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Mechanism of Coal-Measure Gas Enrichment under Multi-Factor Coupling: A Case Study of the Eastern Pingdingshan Mining Area

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ABSTRACT

This study focuses on the Shanxi Formation coal-measure strata in the eastern Pingdingshan mining area and systematically investigates the mechanisms controlling the occurrence and enrichment of coal-measure gas under the coupling effects of sedimentary and tectonic processes. Based on integrated geological datasets, key sedimentary parameters (e.g., mudstone and sandstone ratios) and structural curvature attributes were quantitatively characterized to evaluate their influence on reservoir properties, gas preservation, and migration pathways. The results indicate pronounced spatial heterogeneity in both mudstone and sandstone distributions. Mudstone-dominated zones exhibit strong sealing capacity, favoring gas preservation, whereas sandstone-enriched intervals tend to enhance gas migration. High structural curvature zones are distributed in bands along fold belts and show a strong correlation with coal seam floor undulation. Moderate tectonic deformation promotes fracture development and improves reservoir permeability, while excessive deformation may degrade sealing conditions. The deformation responses of mudstone and sandstone layers are highly consistent, suggesting vertical coherence of tectonic processes. Overall, the coupling of sedimentary and tectonic factors is identified as the primary mechanism governing coal-measure gas enrichment. These findings provide a robust geological basis for favorable zone prediction and the efficient development of coal-measure gas resources.

KEYWORDS

Coal-Measure Gas; Sedimentation; Structural Curvature; Multi-Factor Coupling; Pingdingshan Mining Area.

1. INTRODUCTION

Coal measure strata refer to sedimentary sequences containing coal seams, and the reservoirs developed within them are termed coal-measure reservoirs. These reservoirs are generally characterized by low porosity and low permeability, or medium porosity and low permeability, with storage space dominated by secondary pores[1-4]. Coal-measure gas reservoirs are diverse in type, and their occurrence states vary significantly. Among them, coalbed methane mainly occurs in an adsorbed state, tight sandstone gas predominantly exists in a free state, while shale gas is characterized by the coexistence of both adsorbed and free states. In addition, under specific geological conditions, natural gas hydrates may also form[5,6]. Coal seams and coal-measure mudstones and shales exhibit relatively high gas-generation potential. During geological evolution, hydrocarbons remain in a long-term dynamic coupling process of migration and accumulation [7]. The three types of reservoirs within coal measures show considerable differences in material composition, pore structure characteristics, and spatial distribution patterns. Meanwhile, the occurrence states of natural gas within these reservoirs are diverse[8-10]. The interaction of these factors results in complex controlling mechanisms for the occurrence and enrichment of coal-measure gas, thereby posing higher requirements for its efficient development. Therefore, it is necessary to systematically analyze the geological controlling factors and their differences governing the occurrence and enrichment of coal-measure gas in reservoirs of different lithologie.

Previous studies have extensively investigated the factors influencing the occurrence of coalbed methane. Sun Fenjin et al. [11] proposed that tectonic evolution, hydrodynamic zoning, and the lithologic configuration of roof and floor strata jointly control the enrichment characteristics of coalbed methane. Chen Yue et al. [12] suggested that hydrogeological conditions exert a significant influence on coalbed methane. Jiang et al. [13] summarized that the key characteristics of coalbed methane reservoirs mainly include structural features, coal seam development, coal rank, gas content, permeability, and hydrogeological conditions. Tian et al. [14] argued that factors such as thickness, porosity, permeability, and structural conditions are the main controlling factors for favorable areas of biogenic gas in mudstone. Hong et al. [15] considered that shale gas reservoir characteristics are directly related to lithofacies and depositional environments. Zhou et al. [16] proposed that effective caprock sealing conditions are a prerequisite for the formation of early-stage shale gas reservoirs, while structural conditions are crucial for their later preservation. Yin Lang et al. [17] found that the reservoir capacity of tight sandstone is jointly controlled by sedimentation and diagenesis. Huang et al. [18] revealed that thick sandstone units in different stratigraphic intervals and depths are at different diagenetic stages, and the petrophysical zonation of reservoirs is jointly governed by diagenetic facies dominated by sedimentation, compaction, and dissolution processes.

The development of the “three gases” in coal measures is influenced by multiple factors. Among them, reservoir thickness, gas content, physical properties, and reservoir pressure are direct controlling factors, while tectonic activity, depositional environment, and hydrogeological conditions exert fundamental controls [19-21] . Based on previous studies, these factors can be classified into five categories—reservoir, structure, sedimentation, hydrogeology, and deep factors—which provide a basis for the division of geological units [22, 23].

2. OVERVIEW OF THE STUDY AREA

The Pingdingshan mining area is located in the central part of Henan Province and, together with the Hanliang Mining Area, constitutes the Pingdingshan coalfield. The coalfield covers a total area of approximately 10,000 km², with a coal-bearing area of about 2,951 km². The mining area is mainly distributed in the northern part of Pingdingshan and consists of 13 mines, including No. 5 Mine, No. 6 Mine, No. 12 Mine, No. 13 Mine, as well as Shoushan No.1 Mine. It is located about 140 km south of Zhengzhou and 50 km west of Xuchang. The mining area extends approximately 40 km in the east–west direction and 20 km in the north–south direction, covering an area of about 650 km². The eastern Pingdingshan mining area includes No. 8 Mine, No. 10 Mine, No. 12 Mine, No. 13 Mine, and Shoushan No.1 Mine. Tectonically, this area is located on the southern margin of the North China Plate, within the western Henan fold belt, and is controlled by the northwestward compression of the Qinling–Dabie Orogenic Belt. The mining area and its surroundings exhibit a series of NWW–NW trending, parallel-arranged composite fold structures, accompanied by faults predominantly trending NWW–NW, as well as NNE–NE trending faults [24-26] .

3. SEDIMENTARY CONTROL EFFECTS

Mudstone, as the principal low-permeability surrounding rock in coal-measure strata, directly influences the sealing and preservation conditions of coal-measure gas[27, 28]. The mudstone-to-strata ratio reflects the relative proportion of mudstone within a certain range of the roof and floor of coal seams, and can, to some extent, characterize the sealing capacity of surrounding rocks and its spatial variation. The planar distribution of the mudstone ratio (Fig. 1(a)) indicates a pronounced heterogeneity across the study area, with variations observed both among different mining areas and within individual mines. Relatively high mudstone ratios occur in the southwestern part of No. 13 Mine, the southern part of Shoushan No. 1 Mine, and the central areas of No. 10 and No. 12 Mines. These distribution patterns suggest notable spatial differences in the sealing conditions of surrounding rocks. In areas with higher mudstone ratios, mudstone is more well developed, resulting in better overall sealing capacity, which helps reduce gas migration and provides a relatively stable environment for coal-measure gas occurrence. In contrast, areas with lower mudstone ratios exhibit weaker sealing capacity, enhanced gas migration conditions, and potentially poorer preservation conditions.

Sandstones in the coal-measure strata of the study area are predominantly tight sandstones. Due to the effects of compaction and cementation, their permeability is generally low, and in some local areas even lower than that of adjacent mudstone layers, making it difficult to form effective high-permeability migration pathways [29-31]. Under these conditions, the influence of sandstone on coal-measure gas occurrence is mainly reflected in its role in regulating lithologic assemblages and sealing conditions of surrounding rocks. The planar distribution of the sandstone ratio (Fig. 1(b)) shows significant spatial variability. Higher sandstone ratios are observed in the southeastern part of No. 13 Mine, the central and southern parts of Shoushan No. 1 Mine, and parts of the central area of No. 10 Mine. Combined with the distribution of sandstone thickness and reservoir occurrence, it can be inferred that sandstones in the study area are locally well developed and relatively continuously distributed. When sandstone and mudstone occur in interbedded or interlayered combinations, they contribute to the formation of multi-level, composite surrounding rock structures, thereby enhancing the stability of the coal-measure gas occurrence environment to a certain extent.

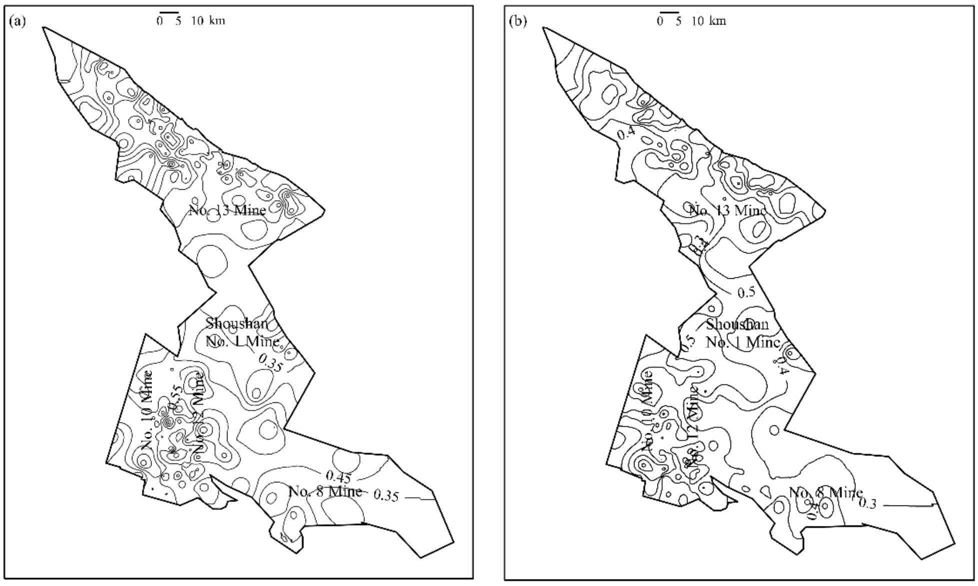

Fig 1 Contour maps of mudstone ratio (a) and sandstone ratio (b) of the Shanxi Formation in the study area

4. TECTONIC CONTROL EFFECTS

Structural curvature is used to characterize the spatial bending and deformation of coal seams, with its magnitude reflecting the relative intensity of structural variation. By superimposing structural curvature with contour maps of the coal seam floor elevation, the relationship between reservoir undulation patterns and tectonic deformation can be intuitively revealed [32, 33].

As shown in Fig. 2(a), high values of structural curvature of coal seams in the study area are mainly distributed in a zonal pattern along the central part of No. 13 Mine, the southern part of Shoushan No.

1 Mine, the southern part of No. 10 Mine, and the southern part of No. 12 Mine. The intensity of coal seam deformation shows a strong consistency with the undulation pattern of the coal seam floor. The greater the structural curvature, the higher the degree of folding deformation and the stronger the tectonic modification.

In terms of coalbed methane occurrence, areas with moderately high curvature correspond to moderate tectonic deformation, which can promote the development of endogenous and structural fractures within coal seams, effectively improving permeability and providing both storage space and migration pathways for gas enrichment. In contrast, extremely high curvature zones are often associated with intensely deformed fold cores, where coal seams may become highly fractured or even damaged, potentially compromising the sealing capacity of roof and floor strata and leading to gas dissipation. Low-curvature areas, however, are characterized by intact coal seam geometry and gentle occurrence, offering more stable preservation conditions for coalbed methane (Fig. 2(a)).

The overall distribution pattern of structural curvature in mudstone layers is highly similar to that of coal seams, with relatively high values mainly concentrated in the northern part of No. 13 Mine, the central part of Shoushan No. 1 Mine, the central part of No. 10 Mine, and the southern part of No. 12 Mine. Thick mudstone layers serve as the primary regional caprocks in the study area, and their deformation characteristics directly control gas preservation conditions. Due to their relatively strong plasticity, mudstones in high-curvature zones may undergo plastic flow and thickening during folding, thereby enhancing local sealing capacity and favoring the preservation of underlying coalbed methane or sandstone gas. However, if deformation is excessively intense, high-curvature zones may also develop open fractures, which can act as vertical migration pathways for gas, thus weakening the sealing performance. In contrast, low-curvature zones exhibit gently dipping, intact thick mudstone layers with uniform and stable sealing capacity, resulting in better overall preservation conditions (Fig. 2(b)).

The structural curvature of sandstone layers follows a similar pattern, with higher values in strongly deformed zones and lower values in weakly deformed areas. High-curvature zones are mainly distributed in the central part of No. 13 Mine, the southern part of Shoushan No. 1 Mine, the southern part of No. 10 Mine, and the southern part of No. 12 Mine, aligning with fold belts and showing a strong deformation correspondence with overlying coal seams and mudstones. This further confirms the vertical consistency of tectonic deformation in the study area. Sandstones in this area are generally low-porosity and low-permeability reservoirs, with productivity largely dependent on natural fracture development. In high-curvature zones, sandstones are more strongly affected by folding and compression, making them more prone to developing natural fractures, which can significantly improve reservoir properties and enhance fluid flow capacity (Fig. 2(c)).

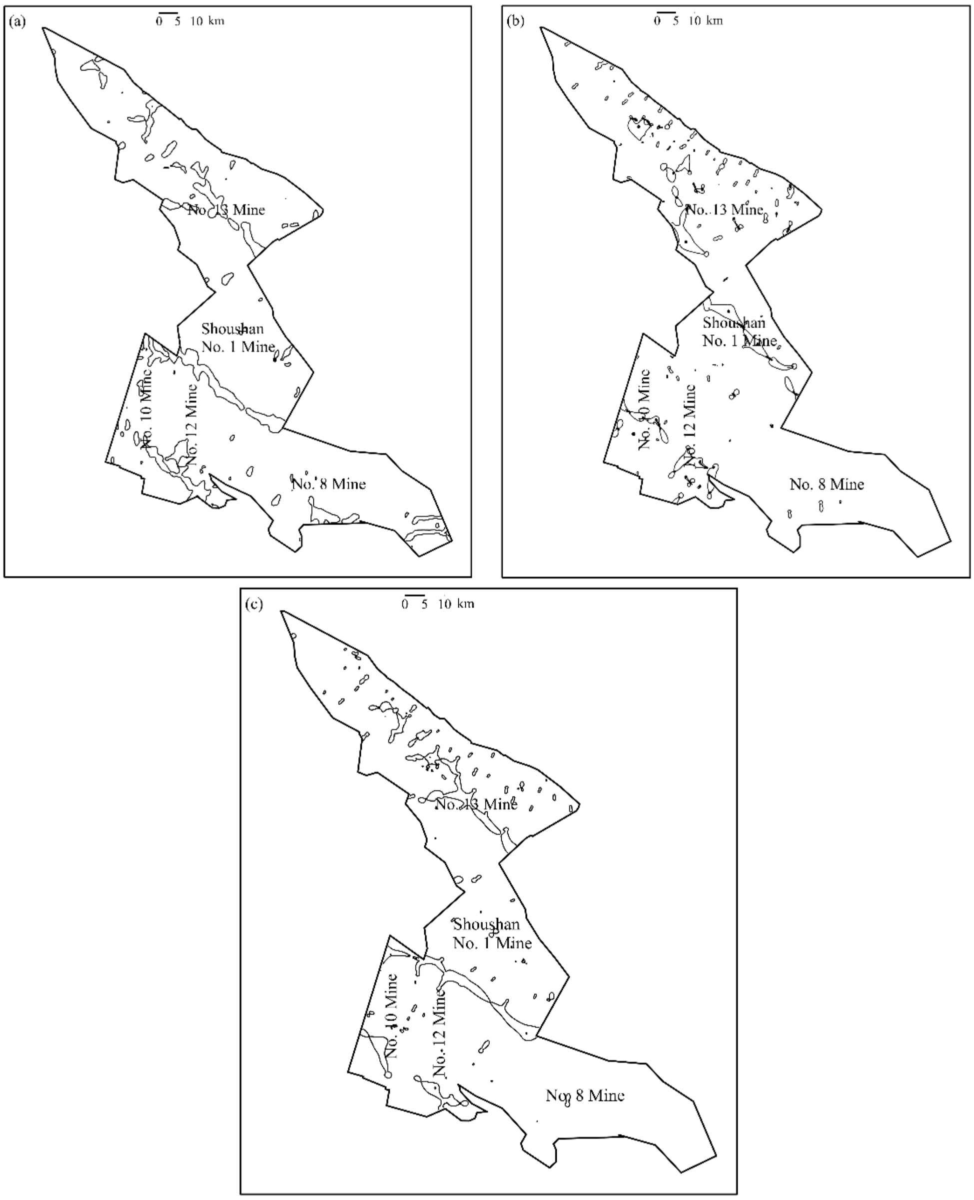

Fig 2 Superimposed maps of structural curvature (red) and contour maps of floor elevation (gray) for the coal seam (a), thick mudstone (b), and thick sandstone (c)

5. CONCLUSIONS

(1) Sedimentary conditions exert a significant influence on coalbed methane enrichment. The lithologic assemblages of the roof and floor surrounding rocks of coal seams vary spatially. Mudstone-developed areas exhibit better sealing capacity, which is favorable for coalbed methane preservation, whereas sandstone-enriched areas tend to have enhanced permeability, facilitating gas migration.

(2) High structural curvature zones of coal seams in the study area are mainly distributed in a zonal pattern along the central part of No. 13 Mine, the southern part of Shoushan No. 1 Mine, and the southern parts of No. 10 and No. 12 Mines. The overall distribution pattern of structural curvature in mudstone layers is highly consistent with that of coal seams, with high-value zones concentrated in the northern part of No. 13 Mine, the central part of Shoushan No. 1 Mine, the central part of No. 10 Mine, and the southern part of No. 12 Mine. The structural curvature of sandstone layers follows a similar pattern, with higher values in strongly deformed zones and lower values in weakly deformed

zones, and is mainly distributed along fold belts in the central part of No. 13 Mine, the southern part of Shoushan No. 1 Mine, and the southern parts of No. 10 and No. 12 Mines.

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