Acta Oceanol. Sin., 2021, Vol. 40, No. 2, P. 95–106
https://doi.org/10.1007/s13131-021-1748-8
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Peat formation and accumulation mechanism in northern marginal basin of South China Sea

Zengxue Li[1]*, Qingbo Zeng[2], Meng Xu[3], Dongdong Wang[1], Guangzeng Song[4], Pingli Wang[1], Xiaojing Li[1], Xue Zheng[1]

[1] Key Laboratory of Sedimentary Mineralization and Sedimentary Minerals in Shandong Province, Shandong University of Science and Technology, Qingdao 266590, China

[2] Beijing Research Center, CNOOC (China) Co., Ltd., Beijing 100010, China

[3] No. 1 Institute of Geology and Mineral Resources of Shandong Province, Ji'nan 250014, China

[4] School of Water Conservancy and Environment, University of Jinan, Ji'nan 250022, China

Received 24 August 2019; accepted 21 June 2020

Abstract

In the present study, the coal-rock organic facies of Oligocene Yacheng Formation of the marginal basin in the South China Sea were classified and divided. In addition, through the correlations of the large-scale coal-bearing basins between the epicontinental sea and the South China Sea, it was concluded that the coal forming activities in the South China Sea presented particularity and complexity. Furthermore, the coal forming mechanisms also presented distinctiveness. The marginal basins in the South China Sea consist of several large and complex rift or depression basins, which are distributed at different tectonic positions in the South China Sea. Therefore, the marginal basins in the South China Sea are not simple traditional units with onshore continental slopes extending toward the deep sea. The marginal basins are known to consist of multi-level structures and distinctive types of basins which differ from the continental regions to the sea. During the Oligocene, the existing luxuriant plants and beneficial conditions assisted in the development of peat. Therefore, the Oligocene was the significant period for the formation and aggregation of the peat. However, the peat did not form in unified sedimentary dynamic fields, but instead displayed multi-level geographical units, multiple provenance areas, instability, and nonevent characteristics. As a result, the marginal basins in the South China Sea are characterized by non-uniform peat aggregation stages. In another words, the majority of the peat had entered the marine system in a dispersive manner and acted as part of the marine deposits, rather than during one or several suitable coal-forming stages. These peat deposits then became the main material source for hydrocarbon generation in all of the marginal basins of the South China Sea. The study will be of much significance for the hydrocarbon exploration in the marginal basins of the South China Sea.

Key words: South China Sea, marginal basins, land-sea interactions, peat dispersion, Oligocene

Citation: Li Zengxue, Zeng Qingbo, Xu Meng, Wang Dongdong, Song Guangzeng, Wang Pingli, Li Xiaojing, Zheng Xue. 2021. Peat formation and accumulation mechanism in northern marginal basin of South China Sea. Acta Oceanologica Sinica, 40(2): 95–106, doi: 10.1007/s13131-021-1748-8

1 Introduction

The Oligocene coastal marsh facies source rock, Miocene marine mudstone, and carbonaceous mudstone are known to be well developed in the sedimentary basins of the South China Sea. It has been determined in previous studies that the main mudstone and carbonaceous mudstone in the Oligocene coastal marsh facies coal series are Type II2 kerogen and Type III kerogen (Liu, 2005, 2010; Feng et al., 2010; Zhu, 2010; Mi et al., 2010; Li et al., 2011b).

The initial substances which form coal are plant material. Peat is formed by a series of biophysical and biochemical processes which occur in plants. Such materials are generally not produced by the denudation process, but rather are grown from and refer to as "authigenic" organic materials. The processes (which do not include the eventual formation of coal) are complex and characteristic of peat deposits. The formations of coal deposits and seams, as a special sedimentary mineral in nature, obviously also follow the basic laws of material formation, processing, and finally aggregation (Li et al., 2011c, 2018). For example, the coal mines in East Asia are formed under the control of geodynamics. However, the formation processes are essentially different from that of the majority of sedimentary rock. Therefore, as special organic sedimentary bodies, the formation processes of coal do not completely follow the sedimentary genetic mechanisms of other types of sedimentary rock.

Peat formation and aggregation are known to have been highly sensitive to environmental conditions. In other words, peat is easily affected and controlled by external conditions. The basic conditions for coal formation in geological history are the results of the interactions and mutual restrictions of the paleo-

Foundation item: The National Natural Science Foundation of China under contract Nos 41872172 and 41672096; the Major National Science and Technology Projects under contract No. 2016ZX05026007-004; the Science Foundation of Shandong Province under contract No. ZR2019QD008.
*Corresponding author, E-mail: lizengxue@126.com

phyte, paleo-climate, paleo-structure, and paleo-geographic conditions (Li et al., 2016). It has been determined that if any of those four basic conditions were not suitable, peat accumulation and coal formation could not have occurred.

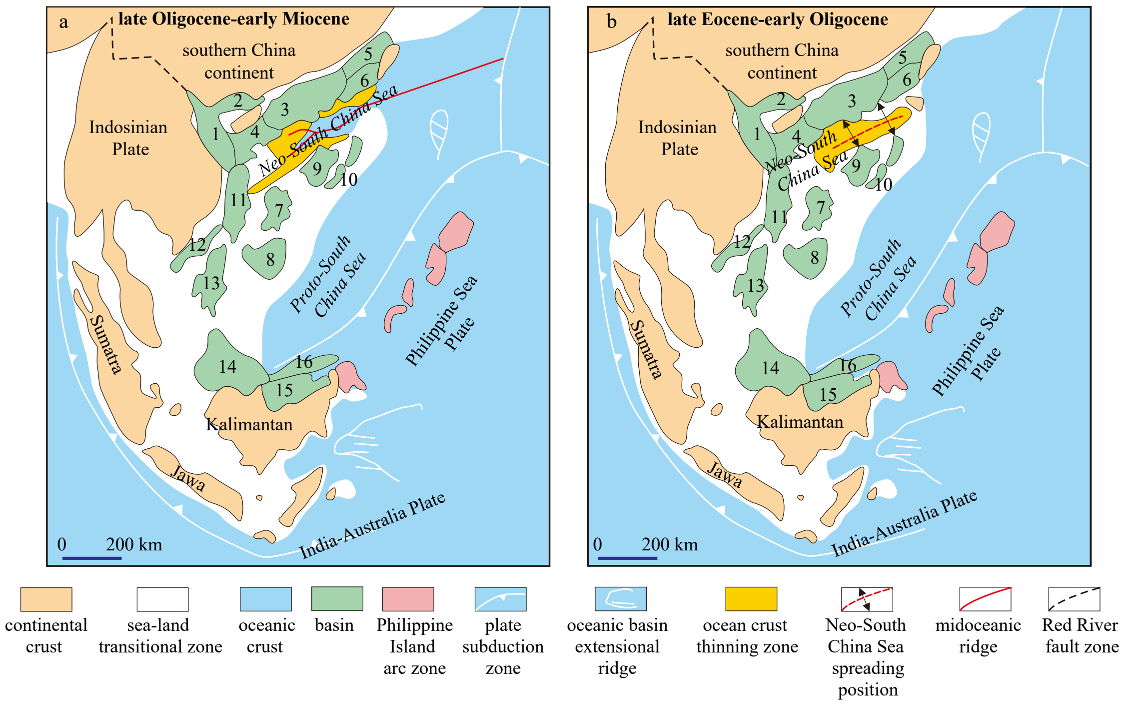
In the present study, based on the comparative analysis results of large surface marine coal basins and marginal sea basins in the South China Sea, the particularity and complexity of coal formation in the marginal sea basins of the South China Sea were investigated. It was determined that the coal formation mechanisms in the marginal sea basins were unique.

2 Geological setting

As detailed in Fig. 1, the tectonic evolution of the South China Sea displayed the characteristics of multiple cycles (Zhang et al., 2015, 2017a) which can be divided into three stages as follows: (1) the formation and development of the Proto-South China Sea; (2) the subduction of the Proto-South China Sea and development of the Neo-South China Sea; (3) the rapid subsidence and shrinkage of the South China Sea. After the Eocene, the Eurasian Plate and the Indian Plate collided together, forming a deep asthenosphere between the two plates flowing in a southeastern direction under the impacting conditions of north-south stress. During the flowing processes, the asthenosphere became blocked by the Pacific Plate in the southeast, and an upwelling mantle was formed. This had led the development of the Neo-South China Sea. It has been determined that from the early Oligocene to the Miocene, a stage existed for the subduction of the Proto-South China Sea and the formation and development of the Neo-South China Sea. This is considered to be the main period for the development of coal-bearing sedimentation in the South China Sea.

The evolution processes of the Paleogene and Neogene basins in the South China Sea are quite special and unique. The characteristics, sedimentary filling, and coal geology of the basins have been extensively studied deeply in previous research projects (Zhang et al., 2010, 2012, 2015, 2017a; Xie et al., 2016; Zhu et al., 2008, 2012; Shen et al., 2010, 2013; Li et al., 2011a, 2012; Shao et al., 2010). In particular, the sedimentary basin evolution processes, hydrocarbon accumulations, and coal formation processes in the South China Sea have been investigated. However, due to the uniqueness of the area, it has proven difficult to define the tectonic backgrounds of the basins. In this study, these types of basins are referred to as "unstable marginal basins" or "relatively active marginal basins". For example, the basins are considered to be different from typical stable marginal basins and typical active marginal basins.

The northern sections of the marginal basins in the South China Sea were found to display the following characteristics. The land-sea transition zones presented evidence of strong tectonic activities. The deep processes of the basin formations were observed to be complex, which was not typical of the more stable continental margins. This indicated that the tectonic activities were similar to active continental margins. However, the plate structures found in active marginal basins had not developed. These differences suggested the basic structures of stable continental marginal basins, even though the stability characteristics of stable continental basins were not observed. Therefore, from the above-mentioned characteristics, it was concluded that the northern parts of the South China Sea contained a type of marginal basin which had the characteristics of both active and stable continental marginal basins. The peat formed and assembled during the tectonic-stable periods differed from that formed and assembled during the tectonic-active periods. During the active periods, the peat may have been destroyed and transported to the pelagic zones, where the peat was deposited as



1. Yinggehai Basin 2. Beibuwan Basin 3. Zhujiang River Mouth Basin 4. Qiongdongnan Basin 5. Taixi Basin 6. Southwest Taiwan Basin 7. Nanweixi Basin 8. Beikang Basin 9. Liyue Basin 10. Palawan Basin 11. Zhongjiannan Basin 12. Mekong Basin 13. Wan'an Basin 14. Zengmu Basin 15. Brunei-Sabah Basin 16. Nansha Trough Basin

Fig. 1. Tectonic evolution diagram of the South China Sea and the adjacent regions (modified from Zhang et al. (2017a)).

dispersive terrestrial organic clastic with other fine-grained materials.

3 Samples and methodology

In accordance with the results of 23 drilling cores (mainly distributed in the northwestern region) and the available logging data of the Qiongdongnan Basin, a sedimentary system map of Yacheng Formation in the Qiongdongnan Basin has been compiled. The mapping process was particularly based on the seismic data processing results of the area and more than 200 seismic sections. In recent years, 40 typical seismic reflection profiles with a wide coverage range in the Qiongdongnan Basin were described in detail. The sedimentary facies development characteristics of each depression within the basin were controlled. In addition, the distributions of the sedimentary facies and sedimentary systems of the Yacheng Formation in Qiongdongnan Basin were successfully established.

The YC13-1-A2 well is one of the total coring wells of the Qiongdongnan Basin. Multiple layers of thin coal seam cores were obtained, with thicknesses generally ranging at approximately 20 cm. Coal samples were obtained from a coal seam in the study area, and under laboratory operation specifications, the samples were independently prepared into regular coal bricks. They were coarsely crushed (<1 mm) in preparation for this study’s microscopic analysis processes. The maceral was observed by a Leica DM-4500P microscope (Leica Microsystems Ltd., German) using reflected light under oil-innersed conditions.

4 Results

4.1 *Luxuriant terrestrial plants represent the primary condition*

In geological history, coal formation is considered to have four basic conditions, which include favorable paleo-climate, paleoflora, paleo-structure, and paleo-geographic conditions (Li, 1999; Shao et al., 2008). Therefore, in order to study coal-forming processes and the coal-forming laws of sedimentary basins, it is necessary to examine the genetic mechanisms from the above-mentioned four aspects (Shao et al., 2008; Li et al., 2018). The luxuriant terrestrial plants act as the primary controlling factor for the formation and assemblage of the peat (Li et al., 2018; Wang et al., 2001; Lv et al., 2010, 2019). The geochemical compositions of terrestrial organic matter during coal formation, along with the marine sediment in the marginal basins of the South China Sea, require further investigation (Li et al., 2007, 2010a, 2010b; Mi et al., 2010; Wang et al., 2015; Xie et al., 2016).

The organic materials of the coal measures and marine mudstone in the northern sections of the South China Sea mainly originate from terrestrial plants. The input amounts of the terrestrial plants within different basins largely determine the abundance of the source rock organic matter. For example, in regard to the Qiongdongnan Basin, during the formation of the coal measures developing at the transitional facies in the Yacheng Formation, and the mudstone developing at the neritic facies in the Lingshui Formation, the terrestrial organic matter is carried into the basin. In addition, the coal measures in the Yacheng Formation consists of large amounts of oleanane, which reflects that the terrestrial angiosperms are the sources and has acted as the material basis of the hydrocarbon organic matter. Therefore, it can be concluded that in the Qiongdongnan Basin, the coal measures in the Yacheng Formation act as the main hydrocarbon source rock, and the mudstone at the neritic facies of the Lingshui Formation act as the secondary hydrocarbon source rock.

The geobiological characteristics of the Qiongdongna Basin in the Yacheng Formation have rarely been examined. Therefore, the available research data regarding the paleo-climate of the area are lacking at the present time. However, it has been determined that climate conditions were important controlling factors for the development of hydrocarbon source rock.

Through the geobiological testing of the LS33-1-1 Well (Fig. 2) in the Lingshui Sag (Li, 2015a), it was found that the polypodiaceaesporites are relatively developed in the Yacheng Formation, with a content ranging from 17.3% to 50.0% (average: 35.1%). The research results indicated two high values at the depths of 4 096 m and 4 160 m, respectively. Therefore, it was concluded that the climate conditions during those periods are beneficial to the growth of the single slit spore of water keel. These xerophytes species are rarely developed in the Yacheng Formation and has only presented small quantities in several successions, with an average value of 3%. However, the content levels of the hygrophilous species could reach 20.7% to 50.0% (average: 35.7%). The above-mentioned testing data indicated that the hygrophytic species palynology presents an absolute advantage in the Qiongdongnan Basin of the Yacheng Formation, thereby reflecting the warm and humid climate conditions are considered to be beneficial to the development of coal measure source rock.

It can be concluded from the aforementioned obtained data that the Oligocene climate is favorable for the development of luxuriant plant species in the northern sections of the South China Sea, and the terrestrial angiosperms act as significant sources for the formation and assemblage of the peat.

4.2 *Paleo-structure and paleo-topography characteristics*

The development of high-abundance hydrocarbon source rock at transitional and marine facies was largely influenced by the paleo-topography characteristics of the region and fundamentally controlled by tectonic activities (Lv et al., 2020). Therefore, the development of the hydrocarbon source rock was obviously influenced by both paleo-structure and paleo-topography.

Paleo-uplift or sub-uplift actions provided good topographical conditions for the development and reproduction of terrigenous higher plants. For example, such actions provided not only terrestrial debris, but also large amounts of organic matter for the sags in the study area. In addition, the secondary sub-sags in the paleo-uplifts, as well as the slope areas in the transitional regions from the paleo-uplifts or sub-uplifts to the sags, were all paleo-topographical units located in shallow water areas where the terrestrial plants of the Yacheng Formation had flourished. Such locations were beneficial to the accumulation of peat and the development of coal seams. Therefore, the three above-mentioned paleo-topographical units were considered to be important areas for the development of hydrocarbon source rock.

In regard to the Oligocene Qiongdongnan Basin, the fault activities and the rift basin structure also controlled the development of coal measures in the transitional facies of the Yacheng Formation to a great extent (Zhang et al., 2007; Zhang, 2010; Song et al., 2014). During the initial Eocene, the NW tension stress field led to the formation of a large number of NE normal faults. This was similar to the eastern fault activities leading to the formations of the Yabei Sag, Songxi Sag, Songdong Sag, and so on. This period occurred during the early rifting stage, during which the sags were isolated from each other. The sages mainly developed as half-graben structures, displaying the topographic characteristics of “multi-sags and multi-uplifts”. As a result of the fault activities, the elevation differences between the two fault walls became larger. The up-thrown walls became the provenance areas, and the down-thrown walls became the sedimentary areas. Lacustrine deposits were developed and distributed sporadically in the sags. During this period, the subsidence rates of the basins were higher than the deposition rates. Therefore, the water levels had continuously deepened, which was favorable for the basins developing hypoxia reduction environments. Those types of environments were conducive to the development and preservation of the hydrocarbon source rock of the Eocene lacustrine facies.

During the syndepositional period of the Yacheng Formation, the seawater intruded into the central basin from the Changchang Sag in the east and from the Lingshui Sag in the west. Therefore, the environment had changed from that of continental facies to transitional facies. The invasion of seawater caused the paleo-uplifts to successively become merged with the seawater, and the coastal plains and tidal flat deposits were widely developed in the areas near the uplifts. These conditions were beneficial to the terrestrial plants to flourish in the facies. In consequence, coal measures had developed and constituted the main hydrocarbon source rock.

During the syndepositional period of the Lingshui Formation, the faults inherited the tectonic patterns and characteristics of the Yacheng Formation and were still active. It was found that a large number of small normal faults had ceased their activities at the top interfaces of the Lingshui Formation (T60). The connectivity of the sags gradually improved, showing the characteristics of unified basin depositions. In addition, fan delta deposits were developed in Yabei, Songxi, and Songdong Sags. The sedimentary environment gradually changed from transitional facies to neritic facies (Li, 2015b)

The differences in tectonic activities within the different areas had led to variations in the development of the sedimentary facie zones. This resulted in major differences in the coal accumulations within the different areas of the Yacheng Formation.

During the sedimentary stage of the Yacheng Formation, the activities of the main faults in the northern depression zone of the basin led to the development of banded fan delta groups in the northern margins of the Yabei and Songxi Sags. However, since the fault activities had become weaker in the southern sections of the Songdong Sag, it was observed that few fan deltas were developed. The faults of the Yabei Sag were basically inactive. Lagoon facies had developed in the northern parts of the central sag where the water levels were relatively deep. However, in the southern areas of the Yabei Sag, the terrain was relatively flat with no developed rivers, which was beneficial to the development of tidal flat facies. In addition, due to the river input, large scale braided river deltas had developed in the northern regions of the Songdong Sag and in the western sections of the Songnan Sag, as shown in Fig. 2.

During the rift-depression stage prior to the expansion of the Neo-South China Sea (Fig. 1), the coal measure source rock were developed at the early Oligocene transitional facies. Then, during the late early Oligocene, transgression occurred within the Qiongdongnan Basin. Subsequently, a bay environment was formed which bore the characteristics of shallowness in the southern and northern sections and deep center areas, with developed fan and braided river deltas, tidal flats, lagoons, and shore-neritic facies (Song et al., 2020). In the Ledong, Lingshui, Songnan, Baodao, Beijiao, and Changchang Sags, mainly neritic facies were evident, with fan and braided river deltas developed in the north margins and inside highland peripheries of the Qiongdongnan Basin. The tidal flats and lagoon facies were mainly developed in the gentle slope areas, and the coastal facies were mainly developed in the basin margins or around the paleo-uplifts. Coal seams were determined to have developed in the coastal plain marshes, lagoon alluvial marshes, and tidal flat marshes.

The organic materials of the Oligocene coal measure and marine mudstone in the Qiongdongnan Basin have mainly originated from terrigenous higher plants. However, due to lack of large rivers, the contributions of foreign organic matter are very limited. The organic matter was most commonly developed on the edges of the basins or the secondary uplifts of the basin. For example, in the Lingnan Low Salient, Songnan Low Salient, and Lingshui Salient, and so on, the higher plants had flourished,

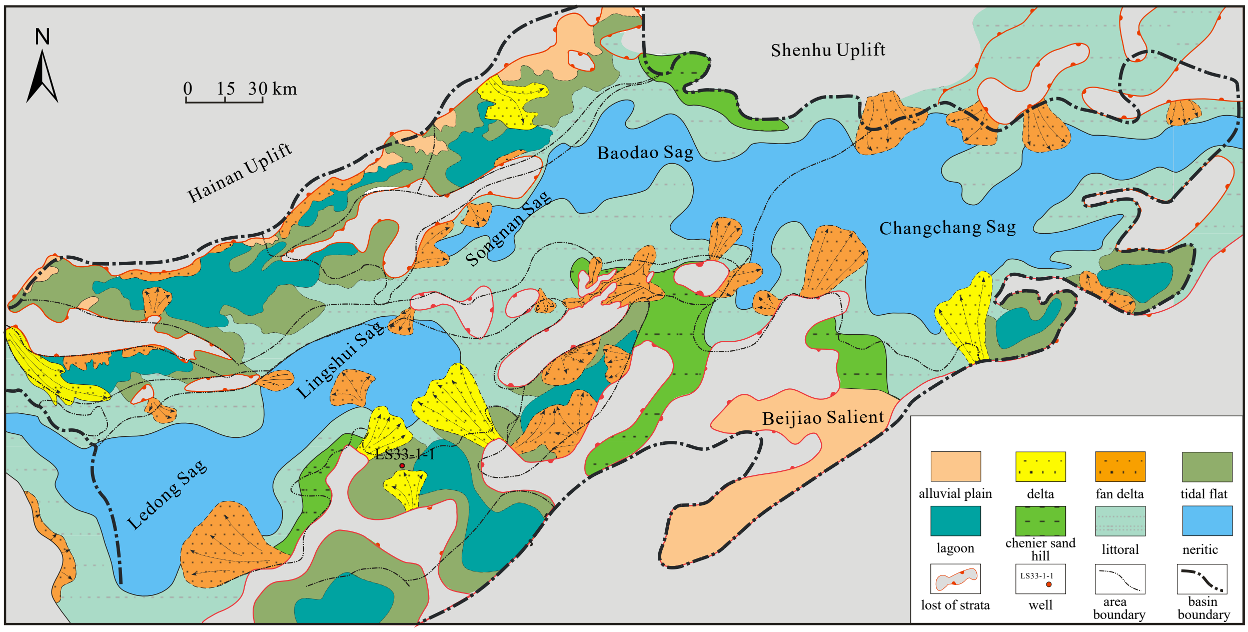


Fig. 2. The sedimentary facies map of Oligocene Yacheng Formation in Qiongdongnan Basin.

thereby providing abundant organic matter for the surrounding sags. It has been determined that in the shallow water areas close to the basin edges or the secondary paleo-uplifts in the basin, particularly in the fan and braided river deltas, coastal plains, and other facies zones, terrestrial plants were abundant. These conditions were conducive to the development of source rock. Therefore, the distances between the sedimentary areas and the basin edges or paleo-uplifts where higher plants developed were the key factors which determined the development of high-quality source rock. For example, the closer the distance was, the more favorable the conditions for the development of source rock with high organic matter abundance would be. In contrast, it was unfavorable for the development of source rock with high organic matter abundance if the distances between the sedimentary areas and the basin edges or paleo-uplifts were too great. However, due to the complexity of the marginal basins in the South China Sea, rift basins had only largely developed in the secondary depressions, sags, or sub-sags of the central basin, low uplifts, and uplifts. Therefore, the provenance areas serving terrigenous were largely developed within different distances of the basin. This had resulted in the peat forming in non-uniform fields which were characterized by multi-level geographical units, multiple sources, non-stability, non-events, non-unified episodes of peat accumulations, and so on. This study concluded that there was no single coal-forming episode which had covered the marginal basins of the South China Sea.

In summary, the organic matter of the terrestrial marine hydrocarbon source rock in the northern regions of the South China Sea remained dominated by higher plants. Meanwhile, algae and other lower organisms were rare. The terrestrial higher plants were abundant in the near shore environments where was rich in organic matter. Therefore, the hydrocarbon source rock had been highly developed in those regions.

4.3 *Characteristics of the main coal-forming organic facies*

Since the concept of organic facies was first proposed by Roger in 1971, increasing amounts of attention have been paid to the research of organic facies. Jones (1981), Brooks and Welte (1987) linked organic facies with sedimentary environments and petrological characteristics, and emphasized the fact that organic facies were specific sedimentary bodies with the same characteristics in space as organic matter. Hao et al. (1994) defined organic facies as stratigraphic units containing certain abundance and specific genetic types of organic matter, and then classified organic facies according to genetic types of kerogen (Table 1). The classification of organic facies should fully reflect the sources, nature, and formation conditions of organic matter in stratigraphic units. However, due to the transformations of organic matter of the same origin in sedimentation-diagenesis processes, and the influences of thermal evolution degrees on kerogen chemical compositions, the scheme proposed by Brooks and Welte (1987) could be divided into organic phases directly based on kerogen H/C atom ratios. Unfortunately, it proved difficult to apply the pyrolysis hydrogen index to basin analyses. Therefore, as detailed in Table 1, Hao et al. (1994) proposed a classification scheme for organic phases based on genetic types of kerogen (organic matter) and proposed the concept of organic sub-facies for the first time. The purpose was to distinguish stratigraphic units with the same sources of organic matter but different depositional and diagenetic transformation processes. In the classification scheme, each organic facies contains a genetic type of marked kerogen. However, small content levels of non-marked kerogen may be included in order to ensure that the organic facies are programmable stratigraphic units. Since the most important parameter to determine the type of organic facies is the genetic type of kerogen, the identification of organic facies must be based on the comprehensive analysis of multiple organic geochemical parameters.

The aim of coal facies analysis is to accurately reconstruct the facies environmental conditions of peat swamps. The two factors of gelation degree and plant type, together with the groundwater impact index (GWI) and plant index (VI) highlight the groundwater levels and vegetation types of an area. Then the above-mentioned four coal rock parameters can be calculated based on the microscopic compositions of the coal and rock, and the maceral is not generally considered. However, maceral is the combination of microscopic coal rock particles, which could potentially better reflect the accumulation conditions of peat (Diessel, 1986, 1992; Dai et al., 2007).

The main research methods of coal facies include biomarker and genetic parameter methods (for example, reference indexes of gelation and organization preserve index value methods); pa-

Table 1. The division of coal-rock organic facies (Hao et al., 1994)

Organic facies	Subfacies	Source of organic matter	Redox condition (probable sedimentary environment)	Genetic types of the typical kerogen	Possible genetic types of kerogen	Product characteristics
A	–	lacustrine phytoplankton	strong reduction environment (deep lacustrine)	algal I type (I a) bacteria I type (I br)	II A-a	high wax oil
B	B	phytoplankton dominate, with a few higher plants	reduction-strong reduction (deep lacustrine, marine)	algal II A type (II A-a)	I a II B-m	oil
	B_1	phytoplankton dominate, with a few higher plants	weak oxidation-weak reduction (deep lacustrine, marine)	algal III type (III a) algal II B type (II B-a)	–	gas, oil
C	–	phytoplankton, higher plants	weak reduction-reduction (deep lacustrine, shallow lacustrine, marine)	mixed II B type (II B-m)	II A-a III w	condensate oil (light oil), gas
D	D	higher plants	weak oxidation-weak reduction (shore-shallow lacustrine or marine, swamp)	wooden III type (III w)	II B-m IV w	gas
	D_1	higher plants	weak oxidation-oxidation (slowly deposited shallow lacustrine, relative deep lacustrine)	chitin II A type (II A-e) chitin II B type (II B-e)	III w IV w	condensate oil (light oil), gas
	D_2	higher plants	weak oxidation-reduction (influence of sea water, homogenization of diagenesis)	chitin II B type (II B-w)	III w	condensate oil (light oil), gas
E	–	higher plants	strong oxidation (alluvial plain, lakeshore, marine)	chitin IV type (IV w) recycling IV type (IV re)	III w II B-e	dry gas

Note: – reprents no data.

lynology methods (for example, in accordance with the dominant judging spores and pollen of the original coal plant communities); mass fraction ratios of vitrinite and inertinite micro-lithotype methods (for example, different microscopic coal rock types are classified as four types of coal facies and a four-terminal end-member coal facies type diagram are set up). Diessel (1986, 1992) proposed two main parameters of tissue preservation index and gelification index, which are considered to be important parameters in coal phase research. These two parameters are mainly applicable to the study of coal phases in low metamorphic coal. It should be pointed out that there are two important factors affecting the preservation of the cellular structure of the material in coal, namely, the degree of gelation and the degree of coal metamorphism. As the Oligocene coal-forming material in the Qiongdongnan Basin is at the peatization stage, the gelation degree is higher and more thorough, the plant cell structure is more completely destroyed and rarely remains (clastic vitrinite can be seen in some cases). Moreover, the coal metamorphic degree (thermal evolution) is higher in Qiongdongnan basin (Table 2). These two factors lead to the destruction of plant cell structure in coal. In addition, the crust components have been almost completely decomposed with only a few remaining in a preservation state. As a result, the above-mentioned two indicators are no longer available. Therefore, the coal facies analysis in this study mainly refer to the scheme proposed by Hao et al. (1994) and classified the coal facies of the Yacheng Formation in Qiongdongnan Basin based on the types of coal-forming plants, Redox conditions, and micro-coal rock particles.

The macerals of the Oligocene coal from the Qiongdongnan Basin were identified and classified according to the latest classifications of the International Committee for Coal and Organic Petrology System (Sýkorová et al., 2005; Kwiecińska and Petersen, 2004; Pickel et al., 2017). According to the optical identification of the polished coal brick, the coal macerals of the Yacheng Formation in the Qiongdongnan Basin were determined to be mainly vitrinite. This study selected coal samples with sampling depth of 4 114 m as an example. It was determined that the content of vitrinite was 95.1%. Among this, the content of collodetrinite was 59.3%; the mean vitrinite content was 35.4%; and the content of structural vitrinite was 0.4%. In this study, only sporopollen was found in the shell group, with a content of 4.7%. In addition, it was determined that the content level of clastic inert plastids was 0.2%, as detailed in Table 2. The content of the crustal group was observed to be very small, and only liptodetrinite was found in some of the optical films. Sporophyte is mainly considered to be a micro-sporophyte, which was found distributed in the mean vitrinite and stromal vitrinite matrix (Fig. 3). The structural vitrinite was rounded and distributed on the collodetrinite matrix, and the cavities were observed to be filled with clay minerals, as illustrated in Fig. 4. Vitrinite reflectance is 1.09%, corresponding to the coal metamorphic stage IV, equivalent to “fat coal and coking coal” on the coal class stage.

Table 2. The coal macerals and metamorphic stages of Yacheng Formation in Qiongdongnan Basin

Serial number	Organic macerals content/%			Inorganic macerals content/%				Averaged *Ro*/%	Metamorphic stages
	Vitrinite	Inertinite	Total organic	Clay type	Carbonate	Sulfide	Oxide		
1	89.7	2.6	92.3	6.9	–	0.4	0.4	1.16	IV
2	94.0	2.1	96.1	3.5	–	0.4	–	1.09	IV
3	59.5	2.2	61.7	34.4	–	0.8	3.1	1.04	IV
4	67.2	1.6	68.8	25.5	–	2.3	3.4	1.06	IV
5	80.2	1.4	81.6	13.7	–	1.8	2.9	1.15	IV
6	77.2	1.4	78.6	12.3	–	1.1	8.0	1.11	IV
7	81.5	2.6	84.1	12.7	–	0.8	2.4	1.20	IV
8	77.4	1.7	79.1	16.8	–	1.2	3.1	1.17	IV
9	58.4	1.4	59.8	26.4	1.9	3.7	8.2	1.18	IV
10	66.7	2.0	68.7	20.8	–	3.8	6.7	1.23	V
11	86.0	2.5	88.5	7.7	–	1.9	1.9	1.21	V
12	71.9	1.7	73.6	21.5	–	1.2	3.7	1.11	IV
13	37.7	0.8	38.5	38.5	3.1	1.9	17.6	0.94	IV

Note: *Ro* represents vitrinite reflectance.

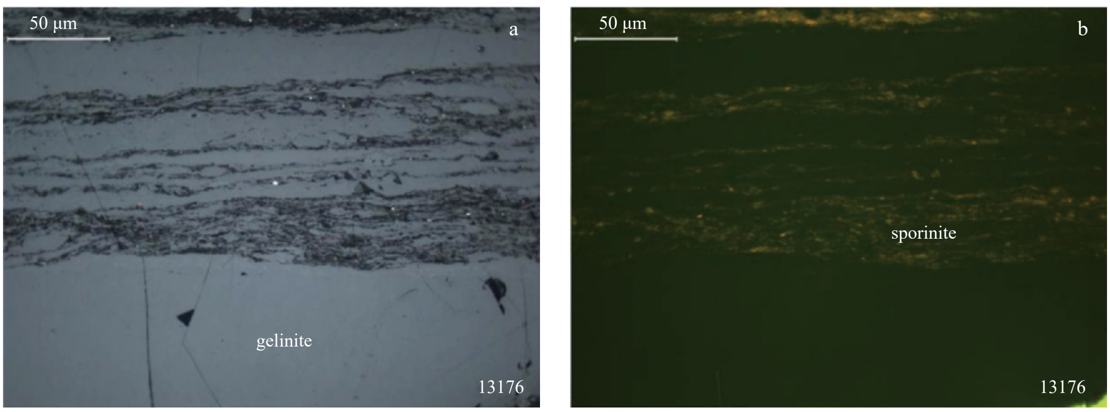


Fig. 3. The reflected light of oil immersed gelinite and sporinite under light (a) and under blue light (b).

In accordance with the division scheme of sedimentary organic facies presented by previous researchers, and the quality characteristics of the coal rock of the Yacheng Formation in the Qiongdongnan Basin, a classification scheme of the organic facies of the coal rock was completed. The results are displayed in Table 3. It was concluded from the classification results that the types of Oligocene coal and rock organic facies were mainly C1, followed by C3 and C4. In addition, Class A and Class B were mainly macerals of lower aquatic organisms, and the content of the sapropelic formation was >1%. Therefore, it was obvious that the coal deposits of the Yacheng Formation in the southeastern section of the Qiongdongnan Basin were mainly humic coal with undeveloped organic facies. Therefore, the two types of coal and rock were not described in this study.

According to the division scheme of sedimentary organic facies by previous researchers and the coal rock quality characteristics of Yacheng Formation in Qiongdongnan Basin, the classification scheme of organic facies of the coal rock was made (Table 3).

C1 Type: covered peat swamp, belonging to the category of middle-low swamps. However, the land source material supply was rich, thereby also indicating the characteristics of eutrophic swamps. The sedimentary environment belonged to littoral shallow seas (lakes), tidal flat swamps, lagoons, or closed swamps. The water environmental conditions were relatively calm, with medium hydrodynamic activities. However, if tidal flat depositions were present, and the overlying platform depositions were developed, then the evolution processes of the organic matter had occurred in relatively reductive water environments. The environments were mainly composed of macerals from higher

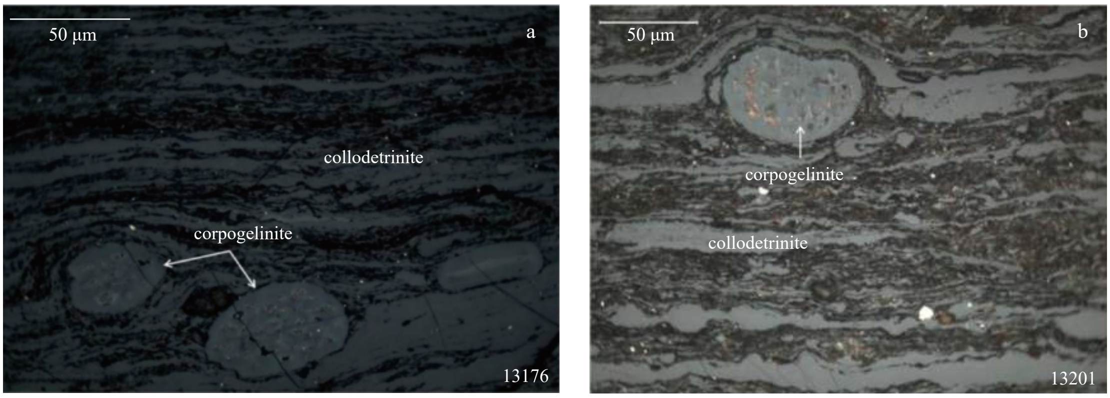


Fig. 4. The reflected light of oil immersed corpogelinite and collodetrinite.

Table 3. The classification of coal rock organic facies

Type of coal rock organic facies		Content of indicators of coal rock and coal quality	Sedimentary environment
A	A1	Derived from macerals of lower aquatic organisms, content of sapropelinite >5%.	Shallow–deep sea (lake) is relatively calm; deep water environment.
	A2	Derived from macerals of lower aquatic organisms, content of sapropelinite 2%–5%.	Littoral–shallow sea (lake) is comparatively calm; shallow-subordinate deep water environment.
	A3	Derived from macerals of lower aquatic organisms, content of sapropelinite <2%.	Littoral–shallow sea (lake) is relatively turbulent; relatively quick subsidence and sedimentation environment.
B	B1	Derived from lower aquatic organisms mixed with terrestrial higher plants, content of sapropelinite >3%.	Littoral–neritic sea (lake); covered swamp environment; weak hydrodynamic.
	B2	Derived from lower aquatic organisms mixed with terrestrial higher plants, content of sapropelinite 1%–3%.	Coastal (lacustrine) swamp; littoral-neritic sea (lake).
	B3	Derived from lower aquatic organisms mixed with terrestrial higher plants, content of sapropelinite <1%.	Littoral–neritic sea (lake), medium swamp, comparatively strong hydrodynamic.
C	C1	It is mainly composed of macerals from higher plants with high content of organic matter and mainly composed of homogenous vitrinite. The ash content in coal is <30%, the sulfur content in coal is >3%, and the sapropelic content is <1%.	Littoral–neritic sea (lake) or tidal flat marsh, covered by platform deposit, lagoon or closed bog, the water environment is relatively calm and the hydrodynamic activity is moderate.
	C2	It is mainly composed of macerals from higher plants with high content of organic matter and mainly composed of clastic vitrinite. The ash content in coal is <20% and the sulfur content in coal is 1%–3%.	Littoral–neritic sea (lake) or tidal flat swamp, covered by thin platform sedimentation, the water environment is relatively calm, the hydrodynamic activity is moderate to strong.
	C3	It is mainly composed of macerals from higher plants with high content of organic matter, mainly composed of clastic vitrinite and inert plastids. The ash content in coal is different, the sapropelic content is 2.5%– 5%, and the sulfur content in coal is <1%.	Littoral–neritic sea (lake) or tidal flat swamp, not covered by platform sedimentation, the water environment is comparatively turbulent, the hydrodynamic is relatively strong, or the delta plain environment, or the swamp water is relatively mobile.
	C4	It is mainly composed of macerals from higher plants, with high content of organic matter and mainly shell body. The ash content in coal is >30%, and the sulfur content in coal is <1%.	Littoral–neritic sea (lake) or tidal flat swamp, not covered by platform sedimentation, the water environment is comparatively turbulent, the hydrodynamic is relatively strong, or the delta plain environment, or swamp with open flow.

plants. The high content levels of organic matter were mainly composed of homogenous vitrinite, with ash content levels in the coal <30%; sulfur content >3%; and sapropelic content <1%. It was determined that the Qiongdongnan Basin had mainly developed this type of organic facies.

C3 Type: swamp with open flow, littoral shallow seas (lakes) or tidal flat swamps. The overlying platform depositions were developed, and the water environment was relatively turbulent with relatively strong hydrodynamic activities. Also, delta plain environments may have been developed, or relatively flowing swamp water with relatively unobstructed drainage systems. Various terrestrial materials were supplied and deposited and the basin was covered with shallow water. The sedimentary characteristics were as follows: it was mainly composed of macerals from higher plants. The high content levels of organic matter were mainly composed of clastic vitrinite and inert plastids. The ash content levels in coal were observed to vary greatly; sulfur content was <1%; and the sapropelic content ranged from 2.5% to 5%.

C4 Type: open flow marshes, littoral and shallow seas (lakes), or tidal flat marshes. The overlying platform depositions were developed, with relatively turbulent water environments and strong hydrodynamic activities. Also, delta plain environments were developed belonging to the category of open flow marshes, with abundant land source material supplies. The macerals of higher plants in the organic matter are mainly of the crustacean group with high content levels. The sedimentary characteristics were as follows: it was mainly composed of macerals from higher plants, with high content levels of organic matter including shell bodies; with ash content levels >30% in the coal; and sulfur content levels of <1%.

5 Discussion

5.1 *Particular characteristics of the peat formation and accumulations and the coal formations in the marginal basins of the South China Sea*

During the initial deposition period of the Yacheng Formation, the Qiongdongnan Basin was dominated by continental facies. Then transgression began to occur, which gradually increased and dominated the area during the middle and late periods (Li et al., 2010a; Shao et al., 2010; Song et al., 2020). The analyses of the Paleogene sedimentary system types conducted by various researchers have revealed some variations. For example, Cai (2009) identified that the Yacheng Formation developed an alluvial fan system; (fan) delta system; coastal plain system; coastal system; and shallow sea system, respectively. Li et al. (2010a) identified an alluvial fan/fan delta-submarine fan system; braided river-braided river delta-subaqueous fan system; and a tidal-lagoon system, of which the latter two identified an alluvial fan/fan delta-submarine fan system; braided river-braided river delta-underwater fan system; and a tide- ping-lagoon system (Fig. 5). Shen et al. (2013) believed that the Lingshui Sag was a future-closed bay during the early deposition of the Oligocene Yacheng Formation, where a tidal- lagoon sedimentary system

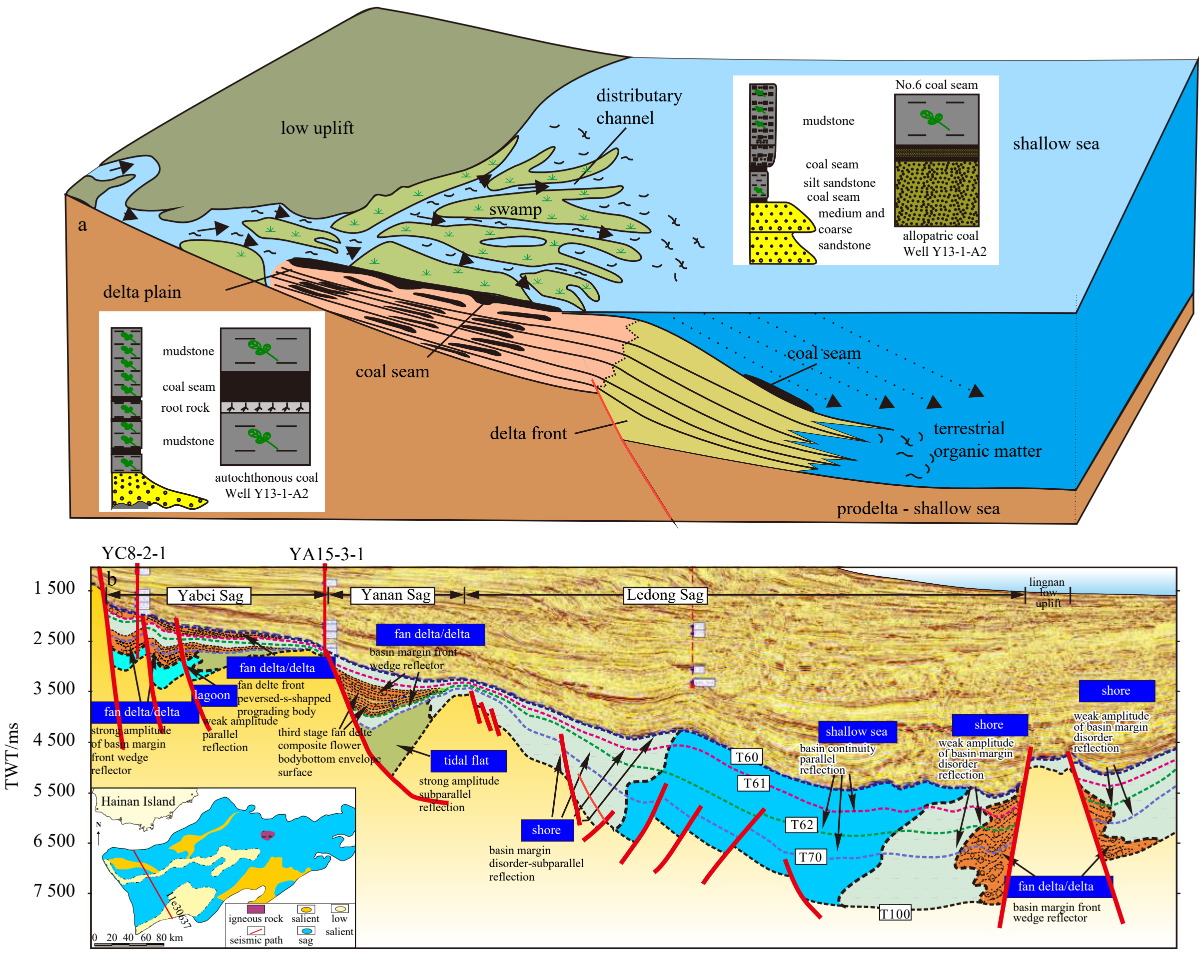


Fig. 5. Model of peat accumulation and coal formation of Y13-1 Depression in Qiongdongnan Basin.

had mainly developed.

The distributions of the sedimentary facies of the Lingshui Formation in Qiongdongnan Basin were mainly controlled by the fault slope belts. In particular, the fault slope belt directly controlled the distribution ranges of the paleo-uplift areas, coastal plain areas, shallow sea (shallow water) areas, and shallow sea (deep water) areas (Zhao et al., 2003). The Lingshui Formation was formed during the late rifting stage, during which time the sedimentary environment was dominated by neritic facies and coastal facies. And basin-floor fans, slope fans, and fan deltas were developed near the faults (Wei et al., 2004; Liu et al., 2006). In the northern depression zone of the Qiongdongnan Basin, the Lingshui Formation was overfilled or balanced filled, and developed a sandstone-mudstone-sandstone triple sedimentary filling structure. These structures contained coal seams, but were weaker than those of the Yacheng Formation. However, in the central depression area, the Lingshui Formation was underfilled, and developed a sandstone-mudstone double sedimentary filling structure. Since the sedimentary filling structure of the Paleogene rift basin was mainly controlled by tectonic subsidence, the changes in the early–late Oligocene sedimentary filling structures reflected the changes in the structural properties of the basin. The tensional faulting activities controlled the Eocene–early Oligocene filling structures of the basin. Meanwhile, the late Oligocene filling structure of the basin was affected by both the tensional faulting activities and the regional background subsidence (Zhong et al., 2004).

The typical basic theories of coal formation include four factors: paleophyte, paleo-climate, paleo-geography, and paleo-structure. Under the conditions of unified tectonic fields and sedimentary fields, the combination of those four factors can form a stable distribution of coal seams. However, in open system consisting of both continental and marine environments, the controlling factors can be complex and changeable. For large rift basins, such as the Qiongdongnan Basin, multiple independent sedimentary systems were developed as shown in Fig. 2. These include fan systems, fan delta systems, and river delta systems developed terrestrial plants. Therefore, the developing peat swamps were also not identical, which had led to mobility in the destruction and reconstruction processes of the peat swamps. The marginal basins of the South China Sea have large uniform backgrounds and continent-marine interaction fields. However, due to the differences in terrestrial plant growth sources, the peat swamp formations and coal seam formations in each basin were both independent of and influenced by the entire basin system.

Therefore, it can be considered that the peat formation and accumulation processes in the marginal basins of the South China Sea were not episodic or eventful, but a type of mixed accumulation with a background of unstable continental margins. The coal seam distributions of the marginal basins in the South China Sea were limited to depressions or even sags. The peat material originated from the peat swamp areas developing in the sedimentary systems. The material may have also come from relative high land areas in small sags with shallow water levels. Eventually, accumulations developed with multiple non-interfering centers. Subsequently, the formed coal seams had not extended far, and could not be compared across depressions or sags. Therefore, the results were the above-mentioned particular characteristics of the peat accumulations and coal formations in the marginal basins of the South China Sea.

5.2 *Correlation analysis results*

Since the late Paleozoic, the coal-forming basins in the continental regions have been relatively independent systems, such as the large epicontinental sea basins in northern China (Fig. 6), along with the large lacustrine basins and small- or medium-sized rift sags or depressions which are independent coal-forming systems. That is to say, large epicontinental basins, such as the late Paleozoic basins in northern China, are typically craton basins. In such basins, the coal-forming processes were controlled by high-frequency and multi-stage sea-level changes during the late Paleozoic. And the dynamic systems, sedimentary dynamic fields, and water systems of the coal formation within the basins were unified. Therefore, the coal formations display the unity of the basins' filling and evolution processes, as well as the regularity of the migration processes.

During the process of coal formation, large epicontinental sea basins can be regarded as relatively closed or semi-closed systems. Although the epicontinental sea basins were sometimes sea basins and sometimes land basins, they were still considered to be closed systems which were characterized by stable patterns when the coal was formed.

Craton basins exhibit unified action fields of deposition, plant flourishing and attenuation, formation and development of peat bogs, waste areas, enrichment zones, and concentration centers. Fine aggregation units can be found in these unified action fields.

The coal-forming processes during those events mainly emphasized the transgressive properties. Those types of events also played a role in controlling the coal-forming processes. However, the accumulation of peat was not considered to be an event. The coal-forming processes of the transgression events occurred after another transgression event, whereas peat accumulation occurred during the sea-level oscillation prior to a large-scale transgression and represented the beginning of a depositional sequence. Therefore, coal seams and their directly overlying marine limestone represent a type of event deposition combination. The coalification processes of peat occurred entirely within a deep-water environment with reductive conditions, in which its gelatinization was relatively complete. Therefore, since the processes caused the peat to quickly become flooded and remain in a deep-water environment, it is considered that there are sudden events, and the transgression surfaces located between the coal seams and the marine limestone were isochronous. The coal seams and their associated roof marine limestone facies were also isochronous deposition layers. It is currently believed that the marine limestone and coal seams were each deposited in single depositional environments, with broad distribution areas and lateral stability. At the same time, since they were also isochronous facies, they could be used as stratum correlation markers (Li et al., 2018).

The sedimentary basements of continental depression basins are known to have been relatively stable, and the expansion and shrinkage actions of the lake water levels had mainly occurred in the lakeside and lakeside delta areas (Wang et al., 2012). During the lake level spreading periods, the swamps in the lakeside plains gradually migrated to the land and formed coal deposits. In contrast, during the lake shrinking periods, the swamps in the lakeside plains gradually migrated to the lake areas. At certain times, the entire lake areas had developed siltation and became shallower, and coal accumulations of major intensity had occurred. The stability of the coal seams which developed during the expansions and shrinkages of the lake levels could be easily observed in the regional correlations.

For the marginal basins in the South China Sea, the interactions between sea and continent areas were strong and had important influences on the coal formation. However, although the marginal basins in the South China Sea were overall large open

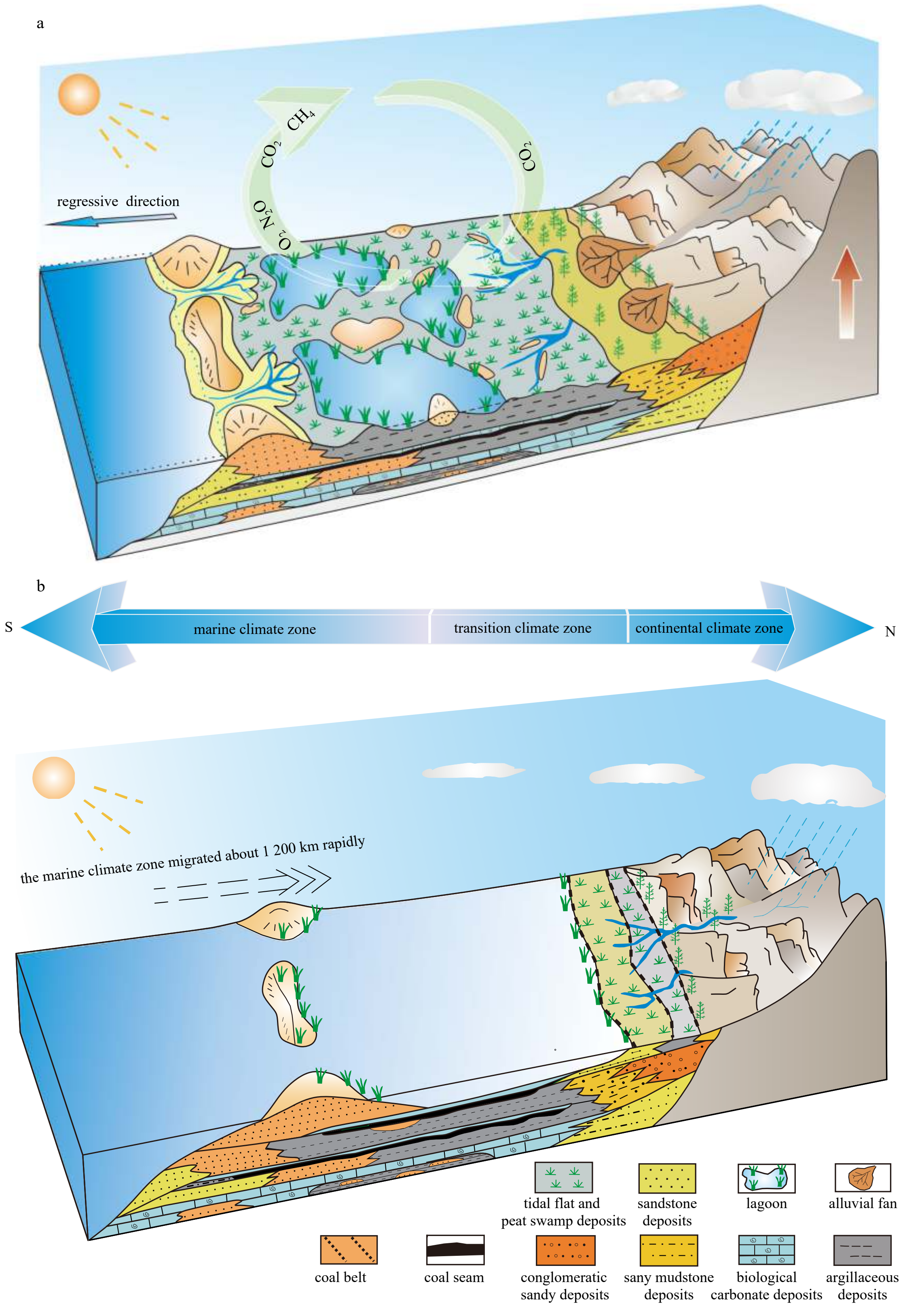


Fig. 6. The transgression, regression coal-forming and climate zone migration of epicontinental sea basin in northern China. a. The regression happened, massive peat swamp developed, and epicontinental marine environment receded. The orange arrow means tectonic uplift. b. The transgression happened, peat swamp was shrunk, and a wide range of epicontinental sea environment occured (modified from Li et al. (2018)).

systems, the peat and coal formations were independent of each other. Therefore, from the perspective of the distribution systems of the sedimentary facies and the sedimentary system, they were relatively independent and dispersed, as detailed in Fig. 2.

In addition, the various fan systems, such as alluvial fans, fan deltas, and deltas, were determined to have had little mutual containment effects in different parts of the basin. Therefore, there was no unity and consistency in the coal-forming fields.

6 Conclusions

The Oligocene of the marginal basins in the South China Sea was an important period of peat formation and accumulation. It has been determined that during that period, peat formation and accumulation occurred under the conditions of relatively flourishing plants and a favorable climate. However, the peat was not formed in unified sedimentary dynamic fields, but showed the characteristics of multi-level geographical units, multiple sources, non-stability, non-episodic, and non-events. It was observed that there were no uniform peat accumulation periods in the marginal basins of the South China Sea.

The particular conditions of the marginal basins of the South China Sea lie in the fact that the marginal basins are not simple units, such as having a single shore with shelf/continental slopes to the deep sea. Instead, they are composed of multi-stage structures from the land to the sea, and multiple types of unique basins exist. The land-sea interactions had strong influences on and control of the coal-forming processes.

In the marginal basins of the South China Sea, the strong continent and sea interactions exerted important influences and controls on the growth of terrestrial plants, peat formation, accumulation, and dispersion, and coal formation. The peat swamps were distributed in different parts of each sedimentary system and were often destroyed. As a result, the peat materials were dispersed into the marine system and became a component of the marine sediment, constituting the main source of hydrocarbon in those areas.

Acknowledgements

We thank the Beijing Research Center of CNOOC (China) Co., Ltd. for providing the data used in this study.

References

Brooks J, Welte D H. 1987. Advances in Petroleum Geochemistry. London: Academic Press

Cai Jia. 2009. Paleogene palaeogeomorphology restoration and its control on sequence patterns and sedimentary characteristics in Qiongdongnan Basin (in Chinese)[dissertation]. Beijing: China University of Geosciences

Dai Shifeng, Ren Deyi, Li Shengsheng, et al. 2007. Coal facies evolution of the main minable coal-bed in the Heidaigou Mine, Jungar Coalfield, Inner Mongolia, northern China. Science in China Series D: Earth Sciences, 50(2): 144–152

Diessel C F K. 1986. On the correlation between coal facies and depositional environments. In: Proceedings of the 20th Symposium on Advances in the Study of the Sydney Basin. Heidelberg: Springer-Verlag, 19–22

Diessel C F K. 1992. An appraisal of coal facies based on macerals characteristics. Australian Coal Geology, 4: 474–483

Feng Yangwei, Qu Hongjun, Zhang Gongcheng, et al. 2010. Mesozoic source-reservoir-seal assemblage characteristics in the Northwest Shelf of Australia. Marine Geology Letters (in Chinese), 26(6): 16–23

Hao Fang, Chen Jianyu, Sun Yongchuan, et al. 1994. Organic facies studies and their use in sedimentary basin analysis. Acta Sedimentologica Sinica (in Chinese), 12(4): 77–86

Jones G. 1981. Book notes. Business History, 23(1): 120–121

Kwiecińska B, Petersen H I. 2004. Graphite, semi-graphite, natural coke, and natural char classification-ICCP System. International Journal of Coal Geology, 57(2): 99–116

Li Juyun. 2015a. Tectonic evolution and its control on coal source rocks in northern depression belt of Qiongdongnan basin (in Chinese)[dissertation]. Beijing: China University of Mining and Technology

Li Shaojie. 2015b. Study on the formation modes of coal-measure source rocks in northern basins of South China Sea (in Chinese) [dissertation]. Beijing: China University of Geosciences

Li Sitian. 1999. Basin analysis and some new studies of coal geology. Earth Science Frontiers (in Chinese), 6(S1): 133–138

Li Xuxuan, Liu Baoming, Zhao Junqing. 2007. Paleogene sequence configuration, depositional filling pattern and hydrocarbon-generation potential in Qiongdongnan basin. China Offshore Oil and Gas (in Chinese), 19(4): 217–223, 239

Li Youchuan, Mi Lijun, Zhang Gongcheng, et al. 2011a. The formation and distribution of source rocks for deep water area in the northern of South China Sea. Acta Sedimentologica Sinica (in Chinese), 29(5): 970–979

Li Zengxue, He Yuping, Liu Haiyan, et al. 2010a. Sedimentology characteristics and coal-forming models in Yacheng Formation of Qiongdongnan Basin. Acta Petrolei Sinica (in Chinese), 31(4): 542–547

Li Zengxue, Li Xiaojing, Li Ying, et al. 2016. Mechanisms of accumulation and coexistence of coal and oil shale in typical basins. Energy Exploration & Exploitation, 34(3): 360–377

Li Zengxue, Lv Dawei, Han Meilian, et al. 2011b. Coal forming environments of the Third Member of Yacheng Formation of the Paleogene in Qiongdongnan Basin for an example. Energy Exploration & Exploitation, 29(2): 179–195

Li Zengxue, Lv Dawei, Zhou Jing, et al. 2011c. Theory and model of coal-bearing system. Acta Geoscientica Sinica (in Chinese), 32(6): 659–667

Li Zengxue, Wang Dongdong, Lv Dawei, et al. 2018. The geologic settings of Chinese coal deposits. International Geology Review, 60(5–6): 548–578

Li Zengxue, Zhang Gongcheng, Li Ying, et al. 2012. The Paleogene coal-bearing basin and coal-measures distribution of China sea area. Earth Science Frontiers (in Chinese), 19(4): 314–326

Li Zengxue, Zhang Gongcheng, Wang Dongdong, et al. 2010b. Identification and correlation of base-level cycles of coal-bearing strata in paleogene system of China Seas: Taking the case of Qiongdongnan Basin as an example. Geoscience (in Chinese), 24(6): 1178–1185

Liu Chuanlian. 2010. Sedimentary environment and micro-sediment characteristics of Oligocene source rocks in Qiongdongnan Basin. Acta Petrolei Sinica (in Chinese), 31(4): 573–578

Liu Zhen, Zhao Yang, Du Jinhu, et al. 2006. Characteristics of “multi-factor controlling and keyfactor entrapping” of formation and distribution of lithologic petroleum reservoirs in continental rift basin. Chinese Journal of Geology (in Chinese), 41(4): 612–635

Liu Zhenhu. 2005. Distribution of sedimentary basins and petroleum potential in southern South China Sea. Geotectonica et Metallogenia (in Chinese), 29(3): 410–417

Lv Dawei, Li Zengxue, Wang Dongdong, et al. 2019. Sedimentary model of coal and shale in the Paleogene Lijiaya formation of the Huangxian Basin: Insight from petrological and geochemical characteristics of coal and shale. Energy & Fuels, 33(11): 10442–10456

Lv Dawei, Li Zengxue, Wei Jiuchuan, et al. 2010. Sequence division of coal strata based on different coal-accumulation theory. Journal of China University of Petroleum (in Chinese), 34(4): 49–56, 66

Lv Dawei, Song Ying, Shi Longqing, et al. 2020. The complex transgression and regression history of the northern margin of the Palaeogene Tarim Sea (NW China), and implications for potential hydrocarbon occurrences. Marine and Petroleum Geology, 112: 104041, doi: 10.1016/j.marpetgeo.2019.104041

Mi Lijun, Wang Dongdong, Li Zengxue, et al. 2010. High-resolution sequence stratigraphic framework and coal-forming features in Yacheng Formation of Qiongdongnan Basin. Acta Petrolei Sinica (in Chinese), 31(4): 534–541

Pickel W, Kus J, Flores D, et al. 2017. Classification of liptinite–ICCP System 1994. International Journal of Coal Geology, 169: 40–61

Shao Lei, Li Ang, Wu Guoxuan, et al. 2010. Evolution of sedimentary environment and provenance in Qiongdongnan Basin in the northern South China Sea. Acta Petrolei Sinica (in Chinese), 31(4): 548–552

Shao Longyi, Lu Jing, Wang Hao, et al. 2008. Advances in sedimentology and sequence stratigraphy of paralic coal measures. Journal of Palaeogeography (in Chinese), 10(6): 561–570

Shen Huailei, Qin Changwen, Wang Dongdong, et al. 2010. Distinguishing methods for coal beds in Yacheng Formation of Qiongdongnan Basin. Acta Petrolei Sinica (in Chinese), 31(4): 586–590

Shen Huailei, Zhang Gongcheng, Sun Zhipeng, et al. 2013. Formation control factor analysis and exploration practice in gas-rich sag in deep-water areas of Qiongdongnan Basin: a case study of Lingshui sag. Acta Petrolei Sinica (in Chinese), 34(S2): 83–90

Song Guangzeng, Wang Hua, Gan Huajun, et al. 2014. Paleogene tectonic evolution controls on sequence stratigraphic patterns in the central part of deepwater area of Qiongdongnan Basin, Northern South China Sea. Journal of Earth Science, 25(2): 275–288

Song Guangzeng, Wang Hua, Wang Zhenfeng, et al. 2020. Sequence stratigraphic architectures and responses to syndepositional tectonic evolution in the Paleogene Lingshui Sag, Qiongdongnan Basin, northwestern South China Sea. International Geology Review, 62(7–8): 1036–1056

Sýkorová I, Pickel W, Christanis K, et al. 2005. Classification of huminite-ICCP System 1994. International Journal of Coal Geology, 62(1–2): 85–106

Wang Dawei, Wu Shiguo, Wang Yingmin, et al. 2015. Deep-water sediment cycles in the Qiongdongnan Basin. Chinese Science Bulletin, 60(10): 933–943, doi: 10.1360/N972014-00477

Wang Hua, Zhang Yuntao, Yang Hong. 2001. Analysis on the sedimentary conditions of thick coalbeds in French faulted coal basins. Coal Geology & Exploration (in Chinese), 29(1): 1–4

Wang Tong, Shao Longyi, Tian Ye, et al. 2012. Sequence stratigraphy of the Jurassic coal measures in Northwestern China. Acta Geologica Sinica, 86(3): 769–778, doi: 10.1111/j.1755-6724.2012.00702.x

Wei Kuisheng, Chu Meijuan, Cui Yingkai, et al. 2004. Characteristics of time-space combination of lowstand system tracts and their exploration significance in eastern Qiongdongnan basin. Oil and Gas Geology (in Chinese), 25(6): 650–665

Xie Yuhong, Li Xushen, Fan Caiwei, et al. 2016. The axial channel provenance system and natural gas accumulation of the Upper Miocene Huangliu Formation in Qiongdongnan Basin, South China Sea. Petroleum Exploration and Development, 43(4): 570–578, doi: 10.1016/S1876-3804(16)30067-2

Zhang Gongcheng. 2010. Tectonic evolution of deepwater area of northern continental margin in South China Sea. Acta Petrolei Sinica (in Chinese), 31(4): 528–533, 541

Zhang Gongcheng, Chen Guojun, Zhang Houhe, et al. 2012. Regular distribution of inside-oil fields and outside-gas fields controlled by source rocks and heat in China offshore basins. Acta Sedimentologica Sinica (in Chinese), 30(1): 1–19

Zhang Gongcheng, Li Zengxue, He Yunpeng, et al. 2010. Coal geochemistry of Qiongdongnan Basin. Natural Gas Geoscience (in Chinese), 21(5): 693–699

Zhang Gongcheng, Mi Lijun, Wu Shiguo, et al. 2007. Deepwater area—the new prospecting targets of northern continental margin of South China Sea. Acta Petrolei Sinica (in Chinese), 28(2): 15–21

Zhang Gongcheng, Qu Hongjun, Liu Shixiang, et al. 2015. Tectonic cycle of marginal sea controlled the hydrocarbon accumulation in deep-water areas of South China Sea. Acta Petrolei Sinica (in Chinese), 36(5): 533–545

Zhang Gongcheng, Tang Wu, Xie Xiaojun, et al. 2017a. Petroleum geological characteristics of two basin belts in southern continental margin in South China Sea. Petroleum Exploration and Development, 44(6): 899–910, doi: 10.1016/S1876-3804(17)30102-7

Zhao Zhongxin, Wang Hua, Lu Yongchao. 2003. Controlling role of fault-break zones on sedimentary system-Taking Qiongdongnan basin as an example. Petroleum Exploration and Development (in Chinese), 30(1): 25–27

Zhong Zhihong, Wang Liangshu, Li Xuxuan, et al. 2004. The Paleogene basin-filling evolution of Qiongdongnan basin and its relation with seafloor spreading of the South China Sea. Marine Geology and Quaternary Geology (in Chinese), 24(1): 29–36

Zhu Weilin. 2010. Petroleum geology in deepwater area of northern continental margin in South China Sea. Acta Petrolei Sinica (in Chinese), 31(4): 521–527

Zhu Weilin, Zhang Gongcheng, Gao Le. 2008. Geological characteristics and exploration objectives of hydrocarbons in the northern continental margin basin of South China Sea. Acta Petrolei Sinica (in Chinese), 29(1): 1–9

Zhu Weilin, Zhong Kai, Li Youchuan, et al. 2012. Characteristics of hydrocarbon accumulation and exploration potential of the northern South China Sea deepwater basins. Chinese Science Bulletin, 57(24): 3121–3129, doi: 10.1007/s11434-011-4940-y