Effects of Igneous Intrusion on Low-rank Coalbed Methane Reservoir Formation in Fuxin Basin, China

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Abstract: Researches of igneous intrusion in Fuxin basin on more complex formation mechanism of low-rank coalbed methane(CBM) reservoir are not only the focus and critical problem of basic geology, but also contribute to improvement of the exploration effectiveness of the same type of reservoirs, serving as one of rare achievement examples of low-rank CBM development. This paper presents a comprehensive research of the reservoir characteristics of the Wangying-Liujia CBM formation, such as the intense control action of the dolerite dike invasion so as to further confirm the effects of igneous intrusion on low rank CBM reservoir formation. The result shows that the dolerite dike invasion not only facilitates large hydrocarbon regeneration, but also obviously improves the Ro of the thick bituminite at the bottom of Fuxin formation. It also greatly improves the coal reservoir property, which helps the groundwater double replenishment along the coal seams outcrop and dolerite dike and the closed pressure water condition formation. Moreover, the research shows that there exists much free gas clearly for the closed fault-preventing gas diffusion. So the cokeite growing area is the most advantageous where the high production CBM wells will distribute in the girdle band along the dike. In summary, concerning low-rank CBM exploration, this paper proposes gas evaluation by using CBM and conventional means.

1. Introduction

China is now the largest producer of coal in the world, and its total coal resources account for nearly 70% of total energy resources. Coalbed methane is a coal seam from classifies unconventional gas, exploitation of CBM reservoir to ensure the safety of national energy strategy and improve the energy structure, reduce the coal mine gas disasters and protect the atmospheric environment is of great significance. The low-order coalbed methane resources have accounted for more than 40% of the total geological resources of coal bed methane in China. The low coal seam gas has become the main development direction of coal bed methane exploration and development in China.

The study of low coal seam gas in foreign countries started early and made rapid progress(Wapes,1998; Anggara F et al.,2014; Clarkson et al.,2011; Carroll et al.,2011; Bergquist,2007; Jr Paul,2007). In the 90 s, based on biogas and secondary CBM reservoiring theory, the first in the United States is given priority to with coal powder River basin has realized the low coal rank CBM commercial development, and quickly spread to other major low coal rank basins (Uintah and Raton, Wind River, et al.). By the end of 2006, the cumulative production of coalbed methane in fanhe basin was 655 x 10^8m³ (US energy bureau website). Under the influence of the United States, other countries have also carried out the exploration and development of low coal seam
gas (Adeboye, 2013; Chalmers, 2007; Korsch, 2009; Smith J W, 1985). About 90% of Australia's coal-bed methane production comes from the bow-mild surat basin, which has a large number of low coal level blocks. In 2012, the coal bed methane production in the bowen basin and surat basin was 25.01 x 10^8m3 and 10.76 x 10^8 m3 respectively. In 2012, the production of CBM in Alberta was 90.3 x 10^8 m3. The potential recoverable reserves of the alberta basin in western Canada are 7.1 x 10^11m3, and the southwest is the high-order coal, and the central and northern regions are low-order coal. The main coalbed methane production area is the Horseshoe Canyon in the north and the Horseshoe Canyon and Belly River coal seam in the south and south. In recent years, Alberta's coal-bed methane industry has grown rapidly, with total investment of more than $2 billion. By the end of 2011, the number of CBM drilling in Alberta was 7,923 (Data Basin, 2012). The commercial success has provided the first-hand information for scientific research and the rapid progress in the related fields of low-coal seam gas (Zelenka, 2014; Robbins, 2016; Clarkson, 2011). It is mainly embodied in the study of gas-bearing measurement method and pore structure and seepage characteristics of low coal rank coal reservoir. Joubert (1974) proposed the moisture content on the methane adsorption capacity restricted by critical moisture content, the influence of the moisture content is lower than the critical point, the increase of the moisture can reduce methane adsorption capacity, but more than a tipping point, reduce the influence can be neglected. Levine (1996) analyzed the relationship between macropores and micropores and carbon content, and found that, with the increase of coal level, the macropores decreased and the micropores increased. Gurdal and Yalin (2001) found that when Ro<1%, the surface area increased with the coal level and then decreased. CBM exploration and development in our country in recent years made a breakthrough in medium - high coal rank after get rapid development, but the low coal rank CBM exploration and development in our country at present is still in the test and small-scale commercialization stage. In addition to the eastern region of Junggar, China's low coal basin mainly includes Fuxin basin, Tuha basin, and Erlian basin in Inner Mongolia. The commercial exploitation of coalbed methane in Fuxin basin has a history of ten years. The primary biological gas in the basin is mostly dispersed, and the two periods of magma activity after coal is formed, and the secondary biological gas and secondary thermal genesis of the current preservation have made up the deficiency of the deep pyrolysis gas source of the coal seam.

Wangying-Liujia Depression, located in the middle part of the Fuxin Basin, covers about 20km2, where CBM resources are abundant with gas content 8~10m3/t and gas in place resource 51.81 x 10^8 m3. Among the thirty CBM development wells in Liujia area, the highest production of a single well is over10,000 m3/day, serving as one of the rare achievement examples of low-rank CBM development.

However, in Fuxin basin, the formation mechanism affected by igneous intrusion is unique and complex. Previous studies (Chen, 2002; Liu et al., 1992; Wang et al., 1998) focused on CBM enrichment characteristics, reservoir evaluation and sedimentary evolution, but ignored the effect of igneous intrusion on coal reservoir reconstruction and secondary hydrocarbons generation. So, based on the results of previous researches in the area, this paper mainly discusses the intense control action of the dolerite dike invasion by studying the geological characteristics of coalbed methane reservoirs in Wangying-Liujia Depression, Fuxin Basin. Some new orientation of exploration which is supposed to direct low rank CBM exploration and development in the future is proposed and recommended.

2. Geological backgrounds

Wangying-Liujia Depression, a interior residual basin formed in the Late Jurassic, is a complex syncline with striking NE-SW (Fig 1). Its NW limb is more precipitous with 8-20° dip and the gently SE limb there mainly include Ping’an F2, Pingxi F2, F8, and Liujia F2 fault, in which the largest one is Ping’an F2 fault. The Ping’an F2 fault strikes NW325°and tends towards SW with the dip of 70~75°. The fall of the fault is 200~210 min the northwest and gradually diminishes toward southwest with 50~30 m. It separates the depression into Wangying and Liujia areas.

The widely developed dolerite dike, close to EW, is the result of the igneous intrusion in Himalayan Orogeny period. It intruded into the coal-bearing strata with long-distance and high-dip. The upper segment of the Lower Cretaceous Fuxin Formation, the main coal-bearing sequence in the
depression in question, formed under a background of lacustrine regression (Chen et al., 2007), when water gradually shoaled in the wake of the lake maximization extension in the Lower Cretaceous. The peat swamp developed widely under the lacustrine delta plain. According to the lithologic characteristics, the Fuxin Formation, with the thickness around 600–800m, was divided into the upper, middle and lower segments (Fig.1). The middle segment, with a thickness of around 120–220m, is the main target stratum, composed of sandstone and fine sandstone with abundant cycadophyte and Ginkgoaceae fossils. The Fuxin Formation contains three coal members from the lower to the upper, i.e. Taiping Member, the Middle Member, and the Sunben Member. The thickest formation of Taiping Member can reach 38.24 m. The reservoir gradually thickens from margin to the center. The total thickness of multi-coal seams can reach 96.07m and the average is 35.21m in Wangying sub-depression and 42.96m in Liujia sub-depression. Oil-bearing sand and oil shale are especially developed at the bottom.

| Strata system | Thickness (m) | Lithology |
|---------------|---------------|-----------|
| Sunjiawan Formation (K_{c}) | 500–100 | The Sunjiawan Formation is composed of gravelstone, glutenite, sandstone and mudstone |
| Fuxin Formation (K_{a}) | 800–1200 | The Fuxin Formation is composed of sandstone, siltstone, gravelstone, mudstone, thick coal seams and plenty of phytotile |
| Shahai Formation (K_{b}) | 800–1000 | The Shahai Formation is composed of gravelstone, siltstone, mudstone, thin coal seams |
| Jiuftung Formation (J_{j}) | 1400–2000 | The Jiuftung Formation is composed of glutenite, siltstone, mudstone and thin coal seams |
| Yixian Formation (Y_{y}) | 2400 | The Yixian Formation is composed of sandstone, mudstone and "Rehe biota" fossil |

Fig 1. Generalized stratigraphic characteristics of the Wangying-Liujia depression

3. Coalbed methane reservoir characteristics

3.1. Geochemistry and Origin

The thick coal seams provide CBM material base. In the depression, the black flame coal is dominant, with litter gas coal in bottom, most of which was mostly dull to semi-bright pitch glance and step-shaped and conchiform fractures (Zhu et al., 2007). The vitrinite average is over 80% and the clay mineral is about 3–10% (Zhang et al., 2000; Kotarba M J, 2001; Su et al., 2005). The well-developed cleat was usually filled with the calcite vein and pyrite.

Based on coalbed methane composition and δ^{13}C, value with -26.6~–64.5‰, in the Wangying-Liujia reservoir, we conclude methane is dominant with abiotic origin inert gas & carbon dioxide interfusion, and the origin of coalbed methane in the Wangying-Liujia reservoirs is very complex, including secondary biogenic gas and migrated thermogenic gas that underwent desorption, diffusion, migration, fractionation, and re-accumulation (Fig 2).
3.2. Desorption volume

The isothermal adsorption result, from LJ—1、LJ—2 wells coal samples, shows that the coal adsorption capacity is comparatively high with Langmuir volume 18~34 m³/t and Langmuir pressure 6~20 MPa (Tab 1). and the gas content is 8.72~12.65 m³/t, average 10.0 m³/t (Fig 3).

Tab 1. Adsorption isotherm data of coals from Wangying-Liujia Depression

| Coal member       | V_L (cm³/g) | P_L (MPa) | Theoretical gas content (cm³/g) | Measured gas content (cm³/g) |
|-------------------|-------------|-----------|--------------------------------|------------------------------|
| Sunben coal member| 21.59       | 9.98      | 8.72                           | 7.14                         |
| Zhongjian coal member | 18.81     | 6.47      | 9.41                           | 8.86                         |
| Taiping coal member | 33.71    | 19.07     | 12.65                          | 8.66                         |

Fig 3. Sorption isotherm for the coal samples from well L1 in the Wangying-Liujia Depression
According to the statistics, the average CBM desorption volume in Wangying coal mine is over 50 m³/t for 14 years (Tab 2), higher than the actual measured gas content. Clearly, abundant free gas exits in Wangying-Liujia Depression.

Tab 2. Statistics on CBM desorption volume of Wangying mine (According to the annual report of Bureau of Mines, Fuxin)

| Mine year | Wangying Mine |
|-----------|---------------|
|           | Relative volume m³/t | Absolute volume m³/min |
| 1991      | 49.12          | 31.92                |
| 1992      | 31.22          | 37.07                |
| 1993      | 41.76          | 37.44                |
| 1994      | 63.34          | 44.28                |
| 1995      | 46.23          | 45.86                |
| 1996      | 72.70          | 53.77                |
| 1997      | 50.50          | 52.30                |
| 1998      | 38.01          | 51.05                |
| 1999      | 79.33          | 43.64                |
| 2000      | 55.53          | 59.85                |
| 2001      | 55.53          | 59.85                |
| 2002      | 40.25          | 27.95                |
| 2003      | 47.90          | 51.50                |
| 2004      | 51.03          | 59.22                |
| 2005      | 45.98          | 49.83                |
| 2006      | 51.35          | 37.91                |
| 2007      | 57.92          | 53.59                |
| 2008      | 48.93          | 57.52                |
| 2009      | 54.43          | 47.29                |
| average   | 51.79          | 47.98                |

3.3. Production characteristics
Firstly, high Pd/Pr and saturation are good for CBM development. According to the actual data, the reservoir pressure is 6.74 MPa in the Sunben coal seams, 6.747 MPa in the Middle coal seams, and 8.238 MPa in the Taiping coal seam, lower than the normal value 9.0–9.3 MPa. Correspondently, the actual measured desorption pressure is 5.0, 5.8, 6.6 MPa. So the high ratio of critical desorption pressure and reservoir pressure achieves 0.74, 0.89 and 0.80. Moreover, the saturation of CBM reservoir formation is around 85–96% (Tab 3).
Tab 3. Reservoir pressure & Saturation of coals in Wangying-Liujia Depression

| Coal member             | Reservoir pressure (MPa) | Critical desorption pressure (MPa) | Pd / Pr | Saturation (%) |
|-------------------------|--------------------------|-----------------------------------|---------|----------------|
| Sunben coal member      | 6.74                     | 4.992                             | 0.74    | 84.83          |
| Zhongjian coal member   | 6.747                    | 5.761                             | 0.89    | 92.24          |
| Taiping coal member     | 8.238                    | 6.592                             | 0.80    | 95.65          |

These mean shorter extraction gas time and quicker CBM production peak value. In Lx for instance, its production is over 1500m$^3$/d in less than 2 months.

Secondly, as the distance from dolerite dike extends, the CBM production progressively decreases (Fig 4). Data show the CBM production near the dolerite dike is higher. In LJ-a & LJ-b, the high production capacity of a single well is over 5500m$^3$/d. Obviously, the wells with high production are usually located along the marginal zone of the dolerite dike. Conversely, as wells are farther from the dike such as LJ-c & LJ-d, the single well production is less than 2000m$^3$/d.

Fig 4. Relationship between single well production and the distance from diabase dike in Wangying-Liujia reservoir

4. Effects of igneous intrusion

4.1. Providing enough gas origin

Apart from the coal near the dike, the vitrinite reflectance of coal in Wangying-Liujia Depression is 0.5–0.75%. The coal rank distribution is controlled by burial and thermal history. At the end of Early Cretaceous, the burial depth of coal seams in Fuxin Formation reached the maximum. During this stage, the coal seams matured under normal paleo-geothermal gradient with 2.51–3.0 °C/100m, then the vitrinite reflectance reached 0.75%. In the late stage of Early Cretaceous, a transitory uplifting and erosion did not clearly affect the coal maturation and gas generation. Moreover, the subsidence in the Cenozoic did not markedly enhance thermal maturity of coal seams in Fuxin Formation. However, in
the Himalayan Orogeny period, the whole uplift of the investigated district with a great deal of magma intrusion resulted in many dikes and sills formation. Thus the abnormal tectonic thermal event, controlled by the magma intrusion, caused the paleo-geothermal gradient to exceed 3.93℃/100m and coal rank largely increased in the narrow contacted zone of dikes or sills. The contacted zone usually extends only several centimeters to several meters, where Ro may be more than 4% (Fig.5). As the coal rank increased and CBM secondary generation followed, the gas generating yield of the cokeite can reach over 500m3/t (Ruppel T C, et al., 1974; Yee D, et al., 1993; Zhang et al., 2005; Yao et al., 2007).

![Fig 5. Upper Jurassic and Lower Cretaceous burial history of CBM Well L-a in Wangying-Liujia Depression, Fuxin Basin](image)

More importantly, along with maturation of the oil-bearing sand and oil shale at the bottom of Fuxin Formation, the direct result of the magma intrusion, the abundant secondary migrated thermogenic gas generated and became the important gas origin in Wangying-Liujia reservoir.

Furthermore, the extensive uplift stage from the end of the Cretaceous to present is the main period of the secondary biogenic gas generation (Meng, 2003; Gong, et al., 1998). Especially, in the Himalayan Orogeny period, the surface water was connected because of the dolerite dike intrusion into land surface. With a great quantity of low salinity surface water supplementation, enough methanococcales accumulated in the coal seams. As a result, the coal degradation reaction took place and abundant secondary biogenic gas generated because of suitable temperature and burial depth. Concerning CBM resource in Wangying-Liujia reservoir, we demonstrate the primary thermogenic gas in the Yanshan Orogeny period is dominant, and the secondary hydrocarbons generation in the Himalayan Orogeny period and the continued secondary biogenic gas are the main supplementary part.

4.2 Improving reservoir physical properties

In Wangying-Liujia Depression, affected by a series of the dolerite dikes with striking NNE, the coal contact metamorphism not only resulted in the secondary hydrocarbons generation, but also greatly improves the coal reservoir physical properties. On the one hand, the coal molecular constitution changed with the coal rank increasing, including the condensation degree of condensed nuclei aromatics increasing and the alkylaryl lateral chain and oxic-functional group decomposing. As a result, the vitrinite percentage increased and the volatile content decreased (Chen, et al., 2007). On the other hand, for the organic material volatilizing (Chen, et al., 2003), a lot of circular & tubular holes gradually formed and markedly increased the coal reservoir porosity. At the same time, a lot of contraction cracks formed with the coal matrix shrinking. Moreover, because the epigenetic cracks controlled by the dynamic compaction of magma intrusion superimpose on the coal cleats, the characters and scale of coal cracks changed and the permeability increased (Wu, et al., 2005).

The caustic and dynamic metamorphism changed the local composition and structure in Wangying-Liujia Depression, so the porosity and permeability of coal reservoir obviously increase near the dolerite
dike. Through the thermal simulation experiment, it was proved that the coal composition and structure were obviously changed, quality decreasing with 10.71~29.11% and frequency of cleat decreasing with 11-20 numbers /5cm from 2-5 numbers /5cm (Chen, et al., 2008). Obviously, the influence decreases with the distance from dolerite dike extending. In other words, the porosity is higher in the zone nearer dolerite dike, it can be clearly found that the cokeite, high coal rank coal with low permeability, fractured coal with high permeability, and normal coal are orderly distributed along the two side of dike. Especially, enough cleats, maximum reaching 120 numbers /m, abundant free gas exists in the cokeite reservoir, which is the other important reason that the desorption volume is largely more than adsorption gas in Wangying-Liujia Depression. So the district near the cokeite contribution is favor of CBM development.

In addition, according to the actual field investigation, the reservoir fractures with striking parallel to the dolerite dikecare dominant and the vertical fractures are litter. So it was predicted that the multi-well interference along the dike would be intense.

4.3. Surface water being connected

Horizontally, the main water bearing zone is the contact metamorphism area and distributes in the girdle band along the dike (Li, et al., 1998). The main aquifers in the Fuxin Formation are conglomerate, sandstone and coal reservoir. Because the aquifers and the aqui fuges are not homogeneous, the hydrodynamic connection among these aquifers is very weak. But, the frequent water bursting & lost circulation and the high water production prove that the surface water was connected by the dolerite dike intrusion into land surface. Generally, the prime average water production is 30~40m³/d and the production plateau average is 30~50m³/d. Especially, in the cokeite growing area near the dike, we confirm the long drainage period and the low drainage efficiency.

In Wangying-Liujia Depression, the widely developed dolerite dikes, intruding into the coal-bearing strata with high-dip, transect the coal-bearing strata and upper sandstone and lead to surface. In the contact metamorphic zone, the ground water changes from outcrop and dike and migrates to the deep part of the depression, which was favorable to groundwater double replenishment and the closed pressure water condition formation. In this area, the hydrodynamic sealing prevented most gas diffusion (Scott A R, et al., 1998), so the CBM accumulation is the optimal. Equally, the mudstone and siltstone in the top of Lower Cretaceous Shahai Formation and Lower Cretaceous Fuxin Formation provide the vertical sealing condition of CBM reservoir formation.

Moreover, the contact metamorphic zone is the pathway of CBM migration and diffusion, where the hydrodynamic condition is interconnected and commutative and all coal seams pertain to a unified hydrodynamic condition.

5. Conclusion

(1) The dolerite dike intrusion in the Himalayan Orogeny period is the critical controlling factor of CBM formation in Wangying-Liujia Depression. The magma intrusion changed the normal geothermal temperature, which not only was favorable to the multi-origin gas formation, but also greatly improved the reservoir physical properties because of the contact metamorphism and condensation. These current wells with high production contribute in the girdle band following the dike.

(2) Based on this particular geological characteristic, we predict that the two flanks of the carbonite and dike would be the optimal area for CBM development, where the groundwater recharged from outcrop & dike and migrated to the deep part of the depression. These were favor of the groundwater double replenishment and the closed pressure water condition formation. So in Wangying-Liujia CBM Depression, the reservoir pressure is nearly unitary, being similar to a conventional litho stratigraphic gas pool.

(3) In summary, through the successful CBM project, it indicated that intensifying abnormal tectonic thermal event research is an essential part of the CBM exploration, because the magma intrusion is a critical controlling factor of CBM formation, especially to the low rank CBM reservoir. Thus, to many Cretaceous coal-bearing basins in the north of China, we imagine that the Jiergalangtu, Zhaokewula &
Baoerguoji sag, etc. are the optimal areas for CBM accumulation, in which widely developed the igneous rock in the Himalayan Orogeny period.

(4) Additionally, to the low rank CBM exploration, we should be compared the conventional nature gas research approach and be combined the CBM & conventional gas evaluation. Especially, We should intensify gas origin research & reservoir evaluation.

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References
[1] Adeboye O O, Bustin R M. Variation of gas flow properties in coal with probe gas, composition and fabric: examples from western Canadian sedimentary basin. Int. J. Coal Geology 2013, 108 (0): 47-52
[2] Chalmers G R L, Bustin R M. The organic matter distribution and methane capacity of the Lower Cretaceous strata of northern British Columbia, Canada. Int. J. Coal Geol. 2007, (70): 289-302
[3] Chen J G, Qin Y, Song Q Y, Song Z M. Coupling Relationship Between Direction of Coalbed Cleat and Methane Drainage Effect and Its Prediction Model. Journal of China University of Mining & Technology, 2003, 32(3): 221-226. (In Chinese)
[4] Chen Z H, Song Y. Formation Processes and Advantageous Models for High-Low-Rank Coalbed Methane Reservoirs. Xinjiang Petroleum Geology, 2007, 26(3):275-278. (In Chinese)
[5] Chen Z H, Jia C Z, Song Y. Effects of tectonic uplift on physical properties of high and low rank coal reservoirs. Petroleum Exploration and Development, 2007, 34(4):461-464. (In Chinese)
[6] Chen Z H, Jia C Z, Song Y. Differences and origin of physical properties of low-rank and high-rank coalbed methane. ACTA PETROLEUM SINCA, 2008, 29(2): 179-184. (In Chinese)
[7] Chen Z S, Research on the features of the storage layer of coal gas seam and yielding. Journal of Liaoning Technical University, 2002, 21, 567-570. (In Chinese)
[8] Clarkson C R, Rahmanian M, Kantzas A, et al. Relative permeability of CBM reservoirs: Controls on curve shape. International Journal of Coal Geology, 2011, 88(4):204-217.
[9] Gong J M, Wen Z H, Dai C S. Reservoir characteristics and exploratory targets of Fuxin Basin. Marine Geology and Quaternary Geology, 1998, 18, 81-90. (In Chinese)
[10] Gürdal G, Yalçin MN, Pore volume and surface area of the Carboniferous coals from the Zonguldak basin (NW Turkey) and their variations with rank and maceral composition. International Journal of Coal Geology, 2001, 48, 133-144
[11] Jiang B, Qin Y, JU Y W, Wang J Y. Research on Tectonic Stress Field of Generate and Reservoir of Coalbed Methane. Journal of China University of Mining & Technology, 2005, 34 (5), 564-569. (In Chinese)
[12] Joubert J. Effect of moisture on the methane capacity of American coals. Fuel, 1974, 53: 186-191.
[13] Korsch R J, Totterdell J M. Subsidence history and basin phases of the Bowen, Gunnedah and Surat Basins, eastern Australia. Australian Journal of Earth Sciences, 2009, 56(3): 335-353.
[14] Kotarba M J. Composition and origin of coalbed gases in the Upper Silesian and Lublin basins. Polish Organic Geochemistry, 2001, 32:163-180.
[15] Levine JR. Model study of the influence of matrix shrinkage on absolute permeability of coal bed reservoirs. In: Gayer, R., Harris, I. (Eds.), Coalbed Methane and Coal Geology: Geological Society Special Publication, 1996, 109, 197-212.
[16] Liu J Y, Wang S Y, Yin J H. Petroleum geological character of Fuxin Basin. Oil and Gas Geology, 1992, 13, 450-457. (In Chinese)
[17] Li M C, Wang S Z, Lei C L. Formation mechanism of the fractured gas reservoir in Wangying
hydrodynamic trap in Fuxin Basin. Natural Gas Industry, 1999, 19(5): 17-20. (In Chinese)

[18] Meng Q S, Yin X, Wang Y. Analysis of coal accumulation and dominating coal-forming factor in Fuxin Basin(I). Journal of Liaoning Technical University, 1998, 17, 254-257. (In Chinese)

[19] Meng Q S. Genetic Analysis of Wangying Mine Gas Pool, Fuxin Basin. Coal Geology of China, 2003, 15(6): 24-26. (In Chinese)

[20] Robbins S J, Evans P N, Esterle J S, et al. The effect of coal rank on biogenic methane potential and microbial composition. International Journal of Coal Geology, 2016, 154-155:205-212

[21] Ruppel T C, Grein C. Adsorption of methane mixtures on dry coal at elevated pressure. Fuel, 1974, 53(3): 152-162.

[22] Scott A R. Hydrogeologic factors affecting gas content distribution in coal beds. International Journal of Coal Geology, 2002, 50, 363-387.

[23] Smith J W, Gould K W, Hart G H, et al. Isotopic studies of Australian natural and coal seam gas. Aus IMM Bulletin, 1985, 290(6):43-51.

[24] Su X B, Lin X Y, Zhao M J. The upper Paleozoic coalbed methane system in the Qinshui basin, China. AAPG Bulletin, 2005, 89, 81-100.

[25] Wang W F, Lu S K, Guo Y X. Tectonic geomertory and type of traps in Fuxin Basin. Journal of the University of Petroleum, China, 1998, 22, 26-30+34. (In Chinese)

[26] Wu C F, Qin Y, Fu X H, Lin B Q. Coal Matrix Flexibility Energy and the Relation with Geological Controlling Factors. Journal of China University of Mining & Technology, 2005, 34(5): 636-639. (In Chinese)

[27] Yao Y B, Liu D M. Adsorption Characteristics of Coal Reservoirs in North China and Its Influencing Factors. Journal of China University of Mining & Technology, 2007, 36(3): 308-314. (In Chinese)

[28] Yee D, Seidle J P, Hanson W B. Gas sorption on coal and measurement of gas content. In: Law B E, Rice D D. Hydrocarbons from Coal. AAPG Studies in Geology, 1993, 38(5), 203-218.

[29] Zelenka T, Taraba B. Sorption of CO2 on low-rank coal: Study of influence of various drying methods on microporous characteristics. International Journal of Coal Geology, 2014, 132:1-5

[30] Zhang J B, Tao M X. Geological significances of coalbed methane carbon isotope in coalbed methane exploration. Acta Sedimentological Sinica, 2000, 18, 611-614. (In Chinese)

[31] Zhang X D, Sang S X, Qin Y, Zhang J, Tang J X. Isotherm Adsorption of Coal Samples with Different Grain Size. Journal of China University of Mining & Technology, 2005, 34(4): 421-432. (In Chinese)

[32] Zhao M P, Wang Y L, Zhou R. Study on the structure factors of the coalbed methane field in Fuxin coal field. JOURNAL OF CHINA COAL SOCIETY, 1999, 23(4): 225-230. (In Chinese)

[33] Zhu Z M, Shen B, Cui H Q. Genetic Analysis of Coal-Bed Methane in Fuxin Basin. Geological Science and Technology Information, 2007, 26(3): 67-70. (In Chinese)