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Genetic relationship between formation, accumulation and migration and dispersion of peat materials in Paleogene – Take the Qiongdongnan Basin as an example

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Abstract

Coal-type source rocks include both coal and terrigenous marine source rocks. By studying the distribution of secondary depressions, uplifts, as well as the characteristics of peat formation and accumulation in the northern marginal sea basin of the South China Sea, and combining them with coal formation characteristics observed in other basins, five genetic theories on the relationship between peat accumulation and dispersed organic matter accumulation are proposed. The northern marginal sea basin of the South China Sea is characterized by "disadvantageous coals formation and favorable terrigenous marine source rocks formation." This paper provides a distribution map of coal seams and terrigenous marine source rocks in the Qiongdongnan Basin and determines their distribution patterns. Research shows that the migration of sedimentary facies in the basins and inner depressions led to the formation and migration of the peat accumulation centers. In addition, the vertical migration of the peat accumulation centers led to planar migration, which is actually a type of coupling relationship.Previous research results have revealed that the formation of coal-type source rock is multi-phased. The marginal sea basin is composed of several fault-depression basins, with each basin developing a second order of depression and uplift. There is no unified basin center or depositional center to be found. As a result, the concentration centers of coal-forming materials also vary greatly. Based on the distribution characteristics of coal-type source rocks in different basins within the marginal sea basins of the South China Sea, the research results have practical significance and provide guidance for exploring coal-type oil and gas reservoirs in this area.

Key words: Coal-type source rock, marginal sea basins, migration of peat aggregation centers, terrigenous marine source rock, Qiongdongnan Basin

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1 Introduction

Previous studies have determined that coal-type rock formations are important types of source rock for oil and gas accumulations in the South China Sea, and their degree of importance is increasing (Zhang et al., 2021, 2022). Coal-type source rocks include two parts, namely coal seam and terrigenous marine source rocks. Coal seam is a layered deposit formed by the accumulation of peat material into layers (in situ or allochthonous) through a series of physical, chemical and biological changes. From the perspective of hydrocarbon source rock type and petrology, "terrigenous marine source rock" means that the organic matter contained in sedimentary rocks of marine origin is coal-type and terrigenous. The distribution characteristics of coal-type source rocks in the entire South China Sea were first studied (Zhang et al., 2010; Li et al., 2012a; Wang et al., 2015). Coal-bearing depressions are distributed in the Pearl (Zhujiang) River Mouth Basin and Qiongdongnan Basin in the northern part of the South China Sea (Zhang et al., 2010), and the tectonic-sedimentary characteristics of coal-bearing source rocks in the marginal sea of the South China Sea were examined (Zhang et al., 2013a). The formation characteristics of coal-type source rocks and coal-derived gas in the Baiyun Depression, Pearl (Zhujiang) River Estuary Basin, were first mentioned (Zhang et al., 2014), and the source rocks of the Lingshui 17–2 gas field in the Qiongdongnan Basin are coal-type source rocks (Zhang et al., 2016). Therefore, it is of theoretical and practical significance to examine the formation and distribution mechanisms of coal-type source rock. Some important insights have been obtained during the study of the formation mechanisms of coal-type hydrocarbon source rock in the marginal sea basins of the South China Sea. For example, it has been determined that peat swamps and peat accumulations have the same basic characteristics of "source-to-sink systems", as well as certain particularities (Li et al., 2021a, 2021b; Song et al., 2021). Those particularities lie in the fact that peat materials are the product of a series of biological, physical, and chemical changes in plant tissue, rather than complex processes, such as weathering and denudation. Therefore, peat material should be classified as authigenic organic matter. At present, the research

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regarding the formation and evolution mechanisms of peat under the background of marginal sea conditions is still at the primary and exploratory stage. For example, the mechanisms of the deposition and accumulation of dispersed coal-forming material and its homologous peat in deep-water zones following the occurrence of large-scale long-distance migration remain unclear, as well as the correlations between the accumulation layers and the dispersion accumulations. Therefore, effective predictions and evaluations of the formation, accumulation, distribution, and evolution of coal-type source rock have been seriously affected.

New developments in coal geology theory: the research and clarification of the formation mechanisms of coal-type source rock definitely involve the basic theory of coal geology. Coal geology is both an old and a new discipline. As a new discipline, coal geology has timely absorbed new ideas and theories, along with such methods as sedimentology, stratigraphy, oil-gas geology, and sequence stratigraphy in recent decades, and thereby has enriched and developed its own theoretical system (Li et al., 1993, 1999, 2018; Li, 1999; Lin, 1987; Dai et al., 2008, 2010, 2015; Sun et al., 1998, 2013, 2017). Hydrocarbon generation of coal are closely related to peat-forming environments (Sun et al., 2013; Liu et al.,2022; Zhao et al., 2021, 2023). Sun et al. (2002) reported that coal formed in relatively oxidized peat conditions may produce lower contents of hydrocarbon than those in relatively reduced peat environment. Inertinite yields the lowest extract organic matter than liptinite and vitrinite macerals (Sun and Horsfield, 2005). The establishment of the basic theory of coal geology, as well as its mature theory and model, were achieved based on detailed studies of coal-forming basins and coal-bearing deposits in various land areas (Shao et al., 1998, 2009, 2017, 2014, 2021; Li, 1994; Dai et al., 2020). In recent years, it has been found that marine mudstone source rock with terrigenous dispersed organic matter as the main organic matter type, are part of coal source rock (Zhang et al., 2019; Li et al., 2021a, b; Wang et al., 2021). Therefore, terrigenous marine source rock should also be considered as components of the coal-forming process.

Coal forming model of a stable continental margin sea basin under ideal background conditions: the model presented in this study is based on the idealized sequence stratigraphic model established by Diessel, which was considered to be ideal and a major breakthrough in coal geology theory. The positions and compositions of coal seams in sequence stratigraphic configuration may be obtained using the Diessel Model (Diessel et al., 2000). The overlapping sequence of the coal seams in the model is assumed and can be realized under ideal conditions. It has been determined using the aforementioned sequence stratigraphic model that low standing system tracts are the main coal-forming environments (Van Wagoner, 1998). Transgressive systems tracts and highland system tracts should not be entirely ruled out for possibly containing developed coal seams. However, they have been observed to have been generally formed in low-standing system tracts or self-margin system tracts.

Scientific problems to be solved related to the formation of the coal-type source rock in the northern marginal sea basins of the South China Sea: under the background of the multiple depressions and fault basins developed in the unified tectonic frameworks of the sea basins in the northern margin of the South China Sea, peat formation and accumulation processes, as well as the correlations between terrigenous organic matter accumulations and dispersed accumulations, are important theoretical problems in the field of coal geology and urgent scientific problems.

Cenozoic basins have developed in China's marginal sea and its adjacent areas. Such basins are generally located in two tectonic environments (for example, the inner and outer margins of continental plates) (Wolfart et al., 1986; Faure et al., 1989; Lambiase et al., 1997; Yao et al., 2004; Li and Li, 2006; He et al., 2007) and are covered by seawater. The genesis and formation model of the marginal sea in the South China Sea were analyzed (Zhang et al., 2015a, 2015b, 2018). The northern continental margin of the South China Sea is a passive continental margin, and the corresponding basins include the Taixinan Basin, Pearl (Zhujiang) River Mouth Basin, and the Qiongdongnan Basin (Zhang et al., 2007; Zhu et al., 2008), as detailed in Fig. 1. The important coal-forming periods in those basins during the early Oligocene and late Oligocene were also the formation and evolution periods of those basins, during which time the following three main coal-forming environments existed: deltas, fan deltas, and tidal flat-lagoons.

The identification of the determination of the binary structural characteristics and descriptions of the coal-type source rock are the latest progress which have been made in the study of the characteristics of coal-type source rock in the marginal sea basins of the South China Sea (Li et al., 2010; Zhang et al., 2013a; Wang et al., 2021), and have important theoretical value and practical significance (Liu et al., 2023). However, such descriptions and theoretical interpretations remain relatively fossilized characterizations and interpretations. That is to say, the compositions of coal-type source rock are vividly characterized and described by "binary structures", namely, terrigenous marine source rock composed of solid layered coal and terrigenous organic matter dispersed in other sediment. Unfortunately, the genetic relationships between coal seams and terrigenous marine source rock have not yet been fundamentally resolved in theory.

2 Geological background and characteristics of the marginal sea basins in the South China Sea

2.1 *Characteristics of the marginal sea basins in the South China Sea*

The most important features of the marginal sea basins in the northern regions of the South China Sea are the unified marginal sea basin tectonic frameworks and the development of multiple depressions and fault basins in the interiors (Zhang, 2010; Zhang et al., 2013b, 2015a, 2015b, 2018; Wang et al., 2014). The basins have the basic attributes of a single basin, as well as independent characteristics, such as the Taixinan Basin, Pearl (Zhujiang) River Mouth Basin, and Qiongdongnan Basin (Fig. 2). Therefore, the composition characteristics of the marginal sea basins in the northern part of the South China Sea include complex spatial structures. The general characteristics of the marginal sea basins in the northern regions of the South China Sea can be summarized as follows: (1) unified continental marginal sea basin spatial frameworks and the development of multiple coal-forming basins with independent attributes, and basin filling and coal-forming processes based on independent basin systems; (2) single independent basins within a unified framework having the characteristics of multi-stage secondary structures, multiple depocenters, and provenances; (3) multiple coal-forming accumulation centers of coal formation. Those characteristics are totally different from the evolution characteristics of the Paleogene coal-forming basins in China's land areas. The Paleogene basins located in land areas are mainly continental lake basins which exist independently, have simple internal structures, and are characterized by coal-formation mainly in the form of minable coal seams (Li et al., 2012a). Therefore, it can be concluded that the study of the coal-forming mechanisms of the marginal basins in

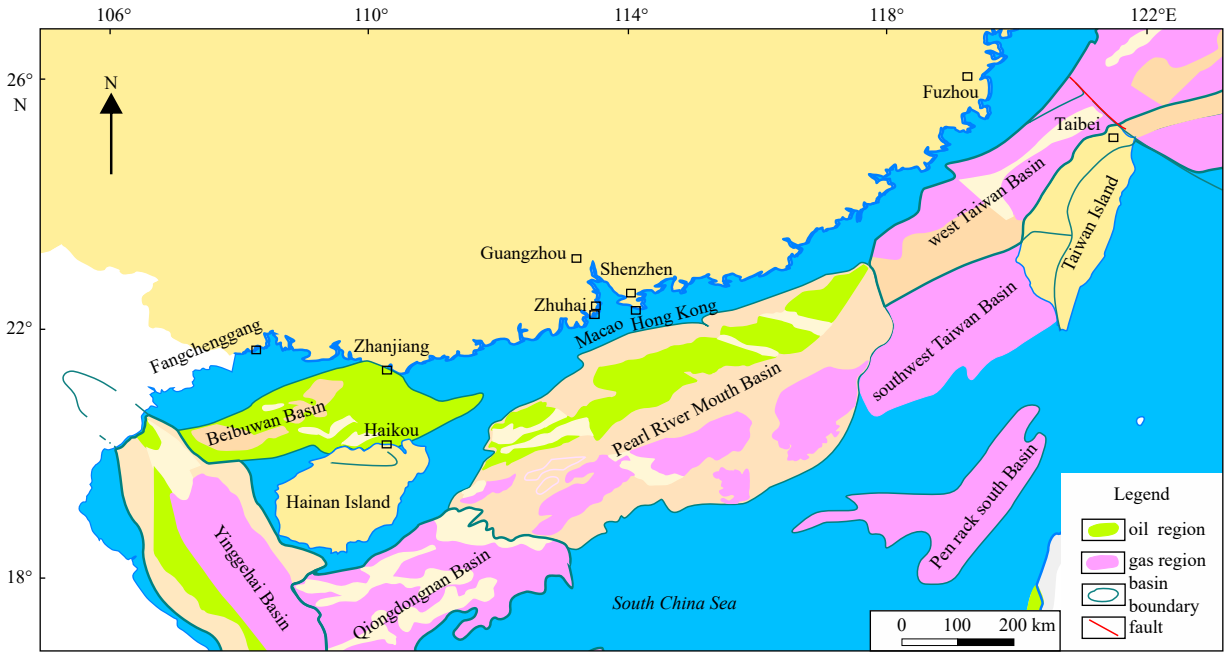

Fig. 1. Distribution patterns of the marginal sea basins in the northern regions of the South China Sea and adjacent areas.

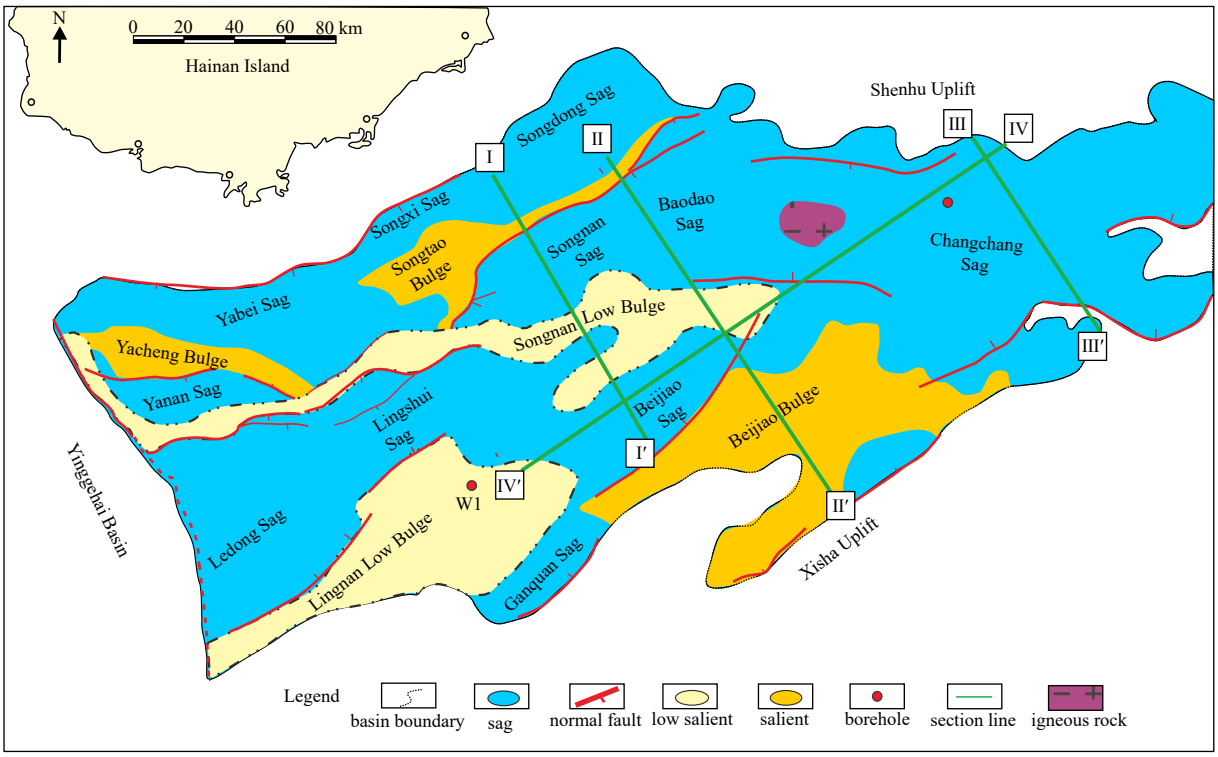

Fig. 2. Distribution patterns of the internal depressions and uplifts in the Qiongdongnan Basin located in the northwestern region of the South China Sea.

the South China Sea represent new topics in the field of coal geology, which will potentially enrich and develop the existing theories regarding coal geology as a new manner of coal formation.

2.2 *The complexity of the structure and the variability of the sedimentary environment in Qiongdongnan Basin*

Taking Qiongdongnan Basin as an example, it shows that the inner basin of the northern margin sea basin of the South China Sea has developed multistage structure, showing the characteristics of paleostructure, paleoflora and paleogeography, multipolarity of provenance and differentiation of paleosediments.

Several typical seismic profiles of Qiongdongnan Basin were selected to analyze the sedimentary facies and sedimentary environment, showing the complexity of sedimentary environment.

2.2.1 *Oligocene seismic profile of the Songnan Sag*

As detailed in Fig. 3, the main body of this examined profile was in the middle of the Songnan Sag and spanned the Song-

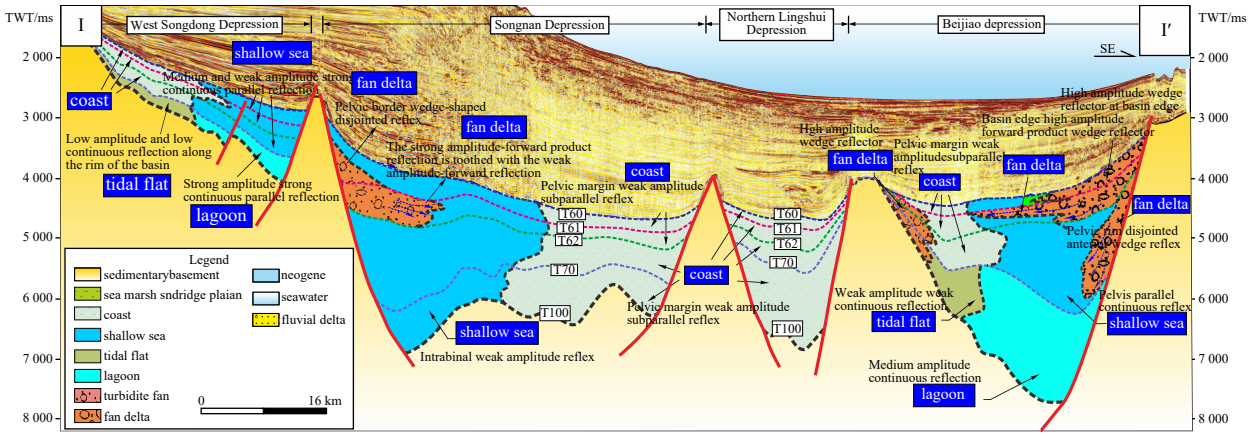

Fig. 3. Oligocene sedimentary facies interpretation of a typical seismic profile in the middle of the Songnan Sag.

dong Sag, Songnan Sag, northern section of the Lingshui Sag, and the Beijiao Sag. Sag structure: the Songdong Sag is a south-faulted and north-overlapping half-graben structure. The Songnan Sag is a double-fault graben (asymmetric) structure, and the northern part of the Beijiao Sag is a symmetric graben structure. The Beijiao Sag is a north-fault south-overlapping half-graben structure. It was determined that five types of sedimentary facies were developed in the Oligocene, including coastal, shallow sea, tidal flats, lagoons, and fan deltas. The fan deltas were particularly well developed and consisted of six fan delta lobes. The fault-controlled steep slopes in the northern part of the Songnan Sag, and the fault-controlled steep slopes in the southern area of the Beijiao Sag, were found to be controlled to form 5-stage lobes. In addition, the northern gentle slope zone of the Beijiao Sag was controlled to form a fan delta complex, which was inherited from and developed by the Yacheng Formation and Lingshui Formation.

2.2.2 *Oligocene seismic profile in the middle of the Baodao Sag*

The main body of this examined profile was located in the Baodao Sag, and spanned the Songdong Sag, Baodao Sag, Songnan Low Uplift, and the southern uplift area, as illustrated in Fig. 4. Sag structure: the Songdong Sag is a south-faulted and north-overlapping semi-graben structure and the Baodao Sag is a north-faulted and south-overlapping semi-graben structure. The Songnan Low Uplift and the southern uplift area contain several developed small depressions. In the examined profile, five types of sedimentary facies were observed to be developed in the Oligocene, including coastal plain, shallow sea, tidal flats, chenier, and braided river deltas. In particular, the braided river deltas were well developed on the gentle slopes in the northern section of the Songdong Sag, and displayed inheritance in the vertical direction. The chenier plain was developed in a relatively closed small depression above the low uplift area.

2.2.3 *Oligocene seismic profile in of the southeastern region of the Changchang Sag*

This profile crossed the eastern and southern uplift areas of the Changchang Sag, as shown in Fig. 5. Sag structure: the Changchang Sag is a nearly symmetrical graben, with relatively closed small depressions developed on the southern uplift. Several types of sedimentary facies were observed to be developed in

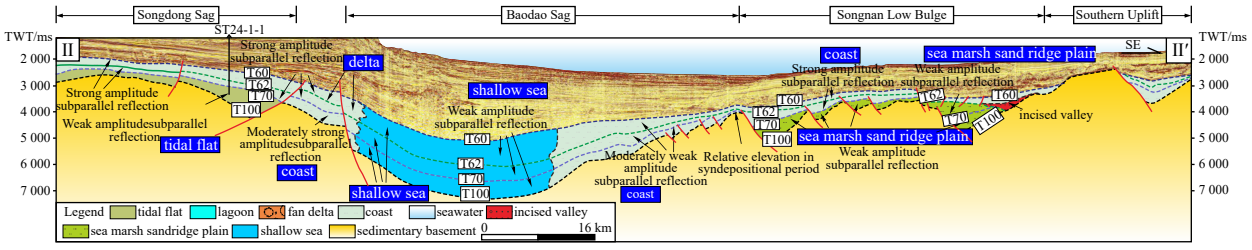

Fig. 4. Oligocene sedimentary facies interpretation of a typical seismic profile in the middle of the Baodao Sag.

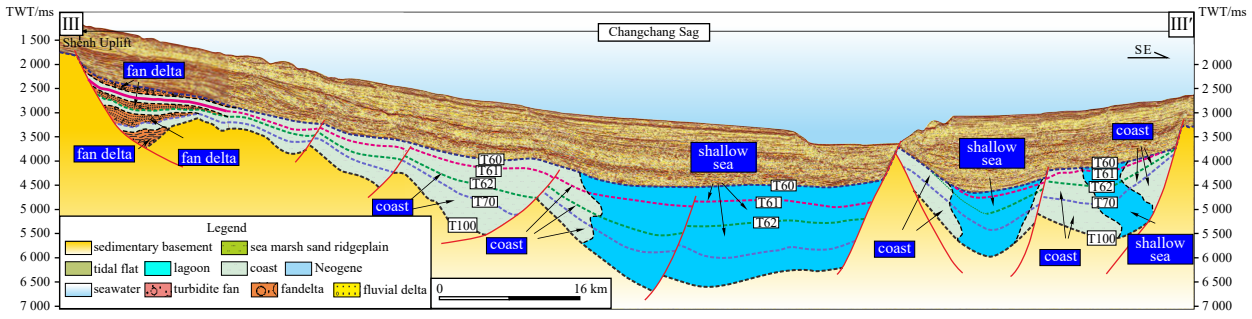

Fig. 5. Oligocene sedimentary facies interpretation of a typical seismic profile in the southeastern section of the Changchang Sag.

the Oligocene, including coastal plain, shallow sea, chenier plains, and fan deltas. In particular, the coastal plain and chenier plain facies were well developed at the basin edge, on the slope of the northern fault terrace, and in the southern small depressions. The fan deltas were developed on the marginal zone of the sag, and four lobes were identified in the Yacheng Formation, which were the first, second, and third members of Lingshui Formation, respectively, and interacted with the shallow sea-plain deposit area in a tooth-like manner.

2.2.4 *Oligocene seismic profile of the Beijiao-Changchang Sag*

This profile was situated in the SW–NE direction, parallel to the structural trend, and spanned the Beijiao Sag, Songnan Low Uplift, and Changchang Sag, as detailed in Fig. 6. The following six types of sedimentary facies were identified in the Oligocene: Coastal plain, shallow sea, tidal flats, lagoons, chenier plains, and fan deltas. It was observed that both coastal plain facies and shallow sea facies were well developed, usually with faults as the boundary between the two. Chenier plain facies were developed in the small depressions above the Songnan Low Uplift. Tidal flat facies were developed in the Beijiao Sag and were found to have obvious sedimentary facies differentiation boundaries with the lagoons. It was also noted that lagoon facies were developed in the Beijiao Sag, with obvious facies differentiation boundaries with the tidal flats. The fan delta facies which were developed in the Yacheng Formation displayed transverse section lens shapes.

As indicated by the above profile descriptions, there were still several sub-grade depressions and secondary uplifts located between the internal depressions and the uplifts in the Qiongdongnan Basin. This study's findings revealed the changes in the sedimentary facies caused by the development of multi-level structures in the basin. In the context of a unified marginal sea basin, it was observed that a number of depressions or fault basins with similar lake basin structures and independent attributes were developed. These basins were characterized with steep/gentle slope structures, as illustrated in Figs 3–6. The marine transegression-regression in the study area was parallel or oblique to the continental margin driven by unified sea level changes. This had resulted in the huge diversity and complexity of the sedimentary environment in the northern part of the basin. Consequently, it had also led to the multi-polarity and complexity of the formation and the development of peat swamp areas, along with the formation and accumulation of peat materials.

3 Formation of different types of coal-type source rock within the marginal basins of the South China Sea

3.1 *Several modes of transport for the peat and its detritus (namely terrigenous organic matter)*

Coal, along with its homologous substances, fall into the peat category. Terrigenous marine source rock is a type of dispersed terrigenous organic matter that is formed by peat accumulating in-situ or accumulating in layers after transport and mixed with fine-grained materials in deep-water zones after large-scale long-distance migration. However, in either formation case (in-situ accumulation or dispersion accumulation), its source is the peat materials formed by peat swamps. The correlations between the accumulation in layers of terrigenous organic matter and dispersion accumulation are important theoretical and practical issues which need to be addressed when determining the distribution laws of coal-type source rock. However, currently there is no mature theoretical discussion on its cause mechanism.

Coal formations and coal-type source rock are two different concepts which cover different contents and mechanisms.

The formation of coal: with plant prosperity as the premise and peat accumulation as the core, there were few or relatively few foreign substances (for example, inorganic sediments) present when the development of a peat swamp environment lasted for a long time period with good continuity of in-situ accumulation, with one or several accumulation centers having developed with strong regularity.

Formation of coal-type source rock (coal and terrigenous Marine source rocks): this type generally refers to the formation of coal seams and terrigenous marine source rock containing mainly terrigenous organic matter. The latter refers to peat material that has been deposited and accumulated in various ways in different locations within a basin, particularly in deep water regions. The formation process is complicated and changeable (Table 1). The environmental conditions of peat accumulation are known to be diverse and may be layered or dispersed. Terrigenous marine source rocks are the main source rocks for gas accumulation in the South China Sea.

As coal-type source rocks, the contributions of coal or terrigenous marine source rock to oil-gas accumulations are not fixed, but mainly dependent on the evolution process and results after the accumulation of peat material. Therefore, it is important to determine the genetic mechanisms of those coal-type substances. The genetic relationships between coal seams and terrigenous marine source rock during deposition and accumulation processes are not simple either-or relationships, but complex and variable ones.

3.1.1 *Coal formation is favorable, the formation of terrigenous marine (or deep water) source rocks is unfavorable*

Under these conditions, thick coal seams are formed under favorable coal-forming environments. However, there will be a lack of sufficient supplies of peat detrital material to be deposited in the deep-water zones in basins. In such cases, the declines in the base levels of the peat swamps will provide good adaptability

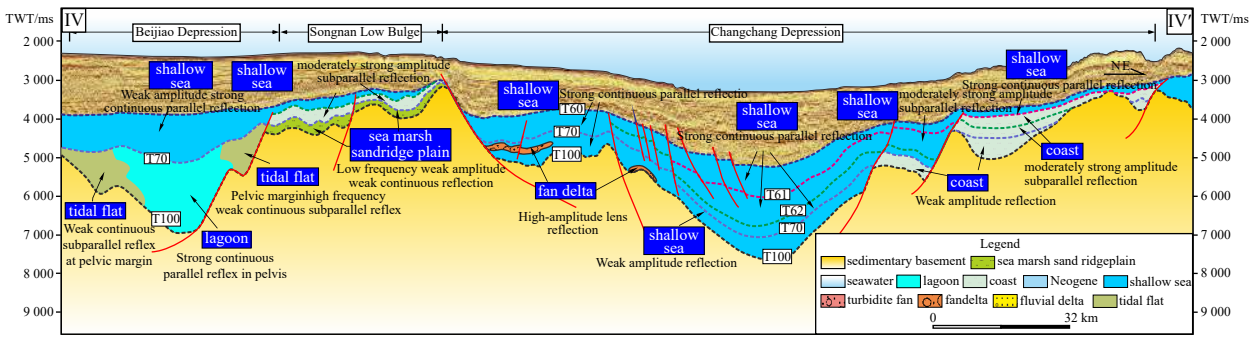

Fig. 6. Oligocene sedimentary facies interpretation of a typical seismic profile in the Beijiao-Changchang Sag.

Table 1. Typical transport patterns of peat and its detritus

Transport patterns of peat and its detritus	Basic characteristics	Mode pattern	Typical basin
Coal formation is favorable; however, the formation of terrigenous marine (or deep water) source rocks is unfavorable.	Thicker coal seams can be formed in the basin, but there is not a sufficient supply of peat detrital material in the deep water area. The continuity of peat accumulation is good; however, local areas of peat bogs are destroyed, resulting in less production of peat or detritus and reduced transport or drift of terrigenous organic matter to the deep water of the basin.	Fig.7A	The early Middle Permian large offshore coal-forming basin in North China, the Mid-Late Permian offshore basin in South North China, the Early Permian Ordos Basin, etc
The formation of coal and terrigenous marine source rocks is relatively favorable.	The peat material deposited in situ in peat bogs exhibits good continuity and a stable distribution. Peat bogs are often destroyed, leading to the continuous and rapid transportation of peat or detritus to the deep water area of the basin where it is deposited, forming a thick source rock that is rich in terrigenous organic matter.	Fig.7B	The late Carboniferous and early Permian epicontinental sea basin in North China, Permian coal basin in South China, etc
The formation of coal is unfavorable, while the formation of terrigenous marine source rocks is favorable.	Many thin and very thin coal seams have developed in coal-bearing strata, with the thickness of each layer generally being less than 1 m. While coal formation can occur, the persistence and continuity of peat accumulation are poor. A significant amount of terrigenous organic matter has been deposited in the deep water deposits of the same basin, forming thick terrigenous marine source rocks rich in terrigenous organic matter.	Fig.7C	The northern marginal sea basins of the South China Sea, especially the Paleogene basins, such as Qiongdongnan Basin and Yinggehai Basin
Both coal formation and the formation of terrigenous marine source rocks are unfavorable	The production and accumulation of peat material are discontinuous, the coal-forming environment is unstable, resulting in thin and discontinuous coal seams. Due to physical damage or wind oxidation, the peat detritus can be transported or drifted to the deep water of the basin, leading to a lower amount of terrestrial organic matter.	Fig.7D	Neogene sediments in the northern margin sea basins of the South China Sea, such as Qiongdongnan Basin and Yinggehai Basin
No coal seam was formed, and only a small amount of terrigenous marine (or deep water) source rocks were formed.	This is a complicated situation. Although no stratified coal has formed in the strata, there is a very small amount of terrigenous organic matter preserved in the deep water of the basin. Therefore, peat bogs and peat production cannot be restored during geological history.		Some Triassic basins in northern China; early sediments in the early late Carboniferous epicontinental basin of North China

in the supplies of peat material, and the in-situ accumulations of peat will continue for a long period of time. Therefore, the characteristics of areas with conditions which are favorable for coal formation but not favorable for the accumulation of terrigenous organic matter are as follows: The peat accumulations have good continuity, but the peat swamps will be partially damaged. Therefore, only small amounts of peat or debris will be produced and less terrigenous organic matter will be transported or drift to the deep-water zones of the basins. Such conditions are not conducive to the development of terrigenous marine source rocks (Fig. 7A).

The mechanism lies in the fact that the aforementioned favorable climate conditions satisfy the continuous prosperity of plants, and the rates of the peat formation and accumulation will be in equilibrium with the rates of the basement settlement for relatively long periods of time; the remains of plants will accumulate in the swamp areas, forming large amounts of peat accumulation and providing peat preservation conditions. The destruction of the peat swamps will be relatively weak, and only small amounts of peat will be transported to the deep-water zones by fluid actions. Alternatively, the peat debris may be completely lost during the transport process due to physical damage and wind oxidation, with only a small part successfully being transported to the far zones and deep-water zones. Finally, terrigenous marine source rocks containing a small amount of terrigenous organic matter are formed.

3.1.2 *The formation of coal and terrigenous marine source rocks is relatively favorable*

Under conditions which are favorable for both coal formation and the accumulation of terrigenous organic matter, both coal and deep-water terrigenous organic matter are developed. Thick coal seams are formed under favorable coal-forming environmental conditions, and there will be sufficient supplies of peat detrital material. Such conditions will be conducive to the deposition of terrigenous organic matter in deep-water zones under the actions of traction flow or gravity flow, and terrigenous marine source rocks with large thickness and distribution range can be formed. The characteristics will be as follows: the peat accumulation will be continuous and stable, but the peat swamps will often experience damages as the result of the peat or debris being rapidly and continuously transported to the deep-water regions in a timely manner, where it mixes with the marine mud and accumulates (Fig. 7B).

The mechanism lies in the fact that the favorable climatic zones provide the climatic conditions for plant prosperity, with the rates of peat formation and accumulation relatively high. However, in such cases, the rates of the basement settlement of the peat accumulation zones will be relatively low. In addition, a large accumulation of peat will be accepted when the two rates are in equilibrium. The humid climate conditions provide enough water sources to form a relatively large alluvial system. Also, paleogeographic conditions are conducive to alluvial deposition, leading to the destruction of some areas of the peat swamps due to the constant transport of peat deposits to the low-lying areas of the basins and even to deep-water zones. The deep-water deposits will be mixed with rich terrestrial organic matter. Under those conditions, plants will flourish and the peat will be rich in organic material.

3.1.3 *The formation of coal is unfavorable, while the formation of terrigenous marine source rocks is favorable*

In conditions that are unfavorable for coal formation but favorable for large amounts of terrigenous organic matter to accumulate in the deep-water zones of basins, terrigenous marine source rocks containing relatively rich terrigenous organic matter will develop. In such cases, the in-situ peat accumulations in the peat swamps will not be continuous due to frequent damages occurring to the peat swamps. As a result, large amounts of peat debris biomass will be formed, which is then transported or drifts over time. Although the sedimentary paleogeographic conditions in such areas create a good coal-forming climate back-

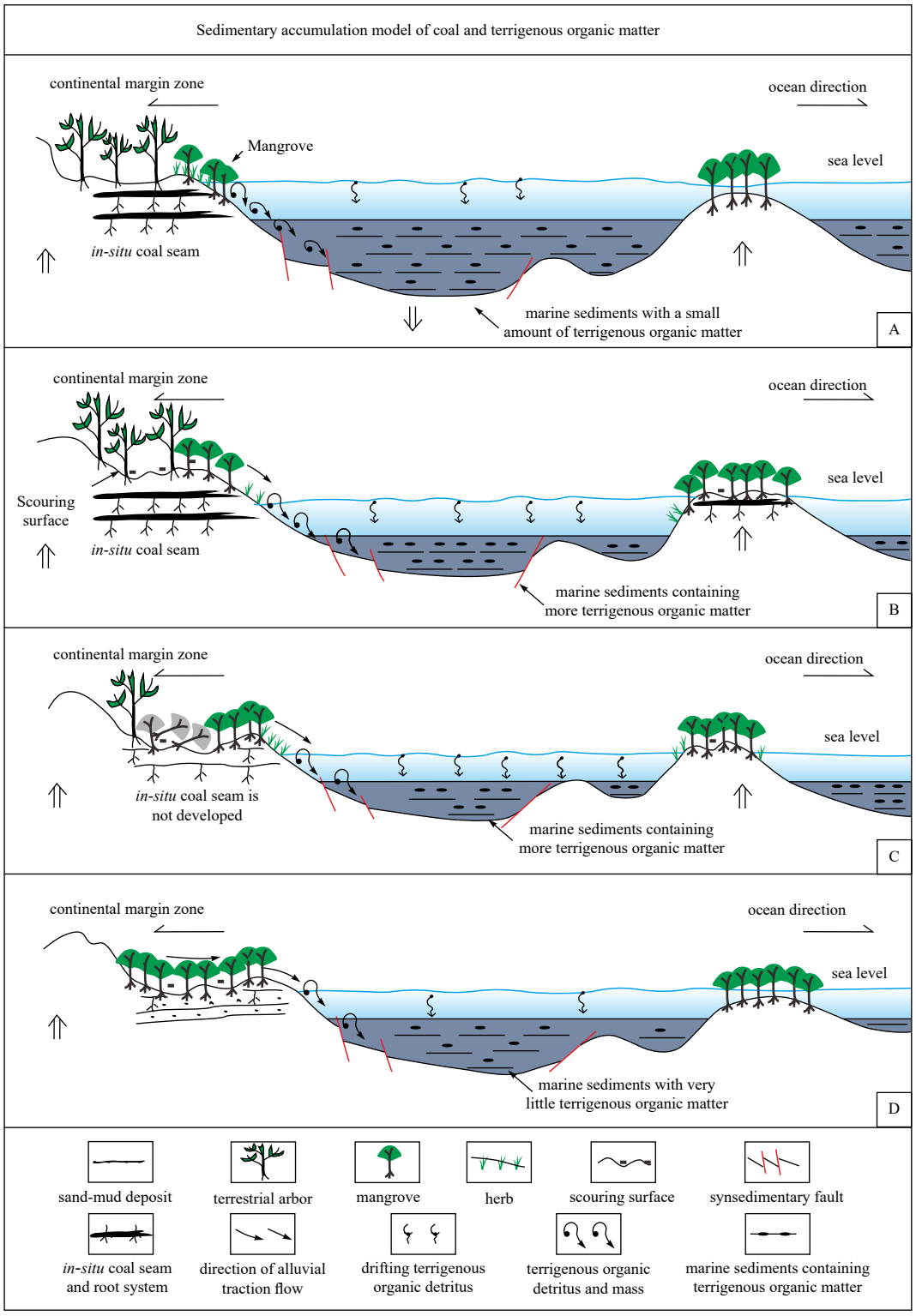

Fig. 7. Several theoretical models of in-situ peat accumulations and peat debris dispersion accumulations.

ground, the changes in the peat swamp base levels will not be conducive to the in-situ accumulation of peat. Furthermore, frequent destructive hydrodynamic mechanisms, such as flood events, storm surge events, gravity currents, large-scale surface currents, and so on, will cause the peat material to be transported to the deep-water areas of the basins over time and mixed with marine argillaceous deposition (Fig. 7C). This model can effectively explain the formation mechanism of coal seams and terrigenous marine source rock in the marginal sea basins of the South China Sea.

In coal-bearing strata, the coal seams in the coal measures will be thin or even not be developed (Fig. 8). In the coal measure sedimentary series, many coal layers and even many coal streaks will be observed, indicating that coal-forming processes

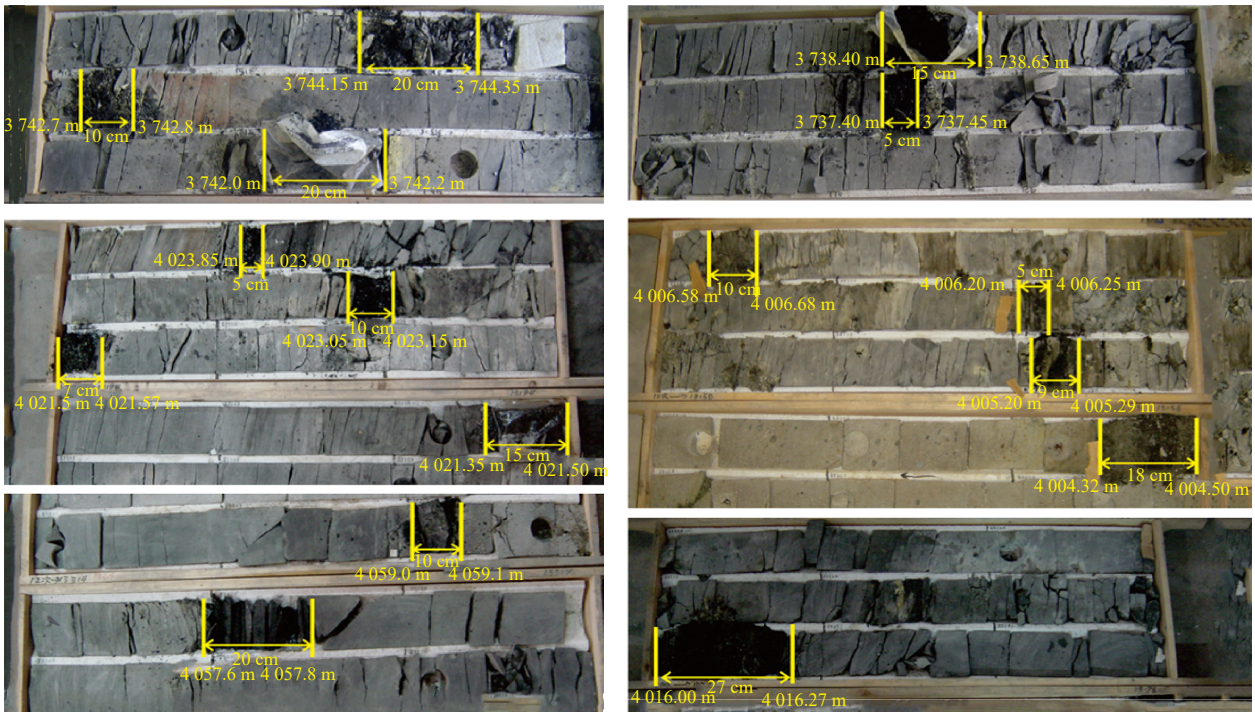

Fig. 8. Drilling results of YA13-1 in the Qiongdongnan Basin revealing thin coal seams in the core of the third member of the Yacheng Formation.

have occurred. However, the persistence and continuity of the peat accumulation will be poor. The most favorable evidence will that there are large amounts of terrigenous organic matter in the deep-water deposits of the same basin, which indicates an accumulation trend with a wide distribution range. Terrigenous marine source rock formations with large thicknesses and rich content of terrigenous organic matter will also present. Such factors are favorable for the development of good coal-type source rock. The transportation mechanisms may include alluvial fans, gravity flow, or large-area surface flow carrying abundant amounts of dispersed terrigenous organic matter that will be deposited in the deep-water zones of the basins and display good inheritance. The most representative examples of this type of environment are the Cenozoic coal-forming environment and the formation of terrigenous organic matter in the South China Sea.

3.1.4 *Both coal formation and the formation of terrigenous marine source rocks are unfavorable*

The conditions which are unfavorable for both coal formation and the accumulation of terrigenous organic matter are characterized by the lack of continuous production and accumulation of peat materials. The coal-forming environments tend to be unstable, and the peat swamps are often damaged by frequent basin tectonic movement and sedimentary events, such as storm surges, flood impact, massive flooding, and so on. The peat bog environment loses its sustainability. As a result, small or smaller amounts of peat debris will be produced, and the peat debris may be physically damaged or impacted by wind oxidation. Therefore, the peat materials will not be transported or drift to the deep-water zones of the basins over time (Fig. 7D).

From the perspective of the macro conditions of the areas described above, the climatic conditions are not conducive to the growth of arge-scale plants, and the prerequisites are insufficient. Moreover, the paleogeographic environments would not create favorable conditions for coal-forming deposition, and the peat accumulation rates would tend to be greater than the basement sedimentation rates. Subsequently, the peat materials would quickly decompose since no favorable transport medium exists for transporting the peat materials to favorable preservation zones, and no terrigenous marine source rock will be formed.

If the transport dynamic conditions are sustained, part of the peat material can be transported to deep water and deposited with Marine pelitic or fine-grained material. But in this case, the amount of peat material transported tends to be smaller.

3.1.5 *No coal seam was formed, and only a small amount of terrigenous marine (or deep water) source rocks were formed*

This is a complicated situation since there is no coal formation in-situ in the peat bogs, while very little terrigenous organic matter is preserved in the deep-water zones of the basins. In this case, the peat bogs and peat production cannot be restored in geological history. The following two possible conditions may exist: (1) the peat bogs will develop in a short period of time but have poor sustainability and little or very little peat material will be formed. Also, there will be no coal with cambium layer distributions; (2) the peat bogs will have a certain scale and long durations and large amounts of peat materials will be formed. However, due to the relatively long durations relatively long in open environments, which may be accompanied by the whole process of the peat bog development, the formed peat materials will be subjected to aerobic and volatile environments for a long time. The plant debris will undergo continuous corruption or decay as the peat material is being broken down.

One or more of the above states may exist within the same basin. In addition, changes in the basin backgrounds may lead to the alternation of the above states, forming clear cycle relationships. Genetic relationships between the above-mentioned types of coal and terrigenous marine source rocks can be found in the northern marginal sea basins of the South China Sea, and the genetic relationships are dominated by three types, as detailed in

Fig. 7C.

3.2 *Formation and migration characteristics of peat materials accumulation centers*

3.2.1 *Rise and fall of the base levels (or sea level changes) controlling the migration of coal-deposits and coal-forming environments*

Based on the sedimentological analysis of the seismic section (Figs 3–6) and in combination with the sequence stratigraphic framework analysis of the same section (Mi et al., 2010), strong evidence is provided for analyzing sedimentary facies migration caused by changes in basin base level (Fig. 9). Simultaneously, the study of sequence stratigraphy has laid a foundation for understanding coal formation patterns. The study of coal-bearing strata in the marginal basin of the South China Sea reveals that coal seams primarily develop during the transgressive systems tract and the early stages of highstand systems tract.

As base levels slowly rise, alluvial plain and delta plain sedimentary environments will be formed on the land side, which are favorable for coal-forming processes. Therefore, the coal seams will mainly appear at the maximum flooding surface. The seaside areas are barrier-lagoon sedimentary environments, which are considered to be favorable for coal formation. Therefore, coal measures mainly appear in transgressive system tracts.

From the Yacheng Formation to the Lingshui Formation in the Qiongdongnan Basin, transgression resulted in coal formation and the coal formation centers (or zones) migrated to the shore until the coal formation processes ended.

The migration of sedimentary facies is the premise and basis for the formation and migration of the coal-type source rock material accumulation centers. The changes in the deposition base levels (cycles) may be converted from seismic facies to sedimentary facies. The vertical migrations of sedimentary facies, which can be interpreted by the seismic facies (progradation and retrogradation), are generally quite clear, and reveal that the coal-forming environments migrated accordingly.

In Fig. 9, it can be seen that for the Yacheng Formation of the Songnan Sag, Songbei Sag, and Lingshui Sag in the Qiongdongnan Basin and the large delta of the upper Enping Formation in the Baiyun Sag of the Pearl (Zhujiang) River Mouth Basin in particular, the vertical migrations of the sedimentary facies interpreted by the seismic facies (progradation and retrogradation) were quite obviously caused by changes in deposition base levels (cycles). Therefore, the basic law of the subsequent migrations of the coal-forming environments was clearly reflected.

3.2.2 *Coupling relationships between the vertical migrations and the plane migrations of coal-forming environments*

It has been determined that vertical migration leads to migration on the plane, constituting a responding and coupling relationship. That is to say, the vertical migrations of coal-forming sedimentary environments will lead to migrations on the plane with regular changes. The migrations of coal-forming sedimentary environments ultimately lead to the formation and migration of the coal-forming belts, zones, and accumulation centers (Fig. 10). The migrations of coal-forming environments are actually the evolution processes of coal-forming basins during coal-forming periods.

With the continuous progress of the transgressions, the scope of the sea areas will continue to expand, and the favorable coal-forming facies belts will constantly migrate toward the shore. The coal-type material accumulation centers also migrate accordingly. Coal-forming zones regularly migrate, with the transfer from autochthonous coal to allochthonous coal considered to be a type of migration., Horizontal migration of coal-forming environments occurred when the peat swamps become damaged. The higher the degree of damage, the longer the migration distance,

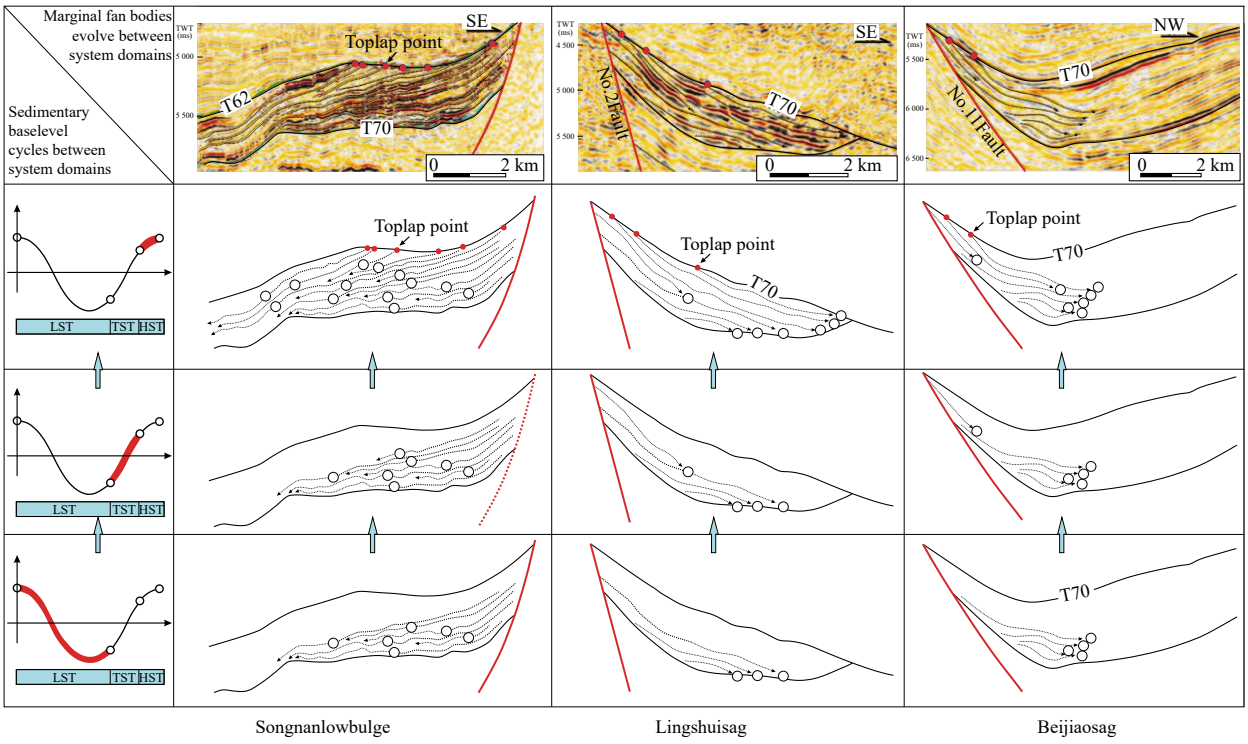

Fig. 9. Sedimentary facies migration characteristics caused by base level changes in the Songnan Sag, Lingshui Sag, and Beijiao Sag of the Qiongdongnan Basin.

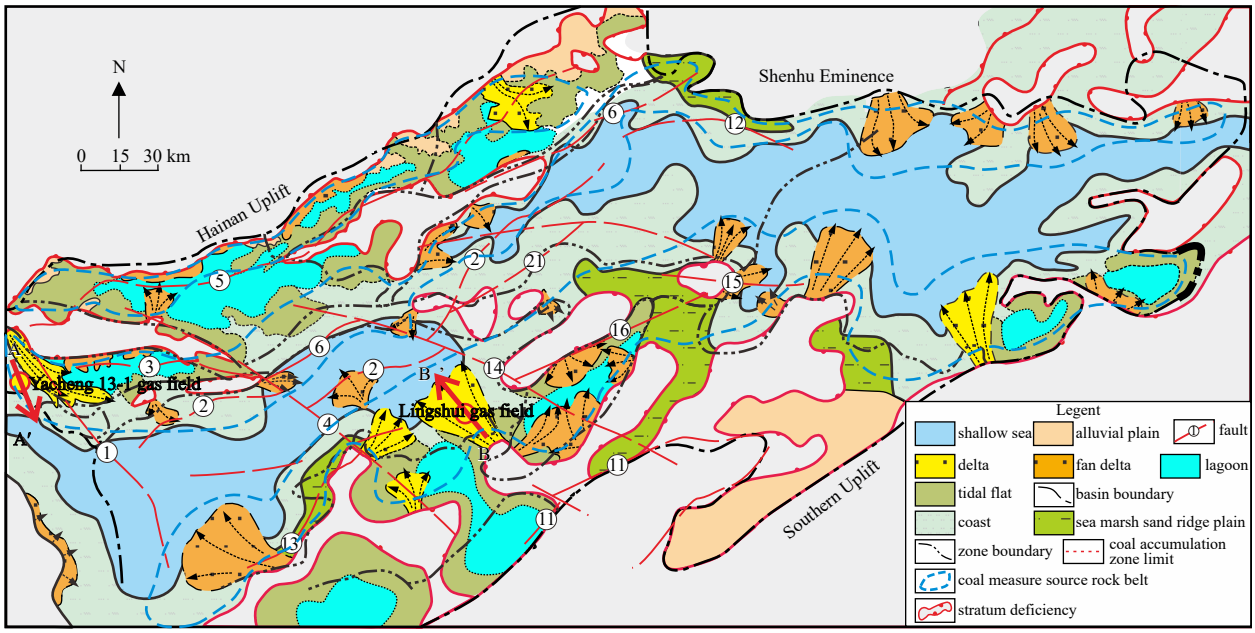

Fig. 10. Three coal-type source rock belts formed during the deposition of the Yacheng Formation in the Qiongdongnan Basin (modified from Zhang et al., 2019).

with the terrigenous organic matter finally being transported in a dispersed form. In fact, plane migration is manifested in two forms: lateral migration and vertical migration. Lateral migration forms favorable coal-forming zones, resulting in the further development of favorable coal-forming zones.

3.3 *Main mechanism of the formation of coal-type source rock in the marginal sea basins of the South China Sea*

The formation processes of the coal-type source rock in the marginal sea basins of the South China Sea display certain features, including multiple stages, multiple modes of coal-type substance accumulation, and the multiplicity of influence and control mechanisms (Fig. 7). One of the prominent features of the marginal sea basins in the northern part of the South China Sea is that there are many large fault structures developed on the continental margin which are characterized by strong activities. The basins are not completely open to the ocean when the sea level changes from shore to sea, which makes the basins conducive to the prosperity of land plants. The accumulation centers represent different depressions or fault basins within the marginal sea basins, rather than the entire marginal sea basins of the South China Sea. Therefore, the whole marginal sea basin and its internal depression are manifested as a basic pattern of multiple centers interwoven with uplift in the depression and depression in the uplift. The accumulations of coal-type materials, including in-situ and off-site accumulations, present patterns of multiple centers (for example, the central zones of the basins) which are basically parallel to the marginal shore zones (Fig. 10). In addition, the depocenters are scattered. In other words, multiple depressions may exist in the basins and the depocenters can be observed to be beaded. The coal-type material accumulation centers are controlled by the dynamic conditions (such as traction flow or gravity flow), as well as the water levels (deep water or shallow water).

Taking the Qiongdongnan Basin as an example, this study found that under the control of the basin margins and the large fault zones in the basins, three coal-bearing source rock belts with beaded distribution had formed at the sections where the uplifts or bulges of the basins transitioned to the depressions. Those three belts included a coal-bearing source rock belt at the northern margin of the northern fault depression; a coal-bearing source rock belt at the northern margin of the central fault depression; and a coal-bearing source rock belt at the southern margin of the central fault depression, as illustrated in Fig. 10. It was found that terrigenousl marine source rocks had formed in the majority of the coal-forming belts. Some of those coal-bearing source rock belts were coal seams directly exposed by drilling cores or cuttings. Others were determined to have the development of coal seams according to comprehensive logging methods that were verified by coal drilling results. Also, the existence of coal measures was determined according to comprehensive seismic inversion methods, also verified by drilling results. In summary, it was confirmed through comprehensive research that the three coal-bearing source rock belts were the most favorable locations for the development of coal-bearing source rock in the Qiongdongnan Basin.

4 Conclusions

(1) This study's research findings revealed that the most important features of the marginal sea basins in the northern section of the South China Sea are the unified frameworks of the marginal sea basins and the development of multiple internal depressions or fault basins. This study selected the Qiongdongnan Basin as an example, and the characterization and analysis of the seismic profiles were completed. The results indicated that the basins showed the grading of ancient structures, ancient plants, and ancient geography, with multipolarity of provenance and differentiation of ancient sediment. Therefore, it was considered that those depressions or faulted basins had the basic attributes of a single basin, as well as independent characteristics.

(2) A theoretical relationship model between peat accumulation and terrigenous organic matter accumulation was proposed in this study. The model included conditions that were favorable for both coal formation and the accumulation of terrigenous

marine source rock; conditions that were favorable for coal formation but unfavorable for the formation of terrigenous marine source rock; conditions that were unfavorable for coal formation but with the formation of terrigenous marine source rock in deep-water deposits; conditions that were unfavorable for both coal formation and the formation of terrigenous marine source rock; and conditions without coal formation but with the formation of small amounts of terrigenous marine source rock in deep-water deposits. The sea basins in the northern margins of the South China Sea were determined to be characterized by conditions unfavorable for coal formation but favorable for the formation of large amounts of terrigenous marine source rock in deep-water zones.

(3) This study's results indicated that the migrations of sedimentary facies in the basins and their internal depressions led to the formation and migration of the coal-type source rock material accumulation centers. The vertical migrations led to the migrations on the plane, constituting a responding and coupling relationship. That is to say, the vertical migrations of the coal-forming sedimentary environments led to the migrations on the plane with regular changes. The vertical and lateral migrations of the coal-forming sedimentary environments eventually led to the formations and migrations of the coal-forming belts, regions, and accumulation centers.

(4) According to the results obtained in this study, the formation processes of coal-type source rock show specific features, including multiple stages, multiple modes of accumulation, and the multiplicity of influence and control mechanisms. The accumulation centers represent different depressions or fault basins within the marginal sea basins, rather than all the marginal sea basins of the South China Sea. In this study, the uplifts within depressions, depressions within uplifts, and the multiple centers were considered to be intertwined.

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