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# Evaluation of fracability and screening of perforation interval for tight sandstone gas reservoir in western Sichuan Basin

Jian-Chun Guo [a], Bo Luo [a], Hai-Yan Zhu [a,*], Yong-Hui Wang [b], Qian-Li Lu [a], Xing Zhao [a]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China
[b] Research Institute of Petroleum Exploration and Development-Langfang, Petrochina, Langfang 065007, China

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ABSTRACT

The western Sichuan tight sandstone gas reservoir is characterized by low porosity, ultra-low permeability, and shale interbedding. The most effective way to exploit this formation would be large-scale hydraulic fracturing. Currently, however, no appropriate method exists for selecting fracturing candidates to maximize the scale of the complex hydraulic fracture system. Therefore, fracability should be evaluated when developing this type of reservoir. In this study, fundamental mechanical experiments are performed to determine the correlation between fracability and its influencing factors. Based on the experimental results, reservoir fracability is evaluated using a new model that integrates all of the related factors. Formations with high fracability are selected as hydraulic fracturing candidates, and a new method for selecting perforation intervals is proposed based on the determined reservoir fracability. As case studies, the appropriate perforation intervals are examined for two wells drilled in the western Sichuan Basin: vertical well XC32 and horizontal well HF-1.



## 1. Introduction

Large-scale hydraulic fracturing is usually essential to the development of low-porosity and low-permeability shale gas reservoirs. This technique can also be applied to the development of tight sandstone gas reservoirs. However, compared to a shale reservoir, it is more difficult to generate a complex fracture system in a tight sandstone gas reservoir because the latter has fewer natural fractures. High fracability is associated with very complex fracture geometries. Therefore, to develop a tight sandstone gas reservoir, it is important to understand and characterize the heterogeneity of its fracability. Fracability, which is the ease with which a shale reservoir can be fractured, is a crucial mechanical parameter of rock that is used to evaluate the likelihood of shale gas extraction. This parameter usually features in the petrophysics reports of unconventional shale reservoirs (Enderlin et al., 2011; Jin et al., 2014).

In recent years, numerous studies have been conducted on reservoir fracability (Fang and Amro, 2014; Su, 2014) by both scholars and corporations. Brittleness (Chong et al., 2010; Britt and Schoeffler, 2009), a parameter that combines the Young's modulus and the Poisson's ratio, can represent a reservoir's fracability to some degree. Usually, a higher level of brittleness implies higher fracability (Rickman et al., 2008). A reservoir's fracability typically increases with increasing proportions of brittle minerals. On the other hand, fracability decreases as the clay mineral content, which exhibits ductile behavior (Jarvie et al., 2007), increases. Researchers have also determined that fracture toughness is an important factor affecting the distribution of fracability because a lower fracture toughness results in a lower breakdown pressure during hydraulic fracturing (Backers and Stephansson, 2012; Bower, 2011). However, the cost of testing fracture toughness is prohibitively high.

To control the cost of exploring, drilling, and large-scale hydraulic fracturing, optimizing the design of the hydraulic fracturing process is important. In particular, with respect to the hydraulic interval, selecting points where the fracability is higher is necessary. Researchers have made many attempts to quantify reservoir fracability (Jin et al., 2014; Fang and Amro, 2014; Jahandideh and Jafarpour, 2014; Li et al., 2013; Mullen and Enderlin, 2012; Yuan et al., 2013; Tang et al., 2012; Tiwari and Ajmera, 2011). Based on laboratory tests, Li[12] derived a failure model and used it to perform a detailed analysis of the mechanical behavior of shales in North America and South China. Li's method combined the rock's mechanical properties and mineralogy to quantify the fracability. To

* Corresponding author. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, 8 Xindu Avenue, Xindu, Chengdu 610500, Sichuan, China.
*E-mail address:* zhuhaiyan040129@163.com (H.-Y. Zhu).

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study the variations in shale fracability, Jahandideh (Jahandideh and Jafarpour, 2014) analyzed the influence of Young's modulus, Poisson's ratio, and mineral components. Mullen (Mullen and Enderlin, 2012) proposed integrating the stratigraphic properties, mineral distribution, and the presence and orientation of plane weaknesses in the present-day stress state to quantify the fracability. Fang (Fang and Amro, 2014) analyzed the influence of non-marine shale fracability such as the sedimentary environment, mineral composition, brittleness, and natural fractures. Tang (Tang et al., 2012) used a weight coefficient to describe the influence of all factors on the shale's fracability. In addition, Yuan (Yuan et al., 2013) considered fracture toughness when evaluating reservoir fracability. Jin (Jin et al., 2014) derived three mathematical models for determining the fracability index and selected the formation with the highest fracability as a fracturing candidate. Meanwhile, shear failures were observed in both microseismic analysis (Hucka and Das, 1974) and numerical simulations (Dong et al., 2004) during the shale reservoir fracturing process. Therefore, it can be inferred that shear strength is crucial to the evaluation of the fracability of a reservoir and can be represented by the internal friction angle (Hucka and Das, 1974).

To maximize the stimulated reservoir volume (SRV) of a tight sandstone gas reservoir during hydraulic fracturing, we have developed a new fracability index model that integrates Young's modulus, Poisson's ratio, the mineral components, tensile strength, fracture toughness, and shear strength. The formations with higher fracability are selected to determine the perforation intervals in field applications.

## 2. Fundamental mechanical experiments

The Upper Triassic tight gas petroleum system in the central western Sichuan Basin was formed in a foreland basin created by the establishment of the Longmenshan Orogeny in the early part of the Late Triassic, along the western edge of the Sichuan Basin. Typically, deep tight sandstone gas reservoirs were developed in the Upper Triassic Xujiahe formation, and the size of the reservoirs has been estimated to be approximately 778.7 billion $m^3$. The Upper Triassic Xujiahe formation includes six reservoirs, identified as Xu1 to Xu6, from the bottom to the top of the western Sichuan Basin (Fig. 1).

The Xu5 formation has attracted considerable attention because it is rich in natural gas, but its exploration presents a great challenge. The exploration area of the Xu5 formation covers approximately 10,570 $km^2$, and it exhibits low porosity (less than 5%) and ultra-low permeability (less than 0.1 mD). In the central western Sichuan Basin, which is an over-pressured and tectonically stressed environment, the pore pressure in the region commonly exceeds 0.0158 MPa/m and is sometimes as high as 0.0204 MPa/m. Test data has shown that the direction of the maximum horizontal stress is 100°–120° from the north. At present, hydraulic fracturing is being carried out in eighteen wells in Xu5, including two horizontal wells, one directional well, and fifteen vertical wells.

To resolve the challenges related to exploration and to enhance the hydraulic fracturing performance in Xu5, it is crucial to evaluate the formation's fracability and then choose a high fracability area as the perforation interval to maximize the SRV.

### 2.1. Triaxial compression test

We obtained 29 rock samples, taken from depths of 3037–3355 m. The specimens were tested at the reservoir temperature of 87 °C under different confining pressures (Table 1). The test results show that the compressive strength ranges from 11.8 to 389 MPa, the Young's modulus ranges from 11.3 to 42.1 GPa, and the Poisson's ratio ranges from 0.09 to 0.49.

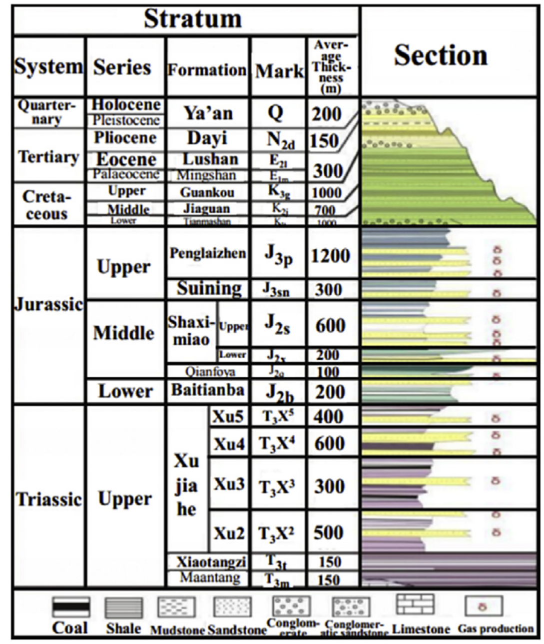


Fig. 1. Stratigraphy of the western Sichuan Foreland Basin (Chen, 2013).

Compared to the Barnett and Eagle Ford shales in Texas, the tight sandstone in Xu5 is considerably more brittle while the shale formation in Xu5 is considerably more ductile (Fig. 2). The rock failure mode changes from splitting failure to double shear failure (Fig. 3) as the confining pressure increases.

### 2.2. Tensile strength test

We obtained 23 specimens, from depths of 3063–3355 m, and performed Brazilian disk-splitting tests on them to determine the tensile strength (Table 2). The results of our experiment show that the Xu5 tight sandstone gas reservoir has high tensile strength, which, to some degree, hinders the extension of hydraulic fracturing and thus limits the reservoir fracability.

### 2.3. Fracture toughness test

Fracture toughness, which represents the ability of rock to resist fracture propagation from preexisting cracks during the hydraulic fracturing process (Bower, 2011), is an important factor affecting the fracability of a reservoir. We obtained 20 standardized samples with diameters of approximately 100 mm, thicknesses of 20 mm, and a crack length of 50 mm; the samples were taken from depths of 2920–3950 m (Table 3).

The center-cracked Brazilian disk specimens were loaded into an MTS8166 rock testing system with no confining pressure (Fig. 4 (a)) and were subjected to load pressure until a precast crack progressed across the entire sample (Fig. 4) (b). Then, the fracture toughness was calculated using the following equation (Dong et al., 2004):

$$K_I = \sigma\sqrt{\pi a}\left[f_{11} + 2\sum_{i=1}^{n} A_{1i} f_{1i} \alpha 2^{(i-1)}\right] \tag{1}$$

where $a$ is the crack half-length (mm), $\alpha$ is the relative crack length, $f_{1i}$ and $A_{1i}$ are the different coefficients, and $\sigma$ is the load pressure (MPa).