

Research Article

Prediction of Fracture Toughness in the Shale Formation Based on Well Logging and Seismic Data: A Case Study of the Lower Silurian Longmaxi Formation in the Sichuan Basin, China

Kaiyuan Liu,¹ Jian Xiong^(b),² Xi Zhang,¹ Xiao Fan,¹ and Le Li¹

¹Geophysical Technology Research Center of BGP Inc., China National Petroleum Corporation, Chengdu 610500, China ²State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China

Correspondence should be addressed to Jian Xiong; 361184163@qq.com

Received 23 July 2020; Revised 25 October 2020; Accepted 20 November 2020; Published 1 December 2020

Academic Editor: Zhouheng Chen

Copyright © 2020 Kaiyuan Liu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The rock physics experiments and fracture toughness tests of shales from the Lower Silurian Longmaxi Formation in the Sichuan Basin in China were carried out. Based on this, the calculation model of the fracture toughness was constructed, thus, the single well evaluation of the fracture toughness in shale formation would be obtained based on the well logging data, which can be used to summarize the spatial distribution characteristics of the fracture toughness in shale formation. However, it is difficult to obtain transverse distribution characteristics of fracture toughness in shale formation based solely on the well logging data. Therefore, in order to investigate the spatial distribution of the fracture toughness, jointing well logging and seismic method could be adopted to quantitatively predict the fracture toughness in shale formation. The results show that fracture toughness of shales is sensitive to acoustic interval transit time and wave impedance. The prediction model of the fracture toughness of shales was constructed, which had a good prediction effect. The fracture toughness values of shales from the Upper Silurian Wufeng-Longmaxi Formation were larger, whereas those of shales from the Lower Silurian Wufeng-Longmaxi Formation were lower. The fracture toughness is mainly distributed in strips along the vertical direction while the distribution area is continuous in the lateral direction, indicating that it has obvious stratification characteristics.

1. Introduction

With the adjustment of energy structure and the increasingly prominent environmental problems, natural gas as a clean energy has received more and more attention, especially the unconventional oil and gas resources, of which shale gas has become a hot spot in the exploration and development of the unconventional oil and gas resources around the world. The US Energy Information Administration (EIA) published assessments of shale gas resources in 42 countries including the US [1], indicating that the technically recoverable reserves of shale gas resource are estimated to be approximately 36.1×10^{12} m³ in China and 17.75×10^{12} m³ in the Sichuan Basin, and there is a significant exploration and development potential of shale gas reservoirs in the Sichuan Basin, China [2]. The efficient development of shale gas reservoirs requires a series of key technologies, such as hori-

zontal well drilling technology and segmental hydraulic fracturing technology [3]. The effects of fracturing reconstruction are closely related to the reservoir properties, mechanical characteristics of rock, etc. After the fracturing of a shale reservoir, the initiation and extension of fractures are the key problems during fracturing, and the brittleness index is an important parameter affecting the efficiency of fracturing. In the aspect of brittleness evaluation of shale, a large number of researchers have obtained a great deal of understandings from experiment evaluation, prediction through well logging, and its engineering application [4-11]. The results of these studies played an important role in the evaluation of the fracability in shale gas reservoirs. However, Bai [12] and Jin et al. [13] reported that the brittleness indexes of some shale gas reservoirs are higher while these shale gas reservoirs are not easier to fracture. And it is recognized that the fracability in shale gas reservoir is related to the brittleness



FIGURE 1: Geological map and sampling location of the investigation area, southern Sichuan Basin (modified after [38]).

and toughness of rock [14]. Meanwhile, the initiation and extension of the fractures during fracturing are also affected by the fracture toughness of shale. When the stress intensity factor at the fracture tip exceeds the fracture toughness, the fracture begins to expand and extend [15]. This indicates that fracture toughness can also be used as an evaluation parameter of fracability in shale gas reservoirs. The fracture toughness and brittleness index can complement each other to evaluate the fracability of shale gas reservoirs. Therefore, the investigation of the fracture toughness in shale formation is of great significance to the exploration and development of shale gas reservoirs.

At present, some researches have made some achievements in the investigation on the fracture toughness in shale formation. Chandler et al. [16], Wang et al. [17], Mahanta et al. [18], Yuan et al. [19], Su et al. [20], Ji et al. [21], and Xiong et al. [22] obtained the distribution range of the fracture toughness of shales from different blocks and discussed the influencing factors of the fracture toughness in shale formation. Then, the predictive methods for the fracture toughness in shale formation were built, so the distribution of the fracture toughness values of shale gas well can be gained based on well logging data. Zhang [23], Wang et al. [24], Hua et al. [25], and Mohammed and Mahmood [26] found that there were good relationships between the fracture toughness of different rocks and the compressive strength or tensile strength, and the empirical equations were established. In other words, the fracture toughness of rocks can be predicted by the compressive strength or tensile strength. Furthermore, some researchers have studied the relationship between fracture toughness and physical properties. Brown and Reddish [27] evaluated the correlation between fracture toughness and density. Chang et al. [28] investigated the correlation

between fracture toughness and porosity. Zhixi et al. [29], Jin et al. [30], Roy et al. [31, 32], Ji et al. [21], and Xiong et al. [33] used some methods including simple regression, linear, nonlinear multiple regressions, artificial neural network, Fuzzy Inference System, and Adaptive Neuro-Fuzzy Inference System to establish empirical relations for predicting the fracture toughness based on the density, P-wave velocity, and S-wave velocity. The above studies show that the empirical equations proposed in the literatures have applicable scope, and different empirical relations have been developed. The quantitative evaluation of engineering sweet spots in shale gas reservoirs has an important reference value for evaluating the degree of development difficulty and the development cost of shale gas reservoirs, which can be used to optimize the construction area with low cost and high-efficiency fracturing [13, 34–37]. The fracability plays an important role in the evaluation of engineering sweet spots in shale gas reservoir, and the brittleness index or the fracture toughness are the key factors in the evaluation of fracability in shale gas reservoirs. Therefore, the investigation on the spatial distribution characteristics of the fracture toughness in shale gas reservoirs is of great significance to the evaluation of engineering sweet spots in shale gas reservoirs. However, there are a few reports on the spatial distribution characteristics of the fracture toughness in shale gas reservoirs.

The goal of this article is to investigate the prediction of the fracture toughness in shale formation based on well logging and seismic data from the Lower Silurian Longmaxi Formation in the Sichuan Basin of China, which can be used to study the spatial distribution characteristics of the fracture toughness. The rock physics experiments and rock fracture toughness tests were carried out, and the relationships between the acoustic parameters and the fracture toughness were discussed. Then, the prediction model of the fracture toughness in shale formation was constructed based on well logging. Combining with the seismic data in the study area, the three-dimensional data of the fracture toughness was calculated, which can be used to study the vertical and lateral distribution characteristics of the fracture toughness in shale gas reservoirs from the Lower Silurian Longmaxi Formation. Finally, we realized the quantitative prediction of the fracture toughness in shale gas reservoirs based on the joint well logging and seismic data.

2. Geological Setting and Prediction Workflow

A shale gas block is located in the Changning-Weiyuan national shale gas demonstration zone in the Sichuan Basin of China, of which the favorable shale gas development area with a buried depth of less than 4000 meters is 4216 km², and the resources are $1.89 \times 10^{12} \text{ m}^3$. The burial depth of the Lower Silurian Longmaxi Formation in this block gradually deepens from northwest to southeast, which is characterized by great differences in burial depth and formation pressure coefficients. The study area can be seen in Figure 1. According to the drilling data in this block, the strata from bottom to the top mainly include the Middle Ordovician Baota Formation, Upper Ordovician Lingxiang Formation, Upper Ordovician Wufeng Formation, Lower Silurian Longmaxi Formation, Lower Silurian Shiniulan Formation, Middle Silurian Hanjiadian Formation, and Permian Liangshan Formation, which can be shown in Figure 2. The Wufeng-Longmaxi Formation is the main production layer for shale gas. Due to the extremely low permeability in the shale formation, the shale gas reservoir in this block can only be exploited commercially through the technologies, including horizontal well drilling technology and segmental hydraulic fracturing technology.

In view of the difficulty in obtaining the low-frequency prediction model of the fracture toughness with little drilling data in the study area, a technical process of prediction of the fracture toughness in shale gas reservoirs by means of jointing well logging and seismic data is proposed, as shown in Figure 3. The rock physics experiments and fracture toughness tests of shale samples were carried out, and some parameters would be obtained including the density, P-wave acoustic interval transit time, S-wave Acoustic interval transit time, P-wave attenuation coefficient, S-wave attenuation coefficient, and fracture toughness. Based on the analysis of the relationships between the fracture toughness and the acoustic properties of shale samples, the prediction model of the fracture toughness through logging data was constructed, which contributes to obtaining higher resolution on the vertical profile of the fracture toughness of shales. However, the vertical profile of the fracture toughness of shales just represents the local formation information because it is unable to describe the lateral distribution characteristics through well data analysis, prediction, interpolation, and simulation. Therefore, based on well logging and seismic data, the jointing well logging and seismic method is used to fabricate synthetic seismic records and conduct joint well seismic calibration, so as to predict the fracture toughness values and

System and formation				Lithology
Mesozoic				
Paleozoic	Permian	Changxing	P ₂ c	
		Longtan	P ₂ l	
		Maokou	P_1m	
		Liangshan	P_1l	
	Carboniferous	Huanglong	C ₂ h	
	Silurian	Hanjiadian	S ₂ h	•••••
		Shiniulan	S ₁ s	
		Longmaxi	S ₁ l	
	Ordovician	Wufeng	O ₃ w	
		Linxiang	O ₃ l	
		Baota	O ₂ b	
	Cambrian		ε	
Shale Coal				
	Mudstone	Limestone		
	Sandstone	Dolomite		
<u> </u>	Conglomerate			

FIGURE 2: Schematic diagram showing the formation system and lithologic profile of the investigation area (modified after [39]).

study the vertical and lateral plane distribution characteristics of the fracture toughness in shale gas reservoirs.

3. Experiment Methods and Data

The shale samples were collected from the Lower Silurian Longmaxi Formation in the Changning area, Sichuan Basin. The fracture toughness test was conducted by using the Cracked Chevron Notched Brazilian Disc (CCNBD) method. And the requirements of sample preparation and related parameters are shown in the literature [40]. The processing pattern of CCNBD of shale samples can be shown in Figure S1 (in the supporting data), and the geometric dimensions of CCNBD samples are represented in Table S1 (in the supporting data). The detailed experimental process can be referred to the literature [22]. Acoustic tests of shale samples were carried out by the transmission method. During the tests, two ultrasonic transducers were placed on both ends of the plug sample. One was used for the emission of P-wave or S-wave, and the other was used for receiving the P-wave or S-wave travel across the sample. The digital oscilloscope can record the waveform of the P-



FIGURE 3: Flow chart of prediction on shale fracture toughness.

wave or S-wave. Based on the obtained waveform information, the arrival time of the first wave of the P-wave or S-wave can be obtained, and the P-wave or S-wave acoustic interval transit time of the sample can be calculated.

The results of acoustic testing and fracture toughness testing were listed in Figures 4-7; some experimental results can be referred to the literature [33]. From Figure 4, the rock physical test results of shale samples show that the volume density of shale samples from the Lower Silurian Longmaxi Formation ranges from 2.35 g/cm³ to 2.54 g/cm³. From Figures 5 and 6, we can observe that the distribution range of P-wave acoustic interval transit time of shales from the Silurian Longmaxi Formation is between 202.67 and 312.67 μ s/m, and that of the P-wave attenuation coefficient is between 45.25 and 93.36 dB/m. The distribution range of S-wave acoustic interval transit time of shales from the Silurian Longmaxi Formation is 387.39~530.77 µs/m, and that of S-wave attenuation coefficient is 51.87~104.11 dB/m. From Figure 7, the fracture toughness test results of shale samples based on the Cracked Chevron Notched Brazilian Disc (CCNBD) method show that the fracture toughness values of shales from the Silurian Formation range from 0.4259 to 1.1667 MPa•m^{0.5}.

In order to establish the prediction model of the fracture toughness and verify the reliability of the model, the experimental data in this study are divided into two groups: the first group contains the first 19 shale samples and the second group includes the last 15 shale samples. The experimental



FIGURE 4: The bulk density of samples.

data from the first group are applied to obtain the laws of the acoustic response to the fracture toughness. Based on this, the prediction model of the fracture toughness can be constructed. The experimental data from the second group are applied to validate the reliability of the prediction model. Therefore, based on the results of the rock physics experiments and the fracture toughness tests, the correlations between the fracture toughness and acoustic parameters of shale samples from the Silurian Longmaxi Formation are shown in Figures S2-S4 (in the supporting data) and Table 1. As shown in Figures S2-S4 and Table 1, the fracture toughness has a negative correlation with the P-



FIGURE 5: The acoustic interval transit time of samples.



FIGURE 6: The attenuation coefficient of samples.



FIGURE 7: The fracture toughness of samples.

wave or S-wave acoustic interval transit time. Meanwhile, relationships between the fracture toughness and the Pwave or S-wave attenuation coefficient can be observed. However, fracture toughness has a positive correlation with the P-wave or S-wave impedances. The findings indicate that the fracture toughness in shale gas reservoirs from the Lower Silurian Longmaxi Formation is sensitive to the acoustic interval transit times and wave impedances.

In the previous research [22], the mineral composition in shales had an impact on fracture toughness, and the brittle minerals had a negative correlation with the fracture toughness. And when the shale rock is contacted with water, fracture toughness of shales could decrease, indicating that the interaction between hydrophilic fluid and shale can easily cause damage to shale rock and shale can be easy to be fractured. The mineral compositions and water contents have an influence on the acoustic propagation law, which can affect the prediction of the fracture toughness. Furthermore, shale has developed bedding and rich in organic matter, and these characteristics can have an impact on the fracture toughness of shales and also on the acoustic propagation law of shales. The acoustic testing and fracture toughness testing are carried out under the same conditions, and the experimental data can be obtained under the same conditions, which can be used to analyse and develop a prediction model. Based on this, the prediction model for calculating the fracture

4. Prediction of the Fracture Toughness by Well Logging

toughness can be established.

Based on the laws of the acoustic response to the fracture toughness, considering the P-wave and S-wave acoustic interval transit time, we construct the calculation model of the fracture toughness by the least square method according to the theory of multiple regression:

$$K_{\rm IC} = -0.00023\Delta t_c - 0.00336\Delta t_s + 2.3431 \left(R^2 = 0.7132 \right),$$
(1)

where $K_{\rm IC}$ represents the fracture toughness; Δt_p represents the P-wave acoustic interval transit time; Δt_s represents the S-wave acoustic interval transit time. The correlation coefficient (R^2) is a criterion for evaluating the fitness, which can be used to illustrate the deviation of data. Obviously, the closer to one the value of R^2 , the less discrete the data [2]. The correlation coefficient can be calculated.

$$R^{2} = \frac{\sum_{i=1}^{n} \left(\widehat{y}_{i} - \overline{y} \right)^{2}}{\sum_{i=1}^{n} \left(y_{i} - \overline{y} \right)^{2}},$$
(2)

where y_i represents the measured fracture toughness of the *i*th sample; \bar{y} represents the average value of the measured fracture toughness of the *i*th sample; \hat{y}_i represents the calculated fracture toughness of the *i*th sample.

The prediction model of the fracture toughness of shales can be used to calculate the fracture toughness value of shale, as is shown in Figure 8. From Figure 8, we can note that the fracture toughness calculated by the proposed model was in agreement with the experimental data, and the average relative error between the calculation values and the measured values of the fracture toughness of shales was 8.43%. Based on this, the second group including some CCNBD samples are chosen to verify the reliability of the model, and the geometric dimensions of CCNBD samples are represented in

		*
Acoustic parameters	P-wave	S-wave
Acoustic interval transit time	$K_{\rm IC} = -0.0041 \Delta t_p + 1.783 \left(R^2 = 0.6113 \right)$	$K_{\rm IC} = -0.0035 \Delta t_s + 2.361 \left(R^2 = 0.7297 \right)$
Attenuation coefficient	$K_{\rm IC} = -0.0129 \alpha_p + 1.6242 \left(R^2 = 0.4215 \right)$	$K_{IC} = -0.0104\alpha_s + 1.5728 \left(R^2 = 0.5234 \right)$
Wave impedance	$K_{\rm IC} = 0.0986 Z_p - 0.2278 \left(R^2 = 0.6456 \right)$	$K_{\rm IC} = 0.253 Z_s - 0.6147 \left(R^2 = 0.713 \right)$

TABLE 1: The relationships between fracture toughness and acoustic parameters of shale samples.

Note: K_{IC} represents the mode I fracture toughness, simplified fracture toughness; Δt_p represents the P-wave acoustic interval transit time; Δt_s represents the S-wave acoustic interval transit time; α_p represents the P-wave attenuation coefficient; α_s represents the S-wave attenuation coefficient; Z_p represents the P-wave impedances; Z_s represents the S-wave impedances.



FIGURE 8: Experimental vs. calculated of fracture toughness of shale samples.



FIGURE 9: Experimental vs. predictive of fracture toughness of shale samples.

Table S1 (in the supporting data), and the results of acoustic testing and fracture toughness testing are listed in Figures 5 and 7, respectively. Then, the fracture toughness values of those samples are predicted based on the model. As is shown in Figure 9, we can note that the predictable accuracy of the prediction model was high, and the predictive values were in excellent agreement with the experimental data. The

average relative error between the prediction values and the measured values of the fracture toughness of shales was 9.64%, which was less than 10%. The results suggest that the calculation model of the fracture toughness of shales has a certain reliability.

Generally, it is much easier for shale gas reservoir to be fractured with a higher brittleness index or lower fracture



FIGURE 10: Continued.



FIGURE 10: The logging profile of the predicted fracture toughness of shales in the study area.

toughness. The predicted well logging profile (Well A and Well B) of the brittleness index and the fracture toughness in the study area is shown in Figure 10. The calculation

equation of the brittleness index based on the mineral compositions in the figure refer to literature [5], that is, Brittleness = Q/(Q + C + Cly) (where Q is the quartz



FIGURE 11: The P-wave velocity profile of the connecting well from well A to well B in the Wufeng- Longmaxi Formation.

contents, C is the carbonates contents, and Cly is the clay minerals contents), which can be used to represent the capacity to create a complex fracture network in shale gas reservoirs. And the calculation equation of the fracture toughness is the prediction model constructed in this paper. As shown in Figure 10, with the increase in the depth, the fracture toughness and the brittleness index change towards opposite directions to some extent. Thus, the fracture toughness tends to decrease when the brittleness index increases. Besides, the fracture toughness values of the shale gas reservoir intervals are lower than that of the nonreservoir intervals. The findings suggest that the fracture toughness can also be used to evaluate the fracability in shale gas reservoirs, and the prediction model of the fracture toughness is reliable. In addition, it can be noted from the well logging profile that the fracture toughness value of shales from the bottom of the Lower Silurian Longmaxi Formation is lower when the organic carbon content is larger, indicating that the shale gas reservoirs in the bottom of the Lower Silurian Longmaxi Formation has relatively good fracability. This is similar to the results from Liu et al. [41], suggesting that the brittleness index of shale formation with high organic carbon content is also large.

5. Quantitative Prediction of the Fracture Toughness

The single well profile of the fracture toughness in shale formation obtained through well-logging data only shows that the fracture toughness varies with the depth. However, the lateral distribution characteristics of the fracture toughness in the study area cannot be got from a single well profile. The single well profile of the fracture toughness (vertical or horizontal well) in shale formation can be obtained, and well interval can be divided into several small sections for fracturing. And the three-dimensional spatial distribution of the fracture toughness in shale formation can be obtained, the area that is easier to fracture can be determined, which can help us to choose the engineering sweet spots of shale gas reservoirs. Therefore, in order to investigate the spatial distribution of the fracture toughness in shale gas reservoirs, jointing well logging and seismic method could be adopted to quantitatively predict the fracture toughness in shale gas reservoirs. Based on the well logging data and seismic data, the spatial distribution prediction of fracture toughness values in shale formation is carried out through the jointing well logging and seismic method. Besides, its vertical and lateral distribution characteristics are studied.

The GeoScope geological magnifying glass software was used in this study. In the GEOLOG module of GeoScope software, the three-dimension seismic data in the study area, the top and bottom interface stratification data of the Liangshan Formation and Wufeng Formation, and the logging data of two wells (Well A and Well B) in the study area were imported, respectively, to make synthetic seismic records and conduct well seismic calibration. This process is mainly used for horizon labeling. The logging accuracy is higher while the seismic accuracy is lower, and the acoustic frequency of logging is different from the seismic. Therefore, the seismic horizon and logging horizon should be jointly calibrated, and then the information from logging and from seismic at the same depth can be obtained. On this basis, the P-wave velocity profile of the connecting well from Well A to Well B in Wufeng Formation to Longmaxi Formation is obtained. As shown in Figure 11, the variation trends of the P-wave velocities of Well A and Well B obtained from well longing are the same to that obtained from seismic. However, the P-wave velocity obtained from well logging is different from that obtained from seismic. Considering that the prediction model of the fracture toughness in this study is built on the basis of the acoustic frequency of logging, it is



FIGURE 12: The relationships between the velocity obtained from well logging and that obtained from seismic inversion.



FIGURE 13: The profile of the fracture toughness values of the Wufeng-Longmaxi formation across Well A to Well B.

necessary to establish the relationship between acoustic velocity from the seismic inversion and the acoustic velocity from the well logging in order to predict the vertical and lateral plane distribution of the fracture toughness in shale gas reservoir. Taking well A as an example, the relationships between the P-wave and S-wave velocity obtained from well logging at the corresponding depth and the P-wave and Swave velocity obtained from seismic inversion are established, respectively. As shown in Figure 12, there are good linear relationships between the velocity obtained from well logging and that obtained from seismic inversion.

On this basis, combined with the prediction model of the fracture toughness constructed in this study (Eq. (1)), the inversion data of the fracture toughness in shale formation can be calculated. Section profiles of fracture toughness values of the Wufeng-Longmaxi Formation in the study area can be obtained by slicing. Figure 13 shows the section pro-

files of the fracture toughness values of the Wufeng-Longmaxi Formation across Well A to Well B. It can be seen from Figure 13 that the fracture toughness varies rapidly in the vertical direction. In the vertical direction, the variation trend of the fracture toughness predicted by the welllogging of Well A and Well B is consistent with that by the seismic profile, indicating that the bottom of the Wufeng-Longmaxi Formation has the characteristics of lower fracture toughness, in which the Well A is known and the Well B is verified. From this perspective, the prediction model of the fracture toughness in this study has certain reliability.

Based on the fracture toughness data of the shales from the Wufeng-Longmaxi Formation, the section profile of the fracture toughness value in the Wufeng-Longmaxi Formation was obtained by time slice. Thus, the vertical and lateral distribution characteristics of the fracture toughness values in the Wufeng-Longmaxi Formation are obtained, as shown



(c) 19 ms from the bottom of Wufeng Formation

FIGURE 14: The plane distribution of the fracture toughness of shales in the bottom of Wufeng-Longmaxi Formation.

in Figure 14. As can be seen from Figures 10 and 14, the fracture toughness values of shales from the Upper Wufeng-Longmaxi Formation in the study area is relatively higher, whereas the fracture toughness values of shale from the Lower Wufeng-Longmaxi Formation is relatively lower. Moreover, in the vertical direction, the fracture toughness values of shales are mainly distributed in strips, the distribution area of the high fracture toughness values and the low fracture toughness values have the characteristics of interval distribution, and the distribution area are continuous in the lateral direction, indicating that it has obvious stratification characteristics. From Figure 14, the Wufeng-Longmaxi Formation in the study area has significantly lower fracture toughness values in a time window from 8 ms to 15 ms near the bottom of the formation. The lower fracture toughness zones are present mainly in the eastern and southern parts of the work area, indicating that the shale gas reservoirs in the bottom of the Upper Ordovician Wufeng-Lower Silurian Longmaxi Formation have relatively good fracability.

6. Conclusions

In this paper, the prediction of the fracture toughness in shale formation based on well logging and seismic data from the Lower Silurian Longmaxi Formation in the Sichuan Basin of China was investigated. The following conclusions are drawn:

- (1) The fracture toughness is negatively correlated with the acoustic interval transit time and attenuation coefficient, whereas it is positively correlated with the wave impedance. The fracture toughness of shales is sensitive to the acoustic interval transit time and wave impedance
- (2) Based on the laws of the acoustic response to the fracture toughness, the prediction model of the fracture toughness was constructed, which is effective in predicting the fracture toughness in shale gas reservoirs. By means of jointing well logging and seismic method, the plane distribution of the fracture toughness in the study area is obtained. Besides, the spatial distribution characteristics of the fracture toughness of shales are investigated
- (3) The fracture toughness of shales from the Upper Wufeng-Longmaxi Formation is larger, whereas that in the Lower Wufeng-Longmaxi Formation is lower. The fracture toughness values are mainly distributed in strips in the vertical direction while the distribution area is continuous in the lateral direction, indicating that it has obvious stratification characteristics

Data Availability

The processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the National Science and Technology Major Project (Grant No. 2019A-3307). We also thank the Young Scientific and Technological Innovation Team of Rock Physics in Unconventional Strata of Southwest Petroleum University (No. 2018CXTD13).

Supplementary Materials

Figure S1: sample processing pattern of CCNBD. Figure S2: the relationships between the fracture toughness and the acoustic interval transit time (left is the P-wave; right is the S-wave). Figure S3: the relationships between the fracture toughness and the attenuation coefficient (left is the P-wave; right is the S-wave). Figure S4: the relationships between the fracture toughness and the wave impedance (left is the P-wave; right is the S-wave). Table S1: geometric dimensions of CCNBD samples. (*Supplementary Materials*)

References

- US Energy Information Administration (EIA), "Technically recoverable shale oil and shale gas resources: an assessment of 137 shale formations in 41 countries outside the United States," 2015, http://www.eia.gov/analysis/studies/ worldshalegas.
- [2] J. Xiong, X. Liu, and L. Liang, "Application of adsorption potential theory to methane adsorption on organic-rich shales at above critical temperature," *Environmental Earth Sciences*, vol. 77, no. 3, p. 99, 2018.
- [3] G. S. Li, M. Sheng, S. C. Tian, H. K. Ge, Z. W. Huang, and X. Z. Song, "Key issues and investigation of horizontal well drilling and multistage fracturing in shale gas reservoir," *Chinese Science Bulletin*, vol. 61, no. 26, pp. 2883–2890, 2016.
- [4] Z. Huo, J. Zhang, P. Li et al., "An improved evaluation method for the brittleness index of shale and its application—a case study from the southern North China basin," *Journal of Natural Gas Science and Engineering*, vol. 59, pp. 47–55, 2018.
- [5] D. M. Jarvie, R. J. Hill, T. E. Ruble, and R. M. Pollastro, "Unconventional shale-gas systems: the Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment," *AAPG Bulletin*, vol. 91, no. 4, pp. 475–499, 2007.
- [6] I. Rahimzadeh Kivi, M. Zare-Reisabadi, M. Saemi, and Z. Zamani, "An intelligent approach to brittleness index estimation in gas shale reservoirs: a case study from a western Iranian basin," *Journal of Natural Gas Science and Engineering*, vol. 44, pp. 177–190, 2017.
- [7] J. Li and W. Li, "A quantitative seismic prediction technique for the brittleness index of shale in the Jiaoshiba Block, Fuling shale gas field in the Sichuan Basin," *Natural Gas Industry B*, vol. 5, no. 1, pp. 1–7, 2018.
- [8] K. S. Mews, M. M. Alhubail, and R. G. Barati, "A review of brittleness index correlations for unconventional tight and ultratight reservoirs," *Geosciences*, vol. 9, no. 7, p. 319, 2019.
- [9] X. Shi, G. Liu, Y. Cheng et al., "Brittleness index prediction in shale gas reservoirs based on efficient network models," *Journal of Natural Gas Science and Engineering*, vol. 35, pp. 673– 685, 2016.
- [10] Q. Wang, B. Zhang, S. Guo, and J. Han, "Effect of anisotropy, angle, and critical tensile stress and confining pressures on evaluation of shale brittleness index—part 1: methodology and laboratory study," *Interpretation*, vol. 7, no. 3, pp. T637– T646, 2019.
- [11] D. Zhang, P. G. Ranjith, and M. S. A. Perera, "The brittleness indices used in rock mechanics and their application in shale hydraulic fracturing: a review," *Journal of Petroleum Science* and Engineering, vol. 143, pp. 158–170, 2016.

- [12] M. Bai, "Why are brittleness and fracability not equivalent in designing hydraulic fracturing in tight shale gas reservoirs," *Petroleum*, vol. 2, no. 1, pp. 1–19, 2016.
- [13] X. Jin, S. Shah, J. C. Roegiers, and B. Zhang, "An integrated petrophysics and geomechanics approach for fracability evaluation in shale reservoirs," *SPE Journal*, vol. 20, no. 3, pp. 518– 526, 2015.
- [14] J. A. Breyer, H. Alsleben, and M. B. Enderlin, "Predicting fracability in shale reservoirs," in AAPG Annual Conference and Exhibition: Making the Next Giant Leap in Geosciences, Houston, 2011.
- [15] S. Kahraman and R. Altindag, "A brittleness index to estimate fracture toughness," *International Journal of Rock Mechanics* and Mining Sciences, vol. 41, no. 2, pp. 343–348, 2004.
- [16] M. R. Chandler, P. G. Meredith, N. Brantut, and B. R. Crawford, "Fracture toughness anisotropy in shale," *Journal of Geophysical Research: Solid Earth*, vol. 121, no. 3, pp. 1706–1729, 2016.
- [17] H. Wang, F. Zhao, Z. Huang, Y. Yao, and G. Yuan, "Experimental study of mode-I fracture toughness for layered shale based on two ISRM-suggested methods," *Rock Mechanics and Rock Engineering*, vol. 50, no. 7, pp. 1933–1939, 2017.
- [18] B. Mahanta, A. Tripathy, V. Vishal, T. N. Singh, and P. G. Ranjith, "Effects of strain rate on fracture toughness and energy release rate of gas shales," *Engineering Geology*, vol. 218, pp. 39–49, 2017.
- [19] J. Yuan, J. Zhou, S. Liu et al., "An improved fracabilityevaluation method for shale reservoirs based on new fracture toughness-prediction models," *SPE Journal*, vol. 22, no. 5, pp. 1704–1713, 2017.
- [20] X. Su, P. Chen, and T. Ma, "Evaluation of shale fracture toughness based on micrometer indentation test," *Petroleum*, vol. 5, no. 1, pp. 52–57, 2019.
- [21] G. Ji, K. Li, G. Zhang, S. Li, and L. Zhang, "An assessment method for shale fracability based on fractal theory and fracture toughness," *Engineering Fracture Mechanics*, vol. 211, pp. 282–290, 2019.
- [22] J. Xiong, K. Liu, L. Liang, X. Liu, and C. Zhang, "Investigation of influence factors of the fracture toughness of shale: a case study of the Longmaxi formation shale in Sichuan Basin, China," *Geotechnical and Geological Engineering*, vol. 37, no. 4, pp. 2927–2934, 2019.
- [23] Z. Zhang, "An empirical relation between mode I fracture toughness and the tensile strength of rock," *International Journal of Rock Mechanics and Mining Sciences*, vol. 39, no. 3, pp. 401–406, 2002.
- [24] J. Wang, J. Zhu, C. Chiu, and H. Zhang, "Experimental study on fracture toughness and tensile strength of a clay," *Engineering Geology*, vol. 94, no. 1-2, pp. 65–75, 2007.
- [25] W. Hua, S. Dong, Y. Fan, X. Pan, and Q. Wang, "Investigation on the correlation of mode II fracture toughness of sandstone with tensile strength," *Engineering Fracture Mechanics*, vol. 184, pp. 249–258, 2017.
- [26] A. Mohammed and W. Mahmood, "Vipulanandan failure models to predict the tensile strength, compressive modulus, fracture toughness and ultimate shear strength of calcium rocks," *International Journal of Geotechnical Engineering*, pp. 1–11, 2018.
- [27] G. J. Brown and D. J. Reddish, "Experimental relations between rock fracture toughness and density," *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, no. 1, pp. 153–155, 1997.

- [28] S. H. Chang, C. Lee, and S. Jeon, "Measurement of rock fracture toughness under modes I and II and mixed-mode conditions by using disc-type specimens," *Engineering Geology*, vol. 66, no. 1-2, pp. 79–97, 2002.
- [29] C. Zhixi, C. Mian, J. Yan, and H. Rongzun, "Determination of rock fracture toughness and its relationship with acoustic velocity," *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, no. 3-4, pp. 49.e1–49.e11, 1997.
- [30] Y. Jin, J. Yuan, M. Chen, K. Chen, Y. Lu, and H. Wang, "Determination of rock fracture toughness _{K IIC} and its relationship with tensile strength," *Rock Mechanics and Rock Engineering*, vol. 44, no. 5, pp. 621–627, 2011.
- [31] D. Guha Roy, T. N. Singh, J. Kodikara, and M. Talukdar, "Correlating the mechanical and physical properties with mode-I fracture toughness of rocks," *Rock Mechanics and Rock Engineering*, vol. 50, no. 7, pp. 1941–1946, 2017.
- [32] D. G. Roy, T. N. Singh, and J. Kodikara, "Predicting mode-I fracture toughness of rocks using soft computing and multiple regression," *Measurement*, vol. 126, pp. 231–241, 2018.
- [33] J. Xiong, Q. Zhang, X. Liu, and L. Liang, "Prediction method and characteristics of the fracture toughness of Longmaxi formation shale in Sichuan Basin," *Chinese Journal of Underground Space and Engineering*, vol. 15, no. S2, pp. 541–547, 2019.
- [34] S. Chen, W. Zhao, Y. Ouyang et al., "Prediction of sweet spots in shale reservoir based on geophysical well logging and 3D seismic data: a case study of lower Silurian Longmaxi formation in W4 block, Sichuan Basin, China," *Energy Exploration* & *Exploitation*, vol. 35, no. 2, pp. 147–171, 2017.
- [35] R. Pan, Q. Gong, J. Yan, and J. Jin, "Elements and gas enrichment laws of sweet spots in shale gas reservoir: a case study of the Longmaxi Fm in Changning block, Sichuan Basin," *Natural Gas Industry B*, vol. 3, no. 3, pp. 195–201, 2016.
- [36] D. Zhao, G. Yinghai, S. Yin, C. Ren, and Y. Wang, "Prediction of geomechanical sweet spots in a tight gas sandstone reservoir: a case study of lower Permian strata in the southern Qinshui Basin, China," *Interpretation*, vol. 7, no. 1, pp. T207–T219, 2019.
- [37] C. Zou, Z. Yang, R. Zhu et al., "Geologic significance and optimization technique of sweet spots in unconventional shale systems," *Journal of Asian Earth Sciences*, vol. 178, pp. 3–19, 2019.
- [38] M. Zhang, C. Zou, P. Guan et al., "Pore-throat characteristics of deep shale gas reservoirs in south of Sichuan Basin: case study of Longmaxi formation in well Z201 of Zigong area," *Natural Gas Geoscience*, vol. 30, no. 9, pp. 1349–1361, 2019.
- [39] S. Chen, Y. Zhu, H. Wang, H. Liu, W. Wei, and J. Fang, "Shale gas reservoir characterisation: a typical case in the southern Sichuan Basin of China," *Energy*, vol. 36, no. 11, pp. 6609– 6616, 2011.
- [40] R. J. Fowell, "Suggested method for determining mode I fracture toughness using cracked chevron notched Brazilian disc (CCNBD) specimens," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 32, no. 1, pp. 57–64, 1995.
- [41] S. Liu, H. Li, and Y. Zhang, "Analysis of TOC content influence on shale brittleness index evaluation," *Well Logging Technol*ogy, vol. 39, no. 3, pp. 352–356, 2015.