Abstract. Hydraulic fracturing has become an important stimulation method for unconventional oil/gas reservoirs to achieve industrial capacity. Fracability evaluation has become one of the most important steps during the reservoir characterization and fracturing job design, which is beneficial for identifying the best candidate fracturing zone. In this paper, we provide a detailed review of the existing fracability evaluation methods. The evolution of the fracability evaluation method from the single-factor method, i.e. the brittleness method, to the multi-factor methods which incorporate brittleness, fracture toughness, in-situ stress as well as natural fracture parameters has been summarized. For the brittleness methods, different definitions of brittleness have been summarized and compared. For the multi-factor fracability evaluation methods, particular emphasis has been placed on illustrating how the factors were selected and incorporated into different fracability evaluation methods and possible field evidences validating the effectiveness of different fracability evaluation methods. In addition, the emerging 3D fracability evaluation attempts based on 3D seismic data and geomechanical analysis, which may serve as a guidance for finding the so-called engineering sweet spots, have been introduced in details. Finally, possible future work to improve the effectiveness of fracability evaluation is discussed.

1. Introduction
With the increasingly prominent contradiction between international energy supply and demand, the exploration, development and consumption of conventional oil and gas resources are becoming rapider. Due to great market demand, the exploration and development of unconventional oil and gas resources has gradually become a hot spot in the current oil and gas resource exploration and development research. China has abundant reserves of unconventional oil and gas resources. According to statistics, 42 major coal-bearing basins in China have coalbed methane reserves with a depth of less than 2000 m in coal beds reaching 3.6×1012 m3; National shale oil reserves reach 719×1013 t; The estimated total amount of shale gas resources has also reached 3.07×1012 m3[1]. Obviously, unconventional energy resources are of great development potential. Unconventional reservoirs always have poor physical properties and almost no natural productivity. And it is difficult to mine effectively with conventional methods. Therefore, the application of appropriate measures to increase production in unconventional reservoirs is necessary and hydraulic fracturing is widely used as a low-cost and efficient way to increase production. The physical properties of unconventional reservoirs in different regions or with different lithologies vary greatly. Effective fracturing operation depends on the accurate fracability evaluation suitable for the reservoirs in that region. The definition of fracability is the property of the reservoir’s degree that it can be...
effectively fractured. Fracability evaluation is a significant pre-fracturing work, which has direct guiding significance for well layout design, layer optimization, and fracturing plan formulation. This paper conducts a comprehensive investigation on the methods of fracability evaluation at home and abroad, and takes the development of fracability evaluation methods as the context, and makes a review of the fracability evaluation methods for different lithologies reservoirs.

2. Fracability evaluation methods for shale reservoirs

The concept of fracability evaluation was first proposed for shale reservoir, and most of the existing fracability evaluation methods are also aimed at shale reservoirs nowadays. Initially, based on knowledge of rock mechanics and on-site construction experience, people intuitively believed that the brittleness of the shale reservoir is the criterion for whether the reservoir is easy to be effectively fractured. A generally accepted view is that plastic shale has a high argillaceous content and is prone to plastic deformation during fracturing, forming simple fractures, while brittle shale has a high content of brittle minerals such as quartz, and it is easy to form complex fractures network during hydraulic fracturing.

2.1. Fracability evaluation based on brittleness

2.1.1. Britteness review

Brittleness refers to the property of a material that failures after only small brittle deformation under the action of external forces (such as stretching, impact). Whether the material is brittle or not is related to its composition, microstructure, stress state and environment. In the field of rock mechanics, scholars have various of opinions on the definition of rock brittleness. According to statistics, there are more than 30 types of brittleness definitions that are widely used, and 20 commonly used types are counted below (table 1). Among them, the two most commonly used definitions for fracability evaluation are: (1) Mechanical brittleness index calculated by elastic parameters such as Young's modulus and Poisson's ratio; (2) Mineral brittleness index defined by the proportion of brittle mineral components.

| Formula | Basic meaning | Testing method | Literature source |
|---------|----------------|----------------|------------------|
| $B_1 = \frac{(H_m - H)}{K}$ | The difference between Macro hardness $H$ and Micro hardness $H_m$ | Hardness Testing | H. Honda and Y. Sanada |
| $B_2 = q \sigma_c$ | $q$ means the percentage of debris less than 0.60mm,c means the compressive strength | Platts impact test | M.M. Protodyakonov |
| $B_3 = \frac{(\tau_p - \tau_r)}{\tau_r}$ | The functional formulas of peak intensity $\tau_p$, and residual intensity $\tau_r$ | Stress-strain test | A.W. Bishop |
| $B_4 = \frac{\varepsilon_r}{\varepsilon_t}$ | Ratio of recoverable strain $\varepsilon_r$ to total strain $\varepsilon_t$ | Stress-strain test | V. Hucka and B. Das |
| $B_5 = \frac{W_r}{W_t}$ | Ratio of recoverable strain energy $W_r$ to total energy $W_t$ | Stress-strain test | V. Hucka and B. Das |
| $B_6 = \frac{\sigma_c}{\sigma_t}$ | The ratio of compressive strength $\sigma_c$ to tensile strength $\sigma_t$ | Intensity ratio | V. Hucka and B. Das |
| $B_7 = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)}$ | The functional formulas of compressive strength $\sigma_c$ and tensile strength $\sigma_t$ | Intensity ratio | V. Hucka and B. Das |
| $B_8 = \sin \varphi$ | $\varphi$ means Internal friction angle | Mohr Circle | V. Hucka and B. Das |
| $B_9 = 45^\circ + \frac{\varphi}{2}$ | The formulas of Internal friction angle $\varphi$ | Stress-strain test | V. Hucka and B. Das |

Table 1. Definition of Britteness Index
For a long time, people believed that shale brittleness was the most important factor influencing fracability, so the brittleness index was used as a very important indicator for quantitatively fracability evaluating in order to screen high-quality shale layers.

2.1.2. Britteness index for shale fracability evaluation
In the early days, some scholars only used the brittleness index as a single index to evaluate the fracturing ability of shale reservoirs. Rickman et al [2] believe that the smaller the Poisson's ratio of shale, the easier it is for shale to form fractures, and the Young's modulus reflects the ability of shale to maintain fractures which meaning that the fracture surface of the shale reservoir with high Young's modulus is more resistant to the embedding of proppant. Therefore, they put forward the brittleness index defined as follows to characterize the brittleness of shale in the Fort-Worth Basin Barnett shale in North America, and used it to evaluate the fracturing ability of shale.

\[
B_I = \frac{YM_{Bl} + PR_{Bl}}{2}
\]

\[
YM_{Bl} = \frac{YM_{CS}}{8 - 1} \times 100\%
\]

\[
PR_{Bl} = \frac{PR_C - 0.4}{0.15 - 0.4} \times 100\%
\]

where, \(YM_{CS}\) is the Young's modulus, 10 GPa; \(PR_C\) is Poisson's ratio, dimensionless; \(YM_{Bl}\) is the normalized Young's modulus, dimensionless; \(PR_{Bl}\) is the normalized Poisson's ratio, dimensionless; \(B_I\) is the brittleness index, dimensionless.
Another method shows that the higher the content of brittle minerals in shale mineral components, the stronger the brittleness of the rock. For example, Jarvie et al.\(^3\) regards quartz minerals as brittle minerals, and proposes that the ratio of brittle minerals to the total shale minerals is used as the brittleness index (Eq. 4) to characterize the brittleness of shale, which is used to evaluate the fracability of shale and screen the fracturing target layer.

\[
B = \frac{W_q}{W_T}
\]

where, \(W_q\) is the content of brittle minerals (quartz), dimensionless; \(W_T\) is the total amount of rock minerals, dimensionless.

Regarding the mineral brittleness index, different scholars have different views on brittle minerals. Wang et al.\(^4\), proposed that brittle minerals include quartz and dolomite. The brittleness index should be defined by the proportion of the total content of the two minerals. Jin et al.\(^5\), believe that the calculation of brittleness index needs to consider the proportion of quartz, feldspar, mica, and carbonate minerals in rock minerals.

What’s more, some scholars believed that the above two brittleness indexes should be comprehensively considered and applied to evaluate the fracability of shale reservoirs. Li et al.\(^6\), proposed a method to comprehensively characterize the brittleness of shale by integrating shale’s elastic parameters and mineral composition.

In summary, shale brittleness index has various definitions and is often used as the only indicator to evaluate fracability. However, it is obviously that taking brittleness index as the only factors means that only the influencing factor at the scale of the rock matrix is considered, and ignoring other scales such as fractures’ initiation and propagation. The limitations are obvious.

2.2. Fracability evaluation based on multi-factors

As unconventional oil and gas resources have received wider attention, the development of unconventional oil and gas has gradually involved deeper burial depths and even offshore unconventional oil reservoirs. This puts forward higher requirements on the fracturing technology, and the accuracy of fracability evaluation also urgently needs to be improved. A large number of research results show that the brittleness index only reflects the mechanical properties or mineral composition characteristics of the reservoir rock itself, and it is difficult to reflect the comprehensive properties of shale in the hydraulic fracturing process, and it is not sufficient to comprehensively evaluate the fracability of shale reservoir rocks either.

2.2.1. Evaluation factors of reservoir characteristics

Based on on-site fracturing experience, theoretical analysis and laboratory experimental results, researchers at home and abroad furtherly proposed various influencing factors on rock matrix scale, such as fracture toughness. Fracture toughness is the property of the rock itself that describes its ability to prevent fracture’s initiation and extension. The magnitude of fracture toughness is related to the difficulty of fracture extension, and the smaller the value is, the easier the fracture is to extend and the more conducive to hydraulic fracturing. Yuan et al.\(^7\) proposed a fracability evaluation method that integrates brittleness index and type I, type II fracture toughness:

\[
F_{\text{frac}} = \frac{2BI}{K_{IC}K_{IIIC}}
\]

where, \(BI\) is the brittleness index, dimensionless; \(K_{IC}\) and \(K_{IIIC}\) are type I and type II fracture toughness respectively, MPa \(\cdot\) m\(^{1/2}\).

Mohamed Salah et al.\(^8\) also proposed another normalized fracability evaluation method (Eq. 6) that comprehensively considers brittleness and fracture toughness. This form of fracability index is normalized according to the maximum and minimum values of the evaluation factors, and the value is between 0-1, which is more convenient for comparison. A new model created by Lai\(^16\), Yuan\(^14\) and Huang\(^9\) also takes fracture toughness into account. The difference is that they measure the brittleness of shale from the perspective of plastic strain energy and elastic strain energy.
where, $\varepsilon_0$ is the strain value when the rock ruptures; $\sigma_s, \varepsilon_s$ are the stress and linear elastic strain of the stress-strain curve; $\sigma_f, \varepsilon_f$ are the stress and strain before the specimen is completely destroyed. Tang et al.\cite{11} proposed two influencing factors, the distribution of natural fractures and the experienced diagenesis of reservoir. The initiation and propagation zone of natural fractures is often the zone with weak formation stress. And the existence of natural fractures reduces the tensile strength of the rock, which has a positive impact on the generation and extension of fractures. On the other hand, the more mature shale reservoirs have better physical properties such as porosity due to hydrocarbon expulsion, which is beneficial for fracturing. Others held the same view and added natural fractures to their models such as Wang\cite{13} and Wu\cite{15}. After research and comparison, Wang\cite{13} found that the stress sensitivity coefficient of the reservoir is positively correlated with the density of natural fractures. A comprehensive evaluation method (2-9) of stress sensitivity and brittleness is proposed.

\[
FI = \frac{B_{f_i} - B_{f_i - \min}}{B_{f_i - \max} - B_{f_i - \min}}
\]

\[
B_{f_i} = \int_0^{c_0} \sigma_s \varepsilon_s d\varepsilon
\]

\[
F_{rac} = \frac{\alpha_i (B_{f_i} - 0.5)}{K_{IC} + K_{IIC}}
\]

where, $X_{id}$ is the stress sensitivity index.

The in-situ stress distribution of reservoir controls the propagation behaviour of hydraulic fractures (direction, shape). The minimum horizontal in-situ stress not only determines the direction of fractures propagation, but also determines the degree of difficulty. The smaller its value, the more conducive to the initiation and extension of fractures. Based on this theory, Yuan et al.\cite{14} proposed a new fracability evaluation method that considers the brittleness, fracture toughness and minimum horizontal stress of shale reservoirs.

\[
FI = \frac{B_{f_i} + X_{id}}{2}
\]

\[
X_{id} = \frac{\chi_{i} - \chi_{i - \min}}{\chi_{i - \max} - \chi_{i - \min}}
\]

Considering the influence of confining in-situ stress on the fracture toughness of the reservoir rock, Mohamed Salah et al.\cite{17} used the Al-Shayea model to calculate the fracture toughness.

\[
K_{IC} = 0.043\sigma_3^* + K_0
\]

Many researchers consider a wide range of factors and then use mathematical methods to link them together to create a new evaluation method. For example, Lai et al.\cite{16} comprehensively considers the characteristics of the reservoirs brittleness coefficient (BL), brittle mineral content (BM), organic carbon content (TOC), clay mineral content (CL), fracture toughness (KC) and horizontal stress difference coefficient (Kh) to establish a targeted evaluation method (2-12). And use the analytic hierarchy process to determine the weight of each factor

\[
FI = 0.3751B_L + 0.2436BM + 0.1534TOC + 0.093KC + 0.093Kh + 0.0419CL
\]

In summary, various new influencing factors based on the characteristics of the reservoir have been widely proposed and applied to fracability evaluation. This means that the fracability of the reservoir is largely determined by its own characteristics.

### 2.2.2. Evaluation factors of fracture initiation and propagation aspects
The ideal result of hydraulic fracturing operations is to form as complex a fracture network as possible and obtain a large reservoir reconstruction volume. The process of fractures propagation cannot be ignored. Therefore, many scholars also study the process and mechanism of fracture initiation and propagation in order to uncover fracability evaluation factors.

Jin et al.\(^{[10]}\) believed that considering the energy consumed by rock failure during fracturing can evaluate the fracability of shale reservoir more precisely. They defined the critical energy release rate (Eqs. 13, 14) and established a new method (Eq. 15) combining with the brittleness index of shale.

\[
G_C = \frac{K_{IC}^2}{E'} \tag{14}
\]

\[
G_{C-N} = \frac{G_{C-N_{\max}} - G_C}{G_{C-N_{\min}} - G_C} \tag{15}
\]

\[
FI = w \times B_n + (1 - w) \times G_{C-N} \tag{16}
\]

where, \(B_n\) is the normalize brittleness index; \(G_C\) is the critical energy release rate; \(G_{C-N}\) is the normalized critical energy release rate; \(w\) is the weight coefficient, the value is 0.5.

They built the intersection graph of fracability, normalized critical energy release rate and normalized brittleness index as shown in Figure 1. The normalized critical energy release rate has a good positive correlation with the fracturing index.

![Figure 1. Cross plot of fracability with critical energy release rate and brittleness index.\(^{[10]}\)](image)

Considering the complexity of rock failure, Zhou et al.\(^{[12]}\) made a combination of fractal dimension and fracture angle to define the rock fracture complexity coefficient (Eq. 16). On the other hand, they also established a positive correlation (Eq. 17) between three stress-strain curve parameters and the damage complexity through experiments. Finally, a new method (Eq. 18) is proposed in combination with the minimum in-situ stress.

\[
F_C = D \times \frac{\alpha}{90} \tag{17}
\]

\[
BI = 0.262E_n + 0.353j_n + 0.385\varepsilon_{pn} \tag{18}
\]

\[
F_1 = BI \left( w_1 F_1 + w_2 S_1 \right) \tag{19}
\]

where, \(F_C\) is the rock fracture complexity coefficient, dimensionless; \(D\) is the fractal dimension, dimensionless; \(\alpha\) is the rock fracture angle, (°); \(j_n\) is the normalized expansion angle, dimensionless; \(\varepsilon_{pn}\) is the normalized peak strain, dimensionless.

Another similar study is that Zhu et al.\(^{[18]}\) combined brittleness \((F_1)\), stress-strain data and destructive fractal properties \((F_4)\), and proposed a new shale fracability evaluation method. Their research shows
that the failure characteristics of rocks can be well reflected in the stress-strain curve. In order to quantify the factors, they defined the following two indicators (Eqs. 19, 20).

\[ F_2 = \frac{\sigma_p - \sigma_r}{\sigma_p} \]  

(20)

\[ F_3 = \frac{\log |k|}{10} \]  

(21)

\[ F_4 = \frac{D}{2} \]  

(22)

Figure 2. Schematic diagram of parameters (stress-strain curve) \(^{[18]}\)

The fracability evaluation of shale had gradually formed the multi-faceted and multi-factor model. In addition to the above, many scholars had put forward other evaluation factors according to the characteristics of the shale in the study area. Such as, internal friction angle, cohesion and so on. But the evaluation model is similar. Moreover, most of the above-mentioned fracturing evaluation methods can only evaluate the near-well zone on single well scale.

3. Fracability evaluation methods for other lithological reservoirs

Due to engineering needs in the exploration and development of unconventional oil and gas resources, reservoir fracturing evaluation has gradually been applied to unconventional reservoirs with other lithologies except shale. Tight sandstone reservoirs, as another common unconventional oil and gas reservoir, are widely used as the object of fracturing evaluation. With reference to the experience of shale fracability evaluation, some scholars have followed the shale evaluation model and applied it to tight sandstone, and the results proved that it is also of applicability. Sun et al \(^{[19]}\) proposed an evaluation method for tight sandstone reservoirs based on brittleness and fracture toughness.

Figure 3. Micro-seismic monitoring results of Fra8 member of Well S \(^{[19]}\)
After the application of this evaluation method similar to shale, on-site seismic data showed that the micro-seismic signal of the preferred layer is strong after hydraulic fracturing (Figure 3), which proves that the fracturing result is good, and the applicability of the evaluation method is further proved. With reference to the evaluation method of shale, He et al.\textsuperscript{[20]} proposed an evaluation method for tight sandstone gas reservoirs that comprehensively considers 9 factors and uses the analytic hierarchy process to determine their weights.

\begin{equation}
F = \sqrt[3]{BI \times B_\alpha \times S_n \times K_n}
\end{equation}

where, $BI, B_\alpha, S_n, K_n$ are mineral brittleness index, mechanical brittleness index, shear strength index and fracture toughness index, respectively.

Different from other existing related studies, Zhu et al.\textsuperscript{[25]} proposes a three-dimensional fracturing evaluation method for tight sandstone reservoirs. They established a three-dimensional model based on the geological structure of the target reservoir, and assigned attributes to the model based on logging data, and finally obtained a complete three-dimensional fracability index distribution (Figure 5). Compared with the traditional evaluation method, this method can obtain a complete three-dimensional evaluation result, which is more instructive for the comprehensive selection of layers and engineering sweet-spots.
4. Summary and outlook
At present, there have been a large number of index models for fracability evaluation at home and abroad, but most of them are for shale. However, the evaluation method for other lithological reservoirs mostly follow the evaluation model of shale. In most cases, the evaluation results are combined with the fracturing plan to select the fracturing advantage area. Only a few of evaluation results are used to guide the design of the well location distribution. Existing multi-factor fracability evaluation methods are in similar pattern. All of them take different factors into consideration based on the characteristics of the studying reservoir, or use different methods to combine these factors to form a new method. For the verification of the new model’s applicability, researchers generally use fractured productivity data or micro-seismic monitoring results for indirect verification, but there is no direct verification method at present. Most of the existing fracability evaluation researches were only applied to the near-well zone of single well, and the inter-well area had not been evaluated. The guiding significance is not comprehensive enough.

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