

Coalbed Methane Geology of the Jurassic Middle-Lower Series, Southern Junggar Basin, China: Low-Rank Coal Forming Environment, Enrichment Characteristics, Accumulation Model, and Resource Evaluation*

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Abstract

The oil and gas exploration and development zone in the southern Junggar Basin is a typical and favorable low-rank Coal Bed Methane (CBM) gathering area; however, so far no breakthrough of CBM exploration has been achieved. This article firstly, based on the analyses of the coal measure strata sedimentary sequence, sedimentary environment and its evolutionary process in this area, illustrates the accumulating characteristics of the low-rank coal. Then, relying on a large number of laboratory tests and field tests, comprehensive analyses have been carried out, presenting the basic geological characteristics of this zone, such as the coal seam distribution, petrology, reservoir property, coal rock thermal evolution, coal rock quality of six sections, as well as the CBM generating and bearing characteristics, the sealing properties of the CBM reservoir's top and bottom rocks, the hydrogeological characteristics preserved by the CBM reservoir. Combining with the tectonic burial history, geothermal history, hydrocarbon evolution and CBM gas saturation changes, the low-rank coal CBM accumulation model of this zone has been revealed. Finally, the CBM resources calculation and comprehensive evaluation of the six sections divided in this zone points out the relatively favorable sections for further exploration in this area. The results here will provide theoretical and practical guidance for the whole basin, and even the nation's low-rank CBM investigation and exploration.

Introduction

Junggar Basin, located in Xinjiang Uyghur autonomous region, is a large coal accumulating basin characterized by low-rank coal CBM resources. The estimations by many scholars (Jianping Ye et al., 1999; Xinmin Zhang, 2002; Qi Yang et al., 2005) show that the low-rank coal CBM resources buried above 2000 m in Junggar Basin amount to $(2.1795 \sim 3.8268) \times 10^{12} \text{ m}^3$, which ranks third in China, next to the Ordos Basin and Qinshui Basin. The coal-bearing strata primarily concentrate in the middle-lower Jurassic Xishanyao Formation (J_{2x}) and the Badaowan Formation (J_1b), its generation, storage, distribution and accumulation characteristics are different from the middle- and high-rank coal accumulating basins in other areas of China. Nowadays, low-rank CBM has become a new hot spot after the CBM exploration and

development breakthroughs in the middle- and high-rank coal beds. The oil and gas exploration and development zone in the southern Junggar Basin (hereinafter referred to as the south Junggar zone) is a favorable coal accumulating part of the basin, which is also one of the main coal mining areas and has been exposed to a relatively high degree of CBM exploration. To study the geological features and accumulation model of the CBM resources in this area will theoretically and practically play a leading role for the whole basin, and even the nation's low-rank coal CBM research and development.

Early in the 1970's, geological prospecting of coalfield had been started in the south Junggar zone; after the 1990's, the breakthroughs in the low-rank CBM exploration in United States (Scott L. Montgomery, 1999; Walter B. Ayers, 2002; Mingxin Tao et al., 2007; Lourdes B. Colmenares et al., 2007; Thomas Gentzis, 2013) enlightens the study on CBM within this region. Stepping into 21st century, CBM resources evaluation and exploration implementation are gradually increasing and spreading. One company/institute after another, like Xinjiang Oilfield Company, Southwest Petroleum University, PetroChina CBM Co., Ltd, PetroChina RIPED, Xinjiang Geology and Mineral Resources Bureau, Xinjiang Coalfield Geology Bureau, Xi'An Research Institute of Coal Science, China University of Geosciences, Canada Terra West Energy Corp., Australia Dart Energy, etc. have carried out CBM geological research and resource evaluation in the south rim of the basin, acquiring a series of research findings and systematic data by drilling 21 CBM prospecting wells. The commercial CBM flow has been recovered from two of the wells, indicating a bright future for CBM exploration in this area. But to date, in the Junggar Basin large-scale breakthroughs in CBM exploration have not been made. Due to the lack of systematic investigations, it is difficult further deepen the CBM exploration in this region. Therefore, it is urgently need to fully digest the existing data and integrate previous achievements to systematically study the geological characteristics and evaluate the CBM resources of the low-rank coal seams in this zone, which can promote the understanding of CBM accumulation and the geological setting in the Junggar Basin, facilitating future exploration and exploitation of low-rank coal CBM in the basin or even in the country.

Geological Background

The study area, nearly an east-west zonal distribution, is located in the north Tianshan Mountain front belt and its adjacent area. Affected by the tectonic movements of Hercynian, Indosinian, Yanshan and Himalaya, a series of faults, folds and intermountain basins developed in the directions of northwest by west, nearly east-west and northeast by east (Yan Song, 1995; Qiu Nansheng et al., 2005; Qi Yang et al. 2005). And with the tectonic movement and sedimentary evolution, rich resources of low-rank coal occurred in the zone, forming the material sources for the large-scale CBM accumulation (Tao Zhang et al., 1995; Hong Zhang et al., 1995; Jianping Ye et al., 1999; Qi Yang, et al., 2005).

The field drilling in the south Junggar zone suggests that the well-developed strata above the basin basement includes the Palaeozoic Carboniferous system and Permian, Mesozoic Triassic, Jurassic and Cretaceous, as well as the Cenozoic Tertiary and Quaternary strata. The coal measure strata predominantly concentrated in the lower and middle Jurassic formation.

Geological history research (Yan Song, 1995; Qiu Nansheng et al., 2005; Qi Yang et al., 2005) shows that the tectonic and sedimentary evolution in this area during the coal-forming period can be divided into four stages: basinal filling and leveling up before coal-forming (C_2 -T), coal-forming in the basin (J_1 - J_2), the cap formation during the late coal-forming period (J_3 - N), and the basinal reconstruction (Q). The coal accumulating phase went through the geological evolution of the early stage settling, the middle stage coal forming and the late stage uplifting.

Under the compressive stress during these processes, intensifying phases and relaxing phases appear alternatively, as is reflected specifically by the advance and retreat of the water body and the alternative variations of the sedimentary environment. The early Jurassic Badaowan Formation and Sangonghe Formation belong to the water-advancing basin overflow deposition, while the Middle Jurassic Xishanyao Formation is a large-scale regressive deposit. During early transgression and late regression, well-developed and widely distributed shallow rivers, lakes, swamps and flood plains constituted the main sedimentary environments, with sufficient material sources and a humid climate favorable for coal-formation. After the late stage tectonic, sedimentary and hydrocarbon evolutions, the low-rank coal measure strata finally formed in the Lower Jurassic Badaowan Formation (J_1b) and the Middle Jurassic Xishanyao Formation (J_2x) ([Figure 1](#)), breeding rich CBM resources.

Coal Measures Sequences and Dispositional Environment

Sedimentary Sequences

The coal measures strata in Junggar Basin were distributed in the Lower and Middle Jurassic, including the Lower Jurassic Badaowan Formation, Sangonghe Formation, and the Middle Jurassic Xishanyao Formation, from bottom to top. These three formations constitute the rock series of the coal accumulating period (Tao Zhang, 1995; Hong Zhang et al., 1998; Qi Yang et al., 2005). Among them, the Badaowan and the Xishanyao formations are dominating coal seams, while the Sangonghe Formation almost contains no coal ([Figure 1](#)).

Badaowan Formation

The bottom of this lower coal formation is filled by fan delta coarse clastics with a thickness of 10-100 m. The rock granularity at the mountain front is large, and decreases towards the basin; multilayer coal streaks or thin coal seams can be seen. The middle-lower part consists of deltaic sediments with a thickness of 100-500 m. The lithology of this dominant coal seam in this formation is mainly sage green sandstone and siltstone. The middle-upper part is filled with lake sediments with thin coal seams and thin siderite layers. Its lithology consists of gray, sage green, grayish yellow mudstone and siltstone with the relatively constant thickness of 300 m or less. Overall, the Badaowan Formation is characterized by the filling sequence of fan delta, delta, littoral and shallow lake and deep lake from the lower to the upper part, reflecting the gradual deepening evolution process of the lake. The strata thickness changes greatly in the plane, ranging from 200 m to nearly 1000 m.

Sangonghe Formation

As a lacustrine formation without coal, the Sangonghe and the underlying Badaowan formation are successive deposits with equivalent depositional area. The lithology is mainly gray, sage green, grayish-yellow sandstone and siltstone, mudstone, acmite interlayers and partly carbonaceous shale interlayers. The lower lithology varies a greatly in that the zone edge is mainly filled with alluvial and diluvial fan sand and conglomerate. Going towards the basin center the lithology gradually changes to siltstone and mudstone of littoral and shallow lake environments. The lithology variation of the upper part that is covered by a 30-50 m grayish black mudstone is small, with siltstone and mudstone as the primary components. It has a thick layer of stable black shale with the thickness of 30 m ~50 m on the top. This formation

belongs to the deposits in the evolution of coal accumulating basin filling process when the lake expanded most, undergoing the shore-shallow lacustrine sediment.

Xishanyao Formation

The base of this upper coal formation contains gray gritstone and conglomerate, in discordant contact with the underlying Sangonghe Formation. The middle part is composed of the delta filling sequence with the overall granularity becoming coarser upwards but then finer. The coal seams mostly developed in the finer filling sequence. The top part is filled with fluvial deposits with the granularity becoming finer upward, where the coal seam development is comparatively poor. Overall, the Xishanyao Formation is characterized by the fan delta-delta filling sequence from bottom to top, indicating water deepening then shallowing. The layer thickness changes greatly, ranging from 100 m to 900 m. Lithology is mainly gray, sage green fine sandstone and siltstone, black thin sandy shale, clay rock, alternating carbonaceous shale and interbedded coal seams and siderite lens, being rich in ginkgo biloba fossil fragments; generally it contains more than 50% coarse clastic rock which intensively distributes in the lower part and around 40% fine clastic rock which developed on the top.

Sedimentary Environment

Through collecting, sorting and analyzing coal exploration data within the zone, three kinds of depositional systems have been identified as the coal forming environments: fan delta, delta, and lacustrine deposits ([Table 1](#) and [Figure 1](#)). The identified flood plain swamp among fans, delta plain swamps and lakeshore swamp constitute the major coal depositional environments, where the coal characteristics and gas storage capacity are different, embodying the typical sedimentary coal controlling and gas controlling model ([Table 2](#)).

The sequence stratigraphy and sedimentary facies analyses, based on the cross sections of 21 drilled wells and five outcrops, further defined the four features of the coal measures strata sedimentary environment and its evolution in the Middle and Lower Jurassic system as follows ([Figure 2](#)):

- (1) The distribution pattern of sedimentary facies belt is controlled by mountain front structure; the mountain provides the main material source. The fan sedimentary system displays a planar distribution pattern with continuous superposed lobate structure along its lateral trend, and increases with water depth, gradually transitioning to a shallow to semi-deep lacustrine setting. Scattered shallow lake sand bars developed.
- (2) The coarse- to medium-clastic sedimentary facies belts in the (fan) delta sedimentary system at the basin edge gradually change to fine-clastic to argillaceous sedimentary facies belts in the semi-deep lacustrine system in the center of the basin. The changes and relationships between planar configuration of sedimentary facies, subfacies and microfacies all exhibit certain regular patterns in the direction from mountains to the basin.

- (3) The distribution pattern of sequence sedimentary facies in each sedimentary period have good inheritance, in that the major provenance is unchanged, only the lake basin size, scope and water depth in different periods vary. However, the water bodies, mostly shallow lakes, are not deep, which is beneficial for plant growth and swamps, providing the environment for forming coal.
- (4) The control that regional terrain has on the river morphology is different due to the varying slope gradients, such as the coarse alluvial fans and fan deltas formed at the steep slope zone, the meandering and far-reaching river delta developed in the gentle slope zone.

Coal Accumulation Pattern

Studies have shown that the main controlling factors of sedimentary sequences of the terrestrial coal basin are tectonic movement, sediment supply and climate conditions, all of which are related to datum plane cycle and the accommodation space (James R. Garrison et al., 1996; Brian P. Coffey et al., 2002; Hongliu Zeng et al., 2004; Hao Wang et al., 2011). The sedimentary sequence within zones can be divided into lowstand system tract, the lake invasion system domain and highstand system tract according to the datum plane cycle and accommodation space, corresponding to three types of coal accumulating patterns: low coal accumulation period, lake invasion period, and high coal accumulation period ([Figure 3](#)).

Low Coal Accumulation Period

During the early period of the lowstand system tract, the lake level significantly lowered, as did the accommodation space. The accommodation spatial growth rate is obviously slower than the rate of organic matter accumulation, the groundwater table declines, plus the higher terrain slope, large-scale erosion and alluvial river redistributed the sediment, preventing peat from accumulating, probably only leaving some isolated, relatively thin and oxidized peat in some low-lying areas. During the late lowstand system tract development, the lake level began to rise but was still lower than the terrain slope break zone, near which (i.e. first lake flooding surface) if the accommodation spatial growth rate is generally the same as the organic matter accumulation rate, coastal marsh peat can be formed. Rainfall type swamps, such as delta plain swamp and lakeshore swamp, widely developed near the late lowstand system tract of the lake flood surface within these zones, also fan flood plain swamps developed in the local piedmont; therefore stable coal seams are widely dispersed.

Lake Invasion Period

The lake invasion system tract formed at the time the lake level rose rapidly. The terrigenous clastic supply shrinks, and the growth rate of the accommodation space is faster than that of the organic matter accumulation. The accommodation spatial growth rate that is faster than the peat forming rate resulted in the annihilation of the settling peat by detrital material, lake or ocean water, making it difficult to form coal seams or continuous peat distribution. So the coal seams did not develop in the lake invasion systems tracts.

High Coal Accumulation Period

The highstand system tract formed during the period the lake level was relatively stable and began to decline, when the accommodation space was still large, and the rich sources continuously deposited as the delta migrated forward. Because of the rapid subsidence of the basement, the delta plain expanded to the center of the lake basin, forming wide-scale and thick delta plain swamp type coal seams. During the Jurassic coal seams growth period, the basement subsidence rate was about 80 mm/ka, which is roughly equal to the peat accumulation rate; therefore, thick coal seams formed in the highstand system tract with quite stable distribution.

The Badaowan and Xishanyao formations in the south Junggar zone were deposited in the highstand and lowstand coal accumulating periods with abundant coal resources gathered. The Sangonghe Formation mainly formed in the lake invasion coal accumulating period, with almost no coal resources deposition.

CBM Enrichment Characteristics

Coal Seam Geological Characteristics

Distribution Characteristics of Coal Seams

The total thickness of coal seams in the Badaowan Formation within this area is between 10-30 m, and in some parts between 30-60 m, with only a few sections more than 60 m ([Figure 4](#)). The total thickness of coal seams of Xishanyao Formation is between 10-60 m, and in a few areas more than 60 m; generally its coal seams are thicker than those of the Badaowan Formation ([Figure 5](#)). Based on the differences of coalfield geology, geographical features, etc., from west to the east in the study area, the coal field can be divided into six sections, as Sections 1-6. [Table 3](#) lists the distribution characteristics of the coal seams in each section: Sections 4-6 of Badaowan Formation and Sections 1, 3, and 4 of Xishanyao Formation exhibit large thickness, stable distribution and high coal bearing coefficient.

Coal Seam Petrology Features

The macroscopic coal rock type in the zone mainly belongs to bright coal, semibright coal and dull coal, accompanied by some fusains. Microscopically, vitrinite is dominant with some inertinite and semivitrinite, while exinite only exists in some areas ([Table 4](#)). Within the vitrinite, degradinite is most abundant with the relative content higher than 80%; also there is a small amount of homocollinite and lean structure vitrinite. In inertinite, fusinite and semifusinite dominate, macrinite is the next. Comparing Badaowan Formation with the Xishanyao Formation, the former has higher vitrinite content, liptinite content and mineral content, while the latter has more inertinite.

Coal Seam Reservoir Properties

The pore connectivity and permeability of coal seams are overall good, with a certain degree of heterogeneity; the adsorption capacity, from strong to weak, is Section 5, Section 4, Section 3, Section 2 and Section 1, displaying great difference among different sections. The geothermal gradient indicates a typical cold basin; coal seam pressure falls in the low to normal pressure range ([Table 5](#)).

Coal Rock Thermal Evolution Characteristics

Vitrinite reflectance, unaffected by composition content of coal rock, can objectively reflect the thermal metamorphic degree of coal rock (Jianping Ye, 1999; Xinmin Zhang, 2002; Maciej J. Kotarbaa et al., 2004). The coal rock vitrinite reflectance of Badaowan Formation within the zone is between 0.45%-0.76%, with an average of 0.616%, coal ranks are primarily lignite and long flame coal. Coal seam vitrinite reflectance of the Xishanyao Formation is 0.66%-0.76%, with an average of 0.697%, coal ranks are long flame coal, non-caking coal and gas coal ([Table 4](#)). The average temperature gradient of the zone, 2.4°C/100 m, is relatively low ([Table 5](#)), resulting in the relatively weak hyperthermal metamorphism and low evolution degree of the coal. The main coal seams are buried between 200-500 m; as the buried depth increases, the increment of the coal vitrinite reflectance is obvious ([Figure 6](#)).

Coal Rock Quality Characteristics

Coal rock quality is one of the geological evaluation criteria, parameters such as the moisture content (Mad, %), ash content (Ad, %), volatile content (Vad, %) and calorific value (MJ/kg) are often used to evaluate the coal quality. By contrasting [Figure 7](#) with [Figure 8](#), it can be seen that the coal rock of Xishanyao Formation and Badaowan Formation in each section show similar quality indexes of low water content, medium ash content, high volatile content, and medium calorific value.

Coal Rock Gas Generating and Bearing Characteristics

Gas generating ability mainly depends on the material composition and degree of metamorphism of the coal. The coal rock thermal simulation experiments showed that (Xinmin Zhang, 2002; Yi Duan et al., 2002; Maciej J. Kotarbaa, et al., 2004), among the three components of coal, vitrinite presents the maximum hydrocarbon generation ability, exinite is next, and inertinite gives the minimum; the total volume of gas generation during the lignite stage is 38-68 m³/t; while during the long flame coal stage, the total volume of gas generation is 41-93 m³/t. Therefore, the content of vitrinite and exinite determines the gas generating ability of coal, the low-rank lignite coal and long flame coal also possess good gas generating ability. The above study confirmed that thick coal seams mainly consisting of lignite and long flame coal are widely distributed in the Badaowan and Xishanyao formations within this area. The relative richness of vitrinite in the coal rock favors the generation of CBM. CBM composition and the methane carbon isotopic values indicate that the hybrid genesis is the primary genetic type of CBM; besides, there are some biogenic and thermogenic contributions ([Figure 9](#)).

Gas content, as the key parameter that determines whether the CBM resources are abundant enough to exploit, controls the CBM recovery of the seams and affects the ultimate gas well production. Method of gas collection and method of desorption adopted for the gas content

measurement for 400 m - 1100 m coal seams in the Badaowan and Xishanyao formations showed that gas content is high in the eastern and central area, and gradually decreases to the west ([Table 6](#)). Gas content of Sections 4 and 5 are the highest, followed by Section 3, and then Section 2, with the gas content of other sections being relatively low. Besides methane, nitrogen and carbon dioxide account for a large proportion. Gas saturation reaches up to 42.2% ~ 89.5%, with 60.0% on average.

CBM Reservoir Sealing Characteristics

Roof and Floor Sealing Properties of the Coal Seams

Research on the coal forming environment shows that the coal measures strata, located in the fine clastic sediment concentrating zone, mainly developed during the low stand system tract of the early water advancing stage and the high stand system tract of the late water retreating stage. The field coal rock coring observations ([Figure 1](#)) also demonstrate that thickness of coal-bearing strata in Badaowan Formation is generally more than 800 m, with the fine clastic rock content of 46.1%; the thickness of coal-bearing strata in the Xishanyao Formation exceeds 900 m, containing 57.3% fine clastic rock. The roof and floor are made up of fine clastic sedimentary bodies, whose lithology is mainly mudstone and carbonaceous mudstone, with some argillaceous siltstone and silty mudstone. The coal seam roof and floor are well-sealed with these fine clastic rocks.

Sealing Properties of the Coal Seams

There are 8 coal seams in the Xishanyao Formation that are thicker than 8 m, 5 of which are greater than 20 m; 4 layers in Badaowan Formation are thicker than 10 m. The gas generated in these super-thick coal seams is stored in the coal pores and adsorbed on the surface. Usually migration from these naturally favorable CBM storage sites to other places hardly happens.

Hydrogeological Features of CBM Reservoirs

The hydrology of this area is relatively simple. Located in an area belonging to the typical arid temperate continental climate, surface drainage is not well developed because of the low annual rainfall; groundwater recharge primarily comes from glacier melt water. The coalfield is mainly situated in the north Tianshan Piedmont, where groundwater and surface drainage both run from the south down to the north, with backflow occurring where there are tectonic blocks. During the process of underground water migrating through pores and fissures to the low-lying areas, vertical evaporation and plant transpiration are the main ways of drainage. Besides the discharge from springs, the mine drainage constructed on the surface is an important way of bedrock fissure water discharge. The groundwater level of this zone is controlled by the local base level of erosion, which is mainly the surface drainage. The existence of groundwater effectively inhibits CBM dissipation. The coal seams containing well-developed fissures are extremely poor watery and confined aquifers. The coal beds directly exposed on the surface accept water supply from atmospheric precipitation and seasonal rivers, which later become runoff water at a certain depth of the coal seams. The variations of the runoff water level affecting the pressure of coal reservoirs brings about the CBM dissipation mode of desorption, diffusion, migration, water-dissolution and runoff, constituting the CBM weathering zone, beneath which good CBM accumulation formation can be preserved.

The CBM Accumulation Model

Affected by the burial history, geothermal history, hydrocarbon generation and evolution in Junggar Basin, the south Junggar zone experienced the fill and leveling up processes from Permian to Triassic, the Early to Middle Jurassic coal-forming stage, and continuous deposition from Late Jurassic to Late Cretaceous, the thickness of the strata overlying the coal reservoir continuously increased until the end of the Cretaceous when the coal seam burial depth reached its maximum, as did the reservoir temperature and pressure. Along with the increase of reservoir temperature and pressure, a large amount of gas was generated and adsorbed inside the coal matrix, leading to matrix expansion and consequently increases of the porosity and permeability. This process, unfavorable for the CBM preservation, accelerated gas desorption, diffusion and migration. As a result of the large amount of gas generated in the Late Cretaceous, however, gas content slightly increased as the buried depth increased ([Figure 10a](#)).

Basin reconstruction caused by the Himalayan movement and cap rock formation in the late coal accumulation period from the Late Cretaceous to the Neocene (K₂-N) were mainly uplift and denudation, which reduced the thickness of the overlying strata, lowered the reservoir temperature and pressure, and brought down the coal seam gas generation. At the same time, the free gas in the coal seam migrated. When the reservoir pressure dropped below the CBM critical desorption pressure, methane adsorbed on the coal matrix began to desorb, diffuse and migrate; however, the decrease of the permeability caused by reservoir pressure drop slowed down this process (R. Marc Bustin, 2000). In addition, the good sealing conditions of the roof and floor helped the coal seams prevent dissipation of CBM. As a result, the gas content of coal seam decreased, yet conserved some quantity ([Figure 10a](#)).

The coal is considered low-rank, and its buried depth reached a maximum in the Late Cretaceous, when the main body of the coal seams stepped into the low mature stage, generating a large amount of hybrid genetic gas, and some primary biogenic gas and thermogenic gas. As the uplift and denudation in Late Neocene occurred, many outcrops on the piedmont were intruded by surface water, which brought the nutrients which nourished numerous bacteria, producing much secondary biogenic gas. A large number of nappe faults generated by the tectonic compression became the channels allowing the rising up of the lower CBM, as is accumulated and preserved in the upper coal seams. Therefore, both of the hydrodynamic seal type of biogenic CBM reservoir and a fault block type of hybrid genetic CBM reservoir occurred in the south Junggar zone ([Figure 10](#)).

CBM Resources Evaluation

Based on the actual characteristics of the south Junggar zone, four basic principles have been set for the resources calculation.

- (1) Division principle for the evaluation unit. Vertically, a single group of coal seams with similar coal rock types, coal quality and coal structures are combined as one calculation unit; horizontally, the coal seam extension of each coal mining area in this zone is taken as the secondary calculation unit.
- (2) Control principle of the coal seam buried depth. Considering the economic development of CBM, only the CBM resources between the weathering zone and 2000 m are evaluated; resources below 2000 m are temporarily ruled out.

- (3) Control principle of the coal measures strata and coal layer thickness. In view of the workability and efficiency of CBM exploration and exploitation, only the methane resources of Badaowan Formation and Xishanyao Formation with layer thickness greater than 0.6 m are evaluated.
- (4) Classification of CBM resources. In consideration of the CBM exploration situation and available data sets from the zone, the CBM resources calculated here is classified as controlled reserves.

In view of the relatively higher degree of coal exploration in each mining area within the zone and the abundant data sets, the calculation method of CBM resources based on coal resources has been adopted here (Boyer C. M. et al., 1998; Xinmin Zhang, 2002; Qingbo Zhao et al., 2009).

The calculation formula is:

$$G = AHDC_{ad}/\cos(\theta)$$

G - CBM resources (m^3).

A - Flat area of calculation range (m^2). With the 1:100,000 coal floor contour map as the base map, geological section method is used to determine the area of each section. Coal seam floor contour map is obtained from coal field, oil and gas exploration drilling and geophysical data.

H - Coal seam thickness (m). The thickness of coal seam is determined by the drilling and geophysical data obtained from the coal, oil and gas exploration. For deep coal seams without drilling and geophysical surveys, predictions of coal reservoir thickness from the graph are used.

D - Coal air drying base density (t/m^3). The measured values acquired from coal field exploration are adopted.

C_{ad} - Coal air drying base gas content (m^3/t). Relatively accurate values of coal seam pressure, Langmuir volume and pressure, and gas saturation have been obtained from CBM stratigraphic or test wells. The coal seam gas content is also acquired from the field measurements.

θ - Coal seam dip angle (degree). Coal geological exploration report is adopted to calibrate the coal seam dip angle of each section.

Moreover, the depth of the weathering zone in each section has been determined according to the vertical distribution characteristics of CBM content.

Substituting the calculation range and various parameters into this calculation method, CBM resource of each section has been respectively calculated ([Table 7](#)). Results show that the CBM resources abundance of these sections is between $(0.42-11.65) \times 10^8 m^3/km^2$, with an average

of $1.25 \times 10^8 \text{ m}^3/\text{km}^2$. The resource abundance of Section 5 is the highest, followed by Section 4. These two sections have an even larger resource abundance than the CBM fields in central and eastern China. Higher resource abundance, as a favorable condition for CBM development, ensures greater rate of return on low investment. It also heralds a bright development prospect of the CBM exploration within this zone.

Many factors affect the quality of CBM resources (Jianping Ye et al., 1999; Xinmin Zhang, 1999; Qi Yang et al., 2005; Qingbo Zhao et al., 2009), this research, embarking upon the actual situation of this zone, selects the geological conditions (including structural complexity and coal seam occurrence), resources (including coal seam thickness and the gas content of coal bed) and the reservoir conditions (including adsorption, permeability and gas saturation), three categories and eight factors in total, as the parameter set for the comprehensive evaluation of CBM resource quality of the zone. Three quantitative score ranges, including 10-7, 7-3 and 3-0, representing large, medium and small contributions respectively, are assigned to factors on the basis of comparing their relative importance to the resources quality. Through the statistical analysis on the variation range of each factor, three levels of high, medium, low; or big, medium and small are used to qualitatively describe the parameters ([Table 8](#)).

Based on the above analyses, CBM comprehensive evaluation parameters and their weight coefficients in each section of the southern edge have been obtained, as shown in [Table 9](#) and [Table 10](#). According to the method above and standards of calculation, comprehensive evaluation scores of the six sections in the south Junggar zone have been achieved ([Table 11](#)). All six sections in the south Junggar zone, in terms of the scores listed in [Table 12](#), are classified as favorable (>7.0), relatively favorable ($3.5-7.0$) and unfavorable prospect areas (<3.5). The favorable and relatively favorable areas for further exploration in the southern rim are Section 4 and Section 5, respectively.

Conclusions

This article is based on the analyses of the coal measures strata sedimentary sequence, sedimentary environment and its evolutionary process in the southern Junggar Basin and illustrates the coal accumulation pattern of the low-rank coal. Through a large number of laboratory experiments and field tests, comprehensive analyses conducted display the coal seam distribution, petrology, reservoir properties, coal rock thermal evolution, coal rock quality of six sections, as well as the CBM generating and bearing characteristics, the sealing properties of the top and bottom rocks of the CBM reservoir, and the hydrogeological characteristics preserved by the CBM reservoir. Combining the tectonic and burial history, geothermal history, hydrocarbon forming history and CBM gas saturation changes, the low-rank coal CBM accumulation model in this zone has been revealed. Finally, the calculation and comprehensive evaluation on the CBM resources of the 6 sections in the zone point out the relatively favorable sections for further exploration in this area.

The research herein shows that, in the southern Junggar Basin the flood plain swamps among fans, delta plain swamps and lakeshore swamp facies that were widely deposited during the Early and Middle Jurassic contain rich low-rank coal resources that gathered in the Badaowan and Xishanyao formations. These coal seams, with characteristics of long flame coal, non-caking coal and gas coal that formed during the high stand and low stand coal accumulation periods, experienced the structural and sedimentary evolution as well as the hydrocarbon generation, producing a large amount of hybrid genetic gas. Depending on the hydrodynamic closure and fault block seal, together with the roof and floor

of coal seams with good sealability, a large amount of CBM was captured and preserved in the super-thick coal seams, creating numerous unique low-rank coal CBM-enriched reservoirs.

Calculation shows that the coalbed methane resources of this area above 2000 m depths amount to $3054.7 \times 10^8 \text{ m}^3$, with the resource abundance between $(0.42-11.65) \times 10^8 \text{ m}^3/\text{km}^2$. Particularly, the resource abundance of Section 4 and Section 5 is even higher than that of the CBM fields in central and eastern China, demonstrating very favorable exploration prospect.

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Stratigraphic Unit			Lithologic Section 1:10000	Sedimentary System			Basic Characteristics			
System	Series	Formation		Microfacies	Subfacies	Facies				
Jurassic(J)	Middle(J ₂)	XiShanyao(J ₂ ^x)		Channel or Interchannel	Delta Plain	Delta	Xishanyao formation, the main coal measure in Jurassic, consists of 3-8 minable coal layers, with seam thickness of 10-60m. It develops wide and exposes in some areas. Its lithology, formed in lacustrine and delta environments, includes gray or dark gray mudstone, silty mudstone, siltstone, fine sandstone and coal, with more gritstone and conglomerate at the bottom. The contact between Xishanyao formation and the underlying Sangonghe formation is discordant.			
				Swamp	Delta Plain or Front					
				Distributary Channel						
				Swamp						
				Channel	Fan Delta Plain	Fan Delta				
			Lower(J ₁)	SanGonghe(J ₁ ^s)		Mud Flat		Shore or Shallow Lacustrine	Lacustrine	Sangonghe formation, without coal seams, distributes widely in the study area. Its lithology, mainly including gray and sage green siltstone, fine sandstone and mudstone, belongs to shallow lacustrine sediment. The sedimentary texture is typical horizontal sand-mud rhythmically alternating bedding. The contact between Sangonghe formation and the underlying Badaowan formation is unconformable.
						Sand Bar				
						Mud Flat				
		Sand Bar or Sand Beach								
	BaDaowan(J ₁ ^b)			Semideep Mud, Mud Flat, Sand Beach, or Swamp	Semideep or Shallow Lacustrine	Delta	Badaowan formation, the other main coal measure in Jurassic, has 3-14 minable coal seams, with thickness of 10-60m. It develops wide and exposes in some areas. Its lithology is mainly comprised of gray or sage green fine sandstone, siltstone, mudstone, carbonaceous shale and thin coal seams, with thick conglomerate layer at the bottom. Most of the contact between Badaowan formation and the underlying Triassic is discordant.			
				Distributary Channel	Delta Plain or Front					
				Swamp						
				Distributary Channel	Interfan Flood Plain					
				Swamp		Fan Delta				
		Channel	Fan Delta Plain or Front							

Figure 1. The stratigraphic sequence, sedimentary system and basic characteristic of coal measures.

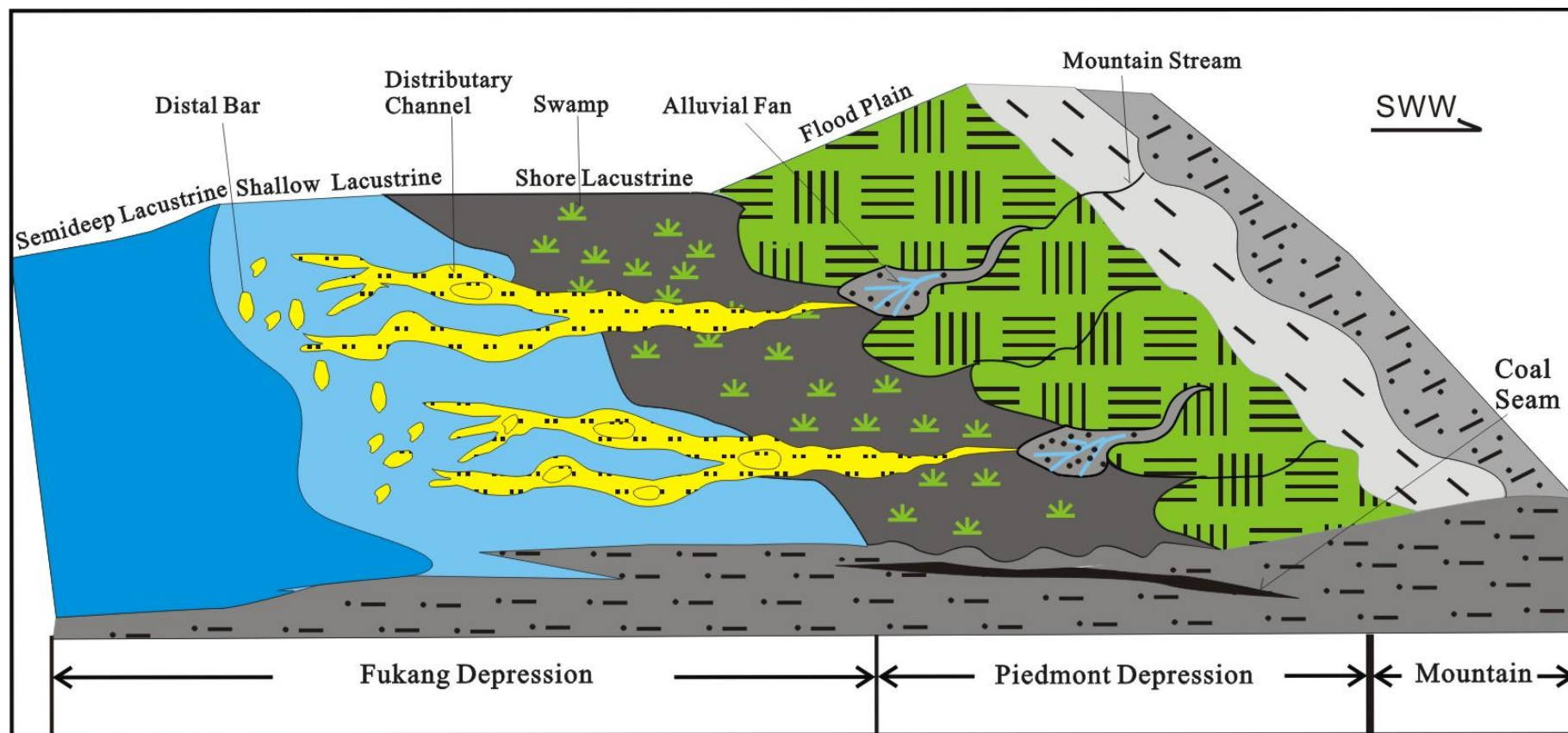


Figure 2. The sedimentary environment and its controlling pattern of coal measures strata in the southern Junggar zone.

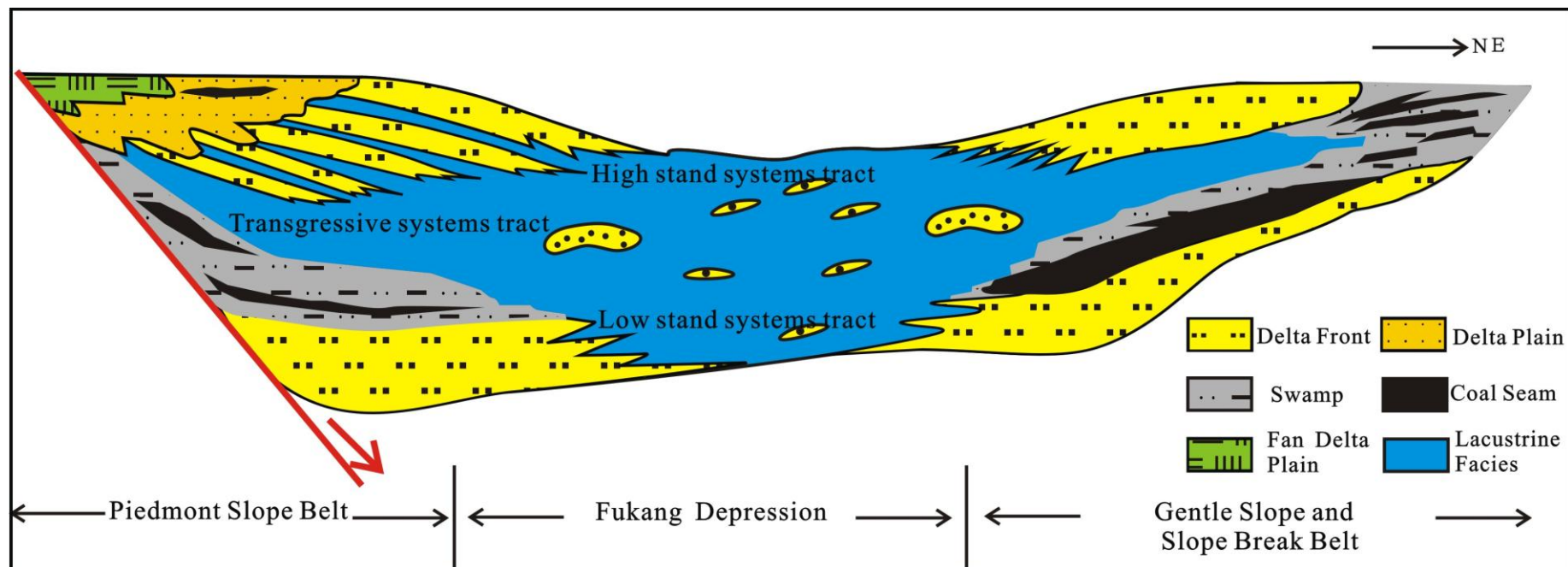


Figure 3. The coal-forming patterns in stratigraphic sequences of low-stand systems tract, transgressive systems tract and high-stand systems tract.

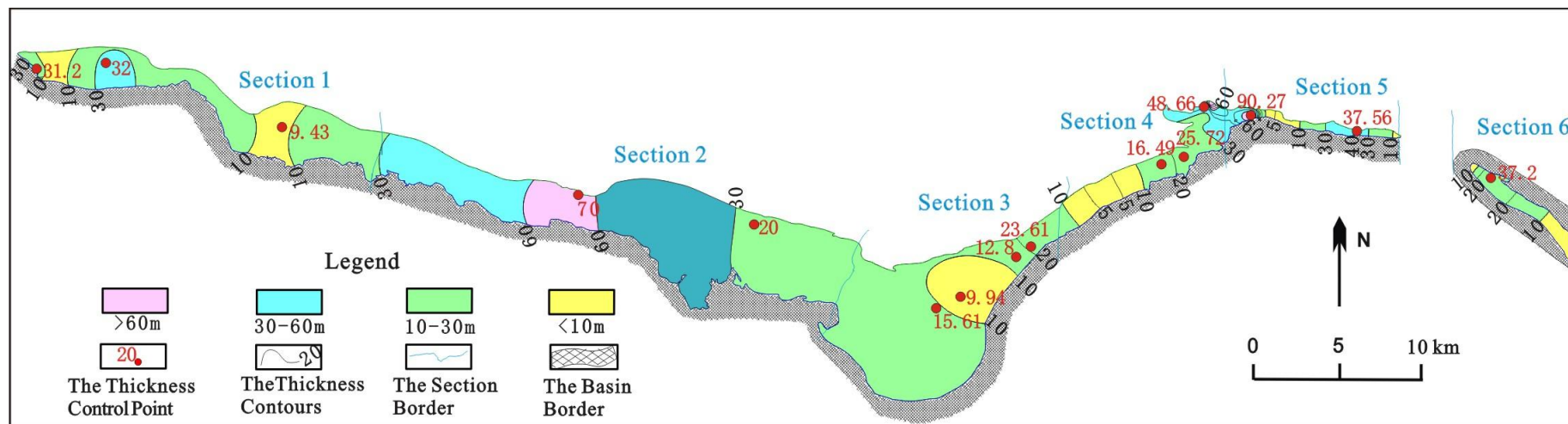


Figure 4. Total coal seam thickness contour map of the Badaowan Formation in southern the Junggar zone.

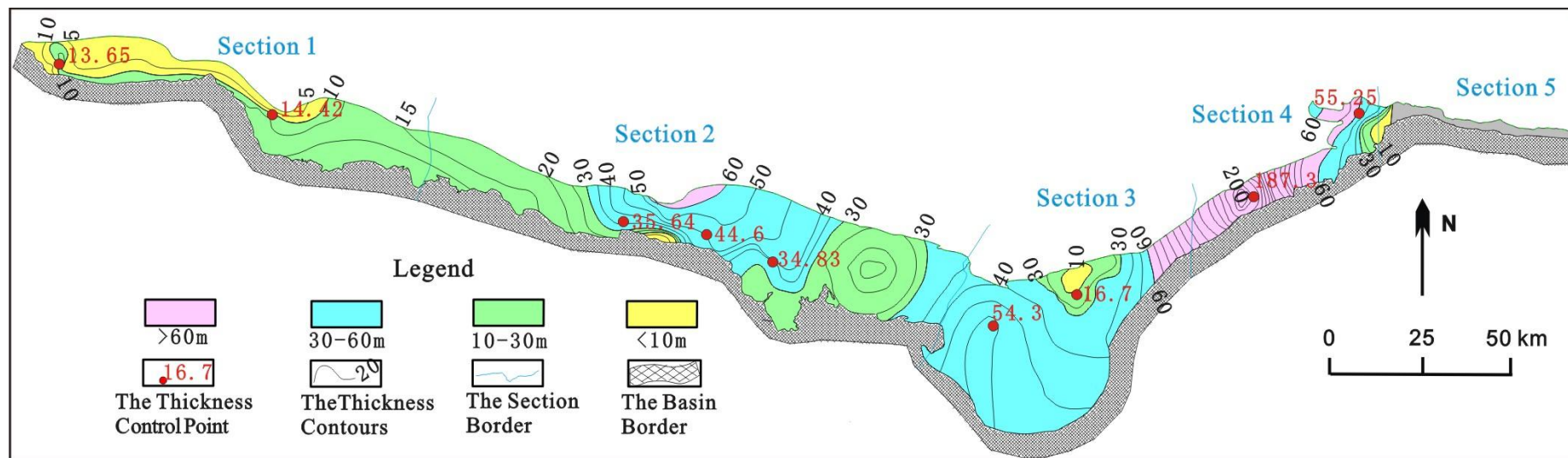


Figure 5. Total coal seam thickness contour map of the Xishanyao Formation in the southern Junggar zone.

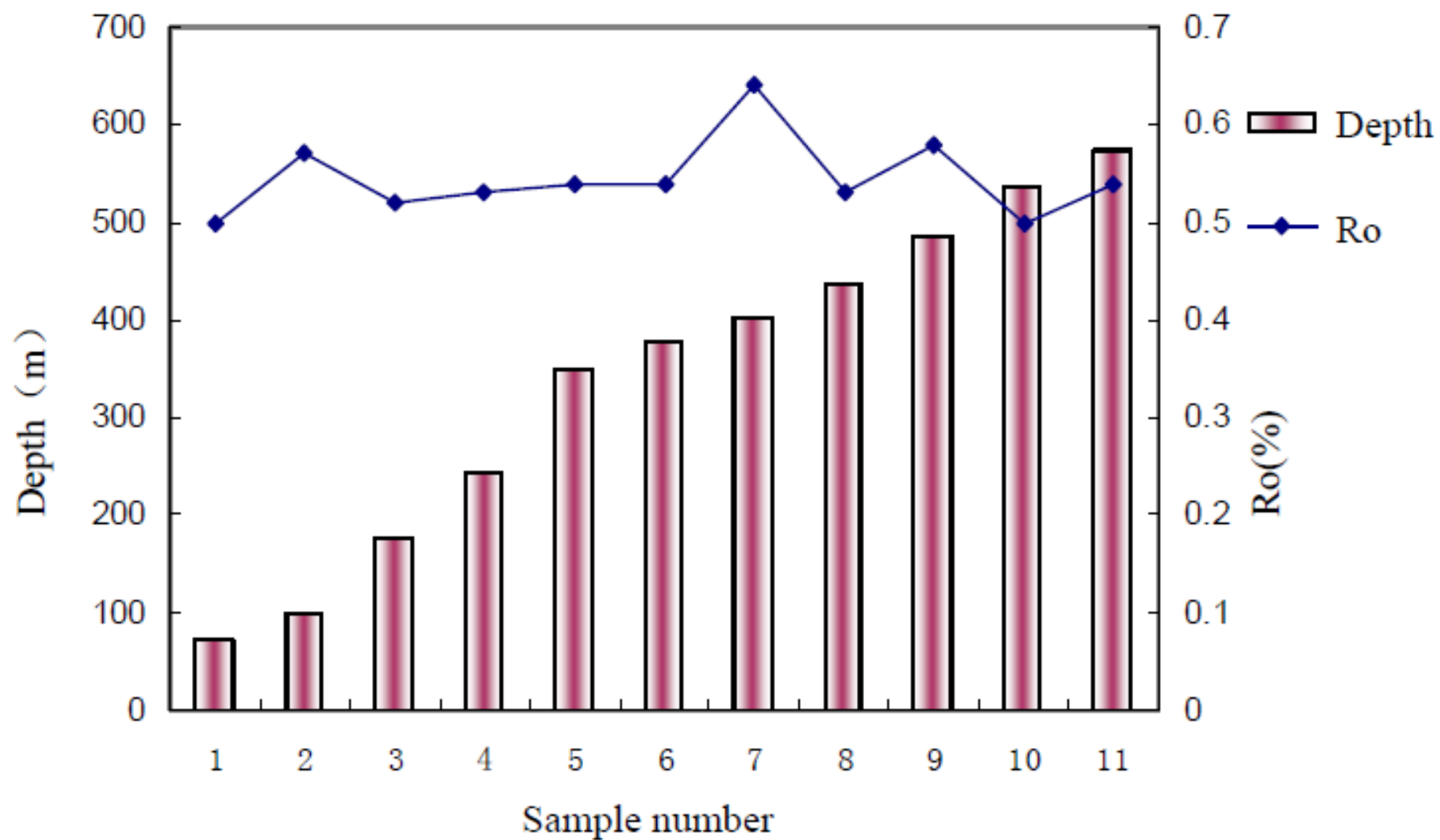


Figure 6. Relationship between buried depth of coal seam and vitrinite reflectance in the Badaowan Formation.

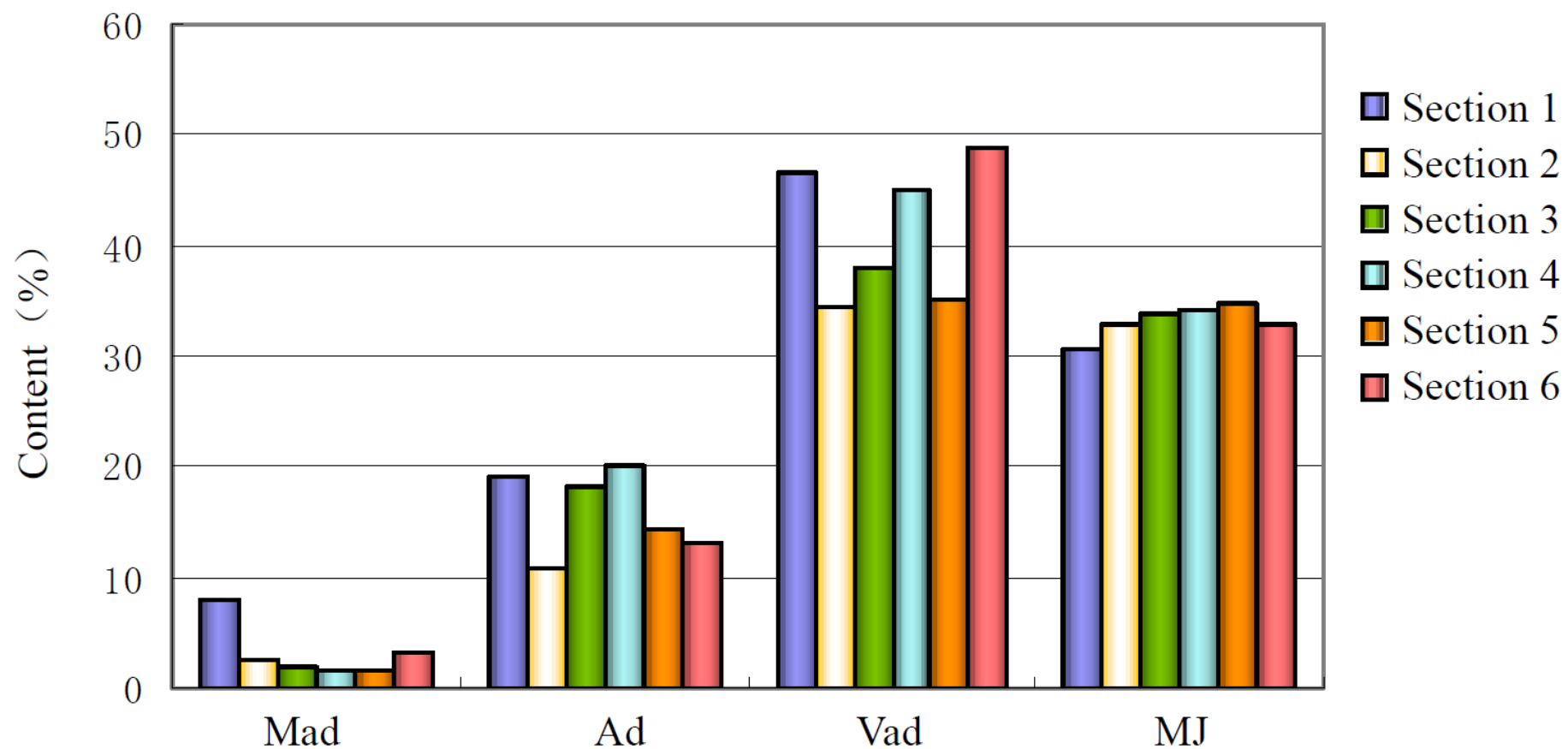


Figure 7. Coal rock quality diagram of Badaowan Formation.

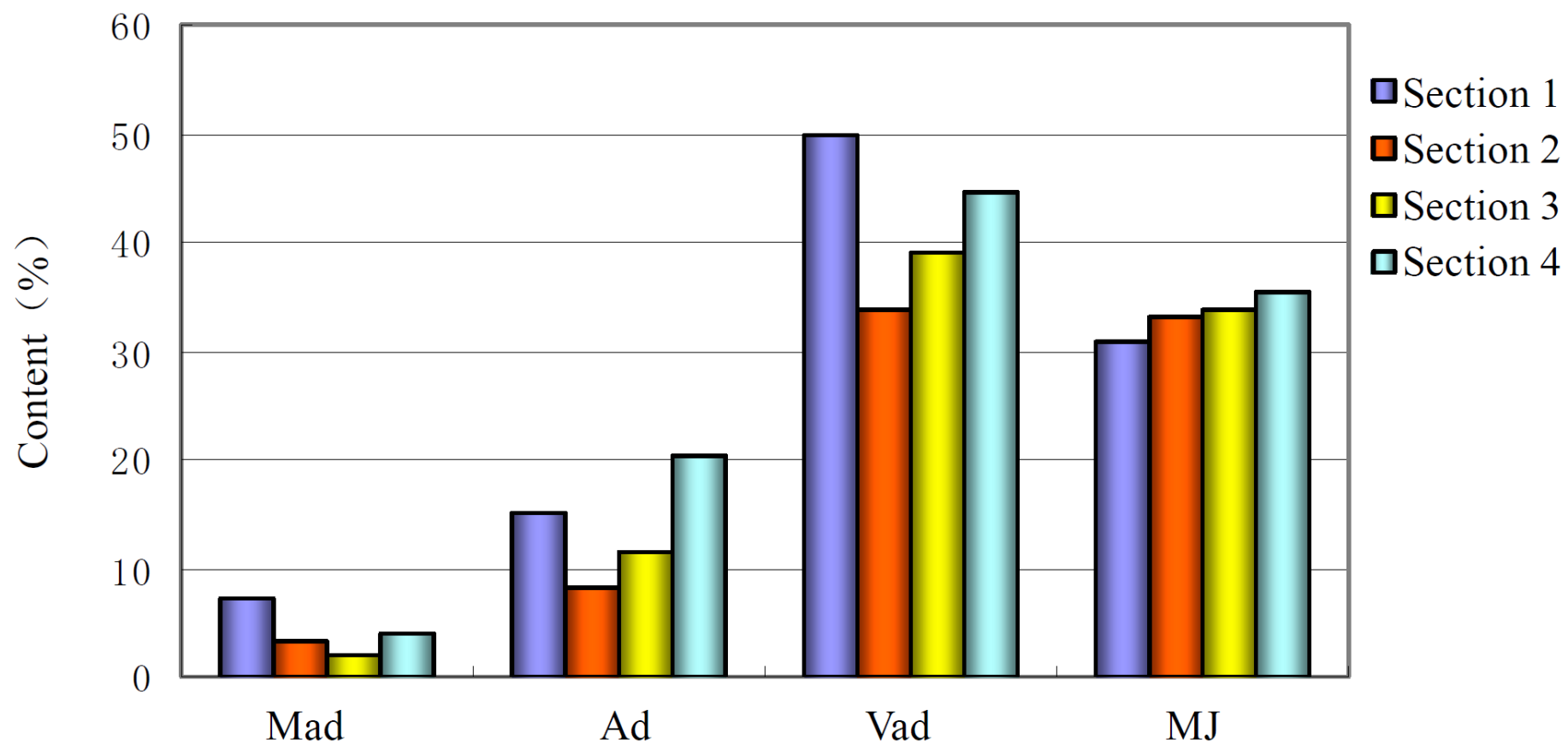


Figure 8. Coal rock quality diagram of Xishanyao Formation.

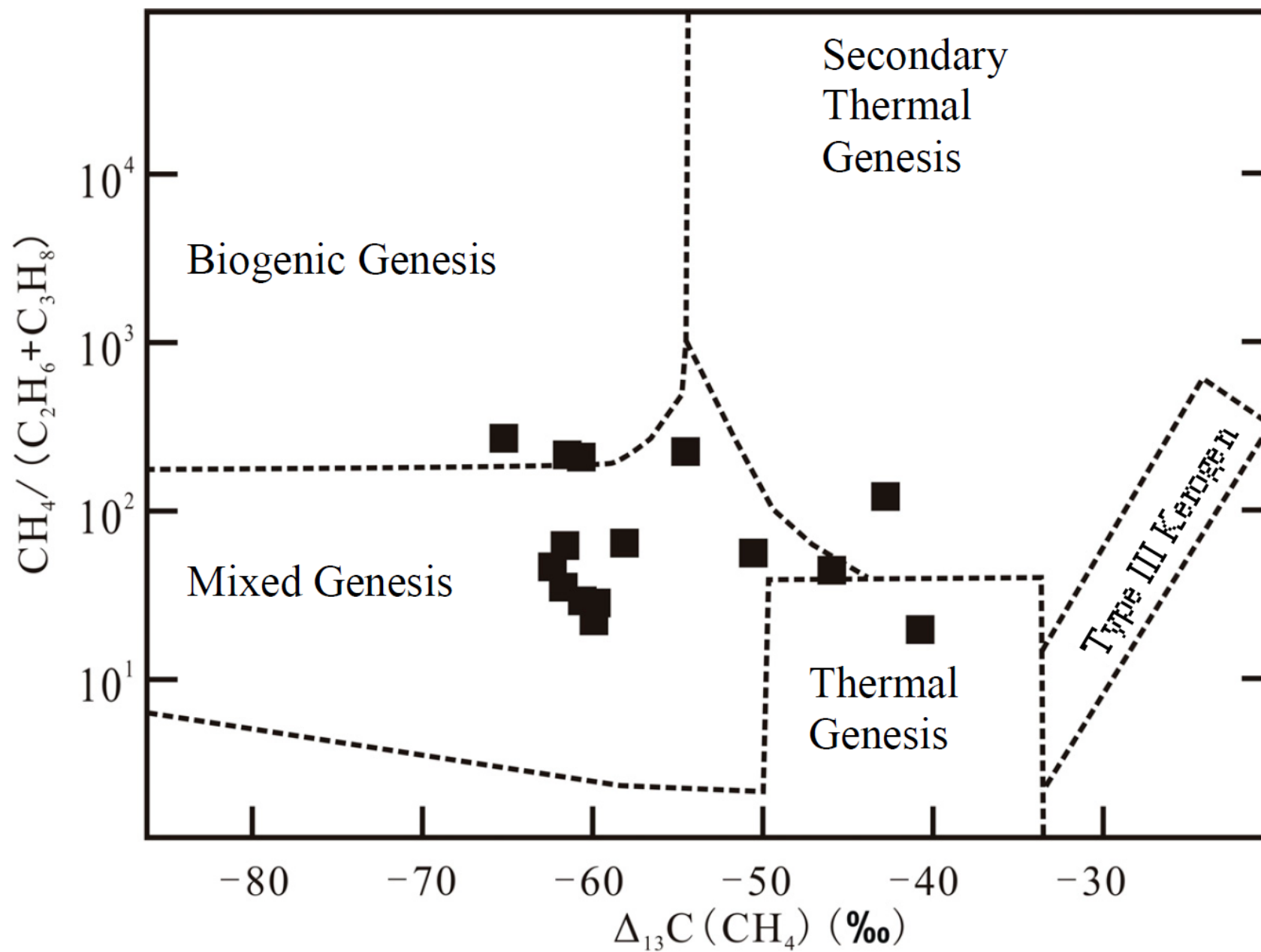


Figure 9. CBM genesis identification in the south Junggar zone.

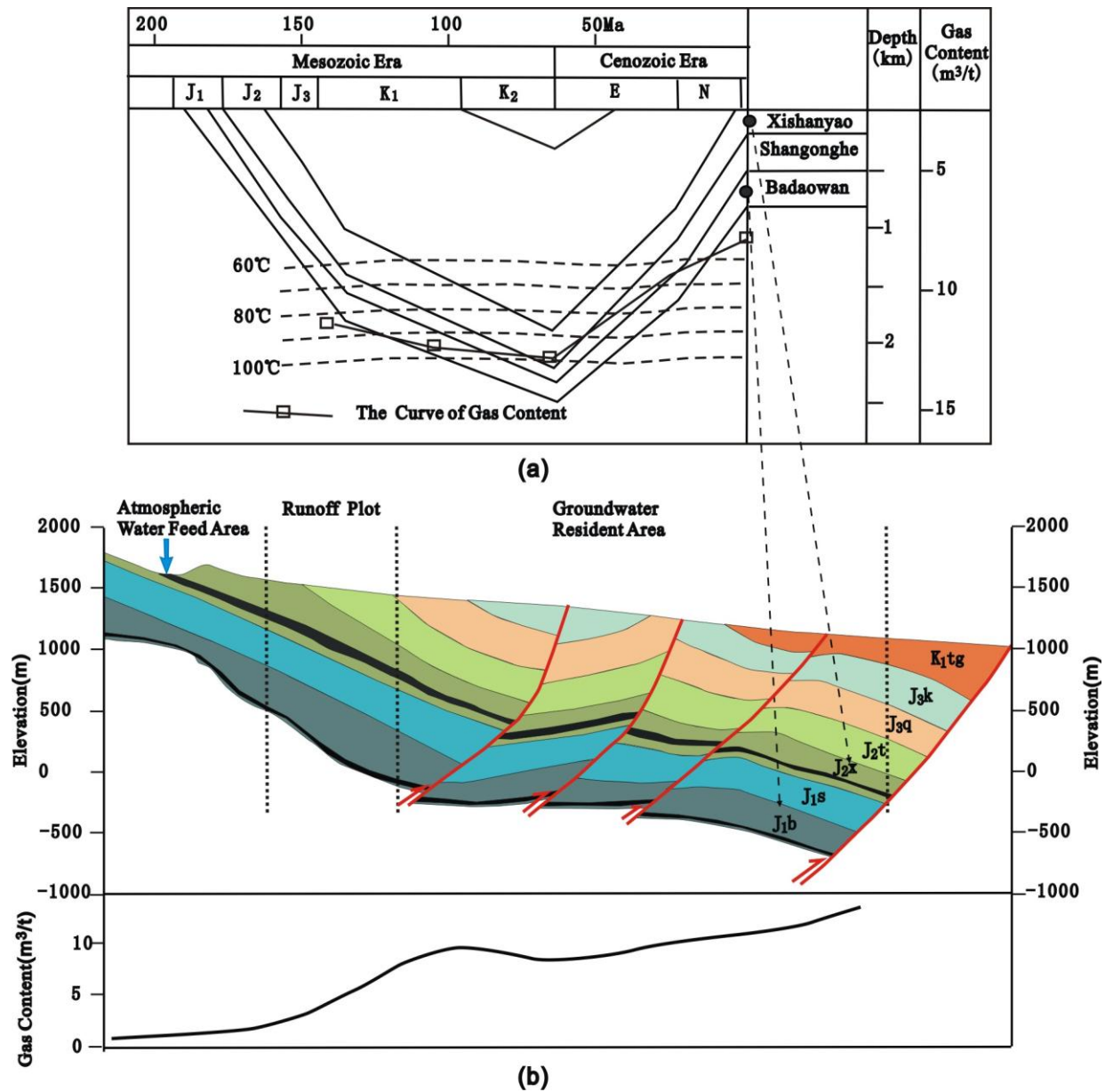


Figure 10. The CBM accumulating model in South Junggar Basin. (a) The relationship diagram of burial history, geothermal history, hydrocarbon forming history and the change of gas content in Junggar Basin (amended from Yan Song et al., 2012). (b) The relationship diagram of the coalbed methane reservoir profile map and the change of gas content in the Junggar Basin.

Sedimentary system	Sub-environment	Microenvironments and their characteristics
Fan delta	Fan delta plain-front complexes, the flood plain among fan deltas	Main sedimentary microenvironments include all kinds of channel and flood plain swamp among fans. The channels perpendicular to the basin rim developed along the slope, distributing in the fan delta plain-front complexes, with the lithology of predominant conglomerate and glutenite, sandstone and mudstone alternating layers of different thickness or mixed layers. This is relevant to the direct extension of the alluvial fans from the mountain passes into the shallow lake. Extensive flood plains developed among the fans, mainly consisting of mudstone and silty mudstone, with coal seams of uneven thickness.
	Delta plain	Main sedimentary microenvironments include distributary channels (channel and natural levee), interdistributary area (crevasse splay and flood swamp), which started from the divarications of the rivers and stopped at lake shoreline or level. Distributary channels act as framework in delta plain, its lithology is mainly gray, light gray, fine sandstone, siltstone and silty mudstone; slabby or festoon cross-bedding developed, also high-energy flat parallel bedding, fast accumulation of massive bedding and low-energy wave bedding caused by sand wave, etc appeared. Gray, grayish yellow, brownish yellow mudstone and silty mudstone developed in the interdistributary area. Besides the grayish green, grayish black mudstone, coal seams of different thickness occurred in the swamp.
Delta	Delta front	Main sedimentary microenvironments include underwater distributary channel, underwater interdistributary area (river mouth bar, distal bar and interdistributary bay), located between lake level and wave base level, distributing like a ring belt along the deltaic place close to the lake. Delta front is the most active delta depositional center, where sand and mud sediments from the river, once entered into the lake, quickly piled up. Due to the repeated washing, winnowing and redistributing actions of the rivers, waves and tides, pure and good sorting sandy deposits belt formed, with coal seam occurrence in some parts.
	Shore-Shallow lake	Main sedimentary microenvironments including sand bar, sand beach, mud flat and swamp which are located between shore lines of flood period and dry period, suffering from alternating flooding and exposure, belongs to strong hydrodynamic and oxidation environment with various abundant creatures. Various types of sedimentary sand bar and sand beach extensively developed with all kinds of water cross-bedding and ripple marks. Coal streaks and seams occurred in relatively developed mud flats and swamps.
Lake	Semideep lake	Main sedimentary microenvironments consisting of cross flow sand sheet and medium deep lake mud is located in the anoxic weak reducing-reducing environments. Dark mudstone and shale or silty mudstone and shale are the primary components with siltstone appearing in some parts. It almost does not contain coal seams.

Table 1. The main identified sedimentary facies and their characteristics in the coal measure strata.

Micro-environments	Sedimentary characteristics	Coal rock characteristics and the gas generation and storage capacity
lakeshore swamp	Low-energy coal-bearing lake shore or arm sediments that developed in humid climate consist of mudstone, carbonaceous mudstone with interlayers of coal seams.	Mainly glossy to dull coal rock characterized by provitrinite, alginite and sporinite; low to medium ash content and low to high sulfur content; poor to good gas generation and relatively poor gas storage capacity.
Delta plain swamp	A series of deltaic plain coal-bearing sediments located on the top of the positive cyclic sequence developed in humid climate.	Mainly glossy to semidull coal rock characterized by provitrinite, degradinite and clastic exinite; contents characterized; low to medium ash content and low to medium sulfur content; good gas generation but relatively poor gas storage capacity.
Flood plain swamp among fan deltas	Swamp facies that developed in flood plains present as the coal-bearing sediments in the upper river "dual structure".	Mainly semibright to dull coal rock characterized by fusinite, degradinite and clastic exinite; low to medium ash content and low to medium sulfur content; poor to good gas generation and relatively poor to good gas storage capacity.

Table 2. Major coal-bearing sedimentary microenvironments and coal facies features.

Sections	Badaowan Formation				Xishanyao Formation			
	Coal seams	Total coal thickness, m	Coal bearing coefficient, %	Distribution characteristics	Coal seams	Total coal thickness, m	Coal bearing coefficient, %	Distribution characteristics
1	3-14	4-33	0.075	Coal seam thickness changes greatly with complicated structure and strong distribution irregularity.	2-9	13-35	10	Larger thickness and stable distribution
2	3-5	—	—	The coal seam is thick in the east and thin in the west with poor stability.	6-40	8-52	Large variation.	Coal seam thickness changes greatly with complicated structure and weak distribution regularity.
3	3-21	1-9	—	Distribution is discontinuous, with bifurcation, mergence and pinching out phenomena.	3-18	8-49	10	Large coal thickness with relatively stable distribution and simple structure.
4	9-24	8-94	12	Stable distribution	9-21	15-112	16	Stable distribution
5	45	42-100	11	Stable distribution	0	0	0	Lost strata
6	6	29-41	9	Stable distribution	0	0	0	Contains no coal

Table 3. The coal seam distribution in different sections.

Sections	Macroscopic characteristics of coal rock	Microscopic characteristics of coal rock				Vitrinite reflectance		Coal rank	
		Vitrinite	Semivitrinite	Inertinite	Exinite	Badaowan	Xishanyao	Badaowan	Xishanyao
1	Mainly bright coal and dull coal, and accompanied by fusains.	75%-85%	10%-12%	10%-15%	Relatively low				
2	Mainly dull coal, generally accompanied by fusains.	27%-60%	6%-23%	6%-61%	0				
3	Primarily bright coal and dull coal, with small amounts of fusains.	8%-81%	<10%	15%-88%	<10%	0.45%-0.76%, 0.62% on average.	0.66%-0.76%, 0.697% on average.	Mainly long flame coal	Mainly long-flame coal and non-caking coal.
4	Primarily bright coal and semibright coal.	86%-94%	little	little	little				
5	Primarily bright coal and semibright coal.	61%	5%	7%	18%				
6	Primarily vitrain and bright coal with fusains.	>87%	0	<10%	<3%				

Table 4. The coal rock features in different sections.

Sections	Poroperm characteristics					Adsorption		Temperature and pressure	
	Porosity	Pore structure	Specific area and pore geometry	Pore size distribution	Permeability, md	Langmuir pressure, MPa	Dry ash free basis langmuir volume, m ³ /t	Geothermal gradient, °C/100m	Pressure gradient, MPa/100m
1	0.2%-16.4%,	Fissure – pore.	Specific area 1.423-1.766 m ² /g; total pore volume 0.441- 0.575 cm ³ /g; average pore diameter 108.67-158.62 nm; micro pore volume fraction 25.4%-63.6%, 44.2% on average.	Mainly big pores. Pore size distribution of Badaowan formation is better than that of Xishanyao formation.	0.22-23.2, 11.0 on average.	Large variation among different sections	Badaowan formation 19.3, Xishanyao formation 16.64.	2.4 on average.	0.84- 0.98.
2	8.4% on average.								
3	7.0%-7.2%, 7.10% on average.								
4		Fissure - pore, pore.		Mainly medium and small pores. Pore size distribution of Badaowan formation is better than that of Xishanyao formation.	0.32-1383.	1.89- 5.82.	16.64.		
5	5.6%-14.4%, 10.05% on average.								

Table 5. The coal seam reservoir properties in different sections.

Sections	Main gas components.	Methane concentration, %	Gas content tested in field, m ³ /t	Gas content tested in lab, m ³ /t		Gas saturation, %	Source of samples
				Air dried basis (G _{ad})	Dry ash free basis (G _{daf})		
1	Methane, nitrogen and carbon dioxide.	Less than 80	0-1	—	—	42.2- 89.5, 60.0 on average.	Coal mine gas
2		About 80	4-7	—	—		Exploration well Changshi 1 and Changshi 2
3		About 80	2.43-15.11	—	—		Stratigraphic well HG-06-03
4		About 80	2.25-14.27	4.96-14.80	5.63-15.78		Exploration well Wucan 1
5		More than 80	4.25-15.63	4.75-15.73	5.25-16.62		Exploration well Fuchan 1 and Fumei1
6	Methane, nitrogen and carbon dioxide.	Less than 80	0-1	—	—		Coal mine gas

Table 6. The coal seam gas content features in different sections.

Sections	Xishanyao formation (10^8m^3)	Badaowan formation (10^8m^3)	Total amount of resources (10^8m^3)	Resource abundance ($10^8\text{m}^3/\text{km}^2$)
1	194.8	56.0	250.8	0.45
2	302.0	48.6	350.6	0.42
3	342.2	190.6	532.8	0.73
4	955.8	499.3	1455.1	7.15
5	0	272.6	272.6	11.65
6	0	192.8	192.8	2.35
Total	1794.8	1259.9	3054.7	1.25

Table 7. CBM resources in different sections.

Parameters		Parameter meaning	Evaluation criteria	Grade	Score
Geological conditions	Structural complexity	The development of faults and folds		simple	10~7
				medium	7~3
				complex	3~0
	Coal seam occurrence	Coal seam dip angle, relief intensity	$\geq 70^\circ$	big	3~0
			$70^\circ\text{-}30^\circ$	medium	7~3
			$\leq 30^\circ$	small	7~10
Resource conditions	Coal seam thickness	Coal seam thickness, stability, and coal reserves	$\geq 50\text{ m}$	big	10~7
			50-20 m	medium	7~3
			$\leq 20\text{m}$	small	3~0
	Coal seam gas content	Gas content, methane concentration	$\geq 5\text{ cm}^3/\text{g}$	high	10~7
			5-4 cm^3/g	medium	7~3
			$\leq 4\text{ cm}^3/\text{g}$	low	3~0
	CBM resource abundance	CBM resource abundance	$\geq 10 \times 10^8\text{ m}^3/\text{km}^2$	high	10~7
			$5\text{-}10 \times 10^8\text{ m}^3/\text{km}^2$	medium	7~3
			$\leq 5 \times 10^8\text{ m}^3/\text{km}^2$	low	3~0
Reservoir conditions	coal seam adsorptivity	Langmuir Volume	$\geq 20\text{ cm}^3/\text{g}$	big	10~7
			20-15 cm^3/g	medium	7~3
			$\leq 15\text{ cm}^3/\text{g}$	small	3~0
	Coal seam permeability	Permeability	$\geq 10\text{ md}$	high	10~7
			10-3 md	medium	7~3
			$\leq 3\text{md}$	low	3~0
	Gas saturation	Gas saturation	$\geq 60\%$	high	10~7
			60-50%	medium	7~3
			$\leq 50\%$	low	3~0

Table 8. CBM resources comprehensive evaluation factors and standards (based on Qingbo Zhao et al., 2012).

Evaluation parameter	Geological conditions		Resource conditions			Reservoir conditions		
	Structural complexity	Coal seam occurrence	Coal seam thickness (m)	Coal seam gas content (cm ³ /g)	CBM resource abundance (10 ⁸ m ³ /km ²)	Langmuir volume (cm ³ /g)	Permeability (10 ⁻³ μm ²)	Gas saturation (%)
Section 1	complex	24	13.85	3.44	0.45	20.80	3.10	27.08
Section 2	medium	20	15.25	3.44	0.42	20.80	3.10	27.08
Section 3	medium	28	14.28	6.20	0.73	18.74	3.10	48.60
Section 4	medium	48	70.65	10.94	7.15	23.04	7.42	70.11
Section 5	medium	45	56.40	12.61	11.65	28.95	3.86	54.88
Section 6	complex	32	18.43	10.28	2.35	26.00	3.86	54.88

Table 9. Summary of CBM evaluation parameters for six sections.

Evaluation parameter	Geological conditions		Resource conditions			Reservoir conditions		
	Structural complexity	Coal seam occurrence	Coal seam thickness (m)	Coal seam gas content (cm ³ /g)	CBM resource abundance (10 ⁸ m ³ /km ²)	Langmuir volume (cm ³ /g)	Permeability (10 ⁻³ μm ²)	Gas saturation (%)
weight	0.12	0.08	0.12	0.14	0.14	0.12	0.16	0.12
weight	0.60	0.40	0.30	0.35	0.35	0.30	0.40	0.30
coefficient	0.20		0.40			0.40		

Table 10. List of evaluation parameter weight coefficients.

Evaluation parameter	Geological conditions		Resource conditions			Reservoir conditions		
	Structural complexity	Coal seam occurrence	Coal seam thickness (m)	Coal seam gas content (cm ³ /g)	CBM resource abundance (10 ⁸ m ³ /km ²)	Langmuir volume (cm ³ /g)	Permeability (10 ⁻³ μm ²)	Gas saturation (%)
Section 1	0.24	0.61	0.25	0.36	0.03	0.87	0.49	0.19
Section 2	0.60	0.64	0.27	0.36	0.03	0.87	0.49	0.19
Section 3	0.60	0.58	0.26	1.05	0.04	0.72	0.49	0.35
Section 4	0.60	0.42	1.20	1.31	0.66	0.96	0.88	1.20
Section 5	0.60	0.44	0.95	1.40	0.99	1.20	0.56	0.59
Section 6	0.24	0.54	0.33	1.27	0.20	1.08	0.56	0.59

Table 11. Scores of CBM comprehensive evaluation parameters for different sections.

Sections	1	2	3	4	5	6
Score	3.04	3.45	4.09	7.23	6.73	4.81
Order	6	5	4	1	2	3

Table 12. CBM comprehensive evaluation scores for six sections of southern rim of Junggar Basin.