Acta Geologica Sinica (English Edition), 2021, 95(1): 121–130

A Comparative Study of the Coal-forming Characteristics of Marginal Sea Basins and Epicontinental Sea Basins

ZHAO Honggang[1], LI Ying[2], CHANG Xiangchun[1], LI Zengxue[1, *], LIU Haiyan[1] and ZHAO Cunliang[3]

[1] *The Shandong University of Science and Technology, Qingdao, Shandong 266590, China*
[2] *Shandong Jiaotong University, Jinan 250357, China*
[3] *Hebei University of Engineering, Handan, Hebei 056038, China*

Abstract: The coal-forming characteristics, as well as the similarities and differences between epicontinental sea basins and continental marginal sea basins developed during different time periods, were analyzed in this study by adopting comparative analysis thoughts and methods. The results obtained in this study revealed that epicontinental basins and marginal sea basins are both characterized by the main development of thin coal seams or extremely thin coal seams. In addition, changes in sea levels were determined to be the main controlling factors for coal formation, and there were similarities in the continent-sea interactions and coal-forming sedimentary systems of the different basins. However, there were also significant differences observed in the sea level change events, basin basement structural characteristics, coal seam stability levels, accumulation and aggregation characteristics, and the migration patterns of coal-forming materials. For example, the marginal sea basins in the South China Sea were found to be characterized by strong tectonic activities, diversity and complexity. The basin structures showed complex patterns of depressions, uplifts and concave or sag uplifts, which tended to lead to greater complexity in the paleogeographic patterns of the coal formations. This had subsequently resulted in complex coal -forming processes and paleogeographic characteristics, in which the coal-forming zones displayed bead-like distributions, and the enrichment areas and centers were scattered. The practical significance of studying the similarities and differences of the coal -forming characteristics between epicontinental basins and marginal sea basins is that the results can potentially be used to guide the predictions of coal-measure coal seam distributions in South China Sea, as well as provide valuable guidance for future explorations of natural gas reservoirs related to coal measures in the South China Sea area.

Key words: thin coal seams, epicontinental sea basins, marginal sea basins in South China Sea

Citation: Zhao et al., 2021. A Comparative Study of the Coal-forming Characteristics of Marginal Sea Basins and Epicontinental Sea Basins. Acta Geologica Sinica (English Edition), 95(1): 121–130. DOI: 10.1111/1755-6724.14630

1 Introduction

In the field of geological history, coal-forming processes are known to occur in large basins of different ages and types. The formations of coal deposits are of important economic value, and coal measures make important contributions to hydrocarbon generation. For example, northern China's large Carboniferous–Permian epicontinental sea basins are typical of the Earth's coal-forming basins. The Cenozoic epicontinental sea basins which have formed in the South China Sea, particularly during the Oligocene Period, are also considered to contain important coal-measure source rock.

Although the epicontinental sea basins and marginal sea basins mentioned in this study are not sedimentary basins from the same period, they have all undergone important coal-forming processes. Relatively speaking, their main characteristics are that the formed coal seams are relatively thin, particularly the coal seams formed in the Paleogene continental marginal sea basin of the South China Sea, and can basically be categorized as thin or extremely thin coal seams (Li et al., 2010a; Mi et al., 2010).

Coal geologists have long studied perspective coal-forming basins, as well as coal-forming paleogeography, coal accumulation rules, and coal occurrence characteristics (Han et al., 1979; Yang et al., 1979; Li et al., 1992; Li and Wei, 1998; Cao et al., 2018). Also, research has been conducted regarding coal-measure petrology and geochemistry (Sun et al. 2002; Sun, 2003), in which important discoveries were made regarding wildfire events in the coal seams of northern China's coal forming basins, along with in-depth analyses of paleoclimate conditions (Sun et al., 2002; Sun et al., 2015; Xu et al., 2020). In recent years, rich achievements have been put forward, which have greatly promoted and enriched the theoretical systems of coal geology. The examinations of coal-forming paleogeographic characteristics are important parts of sedimentary basin analysis and research fieldwork, and distinct characteristics have been revealed. Also, they are one of the most characteristic directions in lithofacies paleogeography research at the present time. Based on the special paleogeography during the important stages of plant evolution and coal-forming periods in geological history, peat mires have been deeply studied and re-

* Corresponding author. E-mail: lizengxue@126.com

recognized (Dai et al. 2020). The Carboniferous-Permian epicontinental sea basins of northern China have long and detailed research histories. In recent years, some new theoretical viewpoints have been put forward, such as coal -forming theories of transgression events in large epicontinental basins (Li et al. 2003). However, in regard to the large-scaled Carboniferous-Permian epicontinental sea coal-forming basins in northern China, it has been speculated that their special tectonic settings and special paleogeographic conditions may require unique coal-forming models.

The study of oil and gas geology, as well as the exploration of natural gas data in the South China Sea, have revealed the tectonic evolution and distribution characteristics of the sedimentary basins in the South China Sea. In addition, the basic conditions have been put in place for further examinations of the coal-forming characteristics and mechanisms of the region. There are many large Cenozoic sedimentary basins located in the South China Sea area. These basins were developed with extremely thick continental and marine strata, and are considered to be favorable prospect areas for China to potentially locate large gas fields (Pang et al., 1995; Gong and Wang, 1997). For example, the Yanan sag in the Qiongdongnan basin, southeast of the Zhusan sag in Pearl River Mouth basin, and south of Yinggehai basin are all considered to be favorable enrichment areas of coal derived gas resources (Zheng et al., 2009; Li Y C et al., 2011).

Although the aforementioned two types of basins were formed during different ages, the epicontinental sea basins were the important Carboniferous-Permian coal-forming basins, which belonged to the category of super large basins. The marginal basins of the South China Sea are Paleogene-Neogene basins. These are also classified as large basins composed of several fault basins, which were controlled by structural factors during the coal-forming periods. Therefore, due to the important coal forming processes which occurred in the epicontinental sea and marginal sea basins, the sea-continental interactions were necessarily the prominent features of the two types of basins. In addition, sea-level changes were the main controlling factors of the deposition, filling, and coal-forming processes of the two types of basins. However, there were also major differences in the characteristics of coal-forming processes, as well as varying accumulation rules for the coal-forming materials. Therefore, it is of major theoretical and practical significance to examine and compare the two types of basins in order to explore the difference mechanisms of the coal-forming processes and coal-forming materials. Determining the similarities and differences, and in particular the similarities and differences in the accumulation laws of the coal-forming materials, will assist in accurately predicting the distribution laws of the coal-measure hydrocarbon generating materials in the South China Sea area. As a result, important guidance can be provided for future explorations of oil and gas resources in the region.

2 Similarities and Differences

Epicontinental sea basins are known as important super-large coal-forming basins in geological history. Moreover, the Cenozoic-Oligocene marginal sea basins in the South China Sea are also considered to be important large energy basins. Since both epicontinental sea basins and continental marginal sea basins are important basins related to continental and sea regions, and there have been found to be both similarities and differences in the attributes, background, and filling evolutions of the two types of basin. This has been found to be particularly true in regard to their coal-forming characteristics.

(1) Northern China's Late Paleozoic epicontinental sea basins

The concept of epicontinental sea basins remains controversial. At times they are called "inland seas", which refers to the waters which go deeply into the interiors of continents. These water bodies are surrounded by continents or islands, and connect with oceans or sea areas only through narrow channels. The marine hydrological characteristics of epicontinental sea basins are clearly affected by the continents in which they are situated. In addition, epicontinental sea basins may also be referred to as "inland surface seas". However, they are quite different from "inland seas". During transgressive periods, marine environments tended to have continental crusts as their sedimentary bases. Meanwhile, during regression periods, continental environmental conditions were often affected by transient transgression processes. That is to say, high frequency sea level changes often occurred.

The scope characteristics of the northern China epicontinental sea basins are roughly equivalent to the North China Platform, as well as the southern stratigraphic regions of northeastern China. During the Carboniferous-Permian Period in northern China, a giant coal-forming zone existed with an area of 800,000 km^2. These findings have attracted a large number of geoscientists, both in China and internationally, to study the strata, paleontology, and mineral resources in the area (Shang, 1997; Li and Wei, 1998). The Late Paleozoic coal-bearing strata in northern China were formed by the re-settlement and sedimentation processes during the Late Carboniferous Period after the northern China uplift underwent denudation at the end of the Late Ordovician Period. Then, during the early Late Paleozoic Period, northern China essentially became a large inland epicontinental coal-accumulating basin (Han et al., 1979). The extremely gentle paleo-slope characteristics (< 0.001°) of its basement regions have proven difficult to determine the angular unconformity of the erosion origins (Li et al., 1992). However, it has been determined that the sedimentary strata are a set of coal-bearing deposits of marine continental alternation.

China's epicontinental sea depositions are major features of the Paleozoic Period. The epicontinental seas are characterized by wide sea areas, shallow sea water levels, and periodic transgression or regression of the sea water. The deposits of marine facies and marine-continent transitional facies frequently interacted with each other, resulting in the development of coal measures, carbonate rock, and argillaceous rock with wide distribution ranges. However, the coal measure thicknesses tend to be narrow (Li and Wei, 1998). On the weathering surfaces formed

after the Middle Ordovician Period, beginning during the late stages of the Middle Carboniferous Period, northern China began to receive deposition. The southern and northern sides of the basins were held by the near EW denudation trending of the Qinling and Yinshan uplifts, respectively, resulting in the northern China region becoming a large inland epicontinental coal-forming basin. The transgression and regression actions of the sea water indicated high-frequency change patterns. The general trend was from strong to weak, with several large transgressions occurring (Li et al., 1996).

(2) Paleogene-Neogene marginal sea basins in the South China Sea

In recent years, many coal geologists have carried out research studies related to the coal geological problems in China's sea areas, including the South China Sea. Those studies have included the sedimentation and filling of coal -forming basins, coal sedimentology, sequence stratigraphic analyses of coal-bearing strata in sea areas, and so on (Li et al., 2009; Mi et al., 2010). It is now believed that the formation and development of coal measures and coal seams in the Qiongdongnan basin are complex and diversified. Coal measure sedimentary systems have been found to not only be related to the hydrodynamic systems of alluviation, but also to the interaction systems between basin water areas and alluviation, which requires further examination from new perspectives (Li et al., 2012, 2015). In recent years, in-depth and detailed research investigations have been conducted and fruitful achievements accomplished, mainly in the following aspects: 1. The analysis of coal measure developmental environments and controlling factors (Cheng and Gao, 2017); 2. Research investigations of coal measure formation models (Li et al., 2010a; Li, 2015); 3. Studies regarding the distribution patterns of coal-bearing basins and coal measures (Li et al., 2010b); 4. The sedimentological characteristics of coal, coal-forming environments, sedimentary organic facies, and coal accumulation modes (Li et al., 2010a, 2010b, 2013; Li Y C et al., 2011; Ren et al., 2011; Zhang et al., 2012; Wei et al., 2013; Wu et al., 2013; Zhang and Zhu, 2013; Xie, 2014; Shen et al., 2016; Zhang et al., 2016; Zhou et al., 2016; Yang, 2017; Shen, 2018; Yi et al., 2018; Liu et al., 2019). In addition, sequence stratigraphic analyses of coal-bearing strata in sea areas have also been gradually carried out (Mi et al., 2010; Wei et al., 2012), and the results of studies regarding the controlling effects of structure on coal measure formations (Xie et al., 2011; Ren, 2015) have also achieved a deeper understanding of coal formations in the marginal sea basins.

The studies related to oil and gas geology, along with the explorations of natural gas data in the South China Sea, revealed the tectonic evolution and distribution characteristics of sedimentary basins in the South China Sea. The data have also provided important information regarding the basic conditions for the examination of coal-forming characteristics and mechanisms. There are known to be many large Cenozoic sedimentary basins located in the South China Sea area. Those basins have been developed with the extremely thick continental and marine strata known to be favorable prospects for large gas field searches in China (Pang et al., 1995; Gong and Wang, 1997; Yan et al., 2020). For example, the Yanan sag of the Qiongdongnan Basin, which is located in the southeastern section of the Zhu III depression of the Pearl River Mouth basin, along with the southern portion of the Yinggehai basin, are considered to be favorable enrichment areas for coal-derived gas resources (Zheng et al., 2009; Li et al.,

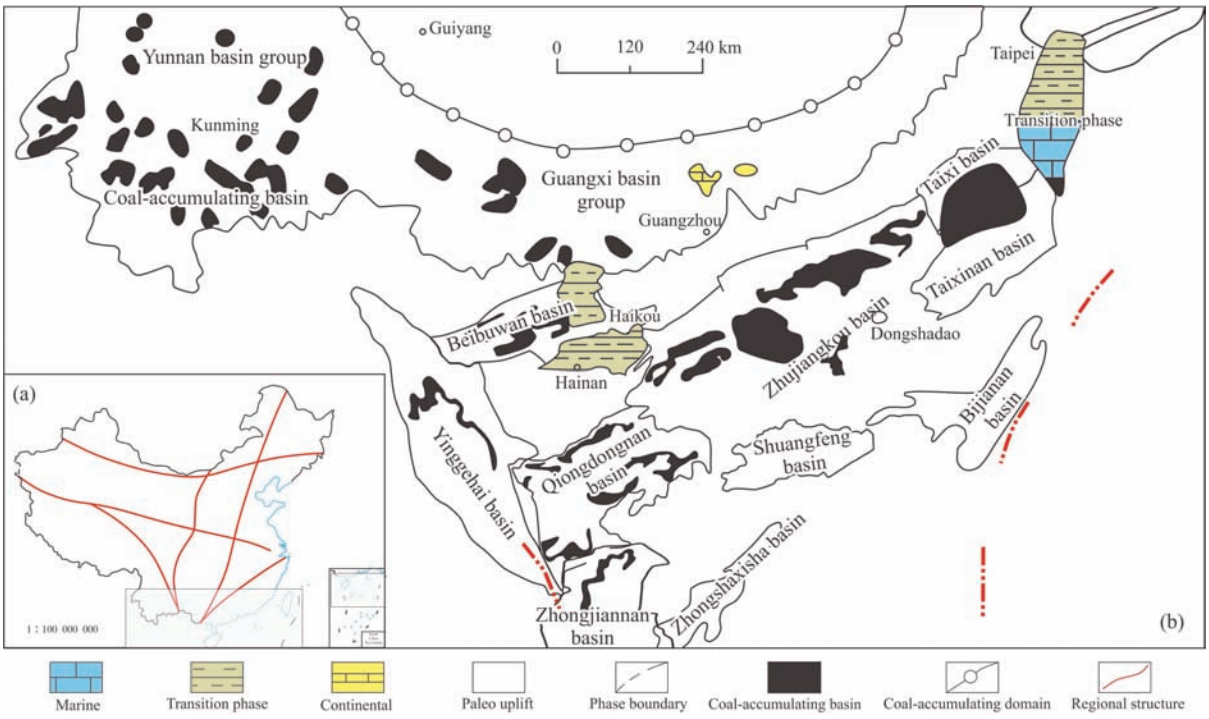

Fig. 1. Paleogeography diagram of the marginal marine coal accumulations during the Paleogene and Neogene Periods in the South China Sea area.

2011).

The tectonic evolution history of the South China Sea is characterized by tectonic cycles (Zhang, et al. 2015, 2017), which can be divided into the following three stages: 1. The formation and development of the proto-South China Sea; 2. The decline of the proto-South China Sea and the development of the new South China Sea; and 3. The rapid subsidence and shrinkage of the South China Sea. Following the Eocene, the collision between the Eurasian plate and the Indian plate led to the southeastern flow of the deep asthenosphere between the two plates under the action of the north-south stress, which was then blocked by the Pacific plate in the southeastern direction. This had resulted in upwellings of the mantle plume and the formation of the new South China Sea. The period ranging from the early Oligocene Period to the Miocene Period was a stage of decline for the proto-South China Sea and formation and development of the new South China Sea. It was also an important period for coal-bearing sediment to develop in the margins of the South China Sea.

The Oligocene Period was an important period of coal formation in the Qiongdongnan basin, during which the deeper parts of the basins had undergone major changes and the pro-South China Sea had gradually disappeared. Subsequently, the new South China Sea had gradually taken shape, and the basement areas of the basin experienced both the disappearance of continental crust and the formation of oceanic crust (Zhang et al., 2015, 2017). Coal formation occurred during the deep transformation period of the basin. This became an mimportant coal-forming stage in the Qiongdongnan basin, resulting in the observed complexity and uniqueness of the coal formations in the basin (Li et al., 2018).

It can be seen from the above-mentioned analysis results that the coal-forming characteristics of the epicontinental and marginal sea basins in the South China Sea (as illustrated in Fig. 1) display the following common features: 1. During the important coal-forming periods, large-scaled coal forming processes had taken place. These were mainly characterized by the development of thin coal seams, extremely thin coal seams, and even shed coal. It has been observed that the coal seams are thin, but generally have many layers. In recent years, there have been special discussions presented by researchers regarding the characteristics of the coal formation processes of the region (Mi et al., 2010; Li et al., 2009; Li Z X et al., 2011); 2. Sea level changes were the main controlling factors for the basin filling and coal formation processes. The rises and falls, advancements and retreats of the sea levels had deeply affected the filling and coal formation processes of the basins; 3. During the processes of basin sedimentation and evolution, the interactions between the continent and sea areas were the main features. That is to say, the basin evolution and sedimentation processes were closely related to both the continent and the sea areas; 4. The coal-forming sedimentary systems were found to be similar for the different basin types, the majority of which being deltas, barrier-lagoons, tidal flats, and fan deltas (Figs. 2 and 3); 5. The general mechanisms of coal formation were also found to be similar. For example, the paleogeography characteristics known to easily lead to coal formation have been found to be closely related to the formations of peat swamps during the formation and evolution processes of deltas, tidal flat-lagoons, and other sedimentary systems.

It was obvious in this study that the following differences in coal formation existed between epicontinental sea basins and the marginal sea basins: 1. The historical ages had differed. For example, the coal-forming basins in the large-scaled epicontinental seas in northern China were formed during the Late Paleozoic Period. Meanwhile, those located in the continental margin sea basins of the South China Sea were formed and developed during the Cenozoic Period. Therefore, the coal-forming backgrounds had large variations; 2. The action mechanism of the sea level changes were different. The major differences were that the epicontinental sea basins in northern China were craton basins within plates, and the sea level changes were eventful. Basically, the continent was in a regression period and shallow seas in a transgression period. The sea level changes were the most important controlling factors for the filling and deposition of the basins and the coal formation processes. Therefore, typical interbedding combinations of marine deposits and coal seams were formed, and the cycles were very clear. Then, during the Cenozoic Period, in the marginal sea basins of the South China Sea, the sea-level changes and tectonic activities had jointly controlled the filling and coal-forming processes of the basin. Therefore, during the critical periods of the basin's development, the tectonic processes had become more important; 3. This study found that there were significant differences in the structural characteristics of the basins, including the basin basements and deeper processes, along with the intensity and mechanism of the continent-sea interactions. The epicontinental sea basins in northern China were intraplate craton basins, which belong to the category of large depression basins. However, the basements of the marginal sea basins in the South China Sea are located in the transitional zone between the continental crust and oceanic crust, with relatively complex basement structures. In regard to the deeper processes, the regional structures and sea level changes were the main controlling factors, and the deeper process and tectonic activities were dominant. In addition, the continental margins of the South China Sea are characterized by the development of multi-level structures and several independent fault basins; 4. Although thin coal seams and extremely thin coal seams have developed in the both types of basins, their stability and comparability tend to vary, often showing major differences. Although the coal seams formed in the epicontinental sea basins are relatively thin, they tend to have strong stability, and can be tracked and correlated in a large scope (Fig. 4). However, the coal seams formed in marginal sea basins are not only very thin, but also tend to be unstable and non-comparative (Mi et al., 2010; Li et al., 2009; Li Z X et al., 2011); 5. The accumulation or aggregation characteristics of the coal forming material in the two types of basins were observed to differ, and the differences could potentially be significant in some cases. For example, the accumulation belts, accumulation areas, and enrichment centers could be clearly identified in the

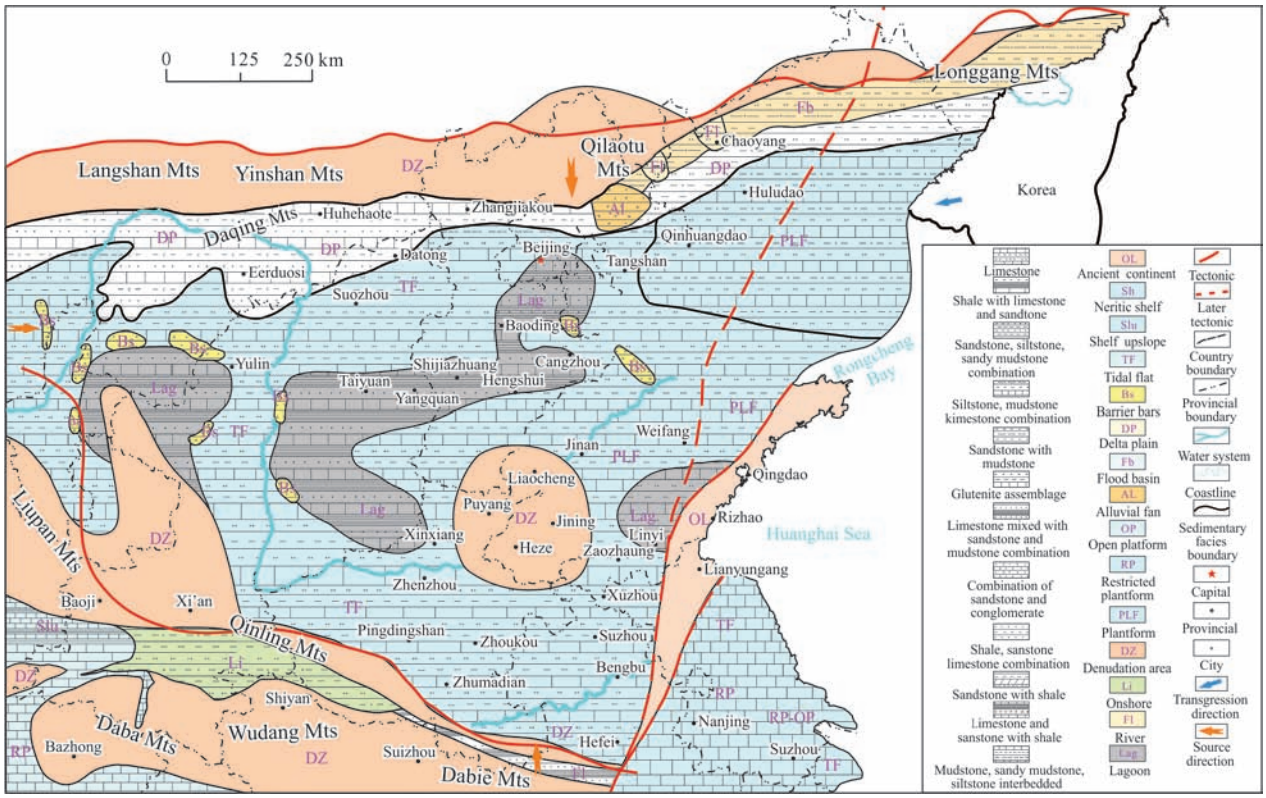

Fig. 2. Coal forming paleogeography during the Late Carboniferous Period in North China.

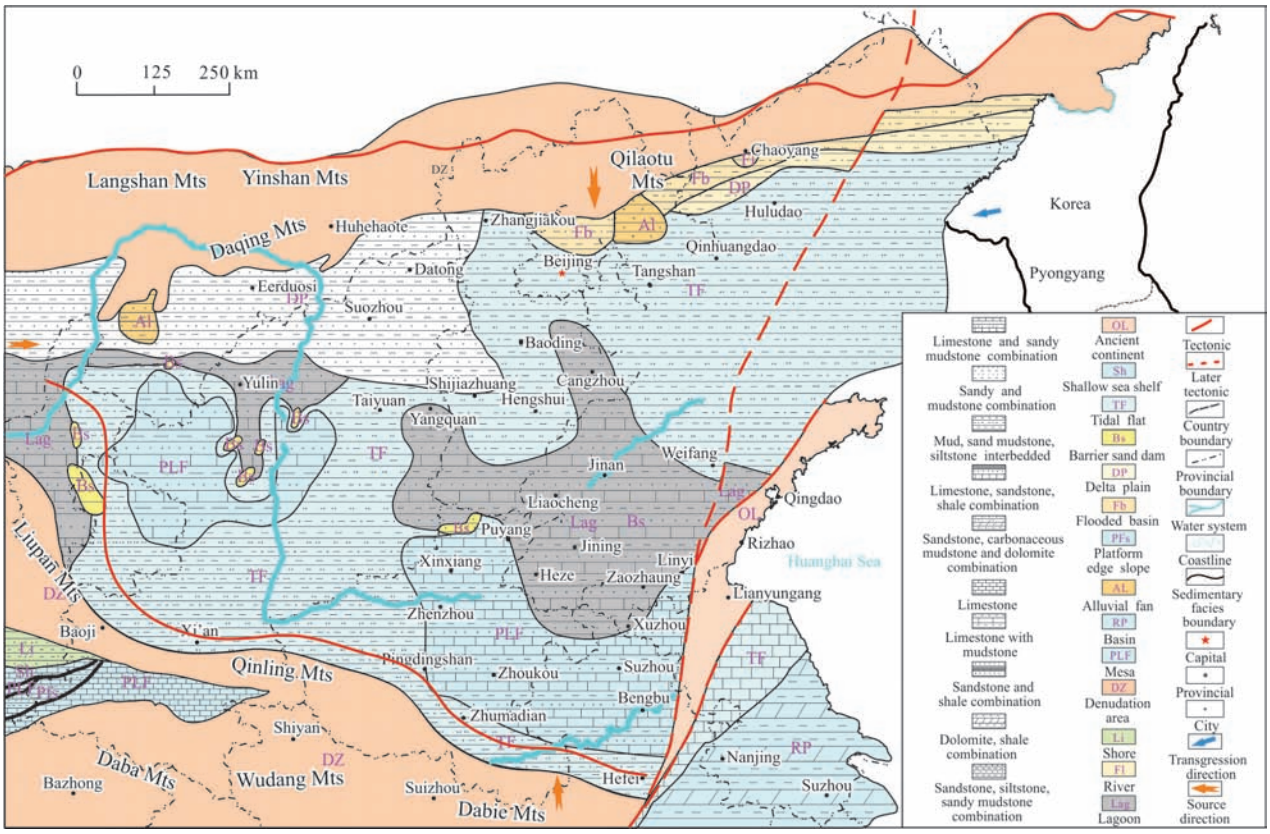

Fig. 3. Coal-forming paleogeography during the Early Permian Period in North China.

epicontinental sea basins, and the laws of migration to the sea or continent were obvious. In contrast, in the marginal sea basins of the South China Sea, there were many sub-basins found to be developed throughout the marginal sea basins, with the majority observed to be faulted basins. The Qiongdongnan basin is considered to be a typical marginal sea basin (Fig. 5). The coal-forming migration processes in the marginal basins of the South China Sea were complicated due to the complex controlling factors of evolution and filling of the basins. The distributions of the coal-forming belts were bead-like, with the enrichment areas and centers found to be dispersed.

3 Characteristics of the Coal-formation Processes in the Epicontinental Sea Basins of the South China Sea

Differing from the stable continental marginal sea basins, the evolution and coal-forming processes of the epicontinental sea basins in the South China Sea were compared with the evolution and coal-forming processes of various types basins throughout geological history. In addition to the above-mentioned differences, the overall evolution law of the coal-forming basins in China was determined to be unique. However, there are only low amounts of drilling data available for the South China Sea at this time. There only relatively more wells in the shallow water areas of the northern basins of the South China Sea, with relatively abundant data of core, cutting, and logging processes, which provide important basic data for the study of coal-bearing source rock. Therefore, based on the analysis results of the coal controlling effects of paleo-environments, controlling effects of paleo-structure and paleo-topography, controlling effects of accommodation space changes, and the sedimentary-structural coal accumulation models of the Qiongdongnan basin in the northern section of the South China Sea, the basic characteristics from the following aspects were summarized in this study.

3.1 Controlling effects of the unique tectonic evolution of the South China Sea on the formation of coal-forming basins

The South China Sea is not in fact a unified basin, but rather is composed of several independent basins. The tectonic activities of the marginal sea basins in the South China Sea led to the diversification and complexity of the continental margin basins. Therefore, the marginal sea basins in the South China Sea are diversified marginal sea basins with strong tectonic activities rather than stable continental marginal sea basins. It can also be said that the basement areas of the marginal sea basins of the South China Sea are not completely unified. They are essentially well-developed and active fault structures. The coal-forming processes in these types of tectonically active marginal sea basins have been determined to be characterized by strong intermittence, transience, and complexity.

The coal-bearing strata of each basin in the South China Sea have their own characteristics. For example, there are coal-bearing strata which developed during the Oligocene and even Miocene Periods in several basins in the northern South China Sea. The basins located in the southern South China Sea are relatively complex. The coal-bearing strata in the southern regions were also developed during the Oligocene, Lower Miocene, and the mid- to late Miocene and Eocene Periods. Overall, the coal-bearing strata in the South China Sea mainly developed during the Oligocene and Miocene Periods, with some in the Eocene Period.

3.2 Multiple fault depressions formed basins independently under the background of the marginal sea basins

Independently formed basins in multiple fault depressions have resulted in a complex pattern of basins within basins, depressions in basins, uplifts in depressions, and concave or sag formations in uplifts. Subsequently, the paleogeographic patterns of coal formation in the South China Sea area are complex.

It is known that the paleo-structure and paleo-topographic conditions had significant controlling effects on the coal development. The existence of paleo-uplifts was the premise of the large-scaled reproduction of terrestrial higher plants, which potentially provided large amounts of organic matter for coal formation. In addition, the shallow overlying water areas, such as the marginal platform areas of the transitions from paleo-uplifts to depressions, as well as gently sloped areas, are known to easily form low-energy swamp environments conducive to peat accumulation. Those types of areas then became favorable places for coal seam development. Previous research has found that among the different tectonic and paleo-topography styles, the shallow overlying water areas, such as the marginal platform areas of the transitions from paleo-uplifts to depressions, gently sloped areas, etc. were favorable for the development of peat mires. Then, the local low-lying portions of the regional paleo-uplifts (depressions in the uplifts), along with the secondary uplifts in the depressions (uplifts in depressions), provided the appropriate water coverage depths, allowing peat mires to easily form and coal seams to develop.

In continent-sea transitional environments (offshore environments), the development positions and accumulated thicknesses of coal measures tend to be controlled by the peat accumulation rates and the increase rates of accommodation spaces. For example, in the sedimentary environments of alluvial plains and delta plains on the land side, coal seams mainly appear at the maximum flooding surface. However, in the barrier-lagoon sedimentary environments on the nearshore side, the coal measures mainly occur in transgressive system tracts. On the plains, a certain scale of coal measure can develop in the depression margin platform areas near the source areas during the maximum flooding periods. For example, the sea levels began to decline during the late stages of the high stand system tracts, and the coal accumulations gradually disappeared. In the portions located above the gradient breaks of the gently sloped zones, the coal accumulations began to occur with low intensity when the sea levels were at the level of the initial transgression surface. Then, during the maximum transgression periods, coal measures were intensively

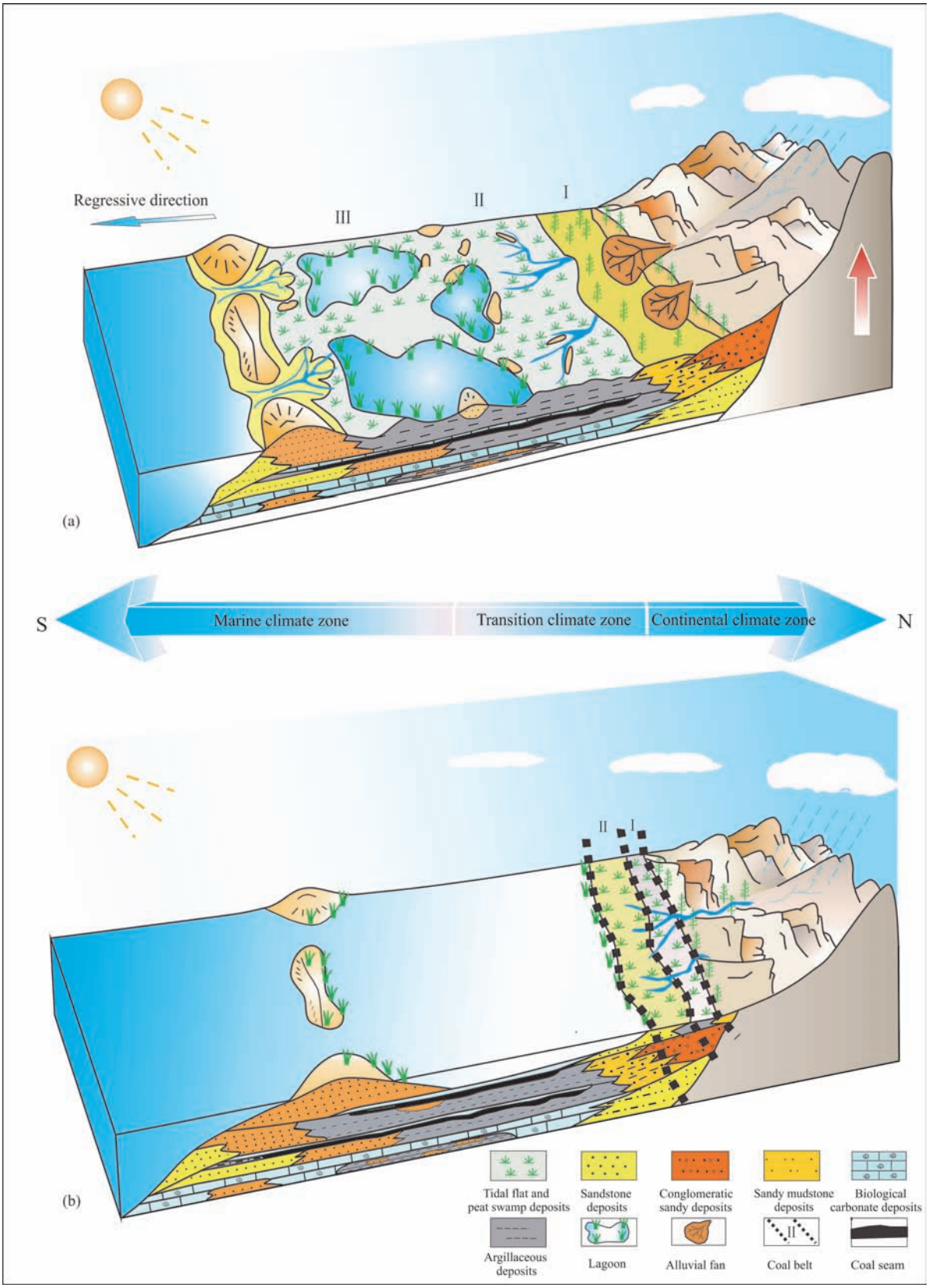

Fig. 4. Coal-forming paleogeographic model and the coal-forming belt distributions during different time periods of regression and transgression in the Carboniferous-Permian epicontinental sea basins of northern China.

developed. Furthermore, during the early sedimentation stages of the high stand system tracts, the coal accumulations had gradually weakened, and then slowly disappeared during the development of the middle and late high stand system tracts (Fig. 5).

3.3 Variations in the coal-forming environmental conditions of each coal-forming basin in the South China Sea

It was observed in this study that fluvial, lakeside, delta, and fan delta deposits were generally developed in the northern and western basin margins of the South China Sea during the Late Eocene and Early Oligocene Periods. In addition, large-scaled delta and coastal deposits were developed in the southern section of the Zengmu basin in the South China Sea, which were considered to be favorable for coal formation. Generally speaking, the coal measures were found to be mainly developed in the shallow water areas in the northern, western, and southern regions of the South China Sea, including delta plains, fan delta plains, river flood plains, lakeside plains, and tidal flats, and so on. During the late Oligocene Period, the scope of the continental basins was reduced, the influence ranges of the sea water had been enlarged. Then, continental lacustrine basins gradually evolved into sea-continent transition facies or marine facies. During the Miocene Period, the majority of the South China Sea was composed of marine sediment, and deltas and fan deltas of different scales were developed in a small scope within the marginal zones of the basins. Consequently, the coal forming conditions were poor, and the coal forming processes were weak.

4 Conclusions

The significance of this research investigation's comparative study of the coal-forming characteristics between epicontinental sea basins and continental marginal sea basins during different time periods was to determine the similarities and differences between them. The goal was to provide guidance for future distribution predictions of coal-bearing coal seams in the South China Sea area, as well as valuable information regarding natural gas reservoirs related to coal measure exploration in the South China Sea area. It was found that through comparative analyses of the coal-forming characteristics of the two types of basins, the following conclusions could be drawn:

(1) The similar features of the coal-forming mechanisms and coal-seam characteristics between the Late Paleozoic epicontinental sea basins in northern China and the Cenozoic continental marginal sea basins in the South China Sea were as follows: 1. The main characteristics included the development of thin coal seams, extremely thin coal seams, and even shed coal; 2. The sea level changes were determined to be the main controlling factors in both types of basin; 3. The continent-sea interactions were the main features; 4. The coal-forming sedimentary systems were observed to be similar. The similarities provided a basis for studying the coal-forming mechanism of the two types of basins, as well as a basis for identifying the accumulation rules of the coal-forming materials.

(2) The differences observed in the coal formation processes of the epicontinental sea basins and the marginal sea basin were more significant as follows: 1. The action mechanisms of sea level changes were different, which were reflected by the fact that the sea level changes of the epicontinental seas were eventual, while those of the marginal seas were transgressive or regressive, with gradual changes occurring; 2. The action intensities and mechanisms of the continent-sea interactions were different due to the differences in the basin structures; 3. Although the coal seams formed in the epicontinental sea

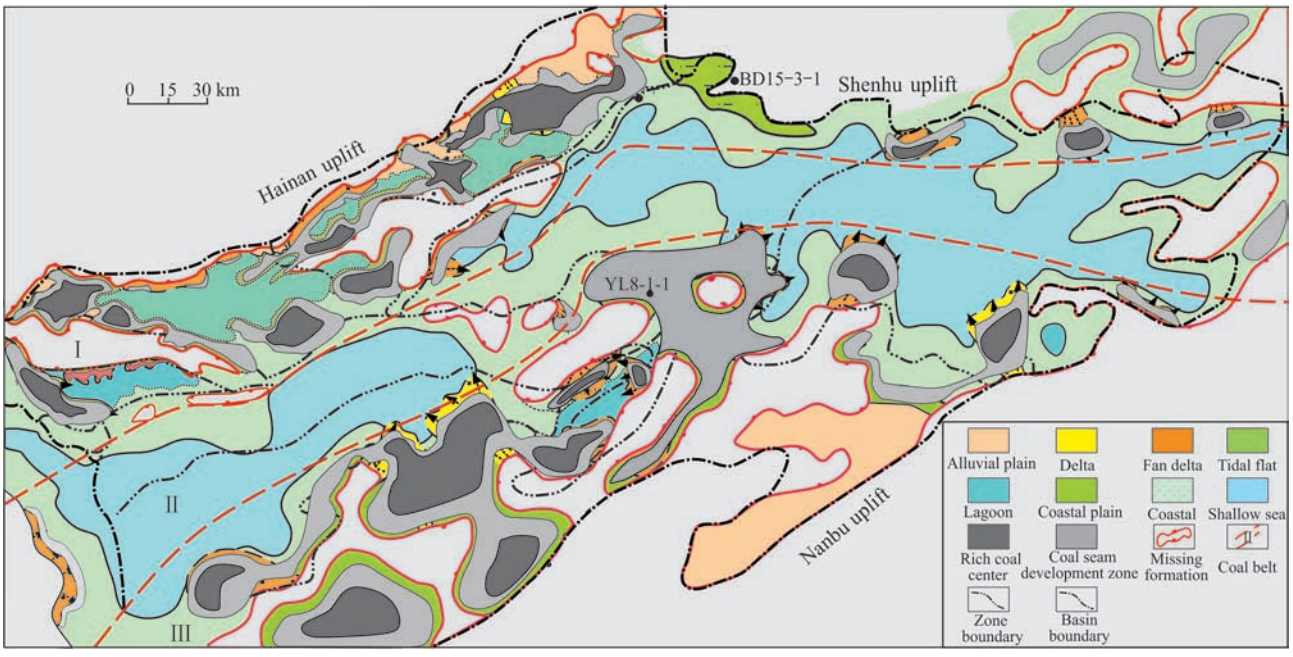

Fig. 5. Distribution characteristics of the coal-forming belts of the Qiongdongnan basin located in the marginal sea areas of the South China Sea.

basins were relatively thin, they had strong stability and could be tracked and compared over a wide range. Meanwhile, the coal seams formed in the marginal sea basins were not only very thin, but also unstable and non-comparative; 4. The accumulation or aggregation characteristics of the coal-forming materials had differed between the two types of basins, with the migration of the coal-forming processes in the marginal sea basins very complex due to the complexity of the controlling factors related to the evolution and filling processes. Therefore, in accordance with the laws of difference, the aforementioned differences were the basis for analyzing the accumulation mechanisms of the coal-forming materials in the two types of basins. The results provided valuable guidance for future explorations of coal-forming material accumulation zones, areas, and enrichment centers.

(3) The strong tectonic activities of the marginal sea basins in the South China Sea has led to the diversification and complexity of the continental margin sea basins. That is to say, the marginal sea basins in the northern regions of the South China Sea are not unified basins, and belong to the category of diversified marginal sea basins with strong tectonic activities. The basin compositions were considered to be complex patterns of basins within basins, depressions within basins, uplifts in depressions, and concave or sags in uplifts, which led to the complexity of paleogeographic patterns of coal formations. This complexity also led to the complicated coal forming processes and paleogeographic evolution conditions. Therefore, the distributions of the coal-forming zones could be considered to be bead-like, while the enrichment areas and centers were dispersed. Therefore, the determinations of the key mechanisms controlling the formation of coal-forming zones and centers will potentially be very helpful in future predictions of the distribution patterns of the hydrocarbon generating materials in coal measures.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (No. 42072188; 41872172; 41672096).

Manuscript received May 22, 2020
accepted Nov. 7, 2020
associate EIC: ZHANG Gongcheng
edited by GUO Xianqing

References

Cao, D.Y., Ning, S.Z., Guo, A.J., Li, H.T., and Chen, L.M., 2018. Tectonic framework of coalfields and tectonic control of coalseams in China. Beijing: Science Presss, 1–415 (in Chinese with English abstract).

Cheng, C., and Gao, L., 2017. Depositional environment and controlling factors of coal measures source rocks of Yacheng Formation in Yabei depression of Qiongdongnan basin. Acta Petrologica et Mineralogica, 36(01): 70–79 (in Chinese with English abstract).

Dai, S.F., Bechtel, A., Eble, C.F., Flores, R.M., French, D., Graham, I.T., Hood, M.M., Hower, J.C., Korasidis, V.A., Moore, T.A., Püttmann, W., Wei, Q., Zhao, L., and O'Keefe, J.M.K., 2020. Recognition of peat depositional environments in coal: a review. International Journal of Coal Geology, 219. https://doi.org/10.1016/ j.coal.2019.103383.

Gong, Z.S., and Wang, G.C., 1997. New thoughts upon petroleum resources potential in offshore China. China Offshore Oil and Gas, 11(1): 1–12 (in Chinese with English abstract).

Han, D.X., Yang, Q., Wang, C.J., Feng, T.Y., Ren, W.Z., and Ren, D.Y., 1979. Coal Geology of China (Vol. 2). Beijing: Coal Industry Press. 1–415 (in Chinese with English abstract).

Li, S.J., 2015. Study on the formation modes of coal-measure source rocks in Northern basins of South China Sea. China University of Geosciences (Master thesis): 1–130 (in Chinese with English abstract).

Li, S.T., Li, Z., Lin, C.S., Yang, S.G., and Xie, X.N., 1992. Some fundamental problems about sequence stratigraphic analysis of coal basin. Coal Geology & Exploration, 21(4): 1–9 (in Chinese with English abstract).

Li, Y., Zhang, G.C., Lv, D.W., Wang, D.D., and Liu, H.Y., 2011. Depositional characteristics and coal forming environment of Yacheng Formation, Qiongdongnan basin. Coal Geology & Exploration, 39(01): 1–5 (in Chinese with English abstract).

Li, Y.C., Mi, L.J., Zhang, G.C., Fu, N., and Sun, Y.M., 2011. The formation and distribution of source rocks for deep water area in the northern of South China Sea. Acta Sedimentae Sinica, 29(5): 970–979 (in Chinese with English abstract).

Li, Z.X., Wei, J.C., Wang, M.Z., and Li, S.C., 1996. Sequence stratigraphic framework and sea-level changes in the Late Palaeozoic epicontinental basin in Northern China. Lithofacies Palaeogeography, 16(5): 1–9 (in Chinese with English abstract).

Li, Z.X., and Wei, J.C., 1998. Sequence stratigraphic analysis in the south of north China Episea basin. Beijing: Geological Publishing House, 267–273(in Chinese with English abstract).

Li, Z.X., He, Y.P., Liu, H.Y., and Lv, D.W., 2010a. Sedimentology characteristics and coal-forming models in Yacheng Formation of Qiongdongnan basin. Acta Petrolei Sinica, 31(4): 542–547 (in Chinese with English abstract).

Li, Z.X., Lv, D.W., Han, M.L., Liu, H.Y., Zhang, G.C., and Wang, D.D., 2011. Coal forming environments of the Third Member of Yacheng Formation of the Paleogene in Qiongdongnan basin for an example. Energy Exploration & Exploration, 29(2): 179–196.

Li, Z.X., Lv, D.W., Wang, D.D., Liu, H.Y., Wang, P.L., and Liu, Y., 2015. The multiple coal-forming theoretical system and its model. Acta Geoscientica Sinica, 36(3): 271–282 (in Chinese with English abstract).

Li, Z.X., Wang, D.D., Lv, D.W., Li, Y., Liu, H.Y., Wang, P.L., Liu, Y., Liu, J.Q., and Li, D.D., 2018. The geologic settings of Chinese coal deposits. International Geology Review, 60(5–6): 548–578.

Li, Z.X., Yu, J.F., Guo, J.B., and Han, M.L., 2003. Analysis on coal formation under transgression events and its mechanism in epicontinental sea basin. Acta Sedimentologica Sinica, 21 (2): 288–297 (in Chinese with English abstract).

Li, Z.X., Han, M.L., Zhang, G.C., Liu, H.Y., Wang, D.D., Lv, D.W., and Li, Y., 2009. Sedimentological characteristics of the coal seams of Yacheng Formation in Qiongdongnan basin, China. Energy Exploration & Exploitation, 27(6): 411–424.

Li, Z.X., Zhang, G.C., Li, Y., Liu, H.Y., Lv, D.W., Shen, H.L., and Shang, L.N., 2012. The Paleogene coal-bearing basin and coal-measures distribution of China sea area. Earth Science Frontiers, 19(4): 314–326 (in Chinese with English abstract).

Li, Z.X., Zhang, G.C., Wang, D.D., Li, Y., Liu, H.Y., and Lv, D.W., 2010b. Identification and correlation of base-level cycles of coal-bearing stratain Paleogene system of China Seas: taking the case of Qiongdongnan basin as an example. Geoscience, 24(06): 1178–1185 (in Chinese with English abstract).

Li, Z.X., Zhou, J., Lv, D.W., Wang, D.D., Liu, H.Y., and Yang, Q.D., 2013. Coal-bearing distribution characteristics of Yacheng Formation in Qiongdongnan basin. Journal of Shandong University of Science and Technology, 32(02): 1–8 (in Chinese with English abstract).

Liu, Y., Liu, H.Y., Yang, H.C., Wang, D.D., Song, G.Z., Lv, D.W., Chen, Y., and Li, Z.X., 2019. Types and characteristics of Paleogene coal-forming sedimentary systems in Qiongdongnan basin. Oil & Gas Geology, 40(01): 142–151 (in Chinese with English abstract).

Mi, L.J., Wang, D.D., Li, Z.X., Liu, H.Y., and He, Y.P., 2010.

High-resolution sequence stratigraphic framework and coal-forming features in Yacheng Formation of Qiongdongnan basin. Acta Petrolei Sinica, 31(04): 534–541 (in Chinese with English abstract).
Pang, X., Chen, J., Dai, Y.D., and Li, P.L., 1995. Study on hydrocarbon accumulation and exploration targets in west Baiyun–Kaiping sag of Pearl River Mouth basin. China Offshore Oil and Gas, 9(4): 237–245 (in Chinese with English abstract).
Ren, G.Y., Xiao, J., Li, Y.L., Liao, J.H., Li, G.L., and Xia, C.Y., 2011. The coal-accumulating environment and coal-forming model of Yacheng Formation in Qiongdongnan basin. Xinjiang Petroleum Geology, 32(06): 621–623 (in Chinese with English abstract).
Ren, J.Y., 2015. Tectonic evolution and the control on coal-measure source rock of the East China Sea and the Northern South China Sea Basins. China University of Mining & Technology (Master thesis): 1–99 (in Chinese with English abstract).
Shang, G.X., 1997. Coal geology of the Late Paleozoic of North China. Taiyuan: Shanxi Science and Technology Press, 91–188 (in Chinese with English abstract).
Shen, W.C., 2018. The coal accumulation model and sedimentary organic facies of Paleogene coal in the Xihu depression. China University of Mining & Technology, Beijing (Ph. D thesis): 1–203 (in Chinese with English abstract).
Shen, Y.L., Qin, Y., Guo, Y.H., Zhao, Z.G., Yuan, X.X., Qu, Z.H., and Xie, G.L., 2016. Development characteristics of coal-measure source rocks divided on the basis of Milankovich coal accumulation cycle in Pinghu Formation, Xihu sag. Acta Petrolei Sinica, 37(6): 706–714 (in Chinese with English abstract).
Sun, Y.Z. 2003. Petrologic and geochemical characteristics of “barkinite” from the Dahe mine, Guizhou Province, China. International Journal of Coal Geology. 56: 269–276.
Sun, Y.Z., Püttmann, W., Kalkreuth, W., and Horsfield, B., 2002. Petrologic and Geochemical Characteristics of Seam 9-3 and Seam 2, Xingtai Coalfield, Northern China. International Journal of Coal Geology, 49: 251–262.
Sun, Y.Z., Zhao C.L., Li Y.H. and Wang J.X., 2015. Anomalous concentrations of rare metal elements, rare-scattered (dispersed) elements and rare earth elements in the coal from Iqe Coalfield, Qinghai Province, China. Acta Geologica Sinica (English edition), 89(1): 229–241.
Wei, H.F., Chen, J.F., Chen, X.D., Cao, B., Guo, W., and Zhang, J.H., 2013. The controlling factors and sedimentary environment for developing coastal coal-bearing source rock. Geology in China, 40(2): 487–497 (in Chinese with English abstract).
Wei, H.F., Chen, J.F., Zhang, T.L., Li, W., Liu, Y.Z., Wu, X.F., and Wang, G.N., 2012. Sequence stratigraphic division and concentrating coal characteristics of Huagang Formation in Xihu depression. Journal of China Coal Society, 37(S1): 149–156 (in Chinese with English abstract).
Wu, Y.K., Hu, M.Y., Liu, Z.F., Zhang, Y., and Yin, B.H., 2013. The sedimentary facies and coal measures source rock distribution of Yacheng Formation in Yabei Sag, Qiongdongnan basin. Natural Gas Geoscience, 24(3): 582–590 (in Chinese with English abstract).
Xie, G.L., 2014. The Coal accumulation patterns of Pinghu Formation in Pingbei area, Xihu depression. China University of Mining & Technology, Beijing (Master thesis): 1–138 (in Chinese with English abstract).
Xie, X.N., Zhang, C., Ren, J.Y., Yao, B.C., Wan, L., Chen, H., and Kang, B., 2011. Effects of distinct tectonic evolutions on hydrocarbon accumulation in northern and southern continental marginal basins of South China Sea. Chinese Journal of Geophyscis, 54(12): 3280–3291 (in Chinese with English abstract).
Xu, Y., Uhl, D., Zhang, N., Zhao, C.L., Qin, S.J., Liang, H.D., and Sun, Y.Z., 2020. Evidence of widespread wildfires in coal seams from the Middle Jurassic of Northwest China and its impact on paleoclimate. Palaeogeography, Palaeoclimatology, Palaeoecology, https://doi.org/10.1016/ j.palaeo.2020.109819.
Yan, W., Zhang, G.X., Xia, B., Zhang, L., Yang, Z., Lei, Z.Y., Yao, H.Q., 2020. Seismic characteristics and development patterns of Miocene carbonate platform in the Beikang basin, Southern South China Sea. Acta Geologica Sinica (English edition), 94(5): 1651–1661.
Yang, L., 2017. Cenozoic coal accumulation regularity and controlling pattern in China offshore. China University of Mining & Technology, Beijing (Ph. D thesis): 1–171 (in Chinese with English abstract).
Yang, Q., Han, D.X., Wang, C.J., Feng, T.Y., and Ren, W.Z., 1979. Coal geology of China (Vol. 1). Beijing: Coal Industry Press. 1–261 (in Chinese with English abstract).
Yi, Q., Shao, L.Y., Qin, L.Z., Shen, W.C., Zhou, Q.Y., Lu, J., Zhang, X., and Liu, J.S., 2018. Sedimentary environment and coal accumulation law of Huagang Formation in Pinghu structural zone of Xihu depression. Coal Science and Technology, 46(02): 73–83 (in Chinese with English abstract).
Zhang, C.L., Shen, Y.L., Qin, Y., Zhao, Z.G., Yang, L., and Xie, G.L., 2016. Development regularities of the coal-measure source rock in Ya-3 Member of Yacheng Formation, Well Y1 in Yanan depression within Qiongdongnan basin. Acta Sedimentologica Sinica, 34(05): 1003–1010 (in Chinese with English abstract).
Zhang, G.C., He, Y.P., and Shen, H.L., 2012. Distribution of Yachen Formation coal measure in Yabei sag in Qiongdongnan basin. Natural Gas Geoscience, 23(4): 654–661 (in Chinese with English abstract).
Zhang, G.C., Qu, H.J., Liu, S.X., Xie, X.J., Zhao, Z., and Shen, H.L., 2015. Tectonic cycle of marginal sea controlled the hydrocarbon accumulation in deep-water areas of South China Sea. Acta Petrolei Sinica, 36(5): 533–545 (in Chinese with English abstract).
Zhang, G.C., Tang, W., Xie, X.J., Zhao, Z.G., and Zhao, Z., 2017. Petroleum geological characteristics of two basin belts in southern continental margin in South China Sea. Petroleum Exploration and Development, 44(6): 849–859.
Zhang, H.T., and Zhu, Y.M., 2013. Coal-forming characteristics of Cenozoic petroliferous basins in offshore China. Xinjiang Petroleum Geology, 34(05): 519–523+495–496 (in Chinese with English abstract).
Zheng, D.W., Zhang, G.W., Yang, W., Sun, G.B., and Xu, X.L., 2009. Great promise for coal-derived gas exploration in China. Natural Gas Industry, 29(9): 50–53+136 (in Chinese with English abstract).
Zhou, Q.Y., Shen, W.C., Zhang, X., Yi, Q., and Shao, L.Y., 2016. The coal-accumulating environments characteristics and coal-forming pattern of Pinghu Formation (Paleogene) in Xihu depression. Journal of Hebei University of Engineering (Natural Science Edition), 33(01): 105–107+112 (in Chinese with English abstract).

About the first author

ZHAO Honggang, born in 1987, male, Ph.D candidate, mainly engaged in the study of energy geology and sedimentary geology. Email: zhaohonggang0601@163.com.

About the corresponding author

LI Zengxue, born in 1954, male, Professor, doctoral supervisor, mainly engaged in the analysis of energy geology and basins. Email: lizengxue@126.com.