Research progress and prospects of coal petrology and coal quality in China

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Abstract Clean utilization of coal depends on the quality of raw coal, which depends on the coal-forming parent materials (petrology and chemical composition of coal), the multiple media of the coal-forming environment, and some epigenetic conditions, such as thermal evolution (coalification), magmatic hydrothermal fluid, groundwater. Based on the research results of predecessors and prediction studies of coal resources since the founding of China, the present status of research on coal petrology, coal quality, coal metamorphism, and coal geochemistry in China is discussed in detail, with emphasis on research progress and the general situation of highly efficient and clean utilization of coal in the technical fields of coking, pyrolysis, combustion, gasification, and liquefaction, and the development prospects of coal petrology and coal quality in China are prospected.

Keywords Coal petrology · Coal quality · Coal metamorphism · Coal geochemistry · Research status · Prospect

1 Introduction

In order to find out the real situation of Chinese coal resources, China has conducted three national coal resources prediction studies under the leadership of the Ministry of Coal Industry since the founding of New China. From 1958 to 1959, the Ministry of Coal Industry organized the first national coal prediction study. From 1973 to 1980, the second national coalfield prediction study was organized, and “China Coalfield Geology” was compiled by scientific research institutes and universities (Yang 1979; Han 1980). The third coalfield prediction study was carried out in 1992–1997; China National Administration of Coal Geology (CNACG) compiled and published “China Coal Quality Review” (Yuan 1999) and “China Coal Resources Prediction and Evaluation” (Mao and Xu 1996). Ministry of Geology and Mineral Resources of China also carried out a national coal prospect prediction study from 1982 to 1988 and published “Coal Petrology and Quality Characteristics and Metamorphic Rules of Chinese Coal” (Li 1997). From 2007 to 2013, CNACG undertook a study of the national coal resources potential evaluation (commonly known as the fourth coalfield prediction study), and China University of Mining and Technology (Beijing) participated in the work of the expert group as a technical support unit. In addition, two small-scale national coalfield prediction studies were carried out by the Ministry of Coal Industry in 1966–1967 and the Ministry of Geology and Mineral Resources of China in 1959–1960 (Hu et al. 2012), and Yang (1987) compiled “Coal Geology Progress”. In 1996, in order to meet the 30th World Geological Congress held in Beijing, Academician Han (1996) edited “Coal Petrology of China”, Academician Yang (1996a) edited “The Coal Metamorphosis in China”, CNACG edited “Atlas for Coal Petrography of China” (Yang 1996b), and Chen (1996) edited “Coal Petrologic Atlas of China”. The above monographs reflect the achievements in coal petrology, coal quality, and
coal metamorphism in China at the end of the twentieth-century. In the twenty-first-century, in response to research on coal conversion and the utilization of modern technology, Bai and Ding (2016) compiled and published “Modern Coal Quality Technology”. In 2016, CNACG (2016) compiled “China Occurrence Regularity of Coal Resources and Resource Evaluation”, which is based on the research results of the major project “National Coal Resources Potential Evaluation of China”.

2 Research status of coal petrology in China

2.1 Overview of research status of coal petrology

The study on coal petrology in China began in 1930s and has a history of nearly 100 years. From 1926 to 1949, it was the pioneering period of coal petrology in China. Since the founding of China, China’s coal petrology has been growing steadily until the 1980s. In the 1990s, great progress was achieved in the study on coal petrology in China. In the twenty-first century, the development of coal petrology in China has reached a new stage. Chinese lithotype classification still uses the categorization of coal according to lustre of the Soviet Union, but there are many special coal species in China.

1. Tectonically deformed coal. According to the complex and multi-period geological structure of China, tectonically deformed coal was specially defined. The Standardization Administration of China made the “Classification of Coal-body Structure” standard to categorize coal into original structural coal, tectonically crushed coal, granulated coal, and mylonitic coal (GB/T 30050–2013). Jiang et al. (2016) summarized the classification and expounded the characteristics of tectonically deformed coal.

2. Sporinite liptobiolith coal. Dai et al. (2006a) found sporinite liptobiolith at Luquan, Yunnan Province. The coal had high contents of cutinite and microsporinite and were classified as cutinitic liptobiolith, sporinite-rich durain, cutinite-rich durain, and sporinitic liptobiolith.

3. Sphagnum coal. Coal petrology and palaeobotany scholars discovered a special coal species in Yunnan Province, Sphagnum coal (named the “white-light coal” by local people) and explored its origins (Lu and Zhang 1986, 1988; Qi et al. 1994; Wang et al. 1997). Its rank could be considered as soft brown coal. For this coal, two varieties of maceral were brought forward as a complement to the ICCP’s maceral classification of brown coal and lignite: sphagnum textinite and sphagnum fusinite.

4. Chinese sclerotia-algal coal. Xie et al. (2001) classified the origins of Chinese sclerotia-algal coal. The results showed that there were obvious differences in physical and chemical composition and characteristics between sclerotia-algal coal and humic coal. The forming environment of sclerotia-algal coal was mainly controlled by pH, Eh value and organic matter content.

5. Bark coal (barkinite). Barkinite was proposed by the Standardization Administration of China in 1991, but has not been recognized by the International Committee for Coal and Organic Petrology (ICCP) and The Society for Organic Petrology (TSOP), and there are many scientific problems that have not been resolved (Hower et al. 2007; Tang et al. 2011). The earliest study of bark coal in China was conducted by the coalfield geologist Hsleh (1933), followed by Han et al. (1983), Guo et al. (1996), Zhong and Smyth (1997), Sun (2001, 2002), Sun and Horsfield (2005), Tang et al. (2011), Jiao et al. (2012) and Wang et al. (2014, 2015, 2018a). “The Nature and Transformation of Bark Coal” compiled by Wang et al. (2018b), which systematically discussed the petrological characteristics of bark coal (barkinite) and rational utilization approaches.

There are several important events about the classification of macerals in Chinese coal. In the 1980s, liptohuminite was categorized according to the classification scheme of peat and soft brown coal macerals (Jin and Qin 1989). In the 1990s, semi-vitrinite and barkinite were classified according to “Classification of Macerals for Bituminous Coal”, and lepidophyte-fusinite, psaronius-fusinite, and other macerals were identified in coal (GB/T 15588–1995). Compared with the international classification scheme, semi-vitrinite was classified as vitrinite by “Classification of Macerals for Bituminous Coal” in 2001 (GB/T 15588–2001), and macrinite was divided into macrinite1 and macrinite2 in 2013 (GB/T 15588-2013). In the 1990s, meta-exinite, meta-vitrinite, meta-inertinite, and the other new macerals were divided according to the classification of macerals of high-rank coals in China (Qin 1994). Li et al. (2000), Chen (2007), and Chen and Ma (2002) summarized and analyzed the distribution characteristics of coal macerals in Chinese coal mines based on “China Coal Resource Database”.

2.2 Geological application of coal petrology

2.2.1 Coal facies

Tang et al. (2001) used coal facies parameters to analyze the relationship between the coal-forming
microenvironment and sulfur in coal, it was found that the characteristics of water medium played a leading role in many factors controlling the microenvironment of marshes. Dai et al. (2007) performed a coal facies study to determine the enrichment facies of gallium and its carrier boehmite in coal. Mao et al. (2011a) combined sequence stratigraphy, coal facies, and coal petrology to discuss the sections change of coal sequence, coal facies, and coal petrology, which enriched the coal-forming theory. Shao et al. (2009, 2017) discussed the research status on coal facies and sedimentary organic facies in Chinese coal measures.

2.2.2 Tectonically deformed coal

The earliest classification of tectonically deformed coal was discussed by Chen et al. (1989a). Su and Fang (1998) divided tectonically deformed coal into four types. Ju et al. (2004) classified tectonically deformed coal into three series and ten categories according to the structural deformation mechanism. In recent years, tectonically deformed coal and its internal structure, deformation mechanism, and chemical and physical changes (Cao et al. 2007; Ju et al. 2005, 2014a; Li et al. 2010, 2012; Song et al. 2013, 2014) are the hot topics of coal geology. Wang et al. (2008) and Ju and Li (2009) reviewed the research status of tectonically deformed coal and its ultrastructure, respectively. Zhang et al. (2016) discussed the orientation growth mechanism of tectonically deformed coal microcrystals. Tectonically deformed coal research is mainly applied to structural geology and safety (Jiang et al. 2009, 2016), and the exploration and development of coalbed methane (Hou et al. 2012).

2.2.3 Organic petrology

At the end of the twentieth century, the development and maturity of coal petrology promoted the emergence of organic petrology. The International Coal Petrology Commission developed into The International Coal and Organic Petrology Commission. The third edition of “Coal Petrology” by Stach was published in 1982 (Stach et al. 1982) and “The Organic Petrology” was published in 1998 (Taylor 1998). Professor Kuili Jin was the first person in China to develop coal petrology into organic petrology, he proposed the classification of organic matter of continental hydrocarbon source rocks (Xiao and Jin 1990a; Wang et al. 1993a, b; Tu et al. 2012) and marine hydrocarbon source rocks (Liu 1994; Qin et al. 1996) in China. Subsequent studies were conducted on the relationship between macerals and the formation of oil and gas (Xiao and Jin 1990b). Scholars used the macerals properties of petrology and geochemistry to research organic sedimentary facies (Yao and Jin 1995; Zhang et al. 1997). Yao et al. (1997) detected a large amount of coal particles in petroleum. Above achievements were included in the monograph “Organic Petrology Research” (Jin 1997).

2.2.4 Coalbed methane

Different macerals and coal ranks involve different generation and storage of coalbed methane. Professor Yong Qin was the first person to apply the coal petrology method to the geology and exploration of coalbed methane in China, followed by researcher Qun Zhang (Zhang and Yang 1999). Many achievements have been made with regard to the physical and mechanical properties of coal petrology (Qin et al. 1999), as well as the coal-body texture and the classification of pore fissures.

2.3 Industrial application of coal petrology

In the past 20 years, coal petrology has been mainly applied to the physical, chemical, and technological characteristics of coal macerals in processing, conversion and utilization, guiding the effective utilization of various coals and the reduction of environmental pollution. Coal blending coking theory is relatively mature (Zhou 1985), and the development of the technical process is manifested in the difference between automation and dynamic detection of coal blending technology. With the development of technology and economy, microscopic photometers have been installed in large-to-medium-sized coking plants and coal preparation plants in China. Reflectance distribution diagrams have been widely used in coal source detection and steam coal blending. The research of maceral properties (Li et al. 2007) and the separation of maceral and surface properties (Dai et al. 1998), coal–water slurry properties (Wei et al. 2003), pyrolysis characteristics (Zhang et al. 1998, 2002; Sun et al. 2002; Zhao et al. 2014a, b), gasification characteristics (Xu and Yan 2003; Tang et al. 2018a), liquefaction characteristics (Ye 2004; Xia et al. 2007; Li 2010; Wang et al. 2013), and combustion characteristics (Zheng and Wang 1992; Shu and Xu 1998; Zhang et al. 2002) have promoted the level and the pace of the industrialization of clean coal technology in China. Tang et al. (2018a) analyzed the petrological characteristics of the gasification residues and found that the dominant organic components were tenuispheres, crassispheres, tenuinetworks, crassinetworks, fusinoids, and inertoids. The micro-analysis of carrier minerals of sulfur and other hazardous elements in coal has developed into clean coal geological technology (Tang et al. 2006), which provides a scientific basis for coal desulfurization and demineralization, as well as the exploration and utilization of coal resources.
2.4 New coal petrology technologies

The traditional methods used in coal petrology are optical microscopy and photometry, and modern coal petrology methods have been greatly improved. Firstly, by the use of light sources, such as in fluorescence and focusing confocal microscopy. Second, by the use of resolution, such as scanning electron microscopy (SEM) (Zhang and Li 2004), transmission electron microscopy (TEM) (Wang et al. 2017a, b, c), atomic force microscopy (AFM) (Yang et al. 1994); Wang et al. (1993b) used TEM to discover super microliptinite in vitrinite. High resolution transmission electron microscopy (HRTEM) was used to study the changes of barkinite during heating (Wang et al. 2018c). Thirdly, by the introduction of large high-technology equipment for the micro-analysis of coal macerals, such as electron microprobes, atom microprobes, proton microprobes, microscopic infrared spectra, secondary-ion mass spectrometry, and in situ plasma mass spectrometry.

In addition, nuclear magnetic resonance (NMR) method (Liu et al. 2016) was used to study liquefaction products, asphalt and macerals of coal. NMR methods can provide various structural information to judge the evolution of organic matter, maturity of crude oil, types of organic matter and sedimentary environment. Electron paramagnetic resonance (EPR) method (Qin et al. 1998a, b) needs to be combined with other methods (such as X-ray diffraction, infrared absorption spectroscopy, nuclear magnetic resonance spectroscopy) to obtain more complete information about coal structure.

The methods and equipment above have enabled scholars to break through the limitation of observing only the morphology and optical physical properties of coal macerals in the past and transformed coal petrology analysis from macro and micro-scale to molecular-scale visualization.

ICCP and TSOP are two famous international conferences on coal petrology. When the International Carboniferous Stratigraphic Conference was held in Beijing in 1987, the ICCP was first held in Beijing, China. TSOP, founded in 1983 in the United States, was held for the first time in Beijing, China, in 2006. Professor Kuili Jin of China University of Mining and Technology, Beijing won the TSOP Contribution Award in 2007. In 2013, the joint annual meeting of ICCP and TSOP was held for the first time in Beijing, marking a new height for the international status of Chinese coal and organic petrology. In August 2018, TSOP was held again in Beijing. In October 2018, Professor Kuili Jin of China University of Mining and Technology (Beijing) received the Thiessen Award of ICCP for his important achievements and outstanding contributions in the field of coal and organic petrology.

3 Research status of Chinese coal quality

The evaluation of coal resources potential involves not only the estimation and evaluation of reserves and resources, but also the evaluation of coal quality. Coal is endowed with heterogeneity; it is not a pure substance. There are few laws about coals and it is difficult to explain some problems (regularity) accurately by chemical reaction kinetics. Because of coal’s complexity and diversity, coal sampling and sample preparation and analysis should be unified and representative.

The China Coal Standards Committee and various industry standards committees have formulated a series of standards for coal quality analysis in China. In 1958, the first coal classification in China was proposed. In the 1970s, China relaunched the project of coal classification. Chen and Yang (1985) improved the Roga index method and put forward the caking index to classify Chinese coal. The China Coal Standards Committee officially announced the new coal classification in 1986. In 2009, the China Coal Standards Committee modified the definition of coal and revised the terms and symbols of coal classification. Chen and Zhang (1995) and Chen (1999, 2000a, b, 2007), and Chen (2019) expounded in detail the principles, parameters and classification system of coal in China.

The third national coalfield prediction study produced the distribution map of Chinese coal species, which was revised by Xi’an Coal Exploration and Research Institute in 2002. In 2013, the coal quality group in the National Coal Resources Potential Evaluation Project won the first prize of the Ministry of Land and Resources. Tang et al. (2013a, b) systematically analyzed the coal quality characteristics of Taiyuan Formation and Shanxi Formation in Shanxi Province, made a detailed study of the distribution of coal quality in China, and completed “The Report on Distribution of Coal Quality in China”.

The study on coal structure has always been a hot topic and the most important basic research subject of coal science. It includes two aspects (Xie 1992, 2002): one is the chemical structure of coal—that is, the molecular structure of coal; the other is the physical structure of coal—that is, the stacking structure and pore structure between molecules. Qin et al. (1998a, b) studied the physicochemical structure and solubility of low-rank coals and other organic matter and proposed a conceptual model of coal composite structure. Zeng and Xie (2004) and Zeng et al. (2005) constructed the theoretical system and methodology of Chinese coal structural chemistry and discussed coal molecular engineering and its key problems. Sun et al. (2004) carried out a quantum chemical study on the...
molecular structure model of coal macerals. Qin et al. (2008, 2010) and Qin (2017) constructed a coal composite structure model and used it to explain bonding reduction and increase of permeability, the solubility and dissolution behavior of small molecules, and the formation mechanism of caking properties. In recent years, many scholars have studied the structure of coals of different metamorphic degrees with different research methods (Li et al. 2013a, 2015, 2017; Yuan et al. 2017), the above achievements enriched the theory of coal structure.

Traditional coal quality analysis is mainly about the organic part of coal. The analysis of adverse inorganic impurities (moisture, ash, sulfur, and carrier minerals of inorganic elements) is another hot topic in coal quality research in the past 30 years. Based on the database of Chinese coal resources, the distribution characteristics of ash yield (Li and Zhai 1992), sulfur content (Chen 1994; Li and Zhai 1994; Li 1998; Luo et al. 2005) and trace elements (Bai et al. 2003) have been summarized. The analysis showed that the ash yield of Chinese commercial coal is mainly medium–low and medium (GB/T 15224.1–1994). According to the geologic era, the lowest ash yield is found in Jurassic coal and the highest ash yield in Paleogene and Neogene coal. The highest sulfur content is found in Late Permian coal in South China, followed by Carboniferous–Permian coal in the Taiyuan Formation in North China, and the lowest sulfur content is found in Jurassic coal (Yuan 1999; Tang et al. 2015a, b).

Many achievements have been made in the study of sulfur in Chinese coals. The occurrence, distribution, and selectivity of sulfur in coal (Liu et al. 1985; Su 1988; Tang 1993; Lei 1993; Ren et al. 1994; Chen 1994; Li and Zhai 1994; Li 1998; Zhou et al. 1999; Luo et al. 2005; Gao et al. 2005; Hu et al. 2005a; Tang et al. 2015a, b) have been discussed in detail, and the current situation of relevant research (Zhou et al. 1999) has been clarified. There are abundant research results for organic sulfur in coal. The occurrence and distribution of organic sulfur (Tang et al. 2002; Hu et al. 2005b; Wei et al. 2015) in China has been systematically analyzed. It has been pointed out that the origin of sulfur dispersion and enrichment in coal is closely related to its sedimentary environment (Tang et al. 1996, 2015a, b; Tang et al. 2001). Origin models of organic sulfur in coal have been proposed (Lei et al. 1994; Dai et al. 2002). Shao et al. (2003) analyzed the geochemical characteristics of Heshan high-organic-sulfur coal. Dai et al. (2008, 2013) put forward the volcanic origin theory of high-organic-sulfur coal in Yanshan, Yunnan province, and the hydrothermal origin theory of high-organic-sulfur coal in Guangxi. The sulfur in Chenxi high-organic-sulfur coal has been studied in detail (Zhao et al. 2014a, b; Li and Tang 2014). Some scholars have discussed the geochemical regularity of trace elements with high-organic-sulfur in coal (Li et al. 2013b; Li and Tang 2013, 2014).

The primary factors affecting coal quality are generally recognized to be the coal-forming parent material (macerals transformed from plants) and coalification. Of course, the coal quality in efflorescent oxygenized belts is always worse. For coal organic matter, factors such as the Eh and pH values of the medium during peat formation are also causes for differences in coal quality. The other one major factor affecting coal quality is the degree of oxidation reduction (Zhao et al. 1994). Many inertinites are formed in an oxidizing environment, and vitrinite bonds formed in strong or weak reducing environments are quite different. Chen (2007) studied the reducibility of coal from a chemical point of view and put forward the concept of coal chemical faces. For the inorganic composition of coal, the mineral matter (ash yield) and sulfur content, as well as the major and trace elements, are undoubtedly related to the coal-accumulating environment. Modern coal quality research has been closely integrated with the system tracts of the sedimentary environment and sequence stratigraphy, which enriched the coal-forming theory and provided a scientific basis for the potential of clean coal processing and utilization.

In China, according to the classification of coal quality and the utilization of coal, new varieties of coal and new concepts have been produced.

(1) High-quality coal. The quality of coal is classified according to classification indicators. The National Technical Committee for Coal Standardization graded the ash yield, sulfur content, and calorific value of coal in 1994, 2004, and 2010, respectively, and ash yield grading was revised in 2018 (GB/T 15224.1–2018). Luo et al. (2015, 2019) interpreted and discussed the national standards for civil and commercial coal. Ash yield and sulfur content of coal resources were ranked statistically in the third coalfield prediction study (Mao and Xu 1996). The concept of high-quality coal was put forward according to its ash yield, sulfur content, calorific value, and washability (Yuan 1999). Cao and Zhao (2003) also put forward three suggestions on attaching importance to the research on high-quality coal resources. When Li et al. (2005) developed the western coal resources, the concept of high-quality coal was redetermined and classified; then, she categorized high-quality coal in the Ordos Basin (Li 2008). Qin et al. (2006) also proposed the classification and overall composition of Chinese high-quality environmental-friendly steam coal types.
(2) Clean coal geology. In view of the impurities and hazardous elements in coal, CNACG appointed experts and scholars to carry out a study of clean coal geology. Various hazardous elements were classified and the clean potential of gas, liquid, and solid utilization was classified into four or five grades (Tang et al. 2006). Wang et al. (2005a) studied the potential pollution comprehensive index and the clean class of hazardous elements in coal. Yang et al. (2011) put forward a classification into six grades and extended it to the evaluation of potential coal resources in various provinces and cities (Chongqing, Guizhou, Hunan, Anhui, and Shanxi). Tang et al. (2012, 2013a, b) classified grade six of coal quality according to the geological characteristics of coal and applied it to the evaluation of coal resources in Shanxi and Inner Mongolia. Based on the clean and efficient utilization of coal, Xie (2014a, b) compiled the “Coal Clean Efficient Conversion” and “China Coal Clean, Efficient, Sustainable Development and Utilization Strategy Research”. The National Energy Administration issued the “Coal Clean and Efficient Utilization Action Plan (2015–2020) “ in April 2015, which set a clear timetable for the clean and efficient utilization of coal in the next 5 years. In October 2018, the International Pittsburgh Coal Conference (PCC) was held in Xuzhou. Scholars exchanged ideas on the theme of “clean coal-based energy, fuel and environment”.

(3) Special and scarce coal. With the production and consumption of coal in China, gas coal, fat coal, coking coal, lean coal, and meager coal for coking have been scarce. The scarcity of high-quality blast furnace injection coal and activated carbon coal, coal rich in beneficial elements (such as germanium, gallium, and lithium), and the environmental hazards of high sulfur, high arsenic, and high mercury in coal, led to the emergence of “special and scarce coal”. Dai and Cheng (1991), Han (1996), and Zeng (2001) put forward the concept of special coal. Dai (2006b, 2010, 2012b, 2015a, b, 2018) and Qin (2009) studied the germanium and gallium resources in coal. Wang and Cao (1990), Ma (2004), and Guo (2018) analyzed coal for coking, blast furnace injection, activated carbon, carbon products, gasification, and other industrial raw materials. Suggestions on strengthening macro-control and rationally organizing production were put forward. The “Classification and Utilization of Scarce and Special Coal Resources” (GB/T 26128–2010) was put forward by the “Standardization Administration of China”. In 2010, CNACG undertook the project “Survey of Scarce and Special Coal Resources”, organized by the Ministry of Land and Resources. In January 2013, Professor Shifeng Dai put forward the concept of “coal-hosted rare-metal minerals” in Hangzhou. Then, he used coal-hosted germanium, gallium, uranium, niobium, rare-earth elements, and other rare-metal deposits as examples to discuss the geological origins, occurrence, and utilization evaluation methods of these deposits (Dai et al. 2014, 2018). Sun et al. (2014) proposed the minimum mining standards for lithium, uranium, thorium, and rare earths in coal. The experts and scholars participating in the 35th International Conference on Organic Petrology (TSOP) in 2018 conducted field research of the Wulautuga coal-hosted germanium deposit in Inner Mongolia.

4 Research status of coalification and coal metamorphism

Coalfield Professional Commission of China Geological Society (2003) summarized the characteristics of Chinese coal metamorphism research before 1997: the hydrothermal metamorphism type of coal and the new hydrothermal metamorphism of coal were proposed and determined in the 1980s and 1990s. Academician Qi Yang (1996a, b) put forward the theory of multi-stage evolution and heat-source superposition metamorphism of coal in China and pointed out that there are four types of heat sources: geothermal, magma, hydrothermal, and the high temperature of deep faults. Coal metamorphism can be divided into two categories: deep metamorphism and abnormal thermal superimposed metamorphism; the latter can be further divided into five types. Professor Dexin Han (1996) divided the metamorphic types into six types: deep metamorphism, magmatic thermo-metamorphism metamorphism, magmatic contact metamorphism, hydrothermal metamorphism, tectonic dynamic metamorphism, and burnt metamorphism. Yang Q (1996a, b), Li (1997), and Wu (1995) put forward the coal metamorphic zoning (belt) and distribution in China.

In the past 25 years, the new achievements in the study of coalification and coal metamorphism in China are mainly as follows, these results enriched the theory of coal metamorphism:

(1) Based on the evolution process of the molecular structure of coal, Qin et al. (1998a, b) put forward the superposition and electron paramagnetic resonance (EPR) step evolution for high-rank coals. Ju et al. (2005) studied the relationship between the nanoscale deformation and the metamorphic
deformation environment of the coal structure. The relationship between geological processes and coal quality (Fu et al. 2016) have been discussed.

(2) The catalytic effects of tectonic deformation on coalification from the stress degradation mechanism and the stress polycondensation mechanism have been explored (Cao et al. 2007); the relationship between coal structure and stress has been explained (Qu et al. 2012, 2015; Ju et al. 2014a), and new parameters of the coal deformation degree index have been put forward (Wei et al. 2017).

(3) The principles and methods of thermodynamic analysis have been combined with the evolutionary history of crust, the history of the thermal evolution of coal basins, and the geochemical characteristics of coal to study coal metamorphism as a dynamic process (Wu et al. 1997; Ren et al. 2007). Based on geothermal fields, the change of coal metamorphism under the synergistic action of geothermal anomaly and magmatic rocks has been analyzed (Wang et al. 2017a, b, c).

(4) In practice, scholars have used logging curves to identify coal rank (Mao et al. 2011b). XRD has been used to analyze coal metamorphic regularity (Zhang et al. 2010). The geological exploration and development of oil and gas and the utilization of coalbed methane have become hot research areas.

5 Research status of geochemistry of coal

In the past 20 years, China has attached great importance to the research of coalbed methane and clean coal technology and has invested a large amount of funding in 973 basic research plans and 863 technology projects, as well as a national support plan and major special projects. Up to now, three Ph.D. thesis examining the trace elements of coal, one Ph.D. thesis studying coal-derived oils, and two Ph.D. thesis investigating coalbed methane have won the title of 100 Excellent Doctoral Dissertations in China. Therefore, both inorganic and organic geochemistry are hot areas of coal quality research.

5.1 Inorganic geochemistry of coal

The study on trace elements in coal has always been an important subject in coal quality. In the 1980s, Sun and Jervis (1986) and Chen et al. (1985, 1989a, b) reported data of trace elements in the first batch of more than 100 coal samples and analyzed the distribution trend of trace elements in Chinese coals, which marked that coal geochemistry in China entered a systematic research stage. Ren et al. (1999, 2006) discussed the distribution characteristics and origins of trace elements in Chinese coals. Bai et al. (2003) analyzed the average contents of trace elements in Chinese coals based on the resources database. Tang and Huang (2004) conducted a detailed research on the trace elements in Chinese coal and clarified the significance of this study; their research results are published in “Trace Elements in Coal”, which contains the background values of 44 trace elements in Chinese coals from different regions. Ren et al. (2006) systematically reviewed the occurrence characteristics and distribution of trace elements in coalfield exploration and coal mines in China; these results are published in “Geochemistry of Trace Elements in Coal”. The latest summary study on the distribution of trace elements in Chinese coal was carried out by Dai et al. (2012a) and examined the content, enrichment, and occurrence of trace elements in China.

Dai et al. (2005) systematically summarized the occurrence and distribution characteristics of major elements in Chinese coal, introduced the concept of “reserve weight” (Ren et al. 2006), and put forward the background values of elements in Chinese coal.

Research has been conducted on some elements in coal: mercury (Zhou 1994; Feng et al. 2001; Bai et al. 2017), fluorine (Luo et al. 2004; Wu et al. 2005), arsenic (Zhao et al. 1998; Chen and Tang 2002), selenium (Zheng 1991; Zhu et al. 2003), uranium (Yao 1988; Chen et al. 2018), lithium (Sun et al. 2013), gallium (Dai et al. 2006b, 2018; Qin et al. 2009), germanium (Hu et al. 1996, 1997; Du et al. 2003; Dai et al. 2012b, 2015a, b), platinum (Dai et al. 2003), and rare earth elements (Zhao 2002; Dai et al. 2018). Many scholars have used the trace elements in coal as the main research object to complete their dissertations, such as Fenghua Zhao, Junying Zhang, Shifeng Dai, Guijian Liu, Liugen Zheng, Cuicui Qi, Jianming Zhu, Daizhen Wu, Mingshi Wang, Wenfeng Wang, Yuhong Xia, Wei Wang.

Extensive research on the migration and distribution of elements in coal in washing (Wang et al. 2005b; Duan 2017), liquefaction (Xia 2009), combustion (Wang et al. 2003; Zhang et al. 2003, 2007), and gasification (Tang et al. 2018a; Wang et al. 2018a, b, c, d, 2019) has also been carried out. Ren and Dai (2009) proposed that we should pay close attention to associated and accompanying mineral resources in coal and coal-bearing strata. Dai et al. (2010, 2012a, 2014, 2016, 2018) pointed out the presence of Nb and other rare-metal deposits in Permian coal-bearing strata in Southwestern China.

Studies on healthy effects of elements in coal have always been a hot topic. Zheng et al. (1999) reviewed the health and disease problems caused by As and F in coal in Southwest China. In 2002, the International Medical Geology Lecture was introduced at China University of
5.2 Organic geochemistry of coal

Organic geochemistry of coal is a science that studies on the composition, structure, and hydrocarbon evolution of coal organic matter. The study of biomarkers is the basis of organic geochemistry of coal, and carbon and hydrogen isotopes are its main research means. Recent advances are mainly in the study of coal-formed hydrocarbons—that is, the study of coal-formed oil and coal-formed gas.

Some achievements have been made in coal geochemistry regarding coal-based products and non-fuel utilization of coal. In 1999, fullerenes (C60) were found in Yunnan coal and began to be studied. Since the advent of graphene in 2004, many scholars have studied coal-based graphene and coal-based graphene quantum dots (Zhang 2015; Tang et al. 2018b; Huan et al. 2019; Huan 2019) according to the characteristics of coal petrology.

Regarding coal-formed oil, there are some monographs written by Fu (1990), Huang (1992, 1995), Fu and Qin (1995), and Wang (1998), and so on. These monographs were popular in China in the 1980s and 1990s and systematically examined the achievements of organic geochemistry of coal in China. “Hydrocarbon Source Rocks in China”, written by Qin (2005), elaborates on hydrocarbon generation and migration of hydrocarbon source rocks types in a coal-forming environment. Advances in the research of coal-formed oil include: signs of coal-formed oil (Hu 1998); mechanisms of coal-formed hydrocarbon generation; hydrocarbon expulsion from coal-bearing strata; evaluation of hydrocarbon generation potential of coal hydrocarbon source rocks; distribution of coal-formed oil (Huang and Lu 1999).

Academician Dai (1982) determined the definition of coal-formed gas in 1982. Chen et al. (1999) considered that the coal-bearing mudstone in the Northwest region, especially in the Turpan-Hami Basin, was the main hydrocarbon source rock, and coal and carbonaceous mudstone were the secondary hydrocarbon source rocks. Su (2005) considered that crude oil from the Middle Jurassic in Northern Sag of Turpan-Hami Basin is strictly not “coal-formed oil”, but “source-mixed oil” formed by deep lacustrine facies and coal-bearing hydrocarbon source rocks. Chen et al. (2006) believed that vitrinite and collodetrinite have a relatively low potential of hydrocarbon generation and do not easily become the main macerals for coal-formed oil, but they can be good gas-prone macerals at the stage of high maturity to over-maturity. Fusinite has an extremely low potential of hydrocarbon generation and cannot be the organic matter for oil generation.

Coalbed methane is an unconventional natural gas formed and reserved in coal seams. Coalbed methane research involves many subjects, such as coalfield geology, natural gas geology, geochemistry, physics, chemistry, seepage mechanics, and so on. It is generally believed that liptinite and vitrinite are the macerals with the strongest potential of gas generation and that inertinite is the weakest. The types of coalbed methane are mainly determined by carbon and hydrogen isotopes (Tao 2005), the origins of coalbed methane are diverse (Qin 2012; Ju et al. 2014b), and the distribution, occurrence, and enrichment patterns of coalbed methane are significantly affected by geological factors (Qin et al. 2017; Liu and Li 2014).

It is generally recognized that coalbed methane is an autogenic and self-reserved unconventional natural gas. The gas content at a certain point in a gas reservoir is the instantaneous value at the dynamic equilibrium state of desorption—absorption—diffusion—seepage (migration), which varies with changes in reservoir temperature, pressure, concentration difference, pressure difference, and water flow. A coalbed methane reservoir has the characteristics of dual-porosity and dual-permeability and has internal and external fractures, face cleats and butt cleats, and pore types (Zhang 2001; Fu et al. 2005). The pore-fracture heterogeneity of coalbed methane reservoirs is controlled by four main geological factors (Liu et al. 2015). Permeability has been classified (Su and Fang 1998; Kang et al. 2017), coal reservoir permeability varies with different gas production stages (Tang et al. 2015a, b), and coalbed methane reservoir permeability is affected by five main factors (Wang et al. 2017a, b, c).

6 Prospects

The characteristics of Chinese resource determine that China is still a big country with coal as the main energy consumption structure. There are still many coal science and engineering problems under exploration, exploitation, processing, conversion, and utilization. China should be the world research center of coal. Resource-saving and clean coal utilization are not only requirements of the world, but also the desire of the nation and the people.

(1) Traditional coal petrology is based on optical microscopy. Modern coal petrology breaks through the limitation of low resolution of optical
microscopy and moves towards electron microscopy and micro-analysis. Using advanced science and technology from both petrology and geochemistry and in the macroscopic, naked-eye, microscale, molecular, and atomic level, the composition and evolution of coal are studied and the research field is expanded.

(2) Recently, researchers at Massachusetts Institute of Technology (MIT) developed a central process unit (CPU) by carbon nanotube (CNT), which some believe is the beginning of artificial carbon-based life. Coal is the most ideal carbon source, which can provide strong material support for carbon-based revolution and artificial carbon-based life. We believe that under the support of coal petrology theory, great progress will be achieved in coal-based carbon materials and high-tech carbon products in the future. Nowadays, the progress of bioscience will promote the theoretical study of coal organic matter, improve the utilization rate of its useful components, detect the effective removal and recycling of coal inorganic matter, and provide a scientific basis and technical assurances for clean coal technology and environmental protection.

(3) Coal is the product of long-term geological evolution, there are a lot of ancient information about geology, geography, climate and biology in coal. The study on coal petrology will be helpful to the exploration of the origin of the universe and human beings in the future. A great deal of ancient information and advanced knowledge cracked in the process of coal petrology research will also contribute to the study of relevant modern basic theories. The research of deep space science, deep drilling science, and deep sea science, the intersection and integration of multiple disciplines, the introduction of new theories, and the wide application of advanced technologies—such as cloud computing, big data and artificial intelligence—will bring new research and applications of new energy sources and materials based on coal petrology and organic petrology.

(4) The research on coal petrology will improve the scientificity and safety of coal mining in China, and promote the efficient processing and utilization of coal chemical industry. The unique coal chemical products (such as graphene and hydrogen energy) and rare metals in coal are important sources of future medical and military materials. In addition, the study of coal petrology will also promote the development of optical, thermal, mechanical and electrical instruments in the future.

In the future, new achievements will emerge in the fields of coal geochemistry, clean coal utilization, coal-based materials (coal-based carbon materials, fullerene, coal-associated minerals), coalbed methane, shale gas, and in basic research and the technological development of new fossil fuel energy.

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