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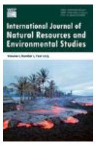

Analysis of Genetic Evolution Mechanism and Controlling Factors of Coalbed Methane

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ABSTRACT

As an important unconventional natural gas resource, the formation mechanism and genetic type of coalbed methane are of great significance to resource evaluation and development. This paper systematically analyzes the genetic types, formation mechanism and control factors of coalbed methane. Studies have shown that coalbed methane mainly includes two types: biogenic gas and thermogenic gas. Among them, biogenic gas is formed in a low-temperature and shallow-buried environment, while thermogenic gas is formed under higher temperature and pressure conditions. The generation of coalbed methane is not a single process, but a gradual transition from biogenic to thermogenic in the process of coalification, showing obvious continuous evolution characteristics. In addition, the formation and enrichment of coalbed methane are controlled by many factors, such as coal rock composition, coal metamorphic degree, temperature and pressure conditions and hydrodynamic force. The research in this paper is helpful to deepen the understanding of the genetic mechanism of coalbed methane and provide a theoretical basis for the development and utilization of coalbed methane resources.

KEYWORDS

Coalbed Methane; Genetic Types; Evolution Mechanism; Control Factors.

1. PREFACE

With the continuous development of the national economy, the demand for fossil fuels is increasing. The depletion of traditional non-renewable resources such as coal and oil poses a huge threat to the country 's energy security. In addition, due to the extensive use of traditional mineral energy, environmental issues are becoming more and more prominent[16]. Therefore, there is an urgent need to find a cheap and clean energy source to meet this growing challenge. [5] Coalbed methane is an unconventional natural gas with high environmental and economic benefits, which has attracted wide attention in the world [7].

Coalbed methane, also known as coal seam methane, is a natural gas in the coal seam. Its main components are methane and other gases. These gases are considered toxic gases during long-term mining. In the late 1970s, due to the energy crisis, the United States adopted preferential tax policies to encourage the development of coal mines, which promoted the development and testing of coal mines. In the early 1980s, coal mines made a major breakthrough and took the lead in commercialization, which fully demonstrated its potential great value and potential, thus triggering a worldwide upsurge in coalbed methane research [12]. The reserves of coal resources in the world are 84.9 ~ 254.9 × 1012m3. The heating rate of coalbed methane is high, about 8000kcal/m3, accounting for about 90 % of conventional natural gas [3]. Coalbed methane is a kind of clean energy, methane content in 80 % ~ 90 %, its combustion produces low CO2 emissions. Coalbed methane is an unconventional natural gas resource with great development potential. At the same time, before the

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mine is mined, the gas in the coal seam is discharged in time, which is conducive to the safe production of the mine and the improvement of the atmospheric environment of the mine.

The formation mechanism of coalbed methane is complex, and its formation and evolution are restricted by many factors. With the continuous development of coal-forming, its biological origin and corresponding gas layer have certain regularity, gradually formed and gradually evolved. In the study of coalbed methane, understanding its formation mechanism is the key to evaluating its resources [8].

2. GENETIC TYPES AND FORMATION PROCESS OF COALBED METHANE

Coalbed methane has become a new unconventional natural gas resource [24]. Coalbed methane is the gas generated and stored in the coal seam during the coalification process [13]. After the plant body is buried, it is converted into peat through the biochemical action of microorganisms, and the peat is transformed into lignite, bituminous coal and anthracite through the geological action dominated by physical and chemical action [1]. In the process of coalification, with the complex physical and chemical changes of coal-forming materials, the content of volatiles and water content decreases, the content of calorific value and fixed carbon increases, and methane-based gases are generated [4]. In the process of coal conversion from lignite to bituminous coal, each ton of coal is accompanied by 280 ~ 350m3 methane and 100 ~ 150m3 carbon dioxide precipitation [9] [17]. In the process of coalification, peat generates biogenic gas and thermogenic gas through biogenic process and thermogenic process respectively [10] [15].

2.1. Biogenetic gas

Biogenetic gas is mainly produced in coal seams at lower temperatures (generally less than 50 °C) through the participation or action of bacteria.

Gases dominated by methane and containing a small amount of other components. The mechanism of biogenic gas production mainly includes the reduction of carbon dioxide and the fermentation of organic acids (usually acetic acid) [6]. Although both of them are carried out in the near-surface environment, most of the ancient biogenic gases are derived from the reduction of CO2 through composition analysis[25]. In the coal seam, the rapid deposition of organic matter, abundant pore space, low temperature and high pH low oxygen environment are favorable conditions for the formation of a large number of biogenic gases [11]. According to its gas generation time, parent material, geological conditions and other factors, it can be divided into two categories: primary biogas and secondary biogas. There is no significant difference between the two in origin [14]. As shown in Fig.1, there are obvious differences in carbon isotope composition and gas characteristics between biogenic gas and thermogenic gas. The methane carbon isotope of biogenic gas is lighter (δ 13 C value is lower), while the carbon isotope of thermogenic gas is relatively heavier, and often accompanied by higher content of heavy hydrocarbon gas. This difference provides an important basis for the identification of coalbed methane genesis.

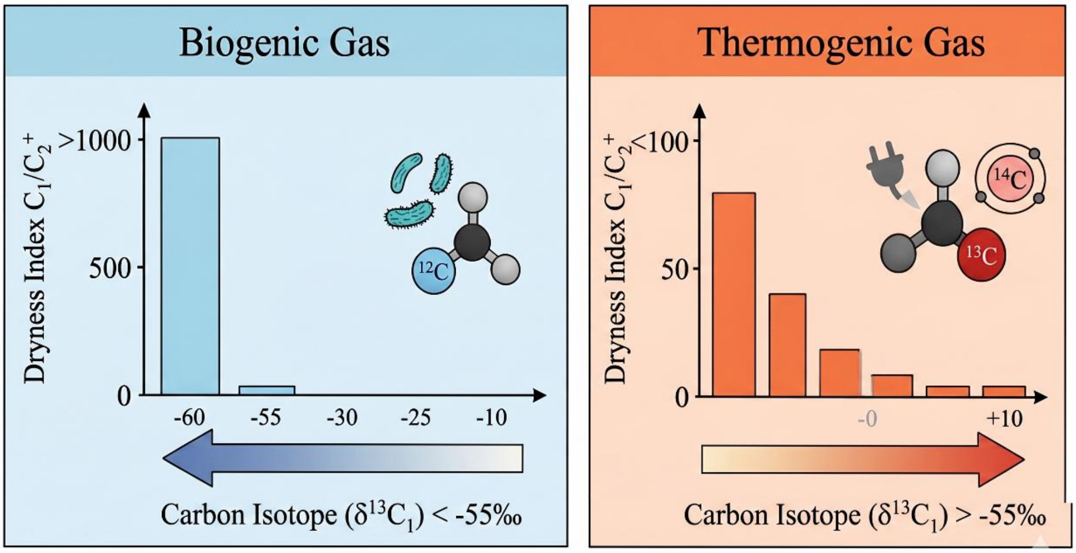

Fig. 1 Comparison of thermochemical characteristics of biogenic gas and chemogenetic gas

2.1.1. Protobiogenic gas

The primary biogenic gas is a gas generated by a series of complex processes such as the decomposition of organic matter such as bacteria in the low metamorphic coal (peat to sub-bituminous coal) in the peat swamp environment in the early stage of coalification. Due to the limited pores in peat or low metamorphic coal, shallow burial, low pressure, and weak adsorption of gas, it is generally believed that primary biogenic gas is difficult to preserve [18]. For the formation stages of primary biogenic gas and thermogenic gas, different scholars have different classification schemes. A.R.Scott et al.used R0 < 0.3 % as the boundary value of primary biogenic gas, while the R0 value of thermogenic gas was 0.5 %. Palmer set the critical value of R0 of (primary) biogas and thermal (genetic) solution gas as 0.5 %. Rice believed that the formation of thermogenic gas began at about 0.6 %. The reason for this difference is that the traditional theory of natural gas genesis believes that biogas is generally formed before the R0 value is 0.3 %, while the pyrolysis gas is formed after the R0 value is 0.6 % ~ 0.7 %, that is, the parent material of gas does not produce gas in the thermal evolution stage of R0 value of 0.3 % ~ 0.6 %. However, studies in recent years have shown that the gas-generating parent material still generates gas at the stage of R0 value of 0.3 % to 0.6 %, and a considerable scale of gas fields can be formed (most of the current gas fields are coal-type gas fields). The gas generated at this stage is called bio-thermal catalytic transition zone gas, that is, organic matter gas generation is a continuous process, and so should coalbed methane.

2.1.2. Secondary biogenic gas

The coal measure strata are uplifted and denuded to the near surface by tectonic action in the later stage, and bacteria can migrate to the coal seam aquifer through flowing water (mostly rainwater). At relatively low temperatures (generally less than 50 °C), bacteria convert the generated moisture in the coal seam into methane and carbon dioxide through degradation and metabolism, forming secondary biogenic gas. The formation age of secondary biogenic gas is generally late (tens of thousands to millions of years ago) [28]. Most of the biogenic gas remaining in the coal seam belongs to secondary biogenic gas [2]. The generation and preservation of secondary biogenic gas requires the following conditions: 1 coal rank is lignite or above lignite ; 2 The area where the coal seam is located has undergone uplift (uplift) ; 3 coal seam has suitable permeability ; 4 along the edge of the basin there is water recharge to the basin coal seam ; 5 bacteria migrate to the coal seam ; 6 The coal seam has high reservoir pressure and trap conditions that can store a large amount of gas [29].

2.2. Thermogenic gas

When the temperature exceeds 50 °C, the coalification is enhanced, the carbon content in the coal is enriched, and a large amount of hydrogen-rich and oxygen-rich volatiles are released (devolatilization). The main components are methane, carbon dioxide and water[26]. At higher temperatures, the decarboxylation of organic acids can also produce methane and carbon dioxide. The formation of thermogenic gases is generally divided into early stage and main stage [19]. (Late stage)

2.2.1. Early stages

Scott believed that in the early stage of coalification, gas was generated from high volatile bituminous coal (R0 between 0.5 % and 0.8 %) [31]. The general characteristic of gas is that it contains more

3. FORMATION MECHANISM AND EVOLUTION PROCESS OF COALBED METHANE

The formation of coalbed methane is a complex geochemical process, and its essence is the comprehensive result of biochemical and pyrolysis of organic matter under different temperature and pressure conditions. As shown in figure 2, with the increase of coalification degree, burial depth and temperature, the formation process of coalbed methane shows an evolutionary trend of gradual transition from biogenic to thermal genesis. In the stage of low temperature and shallow burial, biogenic gas is the main gas. With the deepening of burial, it enters the stage of thermogenic gas generation, and forms biogenic-thermal transition zone gas under certain conditions, which shows obvious stage and continuity characteristics.

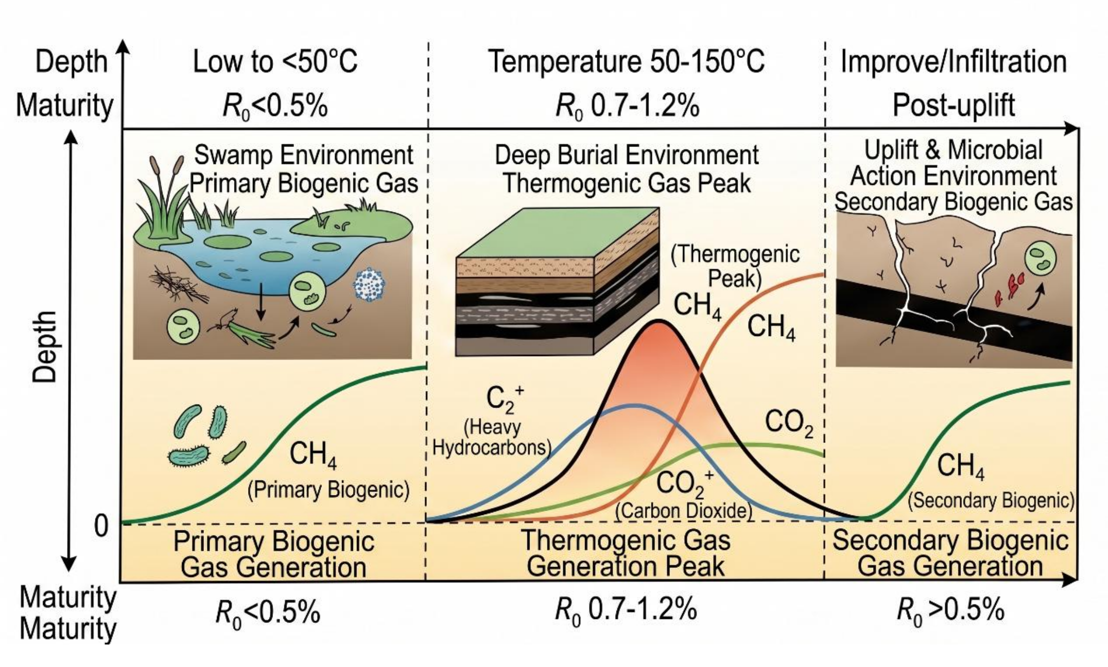

Fig. 2 Genetic evolution of coalbed methane

3.1. Biogenetic mechanism

Under low temperature, low pressure and reducing environment, microorganisms decompose organic matter through metabolism to produce methane and carbon dioxide. This process is highly dependent on environmental conditions, such as temperature, pH, nutrients and microbial community structure, which have an important impact on gas production.

3.2. Thermal genesis mechanism

With the increase of burial depth and temperature, organic matter gradually undergoes thermal cracking reaction to generate gaseous hydrocarbons. This process is mainly controlled by temperature, pressure and organic matter type, and is accompanied by changes in carbon isotope composition. Thermogenic gases usually have high maturity characteristics, and methane is rich in heavy carbon isotopes.

3.3. Bio-thermal evolution process

The generation of coalbed methane is not a single process, but a continuous evolution system. In the early stage of coalification, it was dominated by biological genesis. With the deepening of burial and the increase of temperature, it gradually transitions to thermal genesis. Both of them can exist at the same time and have superposition effect in a certain stage, forming a bio-thermal transition zone gas. In addition, there are obvious differences in formation conditions and gas characteristics between biogenic gas and thermogenic gas: the former is formed in low temperature and shallow buried environment, and the carbon isotope of methane is light ; the latter is formed under the condition of high temperature and deep burial, with high content of heavy hydrocarbons and relatively heavy carbon isotopes in the gas. Therefore, the formation of coalbed methane can be regarded as a dynamic process of gradual evolution from biogenic to thermogenic, which is of great significance to the evaluation of coalbed methane resources.

4. CONTROLLING FACTORS OF COALBED METHANE FORMATION

The formation and occurrence of coalbed methane not only depend on its genetic type and formation mechanism, but also are controlled by a variety of geological factors. These controlling factors interact under different geological conditions, and jointly determine the composition characteristics and enrichment rules of coalbed methane. The formation mechanism of coalbed methane is relatively complex, and the corresponding organic matter types are different in maturity [32]. For the genetic types of coalbed methane, it is not enough to start from the coalbed methane itself. It is also necessary to study the evolution process and evolution characteristics of coal and rock organic matter composition in the process of coalbed methane formation, because under the action of different formation mechanisms, the variation characteristics of gas source parent materials in the process of coalbed methane formation are also different. The composition of coalbed methane is mainly affected by factors such as coal rock composition, coal rank, buried depth of gas generation process and corresponding temperature and pressure conditions[22]. In addition, geological conditions such as hydrodynamics and secondary effects (such as mixing and oxidation) also have a certain influence on the composition of coalbed methane [23]. As shown in Fig.3, the formation and enrichment of coalbed methane are controlled by many factors, such as coal rock composition, coal metamorphism, burial depth, temperature and pressure conditions, hydrodynamic conditions and secondary effects. These factors interact with each other in different geological environments, affecting the process of gas generation, migration and enrichment, and ultimately determining the accumulation characteristics of coalbed methane.

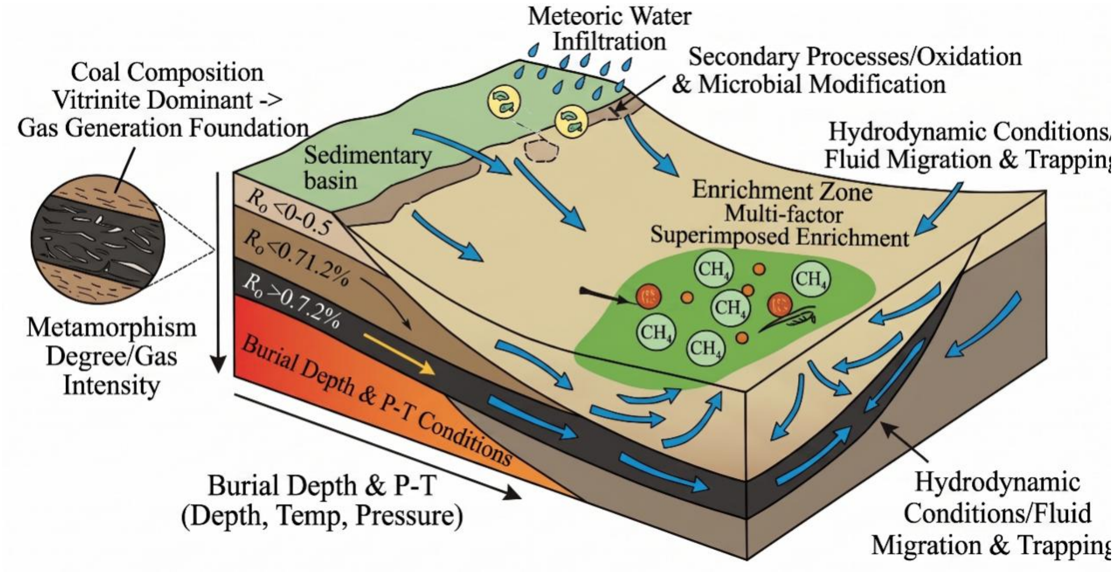

Fig. 3 Coalbed methane enrichment control chart

4.1. Coal rock composition

Coal rock composition is the basic component of coal and the parent material of coalbed methane, so it may be the primary factor affecting the composition of coalbed methane. Most coal is classified as humus (type III kerogen), and its coal rock composition is dominated by vitrinite, and contains a small amount of exinite and inert group. The exinite is usually rich in hydrogen, which is the main maceral of coal-derived oil and has a high hydrocarbon generation capacity. Recent lithofacies and geochemical studies have shown that the thermal evolution pathways of vitrinite and type III kerogen are consistent, mainly generating methane and other gases, and some components of hydrogen-rich vitrinite can also generate liquid hydrocarbons. The gas production of inert group is lower than that of exinite and vitrinite of the same coal rank. The hydrocarbon gas yield of the three coal rock components is the highest in the exinite group, followed by the vitrinite group, and the inert group is the lowest. In medium rank coals (high volatile bituminous coals to medium volatile bituminous coals), sapropelic briquettes (type I and II kerogens, mainly exinite and hydrogen-rich vitrinite) can generate wet gas and liquid hydrocarbon, while humic briquettes (type III kerogens, mainly vitrinite) can generate dry gas. For high metamorphic coal, the main component of coalbed methane is methane, which is formed by the cracking of residual kerogen and early generated heavy hydrocarbons. In general, the δ13C1 values of coalbed methane generated by oxygen-rich kerogen-bearing coal (mainly vitrinite) are larger than those generated by hydrogen-rich kerogen-bearing coal (mainly exinite and hydrogen-rich vitrinite) under the same maturity, while the distribution range of δ13C values of methane and ethane in the former is narrower than that in the latter. This is because the methane isotope generated by the pyrolysis of aliphatic hydrocarbons is lighter, and this methane is dominant in the gas generated by coal seams containing hydrogen-rich kerogen ; the carbon isotope of methane generated by thermal cracking of aromatic hydrocarbons is heavy, which dominates the gas generated by coal seams containing oxygen-rich kerogen. The liquid hydrocarbons generated in the early stage of thermal evolution of coal are retained in the microstructure of coal. At higher temperatures, the liquid hydrocarbon in the coal seam is cracked, and the generated gas has a larger δ13C value than the gas directly produced from the kerogen.

4.2. The metamorphic degree of coal

The degree of metamorphism of coal is an important factor in controlling the amount and composition of gas generation. In general, the higher the degree of coal metamorphism, the more the amount of gas generated. The thermogenic gas generated by low metamorphic coal (sub-bituminous coal ~

medium volatile bituminous coal) is mainly carbon dioxide, while the gas generated by high metamorphic coal (low volatile bituminous coal and above coal rank coal) is mainly composed of methane. The study of coalbed methane in China, Australia and the United States shows that the δ13C value of methane in coalbed methane is related to the coal rank of related coal. Usually, the δ13C value of methane in coalbed methane generated by low metamorphic coal is small, and the δ13C value of methane in coalbed methane generated by high metamorphic coal is large [27]. For the primary coalbed methane without secondary changes, with the increase of coal metamorphism, the methane in the corresponding coalbed methane is enriched in deuterium (δD value is larger) and 13C (δ13C1 value is larger).

4.3. Anger process

There are two processes of biogenesis and thermogenesis in the formation of coalbed methane. Due to the differences between biogenic gas and thermogenic gas in formation time, temperature and pressure, parent material and gas generation mechanism (with or without bacterial activity, etc.), the composition of coalbed methane generated in these two processes is also quite different. Usually, due to the enrichment of 12C by organisms, the δ13C1 value of biogenic gas is small, and the δ13C1 value of methane is generally between-5.5 % and-9.0 % or even lighter. Biogenetic gas is produced by carbon dioxide reduction and organic acid fermentation. Compared with biogenic gas, thermogenic coalbed methane has the following characteristics: 1 Heavy hydrocarbons generally appear in high and medium volatile bituminous coal and coal with higher metamorphic degree ; with the increase of coalification degree, heavy isotope 13C is enriched in methane and ethane (methane δ13C value is greater than-5.5 %). This is because in the process of thermogenic gas formation, with the increase of coalification degree, the 12C-12C bond in gas molecules is more frequently disconnected than the 12C-13C bond, resulting in the enrichment of 13C in the residual gas, so the δ13C1 value of thermogenic gas increases. 3 With the increase of coalification degree, methane is also relatively enriched in deuterium.

4.4. Burial depth and corresponding temperature and pressure conditions

There is a certain relationship between the burial depth of coal seam and the δ13C value of coalbed methane. In general, with the increase of buried depth of coal seam, the 13C value of coal seam methane shows an increasing trend. Compared with deep coalbed methane, shallow coalbed methane is a dry gas and has a smaller δ13C value of methane. According to the data from all over the world, in the case of the same or similar coal rank, the occurrence depth of coalbed methane with smaller δ13C value is generally shallow. With the increase of buried depth of coal seam, the components of coalbed methane also change.

4.5. Secondary effects

The secondary effect of coalbed methane refers to the transformation of the early generated gas. It is mainly the mixing of biogenic gas and thermogenic gas and the oxidation of wet gas components. Secondary effects affect the composition of coalbed methane, especially for shallow coalbed methane. In the shallow part, the coal seam is usually an aquifer with abundant bacteria. There are three ways in which bacteria affect the composition of coalbed methane: 1 Anaerobic bacteria activity leads to the formation of a large number of biogenic gas and mixes with previously generated thermogenic gas. This mixing effect can explain the change of shallow coalbed methane components in some areas. 2 The aerobic bacteria can preferentially act with the wet gas components, so that most of the wet gas is destroyed, so that the δ13C value of the residual wet gas components is also higher than expected. The transformation of wet gas components by this bacteria can also be used to explain the changes of coalbed methane components. The activity of aerobic bacteria causes the oxidation and consumption of methane, which increases the δ13C and δD values of residual methane.

4.6. Hydrodynamic and other geological conditions

In some areas, the influence of geological conditions such as hydrodynamics on the composition of coalbed methane is very obvious, such as the San Juan Basin in the United States. The coalbed methane in the ultra-high pressure area in the northern part of the basin is CO2-rich dry gas, and the coalbed methane in the low pressure area in the south is CO2-poor wet gas. At the edge of the basin that was denuded after the regional uplift, rainwater entered the permeable coal seam, and bacteria also migrated to the coal seam with the flowing water. Under the action of bacterial degradation and its own metabolic activities, secondary biogenic gas is generated, which is a supplementary source of coalbed methane and may form abnormally high gas production.

5. CONCLUSION

In summary, the formation and occurrence of coalbed methane have obvious stages and regularity. The main conclusions are as follows:

(1) Coalbed methane has a clear genetic type and evolution law. Coalbed methane mainly includes two types: biogenic gas and thermogenic gas. Among them, biogenic gas is formed in low temperature and shallow buried environment, and thermogenic gas is formed under high temperature and pressure conditions. In the process of coalification, the two show the continuous evolution characteristics of the gradual transition from biogenesis to thermogenesis.

(2) The generation and enrichment of coalbed methane are controlled by a variety of geological factors. Coal rock components provide the material basis for gas generation. The metamorphic degree of coal determines the gas generation stage and composition characteristics. The burial depth and temperature and pressure conditions control the gas evolution process. These factors are coupled with each other and affect the accumulation characteristics of coalbed methane.

(3) Secondary action and geological conditions have an important role in the transformation of coalbed methane. Hydrodynamic conditions, microbial activities and oxidation can affect gas composition and isotope characteristics, thus changing the distribution and enrichment of coalbed methane, which is of great significance for the evaluation and development of coalbed methane resources.

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