Shale Britteness Index Based on the Energy Evolution Theory and Evaluation with Logging Data: A Case Study of the Guandong Block

Yuwei Li,* Lihong Zhou, Dongping Li, Shengchuan Zhang, Fuchun Tian, Zhimei Xie, and Bo Liu

ABSTRACT: Shale brittleness is a key index that indicates the shale fracability, provides a basis for selecting wells and intervals to be fractured, and guarantees the good fracturing effect. The available models are not accurate in evaluating the shale brittleness when considering the confining pressure, and it is necessary to establish a new shale brittleness model under the geo-stress. In this study, the variation of elastic energy, fracture energy, and residual elastic energy in the whole process of rock compression and failure is analyzed based on the stress–strain curve in the experiments, and a shale brittleness index reflecting the energy evolution characteristics during rock failure under different confining pressures is established; a method of directly evaluating the shale brittleness with logging data by combining the rock mechanic experiment results with logging interpretation results is proposed. The calculation results show that the brittleness decreases as the confining pressure increases. When the confining pressure of the Kong-2 member shale of the Guandong block is less than 25 MPa, the brittleness index decreases significantly as the confining pressure increases, and when the confining pressure is greater than 25 MPa, the brittleness index decreases slightly. It is shown that the shale brittleness index is more sensitive to the confining pressure within a certain range and less sensitive to the confining pressure above a certain value.

1. INTRODUCTION

Shale oil and gas are an important unconventional hydrocarbon resource, and their reserves account for more than 50% of the global unconventional hydrocarbon resources. The effective development of shale oil and gas decides the success of unconventional oil and gas development.1–5 The success of shale oil and gas development in the United States shows that hydraulic fracturing is the only effective way in commercial development of shale reservoirs. Fractured shale formations can form a large scale of fracture network, making it easier for oil and gas to flow into the wellbore.6–12 Therefore, fracturing of shale reservoirs is crucial to the shale oil and gas development.13–16

Accurate evaluation of shale reservoir fracability provides a basis for selecting wells and intervals to be fractured and guarantees the high production of oil and gas. The fracability is a comprehensive index integrating the geological conditions and the engineering technology, and the rock brittleness is considered to be the most important index in fracability evaluation.17–20 Previous studies21–23 have shown that the evaluation of rock brittleness is very important for hydraulic fracturing and mining. So, accurate and efficient evaluation of shale brittleness provides a reference for fracturing evaluation of shale reservoirs24,25 and technically guarantees better fracturing effects.

There is no universal definition of the rock brittleness. Some scholars defined the brittleness as the loss of the material plasticity.26,27 Some scholars defined the brittleness as the overall properties of rock materials and the ability to cause local damage and spatial fracture propagation under the interior...
Table 1. Five Types of Methods for Evaluating the Shale Brittleness

| types          | equation | notation | disadvantage                                                                 | overview                                                                 |
|----------------|----------|----------|------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| mineral components | $B_1 = \frac{W_q}{W_i}$ | $W_q$ is the weight of the quartz mineral, $W_i$ is the weight of the carbonate mineral, $W_{i}$ is the weight of the dolomite, $W_{i}$ is the weight of the feldspar, and $W_{i}$ is the weight of the total mineral. | The effect of stress conditions is not considered; there is no uniform standard for determining the weight of each brittle mineral. | Mineral composition has a significant effect on the mechanical properties of rock materials. Among the existing brittleness evaluation methods, the mineral composition method is classified as qualitative analysis. The more brittle minerals indicate a higher brittleness index. |
| stress–strain curve | $B_2 = \frac{(W_q + W_i)/W_i}{W_{i}}$ | $W_q$ and $W_i$ are the peak stress and the residual stress, MPa, respectively; $\epsilon_q$ and $\epsilon_i$ are the peak strain and the residual strain, respectively; and $K_e$ is the slope of the postpeak curve. | Only consider the influence of the state of the prepeak and postpeak stress–strain curves, and the rock brittleness is applicable in a certain stage of stress failure. | The stress–strain curve directly reflects the rock mechanical behavior and reflects the process from rock deformation and damage to the ultimate loss of bearing capacity under the influence of external loads. The rock brittleness is reflected by different indexes at different stages of the stress–strain curve. |
| elastic parameters | $B_3 = \frac{E_{\max} - E_{\min}}{\rho}$ | $E_{\max}$ and $E_{\min}$ are the maximum and minimum of the elastic modulus within the statistical range, respectively; $\rho_{\text{max}}$ and $\rho_{\text{min}}$ are the maximum and minimum of Poisson’s ratio within the statistical range; and $\rho$ is the rock density, g/cm$^3$. | Ignore the effects of rock failure peak characteristics and the effects of stress conditions. | The brittleness is characterized by the elastic modulus, Poisson’s ratio, and the relationship between them. Young’s modulus reflects the ability of the rock to maintain fracture morphology after fracturing, and Poisson’s ratio reflects the ability of the rock to fracture after compression. Higher Young’s modulus and lower Poisson’s ratio indicate a more brittle shale. |
| modulus parameters | $B_{15} = 1 - \exp\left(\frac{1}{M}\right)$ | $E$ is the elastic modulus, and $M$ is the postpeak modulus. | Ignore the effect of stress conditions, and the evaluation parameters are few and relatively simple. | Use the stress–strain curve to obtain the elastic modulus and the postpeak modulus and propose the brittleness evaluation index with the relationship between them. |
| strength parameters | $B_{16} = \frac{\sigma}{\sigma_i}$ | $\sigma_i$ is the compressive strength, and $\sigma_i$ is the tensile strength, MPa. | Not applicable in the complex stress states, and pure strength parameters cause large error. | Obtain the rock compressive strength, tensile strength, and other strength parameters by experiments and use the ratio of the compressive strength to the tensile strength to characterize the rock brittleness. The higher ratio indicates a more brittle shale. |

**Notes:**

- $E$ is Young’s modulus, MPa; $\nu$ is Poisson’s ratio, dimensionless; $E_0$ is the normalized elastic modulus; $\nu_0$ is the normalized Poisson’s ratio; $E_{\max}$ and $E_{\min}$ are the maximum and minimum of the elastic modulus within the statistical range, respectively; $\rho_{\text{max}}$ and $\rho_{\text{min}}$ are the maximum and minimum of Poisson’s ratio within the statistical range; and $\rho$ is the rock density, g/cm$^3$. 

- $c$ and $t$ are the peak stress and the residual stress, MPa, respectively; $\epsilon_q$ and $\epsilon_i$ are the peak strain and the residual strain, respectively; and $K_e$ is the slope of the postpeak curve.

- $f$ is the weight of the feldspar, and $t$ is the weight of the total mineral. 

- $q$ is the weight of the quartz mineral, $W$ is the weight of the dolomite, $W_i$ is the weight of the feldspar, and $W_{i}$ is the weight of the total mineral.

- $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ are the maximum and minimum of the elastic modulus within the statistical range, respectively; $\rho_{\text{max}}$ and $\rho_{\text{min}}$ are the maximum and minimum of Poisson’s ratio within the statistical range; and $\rho$ is the rock density, g/cm$^3$. 

- $c$ and $t$ are the peak stress and the residual stress, MPa, respectively; $\epsilon_q$ and $\epsilon_i$ are the peak strain and the residual strain, respectively; and $K_e$ is the slope of the postpeak curve.

- $f$ is the weight of the feldspar, and $t$ is the weight of the total mineral. 

- $q$ is the weight of the quartz mineral, $W$ is the weight of the dolomite, $W_i$ is the weight of the feldspar, and $W_{i}$ is the weight of the total mineral.
unevenly distributed stress, and it is caused by the rock heterogeneity. Some scholars presented that the brittleness is the phenomenon that the fracture termination stress is slightly higher than the yield stress. Although no consensus has been reached on the definition of brittleness, they all suggest that the high brittleness rock is immediately destroyed under low strain, and the failure is dominated by fractures with the high ratio of tensile strength to compressive strength, large internal friction angle, and so forth.

Currently, there are more than 40 methods for evaluating the rock brittleness, and five types of methods are applicable in shale brittleness evaluation, as shown in Table 1.

According to Table 1, the stress conditions of the formation rock, i.e., the effect of the confining pressure on the rock brittleness are not considered in the available brittleness evaluation methods, and this is infeasible. In fact, as the confining pressure increases, the rock plasticity is enhanced, the brittleness decreases, and the corresponding brittleness indexes decrease monotonically. The available brittleness evaluation indexes cannot reflect the effect of the confining pressure. In addition, each brittleness index leads to different evaluation results, and there are different problems in different brittleness indexes of the same type of method, and even the same method leads to great differences in evaluation of different rocks. Thus, a theoretical model that accurately evaluates the variation of the shale brittleness under the geo-stress is needed in selecting wells and intervals to be fractured in the shale reservoirs.

2. RESULTS AND DISCUSSION

2.1. Analysis of Applicability of Existing Brittleness Indexes. The effects of the confining pressure on brittleness in available models are illustrated by results of experiments with the cores from the Kong-2 member shale of the Guandong block in Dagang Oilfield. The shale mineral composition data and rock mechanics parameters for calculating the brittleness indexes are shown in Tables 2 and 3.

### Table 2. Mineral Compositions of Cores of the Kong-2 Member Shale

| depth (m)     | 3010.5 | 3211.2 | 3353.5 |
|---------------|--------|--------|--------|
| quartz        | 35     | 25     | 37     |
| carbonate minerals | 8  | 11     |
| calcite       | 10     | 3      |
| zeolite       | 3      | 2      |
| montmorillonite | 14 | 37     |
| illite        | 9      | 9      | 10     |
| feldspar      | 5      | 6      |        |
| potash feldspar | 15 | 26     |
| plagioclase   |        |        | 29     |

A TAW-2000 microcomputer servo rock triaxial testing machine with a stiffness of 30 MN/mm and a loading capacity of 2500 kN is adopted as the experimental apparatus. It can directly measure the failure strength, elastic modulus, Poisson’s ratio, and other parameters of shale samples, as shown in Figure 1.

At the beginning of the test, the loading mode of axial strain control is adopted. When the specimen displays obvious circumferential deformation, the load mode is changed to circumferential strain control. The suggested circumferential strain rate is $10^{-6}$ strain/s. In this study, the specimen size is Φ25 mm × 50 mm. The strain gauge should be installed at both ends of the cylindrical specimen as far as possible. From the experimental tests, the failure forms of some samples are recorded and shown in Figure 2.

### Table 3. Experimental Results of Mechanical Parameters of Cores of the Kong-2 Member Shale

| core number | 13-1-1  | 13-1-2  | 13-1-3  | 13-1-4  |
|-------------|---------|---------|---------|---------|
| confining pressure (MPa) | 5       | 15      | 25      | 35      |
| density (g/cm³)          | 2.25    | 2.28    | 2.24    | 2.27    |
| peak intensity (MPa)     | 87.15   | 120.99  | 139.1   | 165.41  |
| elastic modulus (MPa)    | 11,460  | 14,200  | 14,590  | 15,080  |
| Poisson’s ratio          | 0.307   | 0.349   | 0.341   | 0.316   |
| peak strain              | 0.0086  | 0.0108  | 0.0145  | 0.0150  |
| peak stress (MPa)        | 87.15   | 120.99  | 139.10  | 165.41  |
| yield stress (MPa)       | 54.0    | 63.0    | 72.0    | 81.2    |
| yield strain             | 0.0048  | 0.0046  | 0.0052  | 0.0053  |
| residual strain          | 0.0104  | 0.0130  | 0.0180  | 0.0230  |
| residual stress (MPa)    | 57.5    | 68.0    | 85.0    | 117.0   |

![Figure 1. TAW-2000 microcomputer servo rock triaxial testing machine.](image1.png)

![Figure 2. Failure forms of different shale samples under triaxial compression](image2.png)

calculated based on the mineral composition decrease first and then increase as the depth increases. In fact, the brittleness index based on the mineral composition is not directly related to the core depth or the confining pressure, and it only depends on the brittle mineral components. Thus, this type of evaluation index fails to reflect the effect of confining pressure on rock brittleness.

Figure 3. Variation of the shale brittleness indexes $B_1$–$B_4$ with the well depth based on mineral compositions. (a) Calculation results of brittleness index $B_1$, (b) Calculation results of brittleness index $B_2$, (c) Calculation results of brittleness index $B_3$, (d) Calculation results of brittleness index $B_4$.

Figure 4. Variation of brittleness indexes $B_5$–$B_7$ based on the stress–strain curve with the confining pressure. (a) Calculation results of brittleness index $B_5$, (b) Calculation results of brittleness index $B_6$, (c) Calculation results of brittleness index $B_7$. 
2.1.2. Results of Brittleness Evaluation Based on the Stress–Strain Curve. The brittleness indexes under different confining pressures were calculated with $B_5 - B_7$ in Table 1, as shown in Figure 4. According to Figure 4a–c, the brittleness indexes $B_5 - B_7$ increase first and then decrease as the confining pressure increases, and it reaches the maximum and minimum value under the confining pressures of 15 and 35 MPa, respectively. This is not consistent with the law that the rock brittleness decreases monotonically as the confining pressure increases.

Figure 5. Variation of brittleness indexes $B_8 - B_{11}$ based on elastic parameters with the confining pressure (a) Calculation results of brittleness index $B_8$. (b) Calculation results of brittleness index $B_9$. (c) Calculation results of brittleness index $B_{10}$. (d) Calculation results of brittleness index $B_{11}$.

Figure 6. Variation of brittleness indexes $B_{12} - B_{14}$ based on modulus parameters with the confining pressure (a) Calculation results of brittleness index $B_{12}$. (b) Calculation results of brittleness index $B_{13}$. (c) Calculation results of brittleness index $B_{14}$. 
2.1.3. Brittleness Evaluation Results Based on Elastic Parameters. The brittleness indexes under different confining pressures calculated by the elastic parameter method in Table 1 are shown in Figure 5. According to Figure 5a−d, the brittleness indexes \( B_8, B_{10}, \) and \( B_{11} \) all increase as the confining pressure increases, indicating that the brittleness increases as the confining pressure increases. This contradicts the actual situation. As the confining pressure increases, \( B_9 \) decreases first and then increases. \( B_9 \) does not vary monotonically, which contradicts the law that the rock brittleness decreases monotonically as the confining pressure increases.

2.1.4. Results of Brittleness Evaluation Based on Modulus Parameters. Calculated by the modulus parameter method in Table 1, the brittleness indexes under different confining pressures are shown in Figure 6. According to Figure 6a−c, as the confining pressure increases, \( B_{12} \) and \( B_{13} \) decrease first and then increase, and \( B_{14} \) increases first and then decreases. All brittleness indexes calculated with the above methods do not vary monotonically, which contradicts the law that the rock brittleness decreases monotonically as the confining pressure increases.

2.1.5. Results of Brittleness Evaluation Based on Strength Parameters. Calculated by the strength parameter method in Table 1, the brittleness indexes of the rock under different confining pressures are shown in Figure 7. According to Figure 7a−d, \( B_{15}−B_{18} \) increase as the confining pressure increases, indicating that the rock brittleness increases as the confining pressure increases, which also contradicts the law that the rock brittleness decreases as the confining pressure increases.

Above examples show that the available brittleness indexes cannot be used to evaluate the shale brittleness when considering the effect of confining pressure and even contradict the objective laws. Therefore, it is necessary to establish a new shale brittleness model applicable in the formation under the confining pressure.

2.2. Establishment of a Rock Brittleness Index Based on Energy Evolution Characteristics. Rock failure is the process from energy accumulation to energy dissipation and release and can be manifested by the complete stress−strain curve (Figures 8 and 9). The rock continuously absorbs the outside energy before the curve peak and releases energy to the outside after the curve peak.\(^{45−49}\) If rocks show the different

![Figure 8. Prepeak energy distribution of the stress−strain curve.](image)

![Figure 9. Postpeak energy distribution of the stress−strain curve.](image)
brittleness characteristics, there are significant differences in energy evolution during the failure process. The rock brittleness is evaluated based on the energy evolution characteristics in the entire process of rock deformation and failure.

2.2.1. Establishment of the Prepeak Brittleness Index. If the rock shows the absolute brittleness, the prepeak elastic energy on the stress—strain curve is shown in the triangle area \( S_{ABC} \) in Figure 8, and the yield modulus \( D \) equals the elastic modulus \( E \); plastic deformation does not occur. Actually, the rock is not completely brittle, and there is a plastic yielding stage in the deformation process. A part of the energy is dissipated before the peak. Before the curve reaches its peak, the greater elastic energy \( W_\text{el} \) stored during compression indicates the stronger rock brittleness, which is closer to the ideal brittleness. The ratio of the elastic energy stored in the rock compression process to the elastic energy under ideal conditions is used to characterize the prepeak brittleness, and the higher ratio indicates the stronger brittleness. Thus, by obtaining the corresponding area of the stress—strain curve, we have

\[
W_\text{el} = S_{ABC} = \frac{1}{2} \times AC \times BC = \frac{1}{2} \times \sigma_B \times \varepsilon_B = \frac{\sigma_B^2}{2E} \tag{1}
\]

\[
W_\text{el} = S_{ONC} = \frac{1}{2} \times OC \times CN = \frac{1}{2} \times \varepsilon_B \times E \varepsilon_B = \frac{1}{2} E \varepsilon_B^2 \tag{2}
\]

The prepeak brittleness index \( B_\text{pre} \) is defined as

\[
B_\text{pre} = \frac{W_\text{el}}{W_\text{et}} = \frac{\sigma_B^2}{E^2 \varepsilon_B^2} \tag{3}
\]

where \( W_\text{el} \) is the elastic energy actually stored in the rock under the load, \( J_B \); \( W_\text{et} \) is the elastic energy of the ideal brittle rock under the load, \( J_B \); \( B_\text{pre} \) is the prepeak brittleness index, dimensionless; \( \sigma_B \) is the peak strength of the stress—strain curve, MPa; \( E \) is the elastic modulus, MPa; \( \varepsilon_B \) is the peak strain of the stress—strain curve, dimensionless.

2.2.2. Establishment of the Postpeak Brittleness Index. As shown in Figure 9, the \( S_{ABDE} \) area is the prepeak dissipipated energy \( W_\text{et} \), the \( S_{ABDE} \) area is the rock fracture energy \( W_f \) during fracturing, the \( S_{CBDF} \) area is the continuously loaded energy \( W_\text{et} \) during failure, and the \( S_{SEDF} \) area is the residual elastic energy \( W_{\text{ef}} \) inside the rock when the rock strength drops to the residual strength \( \sigma_C \).

The slope of the line between the peak stress \( \sigma_B \) and the residual stress \( \sigma_C \) is defined as the postpeak modulus \( M \), which reflects the speed of rock failure after the stress reaches its peak.\(^{27} \) The negative postpeak modulus means that the elastic energy accumulated in the rock is not sufficient to support the whole fracturing process, and additional energy \( W_\text{et} \) is loaded to continue rock failure. The more energy provided outside indicates the weaker ability to complete the fracture by the elastic energy accumulated in the rock and the poorer brittleness.\(^{24,50} \) Therefore, the ratio of the energy \( W_f \) provided outside to the fracture energy \( W_f \) during rock fracturing is used to characterize the postpeak brittleness of the rock. The higher ratio indicates the stronger brittleness. The fracture energy \( W_f \) for rock fracture is expressed as

\[
W_f = W_\text{el} + W_\text{a} - W_{\text{ef}} \tag{4}
\]

The energy \( W_\text{a} \) provided outside and the residual elastic energy \( W_{\text{ef}} \) are expressed as

\[
W_\text{a} = \frac{\sigma_B^2 - \sigma_C^2}{-2M} \tag{5}
\]

\[
W_{\text{ef}} = \frac{\sigma_C^2}{2E} \tag{6}
\]

According to eqs 1, 4, 5, and 6, we have

\[
W_f = \frac{\sigma_B^2 - \sigma_C^2}{2EM} \tag{7}
\]

The equation of the postpeak index \( B_\text{post} \) is

\[
B_\text{post} = \frac{W_\text{a}}{W_f} = \frac{\sigma_B^2(E - M)}{E^3 \varepsilon_f^2} \tag{8}
\]

where \( \sigma_C \) is the residual strength of the stress—strain curve, MPa, and \( M \) is the postpeak modulus of the stress—strain curve, MPa.

2.2.3. Establishment of a Comprehensive Brittleness Index. The higher prepeak brittleness index \( B_\text{pre} \) and the lower postpeak brittleness index \( B_\text{post} \) lead to the stronger brittleness. The brittleness index in the whole fracturing process is obtained by taking the reciprocal of the postpeak brittleness index \( B_\text{post} \)

\[
B = B_\text{pre} \times \frac{1}{B_\text{post}} = \frac{\sigma_B^2(E - M)}{E^3 \varepsilon_f^2} \tag{9}
\]

The higher brittleness index calculated by eq 9 indicates the stronger rock brittleness, and the calculation results reflect brittleness variation in the whole fracturing process. The new model is verified in following examples.

2.3. Method of Calculating Rock Brittleness Using Well Logging Data. In this study, a new model of rock brittleness is established based on the energy evolution characteristics in the rock failure process, and several rock mechanical experiments are needed to obtain the elastic modulus \( E \), the peak strength \( \sigma_B \), the peak strain \( \varepsilon_B \), and the postpeak modulus \( M \).\(^{43,54} \) If some mechanical parameters have been obtained in experiments, evaluating the brittleness with easily accessed logging data is feasible, thereby reducing the workload. How to obtain the parameters in brittleness evaluation and calculate the brittleness indexes by logging data are illustrated as follows.

2.3.1. Acquisition of Parameters in Brittleness Evaluation. 2.3.1.1. Elastic Modulus \( E \). The equations of calculating the dynamic elastic modulus and the dynamic Poisson’s ratio of rocks are as follows\(^{43-45} \)

\[
E_d = \frac{\rho_d}{\Delta t_s^2} \times 3 \Delta t_s^2 - 4 \Delta t_p^2 \times 9.299 \times 10^7 \tag{10}
\]

\[
u_d = \frac{1}{2} \Delta t_s^2 - 2 \Delta t_p^2 \tag{11}
\]

where \( E_d \) is the dynamic Young’s modulus of the rock, MPa; \( \rho_d \) is the rock density, \( \text{g/cm}^3 \); \( \nu_d \) is the dynamic Poisson’s ratio of the rock, dimensionless; and \( \Delta t_s \) is the time difference of the shear wave, \( \mu s/ft \).

If only the P wave time difference is available, the S wave time difference can be obtained by eq 12\(^{54} \)

\[
\Delta t_s = \frac{\rho_d \Delta t_p^2}{X \Delta t_p^2 + Y \rho_d + Z} \tag{12}
\]
Table 4. Conversion Coefficient of Dynamic and Static Parameters of the Elastic Modulus and Poisson’s Ratio of the Kong-2 Member Cores of the Guandong Block of Dagang Oilfield

| confining pressure (MPa) | a     | b    | R²  | c     | d     | R²  |
|-------------------------|-------|------|-----|-------|-------|-----|
| 5                       | 1.4805| –16.309| 0.8367 | 2.5507 | –0.1434 | 0.7978 |
| 15                      | 2.1888| –31.322 | 0.8152 | 1.8757 | –0.0268 | 0.7247 |
| 25                      | 1.2864| –12.672 | 0.8902 | 2.9586 | –0.2171 | 0.7867 |
| 35                      | 1.722 | –20.852 | 0.8053 | 3.9286 | –0.3689 | 0.8419 |

where X, Y, and Z are conversion coefficients, which are different in different regions, and X = 0.0077, Y = 73.58, and Z = –102.298 in our study area.

The static Young’s modulus and static Poisson’s ratio (referred to as elastic modulus and Poisson’s ratio for short) are used in calculating the rock brittleness. There is a linear relationship between dynamic and static values of Young’s modulus and Poisson’s ratio56,57

\[
E = aE_d + b
\]  

(13) where \(E\) is the elastic modulus, MPa; \(\nu\) is Poisson’s ratio, dimensionless; \(a\), \(b\), \(c\), and \(d\) are constants, which are obtained by regression of dynamic and static parameters from rock mechanic experiments in different areas.

According to the experiment results of the Kong-2 member cores from the cored wells in the Guandong block of Dagang Oilfield, the correlation coefficients in the conversion formula of dynamic and static parameters of the elastic modulus and Poisson’s ratio under different confining pressures are obtained, as shown in Table 4:

2.3.1.2. Peak Strength \(\sigma_f\). The shale content is obtained by gamma logging, and the peak strength of rocks is calculated with the following equation55

\[
\sigma_f = (0.0045 + 0.0035V_{sh})E_d
\]  

(15) where \(\sigma_f\) is the peak strength, MPa; and \(V_{sh}\) is the shale content, dimensionless.

The equation of calculating the shale content based on the logging data is

\[
\begin{align*}
V_{sh} &= \frac{G_{CUR}SH - 1}{2G_{CUR} - 1} \\
SH &= \frac{GR - GR_{min}}{GR_{max} - GR_{min}}
\end{align*}
\]  

(16)

where \(G_{CUR}\) is the empirical coefficient related to the formation age, and it is 3.7 in the new formation and 2.0 in the old formation;55 \(SH\) is the relative value of natural gamma; \(GR\) is the natural gamma logging value of the target layer; \(GR_{min}\) is the natural log value of pure lithology formation; and \(GR_{max}\) is the natural gamma log value of pure mudstone formation.

2.3.1.3. Peak Strain \(\varepsilon_p\). The peak strain is not directly calculated with the logging data. The peak strain corresponds to the strain when the rock reaches the peak strength during fracturing. Poisson’s ratio is the ratio of the radial strain to the axial strain.58–40 The peak strength reflects the axial deformation capacity of the rock in a certain degree.7 There is a correlation between the peak strain and strength and Poisson’s ratio:

\[
\varepsilon_p = f(\sigma_f, \nu)
\]  

(17) Through statistical analysis of the mechanics data of the Kong-2 member cores in the Guandong block of Dagang Oilfield, the functional relation between the peak strain \(\varepsilon_p\) and \(\sigma_f\) and \(\nu\) under different confining pressures is obtained, as shown in Table 5:

Table 5. Fitted Relationship between the Peak Strain and Strength and Poisson’s Ratio

| confining pressure (MPa) | fit the relation | correlation coefficient |
|-------------------------|-----------------|-------------------------|
| 5                       | \(\varepsilon_p = 0.014(\sigma_f^{0.25}\nu^{0.2}) + 0.0045\) | \(R^2 = 0.7126\) |
| 15                      | \(\varepsilon_p = 0.0306(\sigma_f^{0.25}\nu^{0.2}) + 0.0029\) | \(R^2 = 0.9606\) |
| 25                      | \(\varepsilon_p = 0.0255(\sigma_f^{0.25}\nu^{0.2}) + 0.0046\) | \(R^2 = 0.8484\) |
| 35                      | \(\varepsilon_p = 0.0301(\sigma_f^{0.25}\nu^{0.2}) + 0.0064\) | \(R^2 = 0.7121\) |

According to Table 5, the peak strain \(\varepsilon_p\) is proportional to \(\sigma_f^{0.25}\nu^{0.2}\) with a strong correlation. The higher value of \(\sigma_f^{0.25}\nu^{0.2}\) corresponds to the higher \(\varepsilon_p\).

2.3.1.4. Postpeak Modulus \(M\). During rock failure, the elastic modulus, Poisson’s ratio, peak strength, and peak strain all have a certain effect on the postpeak modulus of the rock. The multiple regression method is used to obtain the relation between the postpeak modulus, the elastic modulus, and Poisson’s ratio:

\[
M = f(E, \nu, \sigma_f, \varepsilon_p)
\]  

(18) Through statistical analysis of the mechanic experimental data of the Kong-2 member cores in the Guandong block of Dagang Oilfield, the functional relation between the postpeak modulus \(M\), the elastic modulus, and Poisson’s ratio under different confining pressures is obtained, as shown in Table 6:

According to Table 6, there is a certain functional relation between the postpeak modulus \(M\), elastic modulus \(E\), Poisson’s ratio \(\nu\), peak strength \(\sigma_f\), and peak strain \(\varepsilon_p\) with a good correlation. The higher \(E\) and \(\sigma_f^{0.25}\nu^{0.2}\) and lower \(\varepsilon_p\) correspond to lower \(M\).

2.3.2. Examples of Calculating Rock Britteness Using Logging Data. The cores were collected from the Guandong block of Dagang Oilfield. Logging data (P wave time difference, rock density, shale content, etc.) of 28 shale cores under different confining pressures are shown in Table 7.

The elastic modulus \(E\), peak strength \(\sigma_f\), and postpeak modulus \(M\) used in calculating the comprehensive brittleness indexes are obtained by using the method in Section 2.3 and applying the logging data in Table 7. The mechanical parameter data from the laboratory’s test are listed in Table 8.

The comprehensive brittleness indexes of different shale cores under different confining pressures were calculated with eq 9 based on the logging data in Table 7 and the core mechanic experiment data in Table 8, respectively \((B\) is the comprehensive brittleness index calculated with the experimental data, \(B^*\) is that calculated with the logging data, \(B_{13}\) is that calculated with the modulus parameters model in Table 1), as shown in Figures 10–13.
It can be clearly seen that the brittleness index calculated by the depth and diﬀerent confining pressures. For cores at the same depth and diﬀerent confining pressures, the brittleness index $B'$ calculated with the logging data and the brittleness index $B$ calculated directly with experimental data show the same trend and the similar results, which indicates that directly calculating the rock brittleness using logging data with the method proposed in this study is feasible. Moreover, in order to illustrate the rationality of the model in this paper, we also add a comparison with the calculation results of model $B_{13}$ in Table 1. It can be clearly seen that the brittleness index calculated by the existing model $B_{13}$ does not show a monotonically decreasing trend with the increase in confining pressure.

In addition, according to Figures 10–13, the calculation results of the brittleness index based on the energy evolution in the entire process of rock failure are in line with the law that the

![Figure 10](https://dx.doi.org/10.1021/acsomega.0c01140)

**Figure 10.** Variation of comprehensive brittleness index of cores X-25, X-215, X-225, and X-235.
brittleness decreases monotonically and continuously as the confining pressure increases. According to the calculation results of comprehensive brittleness index $B$ (Figures 10–13), when the confining pressure is less than 25 MPa, the brittleness index reduction gradients are 0.022/MPa, 0.038/MPa, 0.0205/MPa, and 0.024/MPa, respectively, and when the confining pressure is greater than 25 MPa, the brittleness index reduction gradients are respectively 0.006/MPa, 0.01/MPa, 0.017/MPa, and 0.005/MPa, respectively. When the confining pressure is less than 25 MPa, the brittleness index decreases significantly as the confining pressure increases. When the confining pressure is greater than 25 MPa, the brittleness index decreases slightly as the confining pressure increases, and the curve becomes flat, indicating that the brittleness index is more sensitive to the confining pressure within a certain range and less sensitive to variation of confining pressure when the confining pressure increases to a certain value.

2.4. Discussion. In this study, a new shale brittleness index is established based on the energy evolution characteristics in the entire process of rock compression and failure. The new model reflects the effect of confining pressure on shale brittleness, which is not realized in the previous models. The model was verified with examples of shale brittleness evaluation of the Kong-2 member of the Guandong block in Dagang Oilfield, and the method of directly evaluating shale brittleness using logging data proposed in this study is feasible. The method in this study significantly reduces the experimental and calculation workload and improves efficiency in brittleness evaluation. In practice, we have conducted rock mechanic tests on many wells in a block, and it has the necessary conditions for shale brittleness evaluation. When we need to evaluate the shale brittleness of other wells in the same block, we can directly calculate the shale brittleness by using well logging data. It is no longer necessary to carry out rock mechanic experiments unlike current existing evaluation methods, which require repeated experiments. Therefore, the method in this paper greatly reduces the workload, and the evaluation speed is high. However, the model still needs to be improved. For example, calculation of the brittleness index with logging data need a large number of mechanical experiment results, and there is no theoretical support for acquisition of the peak strain $\varepsilon_p$ and the postpeak modulus $M$. Although the model has a high accuracy in this study, more research is needed to verify whether it is applicable in other blocks. So, there are still many technical problems to be solved in the future research.

3. CONCLUSIONS

(1) This paper establishes a new model reflecting the shale brittleness index under confining pressure and proposes a method for calculating shale brittleness using logging data.

(2) The calculated results of the brittleness index based on the energy evolution characteristics in the entire process of rock failure are in line with the law that the brittleness decreases as the confining pressure increases. The model in this paper is applicable in evaluation of shale brittleness and provides support for selecting wells and intervals to be fractured.

(3) For the Kong-2 member shale of the Guandong block, as the confining pressure increases, the brittleness index decreases significantly when the confining pressure is less than 25 MPa, and the brittleness index decreases slightly when the confining pressure is greater than 25 MPa.

■ AUTHOR INFORMATION

Corresponding Author
Yuwei Li — Engineering and Technology Research Institute, PetroChina Dagang Oilfield Company, Tianjin 300280, China; Institute of Unconventional Oil and Gas, Northeast Petroleum University, Daqing 163318, China; orcid.org/0000-0003-2127-9699; Email: 57868283@qq.com

Authors
Lihong Zhou — Engineering and Technology Research Institute, PetroChina Dagang Oilfield Company, Tianjin 300280, China
Dongping Li — Engineering and Technology Research Institute, PetroChina Dagang Oilfield Company, Tianjin 300280, China
Shengchuan Zhang — Engineering and Technology Research Institute, PetroChina Dagang Oilfield Company, Tianjin 300280, China
Fuchun Tian — Engineering and Technology Research Institute, PetroChina Dagang Oilfield Company, Tianjin 300280, China
Zhimei Xie — Institute of Unconventional Oil and Gas, Northeast Petroleum University, Daqing 163318, China
Bo Liu — Institute of Unconventional Oil and Gas, Northeast Petroleum University, Daqing 163318, China

https://dx.doi.org/10.1021/acsomega.0c01140
ACS Omega 2020, 5, 13164−13175
Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c01140

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS
This research was supported by the China Postdoctoral Science Foundation-funded project (2018 M640289), Natural Science Foundation of Heilongjiang Province of China (YQ2019E007), and Natural Science Foundation of China (41472125 and 51574088).

■ NOMENCLATURE

\[ W_q \] the weight of the quartz mineral

\[ W_c \] the weight of the carbonate mineral

\[ W_d \] the weight of the dolomite

\[ W_f \] the weight of the feldspar

\[ W_t \] the weight of the total mineral

\[ \sigma_p \] the peak stress

\[ \sigma_r \] the residual stress

\[ \varepsilon_p \] the peak strain

\[ \varepsilon_r \] the residual strain

\[ K_{ac} \] the slope of the postpeak curve

\[ E \] elastic modulus, MPa

\[ \nu \] Poisson’s ratio, dimensionless

\[ E_B \] the normalized elastic modulus

\[ \nu_B \] normalized Poisson’s ratio

\[ E_{max} \] maximum of the elastic modulus within the statistical range

\[ E_{min} \] minimum of the elastic modulus within the statistical range

\[ \nu_{max} \] maximum of Poisson’s ratio within the statistical range

\[ \nu_{min} \] minimum of Poisson’s ratio within the statistical range

\[ \rho \] the rock density

\[ M \] the postpeak modulus

\[ \sigma_c \] the compressive strength

\[ \sigma_t \] the tensile strength

\[ B_{pre} \] the prepeak brittleness index

\[ W_{eh} \] the elastic energy actually stored in the rock under the load

\[ W_{at} \] the elastic energy of the ideal brittle rock under the load

\[ E_d \] the dynamic Young’s modulus of the rock

\[ \nu_d \] the dynamic Poisson’s ratio of the rock

\[ \Delta_t \] the time difference of the shear wave

\[ X \] conversion coefficients, in our study area, \[ X = 0.0077 \]

\[ Y \] conversion coefficients, in our study area, \[ Y = 73.58 \]

\[ Z \] conversion coefficients, in our study area, \[ Z = -102.298 \]

\[ V_{sh} \] the shale content, dimensionless

\[ G_{CUR} \] the empirical coefficient related to the formation age

\[ SH \] the relative value of natural gamma

\[ G_{RM} \] the natural gamma log value of pure mudstone formation

\[ B \] the comprehensive brittleness index calculated with the empirical data

\[ B' \] the comprehensive brittleness index calculated with the logging data

\[ B_{13} \] the comprehensive brittleness index calculated with the Modulus parameters model

■ REFERENCES

(1) Wang, Q.; Li, R. Natural gas from shale formation: a research profile. Renew. Sust. Energy Rev. 2016, 57, 1–6.

(2) Mao, S.; Shang, Z.; Chun, S.; Li, J.; Wu, K. An efficient three-dimensional multiphase particle-in-cell model for proppant transport in the field scale. In: Unconventional Resources Technology Conference; AAPG Datapages Inc.: Denver, Colorado, 22–24 July, 2019, DOI: 10.15530/urtec-2019-462.

(3) Zou, Y.; Ma, X.; Zhang, S. Numerical modeling of fracture propagation during temporary plugging fracturing. SPE J. 2019, SPE-199351-PA, DOI: 10.2118/199351-PA.

(4) Yuhashi, Z.; Xinfang, M.; Tong, Z.; Ning, L.; Ming, C.; Sihai, L.; Yinuo, Z.; Han, L. Hydraulic fracture growth in a layered formation based on fracturing experiments and discrete element modeling. Rock Mech. Rock Eng. 2017, 50, 2381–2395.

(5) Liu, B.; Wang, H.; Fu, X.; Bai, Y.; Bai, L.; Jia, M.; He, B. Lithofacies and depositional setting of a highly prospective lacustrine shale oil succession from the Upper Cretaceous Qingshankou Formation in the Gulong sag, northern Songliao Basin, northeast China. AAPG Bull. 2019, 103, 405–432.

(6) Tang, J.; Wu, K.; Li, Y.; Hu, X.; Liu, Q.; Ehlig-Economides, C. Numerical investigation of the interactions between hydraulic fracture and bedding planes with non-orthogonal approach angle. Eng. Fract. Mech. 2018, 200, 1–16.

(7) Tang, J.; Wu, K.; Zuo, L.; Xiao, L.; Sun, S.; Ehlig-Economides, C. Investigation of rupture and slip mechanisms of hydraulic fractures in multiple-layered formations. SPE J. 2019, 24, 2292 SPE-197054-PA.

(8) Guo, X.; Wu, K.; An, C.; Tang, J.; Killough, J. Numerical Investigation of Effects of Subsequent Parent-Well Injection on Interwell Fracturing Interference Using Reservoir-Geomechanics-Fracturing Modeling. SPE J. 2019, 24, 1884 SPE-195580-PA.

(9) Zhang, F.; Mack, M. Integrating fully coupled geomechanical modeling with microseismicity for the analysis of fracturing treatment. J Nat Gas Sci Eng. 2017, 46, 16–25.

(10) Wang, D.; Zlotnik, S.; Dzie, P. A numerical study on hydraulic fracturing problems via the proper generalized decomposition method. CMES-Comp. Model. Eng. 2020, 122, 703–720.

(11) Chen, H.; Onishi, T.; Olalotti-Lawal, F.; Datta-Gupta, A. Streamline tracing and applications in embedded discrete fracture models. J. Pet. Sci. Eng. 2020, 188, 106865.

(12) Chen, H.; Yang, C.; Datta-Gupta, A.; Zhang, J.; Chen, L.; Liu, L.; Chen, B.; Cui, X.; Shi, F.; Bahar, A. Fracture Inference and Optimal Well Placement Using a Multiscalar History Matching in a HPHT Tight Gas Reservoir, Tarim Basin, China. Upstream Oil Gas Technol. 2020, 2, 100002.

(13) Thomas, M.; Pidgeon, N.; Evensen, D.; Partridge, T.; Hassel, A.; Enders, C.; Herr Harthorn, B.; Brashaw, M. Public perceptions of hydraulic fracturing for shale gas and oil in the United States and Canada. Waters Clim. Change. 2017, 8, No. e450.

(14) Li, Y.; Jia, D.; Rui, Z.; Peng, J.; Fu, C.; Zhang, J. Evaluation Method of Rock Brittleness Based on Statistical Constitutive Relations for Rock Damage. J. Pet. Sci. Eng. 2017, 153, 123–132.

(15) Li, Y.; Yang, S.; Zhao, W.; Li, W.; Zhang, J. Experimental of hydraulic fracture propagation using fixed-point multistage fracturing in a vertical well in tight sandstone reservoir. J. Pet. Sci. Eng. 2018, 171, 704–713.

(16) Li, Y.; Long, M.; Tang, J.; Chen, M.; Fu, X. A hydraulic fracture height mathematical model considering the influence of plastic region at fracture tip. Pet. Explor. Dev. 2020, 47, 184–195.

(17) Kahraman, S.; Toraman, O. Y.; Cayirli, S. Predicting the strength and brittleness of rocks from a crushability index. Bull. Eng. Geol. Environ. 2018, 77, 1639–1645.

(18) Nejati, H. R.; Ghazvinian, A. Brittleness effect on rock fatigue damage evolution. Rock Mech. Rock Eng. 2014, 47, 1839–1848.

(19) Liu, B.; Yang, Y.; Li, J.; Chi, Y.; Fu, X. Stress sensitivity of tight reservoirs and its effect on oil saturation: A case study of Lower Cretaceous tight clastic reservoirs in the Hailar Basin, Northeast China. J. Pet. Sci. Eng. 2020, 184, 106484.

(20) Hajabdolmajid, V.; Kaiser, P. Brittleness of rock and stability assessment in hard rock tunneling. Tunnelling Underground Space Technol. 2003, 18, 35–48.
(21) Herwanger, J.; Bottrell, A.; Mildren, S. D. The cements of the brittleness index with applications to hydraulic stimulation. In: Unconventional Resources Technology Conference; AAPG Datapages Inc.: San Antonio, Texas, 20–22 July 2013. Society of Exploration Geophysicists, American Association of Petroleum Geologists, Society of Petroleum Engineers, 2015. p. 1215–1223.

(22) Zhang, F.; Nagel, N. B.; Lee, B.; Sanchez-Nagel, M. The influence of fracture network connectivity on hydraulic fracture effectiveness and microseismicity generation. 47th US rock mechanics/geomechanics symposium; American Rock Mechanics Association, 2013.

(23) Tang, J.; Li, J.; Tang, M.; Du, X.; Yin, J.; Guo, X.; Wu, K.; Xiao, L. Investigation of multiple hydraulic fractures evolution and well performance in lacustrine shale oil reservoirs considering stress heterogeneity. Eng. Fract. Mech. 2019, 218, 106569.

(24) Yang, Y.; Sone, H.; Hsows. A. Comparison of brittleness indices in organic-rich shale formations. 47th US rock mechanics/geomechanics symposium; American Rock Mechanics Association, 2013.

(25) Perez, R.; Marfert, K. Britteness estimation from seismic measurements in unconventional reservoirs: Application to the Barnett Shale. Seg. Tech. Program Expanded 2013, 2258–2263.

(26) Ai, C.; Zhang, J.; Li, Y.; Zeng, J.; Yang, X.; Wang, J. Estimation criteria for rock brittleness based on energy analysis during the rupturing process. Rock Mech. Rock Eng. 2016, 49, 4681–4698.

(27) Algholi, S.; Lashkaripour, G. R.; Ghafoori, M. Strength/ brittle classification of igneous intact rocks based on basic physical and dynamic properties. Rock Mech. Rock Eng. 2017, 50, 45–65.

(28) Zhang, Z.; Gao, F. Experimental reason on energy evolution of red sanstone samples under uniaxial compression. Chin. J. Rock Mech. Eng. 2012, 41, 953–962.

(29) Das, B.; Chatterjee, R. Mapping of pore pressure, in-situ stress and brittleness in unconventional shale reservoir of Krishna-Godavari basin. J. Nat. Gas Sci. Eng. 2018, 50, 74–89.

(30) Hsucka, V.; Das, B. Britteness determination of rocks by different methods. Int. J. Rock Mech. Min. Sci. 1974, 11, 389–392.

(31) Altingr, R.; Guney, A. Predicting the relationships between brittleness and mechanical properties (UCS, TS and SH) of rocks. Sci. Res. Essays 2010, 5, 2107–2118.

(32) Diao, H. Rock mechanical properties and brittleness evaluation of shale reservoir. Acta Petrol. Sin. 2013, 121, 3300–3345.

(33) Zhang, Y.; Fan, C.; Zhong, C.; Ye, Z.; Qin, Q.; Li, R. Study on the evaluation method of organic-rich shale brittleness in complex geological conditions. Geol. Explor. 2018, 54, 1069–1083.

(34) Zhao, D.; Guo, Y.; Chen, L.; Qin, Y.; Qu, H.; Kuang, L.; Wang, X. Discussion on brittleness characteristics and influencing factors of shale gas reservoirs. Uncon. Oil Gas. 2016, 3, 6–11.

(35) Yan, L.; He, C.; Hou, K. A Calculation method for brittleness index of shale gas reservoirs based on the imaging spectroscopy mineral maps: a case study of the lower silurian long maxie shale gas reservoir in the Southern Sichuan Basin. Nat. Gas. Ind. 2019, 39, 54–60.

(36) Yan, R.; Hong, C.; Fengchang, Y. Review of rock brittleness evaluation methods. Oil Geophys. Prospect. 2018, 53, 875–886.

(37) Guo, T. K.; Zhang, S. C.; Ge, H. K. A new method for evaluating ability of forming fracture network in shale reservoir. Rock Soil Mech. 2013, 34, 947–954.

(38) Yu, T.; Ba, J.; Qian, W.; Guo, M.; Wang, E.; Zhang, L.; Tan, W. Research progress on evaluation methods of rock brittleness in unconventional oil and gas reservoirs. Prog. Geophys. 2019, 34, 0236–0243.

(39) Chi, A.; Yuwei, L. The model for calculating elastic modulus and poisson’s ratio of coal body. Open Fuels Energy Sci. J. 2013, 3, 36–43.

(40) Zhong, C.; Qin, Q.; Zhou, J.; Hu, D.; Wei, Z. Brittleness evaluation of organic-rich shale in Longmaxi formation in dingshan area, Southeastern Sichuan. Geo. Sci. Technol. Inf. 2018, 37, 167–174.

(41) Mikael, R.; Atea, E.; Yousefi, R. Correlation of production rate of ornamental stone with rock brittleness indexes. Arab. J. Geosci. 2013, 6, 115–121.

(42) Altingr, R. Correlation of specific energy with rock brittleness concepts on rock cutting. J. South. Afr. Inst. Min. Metall. 2003, 103, 163–171.