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A novel brittleness evaluation method for shale based on nonlinear weighting of mineral composition: a case study of the Qiongzhusi formation in southwestern Sichuan Basin

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Accurate assessment of shale brittleness is crucial for identifying optimal development zones, directly impacting the effectiveness of fracturing stimulation and production forecasting. To address the ambiguity regarding the influence of different mineral components on brittleness in current mineral-based evaluation approaches, this study employs the Analytic Hierarchy Process (AHP) to quantify the brittleness contribution coefficients of diverse minerals based on their distinct physical properties. Moreover, the study considers the nonlinear correlation between mineral content and shale brittleness to enhance the existing mineral-based brittleness index model. Application of this refined model to the Qiongzhusi Formation shale in the southwestern Sichuan Basin reveals a reduction of approximately 34% in the mean relative error compared to traditional methods, demonstrating improved capture of vertical brittleness variations. This model effectively characterizes the vertical variability of shale reservoir brittleness, offering a straightforward construction process, broad applicability, and essential data support for subsequent comprehensive geological and engineering assessments.

KEYWORDS

brittleness evaluation, elastic parameters, mineral composition, Qiongzhusi Formation, shale reservoir

1 Introduction

In recent years, the focus has shifted towards unconventional natural gas reservoirs such as shale gas and coalbed methane due to the diminishing conventional oil and gas reserves and production. Shale gas, in particular, has garnered significant global attention in the realm of oil and gas exploration and development due to its abundant reserves, widespread distribution, and extended extraction lifespan (Jia, 2020; Zhang et al., 2020; Zhao et al., 2025). Shale formations typically exhibit extremely low porosity and permeability. Enhancing individual well productivity and extending stable production periods necessitate fracturing operations, with the assessment of rock brittleness playing a crucial role in the design of fracturing processes for shale oil and gas reservoirs (Lei et al., 2022; Zhu et al., 2022; Wang et al., 2021).

Brittle rocks are susceptible to inelastic deformation, such as cracking, when subjected to external forces (Wang and Wang, 2021; Hucka and Das, 1974; Hajiabdolmajid et al., 2003; Hajiabdolmajid and Kaiser, 2003; Jarvie et al., 2007; Tarasov and Potvin, 2013). Various methods exist for assessing rock brittleness, with no standardized approach. Researchers have proposed diverse methods for calculating the brittleness index (BI), including the mineral composition method (Jin et al., 2015; Jin et al., 2014; Zhang et al., 2016), elastic parameter method (Rickman et al., 2008; Sun et al., 2013; Luan et al., 2014), rock strength method (Hucka and Das, 1974; Altindag, 2003; Meng et al., 2016; Zhang et al., 2016), and stress-strain curve method (Hajiabdolmajid et al., 2003; Hajiabdolmajid and Kaiser, 2003; Mandal et al., 2022). Among these, the mineral composition and elastic parameter methods are commonly utilized in wellbore logging data due to their theoretical clarity, operational convenience, and high-resolution longitudinal profiles derived from the integration of logging and core experiments. Furthermore, some scholars aim to develop a comprehensive brittleness evaluation model by incorporating multiple factors such as mineral composition, mechanical properties, strength parameters, porosity, and energy evolution. A brittleness assessment model was developed utilizing multiple regression analysis, incorporating factors such as friction coefficient, bulk modulus, and shear modulus (Chen et al., 2016). Another study introduced a novel approach for calculating brittleness index, taking into account elastic parameters, mineral composition, and *in situ* stress conditions (Luo et al., 2024). Nonetheless, the applicability of such a comprehensive evaluation method across different geological layers and regions requires further validation. The key to assessing shale reservoir brittleness using elastic parameters hinges on accurately determining parameters like Young's modulus and Poisson's ratio, leveraging triaxial compression test data and array acoustic logging data. It is widely accepted that rocks characterized by higher Young's modulus and lower Poisson's ratio exhibit greater brittleness (Makowitz and Milliken, 2003; Jahandideh and Jafarpour, 2014).

Young's modulus and Poisson's ratio are key indicators of rock brittleness, reflecting factors such as mineral composition, cementation degree, and pore structure. However, the current elastic parameter method has limitations. Firstly, it assumes equal contributions of Young's modulus and Poisson's ratio to rock brittleness without a theoretical basis (Zhang et al., 2017). Secondly, studies have shown its ineffectiveness in distinguishing between brittle rocks rich in quartz and limestone. Thirdly, parameters like bulk modulus and pore pressure also influence brittleness. Given the high cost of acquiring shear wave time difference logging data, the mineral composition method becomes a valuable and often necessary complement. To assess shale reservoir brittleness using this method, identifying mineral compositions and their proportions through ECS (Element Capture Logging), Litho Scanner (Lithology Scanning), or XRD (Whole Rock Mineral Diffraction) experiments is crucial. Currently, this method faces several key challenges. Firstly, varying identification standards for brittle minerals result in significant discrepancies in calculation outcomes. Secondly, distinct minerals exert varying influences on the overall rock brittleness due to their unique physical properties and fracture mechanisms. Existing calculation models typically assign equal importance to all minerals, disregarding variations in their brittleness contributions (Hu et al., 2015; Huo et al., 2018). Lastly, limited research has investigated the nonlinear correlation between minerals and brittleness. Effectively enhancing the accuracy of brittleness assessment depends on scientifically determining the quantitative impact of different minerals on the overall brittleness characteristics of rocks.

To address challenges in shale brittleness assessment, such as ambiguous definitions of brittle minerals and complexities in quantifying individual mineral contributions to overall brittleness, this study introduces a novel approach. Initially, the brittleness index of each mineral constituent is computed based on variations in Young's modulus and Poisson's ratio. Subsequently, the contribution coefficient of each mineral to shale brittleness is determined using the analytic hierarchy process. A new brittleness evaluation model, the mineral component method, is then formulated, accounting for the nonlinear relationship between minerals and brittleness. The model's efficacy is validated through its application to evaluating shale gas reservoirs in the Qiongzhusi formation in the southwest of the Sichuan Basin, China. The study investigates the effects of factors such as confining pressure and temperature on shale brittleness. This research offers a precise methodology for assessing shale reservoir brittleness, furnishing theoretical underpinning and technical guidance for the refined evaluation of unconventional reservoirs and the optimization of favorable zones.

2 Geological setting

The study area is located within the Cambrian Qiongzhusi Formation in the southwestern Sichuan Basin, encompassing parts of Leshan and Zigong cities in Sichuan Province. Structurally, it is situated in the northwestern portion of the southwestern Sichuan depression and forms the southwestern segment of the Weiyuan structure. Influenced by the third phase of the Tongwan movement and the Xingkai movement, the region evolved into the Mianyang–Changning extensional trough, where high-quality hydrocarbon source rocks from the Maidiping and Qiongzhusi formations were deposited. The study area lies on the gentle western slope of this extensional trough (Li, 1998; Li et al., 2020; Liu et al., 2013). The Qiongzhusi Formation is primarily composed of silty shale and black mudstone, with burial depths ranging between 3,400 and 4,000 m. The successful extraction of industrial gas flows from multiple exploratory wells demonstrates the promising potential for shale gas development in this region.

Helium porosity measurements from 281 shale samples in the study area indicate porosity values ranging from 0.4% to 9.2%, with an average of 2.3%. Helium-based permeability ranges from 0.02 to 0.98 millidarcies (mD), averaging 0.20 mD. These results suggest that the reservoir is characterized by ultra-low porosity and ultra-low permeability.

The mineralogical composition of shale directly influences the development of fracturable space within the reservoir. X-ray diffraction (XRD) analysis of whole-rock minerals from Qiongzhusi Formation shale samples in the study area reveals that the shale

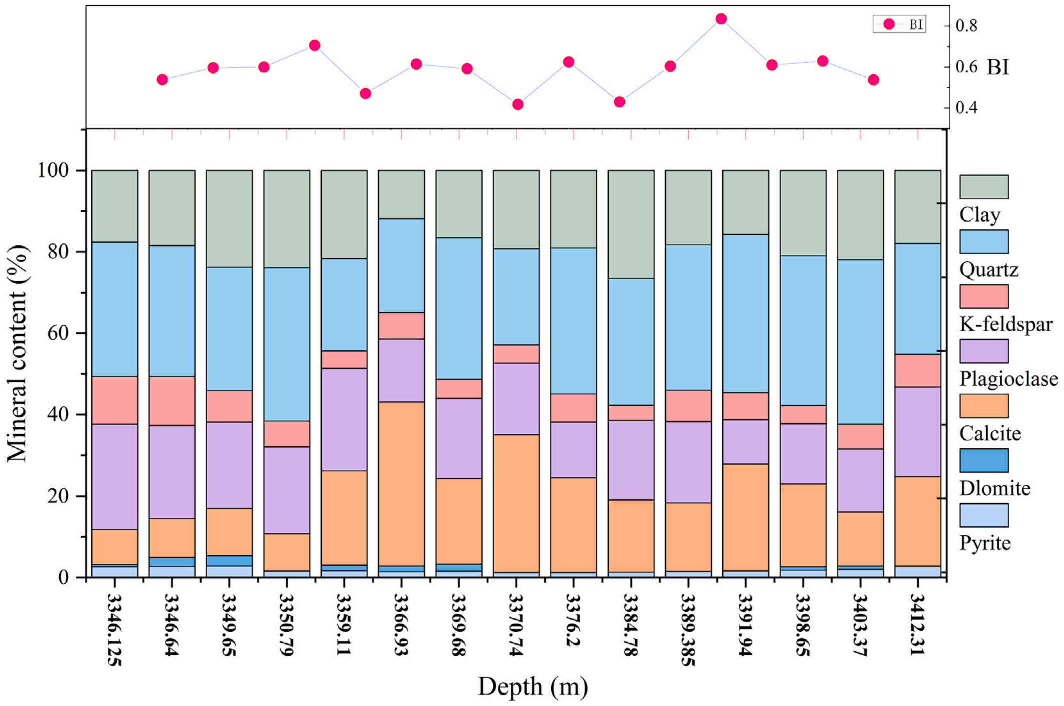

FIGURE 1
Relationship between mineral composition and brittleness of Qiongzhusi Formation shale in southern Sichuan.

is primarily composed of seven minerals: quartz, plagioclase, clay minerals, calcite, k-feldspar, dolomite, and pyrite. Quartz content ranges from 13.1% to 51.5%, with an average of 35.38%; plagioclase content ranges from 5.1% to 35.5%, averaging 21.83%; clay mineral content varies between 6.4% and 44.7%, with an average of 20.4%; and calcite content ranges from 0% to 64.2%, with an average of 10.8%. Overall, the shale reservoir in the study area is characterized by high quartz and feldspar contents and moderate clay mineral content. Notably, core brittleness does not vary with the content of any single mineral (Figure 1). Correlation analysis indicates that there is no significant relationship between mineral composition and the brittleness index (Figure 2). Furthermore, the wide range and significant fluctuations in mineral content (Figure 3) reflect a high degree of heterogeneity in the shale.

The mechanical properties of shale have a direct impact on its brittleness. Considering the *in situ* effective confining pressure and formation temperature, triaxial compression tests were conducted on shale samples under a confining pressure of 50 MPa and a temperature of 100 °C. The Young's modulus of the Qiongzhusi Formation shale ranges from 9,375 MPa to 53,585 MPa, with an average of 24,383 MPa. The Poisson's ratio varies from 0.09 to 0.26, with an average of 0.14. As previously discussed, brittle rocks typically exhibit high Young's modulus and low Poisson's ratio. However, in the study area, no typical negative correlation is observed between these two parameters (Figure 4), indicating a more complex brittleness behavior, which poses challenges for accurate brittleness evaluation.

3 A new model for brittleness evaluation

According to the characteristics and distribution of shale rocks and minerals in the study area, the shale is simplified as an aggregate of seven minerals (pyrite, dolomite, quartz, k-feldspar, plagioclase, calcite, and clay), whose composition jointly determines the shale's overall brittleness, as shown in Figure 5. The physical model of rock volume, which simplifies real rock into sections of uniform properties and treats its macroscopic physical quantities as the sum of their contributions, aligns with the construction philosophy of our brittleness model. This approach is fundamentally different from conventional metrics that define brittleness merely by the proportion of brittle minerals.

According to The Rock Physics Handbook by Mavko (2008) and other related literature, significant differences exist in Young's modulus and Poisson's ratio among different mineral components. Further analysis indicates that the brittleness index also varies considerably between minerals. Therefore, based on the elastic parameter method, the brittleness indices of seven typical minerals—such as quartz and clay—can be calculated using their respective Young's modulus and Poisson's ratio values. Considering the variations in mineral composition across different regions and to enhance the general applicability of the model, the brittleness index of mineral components is calculated using the method proposed by Luan et al. (2014), as shown in Equation 1.

Although the brittleness formula proposed by Rickman et al. (2008)—as shown in Equation 10—is more widely recognized, it may not be well-suited for determining the brittleness

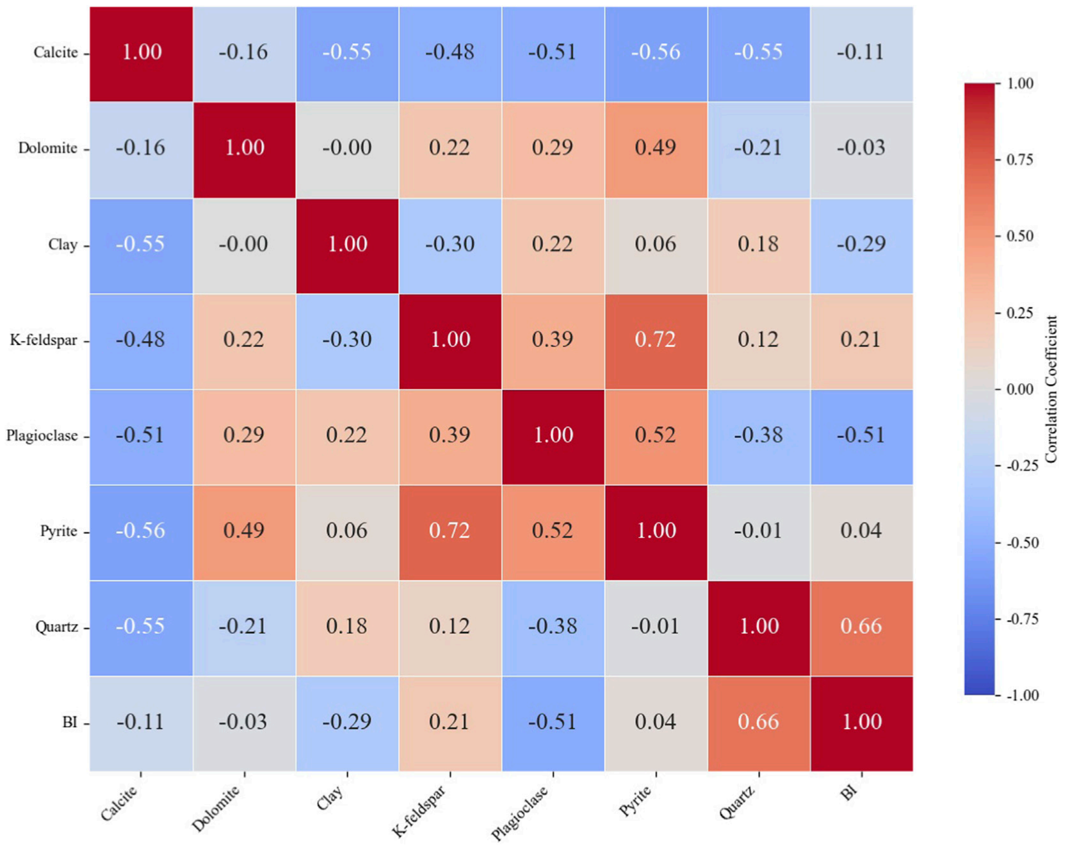

FIGURE 2
Heatmap of the correlation between mineral composition and brittleness index.

weights of different minerals. However, Equation 10 requires the determination of maximum and minimum values of elastic parameters, and variations in mineral composition can lead to significant fluctuations in the calculated weights. Furthermore, there is no consensus in the field of brittleness evaluation regarding which formula is the most accurate. Formula 1 can maximize the preservation of the differential characteristics of different minerals in terms of Young's modulus and Poisson's ratio, which not only enhances the generalization ability of the model, but also facilitates practical operation.

$$BI = \frac{E}{v} \tag{1}$$

where BI is the brittleness index; E is Young's modulus; and v is Poisson's ratio. The calculated brittleness indices of the minerals are presented in Table 1.

In this study, organic matter was grouped with clay minerals during the brittleness modeling process. This treatment is justified for two primary reasons. First, the mechanical properties of organic matter (Young's modulus of 6.26 GPa, Poisson's ratio of 0.14) and clay (Young's modulus of 14.2 GPa, Poisson's ratio of 0.30) are comparable, resulting in similar calculated brittleness indices via Formula 1. Second, given that the reservoir is characterized by low organic carbon content (average TOC of 0.27%), the volume and consequent impact of organic matter on the overall rock brittleness are negligible. It is important to note that this simplification is specific to low-organic reservoirs; for formations with high organic content, explicit inclusion of organic matter as a separate component is necessary for accurate modeling.

In order to more accurately and reasonably determine the contribution of each mineral to shale brittleness, the Analytic Hierarchy Process (AHP) is used to determine the weight coefficients of the mineral components in the brittleness evaluation. Differences in the brittleness index calculated by the elastic parameters method for each mineral are used as the basis for constructing the judgment matrix, thereby avoiding the subjectivity and uncontrollability of relying on expert scoring to determine the weights. The elements in the judgment matrix are determined by the ratio of two minerals (Equation 2):

$$a_{ij} = \frac{BI_i}{BI_j} \tag{2}$$

where a_{ij} is the element of the judgment matrix, and BI_i and BI_j are the brittleness indices of minerals i and j, respectively. The constructed judgment matrix is shown in Table 2.

After the judgment matrix is constructed, the weight (brittleness contribution coefficient) of each mineral can be determined. Comparing the weights determined by three methods, such as feature vector method, geometric average method and arithmetic average method, it is found that the weights solved by the three methods are only different in five decimal places, so the arithmetic

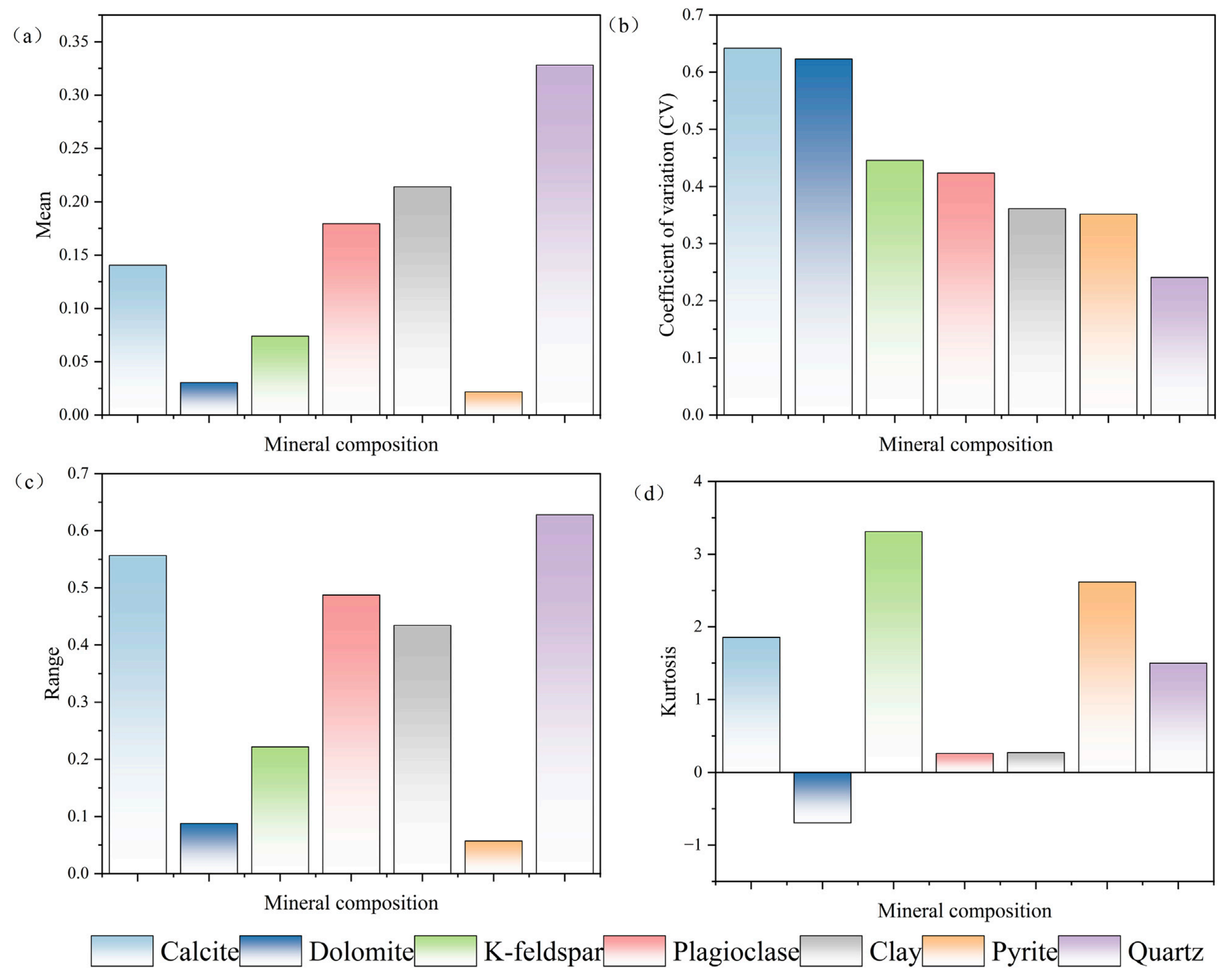

FIGURE 3
Heterogeneity analysis of the Qiongzhusi Formation from Well J1. **(a)** Mean values of mineral components, **(b)** Coefficients of variation of mineral components, **(c)** Ranges of mineral components, **(d)** Kurtosis of mineral components.

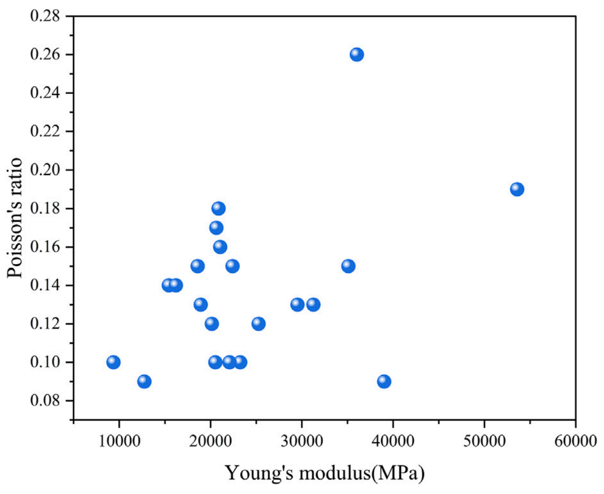

FIGURE 4
Cross plot of Young’s modulus and Poisson’s ratio.

average method with the simplest operation is selected to determine the weight results. The idea is to normalize each column first (Equation 3), and then average each row of the normalized matrix to determine the weight (Equation 4). The formula is as follows:

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{3}$$

$$w_i = \frac{1}{n}\sum_{j=1}^{n} a'_{ij} \tag{4}$$

Where, a_{ij} is the element of the judgment matrix, i.e., the brittleness contribution of mineral *i* relative to mineral *j*; a'_{ij} denotes the sum of the elements in the *j*-th column; and w_i is the brittleness contribution coefficient (weight) of mineral *i*.

After determining the weights (Table 3), a consistency check of the judgment matrix is required to verify the rationality of its construction. The consistency ratio (CR) of the constructed matrix was calculated to be approximately 0.0087, which is much lower

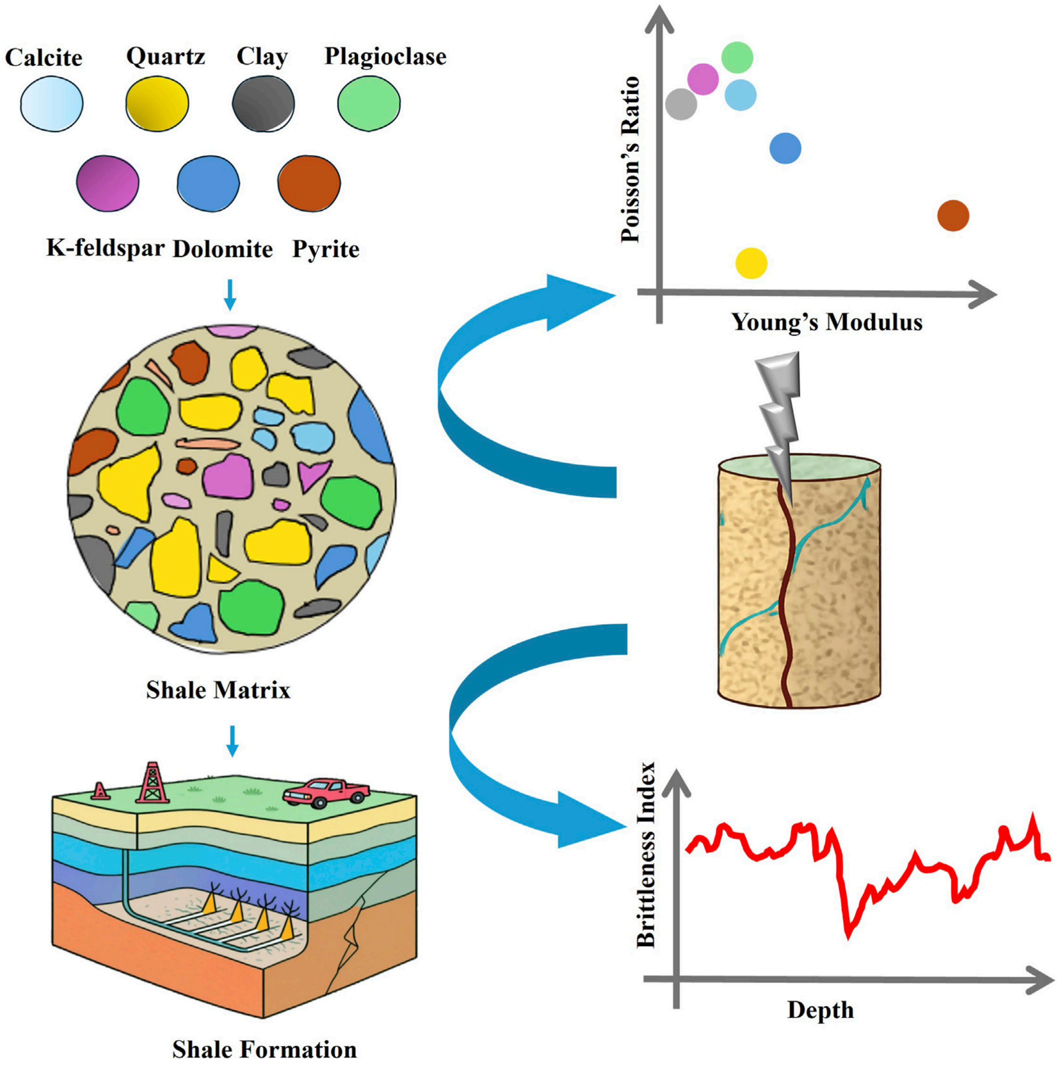

FIGURE 5
Rock physics models for brittleness evaluation.

TABLE 1 Statistical summary of elastic parameters for shale mineral components.

Parameter	Quartz	Dolomite	Pyrite	Clay	K-feldspar	Plagioclase	Calcite
E/(GPa)	95.94	121	305.32	14.2	39.62	69.02	79.58
v	0.07	0.24	0.15	0.3	0.32	0.35	0.31
BI	1,370.57	504.17	2035.47	47.33	123.81	197.20	256.71

than the threshold value of 0.1. Therefore, the consistency check is satisfied, confirming the validity of the judgment matrix.

After the brittleness contribution coefficient of minerals is determined, the brittleness contribution value of minerals at a single depth point can be determined by combining the volume fraction of mineral components.

$$BI_v = \sum_{j=1}^{n} w_i * V_i \tag{5}$$

where BI_v is the mineral brittleness contribution value; w_i and V_i are the brittleness contribution coefficient and volume fraction of mineral i, respectively.

In Equation 5, the overall brittleness of rock has a linear relationship with the volumes of rocks and minerals, but in reality, the functional relationship between rock brittleness and mineral volume is complex, and has a large relationship with the microstructure of rock and mineral (Zhang et al., 2016; Liu et al., 2018). Most of the minerals listed above are

TABLE 2 Constructed judgment matrix.

Influencing factor	Importance of each influencing factor						
	Quartz	Dolomite	Pyrite	Clay	K-feldspar	Plagioclase	Calcite
Quartz	1.00	2.72	0.67	28.95	11.07	6.95	5.34
Dolomite	0.37	1.00	0.25	10.65	4.07	2.56	1.97
Pyrite	1.49	4.04	1.00	43.00	16.44	10.32	7.93
Clay	0.03	0.09	0.02	1.00	0.38	0.24	0.18
K-feldspar	0.09	0.25	0.06	2.62	1.00	0.63	0.48
Plagioclase	0.14	0.39	0.10	4.17	1.59	1.00	0.77
Calcite	0.19	0.51	0.13	5.44	2.08	1.30	1.00

TABLE 3 Contribution coefficient of minerals to brittleness index.

Mineral	Quartz	Dolomite	Pyrite	Clay	K-feldspar	Plagioclase	Calcite
w_i	0.302	0.111	0.449	0.01	0.027	0.043	0.057

brittle minerals (Table 1), while clay is a recognized plastic mineral. Ignoring the mineral structure, it is assumed that the rock consists solely of clay and quartz, an increase in clay content leads to a reduction in rock brittleness. However, the relationship between rock brittleness and clay mineral content is not directly linear. When the clay content is low, the rock brittleness is primarily governed by quartz, resulting in a dominantly brittle response where brittleness decreases gradually. In contrast, at higher clay contents, clay minerals become the controlling factor, and the mechanical behavior shifts toward plasticity, causing brittleness to decrease rapidly and eventually plateau. This transition in the controlling mechanism results in a nonlinear relationship between rock brittleness and clay mineral content.

To further account for the nonlinear relationship between rock brittleness and clay content, the nonlinear response function from the rock volume model is adopted (Xiao et al., 2016), and the above equation is rewritten as:

$$BI_{new} = W_{cl} * V_{cl} + (1 - V_{cl}) * \sum_{j=1}^{6} w_i * V_i \tag{6}$$

In the equation, BI_{new} is the brittleness index based on the new evaluation method; w_{cl} and V_{cl} denote the brittleness contribution coefficient and volume fraction of clay minerals, respectively. The calculated brittleness values are finally normalized to facilitate comparison with other methods. When $V_{cl} = 1$, the lithology corresponds to pure mudstone, and the brittleness index is controlled solely by clay minerals; when $V_{cl} = 0$, the brittleness is determined entirely by other minerals; when V_{cl} lies between 0 and 1, clay minerals contribute plastically to the overall brittleness, a consensus widely accepted in current research.

When the clay mineral content significantly decreases, the value of $(1 - V_{cl})$ increases, leading to a greater contribution of brittle minerals to the overall brittleness and a relatively smaller contribution from clay minerals. Conversely, when the clay mineral content significantly increases, the value of $(1 - V_{cl})$ decreases, resulting in a reduced contribution of brittle minerals and a relatively larger contribution from clay minerals. This effectively characterizes the nonlinear relationship between brittleness and variations in mineral composition.

4 Verification and application

Based on the brittleness evaluation method developed in this study, Equation 6 is applied to the Qiongzhusi Formation shale interval from Well J1 in the southwestern Sichuan Basin. A continuous vertical brittleness index profile is obtained through the following steps: First, the mineral composition is derived from elemental data acquired by lithology scanning logging and is then calibrated against XRD analysis results. Then, the brittleness index is calculated, and the final interpretation result is presented as a logging interpretation diagram (Figure 6). In Figure 6, Track 9 compares the continuous brittleness index curve (curve) calculated by the new method with core-based experimental brittleness index data (bar line). As shown, the two exhibit consistent vertical variation trends.

To validate the new method, a scatter correlation plot between the calculated brittleness index and the experimental brittleness index was drawn (Figure 7). Statistical analysis shows a significant positive correlation between the two, with a coefficient of determination R^2 of 0.64, an average relative error of 9.45%, and a maximum absolute error of 0.1108. These results confirm

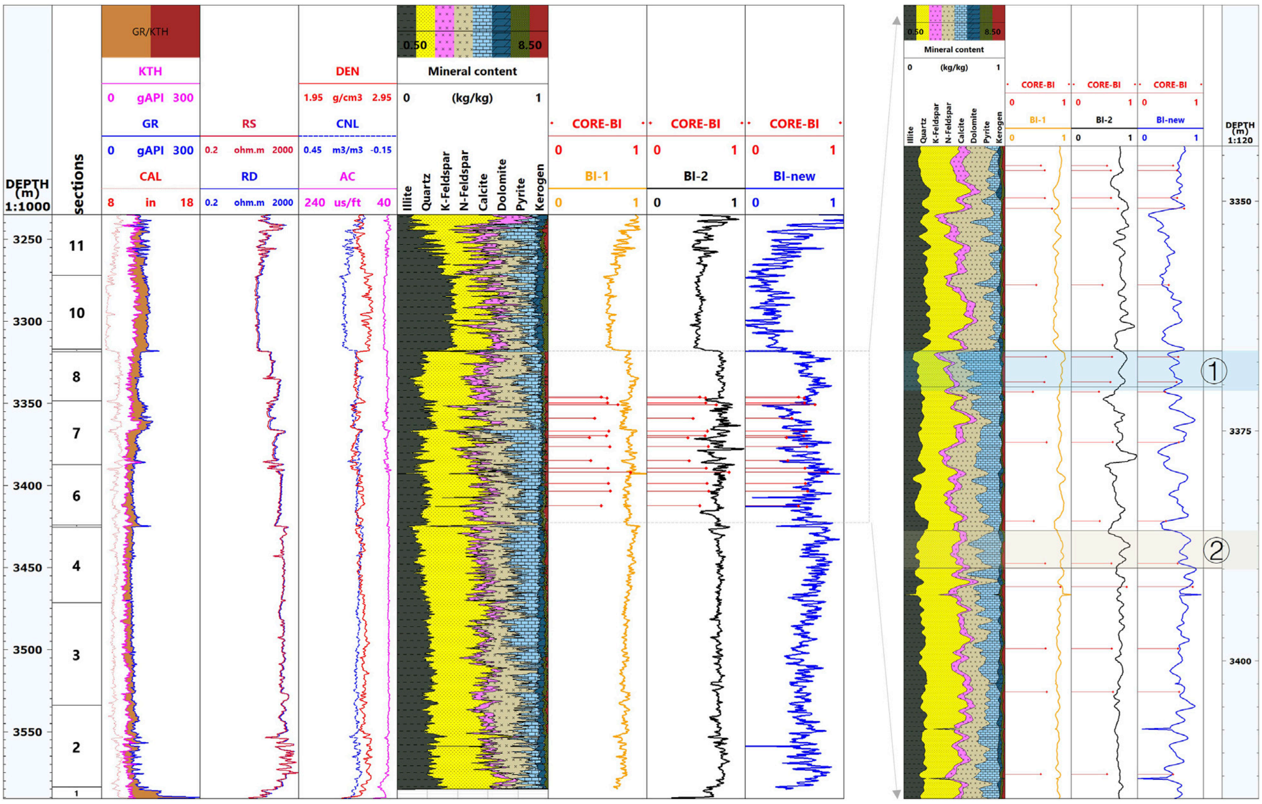

FIGURE 6
Brittleness evaluation results of well J1.

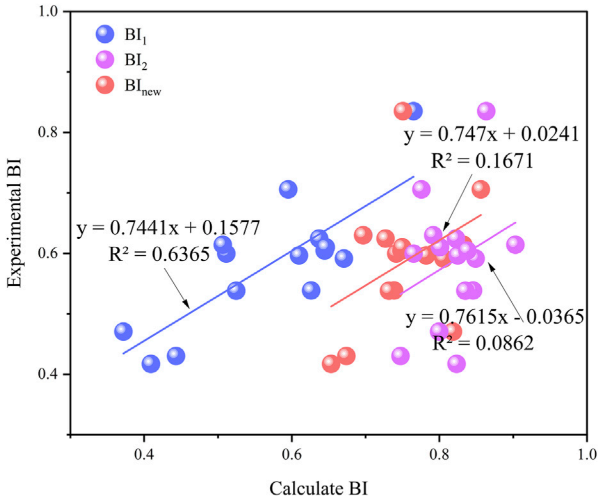

FIGURE 7
Comparison between calculated BI and experimental data.

the effectiveness of the nonlinear mineral-weighted brittleness evaluation method proposed in this study.

In the vertical direction, the shale brittleness of the Qiongzhusi Formation varies significantly, with the 4th and 8th layers having higher brittleness, with an average of 0.70, while the 10th layer with higher clay content has lower brittleness, with an average of 0.24.

In Figure 6, the tracks from left to right are arranged as follows: Track 1: depth (DEPTH: m); Track 2: stratigraphic subzone; Track 3: uranium-depleted gamma (KTH: gAPI), natural gamma logging (GR: gAPI) and caliper (CAL: in); Track 4: apparent resistivity logging curve (RD/RS: ohm. m); Track 5: acoustic-wave slowness logs (AC: us/ft), bulk density (DEN: g/cm3), and neutron porosity (CNL:m3/m3); Track 6: Weight percentage of minerals obtained by lithology scanning logging inversion (kg/kg); Track 7 to 9: core experimental brittleness index (CORE-BI), original mineral composition method brittleness index (BI_1), elastic parameter method brittleness index (BI_2) and new method brittleness index (BI_{new}); Tracks 10 to 13 provide enlarged views of Tracks 6 to 9.

In Table 4, MAE refers to Mean Absolute Error; RMSE refers to Root Mean Square Error; MAPE refers to Mean Absolute Percentage Error; and R refers to the Pearson Correlation Coefficient.

5 Discussion and prospect

5.1 Comparative analysis of results of different brittleness evaluation methods

In this paper, the newly established brittleness evaluation method (BI_{new}) is compared with the traditional mineral

TABLE 4 Error statistics of brittleness indices from different methods.

Model	MAE	RMSE	MAPE	R
BI_{new}	0.0564	0.0676	9.4503	0.7978
BI_2	0.1778	0.1908	32.7752	0.4088
BI_1	0.2318	0.2512	43.3169	0.2936

composition method (BI_1) and elastic parameter method (BI_2). Among them, the traditional mineral composition method is obtained by the calculation formula considering the brittleness of quartz, feldspar, calcite, dolomite and other minerals (Jin et al., 2015):

$$BI_1 = \frac{W_{si} + W_{car}}{W_{si} + W_{car} + W_{clay}} \tag{7}$$

In Equation 7, BI_1 is the rock brittleness index of the traditional mineral composition method, and W_{si}, W_{car}, and W_{clay} are the contents of felsic, carbonate, and clay, kg/kg, respectively. Among them, felsic is mainly composed of quartz and feldspar, and carbonate is mainly composed of dolomite and calcite.

The elastic parameter method is calculated by the classical Rickman brittleness evaluation method (Rickman et al., 2008):

$$\Delta E = \frac{E - E_{min}}{E_{max} - E_{min}} \tag{8}$$

$$\Delta PR = \frac{PR_{max} - PR}{PR_{max} - PR_{min}} \tag{9}$$

$$BI_2 = \frac{\Delta E + \Delta PR}{2} \tag{10}$$

Where ΔE and ΔPR are the normalized Young's modulus and Poisson's ratio, respectively. This approach involves the positive normalization of Young's modulus (Equation 8), the inverse normalization of Poisson's ratio (Equation 9), and their combination to derive the brittleness index (Equation 10).

Comparing the scatter diagram of the calculation results of the three methods (Figure 7), the determination coefficient R^2 of the new method is significantly higher than that of the traditional method, which further verifies its reliability. The error statistical analysis of the three methods (Table 4) shows that the error of the new method is significantly lower than that of the traditional mineral composition method and elastic parameter method, indicating that it has high calculation accuracy.

The correlation between each of the two mineral-based brittleness evaluation methods and individual minerals differs, but clay and plagioclase exhibit a negative correlation with brittleness, that is, they are plastic contributions. The reasons are twofold. First, the physical properties of clay and plagioclase determine their low brittleness. Second, the contents of clay and plagioclase in the study area are relatively high, which are 20.4% and 21.8% respectively, making their impact more significant. The average proportion of pyrite in the study area is only 1.6%, while the proportion of quartz is as high as 35.4%, so the brittleness of the study area is mainly provided by quartz. As shown in the correlation between brittleness index and minerals (Figure 8), the brittleness results from the new method are largely consistent with those from core experiments.

5.2 Necessity analysis of mineral weighting

To evaluate the sensitivity of different methods to variations in mineral composition, two intervals with distinctly different mineral assemblages were selected from Well J1 for comparison of brittleness index values (Figure 6). The first interval is characterized by low quartz (29%) and high calcite (37%) content, whereas the second interval exhibits high quartz (32%) and low calcite (20%) content. The remaining mineral compositions are nearly identical between the two intervals. Given that quartz exhibits significantly higher brittleness compared to calcite, the brittleness index of the first interval is expected to be lower than that of the second interval. Results indicate that the brittleness index calculated using the new method is indeed significantly lower in the first interval (0.56) than in the second interval (0.70), which aligns closely with theoretical expectations. In contrast, the traditional mineral composition method (BI_1) and elastic parameter method (BI_2) yielded similar values for both intervals (BI_1: 0.86 vs. 0.85; BI_2: 0.78 vs. 0.75), demonstrating limited sensitivity to the differences in mineral composition. Furthermore, based on the overall variability observed across the three methods, the new mineral weighting method exhibits significantly higher accuracy than the traditional mineral composition method. This comparison clearly demonstrates that the new method responds more sensitively to changes in mineral composition, thereby confirming the necessity of incorporating mineral weighting in brittleness index calculations.

Several scholars have proposed methods to determine the contribution coefficients of different mineral compositions to rock brittleness in order to improve brittleness index models. Huo et al. (2018) defined brittleness coefficients based on the ratio of Young's modulus to Poisson's ratio for each mineral and standardized these values using quartz as the reference. This approach resulted in brittleness contribution weights for minerals such as pyrite, dolomite, calcite, feldspar, clay minerals, and organic matter. In contrast, Kang et al. (2020) calculated the brittleness contribution coefficients of quartz, feldspar, calcite, and dolomite based on variations in bulk modulus, constructing a new mineralogical brittleness index by applying a weighted sum of brittle minerals. However, this method did not incorporate other critical rock mechanical parameters such as Young's modulus and Poisson's ratio. Currently, most brittleness coefficient calculations rely on a limited number of minerals, such as quartz and clay, which introduces certain limitations in accurately determining the relative brittleness contribution of each mineral. In contrast, this study, based on the physical properties of minerals, comprehensively considers the contribution of multiple minerals to brittleness and employs the Analytic Hierarchy Process (AHP) to scale the brittleness coefficients, resulting in a more reasonable and widely applicable brittleness index model.

Based on the analytic hierarchy process, the brittleness contribution coefficients determined in this study are theoretically applicable to most reservoirs with similar mineral compositions. However, for regions where the mineral composition significantly differs from that of the study area (such as areas where pyrite is undeveloped), is it necessary to recalibrate the method? This study argues that the method remains applicable even when mineral types

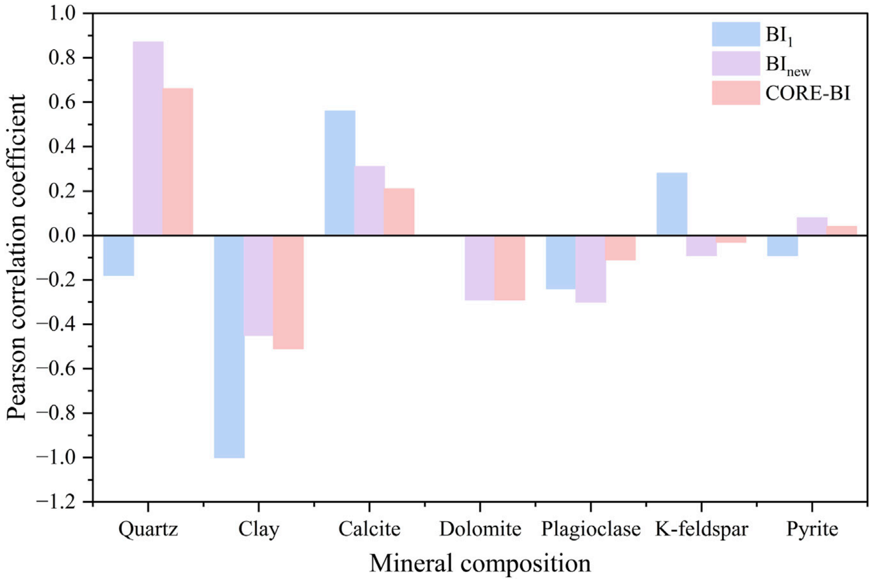

FIGURE 8
Correlation between brittleness index and mineral composition of two minerals.

and content distributions vary. The primary reason is that although the contribution coefficients of different minerals to brittleness may change to some extent (for example, the contribution coefficient of quartz may increase relatively), the normalized results can still effectively reflect the relative differences in brittleness within the reservoir. This ensures the comparability and practical value of the brittleness evaluation results. Therefore, the proposed method demonstrates good adaptability and stability when extended to reservoirs with different geological backgrounds. A more in-depth investigation into this specific aspect will be a focus of our future research.

5.3 Nonlinear discussion on mineral content and brittleness

According to previous research presented in the article, the brittle contribution coefficient of clay minerals is significantly lower than that of other minerals, and clay exhibits plastic behavior in the study area. To explore the relationship between mineral composition and brittleness, an extreme scenario is considered, in which the reservoir consists solely of two mineral components: clay (a plastic mineral) and quartz (a brittle mineral). Based on Equations 5–7, a brittleness response curve under this binary mineral condition is generated (Figure 9). The results indicate that, in both the mineral-weighted sum method (BI_v) and the traditional mineral composition method (BI_1), the relationship between clay content and the brittleness index is linear. In contrast, the new method (BI_{new}) reveals a nonlinear relationship between clay content and the brittleness index, with the degree of nonlinearity increasing as the clay content rises.

According to Equation 10, Young's modulus and Poisson's ratio demonstrate a linear relationship with the brittleness index. Since this method is widely accepted in academic circles, the influence mechanism of minerals on brittleness can be indirectly illustrated by analyzing the relationship between mineral composition and rock mechanical parameters. The variation range of mineral content in the study area is relatively narrow. To investigate this relationship more comprehensively, this study selects intervals with significant variation in clay mineral content from the Qiongzhusi Formation within the study area and the Longmaxi Formation in Weiyuan, an adjacent block. It then examines the variation patterns of rock mechanical parameters with respect to clay content (Figure 10). As shown in the figure, when clay content is below 25%, both Poisson's ratio and Young's modulus exhibit a linear correlation with clay

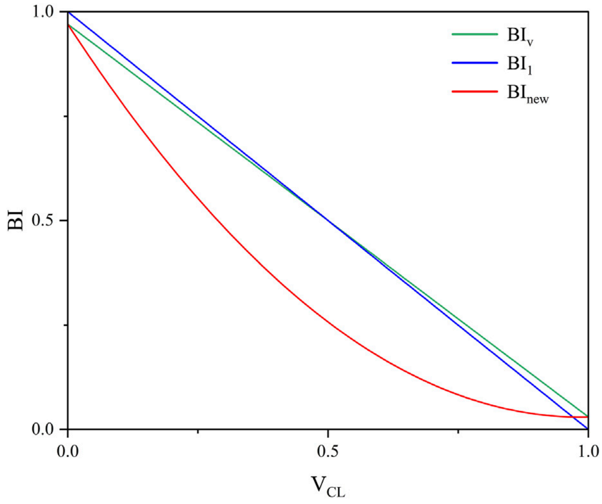

FIGURE 9
Brittleness response function in the quartz−clay binary system.

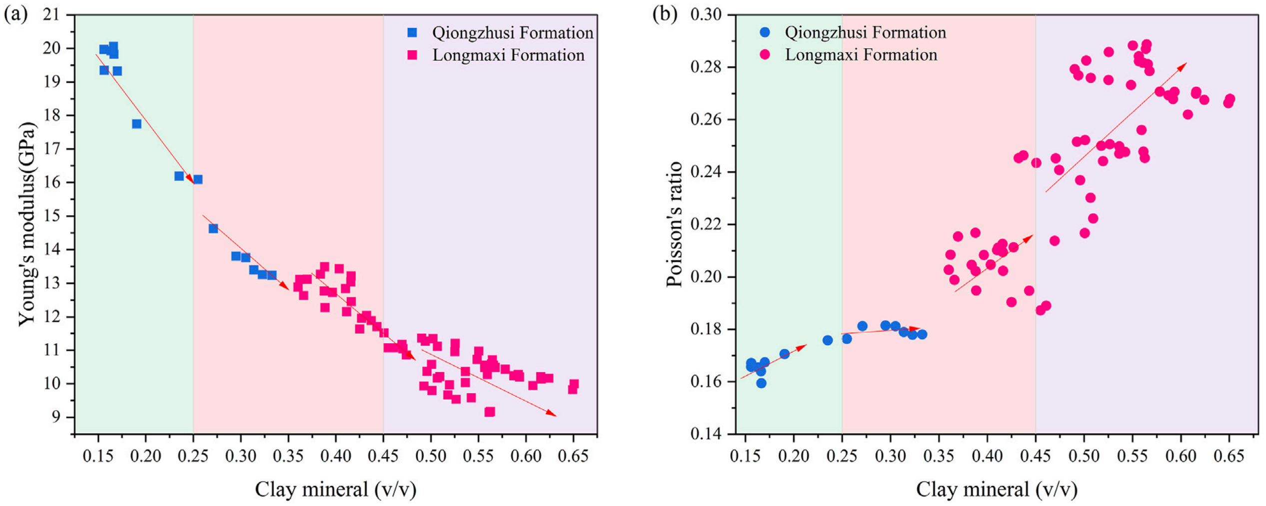

FIGURE 10
Variation of elastic parameters with clay content. **(a)** Variation of Young's modulus with clay content. **(b)** Variation of Poisson's ratio with clay content.

content. When clay content ranges between 25% and 35%, the linear correlation between Young's modulus and clay content weakens, while Poisson's ratio no longer shows a clear linear relationship with clay content. When clay content exceeds 45%, Poisson's ratio displays a pronounced nonlinear relationship with clay content, fluctuating around the fitted trend line. Meanwhile, Young's modulus data points become more scattered and exhibit nonlinear behavior at lower values. Notably, the trend of Young's modulus in Figure 10 closely aligns with the functional variation pattern of the new method (BI_{new}) in Figure 9, providing strong support for the hypothesis that a nonlinear relationship exists between mineral composition and the brittleness index. Given that actual reservoirs are not binary systems, it is reasonable to infer that a multivariate nonlinear relationship exists between mineral composition and brittleness in shale reservoirs with complex mineral assemblages.

Due to experimental limitations, this study attempts to theoretically interpret the microscopic mechanism underlying the nonlinear relationship between mineral composition and brittleness. When the clay content is relatively low (e.g., <25%), brittle minerals such as quartz and feldspar form a continuous load-bearing framework, and external stress is mainly transmitted through the brittle mineral skeleton. Consequently, brittleness decreases only slowly with increasing clay content. As the clay content rises to a moderate level (approximately 25%–45%), clay minerals gradually encase the brittle grains and alter the stress transmission pathways, leading to a transition of macroscopic mechanical behavior toward ductile characteristics and an accelerated reduction in brittleness. When the clay content further increases to a dominant level (e.g., >45%), the mechanical response becomes completely controlled by the clay matrix, and the influence of additional clay content on brittleness is significantly weakened, with the rate of decline tending to stabilize.

5.4 Future research directions

A. The nonlinear relationship between mineral composition and brittleness primarily stems from: 1) Shale being a multi-mineral aggregate with heterogeneous distribution, where brittleness index is not solely determined by individual mineral content. 2) Identical mineral compositions may exhibit drastically different brittle responses due to diagenesis-induced variations in pore structures, microfracture networks, and bedding planes. Notably, this study establishes mineral composition and corresponding mechanical properties as the dominant factors in shale brittleness evaluation based on the following rationale: minerals fundamentally determine the basic brittle characteristics of rocks, while mechanical parameters such as Young's modulus and Poisson's ratio serve as direct physical measures of brittleness. Together, they form the foundational logic for the brittleness evaluation model. Although additional factors including organic matter content and fluid saturation do influence brittleness, their integration presents substantial theoretical and technical challenges—particularly regarding the quantification of coupling effects with mineral properties and the development of generalized correction models. These aspects require further experimental validation and theoretical advancement, and therefore lie beyond the scope of the current investigation.

B. Studies have confirmed that confining pressure and temperature exert significant influence on rock brittleness (Figure 11). Triaxial experiments show that as confining pressure increases, Young's modulus increases markedly while Poisson's ratio changes only slightly, resulting in a higher brittleness index. However, current mineral-based brittleness evaluation methods do not effectively account for the influence of confining pressure, and laboratory conditions cannot fully replicate the *in situ* reservoir environment. Additionally, research has demonstrated that the brittleness index at 100 °C is significantly higher than at

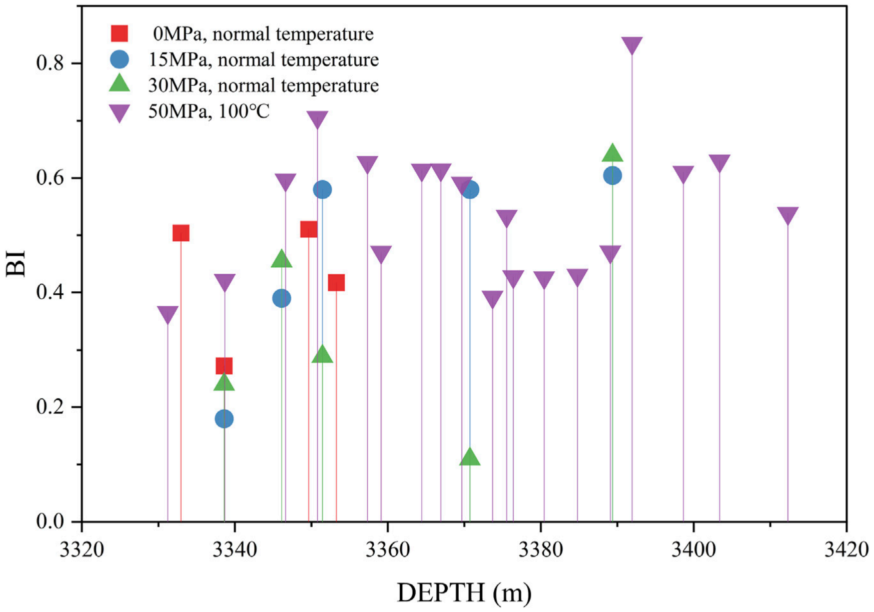

FIGURE 11
Bar chart of brittleness index variation with confining pressure.

room temperature. Therefore, accurate characterization of *in situ* stress and thermal conditions is essential for improving brittleness evaluation methods.

C. Future research should establish a comprehensive brittleness evaluation system incorporating intrinsic factors (mineral composition, pore structure, microfracture development) and external conditions (confining pressure, temperature). It is recommended to use a specific method to integrate various influencing factors into the model. For example, under the premise of complete data, developing pressure-related correction factors for mineral weight or elastic parameters could further improve the current model. Particular emphasis should be placed on characterizing the multivariate nonlinear relationships between mineral components and brittleness indices to achieve accurate predictions of shale reservoir brittleness.

D. Given the current limitations in experimental conditions and data scale, this study's exploration of the nonlinear relationship between mineral composition and brittleness has not yet delved into the underlying rock physics mechanisms or microstructural aspects (such as the directional arrangement of clay fabric, the evolution of pore geometry, and the distribution characteristics of cement). It remains primarily at the stage of data fitting and validation. Future research will integrate rock physics, micro-geology, and computational mechanics methods. This will involve conducting dynamic microstructural observation experiments under high temperature and pressure to capture the evolution of clay fabric, pores, and cement during the brittleness development process (Zhao et al., 2021). Concurrently, numerical simulation techniques (such as the Discrete Element Method and Finite Element Method) will be introduced to quantify the influence weights of microstructural parameters on the macroscopic nonlinear brittleness response, thereby revealing the intrinsic physical mechanisms behind the nonlinear relationship and enhancing the theoretical foundation of the model.

6 Conclusion

1. The shale of the Qiongzhusi Formation in the southwestern Sichuan Basin is mainly composed of seven minerals, including quartz, plagioclase, clay, dolomite, calcite, K-feldspar, and pyrite. The mineral composition varies widely, and there is no typical correlation between the single mineral content and brittleness index, so it is a highly heterogeneous and ultra-low porosity and permeability reservoir.
2. The application example shows that the new brittleness evaluation method can reasonably and effectively reflect the vertical distribution characteristics of shale reservoir brittleness. The results show that the brittleness index of silty shale section (0.70) in the study area is significantly higher than that of clayey shale section (0.49).
3. The new method offers higher accuracy than traditional methods, and the implementation procedure is relatively simple and broadly applicable. In the absence of array acoustic logging data, this modeling idea can also be used to predict Young's modulus and Poisson's ratio.
4. A shale reservoir is a complex aggregation of multi-mineral components, multi-phase fluids and diverse pore types. The popularization of CT scanning, Digital Core Analysis (DCA) and nano-indentation technology provides new opportunities to elucidate the influence of microstructure on macroscopic mechanical properties.
5. Brittleness can characterize the fracturing ability of rocks during fracturing, fracture toughness can characterize the

supportability of fractures after fracturing, horizontal stress difference coefficient can characterize the ability to form complex fracture networks, and permeability can characterize the permeability of produced fluids after fracturing. Therefore, with accurate characterization of these four parameters, a comprehensive evaluation of shale reservoir fracability can be conducted to support the selection of optimal fracturing intervals in horizontal wells.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

WW: Writing – review and editing, Writing – original draft, Methodology, Data curation, Investigation. WX: Writing – review and editing, Funding acquisition, Methodology, Writing – original draft. HM: Writing – review and editing. ZR: Writing – review and editing. QY: Writing – review and editing. PZ: Resources, Writing – review and editing, Software, Supervision.

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Conflict of interest

Author HM was employed by Shenli Well Logging Company, Sinopec.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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