PAPER • OPEN ACCESS

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To cite this article: Kexin Wang 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **300** 022071

IOP Conf. Series: Earth and Environmental Science **300** (2019) 022071 doi:10.1088/1755-1315/300/2/022071

Research on Main Geological Controls and Enrichment Model of Coalbed Methane Distribution in China

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Abstract. The distribution and enrichment of coalbed methane in China are controlled by various geological factors. A systematic study has been carried out on six aspects: geological structure conditions, burial depth, hydrogeological conditions, sedimentary environment, physical properties and magmatic activities of coalbed methane. The results show that tectonic subsidence, hydraulic sealing and gas control, reverse faults and synclinal core are controlled by structural subsidence, hydraulic sealing and gas control. It is advantageous to CBM occurrence; tectonic uplifting, hydraulic migration and dissipation, normal faults, anticlinal core and subsidence pillars are disadvantageous to CBM occurrence; with the increase of coal seam burial depth, the adsorption capacity of CBM increases gradually, and decreases after the critical burial depth; the thicker the thickness of coal seam roof and floor, the more dense of the lithology, the more favorable to CBM preservation; the content of CBM is positively correlated with coal thickness. According to the influence degree of geological factors, the distribution and occurrence of coalbed methane can be summarized as two types: comprehensive control of multiple factors and main control of one or two factors.

1. Introduction

China is rich in coalbed methane resources, with 36.81 trillion m3 of coalbed methane resources buried in a depth of 2,000 m, ranking the third in the world. The development and utilization of coalbed methane is of great significance for coal mine safety production, clean energy utilization and environmental protection. The 12th Five-Year Plan for the development and utilization of coalbed methane in China put forward the plan of "Twelfth Five-Year Plan". During the period of "Twelfth Five-Year Plan", 1 trillion m3 of new proved reserves of coalbed methane would be realized, and the coalbed However, as of the end of 2012, China's proven CBM geological reserves were 55.158 billion m3. In 2013, China's CBM production was only 138.13 billion m3 and surface production was only 2.926 billion m3. These two indicators were far from the 12th Five-Year Plan’s target. At present, CBM production mainly comes from a few coals such as southern Qinshui Basin, southeastern margin of Ordos Basin and Fuxin Coalfield. Therefore, there is an urgent need to find new CBM enrichment and favorable development areas to promote the industrialization of CBM. The formation of CBM reservoirs is not only related to its own conditions such as gas source and reservoir, but also closely related to the later preservation conditions. The generation and storage capacity determines the enrichment of CBM, and the preservation conditions largely result in the formation of CBM reservoirs. Distribution and occurrence of coalbed methane in China are characterized by diversity, which is mainly manifested in many coal-

IOP Conf. Series: Earth and Environmental Science **300** (2019) 022071 doi:10.1088/1755-1315/300/2/022071

bearing basins, coal-bearing series, coal types and coalbed methane reservoir types. Moreover, due to the complex geological structure, complex coal-forming environment, strong reservoir heterogeneity and complex coalbed methane reservoir conditions during coal-forming period, the distribution and occurrence law of coalbed methane is more difficult to grasp. On the basis of previous research results, the distribution and occurrence characteristics of coalbed methane in China, the main controlling geological factors, the enrichment mode of coalbed methane and the characteristics of enrichment area are explored, which can provide reference for searching favorable enrichment areas under similar geological conditions.

2. Main controlling geological factors of coalbed methane distribution and occurrence

Coalbed methane occurs mainly in adsorbed, free, water-soluble and solid-soluble coalbed methane, in which adsorbed coalbed methane accounts for more than 90%. The distribution and occurrence of coalbed methane are influenced by many geological factors. Through the occurrence of coalbed methane in key coal-bearing basins or regions of Henan, Shanxi, Shaanxi, Guizhou, Anhui, Liaoning, Heilongjiang, Chongqing and other provinces (cities) in China[4-26]. The main controlling geological factors of coal seam gas-bearing property are summarized as six aspects: geological structural conditions (including tectonic evolution and structural types), coal seam burial depth, hydrogeological conditions, sedimentary environment, coal reservoir physical properties (including coal metamorphism degree, coal body structure and coal thickness) and magmatic activity.

2.1. Geotectonic conditions

2.1.1. Tectonic evolution. Tectonic evolution history controls the history of sedimentary burial and thermal evolution of coal-bearing strata, thus controlling the formation, occurrence and accumulation of coalbed methane [20], and controlling the formation and distribution of coalbed methane accumulation zones at the basin level. After coal-forming period, tectonic subsidence increases the degree of coal metamorphism and the pressure of coal reservoir by increasing the thickness of the overlying strata of coal seam, thus promoting coal-generating hydrocarbon and coalbed methane absorption. The tectonic uplift after hydrocarbon generation period makes the overlying strata of coal bed eroded, the coal reservoir relieved pressure, and promoted the development of cracks, resulting in the desorption, evacuation and escape of coal bed methane. The effective thickness of overlying strata, that is, the distance between coal bed and the first unconformity surface after gas generation, truly reflects the tectonic movement after the formation of coal bed methane and the stratum uplift and denudation caused by it. The influence on the preservation condition of coalbed methane plays a controlling role in the stratigraphic profile of a coal-bearing basin or region.

Coal-bearing basins in China have undergone multi-stage tectonic processes, and structural uplift has destroyed the preservation of CBM reservoirs to varying degrees. Generally, the later and shorter the time of structural uplift is, the shorter the time of CBM loss is, and the better the preservation of CBM is. [1] In uplift areas which have been denuded for a long time, CBM is continuously lost and the gas content decreases; in later subsidence areas, it is beneficial to the preservation of CBM. In addition, the tectonic evolution history of coal-bearing basins and the changing history of tectonic stress field of coal-bearing basins are controlled, thus it affects the tectonic distribution of coal-bearing strata, structural types and the development degree of coal reservoirs and surrounding rock joints and fissures, and affecs the distribution and occurrence of coalbed methane.

2.1.2. Structural types. Structural types are different in tectonic deformation caused by different tectonic stresses. In the process of formation of different types of geological structures, different tectonic stress fields and their internal stress distributions will lead to differences in occurrence, structure, physical properties and groundwater runoff conditions of coal reservoirs and their capping beds, which will affect the gas-bearing characteristics of coal seams. Generally speaking, the distribution of coalbed methane is related to the distribution of coalbed methane. Structural types with important influence on occurrence mainly include fault structures, folds and subsidence columns [4, 7, 13-14, 20-22].

The influence of fault structure on coalbed methane occurrence is mainly reflected in fault sealing, which depends on the nature of fault, the cementation of fault zone, the lithologic docking relationship between the two sides of fault and the mudstone smearing effect [4]. Previous studies have shown that [4,7,18,22]: (1) Generally speaking, normal faults are mostly open, and their sealing is poor, which is conducive to gas escape; reverse faults are compressive or compressive-torsional, which are good for gas preservation. In the process of tectonic evolution, sometimes the nature of faults changes, and the sealing of coalbed methane changes accordingly. (2) Some faults will destroy the original continuity of aquifer. Shortening the distance between aquifers and coal seams, and making them have hydraulic connection with each other is unfavorable to the preservation of coalbed methane. However, for faults with small drop, there is no cutting aquifer. During the process of fault activity, mylonitic coal zone is formed around faults, which is easy to form coalbed methane enrichment area. (3) Sliding structure will also affect the occurrence of coalbed methane to a certain extent.

The influence of fold structure on coalbed methane occurrence is related to groundwater potential and reservoir pressure. It usually shows the law of syncline gas enrichment [23]. In the core of syncline and its vicinity, low formation water level and high hydrostatic pressure lead to higher reservoir pressure, which is conducive to coalbed methane adsorption; moreover, syncline generally has the mechanism of formation water centripetal flow, plays the role of hydraulic plugging, and is conducive to the preservation of coalbed methane near the back. Under the action of inclined axis and tension stress, the seam and roof confining pressure joints have poor sealing ability, while coalbed methane is easy to migrate and dissipate, and the coalbed methane content is generally low.

The development of subsidence pillars seriously affects the integrity of coal seam occurrence and the gas-bearing property of coal seam. Because of the occurrence of subsidence pillars, the sealing conditions of coalbed methane are destroyed first, and coalbed methane can be diffused into other spaces along with underground circulation; secondly, the formation pressure is reduced, resulting in the desorption of coalbed methane in and around the subsidence pillars, which greatly reduces the content of coalbed methane [13] According to the type of subsidence pillar, the top pillar has the greatest influence on CBM content, followed by the semi-truncated pillar, and the underlying pillar has no direct influence on CBM emission[14].

2.2. Burial depth of coal seam

Generally speaking, the effect of coal seam burial depth on coal seam gas content is as follows: (1) With the increase of coal seam burial depth, the temperature and pressure of coal reservoir gradually increase: the positive effect of initial reservoir pressure is stronger than the negative effect of temperature, which makes free gas transform into adsorbed gas, which is beneficial to the adsorption and preservation of coal seam gas, and the coal seam gas content gradually increases; when the burial depth increases to a certain depth (critical depth), the positive effect of pressure decreases; and the negative effect enhanced, adsorption capacity showed a decreasing trend [27-28]. (2) With the increase of burial depth of coal seam, the sealability of overlying stratum thickness increases, and the pore permeability of coal seam decreases and sealability improves due to compaction, which is beneficial to the storage of coal-bed methane. [18] The functional relationship between burial depth of coal seam and coalbed methane content is not unchanged, sometimes affected by structural location [24].

2.3. Hydrogeological conditions

Coal seam is usually also an aquifer. Groundwater dynamic field controls the fluid pressure, gas-water composition and distribution of coal seam, etc. [29-33]. The influence of coal seam hydrodynamic field on the distribution and occurrence of coalbed methane is mainly embodied in the effect of "recharge-runoff-discharge" hydrodynamic system on coal seam gas content, including two aspects: hydraulic damage of coalbed methane reservoir and hydraulic protection. In the process of migration and evaporation, this process leads to the evaporation of coalbed methane. Hydraulic protection mainly occurs in the process of hydraulic closure and plugging, which is beneficial to the accumulation of coalbed methane [30]. Hydraulic migration and evaporation often occurs in the developed areas of faults with strong water conductivity. Hydraulic closure and gas control occurs in wide gentle inclination or monoclinic with simple structure and undeveloped faults. Commonly seen in asymmetric syncline or monoclinic medium [33], Ye Jianping [34] organically associates coal reservoirs with roof and floor aquifers and other water supply layers which have hydraulic connections with coal seams, and puts forward three types of gas-water two-phase flow systems in closed, semi-closed and open coalbed methane fields, among which the closed type is favorable for coalbed methane enrichment and the open type is unfavorable for coalbed methane enrichment.

For a coal-bearing basin, from the basin margin to the center of the basin, there are successively hydraulic plugging and gas control, water solution carrying and gas control, runoff escaping and gas control and hydraulic sealing and gas control. Coalbed methane content will gradually increase from the basin margin to the slope zone and then to the center of the basin [35]. For example, Weibei coalfield in the southeastern margin of Ordos Basin [27], [33]. In addition, under certain conditions, the hydrodynamic system is related to the generation of secondary biogas, which can form a supplementary source of coalbed methane, which is of great significance to the enrichment and accumulation of low-rank coalbed methane [36].

2.4. Sedimentary Environment

The influence of the properties of roof and floor on the distribution and occurrence of CBM depends on the permeability and gas isolation of roof and floor. It is closely related to the lithology, thickness and development of joint fissures of roof and floor. The thicker the roof and floor of coal seam, the more dense the lithology, the higher the gas content of coal seam, the more loose the structure, the larger the voids, the better the permeability, the lower the sealing degree of coal seam gas, and the easier to seal coal seam gas [18]. The exploration data of Zhengzhuang block in southern Qinshui basin show that the gas content of coal seam is controlled by the thickness of mudstone roof as a whole, and affected by regional tectonic conditions and burial depth (Fig. 1), when the thickness of mudstone roof is less than 9m [26]. In addition, some minerals in mudstone can also adsorb methane, so that the methane concentration in mudstone is higher than or equal to the methane concentration in coal seam, and a smaller concentration difference will effectively prevent the methane from escaping [11].

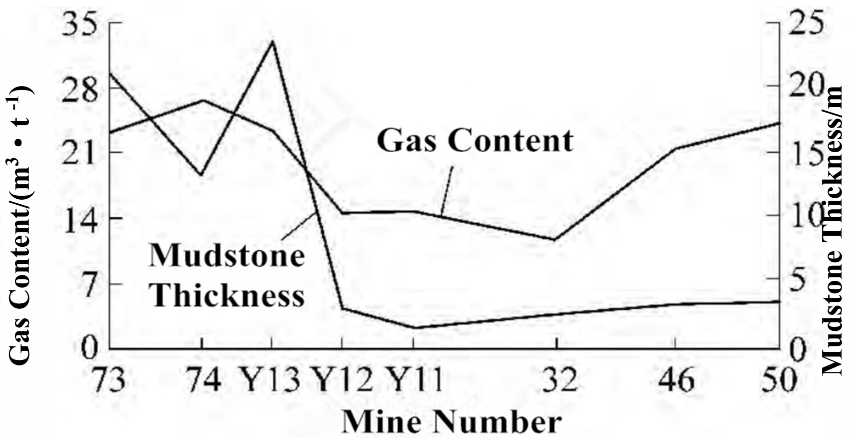

Figure 1. Mudstone Thickness and Gas Content Distribution of No. 3 Coal Seam in Zhengzhuang Block

In addition to capping, a good water-proof layer composed of coal seam roof and floor can effectively block the hydraulic connection between the coal seam and the upper and lower aquifers, thus forming an independent coalbed methane reservoir. Conversely, it is not conducive to the preservation of coalbed

IOP Conf. Series: Earth and Environmental Science **300** (2019) 022071 doi:10.1088/1755-1315/300/2/022071

methane by communicating the groundwater system between the coal seam and the upper and lower aquifers. Limestone, as a karst fissure aquifer, is a disadvantageous lithologic type, such as in Daning-Jixian area. Coal No. 8 is deeper and more metamorphic than coal No. 5, but its gas content is worse than that of coal No. 5. This is mainly because coal No. 5 is mostly mudstone roof and its capping ability is stronger than that of coal No. 8. Moreover, coal No. 8 is affected by Ordovician limestone water, which is not conducive to CBM occurrence [5].

2.5. Coal Reservoir Physical Properties

Coal physical factors affecting the distribution and occurrence of coalbed methane mainly include the degree of coal metamorphism, the structure of coal body and the thickness of coal seam etc. (1) The degree of coal metamorphism not only affects the gas production of coal, but also affects the pore characteristics and adsorption properties of coal, thus affecting the distribution and occurrence of coalbed methane. [37] It is considered that the influence of coal metamorphism on the occurrence of coalbed methane reflects its pore-fissure system shape of coal reservoir. Therefore, the distribution of coal rank in coal-bearing basins will have a certain influence on the distribution of coal-bed gas content. For example, the distribution of CBM resources in Chongqing is mainly controlled by the distribution range of medium and high rank coal [19]. (2) The mechanical properties of coal and rock are relatively weak, and they are vulnerable to tectonic stress transformation resulting in movement and changes in coal structure, resulting in non-uniform migration and distribution of coal-bed gas in coal seams. Under the action of tectonic stress, tectonic coals with different deformation mechanisms undergo dynamic metamorphism, hydrocarbon products are generated, and excess coalbed methane [38], coalbed methane exploration and underground gas outburst show that coalbed methane enrichment areas are usually formed in mylonitic coal belts [4].(3) Coalbed methane content is positively correlated with coalbed thickness [17]. Thick coal belts are also coalbed methane enrichment zones, for example, large coalbed methane enrichment zones. The middle-west part of Ning-Jixian area is a monoclinic structure (buried depth is 700-1000m), which develops a thick coal belt with NE direction, forming a high gas-bearing zone with gas content generally greater than 15 m3/t. The buried depth in the northwest part of the area is 1000-1500m, and the gas content is less than 10 m3/t [5], because of the thin coal seam.

2.6. Magmatic activity

Tectonic heat such as magmatic activity results in physical property transformation of coal reservoir, improvement of coal metamorphism and secondary hydrocarbon generation, which has an effect on gas-bearing property of coal seam [39-40]. The degree of coal bed transformation and metamorphism is related to occurrence, scale and distance from intrusive body. Natural coke, high metamorphic fractured coal, high metamorphic coal and jointed coal magma intrusion gradually occurs from far away to near heat source in annular zones. Thermal intrusion has both advantages and disadvantages of destroying coal reservoir capacity. Therefore, the improvement of CBM occurrence conditions caused by magma intrusion should be given priority consideration. For example, because of the intrusion of diabase in Liujia area of Fuxin coalfield, China, the coal seam is superimposed metamorphism by rock mass baking, which has an impact on CBM content and its occurrence state [6]. Coal seam No.21 in Shuangquan Minefield of Yangyang Mining Area was intruded by late Yanshanian magma, which made the coal metamorphic degree from anthracite to lean coal distribute in a ring pattern, affecting the distribution law of coalbed methane [4]. In Sanjiao-Liulin monoclinic area, the gas content of No.8 coal seam in central part is higher, which is the result of the increase of gas generation due to its proximity to magmatic rock mass and the deepening of coal metamorphism [5]. Practice shows that there are many CBM enrichment areas in China, and geological history has experienced superimposed heating metamorphism caused by magma intrusion, which has improved the gas content of coal seams and permeability of coal reservoirs. It has become a key CBM development area, such as Qinshui CBM field [39].

3. Distribution and occurrence characteristics of coalbed methane in China

According to the influence degree of the above main geological factors on the distribution and occurrence of coalbed methane, the distribution and occurrence of coalbed methane can be summarized as two types: comprehensive control of multiple factors and main control of one or two factors.

3.1. Multivariate integrated control

The distribution and occurrence characteristics of coalbed methane are the result of a combination of various geological factors (three or more). All kinds of geological factors play a certain role in coalbed methane occurrence. For example, No. 21 coal in Xinggong coalfield, Henan Province (including coal seam burial depth, coal seam thickness, coal seam surrounding rock and geological structure) [18], No. 2 coal in Jiaozuo coalfield, Henan Province (coal thickness, effective seam thickness, coal seam overlying development process) Degree and roof and floor wall rock properties) [9], No. 4 coal (geological structure, coal seam buried depth, coal thickness, roof and floor wall rock properties and hydrogeological conditions, , Binchang No. 4 coal, in Binchang mining area, southern Ordos basin southern Shaanxi Province (geological structure, coal seam buried depth, coal seam buried depth, roof and floor wall rock properties and hydrogeological conditions) [17], Sunzhuang exploration area, Huaibi coalffield, Anhui Huaibei coalfield (coal seam buried depth, coal metamorphic degree, coal metamorphic degree, coal thickness, TaTacoal seaseaseam cover and geological structure) [8], For this type of CBM area, CBM enrichment area is the result of rational allocation of various favorable geological factors [15]. The delineation of enrichment area needs to be considered comprehensively according to various geological factors.

3.2. Multi-factor influence, one or two factors dominant type

In a coalbed methane enrichment area, a variety of geological factors determine the overall gas-bearing level of the coalbed in the area, but the heterogeneity of coalbed methane distribution in the area is often controlled by one or two dominant factors, which plays a decisive role in influencing the degree of coalbed methane enrichment in the area. For example, the main control type of hydrogeological conditions is: Luan target area of Shanxi Qinshui Basin [12]; Jincheng area of Shanxi Qinshui Basin [10]; Main control types of hydrogeological conditions: Shuangquan minefield in Anyang mining area, Henan Province[4]; main control types of fold structure and burial depth: No.2 coal in Pingdingshan mining area, Henan Province[16]; main control types of structural and hydrogeological conditions: Zhengzhuang block, Jincheng area, Qinshui basin [20]; main control types of sedimentary environment and structural conditions: Fanzhuang block, Jincheng area, Qinshui basin [21];

4. Coalbed methane enrichment model and prediction of favorable areas

Based on the analysis of the main geological factors controlling the distribution and occurrence of coalbed methane, five modes of low-rank coalbed methane enrichment are put forward by domestic scholars according to the enrichment patterns of coalbed methane in typical coal-bearing basins [40-43], Fu Xiaokang, etc. [45], based on the enrichment laws of coalbed methane in Fanhe Basin and Tiefa Basin, USA, namely, oblique enrichment model, tectonic-hydrodynamic enrichment model, tectonic-lithologic enrichment model, lithologic-hydrodynamic enrichment model and lithologic enrichment model, Sun Ping [42] summarized three modes of low-rank coalbed methane enrichment and accumulation as follow: deep confined overpressure enrichment model, late biogas enrichment model on gentle slope of basin margin and conventional trap hydrodynamic enrichment model at high structural points, Wang Bo and others [43] according to Fuxin Basin, proposed the formation mechanism of coalbed methane enrichment area in Wangying-Liujia area, and put forward the enrichment model of hydrodynamic-rock wall plugging mixed origin fissure-type coalbed methane. [44] Based on the main controlling factors of coalbed methane accumulation in Yilan coalfield, the enrichment model of hydraulic plugging-reverse fault type in Yilan mining area is put forward. According to the high abundance coal seams in southern Qinshui basin, eastern margin of Ordos basin and Northern Huaihe area etc. [29] The formation mechanism of enrichment zone in gas area has established the formation mode of high abundance and medium rank CBM enrichment zone, i.e. dominant superposition enrichment mode of gas content and permeability in slope area and enrichment mode of CBM in brittle-ductile superimposed zone.

Other scholars have summarized the development location or characteristics of CBM enrichment areas in China. Zhao Qingbo et al. [45], Zhai Guangming et al. [2] have summarized the main types of CBM enrichment areas in China, such as the volcanic active areas of structural highs in regional coal-bearing areas, the stable distribution of direct cap rocks, the volcanic active areas of middle uplift structures in depressions, the low-rank and thick coal seams with good shallow sealing conditions, and fault activities. Based on the enrichment rule of coalbed methane in Daning-Jixian area, secondary cleavage development area, Li Wuzhong et al. [46] consider that marsh facies, gentle structure and low value area of in-situ stress in Hejianwan Bay are the most favorable enrichment areas for coalbed methane.

In the later stage of exploration and development, similar CBM enrichment areas can be found by analogy of geological conditions based on existing CBM enrichment models and development characteristics of enrichment areas. As a favorable target area for CBM development, however, CBM enrichment areas are not CBM high permeability areas, so they are not necessarily the most favorable areas for CBM development. At present, the commonly used evaluation methods for optimizing coalbed methane target areas in China include multi-level fuzzy mathematics method based on geographical information system (GIS) [47-54], comprehensive catastrophe theory and fuzzy mathematics method. [61] In the exploration stage, these methods are effective, especially the analytic hierarchy process (AHP). By comparing and judging the importance of the two indicators to determine the weight, the complex problems that are difficult to be analyzed completely by quantitative analysis can well dealt with. However, due to the numerous evaluation indicators, the relative importance of some indicators is mainly determined by experience, and the subjectivity is strong, which may affect the final evaluation effect.

5. Conclusion

The main geological factors controlling the distribution and occurrence of coalbed methane include six aspects: geological structural conditions, burial depth, hydrogeological conditions, sedimentary environment, physical properties of coal seams and magmatic activities. Structural subsidence is beneficial to the occurrence of coalbed methane; tectonic uplift is opposite; reverse fault and synclinal core are favorable structural types; normal fault, anticlinal core and subsidence pillar are disadvantageous structural types. With the increase of coal seam burial depth, the adsorption capacity of coalbed methane increases; after the critical burial depth, the adsorption capacity of coalbed methane decreases; the hydraulic migration and escape can destroy the gas reservoir; the hydraulic sealing and gas control can protect the gas reservoir. The thicker the roof and floor of the coal seam, the more compact the lithology is; and the more advantageous the preservation of coalbed methane is. The mylonitic coal belt is easy to enrich coalbed gas; the content of coalbed methane is positively correlated with the thickness of coal seam. According to the influence degree of main geological factors, the distribution and occurrence of coalbed methane can be summarized as "comprehensive control of multiple factors" and "main control of one or two factors". The enrichment areas and enrichment modes of coalbed methane in China are diverse, and the favorable enrichment areas of coalbed methane can be predicted by analogy of geological conditions.

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