Characteristics of in situ stress and its influence on coalbed methane development: A case study in the eastern part of the southern Junggar Basin, NW China

Haijiao Fu1,2 | Detian Yan1,2 | Shuguang Yang3 | Xiaoming Wang1,2 | Zheng Zhang1,2 | Mengdi Sun1,2

1Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education, China University of Geosciences, Wuhan, China
2Faculty of Earth Resources, China University of Geosciences, Wuhan, China
3CBM Research & Development Center, Xingjiang Coal Field Geology Bureau, Xingjiang, China

Correspondence
Haijiao Fu, Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, China.
Email: fffhj1987@163.com

Funding information
Key project of National Science & Technology, Grant/Award Number: 2016ZX05043-001 and 2016ZX05044-001; Fundamental Research Funds for the Central Universities, Grant/Award Number: CUG170678; National Natural Science Foundation of China, Grant/Award Number: 41690131; Hubei natural science foundation, Grant/Grant/Award Number: 2019CFA028; National Natural Science Foundation for Young Scholars of China, Grant/Award Number: 41902173; Program of Introducing Talents of Discipline to Universities, Grant/Award Number: B14031

Abstract
Based on 54 sets of well test data of 29 coalbed methane (CBM) wells, the distribution characteristic of in situ stress in the eastern part of the southern Junggar Basin and its control on permeability (K), reservoir pressure (P₀), and gas content (G) were discussed systematically. The results show that three types of in situ stress regime exist and are converted corresponding to a certain depth, (1) <600 m is the strike-slip fault regime (σ_H > σ_v > σ_h); (2) 600-1050 m is the stress transition zone (σ_H ≈ σ_v > σ_h); and (3) >1050 m is the normal fault regime (σ_v > σ_H > σ_h).

Regionally, with depths < 1050 m, stress regime also changes from west to east, that is, σ_H > σ_v > σ_h type in the western Miquan, σ_H ≈ σ_v > σ_h type in the middle Fukang, and σ_v > σ_H > σ_h type in the eastern Jimushaer, respectively. Controlled by stress regime and vertical belting, coal K shows a trend of “remarkably decreased, rebounded increase and greatly decreased,” and two decreasing stages (<600 m and > 1050 m) are mainly influenced by horizontal stress and vertical stress, respectively. Taking a burial depth of 1000-1150 m as a boundary, the relationship between G and depth converts from “continually increasing” to “gradually decreasing,” which is in good agreement with the converted interface of stress regime from σ_H ≈ σ_v > σ_h type to σ_v > σ_H > σ_h type. Taking the converted interfaces of G (1000-1150 m), K (800 m), and the prediction depth of the weathered zone (400 m) into consideration, CBM development potential in the study area can be divided into three grades, that is, (1) 400-800 m (high K and medium G), (2) 800-1150 m in Miquan and 800-1000 m in Fukang (medium K and high G), and (3) >1150 m in Miquan and >1000 m in Fukang (low K and poor G). Overall, a key CBM development breakthrough will most likely be made in the study area within the scope of 600-800 m due to the better G and higher K.

KEYWORDS
CBM development, Junggar Basin, permeability, stress regime, vertical belting
1 | INTRODUCTION

In situ stress is a type of internal stress in the earth’s crust that is mainly controlled by gravity and tectonic movement, and the latter has a greater impact on in situ stress formation. Based on this, in situ stress can be divided into overburden stress ($\sigma_v$) and tectonic stress ($\sigma_H$ and $\sigma_s$), and the former is mainly influenced by the overlying rock mass, whereas the latter is mainly related to tectonic movement and rock geological structures. According to the relative relationships of three principal stresses, the classification schemes for in situ stress regime have been divided into the normal fault regime ($\sigma_s > \sigma_H > \sigma_v$), the reverse fault regime ($\sigma_H > \sigma_s > \sigma_v$), and the strike-slip fault regime ($\sigma_H > \sigma_v > \sigma_s$). Stress field data from coal-bearing basins at home and abroad indicate that in situ stress regime often shows an obvious belting phenomenon in the vertical direction. Moreover, vertical variations of the current in situ stress regime have obvious influence on CBM enrichment mechanisms and development conditions.

By controlling the opening or closing of the coal reservoir pore-fracture system, the current in situ stress regime has obvious control effects on $K$, $P_g$, $G$, artificial fracture expansion, and the process of drainage and pressure lowering. $K$ is one of the most important factors in the determination of CBM productivity. The $K$ values of coal reservoirs are mainly composed of 0.01-5 mD in China, which is lowered by 1-2 magnitudes than overseas, for example, the Powder River Basin in North America (>10 mD) and the Surat Basin in Austria (10-30 mD). The research showed that in situ stress had obviously affected coal $K$, and the latter exponentially declined with the increasing of the former. The methane adsorbability of coal reservoirs tends to increase with increasing $P_g$ and decreasing $T_{min}$. By changing the confining pressure of pore fluid, the in situ stress regime can directly control $P_g$ and influence the gas-bearing conditions of the coal reservoir. In general, coal reservoirs usually have greater $P_g$ and $G_v$ values within a compressive stress regime, whereas smaller $P_g$ and $G_v$ values exist in a tensile stress regime.

During the 13th Five-Year Plan period (2016-2020), the southern Junggar Basin becomes the key target zone of CBM exploration and development in China, and its CBM resources (<2000 m) were predicted to be $0.95 \times 10^{12}$ m$^3$. To date, CBM exploration has achieved major breakthroughs in Fukang, southern Junggar Basin, with the highest daily production per well of 1.7125 $\times 10^4$ km$^3$. The first demonstration base of CBM development and utilization was established in Xinjiang in 2013. However, CBM exploration and development are still confronted with a series of difficulties in the southern Junggar Basin, for instance, (1) better gas-production efficiency has only been achieved in Fukang, and the CBM exploration results are relatively poor in other regions; (2) at depths > 1000 m, gas-production efficiency and CBM development are also relatively poor in Fukang; and (3) the lower $P_g$ and gas saturation seriously restrict CBM development efficiency and economic benefits. The studies suggest that the current in situ stress regime should significantly contribute to the differential distribution of CBM enrichment conditions and development potential.

To date, scarcely any studies of in situ stress and its effect on CBM development have focused on the Jurassic coals of the southern Junggar Basin, and it has never been reported in international literature. To systematically discuss the characteristics of in situ stress and its effect on CBM development, a series of well test data from the eastern part of the southern Junggar Basin was systematically collected for the first time (Figure 1). A number of geological analyses were carried out, that is, (a) the distribution rules for in situ stress regime of the Jurassic formations in two-dimensional space, (b) the control mechanisms of stress vertical belting on $K$, (c) the control effects of stress vertical belting on $G$, and (d) the grade division of CBM development potential and (e) the optimization of favorable targets. Both of them can provide a geological basis for the reasonable establishment of a CBM exploration–development program.

2 | GEOLOGICAL SETTING

The Junggar Basin has experienced the Hercynian, Indosinian, Yanshan, and Himalayan tectonic movements since the late Paleozoic, and the additive effects of multiphase stress fields lead to a complex structural configuration. As one secondary structural unit of the Junggar Basin, the piedmont thrust belt of the North Tianshan Mountains is a multiphase superimposed inheritance structural belt, which is usually divided into five secondary structure units (ie, the Sikeshu sag, Qigu fault–fold belt, Huomatui anticlinal zone, Huan anticlinal zone, and the Fukang fault zone) (Figure 2A). Among them, the Fukang fault zone is the main research target in this study, and it is mainly located north of Bogda Mountain and east of the Urumqi–Miquan strike-slip fault and is now shown as a “NE-EW-NW” arcuate tectonic belt on the plane. The front structural belt of Bogda Mountain mainly underwent the Yanshan and Himalayan movements. The Himalayan movement was the main developmental phase of the fault and fold structures, and the critical period of CBM enrichment and adjustment in the study area. Overall, the formation and evolution of Bogda Mountain have obvious controlling effects on the current structural framework and stress field distribution of the study area. The rapid uplift of Bogda Mountain occurred from the late Oligocene to the early Miocene, and a large-scale thrust nappe began to form north of Bogda Mountain. According to the difference between the hanging wall and footwall, the thrust nappe can be divided into an overthrust fault–fold zone...
and a back-thrust fault–block zone from north to south (Figure 2B). Among them, the overthrust fault–fold zone located between the Fukang and Yaomoshan faults was the main target for CBM exploration and development in the study area. Overall, the overthrust fault–fold zone was also shown as a “NE-EW-NW” arcuate tectonic belt, along with a series of anticline and syncline structures. Regionally, tectonic deformation can be characterized as “strong in the center and weak on two sides.” In the eastern part of the southern Junggar Basin, that is, the Fukang region, tectonic
The surface of the southern Junggar Basin is mostly covered by Quaternary strata, and the Jurassic strata are partly exposed at the same time. The Badaowan and the Xishanyao Formations are the coal-bearing strata in the study area, and the Sangonghe Formation that developed between them contains only a small amount of coal streak or nothing (Figure 3). There are differences in the sedimentary environments between the Badaowan and the Xishanyao Formations. The former mainly developed in the fluvial and swamp facies environments, whereas the latter developed in the delta, lacustrine, and swamp facies. Controlled by tectonic and sedimentary environments synthetically, the coal-rich center of the Badaowan Formation is mostly located in the Fukang region, and the coal-rich center of the Xishanyao Formation is located in the Miquan and Jimushaer regions. Therefore, the Badaowan coal in the Fukang region and the Xishanyao coal in the Miquan and Jimushaer regions are selected as prospective targets for CBM exploration and development in the eastern part of the southern Junggar Basin.

### METHODOLOGY

As a common transient well test method, the injection/falloff well test has been widely applied in the CBM field. The schematic diagram of the injection/falloff well tests and in situ stress measurement is shown in Figure 4. Based on log interpretation, the packer is installed on the immediate roof using tubing strings, and the pump injection system and underground equipment are connected through the pipelines. Then, the injection/falloff test and in situ stress measurement are carried out successively. To ensure the data are representative and comparable, all the test data are performed by the same procedure and equipment.

The injection/falloff test was performed in accordance with the Chinese National Standard GB/T 24504-2009 before the in situ stress measurement, including two stages: (I) the steady injection stage (14 hours) and (II) the shut-in stage (24 hours) (Figure 5). Thus, the bottom-hole pressure varies with the change of time that can be recorded using an electric pressure gauge, and the related data are used to calculate
the reservoir parameters such as reservoir pressure and permeability. In general, straight-line analysis and chart board matching analysis are usually used for analyzing the injection/falloff well test data. Here, the data were analyzed by both the semilogarithm and double-logarithm fitting analysis method and were further verified with a historical fitting curve. The permeability obtained from the injection/falloff test is near to the cleat permeability of single-phase fluid.

In situ stress parameters are measured by the multiloop hydraulic fracturing method, according to the China earthquake industry standard DB/T 14-2000. To conduct a full cycle in situ stress measurement, fluid is injected into the wellbore at a higher injection rate for a very short time. Once the pressure is greater than $P_f$ and the coal seams will be opened, pressure value recorded by the electric pressure gauge at this moment is the $P_f$ (Figure 6). To ensure the accuracy of in situ stress measurements, three other cycles are completed by repeating the above steps. Two cycles with good fracture creation and closure are selected to calculate the $P_c$ value following the time square root method.

In this study, 54 seams from 29 vertical wells were tested after completion and before production. According to the onshore vertical well hydraulic fracturing methods, the shut-in pressure ($p_c$) is equal to the minimum horizontal principal stress ($\sigma_h$).

$$\sigma_h = P_c$$ (1)

**FIGURE 4** Schematic diagram of equipment for injection/falloff well test and in situ stress measurement. (modified from Zhao et al)

**FIGURE 5** Injection/falloff curves of typical CBM well in the eastern part of the southern Junggar Basin

**FIGURE 6** In situ stress measurement curves of typical well in the eastern part of the southern Junggar Basin
In the initial hydraulic fracturing cycle, the rock is complete (Figure 6, Circle 1). According to the theory of elasticity, the maximum horizontal principal stress ($\sigma_H$) can be expressed as follows:  

$$\sigma_H = 3P_c - P_f - P_o + T$$  

(2)

where $P_f$ is the breakdown pressure in MPa, $P_o$ is the reservoir pressure in MPa, and $T$ is the tensile strength of coal or rock in MPa.

For two to four circles during the in situ stress measurement, the water is injected into the wellbore again, and the crack will reopen and the refracturing pressure will be gotten. Since the cracks have been produced in the cycle 1, the tensile strength ($T$) of the rock is equal to 0, and therefore, the $\sigma_H$ can be expressed as follows:  

$$\sigma_H(T = 0) = 3P_c - P_f - P_o$$  

(3)

The vertical principal stress ($\sigma_v$) can be estimated from the density and depth of the overburden strata. Li et al systematically analyzed 229 sets of in situ stress data from coal-bearing basins in China and proposed a new prediction equation of the $\sigma_v$ (Equation 4):  

$$\sigma_v \approx 0.023H$$  

(4)

4 | RESULTS

4.1 | Results of injection/falloff and in situ stress tests

A total of 54 injection/falloff and in situ stress test data from 29 CBM wells from the study area were collected and plotted in Figure 7. Within depths ($H$) from 278.4 to 1559.5 m (avg. 804.19 m), the $P_f$ value of the coal reservoir ranges from 5.12 to 25.03 MPa, with an average of 13.71 MPa; the $G_f$ value changes from 1.08 to 2.88 MPa/100 m, with an average of 1.75 MPa/100 m. The $P_o$ value varies from 4.67 to 24.67 MPa (avg. 12.94 MPa), and the $G_o$ value is approximately 0.489-1.32 MPa/100 m (avg. 0.82 MPa/100 m), belonging to a low-pressure reservoir. The $T_{em}$ value changes from 6.32 to 41.28°C, with an average of 23.50°C. Finally, the $K$ value varies from 0.006 to 19.7 mD (avg. 1.82 mD), which is lower by 1-2 orders of magnitude than overseas.

With Equations (1), (2), and (4), the values of $\sigma_h$, $\sigma_H$, and $\sigma_v$ have been calculated (Table 1). The results are that the $\sigma_h$ value ranges from 4.67 to 24.67 MPa, with an average of 12.94 MPa; the $\sigma_H$ value changes from 6.43 to 35.59 MPa, with an average of 18.8 MPa; and the $\sigma_v$ value varies from 6.4 to 35.78 MPa, with an average of 18.46 MPa. According to judging standard (>30 MPa, super strong stress; 18-30 MPa, strong stress; 10-18 MPa, moderate stress; <10 MPa, low stress) proposed by Kang et al, the in situ stress in the study area belongs to moderate–strong stress. Contrasting the $\sigma_h$ values of typical CBM development blocks abroad, for example, Black Warrior Basin in American (1 ~ 16 MPa) and Sydney Basin in Austria (1-10 MPa), the in situ stress strength in the study area is relatively high that is not beneficial for CBM development.

The research shows that the $P_0$, $P_f$, $P_c$, and $T_{em}$ all have linearly increasing trends with the increase in $H$ (Figure 8). The relevant relationships are as follows.

$$P_f = 0.0144 \times H + 2.137 (R = 0.715)$$  

(5)
\[ Pc = 0.0144 \times H + 1.4042 \quad (R = 0.7546) \]  
\[ P_0 = 0.0105 \times H - 1.7517 \quad (R = 0.8397) \]  
\[ T_{em} = 0.0169H + 10.119 \quad (R^2 = 0.7992) \]

where \( H \) represents the burial depth of coal reservoirs, \( m \), and \( R^2 \) represents the correlation coefficient.

Moreover, the \( P_f \) has a linear positive correlation with \( P_c \) and can be written as follows.

\[ P_c = 0.9604 \times P_f - 0.2255 \quad (R = 0.9794) \]

### 4.2 | The spatial distribution characteristics of the current in situ stress regime

#### 4.2.1 | Principal stress ratio change with the depth

Two horizontal components of the tectonic stress are not equal in the eastern part of the southern Junggar Basin, and the ratio of \( \sigma_H \) to \( \sigma_h \) ranges from 1.12 to 1.68, with an average of 1.45. The ratio of \( \sigma_H \) to \( \sigma_v \) is approximately 0.54 ~ 1.81 (avg. 1.04), and if 28 of 54 test points more than 1.0, this indicates that the horizontal stress shows no advantage to the vertical stress in the study area. In general, \( \lambda \) is often used to characterize the relative relationship between horizontal and vertical stress, and it is expressed as Equation 10.

\[ \lambda = \frac{(\sigma_H + \sigma_h)}{2 \sigma_v} \]

The study results from several coal-bearing basins indicate that the \( \lambda \) value usually decreases with increasing \( H \).\(^{4,5,9}\) The statistics suggest that the \( \lambda \) value ranges from 0.5 to 5.0 in the world, and most of them lie within 0.5-1.5.\(^{41}\) According to Equation 10, the \( \lambda \) value of the study area has been calculated as 0.49~1.46 (avg. 0.87), belonging to the scope of the \( \lambda \) values all around the world. In this study, the \( \lambda \) value shows a “three-section” change rule with increasing \( H \) (ie, decrease, stabilize, and decrease) (Figure 9). At depths < 600 m, the \( \lambda \) value is approximately 0.45-1.46 (avg. 0.9) and shows a dispersed and gradually decreasing trend; from 600 to 1050 m, the \( \lambda \) value is approximately 0.49-1.18 (avg. 0.87), with a stable distribution range; at depths > 1050 m, the values of \( \lambda \) (0.55-0.93, avg. 0.76) show a convergent and ever-reducing trend. Overall, \( \lambda \) decreases with increasing \( H \), and the \( \lambda \) value changes from dispersed to convergent, indicating that the proportions of the horizontal stress in the current stress regime weaken gradually with increasing \( H \).
4.2.2 | In situ stress regime change with the depth

Meng et al proposed that the $\sigma_h$ values of sedimentary rocks were approximately equal to 70% of the $\sigma_v$ values, but the former in the study area are less obvious than the latter. In addition to that, the above phenomenon can also be observed in other coal-bearing basins due to high organic matter and the weak rock mechanical strength of coal petrography. As shown in Figure 10, both $\sigma_H$ and $\sigma_h$ of the Jurassic formations decrease with increasing $H$ in the study area, and the relevant relationships are expressed as Equations (11) and (12). In addition, the linear relationship between $\sigma_H$ and $H$ is not obvious, showing a “three-section” change rule (Figure 10).

$$\sigma_h = 0.0142H + 2.1118 \quad (R = 0.7122) \tag{11}$$

$$\sigma_H = 0.0188H + 5.5611 \quad (R = 0.4353) \tag{12}$$

where $H$ represents the burial depth of the coal seam, $m$; and $R^2$ represents the correlation coefficient.

In this study, the division scheme of Anderson (1951) has been used to characterize the current in situ stress regime. Seen from Figure 10, a general trend of in situ stress change can be observed, and three in situ stress regimes transform one another as follows. I: At depths < 600 m, the in situ stress regime of coal reservoirs is $\sigma_H$ (avg. 12.21 MPa) $> \sigma_v$ (avg. 10.31 MPa) $> \sigma_h$ (avg. 8.2 MPa), and the current stress regime is a strike-slip fault regime. II: From 600 to 1050 m, the in situ stress regime begins to show a stress transition zone, that is, $\sigma_H$ (avg. 19.07 MPa) $\approx \sigma_v$ (avg. 18.43 MPa) $> \sigma_h$ (avg. 12.93 MPa). III: At depths $> 1050$ m, both $\sigma_H$ and $\sigma_h$ drastically decrease with increasing depth, and the coal reservoir shows a normal fault stress regime, that is, $\sigma_v$ (avg. 30.9 MPa) $> \sigma_H$ (avg. 26.92 MPa) $> \sigma_h$ (avg. 20.10 MPa), which is beneficial to normal fault activity and indicates an extension zone. Overall, the current stress regime changes greatly in the vertical direction, which has important control effects on CBM enrichment and development conditions.

4.2.3 | Regional variation of in situ stress regime

It was generally considered that tectonic deformation of the Jurassic formations can be characterized as “strong in the center and weak on the two sides” in the study area. The studies show that the current stress strength of the Jurassic coal appears as an “increase first and then decrease” trend, and the middle Fukang is the distribution zone of the strongest tectonic stress field (Table 1) and has a good correlation with the tectonic deformation. The contrast analysis shows that the in situ stress regime also changes from west to east, with depths of the coal seam $< 1050$ m. Regionally, a strike-slip fault regime (ie, $\sigma_H > \sigma_v > \sigma_h$) occurs in the western Miquan, and a normal fault regime (ie, $\sigma_v > \sigma_H > \sigma_h$) develops in the eastern Jimushaer. Moreover, the in situ stress regime is in
The combined geological setting and field investigations suggest the current stress regime is strongly associated with the Himalayan tectonic movement. Since the Himalayan movement began, the study area has been infected by N-S extrusion stress from Bogda Mountain. The high-dipping strata (60°-70°) and more complex fold types are found in the middle Fukang due to the nearest stress source and the strongest tectonic deformation; therefore, its stress regime appears as the coexistence of the strike-slip fault and the normal fault stress regime, that is, $\sigma_H \approx \sigma_v > \sigma_h$ type. In general, the Urumqi–Miquan sinistral strike-slip fault has obvious effects on the current stress regime of the western Miquan, showing a $\sigma_H > \sigma_v > \sigma_h$ type. Moreover, the eastern Jimushaer is far from the stress source, and a significantly smaller horizontal stress leads to the $\sigma_v > \sigma_H > \sigma_h$ type. Finally, the horizontal principal stress of the Fukang (avg. 6.86 MPa) is significantly larger than the Miquan (avg. 5.52 MPa) and Jimushaer (avg. 3.87 MPa) (Table 1), which is beneficial for forming artificial fracture networks during the process of CBM development.

5 | DISCUSSIONS

5.1 | In situ stress influence on coal permeability

As one of the most important factors in the determination of CBM productivity, $K$ has been influenced by complex geological factors, for example, structural framework, in situ stress regime, burial depth, coal structure, and development of natural fractures. Among them, the influence of in situ stress regime on $K$ occurs throughout the whole process of CBM exploration and development. In other words, the pore-fracture system varies with the change of in situ stress regime, along with $K$ of coal reservoirs. The permeability mainly includes matrix permeability and fracture system permeability, and the latter is the main factor that controls the percolation conditions of the coal reservoirs in the actual formation conditions, with the former almost negligible. In general, paleo-tectonic stress fields determined the formation, distribution, and development degree of natural fractures, whereas the current stress regime can control opening/closing of pore-fracture systems, and it then influences the permeability of the coal reservoirs.

Based on different coal-bearing basins, the relationships between in situ stress and the initial $K$ have been discussed by several scholars, and a unified understanding is that in situ stress has a negative exponential correlation with $K$. To discuss the relationship between the current stress regime and $K$ in the study area, the control action of the effective stress $\sigma_c$ (i.e., $(\sigma_H + \sigma_h + \sigma_v/3) - P_n$) on $K$ has been discussed, except for three principal stresses (i.e., $\sigma_H$, $\sigma_h$, and $\sigma_v$). As shown in Figure 12, in situ stress parameters have the best pow-exponent correlations (superior to exponent) with $K$, and the latter
decrease with increasing of the former. The $R^2$ values between the stress parameters with $K$ are $\sigma_H$ (0.5031), $\sigma_h$ (0.4613), $\sigma_v$ (0.4472), and $\sigma_e$ (0.2262), indicating that permeability of coal reservoirs is mainly controlled by tectonic stress (ie, horizontal main stress), with a weaker influence from overburden stress. Moreover, coal $K$ drastically reduces when the $\sigma_H$, $\sigma_h$, $\sigma_v$, and $\sigma_e$ values are more than 10 MPa, 15 MPa, 20 MPa, and 10 MPa, respectively, and high values of $K$ begin to disappear (Figure 12). The low $K$ is not conducive to the drainage and pressure lowering of coal reservoirs and CBM seepage effect, so the tectonic position with suitable stress field conditions may be selected for CBM development in the study area.

The research shows that the $K$ value is not a simple decreasing process with the increase in $H$, but appears as a trend of “remarkably decreasing, rebounded increase and greatly decreasing” (Figure 13). The contrast analysis shows that the change rule for $K$ has an obvious correlation with the vertical change of in situ stress regime. (a) At depths < 600 m, $K$ drastically decreases with increasing $H$, and the current stress regime is the $\sigma_H > \sigma_v > \sigma_h$ type. The analysis suggests that the pore-fracture system closes gradually under the horizontal crushing stress, and $K$ decreases from 13.48 to 0.0041 mD (avg. 4.16 mD). (b) At depths of 600-1050 m, $K$ has a short-resilient process (ie, 600-800 m), which is closely associated with the coexistence of the strike-slip and the normal fault regimes (ie, $\sigma_H \approx \sigma_v > \sigma_h$ type). In this stage, the extensive stress can open the pore-fracture system or some weak interface, leading to abnormally high-value sectors of coal $K$. (c) At depths > 1050 m,
the current in situ stress is beneficial to normal fault activity with an extensional stress environment. However, vertical stress dramatically increases with increasing $H$ in this stage, leading to a quick closing of the pore structure and a sharp decrease in $K$. The normal fault regime existing in deep formations can also be observed in the eastern Ordos Basin and the Qinshui Basin.\(^8,9\) The change rule for coal $K$ is mainly controlled by the influence of the current in situ stress on the pore-fracture system.

At depths $> 600$ m or $< 1050$ m, the coal pore-fracture system twice experiences quick closing under the actions of horizontal stress and vertical stress, respectively, along with two decreasing stages of coal $K$. Overall, the important challenge for CBM exploration and development of deep formations ($>800$ m) is “extremely low $K$ and strong stress field” in the eastern part of the southern Junggar Basin (Figure 13).

### 5.2 In situ stress influence on initial reservoir pressure

The $P_o$ is the fluid pressure of the pore-fracture system prior to the CBM development.\(^22,23\) The $P_o$ reflects the flowing capacity of methane gas and formation water from the pore-fracture system to the wellbore, and it has great significance for the CBM development effect.\(^53\) The $P_o$ is closely related to the current in situ stress regime, and the latter can affect the former by exerting confining pressure on the fluid of the pore-fracture system.\(^54\) In general, coal reservoirs usually have greater $P_o$ and $G_o$ values within a compressive stress regime, whereas smaller $P_o$ and $G_o$ values existed in a tensional stress regime.\(^23\) In the study area, the $P_o$ values change from 1.67 to 18.91 MPa (avg. 6.69 MPa), and the $G_o$ values are approximately 0.489-1.32 MPa/100 m (avg. 0.82 MPa/100 m). Additionally, a low-pressure environment might not be beneficial to CBM enrichment and preservation.

![FIGURE 13](image) Permeability ($k$) vs depth

![FIGURE 14](image) The relations between vertical stress ($\sigma_v$), minimum horizontal principal stress ($\sigma_h$), and maximum horizontal principal stress ($\sigma_H$) with reservoir pressure ($P_o$); and the relation between horizontal differential principal stress ($\sigma_H-\sigma_h$) with initial reservoir pressure gradient ($G_o$). $R^2 = \text{correlation coefficient}$
The research shows that the $P_o$ value linearly increases with increasing $\sigma_H$, $\sigma_h$, and $\sigma_v$ values in the study area (Figure 14A–C). Among them, the $R^2$ value between the stress parameters with $P_o$ is $\sigma_v$ (0.8397), $\sigma_h$ (0.6989), and $\sigma_H$ (0.4568), that is, $\sigma_v$ has the most effective control on $P_o$, followed by $\sigma_h$ and $\sigma_H$. The main reason is that the $\sigma_H > \sigma_v > \sigma_h$ type only occurs in shallow formations (<600 m); at depths > 600 m, the growing rate of vertical stress begins to be more than horizontal stress, along with the stress field changing from the $\sigma_H > \sigma_v > \sigma_h$ type to the $\sigma_v > \sigma_H > \sigma_h$ type, and vertical stress provides a more important contribution to increasing $P_o$. Meng et al also proposed that vertical stress has obvious influences on $P_o$ under the normal fault regime.23 Moreover, the $\sigma_h$ and $\sigma_H$ are often perpendicular and parallel to the pore-fracture system, respectively, so the $\sigma_h$ may have the more obvious influence on $P_o$ under the normal fault regime.23 Based on the relationships between the tectonic stress field (ie, horizontal stress) and reservoir characteristics, Qin et al proposed that the $G_o$ of coal reservoirs logarithmically increases with increasing the horizontal differential principal stress (ie, $\sigma_H - \sigma_h$).55 However, there is no correlation between the $G_o$ value and the "$\sigma_H - \sigma_h$" value (Figure 14D) in the study area, further indicating that the horizontal stress has poor control action on $P_o$.

![FIGURE 15](image)

FIGURE 15  Gas content and reservoir pressure gradient vs depth

The gas content ($G$) of coal reservoirs is influenced by complex geological factors, for example, coal rank ($R_o$), $T_{em}$, $P_o$, and coal macerals.24,56,57 Among them, the $G$ value tends to increase with the increase in the $R_o$ and $P_o$, whereas the $T_{em}$, moisture content, and ash yield are not beneficial to gas absorption of coal reservoirs.58,59 When the $R_o$, $T_{em}$, and coal macerals are relatively stable, as discussed above, the current in situ stress regime controls the $P_o$ and affects the $G$ and saturation of coal reservoirs. To discuss the influence of the vertical change of in situ stress regime on the $G$ of coal reservoirs, two CBM wells (A and B) from the Miquan and Fukang regions have been selected to analyze the relationship between the $G$ and the $P_o$ with the $H$. Seen from Figure 15, the $G$ obviously increases with increasing $H$ (<1000-1150 m), though the outliner of the $G$ might occur in local positions, due to the difference of hydrodynamic or roof lithology. However, the $G$ values begin to dramatically decrease with increasing $H$, when the depths in Miquan and Fukang are more than 1150 m and 1000 m, respectively. The analysis suggests that the changing interface of the $G$ is rather consistent with the interface of in situ stress changing from the $\sigma_H \approx \sigma_v > \sigma_h$ type to the $\sigma_v > \sigma_H > \sigma_h$ type. Overall, the vertical belting of in situ stress regime may have a vital effect on the vertical change of the $G$, and the $H$ (1000-1150 m) may be used to divide the shallow and deep CBM in the study area. Moreover, the change rule for the $G$ has good consistency with the $G_o$, that is, the larger the $G_o$, the higher the $G$. The analysis indicates that a sharply decreasing $G$ value is mainly caused by two main reasons within the depths > 1000-1150 m. The first is

5.3 | In situ stress influences on gas content

The gas content ($G$) of coal reservoirs is influenced by complex geological factors, for example, coal rank ($R_o$), $T_{em}$, $P_o$, and coal macerals.24,56,57 Among them, the $G$ value tends to increase with the increase in the $R_o$ and $P_o$, whereas the $T_{em}$, moisture content, and ash yield are not beneficial to gas absorption of coal reservoirs.58,59 When the $R_o$, $T_{em}$, and coal macerals are relatively stable, as discussed above, the current in situ stress regime controls the $P_o$ and affects the $G$ and saturation of coal reservoirs. To discuss the influence of the vertical change of in situ stress regime on the $G$ of coal reservoirs, two CBM wells (A and B) from the Miquan and Fukang regions have been selected to analyze the relationship between the $G$ and the $P_o$ with the $H$. Seen from Figure 15, the $G$ obviously increases with increasing $H$ (<1000-1150 m), though the outliner of the $G$ might occur in local positions, due to the difference of hydrodynamic or roof lithology. However, the $G$ values begin to dramatically decrease with increasing $H$, when the depths in Miquan and Fukang are more than 1150 m and 1000 m, respectively. The analysis suggests that the changing interface of the $G$ is rather consistent with the interface of in situ stress changing from the $\sigma_H \approx \sigma_v > \sigma_h$ type to the $\sigma_v > \sigma_H > \sigma_h$ type. Overall, the vertical belting of in situ stress regime may have a vital effect on the vertical change of the $G$, and the $H$ (1000-1150 m) may be used to divide the shallow and deep CBM in the study area. Moreover, the change rule for the $G$ has good consistency with the $G_o$, that is, the larger the $G_o$, the higher the $G$. The analysis indicates that a sharply decreasing $G$ value is mainly caused by two main reasons within the depths > 1000-1150 m. The first is
that in situ stress regime begins to become a normal fault regime, and the extensional stress environment is not beneficial to CBM preservation. The second is the negative effect of $T_{em}$ on methane adsorbability is stronger than the positive effect of the $P_o$, leading to a sharp decrease in the $G$, which is consistent with Qin et al.\textsuperscript{60} Overall, the current in situ stress regime has an important effect on the $P_o$ and the $G$, and further affects gas saturation of CBM reservoirs. The statistics show that gas saturation greatly varies from 1.62% to 83.07% (avg. 15.87%) in the study area, and low $P_o$ plays an important role in the formation of undersaturated CBM reservoirs.

### 5.4 Grade division for CBM development potential

In general, CBM development potential is mainly influenced by two key geologic parameters (ie, $G$ and $K$), and the higher the $G$ and the larger the $K$, the greater the CBM development potential.$^{61-65}$ The current in situ stress regime controls opening/closing of the pore-fracture system and affects the $K$, $P_o$, and $G$ of coal reservoirs. As discussed above, under the dominance of the current stress regime, there is an obvious transition interface for the gas content (A) that is controlled by the positive effect of the $P_o$ and the negative effect of $T_{em}$ and the $G$ apparently decreases below interface A. Moreover, the $K$ also has an obvious converted interface (B) under the influence of in situ stress regime, and the $K$ values sharply decrease below interface B. Overall, the converted interface B for the $K$ (800 m) is slightly shallower than the $G$ for interface A (1000-1150 m). The gas composition data indicate that the depth of the weathered zone is approximately 400 m,$^{30}$ and the $G$ value increases with increasing $H$ (<1000-1150 m).

Combined with the transition interfaces A (1000-1150 m) and B (800 m), and the depth of the weathered zone (400 m), CBM development potential in the study area is divided into three grades vertically (Figure 16), that is, (1) 400-800 m (high $K$ and medium $G$); 2) 800-1150 m in Miquan and 800-1000 m in Fukang (medium $K$ and high $G$); and (3) >1150 m in Miquan and >1000 m in Fukang (low $K$ and poor $G$). Therefore, under the dominance of the current stress regime, the main targets of CBM development in the study area should be positioned on 400-800 m, and the 600-800 m is the most probable to make a key breakthrough, due to better $G$ and higher $K$.

### 6 CONCLUSIONS

1. Three types of in situ stress regime exist and are converted corresponding to a certain depth: (a) <600 m is the strike-slip fault regime ($\sigma_H > \sigma_v > \sigma_h$); (b) 600-1050 m is the stress transition zone ($\sigma_H = \sigma_v > \sigma_h$); and (c) >1050 m is the normal fault regime ($\sigma_v > \sigma_H > \sigma_h$). Regionally, with depths < 1050 m, in situ stress regime changes from west to east, that is, $\sigma_H > \sigma_v > \sigma_h$ type in the western Miquan, $\sigma_H \approx \sigma_v > \sigma_h$ type in the middle Fukang, and $\sigma_v > \sigma_H > \sigma_h$ type in the eastern Jimushaer, respectively. For coal depths > 1050 m, the regional stress regime all appears as the $\sigma_v > \sigma_H > \sigma_h$ type.

2. The change rule of $K$ is mainly controlled by the influence of the current stress regime on the pore-fracture system. $K$ is not a simple decreasing process with increasing $H$, but appears as a trend of “remarkably decreasing, rebounded increase and greatly decreasing.” At depths > 600 m or < 1050 m, the coal pore-fracture system twice experiences quick closing under the actions of horizontal stress and vertical stress, respectively, along with two decreasing stages of coal $K$.

3. Take the depths of 1000-1150 m as a boundary, the $G$ value changes from “remarkably increasing” to “dramatically decreasing” in the study area. The vertical belting of in situ stress regime may have a vital effect on the vertical change of the $G$ value, and the changing interface of the $G$ value is rather consistent with the interface of the current stress regime changing from the $\sigma_v \approx \sigma_H > \sigma_h$ type to the $\sigma_v > \sigma_H > \sigma_h$ type.

4. Combined with the transition interfaces A (1000-1150 m) and B (800 m), and the depth of the weathered zone (400 m), CBM development potential is divided into three grades vertically in the study area. The main targets of CBM development in the study area should be positioned on 400-800 m, and the 600-800 m is the most probable to make a key breakthrough, due to better $G$ and higher $K$. 

---

**FIGURE 16** Grade specification for CBM development potential in the eastern part of the southern Junggar Basin.
ACKNOWLEDGMENTS

This work was financially supported by the Key Project of National Science & Technology (2016ZX05043-001, 2016ZX05044-001), the National Natural Science Foundation for Young Scholars of China (41902173), the Fundamental Research Funds for the Central Universities (CUG170678), the National Natural Science Foundation of China (41690131), Hubei Natural Science Foundation (2019CFA028), and the Program of Introducing Talents of Discipline to Universities (B14031). The authors are grateful to the editor and four anonymous reviewers for their careful reviews and detailed comments.

ORCID

Haijiao Fu https://orcid.org/0000-0001-9292-1824

REFERENCES

1. Hoek E, Brown ET. Underground Excavations in Rock. London: The Institution of Mining and Metallurgy; 1980.

2. Zhao DA, Chen ZM, Cai XL, Li S. Analysis of distribution rule of geostress in china. Chin J Rock Mech Eng. 2007;26(6):1265-1271.

3. Kang H, Zhang X, Si L. Study on in-situ stress distribution law in deep underground coal mining areas. ISRM International Symposium on Rock Mechanics – SINOROCK 2009, 19-22 May. China: The University of Hong Kong; 2009.

4. Anderson EM. The Dynamics of Faulting and Dyke Formation with Application to Britain, 2nd edn. Edinburgh: Oliver & Boyd; 1951.

5. Brown ET, Hoek E. Trends in relationships between measured in-situ, stresses and depth. Int J Rock Mech Mining Sci Geomech Abs. 1978;15(4):211-215.

6. Stacey TR, Wesseloo J. The in-situ stress regime in Southern Africa. ISRM Congress; 1999.

7. Zoback ML. First- and second-order patterns of stress in the lithosphere: the world stress map project. J Geophys Res Solid Earth. 1992;97(B8):11703-11728.

8. Li Y, Tang D, Xu H, Yu T. In-situ stress distribution and its implication on coalbed methane development in liulin area, eastern ordos basin, china. J Petrol Sci Eng. 2014;122:488-496.

9. Zhao J, Tang D, Xu H, Li Y, Li S, Tao S. Characteristic of in-situ stress and its control on the coalbed methane reservoir permeability in the eastern margin of the Ordos Basin, china. Rock Mech Rock Eng. 2016;49(8):3307-3322.

10. Sun LZ, Kang YS, Wang J, et al. Vertical transformation of in-situ stress types and its control on coalbed Reservoir permeability. Geol J China Univ. 2017;23(1):148-156.

11. Nelson CR. In Deep Coalbed Gas plays in the U.S Rocky Mountain Region: AAPG Annual Convention and Exhibition. Denver: American Association of Petroleum Geologists; 2003.

12. Meng ZP, Lan Q, Liu CL. In-situ stress and coal reservoir pressure in Southeast margin of Ordos basin and their coupling relations. Journal of China Coal Society. 2013;38(1):122-128.

13. Tao S, Pan ZJ, Tang SL, Chen SD. Current status and geological conditions for the applicability of CBM drilling technologies in China: A review. Int J Coal Geol. 2019;202:95-108.

14. Tao S, Chen SD, Pan ZJ. Current status, challenges, and policy suggestions for coalbed methane industry development in China: A review. Energy Sci. Eng. 2019;7(4):1059-1074.

15. Chen SD, Tang DZ, Tao S, Zhao JL, Li Y, Liu WQ. Discussion about “critical depth” of deep coalbed methane in Zhenzhuguan area, Qinshui Basin. J China Coal Soc. 2016;41(12):3069-3075.

16. Ju W, Shen J, Qin Y, et al. In-situ stress state in the Linxing region, eastern Ordos Basin, China: Implications for unconventional gas exploration and production. Mar Pet Geol. 2017;86:66-78.

17. Ju W, Jiang B, Qin Y, et al. The present-day in-situ stress field within coalbed methane reservoirs, Yuwang Block, Laochang Basin, south China. Mar Pet Geol. 2019;102:61-73.

18. Scott AR, Kaiser WR, Ayers WB Jr. Thermogenic and secondary biogenic gases, San Juan basin, Colorado and New Mexico—implications for coalbed gas producibility. AAPG Bulletin. 1994;78(8):1186-1209.

19. Wang JJ, Tang DZ, Jing Y. Analytical Solution of Gas Flow in Rough-Walled Microfracture at In Situ Conditions. Water Resour Res. 2019;55:60001-66017.

20. Brace WF. A note on permeability changes in geologic material due to stress. Pure Appl Geophys. 1978;116(4–5):627-633.

21. Ju W, Jiang B, Miao Q, Wang LL, Qu ZH, Li M. Variation of in-situ stress regime in coal reservoirs, eastern Yunnan region, South China: Implications for coalbed methane production. AAPG Bulletin. 2018;102(11):2283-2303.

22. Pang SY, He XH. Influence of crustal stress on coalbed methane exploration and developing. China Mining Magazine. 2014;23(2):173-177.

23. Meng GX. Study on ground stress field features and its impact on coal reservoir pressure and permeability. Coal Geol China. 2017;29(3):21-27.

24. Fu HJ, Tang DZ, Xu H, Xu T, Chen BL, Hu P. Geological characteristics and cbm exploration potential evaluation: a case study in the middle of the southern Junggar basin, NW China. J Nat Gas Sci Eng. 2016;30:557-570.

25. Fu HJ, Tang DZ, Xu T, Xu H, Tao S, Zhao JL. Preliminary research on CBM enrichment models of low-rank coal and its geological controls: a case study in the middle of the southern Junggar basin, NW China. Mar Pet Geol. 2017;83:97-110.

26. Wang YT, Liu R, Wang F, Xiang Y, Xue L, Qiao WL. Strategy of CBM Industrialization in Junggar Basin. China Petrol Explor. 2015;20(5):81-88.

27. Carroll AR, Yunhai L, Graham SA, et al. Junggar basin, north-west China: trapped Late Paleozoic ocean. Tectonophysics. 1990;181(1):1-14.

28. Scheltema M, Zhang LF, Xiao WJ, Zhang JL. Northward subduction- related orogenesis of the southern Altaiids: constraints from structural and metamorphic analysis of the HP/UPH accretionary complex in Chinese southwestern Tianshan, NW China. Geosci Front. 2015;6(2):191-209.

29. Glorie S, Grave JD. Exhuming the Meso-Cenozoic Kyrgyz Tianshan and Siberian Altai-Sayan: A review based on low-temperature thermochronology. Geosci Front. 2016;7(2):155-170.

30. Fu HJ, Tang DZ, Pan ZJ, et al. A study of hydrogeology and its effect on coalbed methane enrichment in the southern Junggar Basin, China. AAPG Bulletin. 2019;103(1):189-213.

31. Wu JJ, You LP, Yang HS. Structural evolution and hydrocarbon accumulation of Fukang Fault Zone in Junggar Basin. Xinjiang Petroleum Geology. 2013;34(1):36-40.
32. Li MH, Li Z, Liao JD. Analysis of ground stress in the southern part of Junggar Basin and discussion of the related issues. *Xinjiang Geol.* 2005;23(4):343-346.

33. Zhou F, Mei LF, Liu L, Tang JG, Yan SL, Luo JC. Numerical simulation of tectonic stress field during himalayan movement in southern margin of Junggar basin. *Xinjiang Petrol Geol.* 2005;26(6):640-643.

34. Zuber MD, Sparks DP, Lee WJ. Design and interpretation of injection/falloff tests for coalbed methane wells. *SPE Annual Technical Conference and Exhibition.* New Orleans, LA: Society of Petroleum Engineers; 1990:425-434.

35. Levitan MM. Application of water injection/falloff tests for reservoir appraisal: new analytical solution method for two-phase variable rate problems. *SPE Journal.* 2003;8(4):341-349.

36. GB/T 24504-2009. The method of injection/falloff well test for coalbed methane well (in Chinese with an English abstract); 2009.

37. DB/T 14–2000. Code of hydraulic fracturing and overcoring method for in-situ stress measurement (in Chinese with an English abstract); 2000.

38. Haimson BC, Fairhurst C. In-situ stress determination at great depth by means of hydraulic fracturing. In: Somerton WH ed. *Rock Mechanics-Theory and Practice.* Berkeley, California: American Institute of Mining Engineers; 1970:559-584.

39. Hubbert MK, Willis DG. Mechanics of hydraulic fracturing: Petroleum Transactions. *Am Inst Mining Metall Petrol.* 1957;201:153-168.

40. Bredehoef JD, Wolff RG, Keys WS, Shuter E. Hydraulic fracturing to determine regional in-situ stress regime, Piccance Basin, Colorado. *Geol Soc Am Bull.* 1976;87(2):250-258.

41. Li P, Miao SJ. Analysis of the characteristics of in-situ stress regime and fault activity in the coal mining area of China. *J China Coal Soc.* 2016;41(S2):319-329.

42. Chen SD, Tang DZ, Tao S, et al. In-situ stress measurement and stress distribution characteristics of coal reservoirs in major coalfields in China: Implication for coalbed methane (CBM) development. *Int J Coal Geol.* 2017;182:66-84.

43. Wang FK, He JP, Liang YP, Luo YJ, Liao ZW, Li L. Study on the permeability characteristics of coal containing coalbed methane under different loading paths. *Energy Sci Eng.* 2018;6(5):475-483.

44. Li Y, Wang ZS, Pan ZJ, Niu XL, Yu Y, Meng SZ. Porosity and its fractal dimensions of transitional shale: A cross-section from east margin of the Ordis Basin, China. *Fuel.* 2019;241:417-431.

45. Tao S, Gao LJ, Pan J. Swelling of clay minerals and its effect on coal permeability and gas production: A case study of southern Qinshui Basin, China. *Energy Sci Eng.* 2019;7(2):515-528.

46. Tao S, Pan ZJ, Chen SD, Tang SL. Coal seam porosity and fracture heterogeneity of maroclitotypes in the Fanzhuang Block, southern Qinshui Basin, China. *J Natural Gas Sci Eng.* 2019;66:148-158.

47. Fu HJ, Tang DZ, Xu T, et al. Characteristics of pore structure and fractal dimension of low-rank coal: a case study of lower Jurassic Xishanyao coal in the Southern Junggar Basin, NW China. *Fuel.* 2017;193:254-264.

48. Huang CG, Zhang YB, He JF, Luo YJ, Sun ZG. Permeability improvements of an outburst-prone coal seam by means of presplitting and blasting with multiple deep boreholes. *Energy Sci Eng.* 2019.; https://doi.org/10.1002/ese3.426.

49. Enever IR, Bocking MA, Clark IH. The application of in-situ stress measurement and numerical stress analysis to coalbed methane exploration in Australia. In: *SPE Asia Pacific Oil and Gas Conference.* Melbourne, Australia: Society of Petroleum Engineers; 1994;372-381.

50. Somerton WH, Söylemezoglu IM, Dudley RC. Effect of stress on permeability of coal. *Int J Rock Mech Min Geomech Abs.* 1975;12(5-6):129-145.

51. Meng ZP, Tian YD, Li GF. Characteristics of in-situ stress in Southern Qinshui Basin and its research significance. *J China Coal Soc.* 2010;35(6):975-981.

52. Xu H, Sang S, Yi T, Zhao X, Liu H, Li L. Control mechanism of buried depth and in-situ stress for coal reservoir permeability in western Guizhou. *Earth Sci.* 2014;39(11):1507-1516.

53. Bustin AM, Bustin RM, Moudrakovski IL, Takeya S, Ripmeester JA. Formation of methane clathrate hydrates in cold moisture: Implications for coalbed methane resources and reservoir pressures. *Energy Fuels.* 2016;30(1):88-97.

54. Sone H, Zoback MD. Time-dependent deformation of shale gas reservoir rocks and its long-term effect on the in-situ state of stress. *Int J Rock Mech Min Sci.* 2014;69:120-132.

55. Qin Y, Zhang DM, Fu XH, Lin DY, Ye JP, Xu ZB. A discussion on correlation of modern tectonic stress field to physical properties of coal reservoirs in central and Southern Qinshui Basin. *Geol Rev.* 1999;45(6):576-583.

56. He SP, Lin Q, Zhang CJ. Ground stress field characteristics and its influence on coal and gas outburst in Qidong well field. *Coal Geol Expl.* 2014;42(2):9-13.

57. Li Y, Yang JH, Pan ZJ, Meng SZ, Wang K, Niu XL. Unconventional Natural Gas Accumulations in Stacked Deposits: A Discussion of Upper Paleozoic Coal-Bearing Strata in the East Margin of the Ordos Basin, China. *Acta Geol Sinica.* 2019;93(1):111-129.

58. Pan ZJ, Connell LD. Modelling permeability for coal reservoirs: a review of analytical models and testing data. *Int J Coal Geol.* 2012;92:1-44.

59. Yin TT, Liu DM, Cai YD, Zhou YF. Methane adsorption constrained by pore structure in high-rank coals using FESEM, CO2 adsorption, and NMRC techniques. *Energy Sci Eng.* 2018;7(1):255-271.

60. Qin Y, Sheng J, Wang BW. Accumulation effects and coupling relationship of deep coalbed methane. *Acta Petrolei sinica.* 2012;33(1):48-54.

61. Wang S, Elsworth D, Liu J. Mechanical behavior of methane infiltrated coal: the roles of gas desorption, stress level and loading rate. *Rock Mech Rock Eng.* 2013;46(5):945-958.

62. Wu S, Tang D, Li S, Chen H, Wu H. Coalbed methane adsorption behavior and its energy variation features under supercritical pressure and temperature conditions. *J Petrol Sci Eng.* 2016;146:726-734.

63. Qin Y, Shen J. On the fundamental issues of deep coalbed methane geology. *Acta Petrolei Sinica.* 2016;37:125-136. (in Chinese with English abstract).

---

**How to cite this article:** Fu H, Yan D, Yang S, Wang X, Zhang Z, Sun M. Characteristics of in situ stress and its influence on coalbed methane development: A case study in the eastern part of the southern Junggar Basin, NW China. *Energy Sci Eng.* 2020;8:515–529. [https://doi.org/10.1002/ese3.533](https://doi.org/10.1002/ese3.533)