and averaging around 50.2%. Their clay mineral content was between 20.4% and 40.9%, with an average of 32.4%. Their carbonate mineral concentrations were relatively low, varying from 15.1% to 21.8% and averaging 17.5%. Their average pyrite content was 2.2%. The samples from well DY4had brittle mineral content ranging from 40.8% to 66.1% and averaging 51.6%. Their clay mineral content was between 18.2% and 42.3%, with an

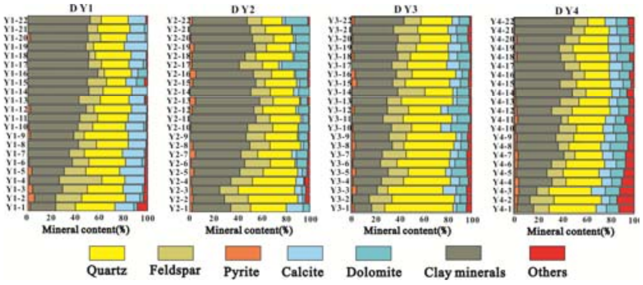

Fig. 1 — Relative mineral content of the samples of the Wufeng-Longmaxi shales in the DS area

Table 2 — Brittleness index based on mineral composition for the Wufeng-Longmaxi shales in the DS area

Well location	Mineral composition (%)			BRIT$_1$ (%)
	Brittle minerals (quartz, feldspar and pyrite)	Carbonate minerals (calcite and dolomite)	Clay minerals (illite, chlorite, smectite, etc.)	
DY1	$\frac{35.5 \sim 57.6}{45.3}$	$\frac{14.5 \sim 16.8}{15.5}$	$\frac{26.2 \sim 49.2}{39.2}$	$\frac{36.2 \sim 58.7}{45.8}$
DY2	$\frac{31.4 \sim 56.5}{43.8}$	$\frac{8.8 \sim 26.0}{16.0}$	$\frac{22.9 \sim 48.4}{39.7}$	$\frac{31.8 \sim 58.1}{44.7}$
DY3	$\frac{39.3 \sim 62.6}{50.2}$	$\frac{15.1 \sim 21.8}{17.5}$	$\frac{20.4 \sim 40.9}{32.4}$	$\frac{39.2 \sim 62.7}{50.2}$
DY4	$\frac{40.8 \sim 66.1}{51.6}$	$\frac{13.7 \sim 19.7}{16.0}$	$\frac{18.2 \sim 42.3}{32.3}$	$\frac{40.8 \sim 61.7}{51.6}$

average of 32.3%. The content of carbonate minerals was low, ranging from 13.7% to 19.7% and averaging16.0%. The pyrite content of these samples was 2.6% on average.

The mineral composition analysis reveals that the core samples from different wells differed in mineral composition. Overall, as the depth increases, the content of clay minerals tends to decrease while the content of brittle minerals (quartz, feldspar and pyrite) tends to increase. Overall, the overall brittleness of the shales increases with increasing burial depth.

Brittleness characterization based on mineral composition normally involves calculating the ratio of the amount of brittle minerals to the total amount of minerals present in a rock. To evaluate the brittleness of the Wufeng-Longmaxi shales in the study area, the BRIT based on mineral composition (BRIT_1)was calculated for the shale samples from the aforementioned four wells. The results (Table 2) shows that the shale samples from well DY1 ranged in BRIT_1 from 36.2% to 58.7%, with an average of 45.8%. The samples from well DY2 ranged in $\text{BRIT}_1$from 31.8% to 58.1%, with an average of 44.7%. The samples from DY3 hadBRIT_1ranging from 39.2% to 62.7% and averaging 50.2%. The BRIT_1 of the shale samples from DY4 varied between 40.8% and 61.7% and was 51.6% on average.

Results and Discussion

The results of mineral composition analysis and BRIT calculation based on mineral composition demonstrate that the shales in the Wufeng and Longmaxi Formations have a medium level of brittleness overall, with an average BRIT based on mineral composition of 48.6%, and the shales in wells DY3 and DY4 had relatively high brittleness with BRIT values exceeding 50%.

Mechanical properties are seen as another key indicator for evaluating shale brittleness[34-37]. The core samples used in this experiment were 25 mm in diameter and 50mm in length. In order to reduce the influence of bedding planes (anisotropy) on the experiment [38], all the samples to be tested were drilled parallel to bedding planesand contained no fracture. The compressive strengths of these samples under different confining pressures were then experimentally measured using the RTR-1000 system, an apparatus for high-temperature and high-triaxial compression tests provided by an American company, GCTS.

The observations of the failed shale samples reveal three failure modes of the samples under different confining pressures (Fig. 2): splitting, bidirectional shear, and unidirectional shear [39]. Under low confining pressures (0MPa and 20MPa), the shale samples failed largely due to splitting (Y1-a, Y3-a, and Y3-b) and most of them were fragmented. They contained large numbers of microcracksand some were split by fractures running approximately axially throughout the samples. Under medium confining pressures(24MPa, 27MPa, 30MPa, and36MPa), the rock samples failed primarily due to bidirectional shear (Y2-b, Y2-c, Y2-d, and Y1-d). The fractures in them were inclined with respect to the axis of the cylindrical samples and rarely cut through the samples. The propagation of some fractures was interrupted by other fractures and microcracks arose at the tips of main fractures. Under high confining pressures (48MPa, 50MPa, and55MPa), the rock samples failed by bidirectional or unidirectional shear and exhibited no or a few microcracks (Y4-cY1-c, Y2-f, Y2-g, and Y1-f).

As can be seen in the figure above, the number of axially propagating fractures decreased with increasing confining pressure applied. This is possibly because a higher confining pressure led to a higher level of energy needed to cause fracture and the internal energy stored in the rock was then mostly released as 1 or 2 cracks grew under high confining pressures. Analysis of failure modes of shales from different burial depths under confining pressures can provide a basis for determining operational parameters and measures during hydraulic fracturing.

The stress-strain curves obtained by the mechanical tests demonstrate that the shale samples' compressive

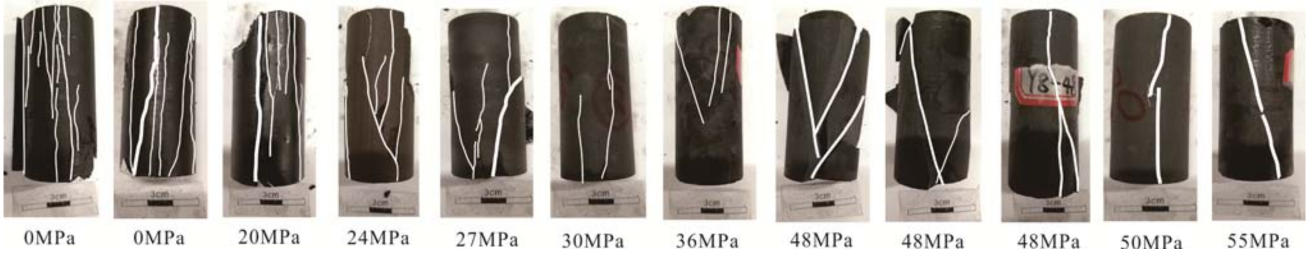

Fig. 2 — Failure modes of shale samples under different confining pressures

strength grew with increasing confining pressure (Fig. 3). Before failure, the samples underwent elastic strain when the confining pressure was within a certain range and the corresponding portions of the stress-strain curves were steady upward and linear. After the confining pressure exceeded a particular level, the samples began to deform plastically. When the axial stress peaked, the samples fractured significantly and crackled. Under the experimental confining pressures, the shale samples showed overall BRIT values roughly between 40% and 60%. A higher confining pressure was associated with a smaller number of microcracks and a lower level of shale brittleness.

Rocks with a lower Poisson's ratio and higher Young's modulus normally have greater brittleness [40]. As both Poisson's ratio and Young's increase with increasing confining pressure overall, the actual conditions of rocks should be considered in the experimental analysis of the two parameters and brittleness calculation based on them. An analysis of the experimental elasticity parameters of the rock samples from different wells suggests that the elastic modulus was linearly and positively related to the confining pressure, and the coefficient of correlation between them fell within the range of 0.5534 to 0.9456 (Fig. 5). In comparison, the samples' Poisson's ratio showed a strong, non-linear trend over the experimental range of confining pressure, with the coefficient of correlation between them varying from 0.7349 to 1(Fig. 6). The sharp growth in this parameter is possibly due to the sharp closure of the microcracks in the samples [41, 42]. Therefore, the BRIT calculated from the two parameters tended to decrease with increasing confining pressure (Fig. 4). Table 3 shows the BRIT_2values of the shale samples. The samples from well DY1 ranged in BRIT_2 from 40.7% to 61.6%, with an average of 49.5%. The samples from well DY2 ranged in BRIT_2 from 50.3% to 59.4%, averaging 55.7%. The BRIT_2 of the samples from well DY3varied from 41.6% to 56.8% and was 50.5% on average. The index values for the samples from well DY4 were between 53.9%-57.6%, with an average of 55.8%.

Overall, as the confining pressure declined, the shale samples from the Wufeng and Longmaxi Formations in the study area failed more thoroughly and became more brittle. With BRIT_2 ranging from 40.7% to 61.6% and averaging 52.6%,these samples were classified as having medium brittleness.

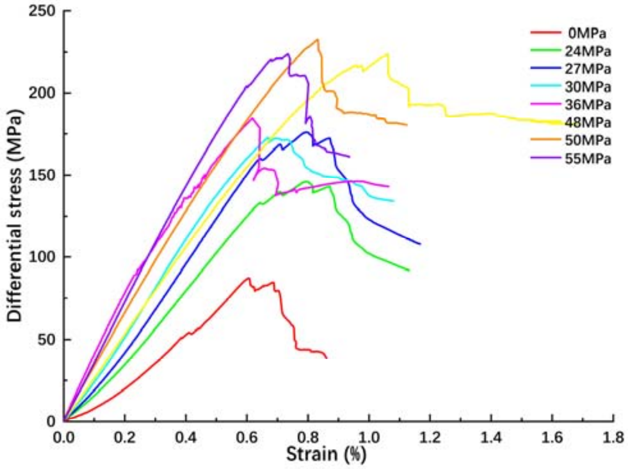

Fig. 3 — Stress-strain curves for the shale samples under different confining pressures

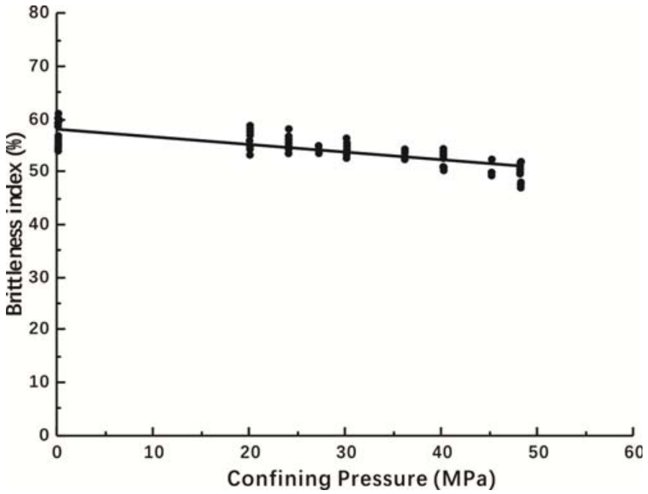

Fig. 4 — BRIT variation with confining pressure

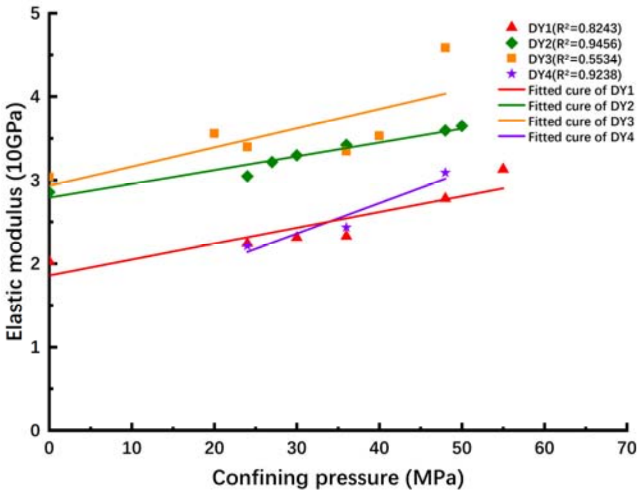

Fig. 5 — Young's modulus variation with confining pressure

Table 3 — Mechanical parameters of core samples of the Wufeng-Longmaxi shales and their BRIT based on elasticity parameters

Well location	Sampling depth, H (m)	Sample No.	Confining pressure (MPa)	Elastic modulus, E (under 10GPa)	Poisson's ratio,μ	$BRIT_2$ (%)
DY1	2025.50~2025.70	Y1-a	0	2.0275	0.201	47.1
	2044.87~2045.04	Y1-b	24	2.2430	0.166	55.7
		Y1-c	30	2.3130	0.139	61.6
		Y1-d	36	2.3288	0.193	50.9
		Y1-e	48	2.7818	0.260	40.7
		Y1-f	55	3.1336	0.270	41.2
DY2	4353.00~4355.60	Y2-a	0	2.8590	0.188	55.7
	4357.50~4357.72	Y2-b	24	3.0505	0.195	55.6
	4362.10~4362.30	Y2-c	27	3.2202	0.200	55.9
		Y2-d	30	3.3002	0.185	59.4
		Y2-e	36	3.4250	0.195	58.3
		Y2-f	48	3.5966	0.220	54.5
		Y2-g	50	3.6501	0.243	50.3
DY3	2208.50~2209.24	Y3-a	0	3.0395	0.195	55.6
	2225.56~2225.82	Y3-b	20	3.5606	0.214	55.5
	2237.61~2237.83	Y3-c	24	3.3993	0.232	50.7
	2242.53~2242.67	Y3-d	36	3.3489	0.200	56.8
	2274.00~2274.24	Y3-e	40	3.5304	0.275	43.1
		Y3-f	48	4.5865	0.320	41.6
DY4	3625.60~3627.10	Y4-a	24	2.2133	0.174	53.9
	3715.30~3715.40	Y4-b	36	2.4345	0.163	57.6
		Y4-c	48	3.0935	0.195	56.0

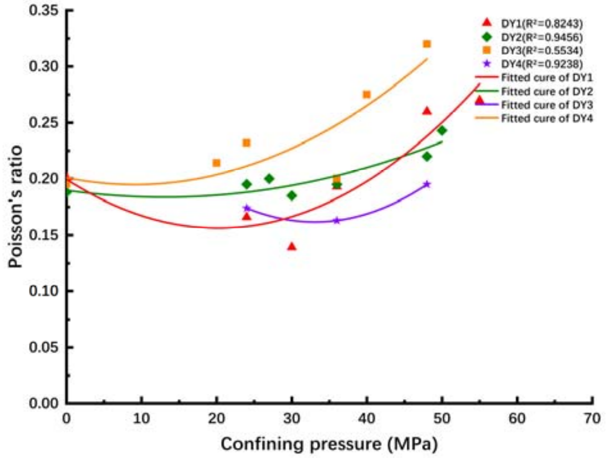

Fig. 6 — Poisson's ratio variation with confining pressure

Comprehensive analysis of shale brittleness

A ternary plot was drawn to depict and compare the mineral composition of the shales from the study area with the shales from the Barnett Formation and some important shale gas-producing regions in China (Fig. 7a). The plot clearly shows that the brittle mineral content of the Wufeng-Longmaxi shales (ranging from 44.2% to 51.6% and averaging 48.0%)is much higher than that of the shales from other regions in China, but it is slightly lower than the

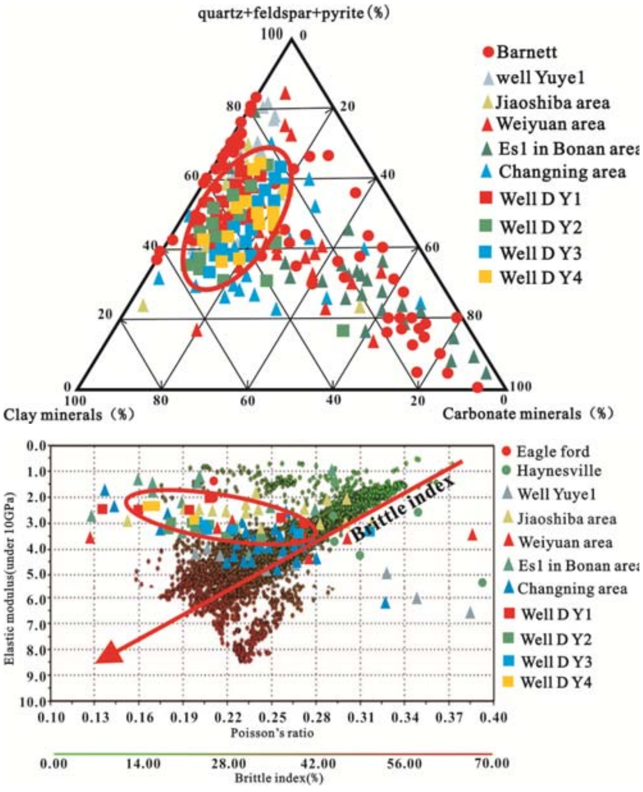

Fig. 7 — Comparisons of (a) mineral composition and (b) elasticity parametersof shales from different regions

Barnett Shale's. The mechanical parameters of the samples from wells DY1-DY4 in the study area were plotted and compared with those of shales from other regions in Fig. 7b. As shown in Fig. 7b, the points located in the left lower area of the diagram indicate high shale brittleness. The BRIT of the shales at wells DY1-DY4varied from 40.7% to 61.6% and averaged 52.6%, generally higher than those of shales from other regions in China.

To further evaluate the fracturability of the shales in the study area, the relationship between TOC and brittle mineral content was analyzed. The results show that the TOC content of the Wufeng-Longmaxi shales in the DS area varied with brittle mineral content and BRIT in similar patterns (Fig. 8).

The TOC content of the shales increased with the brittle mineral content and a strong correlation exists between them (R2=0.7942). When TOC＜50%, the average brittle mineral content of the shales was less than 50%. When TOC＞2%, the average brittle mineral content was greater than 50%. After TOC exceeded 3%, the average brittle mineral content reached above 65%.

The shales' BRIT1 was significantly correlated with TOC (R2=0.8281) and highly dependent on brittle mineral content. When TOC＞3%, the shales' BRIT1values were greater than 60%. When TOC was between 2% and 3%, the BRIT1values varied from 50% to 60%.When TOC＜2%, the BRIT1 values were largely below 50%. In comparison, the correlation between BRIT2 and TOC was relatively weak (R2=0.6134). This is possibly because though the rock's elastic modulus tended to increase with increasing content of brittle minerals overall despite the variation caused by change in burial depth (confining pressure). When TOC＞2%, the BRIT2 values were between 50% and 60%. When TOC＜2%, the BRIT2 values were less than 50%. The analysis can conclude that there are relatively strong correlations among brittle mineral content, BI, and TOC.

Fracturability analysis and application

Previous research has found that shale brittleness is controlled mainly by quartz content, clay content, brittleness, mechanical properties, diagenesis, organic matter content, and naturally occurring gamma radiation. The content of brittle minerals, BRIT and mechanical properties are the main indicators used to determine whether hydraulic fracturing can produce a fracture network or other complex fracture systems in shale formations in order to achieve commercially recoverable gas flow.

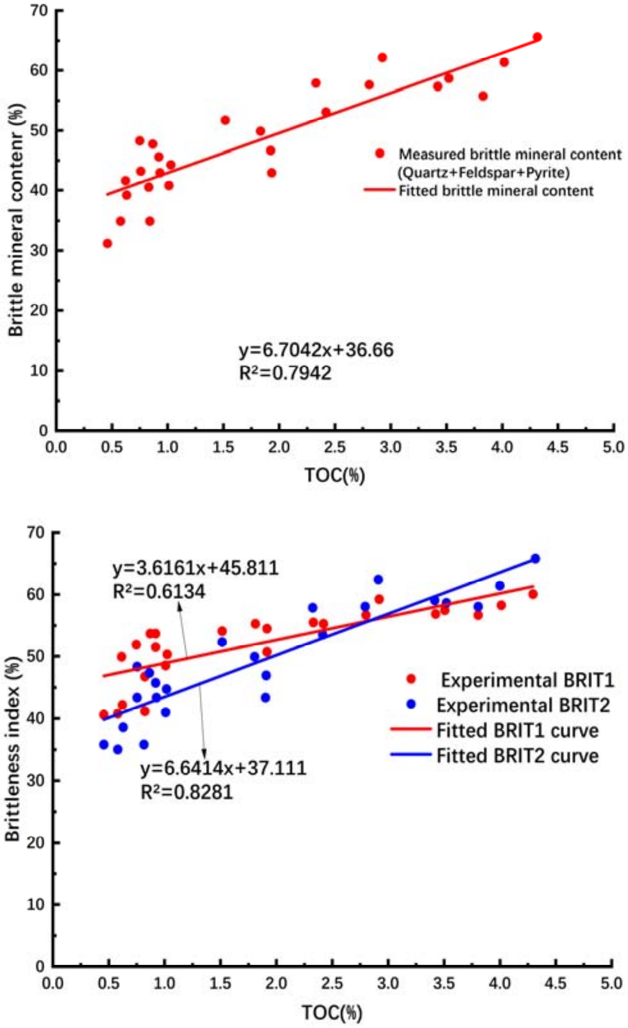

Fig. 8 — Relationships of TOC to brittle mineral content and TOC

The lithology logs of the Wufeng-Longmaxi shales in the DS area reveal that the upper portion of the target formations has relatively high silica content while the lower portion has lower silica content and higher organic carbon content. Therefore, the lower portion is recognized as a zone favorable for occurrence of shale gas reservoirs. The shale samples analyzed in this study were all collected from this zone. As the mineral composition varies vertically across the target formations, and the shales' mechanical properties also vary, it is necessary to use well logs in the brittleness evaluation in order to identify favorable zone more accurately. Data on elasticity parameters(E and μ), brittleness index (BRIT), brittle mineral content (%),naturally occurring gamma radiation (GR), and total organic

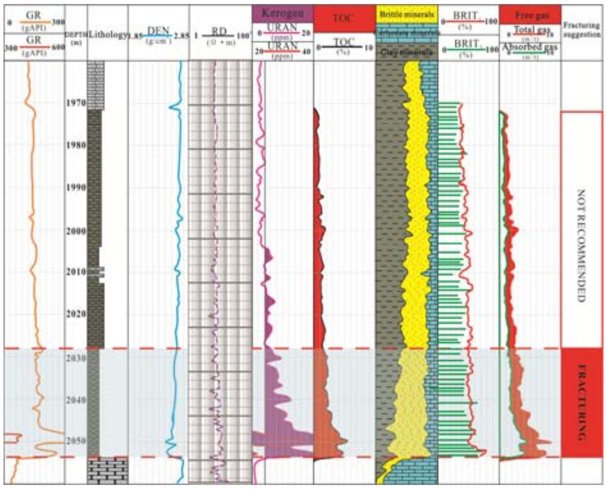

Fig. 9 — Fracturability evaluation of the Wufeng-Longmaxi shales in well DY1 in the DS area (modified from SINOPEC Exploration Southern Company)

content (TOC) can offer a basis for delineating fracturable shale reservoirs [43].

Take for example the Wufeng and Longmaxi Formationsin well DY1, which have proved favorable for accumulation of natural gas. The vertical distribution of shale BRIT across this well was calculated from mineral composition derived from the well logs using the aforementioned calculation method. The index values calculated and other relevant parameters were then analyzed in order to preliminarily delineate the location that is suitable for hydraulic fracturing in this well.

The analysis results reveal that shale gas could occur in the zone at depths of 1972 to 2054.2m in well DY1. The lower part of the Longmaxi Formation and the Wufeng Formation are composed primarily of silty mudstone, mudstone and organic-rich shale and exhibit noticeably high levels of GR and low densities (DEN) in the well logs. The highGR is attributed to the high content of uranium (URAN), which has extremely great absorption capability for gamma radiation. The region with highGR is more than 20 m thick. There is only a weak correlation between electrical resistivity (RD) and GR. Due to the increasing concentrations of organic matter (gas content + kerogen) and carbonate minerals, the RD gradually increases to700Ω·m. The correlation between TOC and gas content is relatively significant. Brittle mineral content steadily increases with increasing burial depth. Quartz content is higher than 40% across the region. The clay content is lower than 30% and tends to decrease with depth. Vertically, the shale brittleness increases with increasing depth overall, peaking at 80% (Fig 9).

The shale brittleness evaluation, combined with a comprehensive analysis of all well logs, demonstrates that the shale at depths of 2027-2054.2m (27.2m thick) in well DY1 is relatively favorable for accumulation of natural gas. The average BRIT value in this zone exceeds 50%, indicating that hydraulic fracturing is applicable to this zone for the purpose of improving production.

Conclusions

Brittleness of the Wufeng-Longmaxi shales in the DS area is controlled mainly by the content of quartz, feldspar, and pyrite. Shales' BRIT calculated based on mineral composition ranged from 36.2% to 62.7%, with an average of 48.6%. The BRIT values were greater than 50% in wells DY3 and DY4.

The BRIT analysis based on mechanical experiment reveals three failure modes of the shales under different confining pressures: splitting, bidirectional shear, and unidirectional shear. The BRIT based on elasticity parameters of the shales was between 40.7% and 61.6%, averaging 52.6%.

Compared to the shales in other important shale gas-producing regions in China and other countries, the Wufeng-Longmaxi shales in the DS area have above-average brittleness from the perspectives of mineral composition and elasticity parameters. Strong correlations exist between brittle mineral content, BRIT, and TOC.

The study finds that shale gas reservoirs are relatively developed in the Wufeng Formation and the lower part of the Longmaxi Formation at well DY1.The zone at depths of 2027-2054.2m（27.2m）is relatively favorable for the accumulation of shale gas. This zone exhibits high naturally occurring gamma radiation (GR), low densities (DEN), high electrical resistivity (RD)， high organic matter content (TOC+kerogen), high gas content (adsorbed and free gas), and high brittleness index (exceeding 50% on average). Therefore, it is reasonable to conclude that this zone can be stimulated by hydraulic fracturing for greater production.

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References

1 Zhou, C.N., Dong, D.C., and Wang, S.J., Geological characteristics, formation mechanism and resourcepotential of shale gas in China. *Petrol Explor Dev*, 37(2010)641-653.

2 Sun, H.C., Tang, D.Z.,Shale Gas Formation Fracture Stimulation in the South Sichuan Basin.*Journal of Jilin University(Earth Science Edition)*, S1(2011)34-39.

3 Yuan, J.L., Deng, J.G., Zhang, D.Y., Li, D.H., Yan, W., Fracability evaluation of shale-gas reservoirs. *Acta Petrol Sin*, 34(2013)523-527.

4 Ren, L., Lin, R., Zhao, J.Z., Simultaneous hydraulic fracturing of ultra-low permeability sandstone reservoirs in China: Mechanism and its field test. *Journal of Central South University*, 22(2015)1427-1436.

5 Zhang,C.C., Wang, Y.M., Dong, D.Z., Li, X.J., Guan, Q.Z., Evaluation of the Wufeng–Longmaxi shale brittleness and prediction of “sweet spotlayers” in the Sichuan Basin. *Natural Gas Industry*, 36(2016)51-60.

6 Jiang, Y.Q., Dong, D.Z., Qi, L., Shen, Y.F., Jiang, C.,He, F.W., Basic characteristics and evaluation of shale gas reservoir. *Natural Gas Industry*, 30(2010)7-12.

7 Wang, P., Ji, Y.L., Pan, R.F., Wang, Z.Z., Wu, Y., A comprehensive evaluation methodology of shale brittleness: A case study from the Lower Silurian LongmaxiFm in Block W, Sichuan Basin. *Natural Gas Industry*, 33(2013)48-53.

8 Xu, G.C., Zhong, G.H., Xie, B., Huang, T.J., Petrophysical experiment-based logging evaluation method of shale brittleness. *Natural Gas Industry*, 34(2014)38-45.

9 Fu, Y.Q., Ma, F.M., Zeng, L.X., She, C.Y., Chen, Y.,Key technology of fracturing test evaluation for shale gas reservoir.*Natural Gas Industry*,31(2011)51-54.

10 Bowker, K.A. Barnett Shale gas production, Fort Worth basin: Issues and discussion. *AAPG Bull*, 91(2007)523-533.

11 Tang, Y., Xing, Y., Li, L.Z., Zhang, H.B., Jiang, S.X.,Influencing factors and evaluation methods of shale reservoir fracturing. *Geosci Front*, 19(2012)356-363.

12 Li, Q.H., Chen, M., Fred, P.W., Jin, Y., Li, Z.M., Jin, Y., Li, Z.M., Effect of engineering factors on shale gas production-Taking Haynesville shale gas reservoir in North America as an example.*Natural Gas Industry*, 32(2012)54-59.

13 Fang, D.Z., Zeng, H., Wang, N., Zhang, Y., Study on high production factors of high-pressure shale gas from HaynesvilleShale Gas development data. *Oil Drilling & Production Technology*, 2 (2015)58-62.

14 Chen, Z., Zeng, Y.J., Present Situations and Prospects of Multi-Stage Fracturing Technology for Deep Shale Gas Development.*Petroleum Drilling Techniques*,1(2016)6-11.

15 Ju, Y.W., Bu, H.L., Wang, G.C., Main characteristics of shale gas reservoir and its influence on reservoir reconstruction.*Adv Earth Sci*, 29(2014)492-506.

16 Yang, H.Y., Analysis of influencing factors on Brittleness of shale reservoir. China University of Geosciences, 2014.

17 Montgomery, S.L., Jarvie, D.M., Bowker, K.A., Pollastro, R.M., Mississippian Barnett Shale, Fort Worth basin, north-central Texas: Gas-shale play with multi–trillion cubic foot potential. *AAPG Bull*, 90(2005)963-966.

18 Mullen M.J., Blauch, M., Rickman, R., Petre, E., Grieser, B., A Practical Use of Shale Petrophysics for Stimulation Design Optimization: All Shale Plays Are Not Clones of the Barnett Shale// SPE Technical Conference and Exhibition. Society of Petroleum Engineers, 2008.

19 Li, Q.H., Chen, M., Jin,Y., Zhou, Y., Rock Mechanical Properties of Shale Gas Reservoir and their Influences on Hydraulic Fracture// International Petroleum Technology Conference. 2013.

20 Zhou, H., Meng, F.Z., Zhang, C.Q., Xu, C.R., Lu, J.J., Quantitative evaluation of rock brittleness based onstress-strain curve.*Chinese Journal of Rock Mechanics and Engineering*,33(2014)1114-1122.

21 Ma, Y.P., Wang, X.L., Li, G., Shi, Z.G., Zhao, D.F., Comprehensive evaluation of brittle shale reservoirs-Taking Sichuan basin five peak group - Longmaxi group as an example.*Journal of Jilin University(Earth Science Edition)*, 2015.

22 Hou, Z.K., Yang, C.H., Wei, X., Wang, L., Wei, Y.L., Xu, F., Wang, H., Experimental study on the brittle characteristics of Longmaxi formation shale.*Journal of China Coal Society*, 41(2016)1188-1196.

23 Jarvie, D.M., Hill, R.J., Ruble, T.E., Pollastro, R.M., Unconventional shale-gas systems: the Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. *AAPG Bull*, 91(2007)475-499.

24 Chen, J., Xiao, X.M.,Mineral composition and brittleness of three sets of Paleozoicorganic-rich shales in China South area. *Journal of China Coal Society*, 38(2013)822-826.

25 Li, J.Y., Mineral composition and brittleness analysis of shale in Dongying depression.Acta Sedimentol Sin, 31(2013)616-620.

26 Hucka, V., Das, B., Brittleness determination of rocks by different methods. *Int J Rock Mech Min*, 11(1974)389-392.

27 Guo, Z., Li, X.Y., Liu, C., Feng, X., Shen, Y., A shale rock physics model for analysis of brittleness index, mineralogy and porosity in the Barnett Shale. *J Geophys Eng*, 10(2013)025006.

28 Diao, H.Y., Rock mechanical properties and brittleness evaluation of shale reservoir. *Acta Petrol Sin*, 29(2013) 344-350.

29 Grieser, W.V., Bray, J.M.,Identification of Production Potential in Unconventional Reservoirs. 2007.

30 Sondergeld, C.H., Newsham, K.E., Comisky, J.T., Rice,M.C., Rai, C.S.,Petrophysical Considerations in Evaluating and Producing Shale Gas Resources// Society of Petroleum Engineers, 2010.

31 Passey, Q.R., Bohacs, K., Esch, W.L., Klimentidis， R., Sinha, S., From Oil-Prone Source Rock to Gas-Producing Shale Reservoir - Geologic and Petrophysical Characterization of Unconventional Shale Gas Reservoirs. Beijing, 2010, 131350.

32 Chen, Y., Huang, T.F.,, Liu, E.R., Rock physic(*University of Science & Technology China Press Anhui Province)*, 2009.

33 Qin, X.Y., WangZ.L., Yu, H.Y., Chen, H., Lei, Y.H., Luo, X.R., Zhang, L.X., Jiang, C.F., Gao, C., A new method for evaluating shale brittleness based on rock physics and mineral composition. *Nat Gas Geosci*, 27(2016)1924-1932.

34 Lawn, B.R., Marshall, D.B., Hardness, Toughness, and Brittleness: An Indentation Analysis. *J Am Ceram Soc*, 62(2010)347-350.

35 Li, Q.H., Chen, M., Jin, Y., Wang, F.P., Experimental research on failure modes and mechanicalbehaviors of gas-

bearing shale. *Chinese Journal of Rock Mechanics and Engineering*, 31(2012)3763-3771.

36 Laban,i M.M., Rezaee, R., The Importance of Geochemical Parameters and Shale Composition on Rock Mechanical Properties of Gas Shale Reservoirs: a Case Study From the Kockatea Shale and Carynginia Formation From the Perth Basin, Western Australia. *Rock Mech Rock Eng*, 48 (2015) 1249-1257.

37 Meng, F., Zhou, H., Zhang, C., R, X., Lv, J., Evaluation Methodology of Brittleness of Rock Based on Post-Peak Stress–Strain Curves. *Rock Mech Rock Eng*, 48(2015)1787-1805.

38 Heng, S., Yang, C.H., Zhang, B.P., Guo, Y.T., Wang, L., Wei, Y.L., Experimental research on anisotropic properties of shale. *Rock and Soil Mechanics*, 36(2015)609-616.

39 Liang, L.X., Zhuang, D.L, Liu, X.J., XiongJ., Study on Mechanical Properties and Failure Modes of Longmaxi Shale. *Chin J Undergr Space Eng*, 13(2017) 108-116.

40 Ding, W.L., Li, C, Li, C.Y., Xu, C.C., Jiu, K., Zeng, W.T, Main controlling factors of shale fracture development and its influence on gas bearing property.*Geosci Front*,19(2012) 212-220.

41 Liu, B., Xi, D.Y., Ge, N.J., Wang, B.S., Anisotropy of Poisson's ratio in rock under different confining pressures. *Chinese Journal of Geophysics*, 45(2002) 880-890.

42 Peng, J., Rong, G., Zhou, C.B., Peng, K., A study of crack closure effect of rocks and its quantitative model. *Rock and Soil Mechanics*, 37(2016)126-132.

43 Sima, L.Q., Wen, D.N., Yan, J.P., Tan, M.L., Deng, H.Y., Fracturing Hierarchy Analysis and Fracturing Height Prediction Method in Shale Reservoirs. *Well Log Technol*, 39(2015)622-627.