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Coal Adsorption Isotherms, Gas Content and Geological Controls of Bide-Santang Basin in China

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Abstract: The adsorption isotherms of Bide-Santang Basin's main coal seams is studied based on analyzing two Coalbed Methane (CBM) wells in Huale exploration region and testing the coal samples and the major geological factors are also discussed. A conclusion has been made that the adsorption capacity of Bide-Santang Basin's main coal seams is high. The Langmuir volume (V_L) of dry ash-free basis range from 17.69 m^3/t to 21.38 m^3/t and the average is 19.46 m^3/t. The methane saturation of the coal reservoir is lower than 100%, commonly ranging from 75.04 to 105.55% and the average is 84.51%. It indicates that coal reservoir in the research area is undersaturation. The critical desorption pressures are between 1.22 MPa and 9.1 MPa and the average is 3.25 MPa. The coalbed methane theory recovery rates are between 19.96 and 46.15% with average of 34.51%. The main effect geology factors on the adsorption in this area are reservoir pressure, depth of burial, degree of coalification and characteristics of pores. The reservoir pressure and depth of burial are positively related with the gas content. The higher of the degree of metamorphism is, the stronger adsorbability of CBM is. The well-developed micropores and mesopores contribute to the adsorption capacity of CBM.

Keywords: Adsorption isotherms, bide-Santang basin, coalbed methane, coal reservoir, geological controls, main coal seams

INTRODUCTION

Underground coal mines emitting large quantities of methane to atmosphere is one of the sources of methane and the Coalbed Methane (CBM) has been an important potential resource since the late 20th century and will be the clean fuel in the future (Longwell *et al*., 1995; Flores, 1998). The amount of CBM generated at a specific operation depends on the gassiness of the coal seam and any underlying and overlying formations, operational variables and geological conditions. Presently, many research projects focus on adsorption, predictions of methane content in coals under equilibrium conditions and influences factors of the methane content. Effect factors on methane content include coal rank, temperature, pressure, moisture content and composition (Bustin and Clarkson, 1998; Gentzis *et al*., 2006; Tang *et al*., 2007; Kedzior, 2009; Yao *et al*., 2009). Gas content generally increases with increasing depth and rank (Markowski, 1998; Pashin, 2010). With a numerical simulation study, a certain amount of methane was generated and began to accumulate in coal seams with middle-high volatile bituminous coal (Gentzis and Bolen, 2008; Wei *et al*., 2010; Keim *et al*., 2011). Besides, the ash content and the lithology of the overlying strate may influence the distribution (Drobiniak *et al*., 2004; Hackley *et al*., 2009). However, coal permeability tends to decrease with depth and some studies show that there is not a direct relationship between coal type and coalbed gas storage. Commercially successful wells are characterized by coals with high gas yields at shallow depths (Bodden III and Ehrlich, 1998). Shallower (<600 m) coal samples consistently are undersaturated with respect to CH_4 adsorption isotherms; deeper (>600 m) coal samples containing less moisture range from under-to oversaturated with respect to their CH_4 adsorption capacity (Langenberg *et al*., 2006; Hackley *et al*., 2007). Strong hydrodynamic actions have an unfavorable impact on CBM reservoir formation. The gas volume and hydrodynamic intensity were negatively correlated and low hydrodynamic flow conditions might result in highly productive and enriched areas of high rank CBM (Wang *et al*., 2009). Basin hydrodynamics causes low gas content in the shallow subsurface (<20 m^3/t) and high gas content at the deep part of basin (>20 m^3/t) (Su *et al*., 2005a; Holz *et al*., 2010). Well developed normal faults, interlayer slip structure and presence of mylonitic coal usually result in low gas content (Jiang *et al*., 2010) and the

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igneous intrusions have had a very positive effect on coalbed methane development. The coalbed methane content is one of an important index to evaluate a CBM area. However, the law of gas content is different in different research. The Bide-Santang basin as a new CBM enrichment area in western of Guizhou Province, the coalbed methane content is researched with limited data. In this study, we characterize the adsorption isotherm, coal rank, depth of burial, reservoir pressure and the characteristics of the pores variability on the coalbed methane content.

EXPERIMENTAL

Sample geologic setting: The Bide-Santang basin (Fig. 1) is a retro-syncline, a remained basin that located on the interface of Shuicheng country and Liuzhi in Guizhou Province. The Bide-Santang basin consists of Bide syncline, Jiajia anticline, Shuigonghe syncline, Bainijing syncline, Santang syncline, Agong syncline and Zhuzang syncline. Bide-Santang basin is the main part of Zhijin-Nayong coalfield (Yang *et al*., 2011).

There are many coal seams in the research area, of which more than 18 layers are minable. The shallow minable coal seams are 2, 5 and 6#, respectively. The lithotypes are mainly semi-bright coal, secondarily semi-dull coal in the main coal seams in the studied area (Yang *et al*., 2010).

Sampling and lab analysis: For this study, a series of coal samples were obtained from CBM exploration boreholes as well as underground coal mines in the Bide-Santang basin. 11 coal samples from different coal mines were collected for coal characteristics, vitrinite reflectance and mercury intrusion porosimetry (MIP) testing and isothermal methane sorption experiments were done on seven samples (3, 5, 6#, respectively coal samples in No.1 hole and 2, 5, 6-1, 6-2#, respectively coal samples in No.2 hole) from CBM exploration boreholes.

Coal petrology, proximate and ultimate analysis: The coal petrology, proximate analysis of coal and ultimate analysis of coal were done respectively base on the GB/T 6948-2008, GB/T 212-2008 and GB/T 476-2001 and the results were showed in Table 1 and 2.

It can be found from Table 1 and 2 that the maximum reflectance of vitrinite range from 1.76 to 3.52%, it indicates that the degree of metamorphism of coal is high. The content of fixed carbon vary from 67.19 to 85.74%, the minimum value appears in Bide syncline. The ash content and volatile content have an opposition with the content of fixed carbon, it is consistent with the fact that the Bide syncline develops meagre coal, while the other research areas develop anthracitic coal in Bide-Santang basin.

The MIP testing were done in the key laboratory of coalbed methane resources and dynamic accumulation process in China University of Mining and Technology

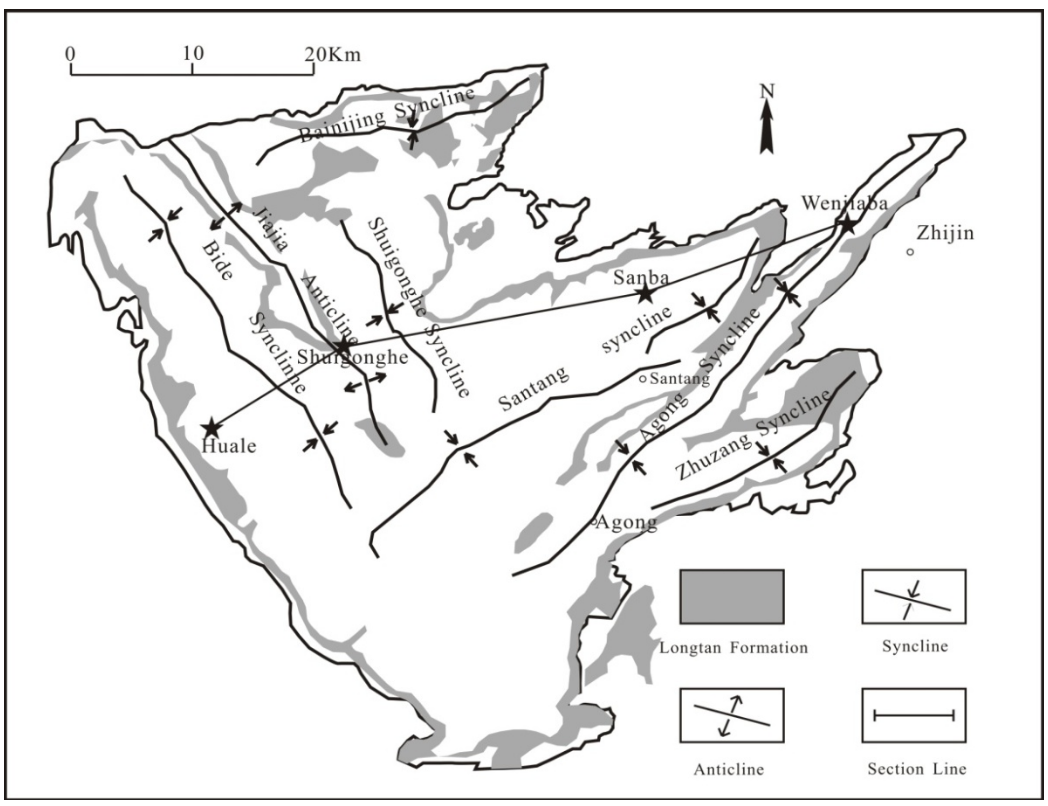

Fig. 1: Structure map of Bide-Santang basin

Table 1: Coal elements characteristics analyses of Bide-Santang basin

Samples	Mad/%	Ad/%	V (daf)/%	FC.d/%	St.d/%	C (daf)/%	H (daf)/%	O (daf)/%	N (daf)/%
FHS	2.23	9.16	5.610	85.74	1.90	91.74	2.88	2.3	0.99
XDM	1.50	10.8	7.110	82.82	2.29	90.66	3.42	2.23	1.12
HT	2.35	9.59	6.630	84.42	0.37	92.31	3.13	3.07	1.09
BD	1.00	19.4	16.66	67.19	1.17	88.47	3.91	4.94	1.23
YLW	1.17	6.90	8.730	84.97	0.79	91.21	3.64	2.86	1.45
FX	2.02	20.0	13.35	69.28	0.31	87.30	2.82	8.65	0.84
ZJZ	1.18	17.9	8.950	74.72	2.23	89.91	3.61	2.45	1.31
ZW	2.18	10.3	6.110	84.20	0.47	92.84	3.07	2.45	1.12
BL	1.59	7.88	7.380	85.33	1.32	91.46	3.53	2.37	1.20
JF	1.12	14.5	7.140	79.43	1.56	91.58	3.36	2.03	1.21
HBLH	1.19	12.7	9.730	78.81	2.43	89.75	3.58	2.63	1.25

Table 2: Coal macerals characteristics analyses of Bide-Santang basin

	Organic content %		Inorganic content %				
Samples	Vitrinite	Inertinite	Clay	Carbonate	Sulfide	Oxide	VR %
HS	78.10	3.20	4.10	0.60	10.50	3.50	3.52
XDM	77.10	8.50	5.00	0.00	9.40	0.00	2.81
HT	83.90	10.40	3.10	0.00	0.50	2.10	3.23
BD	52.70	29.20	0.50	0.00	5.70	11.90	1.76
YLW	69.00	19.70	5.40	0.00	0.50	5.40	2.47
FX	80.40	17.90	1.70	0.00	0.00	0.00	3.26
ZJZ	63.80	22.20	1.80	0.00	1.20	11.00	2.40
ZW	82.40	10.80	6.80	0.00	0.00	0.00	3.03
BL	75.20	18.20	3.00	0.00	1.20	2.40	2.58
JF	70.10	11.30	0.00	0.00	3.70	14.90	3.00
HBLH	59.40	32.40	0.00	0.00	2.50	5.70	2.15

(CUMT) with AUTO IV 9500.The maximum pressure of the instrument can reach to 228 MPa, the testing diameter of the pores range from 5nm to 360 μm. The coal samples were dealt with in the vacuum drying oven at 150 °C for one h before testing.

The isothermal methane sorption experiments were done in Coal Mine Exploration of Guizhou Province. The coal samples were equilibrated with moisture for at least 48 h prior to analysis, with the diameters range from 0.18 to 0.25 mm. 6 pressure points were collected up to about 8MPa for each sample at 30 °C. According to the equilibrium pressure and temperature of reference cylinder and sample cylinder, the adsorption capacity of different equilibrium pressure points can be got.

The gas sorption isotherms in coal were modeled using the Langmuir isotherm:

$$\frac{p}{V} = \frac{p}{V_L} + \frac{p_L}{V_L} = \frac{1}{V_L} p + \frac{p_L}{V_L} = Ap + B \qquad (1)$$

where,

p = The equilibrium gas or vapor pressure
V = The volume of gas absorbed
V_L = The Langmuir volume
p_L = The Langmuir pressure
$V_L = 1/A$
$p_L = BV_L = B/A$

According to formula (1), the parallel scatter plot can be drew with the p as x-axis and the p/V as y-axis. The points' regression equation can be got with the method of the minimum aquares. Then the Langmuir volume (V_L) and Langmuir pressure (p_L) can be got.

RESULTS AND DISCUSSION

Experiment results and analysis: The pressure and sorption of the coal samples were obtained from the isothermal methane sorption experiments in the equilibrated state and sorption results were adjusted to dry ash-free basis. Table 3 shows the result of the isothermal methane-adsorbing experiments. Figure 2 and 3 show the isothermal adsorption curves of different samples.

The gas saturation, critical desorption pressure and theory recovery can be obtained from the isothermal adsorption curves (Table 4). The gas saturation of the research area is generally lower than 100% ranging from 75.04 to 105.55%. It indicates that the reservoir is under saturated with the average saturation 84.51%. The critical desorption pressure ranges from 1.22 to 9.1 MPa and the theory recovery rate varies from 19.96 to 46.15%.

Geological control factors on sorption: Compared with the geological conditions and characteristics of the coal reservoir (Zhu *et al*., 2008; Gao *et al*., 2009), the amount of gas adsorbed in coal is primarily related to pressure, depth of burial and reservoir characteristics.

- **Influence of pressure:** The sorption of methane increases with the increase of pressure when the other factors are in the same state, while the increase is different in the different pressure areas. In the condition of low pressure, the sorption can be mapped out in linear progression from the pressure. The methane content has a linear relationship with the reservoir pressure in the

Table 3: The isothermal adsorption experiment results of coal samples in Huale exploration region

Drill hole	Sample	*RP* (Mpa)	*V* (m^3/t)	V_L (m^3/t)	P_L (Mpa)
No.1 hole	3#	—	11.78	17.69	1.08
	5#	4.41	11.64	19.36	1.09
	6#	4.68	12.33	18.61	0.62
No.2 hole	2#	5.12	19.23	20.71	0.70
	5#	—	15.14	21.38	1.20
	6_{-1}#	5.69	14.40	18.81	0.56
	6_{-2}#	5.69	14.07	20.36	1.10

RP: Reservoir Pressure; *V*: Actual Measurement Methane Content; V_L: Langmuir volume for CH_4 sorption P_L: Langmuir pressure for CH_4 sorption

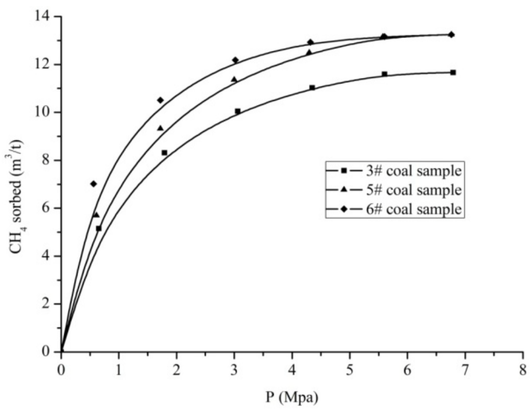

Fig. 2: The adsorption isothermal curve of coal samples of No.1 hole in Huale exploration region

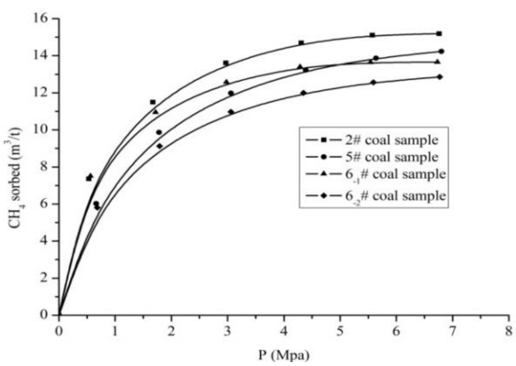

Fig. 3: The adsorption isothermal curve of coal samples of No.2 hole in Huale exploration region

Huale exploration area, i.e., gas content increases with the increase of the reservoir pressure (Fig. 4)

- **Influence of depth of reservoir:** The depth of coal reservoir increases with the increase of crustal stress, reducing the aeration of coal seames and surrounding rocks, the methane's liquidity is decreased, it's in favour of the save of the CBM. Within the certain depth, the methane content increases with the increase of the depth of the reservoir. The shallow minable coal seams in the Bide-Santang basic are limited to the zone of weathering, the rate of increase of gas content is rapidly. Therefore, as shown in Fig. 5, the CH_4 sorption capacities of the samples analysed show a direct positive correlativity with the depth of burial, i.e., the gas content increases with the increase of the depth of burial in the research area.

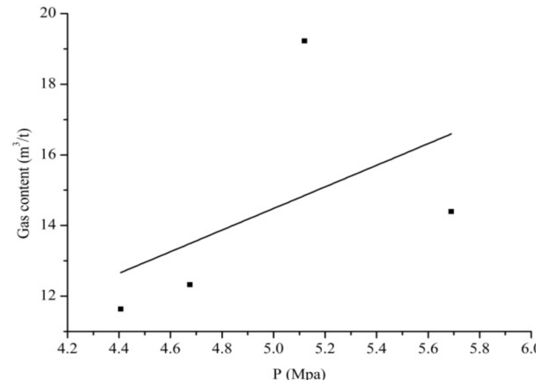

Fig. 4: Relational graph of reservoir pressure and gas content in Huale exploration region

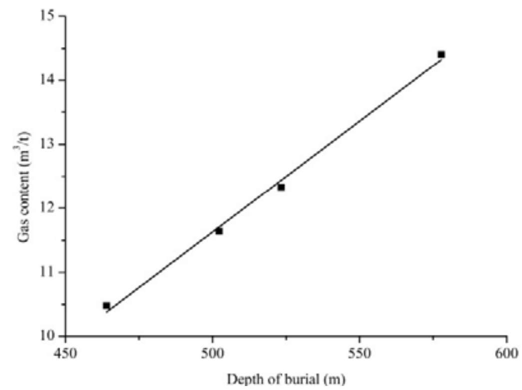

Fig. 5: Relational graph of depth of burial and gas content in Huale exploration region

- **Influence of coal rank:** Previous work has revealed that sorption capacity is closely related to coal rank and proposed a variety of relationships between gas sorption between gas sorption

Table 4: Measured saturation and critical desorption pressure of CBM in Huale exploration region

		Gas content (m^3/t)		Pressure (Mpa)		Gas saturation	Critical desorption	Theory recovery
Drill hole	Sample	*V*	V_L	*P*	P_L	(%)	*Pcd* (Mpa)	(%)
No.1 hole	5#	11.64	19.26	4.41	1.09	75.38	1.67	35.29
No.2 hole	6#	12.33	18.61	4.68	0.62	75.04	1.22	19.96
	2#	19.23	20.71	5.12	0.70	105.54	9.10	46.15
	6_{-1}#	14.40	18.81	5.69	0.56	84.08	1.80	27.43
	6_{-2}#	14.07	20.36	5.69	1.10	82.46	2.46	43.73

RP: Reservoir Pressure; *Pcd*: Depleting pressure, 0.7MPa

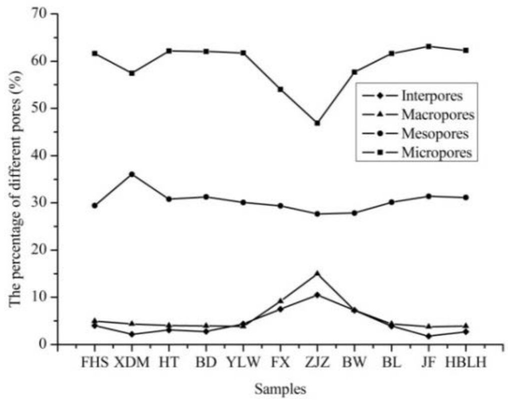

Fig. 6: The percentage of different pores sizes of different coal samples

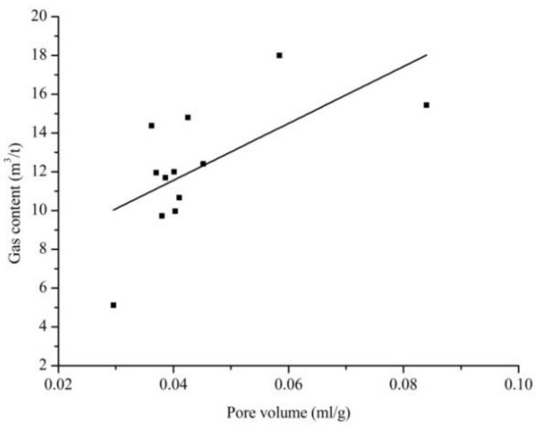

Fig. 7: Graph of pore volume and content of gas

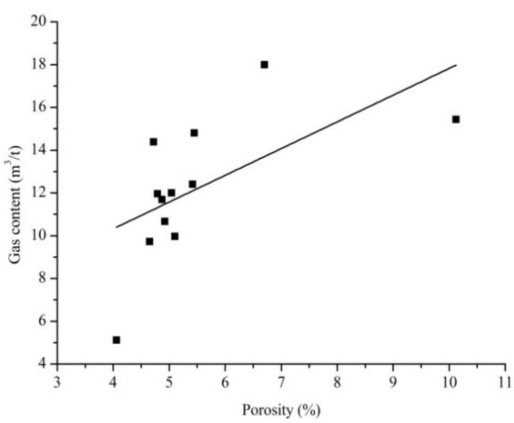

Fig. 8: Graph of porosity and content of gas

capacity and coal rank (Fang *et al*., 2003; Su *et al*., 2005b; Faiz *et al*., 2007). In addition, the degree of metamorphism of coal determines adsorption space influencing adsorption isotherm and methane content of the CBM. Some studies indicated that from the high volatile bituminous to anthracite, CH_4 sorption capacity and porosity decrease

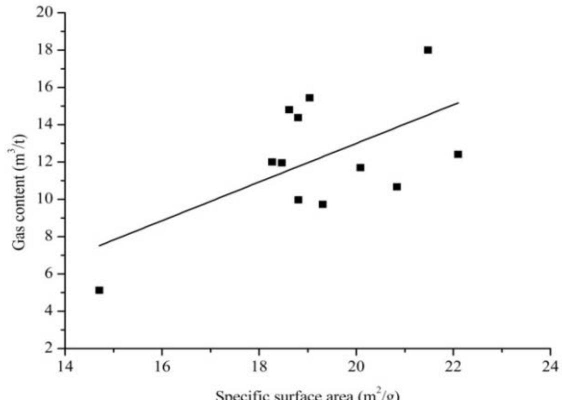

Fig. 9: Graph of specific surface area and content of gas

with rank to a minimum at the medium volatile bituminous stage, then followed by increases with increases of coal rank.

- **Influence of characteristics of pore and fractures:** Porosity and pore size distribution in coal have a major impact on its internal surface area and gas storage capacity. Bituminous coals are dominated by micro-pores, whereas lower rank coals are likely to contain higher volumes of larger pores. In general, the total open porosity and internal surface area of coal decreases with increases in rank from high volatile bituminous (VR~0.7%) to medium volatile bituminous (VR~1.4%) and with further increases in rank they increase (Moffat and Weale, 1955). Several studies have demonstrated that vitrinite contains higher volumes of micro-pores than inertinite at a given rank (Harris and Yust, 1979; Unsworth *et al*., 1989).

The structural fractures are well developed in the main coal seams in the Bide-Santang basin and the fractures usually cut the coal into pieces. Most of the structural fractures are filled with pyrites and calcites. Consequently, the reduced connectivity of the pores and fractures lead a negative impact on the permeability of the coal reservoir. Endogenic cracks are also well developed in the coal samples. Some of the cracks cut through the pores, reinforcing the connectivity of the pores and fractures and offering a passageway for CBM diffusion and Darcy.

In the study, micropores and mesopores occupy a large proportion of the coal samples, while the macropores and interpores are not well developed (Fig. 6). Micropores and mesopores are the main space for CBM sorption, especially the micropores. In Fig. 7 to 9, the pore volume, porosity and specific surface area have a positive correlativity with the methane content. For example, the pore volume, porosity and specific surface area increases with the increases of the methane content.

CONCLUSION

The coal rank is high in the Bide-Santang basin. The content of vitrinite ranges from 22.3 to 83.9% and the Reflectance of Vitrinite (VR) ranges from 1.05 to 3.52%. The Langmuir volume of the main coal seams ranges from 17.69~21.38 m^3/t. The Langmuir pressure varies from 0.56~1.2 MPa and the reservoir pressure ranges from 4.4~5.7 MPa. The gas saturation of the research area is lower than 100% commonly, in the range of 75.04 to 105.55% and it indicates that the reservoir is undersaturated with the average of 84.51%; the critical desorption pressure ranges from 1.22 to 9.1 MPa and the theory recovery varies from 19.96 to 46.15%.

The main geological controls on the characteristic of adsorption isotherms in the Bide-Santang basic are primarily related to reservoir pressure, depth of burial, coalification degree and property characteristics of pores and fractures. The methane content has a linear relationship with the reservoir pressure in the research exploration area. The CH_4 sorption capacities of the samples analyzed show a significantly opositive correlativity with the depth of burial in the shallow coal seams. The higher of the coal rank and the more development of the micropores and mesopores are the better for the sorption and save of the CBM is. Therefore, coal rank and the characteristics of pores and fractures are the main controlling factors for the sorption of the methane.

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