ORIGINAL ARTICLE

Characteristics of in situ stress and its influence on coal seam permeability in the Liupanshui Coalfield, Western Guizhou

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Funding information
(1) National Natural Science Foundation of China (41572140, 41872170); (2) National Major Science and Technology Projects of China (2016ZX05044); (3) Fundamental Research Funds for the Central Universities (2020CXNL11); (4) Assistance Program for Future Outstanding Talents of China University of Mining and Technology (2020WLJRCZL090)

Abstract
The current in situ stress regime is of great significance to the exploration and development of coalbed methane (CBM). In this study, the vertical stress ($\sigma_v$), maximum horizontal principal stress ($\sigma_h$), and minimum horizontal principal stress ($\sigma_h$) in the Liupanshui Coalfield were studied. Variations of the maximum and minimum envelopes and trend lines of the lateral pressure coefficient ($\lambda$) with depth were obtained, and the non-monotonic decrease of permeability with burial depth was determined. On this basis, the effect of in situ stress on the coal reservoir permeability was evaluated. The results show that the average vertical stress gradient of the main coal seam in the Liupanshui Coalfield is 0.024 MPa/m. Generally, there are two stress regimes of $\sigma_h > \sigma_v > \sigma_h$ (44.23%) and $\sigma_v > \sigma_h > \sigma_h$ (46.15%); $\sigma_h > \sigma_h > \sigma_v$ accounts for a smaller proportion (9.62%), and only occurs in relatively shallow coal seams (<622.85 m). In the range of the tested burial depths, for <600 m, $\sigma_h > \sigma_v > \sigma_h$ is dominant; $\sigma_v > \sigma_h > \sigma_h$ is dominant between 600 and 800 m; and between 800 and 980 m, the coal reservoir is affected by both $\sigma_h > \sigma_v > \sigma_h$ and $\sigma_v > \sigma_h > \sigma_h$, representing a transition zone between the two stress states. With the increase of burial depth, the permeability of the coal reservoir shows a complex non-monotonic decline, and the variation of the permeability of the coal reservoir differs under the influence of different stress regimes. Further analysis shows that under the background of stress regime transformation, permeability is mainly affected by the stress value, horizontal principal stress difference, stress regime, and coal cleat, indicating that in situ stress is the main controlling factor of coal reservoir permeability in the Liupanshui Coalfield.

KEYWORDS
coalbed methane, in situ stress, Liupanshui Coalfield, permeability, synthetic density logging
1 | INTRODUCTION

China is rich in coalbed methane (CBM) resources. According to the available statistics, the amount of CBM resources at shallow depths up to 2000 m is $3.681 \times 10^4$ billion m$^3$. However, most coal seams experience multistage superposition and transformation, as well as tectonic stresses of different properties and intensities, and thus show the characteristics of strong heterogeneity and strong stress sensitivity. The exploration and development of CBM is greatly affected by the current in situ stress changes of coal reservoirs.

Generally, in situ stress refers to the internal stress that exists in the crust, which is mainly formed by the combination of gravity stress, tectonic stress, pore pressure, thermal stress, and residual stress, among which tectonic stress and gravity stress are the main sources of in situ stress. Tectonic stress is mainly controlled by tectonic movement and rock geological structure, with high complexity and uneven spatial distribution, and its planar and vertical distributions are difficult to describe by mathematical functions. According to the relative relationship between vertical stress ($\sigma_V$) and tectonic stress (including maximum horizontal principal stress ($\sigma_H$) and minimum horizontal principal stress ($\sigma_h$)), Anderson (1951) divided in situ stress into the normal faulting stress regime ($\sigma_V > \sigma_H > \sigma_h$), strike-slip faulting stress regime ($\sigma_H > \sigma_V > \sigma_h$), and reverse faulting stress regime ($\sigma_H > \sigma_h > \sigma_V$). The current in situ stress regime is not only one of the main parameters affecting the construction effect of hydraulic fracturing, but also an important factor affecting reservoir fluid migration and accumulation. Therefore, in the initial stage of CBM development in China, using various methods to better understand in situ stress is an effective means of CBM exploration and development. At present, the commonly used methods for in situ stress measurement include mechanical methods, geophysical methods, and geological methods.

For this paper, based on 25 CBM vertical wells in the Liupanshui Coalfield, the average vertical stress gradient of strata at depths <980 m in this area was estimated using density logging data, and the horizontal principal stress components were calculated using injection/fall-off and in situ stress measurement data. The three components of the stress tensor ($\sigma_V$, $\sigma_H$, and $\sigma_h$) and the main stress regimes of coal-bearing strata were determined. Based on the above research, combined with the variation of coal reservoir permeability with burial depth in this area, the control mechanism of permeability was explored, including different stress values, horizontal principal stress differences, and the stress regime.

2 | GEOLOGICAL SETTING

Located in the passive margin fold belt of the upper Yangtze Block of the southern Yangtze Plate, the western Guizhou area is an important part of the upper Yangtze coal-accumulating sedimentary basin in the Upper Permian of western Guizhou, eastern Yunnan, and southern Sichuan. Tectonic activities during the Yanshanian and Himalayan led to the disintegration of the prototype basin, and formed a large number of synclines and synclinoria, which became important coal-controlling structures in this area. These coal-bearing synclines are ideal for the commercial development of CBM in southwestern China.

The Liupanshui Coalfield is located along the middle-north segment of the Liupanshui fault in southern Guizhou, Yangtze Block. The coalfield is bounded and controlled by the Yadu-Ziyun fault, NW-trending folds and faults are formed in the northeast, the syncline is open, and the anticline is closed. The south of the coalfield is bounded by the Huangnihe-Panjiazhuang fault and is affected by it, characterized by a NE-trending fold and fault structure. The central part of the coalfield is compressed from the north and blocked to the south, forming a mountain-shaped structure, which is dominated by NW-trending effective folds. The main strata exposed in the study area cover a large time span, including Carboniferous, Permian, Triassic, Jurassic, Paleogene, and Quaternary deposits, among which the Permian and Triassic are the most widely distributed. In the Late Permian, the area was characterized by continental, continental-marine transitional, and shallow marine sedimentary environments. During this interval, because of frequent transgression and regression, multiple coal-bearing strata were formed, represented by the Longtan and Changxing formations.

3 | METHODS AND MATERIALS

3.1 | Data

In most CBM wells in the study area, density logging, injection/fall-off tests, and in situ stress measurement were used to test reservoir physical properties after completion and before production. For this paper, the data of 54 levels of coal seams in 25 CBM wells were collected and collated; of these wells, density logging data were available for 11 wells, and the density logging sections covered 32 layers. Prior to the calculation phase, the quality of the collected data was checked and corrected.

Figure 2 shows the workflow of calculating stress parameters using density logging data, injection/fall-off tests, and in situ stress measurements in this work. The vertical stress of the tested coal seam in each well was calculated using the density logging data, the vertical stress gradient of the shallow layers up to 980 m depth in the study area was then estimated, and the horizontal principal stress of the main coal seams was calculated using the well test and in situ stress measurement data.
**FIGURE 1** Tectonic framework and distribution of coal-bearing synclines in western Guizhou Province, China

**FIGURE 2** Workflow for calculating stress parameters using injection/fall-off tests, in situ stress measurements, and density logging data
3.2 | Density logging

Density logging data are typically used to estimate overburden pressure or $\sigma_v$.\textsuperscript{21,22} The calculation equation is as follows:

$$\sigma_v = \int_0^H \rho(H) \cdot g dH$$  \hspace{1cm} (1)

where $\sigma_v$ is the vertical stress (MPa), $\rho(H)$ is the density of the formation at the depth $H$ (g/cm$^3$), and $g$ is the gravitational acceleration (m/s$^2$).

The necessary curve depth correction and environmental impact correction for density logging were carried out. Some vertical well density logging data in the study area were not recorded from the surface (e.g., Well 4 had a depth of 887 m and the starting point of density logging was 250 m), resulting in a lack of shallow density logging data. Thus, an exponential equation was used to fit the formation density of the missing sections of shallow logging data to fill the data gaps between the surface and the starting points of logging.\textsuperscript{23,24}

The equation is as follows:

$$\rho(H)_{\text{syn}} = R_S + (\text{TVD} - \text{AG})/3125a$$  \hspace{1cm} (2)

where $\rho(H)_{\text{syn}}$ is the fitting density for the shallow section, $R_S$ is the surface sediment density (with a default value of 1.90 g/cm$^3$, based on the Gulf of Mexico), TVD is the true vertical depth, AG is air gas, $a$ is the exponent coefficient (default value: 0.6, for Gulf of Mexico), and all depths in the equation are in feet.\textsuperscript{25}

3.3 | Injection/fall-off tests and in situ stress measurement

Injection/fall-off is a single transient test of well pressure, which is suitable for high- and low-pressure reservoirs, and is the most commonly used well testing method in CBM wells (Figure 3). In this test, water is injected into the wellbore for a period of time with a relatively stable displacement and an injection pressure lower than the fracture pressure of the coal seam, and then the well is closed, such that the pressure and the original reservoir pressure tend to gradually become balanced.\textsuperscript{26} Pressure gauges are used to record the variation of bottom hole pressure with time in the injection and shut-in stages. The semilogarithmic curve and double logarithmic curve fitting methods are used to analyze the data, and fall-off curve fitting is used to test the analysis results. The parameters of the target coal seam permeability, investigation radius, skin factor, formation coefficient, and reservoir pressure of each CBM well are thus obtained. In addition, combined with the burial depth of the coal seams, the reservoir pressure gradient can be calculated.

3.4 | In situ stress magnitude calculation

After the end of the fall-off test, in situ stress measurement is carried out. During this measurement, fluid is injected into the wellbore at a high injection rate over a very short time. When the bottom hole pressure is higher than the coal seam fracture pressure ($P_f$), the target layer is opened under the action of the minimum horizontal principal stress. At the moment of the rupture of the coal seam, the pressure is greatly reduced because the liquid cannot be replenished in time; thus, the critical pressure recorded by the digital pressure gauge represents the $P_f$ of the coal seam. Then, the well is shut and the pressure fall-off data are obtained through the digital pressure gauge. According to the hydraulic fracturing method of onshore vertical wells, when the fracture is closed, the fracture closure pressure ($P_C$) is considered equal to $\sigma_h$.\textsuperscript{27} Therefore, the $P_f$ of the coal seam can be obtained from the water injection curve, and the $P_C$ can be determined according to the pressure fall-off curve. To ensure the accuracy of the measured data, four periods of in situ stress measurements are carried out, and the periods with good fracture and closure effects are selected and analyzed by the time square root method. Then, parameters such as the fracture pressure, and closure pressure of the target coal seam of each CBM well are obtained. Combined with the burial depth of coal seams, the fracture pressure gradient, and closure pressure gradient can be calculated.

3.4 | In situ stress magnitude calculation

There are three main methods to determine the current in situ stress:\textsuperscript{5,10,28-30} (1) actual stress measurement, (2) calculation based on the logging curve and an empirical model, and (3) numerical simulation. In this study, $\sigma_H$ and $\sigma_h$ were
calculated using the actual stress measurement data, and the \( \sigma_v \) values of some wells were calculated using density logging data. Based on the vertical stress gradient (\( \gamma \)) of the optimized synthetic density logging, the \( \sigma_v \) values of the target coal seams of the CBM wells with non-density logging data were calculated.

Generally, in case of no fluid flow in vertical wells, \( \sigma_h \) is considered to be equal to \( P_C \), and its equation is as follows:

\[
\sigma_h = P_C
\]  

(3)

According to the theory of elasticity, \( \sigma_H \) can be expressed as:

\[
\sigma_H = 3P_C - P_f - P_0 + T
\]  

(4)

where \( P_f \) is the fracture pressure of the target layer (MPa), \( P_0 \) is the reservoir pressure (MPa), and \( T \) is the tensile strength of the coal and rock.

The in situ stress measurement goes through four cycles. For the second to fourth cycles, the fracture is reopened after the water is injected into the wellbore from the wellhead, and the repeated fracture pressure is determined. Because the crack has been produced in the first injection/fall-off cycle, the \( T \) of the rock is 0. Therefore, the above equation can be rewritten as follows:

\[
\sigma_H = 3P_C - P_f - P_0
\]  

(5)

For CBM wells without density logging data, \( \sigma_V \) can be estimated from the stress gradient of the overlying strata and the depth of the target layer \(^{31,32}\):

\[
\sigma_V = \gamma H
\]  

(6)

where \( \gamma \) is the stress gradient (MPa/m), and \( H \) is the burial depth (m).

3.5 | In situ stress anisotropy

The lateral pressure coefficient (\( \lambda \)) refers to the ratio of the average horizontal principal stress to \( \sigma_V \), which is an effective parameter to characterize the in situ stress distribution. Its calculation equation is shown in Equation \(^{7,32} \). In addition, \( \lambda \) is generally considered to be proportional to the reciprocal of burial depth, as indicated in Equation \(^{10,33} \):

\[
\lambda = (\sigma_H + \sigma_h)/2\sigma_V
\]  

(7)

\[
\lambda = a/h + b
\]  

(8)

In this equation, both \( a \) and \( b \) are coefficients.

In order to quantitatively evaluate the difference of stress in different directions of coal reservoir, the concept of in situ stress anisotropy is introduced \(^{34,35} \) and the formula is as follows:

\[
AI_{I_s} = \sqrt{(\sigma_H - \bar{\sigma})^2 + (\sigma_h - \bar{\sigma})^2 + (\sigma_V - \bar{\sigma})^2} \bar{\sigma}
\]  

(9)

where \( AI_{I_s} \) is the anisotropy parameter of in situ stress, \( \bar{\sigma} \) is the average value of \( \sigma_H \), \( \sigma_h \), and \( \sigma_V \). The increase in \( AI_{I_s} \) means that the anisotropy increases, and the decrease of \( AI_{I_s} \) means that \( \sigma_H \), \( \sigma_h \), and \( \sigma_V \) tend to be the same.

4 | RESULTS AND DISCUSSION

4.1 | Magnitude of vertical stress (\( \sigma_V \))

As a key step in the workflow, the lack of shallow density logging data is considered to be a challenge for this study. Therefore, in the absence of shallow logging data, synthetic density logging data were used for five CBM wells (Wells 4, 7, 9, 10, and 11). The vertical stress profiles of the above wells were generated by combining the shallow exponential equation fitting density and logging measured density for the whole formation. The calculation equation for shallow synthetic density is shown in Equation 2. Because the density calculated based on the default fitting parameters is not consistent with the actual density, \( R_S \) and \( \alpha \) are modified, and the fitting effect of the modified curve is better. Taking Well 4 as an example, two density profiles were simulated. The values of \( \alpha \) were 0.6 and 0.1, and values of \( R_S \) were 1.9 g/cm\(^3\) and 1.72 g/cm\(^3\), respectively. As shown in Figure 4, when the vertical depth was 886 m, \( \sigma_V \) was 21.95 MPa, and the stress gradient was 0.025 MPa/m.

The density logging data of 11 wells in the study area were collected. Among them, six wells were in the Panguan syncline, which had an average stress gradient of \(-0.024\) MPa/m; two wells were in the Faer syncline, which had an average stress gradient of \(-0.023\) MPa/m; two wells were in the Tucheng syncline, which had an average stress gradient of \(-0.025\) MPa/m; and one well was in the Dahebian syncline, which had an average stress gradient of \(-0.025\) MPa/m. It was determined that the average stress gradient of the 11 wells was \(-0.024\) MPa/m, and that the stress gradient of different coal-bearing synclines in the study area was stable (0.024 ± 0.001 MPa/m). The density logging section covered 30 well testing levels, accounting for 57.69% of the total well testing levels. This value is considered to be relatively representative (Table 1).

The above average stress gradient (0.024 MPa/m) was taken as the average value of the drilled strata in the study area, and the vertical stress of the main coal seams in other wells was then calculated (Table 2).
4.2 Test parameters of injection/fall-off tests and in situ stress measurements

In this study, the injection/fall-off and in situ stress measurement data of 52 well test levels in the study area were collected, and the burial depth of coal seams was between 236.295 and 978.66 m. The coal seam $P_f$, $P_C$, and $P_0$ all increased linearly with increasing depth, and the correlations are as follows (Figure 5). This law of change is consistent with the southern Qinshui Basin, the southeastern margin of the Ordos Basin, the southern margin of the Junggar Basin, and eastern Yunnan.

1. Fracture pressure (Figure 5A):

$$P_f = 0.0694h + 2.6378$$  \hspace{1cm} \text{(10)}

2. Shut-in pressure (Figure 5B):

$$P_C = 0.0157h + 1.6978$$  \hspace{1cm} \text{(11)}

3. Reservoir pressure (Figure 5C):

$$P_0 = 0.0110h - 0.7052$$  \hspace{1cm} \text{(12)}

In addition, there is an obvious positive correlation between $P_f$ and $P_C$ (Figure 5D), and the fitting equation is as follows:

$$P_f = 1.0903P_C + 0.6876$$  \hspace{1cm} \text{(13)}

The injection/fall-off test results show that the permeability was between 0.0018 and 1.46 mD, with an average value of 0.26 mD, which is consistent with a typical low permeability reservoir (Figure 6).
4.3 Magnitude of horizontal in situ stress components

The value of $\sigma_h$ is calculated by Equation 3, and $\sigma_H$ is calculated by Equation 4. Combined with the calculation results of $\sigma_V$ in Section 4.1, the variations of $\sigma_H$, $\sigma_h$, and $\sigma_V$ with burial depth are shown in Figure 7. The value of $\sigma_H$ was between 4.63 and 25.42 MPa (average: 15.46 MPa). The maximum horizontal principal stress gradient was between 1.21 and 4.56 MPa/100 m (average: 2.47 MPa/100 m); $\sigma_h$ was between 3.55 and 21.01 MPa (average: 11.70 MPa). The minimum horizontal principal stress gradient was between 1.12 and 2.99 MPa/100 m (average: 1.86 MPa/100 m); $\sigma_V$ was between 4.65 and 22.36 MPa (average: 15.37 MPa). Overall, 73.08% of the $\sigma_h$ values were >10 MPa. The ground stress in this area was higher than that in other CBM-producing areas around the world, such as the Black Warrior Basin in

| TABLE 1 Vertical stress and stress gradient of main coal seams in CBM wells with density logging curves |
| Wells | Coal seam number | Depth (m) | Vertical stress (MPa) | Stress gradient (MPa/m) | Average stress gradient (MPa/m) |
|-------|-----------------|-----------|----------------------|------------------------|-------------------------------|
| Well 1 | No.3 | 558.05 | 14.20 | 0.025 | 0.024 |
| | No.10 | 611.10 | 15.44 | 0.025 | |
| | No.13 | 641.58 | 16.17 | 0.025 | |
| | No.22 | 706.93 | 17.65 | 0.025 | |
| Well 2 | No.3 | 314.97 | 7.97 | 0.025 | |
| | No.22 | 483.91 | 12.00 | 0.025 | |
| | No.26 | 508.54 | 12.56 | 0.025 | |
| | No.29 | 527.61 | 13.00 | 0.025 | |
| Well 3 | No.12 | 871.78 | 20.09 | 0.023 | |
| | No.22 | 948.44 | 21.72 | 0.023 | |
| | No.27 | 978.66 | 22.36 | 0.023 | |
| Well 4 | No.6 | 674.45 | 16.95 | 0.025 | |
| | No.12 | 722.09 | 18.08 | 0.025 | |
| | No.18 | 774.39 | 19.31 | 0.025 | |
| | No.24 | 832.89 | 20.68 | 0.025 | |
| Well 5 | No.12 | 744.81 | 18.80 | 0.025 | |
| | No.16 | 771.86 | 19.41 | 0.025 | |
| Well 6 | No.3 | 518.17 | 11.15 | 0.022 | |
| | No.10 | 558.61 | 12.01 | 0.021 | |
| | No.12 | 575.28 | 12.35 | 0.021 | |
| | No.18 | 622.85 | 13.33 | 0.021 | |
| Well 7 | No.13 | 236.30 | 4.65 | 0.020 | |
| | No.15 | 264.56 | 5.18 | 0.020 | |
| | No.16 | 285.57 | 5.56 | 0.019 | |
| Well 8 | No.5 | 599.00 | 14.83 | 0.025 | |
| | No.7 | 637.70 | 15.77 | 0.025 | |
| | No.13-1 | 652.49 | 16.12 | 0.025 | |
| | No.13-2 | 659.00 | 16.26 | 0.025 | |
| Well 9 | No.29 | 864.90 | 20.82 | 0.024 | |
| Well 10 | No.9 | 609.00 | 15.16 | 0.025 | |
| Well 11 | No.C409 | 849.36 | 21.23 | 0.025 | |
| | No.C406 | 868.33 | 21.63 | 0.025 | |

| TABLE 2 Vertical stress of main coal seams in non-density logging curve wells in the study area |
| Wells | Coal seam number | Depth (m) | Vertical stress (MPa) |
|-------|-----------------|-----------|---------------------|
| Well 12 | No.17 | 569.17 | 13.66 |
| | No.18 | 605.19 | 13.42 |
| | No.22 | 639.25 | 15.34 |
| | No.24 | 650.89 | 15.62 |
| Well 13 | No.1 | 648.81 | 15.57 |
| | No.7 | 697.90 | 16.75 |
| | No.9 | 713.67 | 17.13 |
| | No.10 | 725.90 | 17.42 |
| Well 14 | No.5 | 319.40 | 7.67 |
| | No.6 | 363.63 | 8.73 |
| | No.9 | 384.41 | 9.23 |
| | No.12 | 442.33 | 10.62 |
| Well 15 | No.3 + 4 | 671.07 | 16.11 |
| | No.10 + 11 | 746.33 | 17.91 |
| | No.15 | 785.82 | 18.86 |
| | No.17 | 815.26 | 19.57 |
| Well 16 | No.1 + 3 | 619.26 | 14.86 |
| | No.9 | 661.23 | 15.87 |
| | No.16 | 738.90 | 17.73 |
| | No.27 | 920.03 | 22.08 |
| Well 17 | No.3 | 645.53 | 15.49 |
| | No.5 | 689.63 | 16.55 |
| | No.12 | 721.50 | 17.32 |
| | No.19 + 20 | 781.07 | 18.75 |
| | No.27 | 876.02 | 21.02 |
| Well 18 | No.5 | 580.00 | 13.92 |
| | No.7 | 630.00 | 15.12 |
| | No.23 | 806.00 | 19.34 |
| Well 19 | No.6 | 671.80 | 16.12 |
| Well 20 | No.6 | 647.00 | 15.53 |
| Well 21 | No.6 | 644.10 | 15.46 |
| Well 22 | No.6 | 612.00 | 14.69 |
| Well 23 | No.3 | 624.00 | 14.98 |
| Well 24 | No.3 | 635.10 | 15.24 |
| Well 25 | No.13 | 621.24 | 14.91 |
Within the total dataset, 23 sets of data belong to a strike-slip faulting stress regime ($\sigma_H > \sigma_V > \sigma_h$), accounting for 44.23%; 24 sets of data belong to a normal faulting stress regime ($\sigma_V > \sigma_H > \sigma_h$), accounting for 46.15%; and five sets of data belong to a reverse faulting stress regime ($\sigma_V > \sigma_h > \sigma_H$), accounting for 9.62% (Figure 5). These results are consistent with the understanding obtained from the statistics of several major CBM fields in China by Chen et al.\textsuperscript{37}

Liupanshui Coalfield has experienced multiperiod tectonic stresses, thus leading to a complex stress regime. As shown in Figures 8 and 9, there are three types of stress fields in the study area, which may be caused by complex local structures. With an increase in depth, the probability of the occurrence of a reverse faulting stress regime decreases to 0, indicating that the growth rate of $\sigma_h$ is less than those of $\sigma_H$ and $\sigma_V$.

When the burial depth is <600 m, the strike-slip faulting stress regime is dominant, and the normal faulting and
reverse faulting stress regimes each account for certain proportions, which indicates that there are differences in the stress states of shallow coal seams in different parts of the study area. Shallow coal seams are greatly affected by the structure. When the burial depth is between 600 and 800 m, the proportion of the normal faulting stress regime increases greatly. In this depth range, $\sigma_V$ increases linearly with increasing burial depth, and the growth rate of $\sigma_H$ is less than that of $\sigma_V$ and tends to first decrease and then increase. The growth rate of $\sigma_H$ is the smallest. When the burial depth is between 800 and 980 m, the main coal-bearing strata are affected by both the normal faulting and strike-slip faulting stress regimes. In the depth range of 600-980 m, the main coal-bearing strata are affected by both the normal faulting and strike-slip faulting stress regimes. The deep (>1,000 m) well data collected by Kang, et al. in the Bide-Santang Basin in an adjacent area show that the stress regime was of the normal fault type. Based on this, it is inferred that with the further increase in drilling depth in the future, the deep coal seams in the study area will mainly be controlled by the stress regime of the normal fault type.

4.4 Principal stress ratio variation with depth

For the Liupanshui Coalfield, $\lambda$ is between 0.49 and 1.57, with an average of 0.91. In the Panguan syncline, this value ranges from 0.49 to 1.34, with an average of 0.91; in the Tucheng syncline, it ranges from 0.70 to 1.57, with an average of 0.95; and in the Faer syncline, it ranges from 0.63 to 0.99, with an average of 0.87 (Figure 10A).

According to an analysis of 3,586 data points collected by Yang et al., the $\lambda$ values of Chinese mainland strata are within the range defined by Equation 14. The trend line of $\lambda$ for the Liupanshui Coalfield satisfies Equation 15, and the inner and outer envelopes satisfy Equation 16. These two curves can be regarded as the upper and lower limits of $\lambda$ in
the Liupanshui Coalfield. As shown in Figure 10A, all the lateral pressure coefficients of the Liupanshui Coalfield are in the area bounded by the inner and outer envelopes of the Chinese mainland. These equations are expressed as follows:

\[
\frac{8.57}{h} + 0.32 \leq \lambda \leq \frac{350.16}{h} + 1.00 \quad (14)
\]

\[
\lambda = \frac{135.00}{h} + 0.68 \quad (15)
\]

\[
100.26/h + 0.31 \leq \lambda \leq \frac{220.96}{h} + 1.03 \quad (16)
\]

The value of \( \lambda \) can characterize the relative magnitude between the horizontal principal stress and \( \sigma_V \). With the increase in burial depth, \( \lambda \) decreases slowly, indicating that gravity stress has progressively more influence on in situ stress. Meanwhile, \( AI_\sigma \) and \( \sigma_H - \sigma_h \) show similar characteristics of change. Both of them take 700 m as the limit, and gradually increase when the burial depth is <700 m and decrease when the burial depth is more than 700 m. It shows that under the background that \( \sigma_V \) increases steadily with the burial depth, \( AI_\sigma \) is mainly controlled by \( \sigma_H - \sigma_h \) (Figure 10B,C).

When the burial depth is more than 800 m, \( AI_\sigma \) and \( \sigma_H - \sigma_h \) are significantly reduced. Most values of \( \lambda \) are <1, indicating that at 800 m, gravity stress begins to become dominant in the overlying strata of the deep coal seams (Figure 10A). This finding is consistent with the analysis results in Section 4.3. \( \lambda \) also shows a small increase in the depth, which is consistent with the reversal of the stress regime.

### 4.5 Implication for coal permeability

Coal reservoir permeability is one of the key factors determining CBM productivity,\(^{40,41}\) which is mainly affected by effective stress, matrix shrinkage, and gas slippage in the process of CBM development.\(^{42-44}\) Previous studies generally suggested that the permeability of a coal reservoir decreases exponentially with the increase of effective stress. In the initial stage of CBM development or in an undeveloped coal reservoir, the coal reservoir is in a state of stress equilibrium, and the permeability is mainly affected by in situ stress and the coal cleat system. The increase of burial depth and stress concentration caused by local structure will lead to the exponential decrease of permeability.\(^{45-48}\)

Under the background of a high-pressure compression structure, the permeability of a coal reservoir changes regularly with burial depth, but its trend is not monotonous.\(^{49}\) Li, Tang, Xu, and Yu\(^{50}\) revealed that the permeability of coal decreased to a depth of about 700 m and then increased from a depth of 700 m to about 1050 m in the Liulin area, eastern Ordos Basin. Sun et al\(^{50}\) found that the coal seam permeability of the Shizhuang CBM block decreased to a depth of...
about 950 m, increased at depths of more than 1100 m. Chen, Tang, Tao, Xu, Li, Zhao, Ren, and Fu also found a similar non-monotonic change in permeability in the south of the Qinshui Basin and at the eastern margin of the Ordos Basin.\(^3\)

It was also noted that in the vertical direction, the permeability-depth profile in the study area had the characteristics of high permeability (<400 m)-low permeability (400-600 m)-high permeability (600-800 m)-low permeability (800-980 m) (Figure 11).

Further analysis shows that the variation of coal reservoir permeability with burial depth differs under different stress regimes. A relative high permeability zone under the control of a normal faulting stress regime mainly appears in the burial depth interval of 600-800 m (Figure 11A), a relatively high permeability area under the control of a strike-slip faulting stress regime mainly appears in the burial depth ranges of <400 m and 600-800 m (Figure 11B), and the reverse faulting stress regime mainly appears at depths shallower than 650 m; in addition, the permeability decreases with the increase of burial depth (Figure 11C). The results of the comparison show that when the burial depth of the coal seam is more than 600 m, the coal permeability in a normal faulting stress regime is higher than that in a strike-slip faulting stress regime, which is due to the low compressive stress under normal faulting stress regime.\(^5^1\),\(^5^2\)

With the increase in burial depth, the principal stress increases linearly (Figure 7), but the permeability does not simply decrease exponentially with the increase of principal stress, which is worthy of further exploration. The appearance of the shallow hyperpermeability zone (0-400 m) is essentially attributed to the opening of cracks caused by stress relaxation under near-surface conditions (Figures 10C, 11B, and 12). The smaller \(\sigma_H - \sigma_h\) shown in Figure 10C provides evidence for horizontal stress relaxation. The decrease of permeability in the range of 400 to 600 m reflects that the permeability is very sensitive to stress, which is affected by strong structural compression; the horizontal principal stress increases, and the stress regime is mainly of the strike-slip faulting type, which is affected by horizontal compressive stress. The vertical fractures are closed, and the permeability decreases greatly. In the range of 600 to 800 m, \(\sigma_H - \sigma_h\) and \(AI_p\) reach their peak and then begin to decrease. Between this zone, \(\sigma_H - \sigma_h\) and \(AI_p\) reach their highest. The high \(\sigma_H - \sigma_h\) and \(AI_p\) may enhance the initial friction failure state of coal,\(^3\)\(^8\) and its positive effect on permeability is greater than the negative effect of stress increase, which leads to the increase of permeability in this zone. For the points under the control of the normal faulting and strike-slip faulting stress regimes (Figure 11A and 11B), the permeability of coal increases with the increase of the principal stress difference. In the range of 800 to 980 m, the principal stress values reach 14.50 MPa, 18.45 MPa, and 22.75 MPa, respectively (Figure 7). Coupled with the decrease of \(\sigma_H - \sigma_h\), the coal reservoir is strongly squeezed by three-dimensional stress, and the coal permeability decreases with the increase of stress. The permeability of coal is also controlled by the natural fracture structure and its degree of opening. The structure of the study area is complex, and there are two structural types of coal\(^5^3\): the fold genetic type and fault genetic type. The complexity of the coal reservoir cleat system and strong stress sensitivity may be the main reasons for the discrepancy between the permeability variation in the study area and the conventional understanding that permeability decreases exponentially with the increase in burial depth/stress.

Generally, the vertical change of permeability is affected by vertical stress, local tectonic stress, and the coal cleat

FIGURE 11 Permeability varies with burial depth under different stress regimes. Coal reservoir permeability variation with burial depth under a normal faulting stress regime (A), coal reservoir permeability variation with burial depth under a strike-slip faulting stress regime (B), and coal reservoir permeability variation with burial depth under a reverse faulting stress regime (C)
system. The data collected in this study are relatively few, and the above judgment is preliminarily. It needs to be verified and improved after more data are obtained, and the non-monotonic decline characteristics of increasing permeability with burial depth need to be studied further.

5 | CONCLUSIONS

In this paper, the in situ stress characteristics of coal seams in Liupanshui Coalfield were studied, the non-monotonic decrease of permeability with burial depth was revealed, and the effect of in situ stress on the coal reservoir permeability was evaluated. The main conclusions are as follows:

1. The average stress gradient of different coal seams in Liupanshui Coalfield is about 0.024 MPa/m. There are mainly two stress regimes: normal faulting type (46.15%) and strike-slip faulting type (44.23%). The proportion of reverse faulting type is only 9.62%.

2. In the ranges of different depths, there is a phenomenon of mutual transformation of the stress regime. The stress regime of the shallower than 600 m is mainly of the strike-slip type, the stress regime of 600-800 m is dominated by the normal faulting type, and the 800-980 m interval is influenced roughly equally by both the normal faulting type and strike-slip faulting type. With the increase of burial depth, \( \lambda \) gradually decreases to a fixed value, and that value is generally <1, indicating that the vertical stress of the deep formation becomes the principal stress.

3. The variation of coal reservoir permeability with burial depth is different under different stress regimes. With the increase in burial depth, the permeability decreases non-monotonously, and its value is controlled by the relative magnitude of in situ stress.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (41572140, 41872170), the National Major Science and Technology Projects of China (2016ZX05044), the Fundamental Research Funds for the Central Universities (2020CXNL11), the Assistance Program for Future Outstanding Talents of China University of Mining and Technology (2020WLJCRCL090).

CONFLICTS OF INTEREST

The authors declare no competing financial interest.

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**How to cite this article:** Fang X, Wu C, Jiang X, Liu N, Zhou D, Ju Y. Characteristics of in situ stress and its influence on coal seam permeability in the Liupanshui Coalfield, Western Guizhou. *Energy Sci Eng.* 2021;9:1773–1786. [https://doi.org/10.1002/ese3.950](https://doi.org/10.1002/ese3.950)