



Quantitative characterization of the brittleness of deep shales by integrating mineral content, elastic parameters, in situ stress conditions and logging analysis

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Abstract

Deep shale reservoirs (3500–4500 m) exhibit significantly different stress states than moderately deep shale reservoirs (2000–3500 m). As a result, the brittleness response mechanisms of deep shales are also different. It is urgent to investigate methods to evaluate the brittleness of deep shales to meet the increasingly urgent needs of deep shale gas development. In this paper, the quotient of Young's modulus divided by Poisson's ratio based on triaxial compression tests under in situ stress conditions is taken as SSBV (Static Standard Brittleness Value). A new and pragmatic technique is developed to determine the static brittleness index that considers elastic parameters, the mineral content, and the in situ stress conditions (BIEMS). The coefficient of determination between BIEMS and SSBV reaches 0.555 for experimental data and 0.805 for field data. This coefficient is higher than that of other brittleness indices when compared to SSBV. BIEMS can offer detailed insights into shale brittleness under various conditions, including different mineral compositions, depths, and stress states. This technique can provide a solid data-based foundation for the selection of 'sweet spots' for single-well engineering and the comparison of the brittleness of shale gas production layers in different areas.

Keywords Deep shale reservoirs · Brittleness · Pressure effect · Evaluation method · Longmaxi formation · Sichuan Basin

1 Introduction

Horizontal well technology and staged hydraulic fracturing technology have promoted the large-scale commercial development of shale gas (Xie 2018). Shale gas in China can be divided into four zones based on burial depth: shallow (< 2000 m), moderately deep (2000–3500 m), deep (3500–4500 m), and ultra-deep (> 4500 m) (Ministry of Land and Resources of PRC 2014). Deep shale gas reservoirs are significantly different from moderately deep shale gas reservoirs at higher confining pressures (Xiong et al.

2016; He et al. 2022; Yong et al. 2022), which easily leads to a decrease in shale brittleness (Kim et al. 2021; Liu et al. 2022a, b, c).

Stress–strain curves are the most complete indicator of the whole-process characteristics of the failure modes of rock at the point of failure, and can fully reflect the mechanical characteristics of rocks both before and after failure occurs (Dou et al. 2021). Based on the results from triaxial compression tests, different scholars have selected different mechanical parameters and characteristic values to establish the quantitative calculation formulas of rock brittleness. Ding et al. (2019) characterized the brittleness as the difference between the peak strength and residual strength on the stress–strain curve. Guo et al. (2015) characterized brittleness as the difference between the compressive strength and tensile strength of rocks or the magnitude of the internal friction angle. Zhu et al. (2018) characterized the brittleness as the difference between peak strain and residual strain. Mandal et al. (2022) defined the mechanical brittleness index based on the peak strain and the postpeak slope gradient. Although the method of evaluating reservoir brittleness through triaxial compression tests on cores is generally

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considered to be the most reliable, the method is difficult to widely use in the field due to the limited coring length that is possible on site as well as the long time expenditure and high financial cost of conducting the triaxial compression test evaluation method (Liu and Sun 2015).

The quantitative evaluation of rock brittleness by conducting stress–strain curves is limited only to triaxial compression test analyses and cannot meet the needed quantity capacity of evaluating the rock brittleness of deep shale reservoirs. Triaxial compression tests on shales with different brittle mineral contents show that when the burial depth is shallow, the brittle mineral content is close to the shale brittleness index (Li 2022). An increase in the burial depth increases the in situ temperature and confining pressure, and the mechanical behavior of the shale changes from brittle to ductile characteristics (Yong et al. 2022). High temperatures can increase the ductility of the mineral present in the rock via dislocation slip between clay minerals (He et al. 2022). With increasing confining pressure, the shear fracture area gradually widens, and the shear angle also increases gradually (Zou et al. 2021). Based on the analysis of the influence of in situ stress conditions on the mechanical parameters of shales, the mechanical parameters that can indirectly reflect the influence of in situ stress conditions are found. With the advantages of log data in a continuous and highly accurate manner, a logging method that is suitable for evaluating the brittleness of field shale reservoirs is established, which is both conducive to obtaining the continuous brittleness index profiles on site and economically convenient for the effective screening of "sweet spots" for projects (Yasin et al. 2018). The brittleness evaluation method is not only scientific and reasonable but also simple and practical.

In this paper, a new and pragmatic technique is developed to quantitatively characterize the brittleness of deep shales by integrating mineral content, elastic parameters, and in situ stress conditions. First, the quotient of Young's modulus divided by Poisson's ratio based on triaxial compression tests under in situ stress conditions is taken as the static standard brittleness value (SSBV). The quotient of Young's modulus divided by Poisson's ratio of a single mineral at standard pressure and temperature is taken as the intrinsic brittleness value. Second, some brittleness indices have been proposed based on considering one or more factors such as mineral content, elastic parameters, and in situ conditions. If factor values come from experimental data, brittleness indices are called static, and if factor values come from well logging interpretation results, brittleness indices are called dynamic. Finally, the brittleness index of deep shales is determined continuously in some wells in western Chongqing, China, and the novelty, accuracy, and practicality of the dynamic in situ brittleness index are fully elaborated through comparative analysis with other data.

2 Method

2.1 Triaxial compression tests

(1) Test scheme and sample preparation.

The shales in strata are actually under triaxial stress, so the in situ stress conditions will affect the basic mechanical properties of rocks, and the brittleness characteristics and fracture modes of rocks at different confining pressures will also be moderately different (Wang et al. 2022). To study the influence of in situ stress conditions on rock brittleness, conventional triaxial compression tests were carried out using shales that do not have microcracks. The shale sample has high brittleness and can be considered to be isotropic rock materials. Triaxial compression tests on shales can reflect the influence of formation stress conditions on the mechanical properties, fracture modes and brittleness of rocks (Geng et al. 2016).

A numerical control core preparation system was adopted to prepare a sample, and the downhole shale was drilled and cored into a cylindrical sample with a diameter of 25 mm. Then, both ends of the sample were cut and ground to prepare a standard rock sample with a size of 25 mm × 60 mm. The parallelism deviation of the two ends of the sample is no more than 0.05 cm, and the size deviation of the two ends of the sample is no more than 0.02 cm.

(2) Experimental principle and equipment.

The rigid servo-controlled rock mechanics testing system TAW-2000 was selected as the triaxial compressive strength experimental equipment. The rigidity of the equipment is 40 MN/mm, the loading capacity is 2000 kN, and the upper limit of the confining pressure is 200 MPa. The instrument can directly measure the failure strength, Young's modulus, Poisson's ratio, etc., of shales in one test. The density of the rock sample was measured by the volume method. The temperatures, corresponding temperature, overburden pressure, confining pressure and pore pressure are selected as the experimental conditions according to the characteristics of the shale gas layer of the sample.

The set experimental conditions were as follows: overburden pressure 51.4–106.3 MPa, confining pressure 41.2–85.1 MPa, and pore pressure 23–70.9 MPa. The triaxial compression test results of the shale show that the compressive strength is 226.5–482.4 MPa, Young's modulus is 28.2–51.2 GPa, and Poisson's ratio is 0.205–0.368. It can be seen from the triaxial compression test results that the triaxial compressive strength of rocks increases with increasing confining pressure (Table 1).

Table 1 Triaxial compression test results

Well No.	Layer	Density (g/cm ³)	Experimental conditions				Experimental results		
			Temperature (°C)	Overburden pressure (MPa)	Confining pressure (MPa)	Pore pressure (MPa)	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio
X202	L114	2.58	58.5	51.4	41.2	23	226.51	30.14	0.245
R203	L111	2.605	127.7	106.3	85.1	64.6	448.98	31.93	0.226
H202	L112	2.56	122.3	102.3	81.8	65.9	388.66	33.28	0.239
H201	L111	2.623	125.7	106	84.8	58.6	433.36	33.41	0.246
H204	L113	2.62	106	92.1	80.1	70.9	482.37	40.6	0.213
H204	L113	2.6	106	92.1	80.1	70.9	480.36	38.04	0.207
Z202	L113	2.655	93	98.9	79.1	64.6	376.09	28.21	0.23
Z202	L112	2.653	93	99	79.2	64.7	328.95	32.26	0.262
Z202	WF	2.645	93	99.2	79.4	66.2	360.59	30.76	0.205
Z202	WF	2.592	93	99.2	79.4	66.2	327.62	31.48	0.214
N227	L112	2.6	103	91.7	73.4	64.7	379.61	41.24	0.295
N227	L112	2.57	103	91.7	73.4	64.7	340.78	40.63	0.314
N227	L112	2.58	103	91.7	73.4	64.7	327.67	35.82	0.343
N213	L112	2.489	68.9	62.2	49.8	37.9	324.43	37.27	0.23
N213	L112	2.517	68.9	62	49.7	37.8	370.48	37.47	0.26
N213	L112	2.517	68.9	62	49.7	37.8	414.95	41.96	0.241
N217	L113	2.58	103	91.2	73	64.4	315.67	49.80	0.368
N217	L113	2.57	103	91.2	73	64.4	279.77	32.69	0.265
N217	L112	2.61	103	91.7	73.4	64.7	334.75	33.46	0.336
N217	L112	2.6	103	91.7	73.4	64.7	296.05	32.44	0.264
N216	L112	2.606	80	57.7	47.1	42.1	349.09	51.19	0.257

XRD was conducted based on the oil and gas industry standard SY/T 5163–2010 analysis method for clay minerals and non-clay minerals in sedimentary rocks. Before the test, the sample was crushed and ground into powder. After drying, its XRD pattern was tested with an X-ray diffractometer. The mineral component content was determined by the correlation between the mineral content and the intensity of the diffraction characteristic peak.

The XRD analysis results show that the clay content of the sample is 7%–35%, the quartz content is 12.0%–77.1%, the feldspar content is 0.8%–10.8%, the calcite content is 4%–28%, the dolomite content is 1.1%–39.0%, and the pyrite content is 1.3%–11.8% (Table 2).

2.2 Recommended brittleness evaluation methods

There are various methods for evaluating the brittleness of rocks in different disciplines, contexts, and test methods (Zhang et al. 2016; Huo et al. 2018). The methods used to characterize brittleness differ depending on the context. One commonly used approach is to use elastic parameters based on Young's modulus and Poisson's ratio to distinguish the brittleness of shales. Poisson's ratio reflects a rock's ability to deform under pressure, with lower values indicating greater

brittleness. Young's modulus reflects a rock's ability to resist deformation under pressure, with higher values indicating greater brittleness.

Rickman's brittleness index (RBI) is a measure of a rock's brittleness that is calculated as half the sum of the normalized Young's modulus and Poisson's ratio (Rickman et al. 2008). "Normalized" means that the values of Young's modulus and Poisson's ratio have been adjusted to a common scale so that they can be combined in the RBI calculation.

$$\text{RBI} = 0.5 \times \frac{E - E_{\min}}{E_{\max} - E_{\min}} + 0.5 \times \frac{v_{\max} - v}{v_{\max} - v_{\min}} \quad (1)$$

where, RBI is Richman's brittleness index, which is dimensionless; E , E_{\max} and E_{\min} are Young's modulus, maximum Young's modulus and minimum Young's modulus, respectively, in GPa; and v , v_{\max} and v_{\min} are Poisson's ratio, maximum Poisson's ratio and minimum Poisson's ratio, respectively, which are dimensionless.

The RBI result calculated by many scholars with this formula based on triaxial compression test data increases with an increase in confining pressure, which is contrary to the rock fracture characteristics determined from triaxial compression tests (Liu et al. 2022a, b, c).

Table 2 Relative content characteristics of the main mineral components determined by XRD

Well No.	Layer	Total clay content (%)	Quartz (%)	Feldspar (%)	Calcite (%)	Dolomite (%)	Pyrite (%)
X202	L114	29.8	34.5	6.0	10.9	9.7	9.1
R203	L111	22.5	53.9	4.5	4.5	2.8	11.8
H202	L112	16	59.2	6.4	4.7	9.6	4.1
H201	L111	11.2	74.2	2.6	5.7	4.3	2.0
H204	L113	7	63	3	6	18	3
H204	L113	11	48	2	18	17	4
Z202	L113	33.0	47.8	7.2	4.0	2.0	6.0
Z202	L112	26.3	47.4	10.8	7.9	4.4	3.2
Z202	WF	14.1	68.8	3.2	6.3	1.9	5.7
Z202	WF	10	77.1	0.8	6.1	4.7	1.3
N227	L112	28	22	7	24	15	4
N227	L112	28	22	7	24	15	4
N227	L112	28	22	7	24	15	4
N213	L112	11.8	59.3	3.9	14.6	7.7	2.7
N213	L112	16.7	56.7	4.5	11.7	7.6	2.8
N213	L112	16.7	56.7	4.5	11.7	7.6	2.8
N227	L113	35	40	9	4	6	6
N227	L113	35	40	9	4	6	6
N227	L112	15	12	2	28	39	4
N227	L112	15	12	2	28	39	4
N216	L112	22.6	55.6	7.9	10.5	1.1	2.3

There are two ways to measure the quotient of Young's modulus divided by Poisson's ratio. One is the static method, which is used to obtain Poisson's ratio, Young's modulus and compressive strength under specific confining pressure conditions through triaxial compression tests on rocks in the laboratory, which is the static standard brittleness value (SSBV) in this paper (Guo et al. 2013). They deemed that the greater the value, the better the brittleness of rocks.

$$\text{SSBV} = \frac{E}{\nu} \quad (2)$$

where SSBV is the static standard brittleness value, GPa.

The other is the dynamic method, which is the dynamic standard brittleness value (DSBV) in this paper. It is used to calculate the Young's modulus and Poisson's ratio based on the logging data for density, acoustic information, etc., as shown in Eq. (2).

Feng et al. (2018) found that a very poor correlation exists between the SSBV obtained by experiments and the DSBV obtained by logging calculations. In addition, accurate shear wave logging information is required to calculate DSBV, which is not often measured because of its high financial cost. Therefore, the DSBV method cannot be widely used in the field.

Minerals are the basis of shale skeletons, and their different compositions and contents directly determine the differences among shale properties. The brittleness index of the mineral content method is based on the mineral composition of shales to characterize brittleness, reflecting the brittleness difference between shales of different lithofacies. There are two ways to measure the brittleness index of the mineral content method. One is the static method, which is used to measure mineral content by the XRD method. The other is the dynamic method, which is used to obtain the brittleness index by the multiminerall logging interpretation method. This method is convenient and fast. By the calibration of mineral analysis by XRD or thin section samples, continuous interpretation results with reliable accuracy can be obtained using this method. Its disadvantage is that the brittleness is only expressed by the mineral content, and it does not fully account for differences in the mechanical properties of specific minerals.

After considering the advantages and disadvantages of the methods mentioned above, the author proposes using the quotient of Young's modulus divided by Poisson's ratio of a single mineral at standard pressure and temperature as the intrinsic brittleness value. The brittleness index, which combines elastic parameters and mineral content, is denoted

as BIEM and is defined as the product of the intrinsic brittleness value and the mineral volume. By using this method, we can more accurately characterize the brittleness of different types of shales.

$$BIEM = V_{QA} \times B_{QA} + V_{DO} \times B_{DO} + V_{PY} \times B_{PY} + V_{FD} \times B_{FD} + V_{CA} \times B_{CA} \tag{3}$$

where $V_{QA}, V_{DO}, V_{PY}, V_{FD}, V_{CA}$ is the relative percentage content of quartz, dolomite, pyrite, feldspar and calcite, respectively, and $B_{QA}, B_{DO}, B_{PY}, B_{FD}, B_{CA}$ is the intrinsic brittleness value of quartz, dolomite, pyrite, feldspar and calcite minerals, which are 1433, 462, 364, 323 and 262, respectively.

A new method called BIEMS (Brittleness Index by Elastic Parameters, Mineral Content, and In Situ Stress Conditions) has been proposed, which incorporates the overburden pressure, pore pressure, and confining pressure data obtained from triaxial compression tests of the same sample to improve the accuracy of the BIEM.

$$BIEMS = \frac{V_{QA} \times B_{QA} + V_{DO} \times B_{DO} + V_{PY} \times B_{PY} + V_{FD} \times B_{FD} + V_{CA} \times B_{CA}}{\alpha_p} \tag{4}$$

$$\alpha_p = \frac{p_0 - p_f}{p} \tag{5}$$

where, BIEMS is the brittleness index by integrating elastic parameters, mineral content and in situ stress conditions, in GPa; α_p is the in situ stress conditions coefficient, which is dimensionless; and $p_0, p_f,$ and p are the overburden pressure, pore pressure and confining pressure, respectively, in MPa.

Equations (4) and (5) can be used to calculate the dynamic brittleness index by integrating elastic parameters, mineral content, and in situ stress conditions (DBIEMS) by combining optimized logging interpretation results and field measurement data for relative mineral content, overburden pressure, pore pressure, and confining pressure. The resulting DBIEMS can be used to establish a continuous brittle profile of reservoirs, making it easier to identify optimal zones for hydraulic fracturing across different intervals and well areas.

This paper uses the square of the Pearson correlation coefficient (coefficient of determination) to measure the degree of correlation between two variables (Walpole 2012). The accuracy of the BIEM and BIEMS methods was compared using the SSBV, which is the quotient of Young's modulus divided by Poisson's ratio obtained from triaxial compression tests. Cross plots of BIEM and BIEMS versus SSBV (Figs. 1 and 2)

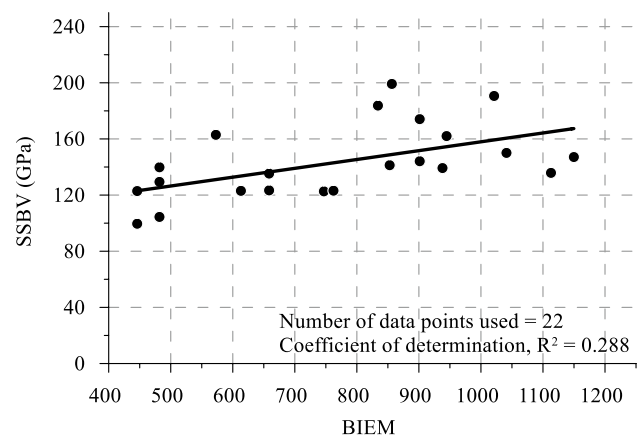


Fig. 1 Cross plot of BIEM versus SSBV

showed that the coefficient of determination between BIEMS and SSBV was higher (0.555) than that between BIEM and SSBV (0.288).

3 Example applications

3.1 Overview of the research area

The Yuxi block in western Chongqing, China, is located at the intersection of the low and gentle structural area of the Central Sichuan Uplift in the Sichuan Basin and the low and steep fold belt of southern Sichuan (Fig. 3). The region features narrow anticlines and wide, gently sloped

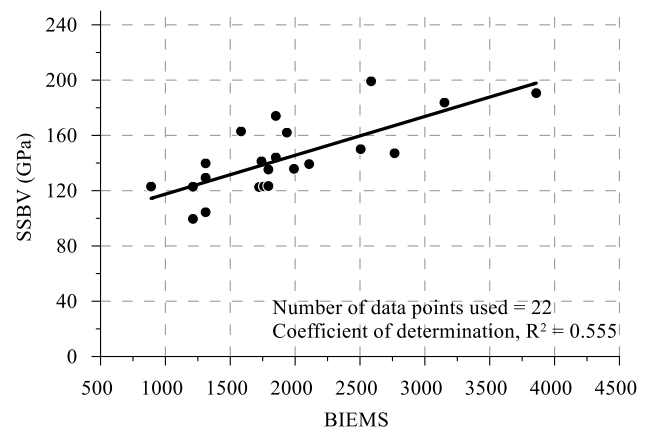


Fig. 2 Cross plot of BIEMS versus SSBV

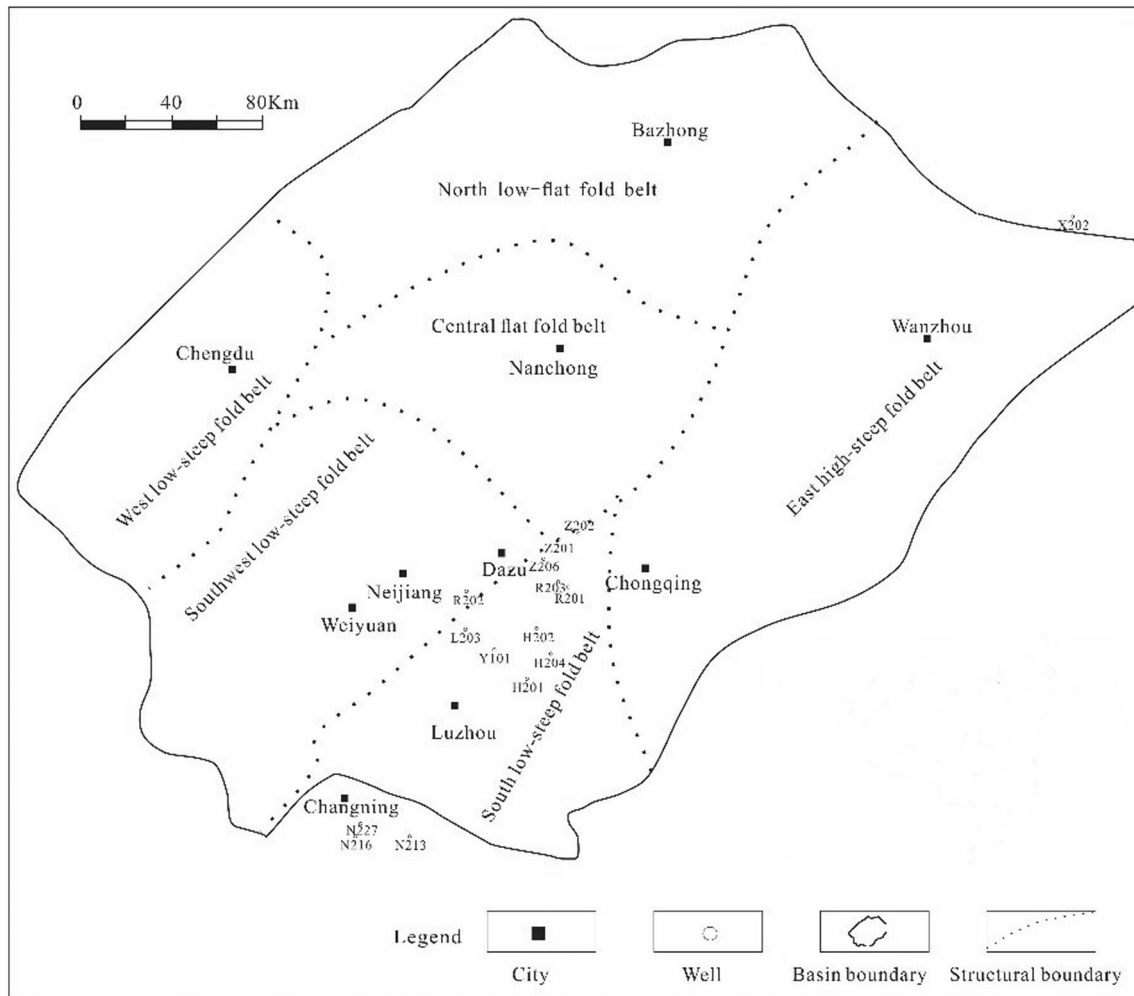


Fig. 3 Location map of the survey area

synclines, with the Wufeng Formation and submember I of member I of the Longmaxi Formation comprising the vertical reservoirs. The latter can be further divided into four layers: L111, L112, L113, and L114. Since 2018, exploration and development in the Yuxi block have shown that deep shale reservoirs hold commercial value and significant production has been obtained from gas testing. Additionally, appraisal wells indicate strong development potential. However, the block's single-well stimulation effect has lagged behind that of blocks like Changning and Luzhou (He et al. 2020).

More than 70% of the Yuxi block's area consists of layers with burial depths exceeding 4000 m. Consequently, it is the shale gas evaluation area with the most severe in situ stress conditions in southern Sichuan. The average minimum horizontal principal stress ranges from 40 to 75 MPa in the Changning block, 55–85 MPa in the Weiyuan block, 70–95 MPa in the Luzhou block, and 75–95 MPa in the Yuxi block. The difference between the

average maximum horizontal principal stress and the average minimum horizontal principal stress ranges from 6 to 12 MPa in the Changning block, 8–15 MPa in the Weiyuan block, 11–17 MPa in the Luzhou block, and 16–20 MPa in the Yuxi block. These differences show that the brittleness response mechanism of the Yuxi block is different from that of other blocks, despite having the same mineral compositions (Liu et al. 2022a, b, c).

3.2 Parameter selection and calculation process

The relative content of minerals in shale gas reservoirs within the Yuxi block can be calculated using the optimized logging interpretation method. This method employs a multimineral model consisting of eight components: quartz, feldspar, dolomite, calcite, pyrite, clay, kerogen, and pores. These components are used to interpret logging data, and nine different logging curves including gamma ray (GR), density (DEN), acoustic (AC),

Table 3 Logging response characteristic values of mineral skeleton components and pore fluids

Component type	GR (API)	AC (Us/ft)	CNL (%)	DEN (g/cm ³)	Pe (b/cm ³)	U (10 ⁻⁶)	Th (10 ⁻⁶)	K (%)	Rt (Ω m)
Quartz	0	55.50	-2.00	2.65	4.79	4.79	0	0	5.00×10 ⁵
Feldspar	220	69.00	-2.00	2.62	7.50	7.21	1.10	10.50	4.30×10 ⁶
Dolomite	0	43.50	1.00	2.87	8.00	9.00	0	0.30	8.00×10 ¹⁰
Calcite	-1	48.00	-1.00	2.71	13.77	13.77	0	5.00	7.20×10 ⁷
Pyrite	0	39.20	-3.00	5.00	82.30	0	0	0	4.00×10 ⁻⁴
Clay	250	49.50	35.00	2.50	18.00	9.00	20.00	0.58	50.00
Kerogen	2050	135.00	0.30	1.30	0.22	300.00	40.00	50.00	8.00×10 ¹²
Pore (Fluid)	0	189.00	100.00	1.00	0.30	0.36	0	0	0.05

compensated neutron (CN), photoelectric factor (Pe), uranium (U), potassium (K), thorium (Th), and resistivity (Rt) are used to generate logging curve response equations. The constraints of the multiminerall model are fully considered in the interpretation process (Liu et al. 2021).

$$F_i(A, X) = a_{fi}\varnothing + a_{cli}V_{cl} + a_{koi}V_{ko} + \sum_{j=1}^5 a_{mi,j}V_{mj} \quad (6)$$

According to the actual characteristics of shale gas reservoirs, the logging curve response equations shall meet the following conditions:

$$\begin{cases} \varnothing + V_{cl} + V_{ko} + \sum_{j=1}^5 V_{mj} = 1 \\ 0 \leq \varnothing, V_{cl}, V_{ko}, V_{mi} \leq 1 \end{cases} \quad (7)$$

where, $j = 1, 2, \dots, 5$ is the quantity of skeleton minerals of brittle minerals such as quartz, calcite, dolomite, feldspar and pyrite; $i = 1, 2, \dots, 9$ is the quantity obtained from logging methods such as GR, DEN, AC, CNL, Pe, U, K, Th and Rt; $F_i(A, X)$ is the value of the i th logging curve; a_{fi} is the i th logging curve response value of pore fluid; a_{cli} is the i th logging curve response value of clay content; $a_{mi,j}$ is the i th logging curve response value of the j th brittle mineral; a_{koi} is the i th logging curve response value of kerogen; \varnothing is the relative content of pores; V_{cl} is the relative content of clay minerals; V_{ko} is the relative content of organic matter; and V_{mj} is the relative content of the j th brittle mineral. The values of a_{fi} , a_{cli} , $a_{mi,j}$ and a_{koi} are shown in Table 3.

In the current interpretation process of well log data, quartz, feldspar, dolomite and calcite minerals are usually regarded as brittle minerals, and the dynamic brittleness index based on the content proportion of brittle minerals in all minerals (hereinafter abbreviated as DBIM) is calculated, as shown in Eq. (7).

$$DBIM = \frac{V_{QA} + V_{FD} + V_{CA} + V_{DO}}{V_{QA} + V_{FD} + V_{CA} + V_{DO} + V_{CL} + V_{KO} + V_{PY}} \quad (8)$$

where V_{QA} , V_{FD} , V_{CA} , V_{DO} , V_{CL} , V_{KO} , V_{PY} are the relative contents of quartz, feldspar, calcite, dolomite, clay minerals, kerogen and pyrite from logging interpretation, respectively, given in %.

As an example, this well has shear wave logging information, so Young's modulus E and Poisson's ratio ν have been calculated using logging methods. RBIL based on the Young's modulus and Poisson's ratio from logging interpretation can be obtained by setting the maximum value E_{max} of Young's modulus to 100 GPa, the minimum value E_{min} of Young's modulus to 10 GPa, the maximum value ν_{max} of Poisson's ratio to 0.5, and the minimum value of Poisson's ratio ν_{min} to 0.1 and using Eq. (1) for reference. In addition, using Eq. (2), the DSBV based on the Young's modulus and Poisson's ratio from logging interpretation can be obtained.

The overburden pressure in this paper is obtained by multiplying the overburden pressure gradient and depth. According to the field measured data, the overburden pressure gradient coefficient is taken as 2.57 MPa/100 m. The pore pressure is obtained by multiplying the pressure coefficient and the hydrostatic pressure at the same depth. The formation pressure coefficient is taken as 1.8, which is measured during the gas testing process. The confining pressure is obtained by multiplying the gradient of the minimum horizontal principal stress and the depth, and the gradient of the minimum horizontal principal stress is 2.35 MPa/100 m.

Based on the relative content of various minerals from logging interpretation, the dynamic brittleness index, DBIEMS, can be calculated by using Eqs. (4) and (5).

4 Results and discussion

The mineral composition, Young's modulus, Poisson's ratio, fracture pressure and brittleness evaluation results of various methods for well Z206 in the Yuxi Block are shown in Fig. 4. The formation names from bottom to top in Fig. 4 are the Baota Formation, Wufeng Formation, and layers L111, L112, L113 and L114 and L12 submember of the Longmaxi Formation.

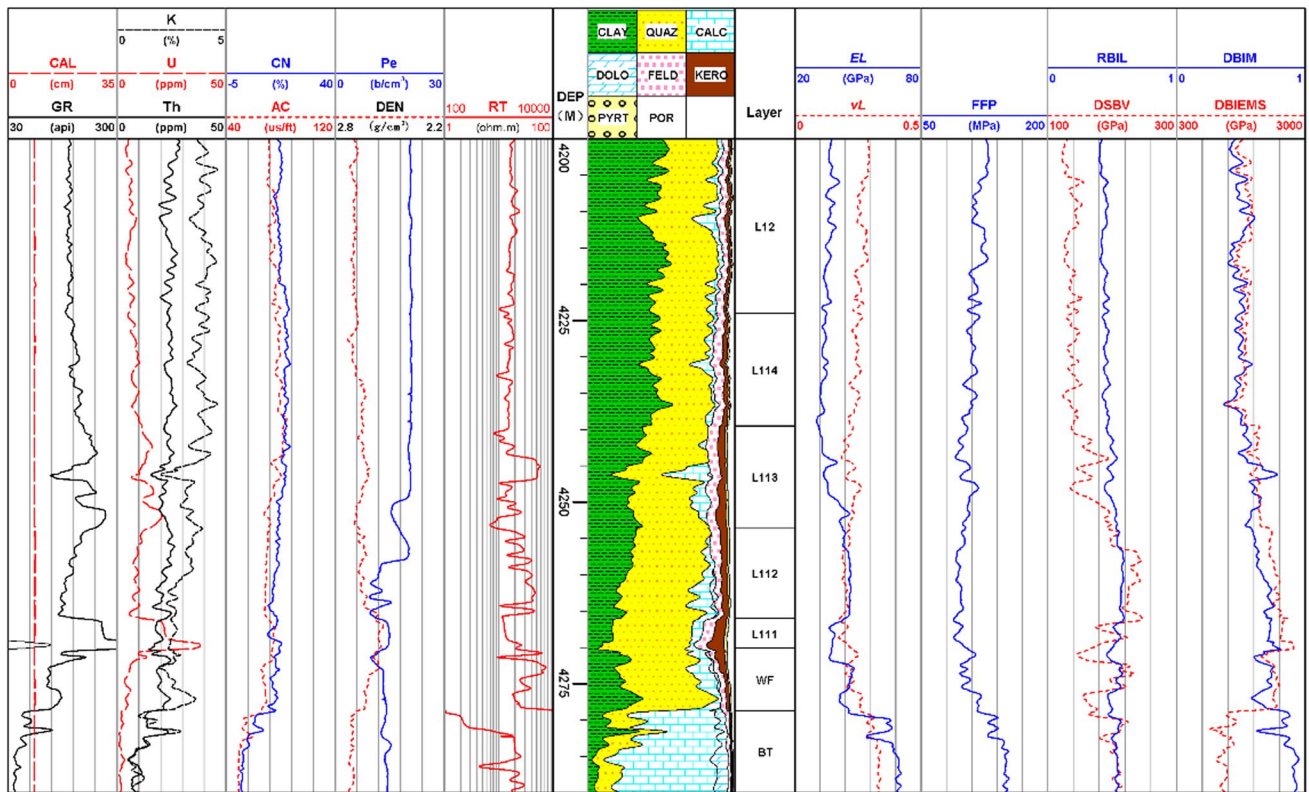


Fig. 4 Comprehensive chart of the original logging data and processing results of the mineral content, mechanical parameters and dynamic brittleness index. *Note:* *EL* is the dynamic Young's modulus obtained using the logging interpretation method, *vL* is the dynamic

Poisson's ratio obtained using the logging interpretation method, and *FFP* is the fracture pressure obtained using the logging interpretation method

The overall trend of the DBIEMS from the bottom to the top elevations, is from small to large and then to small, and the maximum brittleness index value exists at the L111 layer, generally above 2400 GPa, and gradually decreases traveling upward in the Longmaxi Formation. In the shale reservoirs of the Longmaxi Formation of well Z206, the quartz content decreases gradually from the bottom to the top elevations, and the clay mineral content increases gradually from the bottom to the top elevations (Fig. 4). The characteristics of the correlation between the dynamic brittleness index feature of the pressure-mineral-Poisson's ratio/Young's modulus method and the regular change trend of mineral components are consistent with the viewpoint recognized by many scholars that mineral components and their distribution characteristics are the main factors affecting the mechanical brittleness of shale reservoirs (Li 2022).

The DBIEMS is consistent with the change rule of mineral components, which is also related to the change in the sedimentary environment of the Longmaxi Formation, looking at it from the bottom-to-top perspective. The shale reservoirs at the bottom of the Longmaxi Formation were

deposited after the important environmental change node at the turn of the Ordovician–Silurian period and existed in the sedimentary background for the end of a global ice age, and were present for the rapid rise of bodies of water, which caused very good gradual and gentle water deposition conditions, and good organic matter preservation conditions existed at the bottom of water bodies (Wu et al. 2020). In addition, the quartz minerals deposited in this period are mainly bioclastic siliceous, with a high proportion of quartz content, forming good mechanical brittle skeletons (Ji et al. 2020).

The rock mechanics testing system TAW-2000 was selected to carry out triaxial compression tests on well Z206 in the Yuxi block. According to the actual geological conditions of the target formations of the well, by setting the experimental conditions as follows: temperature to 120 °C, overburden pressure to 105 MPa, confining pressure to 96 MPa and pore pressure to 70 MPa, the compressive strength, Young's modulus, Poisson's ratio and other parameters of shale samples from the layers of the Wufeng Formation and Longmaxi Formation were

Table 4 Triaxial test data of well Z206 and SSBV values

Layer	Density (g/cm ³)	Experimental conditions				Experimental results			SSBV
		Temperature (°C)	Overburden pressure (MPa)	Confining pressure (MPa)	Pore pressure (MPa)	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio	
L114	2.64	120	105	96	70	333.55	30.48	0.328	92.9
L113	2.63	120	105	96	70	396.59	30.58	0.255	119.9
L112	2.63	120	105	96	70	346.49	27.98	0.252	111.1
L111	2.57	120	105	96	70	313.69	30.81	0.215	143.3
L111	2.58	120	105	96	70	331.61	31.07	0.198	159.9
WF	2.62	120	105	96	70	398.63	33.56	0.288	116.5

directly measured. The results in Table 4 show that the compressive strength is 313.69–398.63 MPa, the Young's modulus is 27.98–33.56 GPa, and the Poisson's ratio is 0.198–0.328.

When the number of test samples is 5, the degree of freedom is 4, and the confidence level is 95%. If the square of the Pearson correlation coefficient exceeds 0.77, it can be judged as a significant correlation. The larger the value is, the better the correlation.

By comparing the static parameters (Young's modulus E , Poisson's ratio ν) obtained from the triaxial compression tests with the dynamic parameters (Young's modulus EL , Poisson's ratio νL) obtained from logging interpretation, it can be found that the static Young's modulus distribution obtained from the experiment is relatively concentrated, but the dynamic Young's modulus distribution obtained from logging interpretation is very discrete; moreover, the correlation between the static Poisson's ratio obtained by the experiment and the dynamic Poisson's ratio obtained

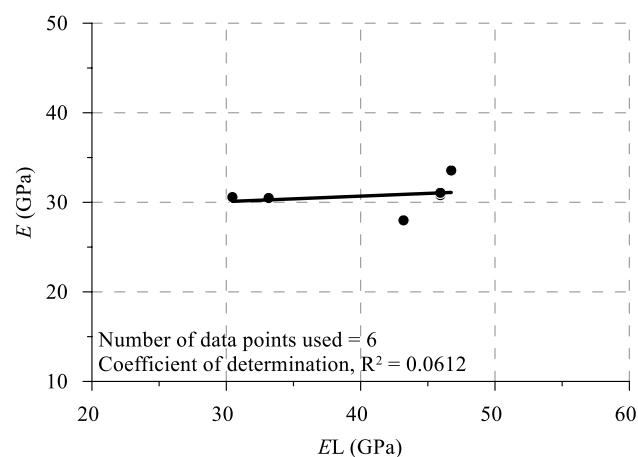


Fig. 5 Cross plot of static Young's modulus versus dynamic Young's modulus

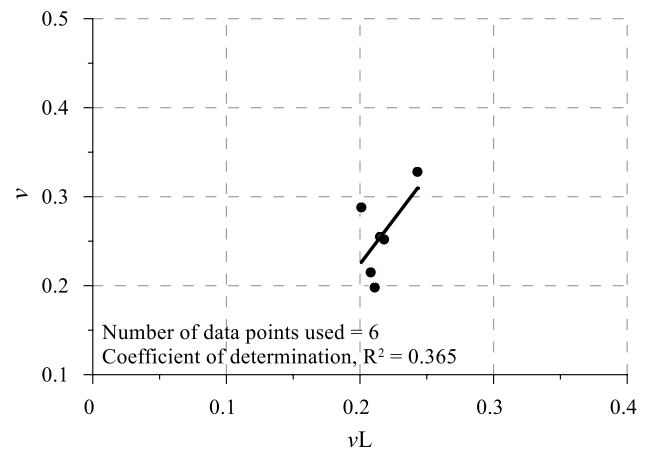


Fig. 6 Cross plot of static Poisson's ratio versus dynamic Poisson's ratio

by logging interpretation is slightly better than that of the Young's modulus parameters obtained by the two methods (shown in Figs. 5 and 6), but it is still far below the threshold value (0.77) of the squared value of the correlation coefficient required by significant correlation. The reason is that the logging interpretation is based on the assumption of completely elastic characteristics to calculate the dynamic Young's modulus and dynamic Poisson's ratio, which is far from the actual conditions of the shale formations.

Based on the Young's modulus and Poisson's ratio data of shales in each layer measured by the triaxial compression test of well Z206, SSBV was calculated using Eq. (2) (shown in Table 4). The calculation results show that the brittleness index of the samples from layer L111 is much higher than that of samples from other layers under the same temperature, overburden pressure, confining pressure and pore pressure conditions.

The coefficient of determination between the DSBV that was calculated based on the dynamic Young's modulus and the dynamic Poisson's ratio obtained using the logging

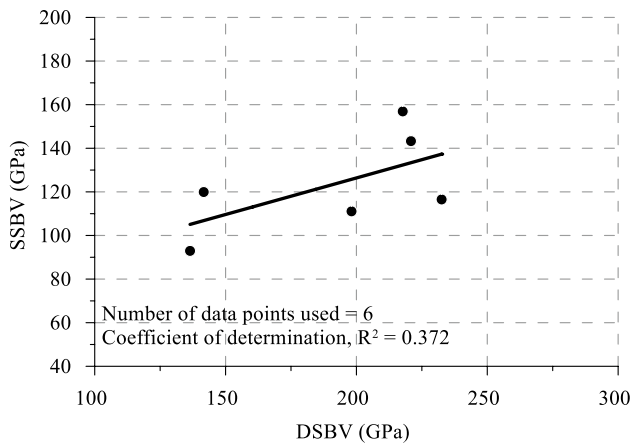


Fig. 7 Cross plot of DSBV versus SSBV

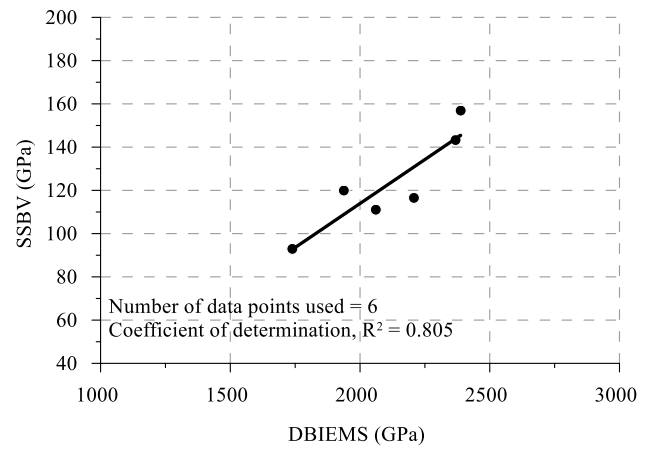


Fig. 10 Cross plot of DBIEMS versus SSBV

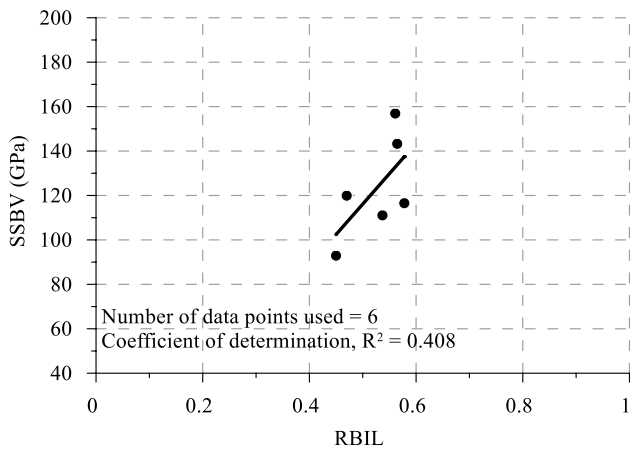


Fig. 8 Cross plot of RBIL versus SSBV

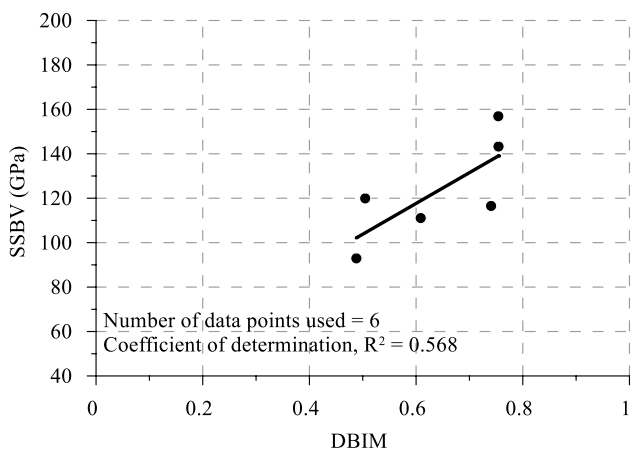


Fig. 9 Cross plot of DBIM versus SSBV

interpretation method and the SSBV is only 0.365 (Fig. 7), which is far lower than the threshold (0.77) of the square value of the correlation coefficient required by significant correlation. Therefore, due to the strong instability of the Young's modulus parameter obtained from logging interpretation, there is still a large amount of uncertainty in the brittleness evaluation of shale formations when based on the calculation of the DSBV simply using the Young's modulus and Poisson's ratio parameters from logging interpretation (Rybacki et al. 2015, 2016).

The cross plots are shown in Figs. 8, 9 and 10 which compare the static brittleness index SSBV with the dynamic brittleness index RBIL, the dynamic brittleness index DBIM and the dynamic brittleness index DBIEMS proposed in this paper, respectively. The figures show that the square value of the Pearson correlation coefficient between the DBIEMS established in this paper and the static brittleness index SSBV exceeds 0.77, which can be judged as a significant correlation.

In addition, the density of natural fractures can be used as an important indicator of the development of brittle characteristics in a region or layer. According to the statistical results of fractures observed in the cores, the fracture density in layer L111 in well Z206 is the largest, the fracture densities of layer L112, Wufeng Formation, layers L113 and L114 are relatively small, which are in good agreement with the DBIEMS proposed in this paper (Table 5).

The magnitude of the formation fracture pressure is mainly controlled by factors such as the triaxial stress state, reservoir fracture density, reservoir brittleness, physical properties of the reservoir, and external force action modes (Chang et al. 2022). In a local area, the rock's brittleness has a great influence on the formation fracture pressure. In

Table 5 Statistics of observed fractures in cores from well Z206

Layer	Core length (m)	Total number of fracture	Fracture density (piece/m)
L114	14.43	12	0.83
L113	14.04	13	0.93
L112	12.37	19	1.54
L111	4.25	29	6.82
Wufeng formation	8.55	12	1.4

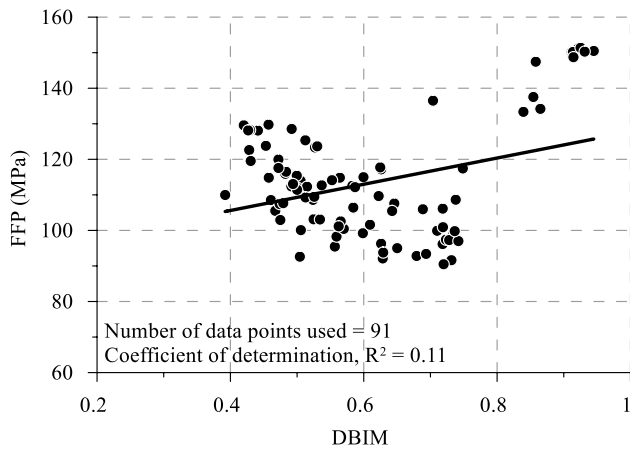


Fig. 11 Cross plot of DBIM versus FFP

this paper, the rock fracture pressure value calculated by the H-F theoretical model based on pore elasticity theory and with considerations for the permeation of fracturing fluids, is used as the standard to compare the reliability of various brittleness methods.

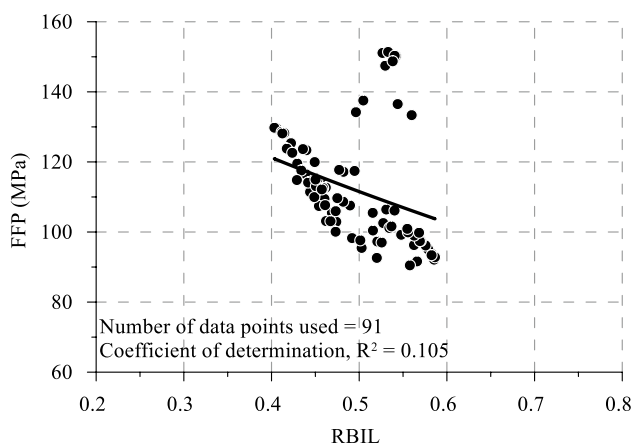


Fig. 12 Cross plot of RBIL versus FFP

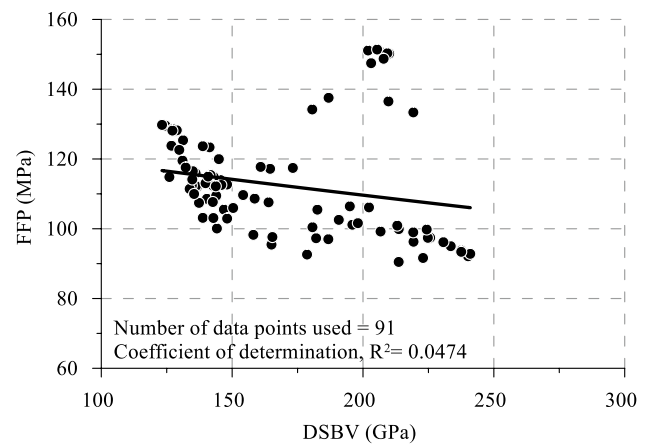


Fig. 13 Cross plot of DSBV versus FFP

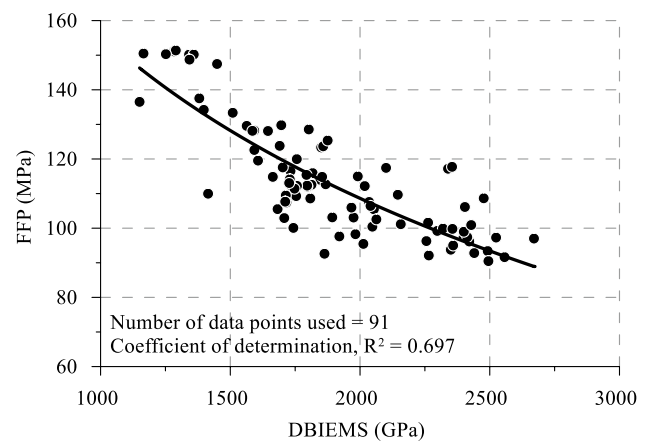


Fig. 14 Cross plot of DBIEMS versus FFP

In Fig. 4, the overall trend of the fracture pressure development is from large to small and then to large, and the minimum value of the fracture pressure is at the L111 layer. By averaging the brittleness calculation results and the fracture pressure values at an interval spacing of 1 m, the cross plots obtained are shown in Figs. 11, 12, 13 and 14. It can be seen from the figures that the DBIEMS shows the highest correlation with the fracture pressure.

5 Conclusions

BIEMS integrates the influences of factors such as mineral content and triaxial stress on brittleness, and the definition of this index is scientific and reasonable.

DBIEMS only needs to utilize conventional logging data and conventional pressure test data, and the process of calculating this index is simple, fast, and inexpensive. Moreover, it has a higher correlation with FFP than DBIM, RBIL and DSBV. It can be used to characterize the brittleness of shales in different regions and depths.

The application results of BIEMS present in the deep shales located in Western Chongqing, China, indicate that the location with the strongest brittleness of the deep shales in Western Chongqing is located in L111 in the lower part of the Longmaxi Formation and gradually weakens traveling upward. This is consistent with the change rule of mineral composition and the evolutionary trend of the sedimentary environment.

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