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Coal resources and coal geology in China

China holds the premier place in the world in terms of coal resources. The coal mainly accumulated in four periods: the Carboniferous–Permian, Jurassic, Cretaceous and Tertiary. The Carboniferous–Permian coal formed in a paralic environment on the stable Sino–Korean and Yangtze blocks. Jurassic coal accumulated in continental basins in the north of the Kunlun–Qinling orogenic belts; some Jurassic basins, such as the Ordos and Junggar basins, contain giant-size reserves. Cretaceous coal was mainly deposited in the fault-bounded basins of north-east China, similar to that in the Basin and Range Province in the United States. In the Tertiary, coal was mainly deposited in the basins of the circum-Pacific region and Yunnan Province. The accumulation of coal was predominantly controlled by palaeoclimate, tectonic framework and palaeogeography.

Introduction

China, rich in coal resources, is one of the largest coal-producing countries in the world. The total area underlain by coal is about 550 000 km² and since the 1950s, about 900 billion tonnes of coal have been discovered and proved while up to 3 200 billion tonnes of potential resources of coal have been predicted above a vertical depth of 1500 m. Over the last two decades, a series of new under-

standings and successes in exploration have resulted from integrated studies including:

- integrated analysis of basin formation and evolution in terms of their dynamic tectonic settings;
- study of depositional systems, sequence stratigraphy and sea-level changes on a basin scale;
- investigation of coal-rich zones and high quality coal-rich units and
- research on the regional zonation of coalification and the genetic relation between coal and oil/gas.

The nature of the coal-bearing basins, the palaeoclimate and the tectono-geographic settings of the basins are the major factors controlling regional coal accumulation. The distribution and characteristics of coal seams within the basins are mainly attributed to the configuration of depositional systems and the palaeostructural conditions.

The distribution and constitution of coal

There have been four important coal-forming periods in China: the Carboniferous, Permian, Early–Middle Jurassic and Early Cretaceous (Figure 1). Coal accumulation during each period was concentrated in certain places (Wang, Z, 1991), and obviously controlled by the tectonic framework.

The Carboniferous and Early Permian coal was mainly accumulated in the Huabei (north China) depositional basin, stretching over 12 provinces in the district of Sino–Korean block. The coal resources in this district account for 20% of the total reserves of the whole country. Since the 1970s, a number of new coalfields have been found beneath the Quaternary sediments in the Huabei plain.

The Late Permian coalfields in China are distributed over a large area to the south of the Yangtze River, and concentrated in the western Guizhou, eastern Yunnan and southern Sichuan Provinces. The coal formed in this period accounts for 10% of the total reserves of the country.

The Early–Middle Jurassic coalfields are mainly located to the north of the Kunlun–Qinling orogenic

Figure 1 The distribution of coal resources between the districts of China and in geological time (Coal resources in Tibet are not included).

P($P_2 \gg P_1$) Permian in south China
 C₃+P Late Carboniferous and Permian in north China
 J₁₋₂ Early-middle Jurassic
 K Cretaceous

Figure 2 *Distribution of Permo-Carboniferous coalfields and tectonic setting in the Huabei district.*

Od	Ordos;	Dn	Datong-Ningwu;
Qs	Qinshu;	Hl	Helan;
Kl	Kailuan;	Hn	Huainan;
Td	Taihangdong	Lh	Luxi-Huaipei;
Yx	Yuxi	Tz	Taizihe

belts. The coal accumulated in this period accounts for 60% of the total in China. A few giant coal-bearing basins such as the Ordos, Junggar and Turpan-Hami basins have been found, each containing more than 500 billion tonnes of coal.

The Early Cretaceous coal-bearing basins, mostly fault-bounded basins, were mainly developed in the eastern part of the Inner Mongolia Autonomous Region and the Heilongjiang, Jilin and Liaoning provinces. The coal accumulated in this period accounts for 7% of the total reserves.

Apart from the four major coal accumulation periods, some economically important local coalfields were formed during the Triassic and Tertiary, although they only account for 3% of the total.

A full spectrum of rank is represented in Chinese coal but half of them are low rank bituminous coal most of which is used for power generation and in other industries. Coking coal accounts for one fifth of the total coal resources.

In China, 70% of the energy consumed is generated from coal. It has been used by industries as an important raw material for years but recently, in order to reduce environmental pollution, coal purification and new energy conversion methods have begun to be developed. The large amounts of low-sulphur, low-rank coal reserves provide a good basis for reducing environmental pollution in the near future.

Palaeozoic coal

Large Palaeozoic, coal-bearing basins formed at low palaeolatitudes, in the Sino-Korean and Yangtze micro-continents as they drifted in the same direction from the south to the north. The Sino-Korean continent eventually collided with the Siberia plate to the north and became the southern part of Pangea during the Carboniferous. Between the Sino-Korean block in the north and the Yangtze block in the south, is the Qinling orogenic belt, where no ophiolite or deep oceanic sediment has been found but which does contain some Carboniferous-Permian shallow marine sediments. This, together with palaeomagnetic data (Wang et al., 1990) suggests that the two blocks were close to each other. The Changnin g-Menglian suture belt, representing the palaeo Tethys ocean, extended northwestwards to the west of the Yangtze block during the Carboniferous and Permian. Stable cratonic platforms surrounded by ocean are favourable for widespread coal accumulation. Extensive epeiric seas covered the platforms when the sea level rose and peat swamp probably developed on broad coastal plains as sea level dropped. A high frequency of sea level changes have been recorded in the Permo-Carboniferous systems and these, together with on-going subsidence, determined the characteristics of basin fill and the coal accumulation.

Coal in the Huabei District

Permo-Carboniferous coal deposition occurred on two types of basements in the Huabei (north China) district. The Sino-Korean continental block was the site of the major Huabei basin, and the Proterozoic-Early Palaeozoic aulacogen along the west margin of Helan Mountains, was where the Carboniferous and Permian coal-bearing system developed (Figure 2). The latter reached a thickness of 3000 m owing to the reactivation of basement faults (Lin Changsong et al., 1991). The Sino-Korean block was uplifted in the Late Ordo-

vician and there was no sedimentation in the basin until the Late Carboniferous when transgression occurred. The transgression came mainly from the east, south-east and south-west, while the terrigenous clastics supply was predominantly from the marginal highland in the north. The epeiric sea was shallow with a very flat sea floor so that small-scale fluctuations in the relative sea level resulted in transgression or regression over large areas. This process may have had a major control over basin fill and coal deposition.

The Lower Permian and Upper Carboniferous strata are an evolutionary series deposited under a regime which evolved from regional transgression to regression, and consisting of the Benxi, Taiyuan, Shanxi and lower Shihezi formations. The Taiyuan and Shanxi formations are the major coal-bearing measures. A series of parasequences has been identified in the formations. Densely spaced boreholes show that most of these parasequences or parasequence sets are correlatable throughout the basin. Fluctuation in relative sea level is regarded as the cause of cyclical sequences over such a broad area.

The Late Carboniferous to Early Permian epeiric sea depositional systems in the Huabei basin show a regular latitudinal zonation from the north to the south (Yang Qi et al., 1988). Fluvial deposits were developed along the northern margin and laterally changed into a deltaic-clastic shoreline system and then into a carbonate tidal flat-shallow carbonate platform system in the south. The deltaic sequences are characterized by a thin deltaic front and widespread deltaic plane facies. As a result of sea level changes, regression and progradation of the system tracts took place simultaneously on a large scale (Lin Changsong et al., 1995). The shoreline facies, including lagoon-barrier and tidal deposits, are characteristic of the mid-tidal environment. To the south, the facies associations are dominated by tidal flat and shallow marine carbonate deposits, in which storm-wave generated carbonate beds are common (Long Yaoshen et al., 1991). Detailed analysis of facies architecture of the Permo-Carboniferous section has shown that the clastic systems formed during an early transgression stage and were modified mainly by wave energy, while those developed during the late stage of transgression or before the regional regression, were mainly reworked by tidal energy (Lin Changsong et al., 1995). Towards late Early Permian time, fluvial processes increased intensively and the fluvial-deltaic system prograded to the south. The Late Palaeozoic deposition in the Huabei depositional basin was terminated with the orogenic activity that closed the Qinling sea by the collision between the North and the South China blocks during the Middle Triassic.

The important Permo-Carboniferous coalfields in the Huabei Basin are concentrated in Shanxi, Ningxia and Anhui. In the northern part of the basin, most of the mineable coals are associated with deltaic/clastic shoreline deposits (Chen Zhonghui, 1989; Lin Changsong et al., 1991). The extensive abandoned deltaic plains associated

with shoreline environments provided a favourable platform for the formation of continuous and thick coal seams, enhanced by the stable tectonic setting. Thick coal seams commonly occur in the upper parts of the regressive parasequence sets in the section. As the deltaic systems prograded southwards with the regional regression, the coal-rich zones migrated also southwards from the Late Carboniferous to the Early Permian (Tong Yuming and Lin Ke, 1989). In the Helan Mountain area, along the north-west margin, the coal seams are thicker and multi-bedded owing to the relatively rapid subsidence caused by basement faulting.

Coal in The Yangtze District

The Permian was the most important coal-forming period in southern China and Permian coal series are widely distributed over all the southern provinces. The basins are mainly distributed in Fujian and Guangdong provinces, but the reserves are relatively small. Most of the Permian coals were formed in the Late Permian and about 80% of the coal is in the western part of Guizhou, the southern part of Sichuan and the eastern part of Yunnan. During Permian time, the Yangtze block drifted to the northern margin of Tethys and was close to the Sino-Korean block which had been part of the Pangea. During the Early Permian, carbonates were developed over the whole of southern China, possibly because of postglacial, global sea level rise. Following this, the major coal accumulation took place in southern China during the Late Permian. Rifting occurred along the western margins and the southern part of the Yangtze block, resulting in the most intensive late Palaeozoic basaltic eruptions (Luo Zhili et al., 1990), of which the Permian Emeishan basalt was the most extensive. The Song-Pang and Simao microblocks, located to the west of the Yangtze block, probably had both been part of the original Yangtze block and were later separated by rifting. Late Permian coal mainly accumulated in the south-western part of the Yangtze block, stretching over Yunnan, Guizhou and Sichuan in an extensional setting.

From the Kangdian old land in the west to the east and south-east, the facies associations show a regular transition from fluvial to deltaic/clastic shoreline and carbonate deposits. Reefs of the marginal carbonate platform facies are seen along the border between Guizhou and Guangxi. Further to the south, small carbonate islands developed in Guangxi, where the fault troughs, separated by isolated fault blocks, are filled with semi-deep water deposits (Figure 3) (Li Sitian et al., 1990; Xia Wenchen et al., 1994;).

The economically important coal of the Yangtze block is in the Liupanshui coalfield in the north-western part of Guizhou Province. This is the largest coalfield in southern China with total reserves of up to 60 billion tonnes. The coal measures were mostly formed in abandoned deltaic plains, which were protected seaward by a broad

carbonate platform and reefs. Tectonically this coal-forming area is located along the Yangtze block margin where faulting resulted in relatively rapid subsidence. The development of depositional systems tracts and the formation of coal seams was strongly influenced by the relative sea level fluctuation. About 30 parasequences have been identified in the Upper Permian Longtan Formation in the western part of Guizhou. There are no lowstand tracts within the Yangtze block but highstand and transgression system tracts occur. Abyssal or bathyal deposits developed only in the tectonically active troughs.

Mesozoic coal

By the end of the Middle Triassic, the main part of the China continent had merged, and upon it a variety of continental basins had developed (Li Sitian et al., 1990). The Kunlun-Qinling orogenic belts and Sanjiang area are all the result of plate convergence or collision during Indo-China time. During the Late Triassic, foreland basins developed in the areas around the northern flank of the Qinling and on the north-western front of the Yangtze block. In southern China, the Late Triassic coal-bearing basin was a large epeiric sea, which received sediments over a large area, but only locally contains mineable coals, such as in the Chuxiong basin.

Large Jurassic coal-bearing basins

There are a number of giant Jurassic coal-bearing basins in China, such as the Ordos, Junggar and Turpan-Hami basins (Figure 4). They are all inland basins predominantly filled by lacustrine deposits (Wang Jingbin, et al., 1988; Wu Chongyun et al., 1992). Tectonically, the formation of these basins was closely related to thrusting and flexuring. In the Jurassic, the Qinling-Kunlun orogenic belts already had a strong influence on the continental climate. High humidity, favourable for peat swamp development, was restricted to a zone north of the mountain belt and only red beds were formed in the southern China.

The Ordos basin

Coal reserves in the Ordos basin are up to 700 billion tonnes or more, mostly of low-rank bituminous coals with very low ash and sulphur contents. This is one of the most prospective coal-producing basins in terms of size, coal quality and access to transport and a new coal-producing base is being established in the Shenmu area, north-east of the basin. The Ordos basin, formed during a post-foreland stage, is very flat and only slightly deformed. It rests unconformably on an Upper Triassic foreland basin. Palaeogeographical reconstruction has shown that the relatively small coalfields around the central

basin, including Datong, Ningwu and Rujigou, are all parts of an original basin which became isolated by deformation and erosion. The present basin is probably only half of its original size, and the former lacustrine centre is now located in the present basin's eastern margin. Major coal development took place on lacustrine deltaic plains and lacustrine bays encroaching around a central lake (Li Sitian et al., 1992). Several coal-rich units, each with an area of about 400–1000 km², have been delineated by using bore-hole data. They are commonly coincident with deltaic lobes or lake bays. The combined thickness of mineable coal seams is over 20 m and the primary zonation of coal facies is commonly circular in plan, consistent with the shape of the coal-rich units.

Figure 3 The distribution of Late Permian coal-rich zones and the tectono-palaeogeographic setting in the Yangtze coal district.

Figure 4 Distribution and tectonic setting of Mesozoic and Cenozoic coal-bearing basins.

Od Ordos; Dt Datong; Jg Junggar; Th Tuha; Yl Yili; Tm Tarim; Sc Sichuan; Cx Chuxiong; Hl Hailaer basin group; El Erlian basin group; Sl Songliao basin group; Sm Sanjiang-Muling; Bh Bohaiwan; Es East China Sea; Pl Pearl; Zt Zhaotong.

The Junggar and Turpan-Hami basins

These basins were first formed during the Carboniferous and Early Permian when they received turbidite sediments. By the Late Permian they had become shallow and very thick oil shales accumulated. Later, nonmarine Mesozoic basins were developed. Hsu (1989) explained this long history by means of a model in which he proposed that the basin evolved from a backarc, via a relic backarc, into a foreland basin. The continuous flexuring in the Jurassic was related to orogenic movement in the Tianshan mountain belt. The Lower and Middle Jurassic Badaowan and Xishanyao formations contain widespread, very thick coal seams and very large reserves. The coal-forming settings were mainly lacustrine fan delta, delta and lake bay environments. The Jurassic coal series in the Turpan-Hami district are similar to those in Junggar basin. They might have originally belonged to one large basin. Investigation has shown that the coals in the Badaowan Formation, rich in exinites and fluorescent vitrinites, are probably important oil and gas source rocks. Commercial oil reservoirs have been proved in the Turpan-Hami basin.

There are other Jurassic coal-bearing basins in the Xinjiang Uygur Autonomous Region, such as the Tarim (north margin) and the Ili basins, but most of the Lower and Middle Jurassic coal resources are concentrated in the basins discussed above.

Early Cretaceous fault-bounded basins

Early Cretaceous coal-bearing fault-bounded basins are found mainly in the Inner Mongolia Autonomous Region and the Heilongjiang, Jilin and Liaoning provinces of north-east China. Con-

temporeaneous basins can be found to the south of the Yinshan Mountain Range (about 4°N), but they were formed in a semi-dry climatic zone (Figure 4). This basin system, named the 'Northeast Asia Mesozoic Basin System' (Li Sitian et al., 1988), was not discovered until the 1970s being mostly covered by younger sediments. The basin system, composed of grabens, half- or complex grabens and separated by horsts, is distributed over a large area of about 2 000 000 km^2 , extending from north-east China to Mongolia and the Lake Bajkal district of Russia. More than 150 fault-bounded basins have been delineated within the territory of China.

Structurally, this basin system is similar to the Basin and Range Province in the USA (Eaton, 1982) and was formed by regional extension accompanied by strike-slip faulting. The fault-bounded basins in China mainly lie in two zones: the first, west of the Dahinggan Mountain Range, including the Hailaer and Erlian basin groups; the second, east of the Dahinggan Mountain Range, extending from the western and northern Liaoning northward to the deep part of the Songliao Basin. These basins are relatively small in area, usually about 1000 km^2 , but may contain very thick coal seams (>50m). In some basins such as the Shengli basin, the cumulative thickness of coal seams may exceed 200 m. The total coal reserves in the basin system is about 200 billion tonnes. All of the deposits are continental, dominated by lacustrine and lacustrine fan delta sediments and the coals are mostly low-rank bituminous or brown coals with low ash and low sulphur contents. Dark lacustrine mudstones, some up to 1000 m thick, can be found in some basins. Many small oil fields have been discovered and it has been proven that about 40 Early Cretaceous fault-bounded basins, buried deeply beneath the Songliao basin, are very important gas (including coal-related gas) sources.

Cenozoic coal and potential resources

The closure of palaeo-Tethys, the collision of the Indian and Eurasian plates and the uplift of the Qinghai-Xizang Plateau, resulted in significant climatic variations. In the continent of China a dry climate has been prevalent since the Cretaceous. So, the Cenozoic coal-bearing basins were formed only around the Pacific Ocean, and concentrated in north-east China and Yunnan and Guangxi provinces in southern China. Tertiary coals formed mostly in strike-slip basins some of which contain coal seams, hundreds of metres in thickness (e.g. the Xiaolongtan and Xianfeng basins in Yunnan and the Fushun basin in Liaoning). Up to now about 300 basins of this type have been discovered and most of them are located in Yunnan. The largest Zhaotong basin has reserves of some 8.2 billion tonnes. The Bohaiwan basin is a well known Tertiary oil-bearing rift basin and in the northern part of the basin, the Lower Liaohe area, economically important coals are also present. The Tertiary coals in Taiwan were mainly formed in Miocene paralic depressions, which resulted from thermo-subsidence developed upon underlying fault grabens. By the end of Miocene, these basins had evolved to foreland basins through arc-continent collision. Most of the present sea floor in the modern East China Sea was dry land during the Early Tertiary. In the East China Sea and the South China Sea, the Early Tertiary basins such as the Pearl River Mouth Basin, Beibuwan and Qiongdongnan basins in the northern margin of the South China Sea, commonly contain coal seams associated with lacustrine or marine mudstones, mainly deposited in basal grabens. These coals and mudstones are major oil and gas source rocks. The coal-bearing Pinghu Formation in the East China Sea was formed in paralic basins, with tens of coal seams. Studies have shown that these coals, with high contents of exinites and hydrogen-rich vitrinites, also have high potential as oil source rocks.

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