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Structural characteristics of central depression belt in deep-water area of the Qiongdongnan Basin and the hydrocarbon discovery of Songnan low bulge

Mo Ji[1], Qingbo Zeng[1], Haizhang Yang[1], Shuai Guo[1], Kai Zhong[2, 3*]
[1] CNOOC Research Institute Co., Ltd., Beijing 100028, China
[2] State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
[3] Marine Resource Research Center, Tongji University, Shanghai 200092, China

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Abstract

The Qiongdongnan Basin has the first proprietary high-yield gas field in deep-water areas of China and makes the significant breakthroughs in oil and gas exploration. The central depression belt of deep-water area in the Qiongdongnan Basin is constituted by five sags, i.e. Ledong Sag, Lingshui Sag, Songnan Sag, Baodao Sag and Changchang Sag. It is a Cenozoic extensional basin with the basement of pre-Paleogene as a whole. The structural research in central depression belt of deep-water area in the Qiongdongnan Basin has the important meaning in solving the basic geological problems, and improving the exploration of oil and gas of this basin. The seismic interpretation and structural analysis in this article was operated with the 3D seismic of about 1.5×10^4 km^2 and the 2D seismic of about 1×10^4 km. Eighteen sampling points were selected to calculate the fault activity rates of the No.2 Fault. The deposition rate was calculated by the ratio of residual formation thickness to deposition time scale. The paleo-geomorphic restoration was obtained by residual thickness method and impression method. The faults in the central depression belt of deep-water area of this basin were mainly developed during Paleogene, and chiefly trend in NE–SW, E–W and NW–SE directions. The architectures of these sags change regularly from east to west: the asymmetric grabens are developed in the Ledong Sag, western Lingshui Sag, eastern Baodao Sag, and western Changchang Sag; half-grabens are developed in the Songnan Sag, eastern Lingshui Sag, and eastern Changchang Sag. The tectonic evolution history in deep-water area of this basin can be divided into three stages, i.e. faulted-depression stage, thermal subsidence stage, and neotectonic stage. The Ledong-Lingshui sags, near the Red River Fault, developed large-scale sedimentary and subsidence by the uplift of Qinghai-Tibet Plateau during neotectonic stage. The Baodao-Changchang sags, near the northwest oceanic sub-basin, developed the large-scale magmatic activities and the transition of stress direction by the expansion of the South China Sea. The east sag belt and west sag belt of the deep-water area in the Qiongdongnan Basin, separated by the ancient Songnan bulge, present prominent differences in deposition filling, diaper genesis, and sag connectivity. The west sag belt has the advantages in high maturity, well-developed fluid diapirs and channel sand bodies, thus it has superior conditions for oil and gas migration and accumulation. The east sag belt is qualified by the abundant resources of oil and gas. The Paleogene of Songnan low bulge, located between the west sag belt and the east sag belt, is the exploration potential. The YL 8 area, located in the southwestern high part of the Songnan low bulge, is a favorable target for the future gas exploration. The Well 8-1-1 was drilled in August 2018 and obtained potential business discovery, and the Well YL8-3-1 was drilled in July 2019 and obtained the business discovery.

Key words: Qiongdongnan Basin, deep-water area, structural differentiation

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1 Introduction

The Qiongdongnan Basin was extensively studied in its structural characteristics, as its special geotectonic location and abundant oil and gas resources. Li and Zhu (2005) considered that the fault activity in the Qiongdongnan Basin can be divided into four stages: Eocene–early Oligocene (Yacheng period), late Oligocene (Lingshui period), early–middle Miocene and late Miocene–Quaternary, the NE-trending and near EW-trending basement faults in the Paleogene are “faults controlling basin and belts”, and the faults had strong vertical dredging capacity during the early–middle Miocene. Li et al. (2006) believed that the Qiongdongnan Basin experienced two stages of extension process (Eocene–early Oligocene and late Oligocene), forming two types of rift structural styles (half-graben and graben) and the architecture characteristics of “zoning in north-south, segmenting in east-west”. Xie et al. (2007) suggested that NE- and NW-trending faults predominate the eastern part of the Qiongdongnan Basin, while near EW-trending faults predominate the west-

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*Corresponding author, E-mail: zhongkai@tongji.edu.cn ern part, and the NW-trending faults are adjustable tension-shear faults of the EW- and NE-trending faults. Yin et al. (2010) quantitatively calculated the activity of the main fault systems in the Qiongdongnan Basin, and concluded that the fault systems mainly presented in simple growth model and connected growth model, experienced the Eocene–early Oligocene rift episode and late Oligocene fault-depression transition episode, and controlled the basic structural pattern in the deep part of the basin.

However, due to limited data availability, the previous studies on structural characteristics of the central depression belt in the Qiongdongnan Basin were unsuccessful in three aspects. First, the evolution characteristics and laws of fault systems were not identified clearly. Second, it was unknown why the sags were very different in architecture and structural style from region to region. Third, the genetic mechanism of fault system was not explained scientifically and reasonably.

In recent years, the 3D seismic data in the deep-water area of the Qiongdongnan Basin have been greatly updated, with an additional area of about 1.7×10^4 km^2, which provides a good data base for analyzing the structural characteristics of the central depression belt in the deep-water area of the Qiongdongnan Basin. In this paper, from the structural prospective, the central depression belt in the deep-water area of the Qiongdongnan Basin was analyzed in respect of fault characteristics, sag architecture, structural evolution, the paleo-tectonic pattern and paleo-geomorphology formed by faults control the development of sedimentary systems, and the spatial and temporal distribution of sand bodies on the basis of regional seismic interpretation, with the Ledong-Lingshui sags and Songnan-Baodao-Changchang sags as examples. Finally, the east-west structural differentiation of the central depression belt and its petroleum geological significance were clarified. The analysis of structural characteristics of the central depression belt in the deep-water area of the Qiongdongnan Basin is of great significance for solving the basic geological problems of the basin and improving oil and gas exploration, as well as for enhancing the formation and evolution of the South China Sea.

2 Geological setting

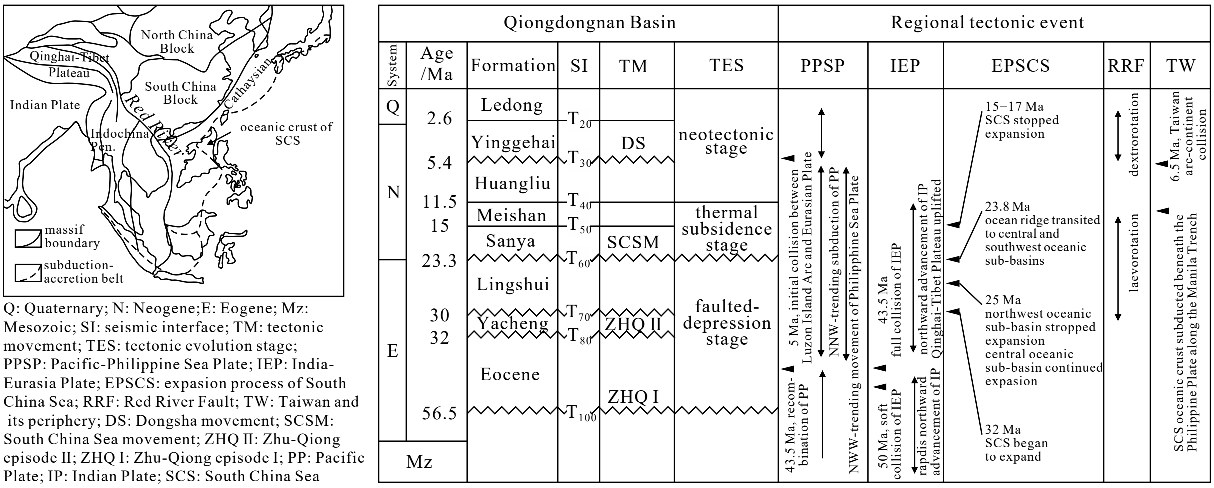
The Qiongdongnan Basin is located in the sea area between Hainan Island and Xisha Islands in the northern South China Sea. Residing at 15°37′–19°00′N and 109°10′–113°38′E, this basin as a whole is in NE-trending, is separated from the Yinggehai Basin by the No.1 Fault in the west, and neighbors the Zhu Ⅱ and Zhu Ⅲ depressions through the Shenhu Uplift in the northeast. Since 2011, great breakthroughs have been made in oil and gas exploration in deep-water area of the Qiongdongnan Basin, including the Lingshui 17-2 and Lingshui 25-1 gas fields, which are the first proprietary deep-water high-yield gas fields discovered in China. The deep-water area of the Qiongdongnan Basin is about 5.3×10^4 km^2, with a maximum water depth of 3 000 m, and includes the central depression, Songnan low bulge and Lingnan low bulge. It comprises five sags, i.e. Ledong Sag, Lingshui Sag, Songnan Sag, Baodao Sag and Changchang Sag, and is generally a Cenozoic extensional basin with the pre-Paleogene basement.

The Qiongdongnan Basin is developed on the northern continental margin of the South China Sea, at the junction of the Eurasian, Pacific and Indo-Australian plates. Its regional geology is affected by tectonic events such as subduction of the Pacific Plate, uplift of the Qinghai-Tibet Plateau, expansion of the South China Sea, and strike-slipping of the Red River Fault (Fig. 1). The tectonic cycle of the South China Sea can be divided into three stages (Zhang et al., 2007, 2015a, 2015b, 2018):

(1) The formation and development stage of the ancient South China Sea. The Pan-South China Massif, Indosinian Massif and Borneo Massif merged into a small “Ancient South China Sea Massif” during the early period. Accompanied by the subduction of the ancient Pacific Ocean, the ancient South China Sea Massif was broken at the end of Mesozoic, giving rise to the Qiongdongnan Basin–Zhu Ⅱ Depression zone on the northern margin of the Pan-South China Continent.

(2) The stage of the subdaction of the ancient South China Sea and the development of the new South China Sea. The lithosphere of the South China Sea oceanic basins and their surrounding areas thinned and the heat flow value increased. With the expansion of the South China Sea and the transition of the mid-oceanic ridge, the tectonic evolution of the Qiongdongnan Basin–Zhu Ⅱ Depression zone experienced faulted-depression and thermal subsidence stages.

(3) The rapid subsidence and shrinkage stage of the South China Sea (15.5 Ma to present). Along with the uplift of the Qinghai-Tibet Plateau and the strike-slip activity of the Red River-Ailaoshan Fault, much thick deposits were developed in the inflow regions of rivers on the northern margin of the South China Sea. For example, the Qiongdongnan Basin developed the Red River delta system, and the Zhu Ⅱ Depression developed the Zhujiang



Q: Quaternary; N: Neogene;E: Eogene; Mz: Mesozoic; SI: seismic interface; TM: tectonic movement; TES: tectonic evolution stage; PPSP: Pacific-Philippine Sea Plate; IEP: India-Eurasia Plate; EPSCS: expasion process of South China Sea; RRF: Red River Fault; TW: Taiwan and its periphery; DS: Dongsha movement; SCSM: South China Sea movement; ZHQ II: Zhu-Qiong episode II; ZHQ I: Zhu-Qiong episode I; PP: Pacific Plate; IP: Indian Plate; SCS: South China Sea

Fig. 1. Terrains and regional tectonic events in the South China Sea (modified from Zhou et al. (2005); Zhang (2010); Xie et al. (2015)).

River delta system.

According to drilling results, the Qiongdongnan Basin contains the following strata (from bottom to top): Eocene (?), Oligocene Yacheng Formation (E_3y) and Lingshui Formation (E_3l), Miocene Sanya Formation (N_1s), Meishan Formation (N_1m) and Huangliu Formation (N_1h), Pliocene Yinggehai Formation, and Quaternary Ledong Formation (Fig. 1). The fault characteristics, sag architecture and tectonic evolution of the central depression belt in the deep-water area of the Qiongdongnan Basin are influenced by its tectonic location and regional tectonic events, with special east–west differentiation.

3 The data and methods

In recent years, the 3D seismic data in the deep-water area of the Qiongdongnan Basin have been greatly updated. The seismic interpretation and structural analysis in this article was operated with the 3D seismic of about 1.5×10^4 km^2 and the 2D seismic of about 1×10^4 km.

Eighteen sampling points were selected to calculate the fault activity rates of the No.2 Fault by the following equation:

$$V_{\mathrm{f}} = \frac{\Delta H}{T} = (H_{\mathrm{d}} - H_{\mathrm{u}})/T, \qquad (1)$$

where, V_{f} is the fault activity rate; T is the deposition time; H_{d} is the formation thickness at the downthrown side; H_{u} is the formation thickness at the upthrown side (Li et al., 2000).

The deposition rate was calculated by the ratio of residual formation thickness to deposition time scale. The maximum thickness of the Yacheng Formation and Lingshui Formation were estimated by the seismic interpretation and the formula method time-depth conversion. The time scale of Yacheng Formation and Lingshui Formation were used as 32–30 Ma and 30–23.3 Ma.

The paleo-geomorphic restoration was obtained by residual thickness method and impression method. The top of Lingshui Formation was selected as the recovery datum as the flattening layer. The initial thickness was acquired by seismic interpretation of strata attitude and angular unconformity. The paleo-geomorphic restoration was finally determined by the impression method with the distribution of the initial strata thickness. The paleo-geomorphic restoration was proceeded without the compaction correction due to the inaccurate compaction correction parameters by rare well drilling the Yacheng Formation and Lingshui Formation.

4 Fault characteristics and sag architecture

Faults in the central depression belt in the deep-water area of the Qiongdongnan Basin were mainly developed during the Paleogene, and chiefly strike in NE–SW, E–W and NW–SE directions. The NE–SW faults are large and represented by the No.2 Fault on the north side of the Ledong Sag, Lingshui Sag, Songnan Sag and Baodao Sag. The E–W faults are mainly developed in the Baodao-Changchang sags and represented by the No.15 Fault. The NW–SE faults are developed in the south side of the Songnan low bulge, and represented by the No.14 Fault (Fig. 2).

4.1 *Geometric characteristics of faults*

The No.2 Fault is the most representative NE–SW fault in the deep-water area of the Qiongdongnan Basin. It runs through the

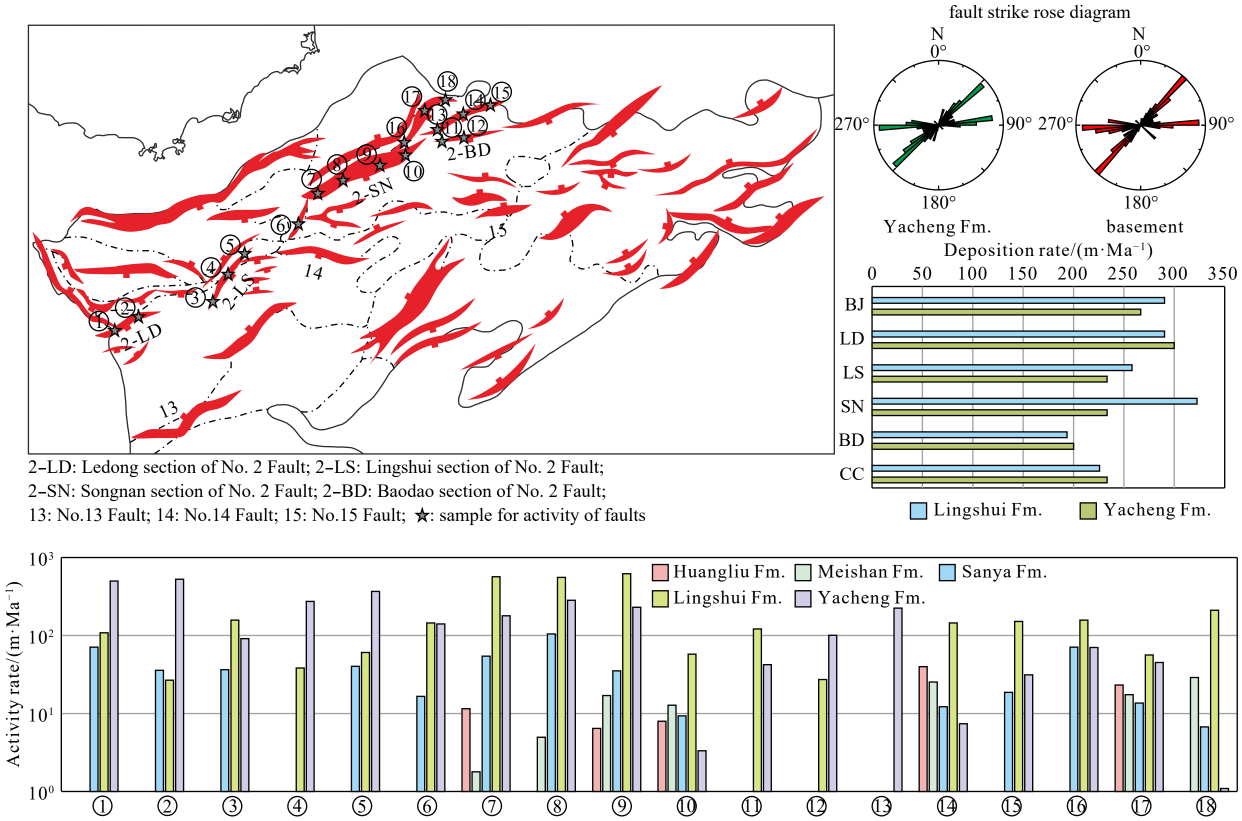


Fig. 2. Distribution and activity rate of major faults in the central depression belt of the Qiongdongnan Basin. BJ: Beijiao Sag, LD: Ledong Sag, LS: Lingshui Sag, SN: Songnan Sag, BD: Baodao Sag, CC: Changchang Sag, Fm.: formation.

central depression, with a length of about 300 km. It can be divided into the Ledong section, Lingshui section, Songnan section and Baodao section, with fault transition belt between the sections (Fig. 2). The Ledong section consists of three faults striking in near E–W and NEE–SWW, which are connected with end to end, and S-dipping fault surface; their upthrown sides are the Yanan low bulge, and their downthrown sides are the Ledong Sag. On the seismic section, there are fault surface waves with relatively continuous, strong reflection and medium–low frequency. The fault surfaces are listric with apparent dip angle of 50°–70° and stopped at the end of the deposition of the Sanya Formation. The Lingshui section consists of one NE–SW fault, with SE-dipping fault surface. Its upthrown side is the Lingshui low bulge, and its downthrown side is the Baodao Sag. On the seismic section, there is no clear fault surface wave, thus the fault surface position can be confirmed by the significant changes of wave group characteristics at its two sides. The fault stopped at the end of deposition of the Lingshui Formation. The Songnan section consists of two NEE–SWW striking faults, with SSE-dipping fault surfaces. Their upthrown sides are the Songtao bulge, and their downthrown sides are the Songnan Sag. On the seismic section, there are fault surface waves with relatively continuous, strong reflection and medium–low frequency. The fault surfaces are listric with apparent dip angle of 50°–70°. The fault stopped at the end of deposition of the Sanya Formation. The Baodao section consists of two NEE–SWW striking major faults. The east end of the faults is scattered as a broom, and their fault surfaces dip to SSE. Their upthrown sides are the Songtao bulge, and their downthrown sides are the Baodao Sag. On the seismic section, there are fault surface waves with relatively continuous and strong reflection and medium–low frequency. The fault surfaces are listric and “Y”-shaped with apparent dip angle of 50°–70°. The fault stopped at the end of deposition of the Sanya Formation. The No.2 Fault partially controls the deposition of the Yacheng and Lingshui Formations in the Songnan and Baodao sags, but no obvious control effect on the deposition and subsidence of the Ledong Sag and Lingshui Sag have.

The EW faults mainly distribute in the central part of the Baodao and Changchang Sags, and most of them control deposition and subsidence centers. The near EW faults in the Baodao Sag extend about 30–50 km on plane, and stop at the end of the deposition of the Lingshui Formation. The north side of the Baodao Sag develops a near EW fault dipping to the south, and the south side develops two near EW striking faults dipping to the north. Among them, the near EW fault at the north margin of the Songnan low bulge is the regional No.15 Fault. The strata in the Baodao Sag become apparently thicker at the position being retained by the near EW faults. This means that the EW faults mainly control the deposition and subsidence centers of the Baodao Sag. It is probably affected by the NS trending stress field of the extension of the South China Sea.

The EW faults in the Changchang Sag extend about 20–60 km on plane, and stopped at the end of the deposition of the Lingshui Formation. The north side of the major part develops two near EW faults dipping to the south, and the south side develops two near EW faults dipping to the north. The Paleogene in the major part becomes apparently thicker at the position being retained by the near EW faults. This means that the EW faults mainly control the deposition and subsidence centers of the Changchang Sag.

The NW–SE faults are mostly associated with bulge or low bulge. They are mainly developed in the western margin of Yacheng and Songtao bulges in the shallow-water area, and represented by the No.14 Fault at the northeastern margin of the Lingshui Sag in the deep-water area. Its upthrown side is the Songnan low bulge, and its downthrown side is the Lingshui Sag, extending about 60 km on plane. Previous studies suggested that this fault is the eastward extension of the Lingshui section of the No.2 Fault. It has been verified by the new 3D seismic data that they are not the same fault. The NW trending No.14 Fault should be the result of local stress concentration caused by the barrier of the Songnan low bulge.

4.2 *Kinematic characteristics of faults*

The fault activity rate at the Ledong-Lingshui section of the No.2 Fault is 0.1–0.5 m/ka during the Yacheng period, 0.03–0.7 m/ka during the Lingshui period, and about 0.03 m/ka or approaches to zero during the Sanya period. The fault activity rate at the Songnan section of the No.2 Fault is 0.1–0.3 m/ka during the Yacheng period, 0.1–0.6 m/ka during the Lingshui period, and about 0.01 m/ka during the Sanya period. The fault activity rate at the Baodao section of the No.2 Fault is about 0.1 m/ka during the Yacheng period, 0.1–0.2 m/ka during the Lingshui period, 0.01–0.02 m/ka during the Sanya period, and 0.02–0.04 m/ka during the Meishan period. Clearly, each section of the No.2 Fault has different activity rates during different periods, with the characteristics of being early in the west and late in the east (Fig. 2).

Moreover, according to the statistical result of the major fault strike directions in the deep-water area of the Qiongdongnan Basin, the basement faults dominantly strike in near EW (80°–260°) and NE–SW (40°–220°) directions, indicating that the main stress direction in this period should be SSE–NNW (150°–330°) (Fig. 2). The faults in the Yacheng Formation mainly strike in near EW (80°–260°) and NE–SW (50°–230°) directions, indicating that the main stress direction in this period should be SSE–NNW (155°–335°) (Fig. 2). The strike directions of the main faults in the deep-water area of the Qiongdongnan Basin during the faulted-depression stage were basically consistent, suggesting that the direction of the regional stress field has not changed.

4.3 *Sag architecture*

The central depression belt in the deep-water area of the Qiongdongnan Basin has five sags: the Ledong Sag, Lingshui Sag, Songnan Sag, Baodao Sag and Changchang Sag (Fig. 3).

The Ledong Sag is located at the westernmost end of the central depression. It is separated from the Yanan low bulge by the No.2 Fault in the north, from the Lingnan low bulge by the No.13 Fault in the south, from the Yinggehai Basin by the Zhongjian bulge in the west, and connected with the Lingshui Sag in the east, covering a total area of 7 300 km^2. The overall architecture of the Ledong Sag is generally characterized by an asymmetric compound graben between the No.2 Fault in the north and the No.13 Fault in the south. The No.2 Fault and No.13 Fault have limited control effect over the deposition and subsidence of the Sag. The deposition and subsidence centers were developed in the central-south part of the Sag, with a maximum sedimentary thickness of about 15 000 m and a Paleogene thickness of about 7 500 m. The Ledong Sag is the deepest subsidence center of the Qiongdongnan Basin (Figs 3 and 4).

The Lingshui Sag is located in the central-west part of the central depression. It is separated from the Lingshui low bulge by the No.2 Fault in the north, from the Lingnan low bulge by the No.14 Fault in the south, connected with the Ledong Sag in the west, and separated from the Songnan low bulge by a NW fault in the east, covering a total area of 3 800 km^2, and extending in near NE–EW direction. The Oligocene depositional structure in the Lingshui Sag shows east–west differentiation. The western part

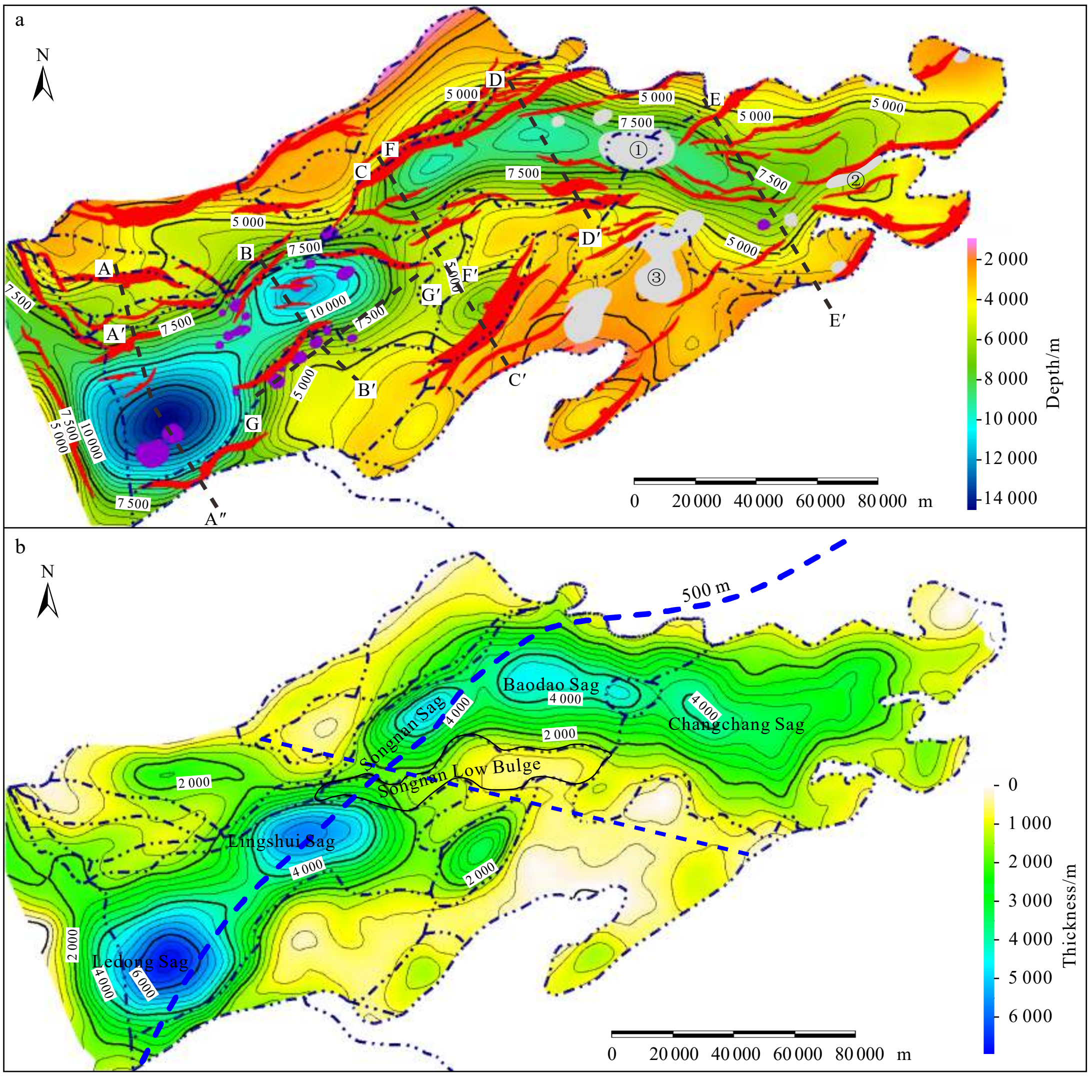


Fig. 3. Basement structure map and seismic section location of the Qiongdongnan Basin (a); Paleogene isopach map (b).

presents a double-faulted graben architecture controlled by the No.2 Fault in the north and by NE faults in the south. The eastern part is a gentle-slope and faulted-terrace half-graben architecture controlled by the NW-trending No.14 Fault, being faulted in the north and overlapped in the south. The Lingshui Sag was a partially fault-controlled separate sub-sag during the deposition of the Yacheng Formation; during the deposition of the Lingshui Formation, the deposition and subsidence centers of this sag were unified to the center. The thickness of the Paleogene in the Lingshui Sag is about 6 800 m (Figs 3 and 4).

The Songnan Sag is located in the central part of the central depression. It extends in NE direction with an area of about 2 000 km^2. It is separated from the Songtao bulge by the No.2 Fault in the north, connected with the Songnan low bulge in the

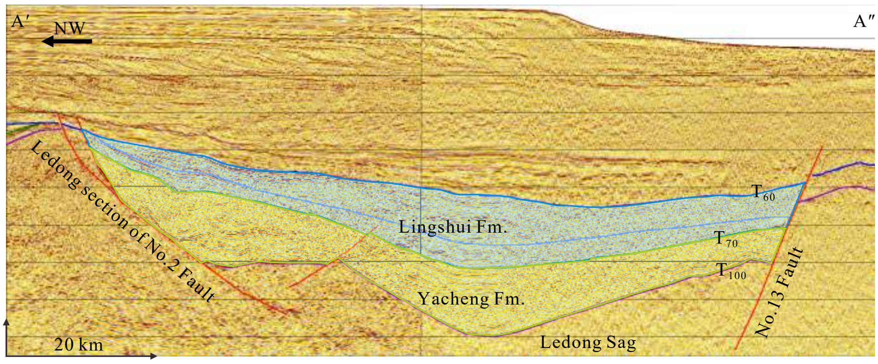


Fig. 4.

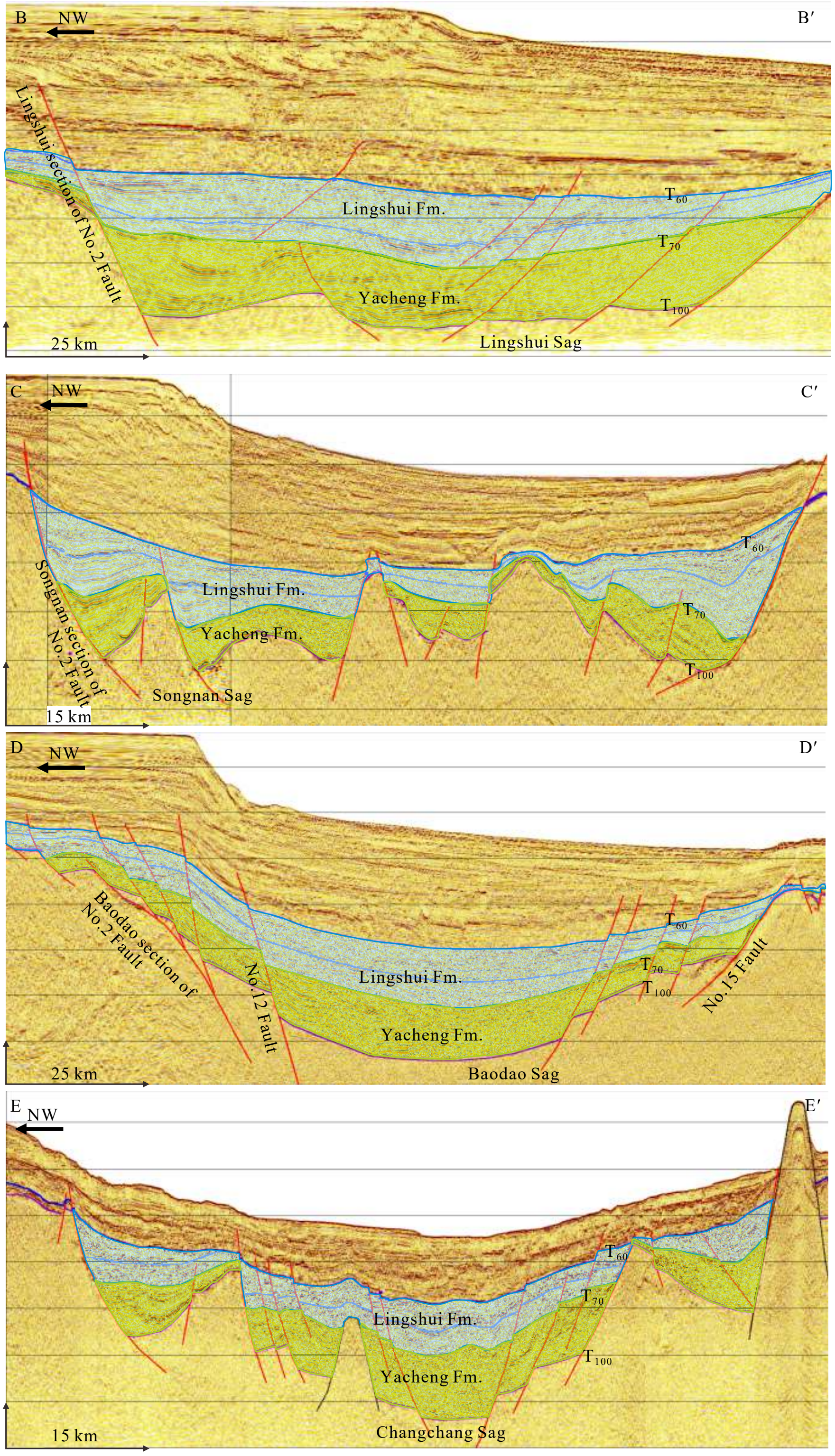


Fig. 4. Typical seismic sections in the central depression belt of the Qiongdongnan Basin. Section locations are shown in Fig. 3a. Fm.: formation.

southwest, and connected with the Baodao Sag in the east. The whole Songnan Sag is a half-graben controlled by the No.2 Fault in the north, being faulted in the north and overlapped in the south. The No.2 Fault displays a listric section and controls the Paleogene deposition. The Paleogene thickness in the sag is about 6 400 m (Figs 3 and 4).

The Baodao Sag is situated in the central-east part of the central depression. It is connected with the Songnan Sag in the west, striking in near EW direction, bounded by the NE–EW trending No.2 Fault and No.12 Fault in the north, and separated from the Songtao low bulge by the near EW trending No.15 Fault in the south, with an area of about 6 000 km^2. The western part of the sag is a gentle-slope faulted-terrace half-graben architecture controlled by the No.2 Fault, being faulted in the north and overlapped in the south. The Paleogene is wedge-shaped and onlapped on the Songtao low bulge. The maximum thickness is at the root of the No.2 Fault, with a thickness of 4 400 m (Figs 3 and 4). The east architecture changes. The No.2 Fault is decomposed from a listric fault to be a series of right-step oblique faults. The Baodao Sag is changed to be an asymmetrical double-faulted graben architecture controlled by the No.12 Fault and No.15 Fault striking near EW direction.

The Changchang Sag is located at the easternmost end of the central depression and separated from the Baodao Sag by a volcanic belt. Its strike direction is basically the same as that in the eastern part of the Baodao Sag, namely, near EW. The sag is separated by a series of oblique faults from the Shenhu Uplift in the north, and is the southern uplift area in the south. It extends eastward naturally to connect with the northwest sub-basin of the South China Sea, covering an area of about 14 000 km^2. The Changchang Sag has complex architecture. Its western part is a double-sided faulted-terrace graben, with the north and south sides controlled by the near EW fault system which presents a step-shaped profile. Its eastern part demonstrates a series of faulted-terrace half-grabens being faulted in the south and overlapped in the north, and the filling strata are obviously northward onlapping. The Paleogene deposition and subsidence centers coincided, and continued to develop in the central part of the sag, with a maximum thickness of about 4 000 m (Figs 3 and 4).

This research compared and calculated the activity rates of main faults and sedimentary rate of each sag in the deep-water area of the Qiongdongnan Basin. In the Ledong Sag, the maximum sedimentary rate is 0.30 m/ka for the Yacheng Formation, and 0.29 m/ka for the Lingshui Formation. In the Lingshui Sag, the maximum sedimentary rate is 0.23 m/ka for the Yacheng Formation, and 0.26 m/ka for the Lingshui Formation. In the Baodao Sag, the maximum sedimentary rate is 0.20 m/ka for the Yacheng Formation, and 0.19 m/ka for the Lingshui Formation. In the Changchang Sag, the maximum sedimentary rate is 0.23 m/ka for the Yacheng Formation, and 0.23 m/ka for the Lingshui Formation. In the Songnan Sag, the maximum sedimentary rate is 0.23 m/ka for the Yacheng Formation, and 0.32 m/ka for the Lingshui Formation. In summary, during the sedimentary periods of the Paleogene Yacheng and Lingshui Formations, the sedimentary rates of Ledong, Lingshui, Baodao and Changchang sags were often greater than and/or equal to the fault activity rates, while those of the Songnan Sag were lower than the fault activity rates (Fig. 2).

The architectures of the sags in the deep-water area of the Qiongdongnan Basin change regularly from west to east. They are (asymmetric) grabens in the Ledong Sag, western Lingshui Sag, eastern Baodao Sag and western Changchang Sag, and half-grabens in eastern Lingshui Sag, eastern Changchang Sag and Songnan Sag. Since the Neogene, the sedimentation of strata is not controlled by faults. Shelf slope break zones are developed in the northern part of the deep-water area.

5 Tectonic evolution and east-west differentiation

5.1 *Tectonic evolution*

The tectonic evolution of the Qiongdongnan Basin is influenced by regional tectonic events, such as the subduction of the Pacific-Philippine Sea Plate, collision of the India-Eurasia Plate, uplift of the Qinghai-Tibet Plateau, expansion of the South China Sea, and the strike-slipping of the Red River Fault. The Ledong-Lingshui sags are near the Red River Fault zone, thus the Qinghai-Tibet uplift event resulted in large-scale subsidence of the Ledong-Lingshui sags during the neotectonic stage. The Baodao-Changchang sags are close to the northwest oceanic sub-basin, thus the South China Sea expansion event resulted in the change of fault stress direction and the development of large-scale magmatic activity in the Baodao-Changchang sags. Therefore, we established the tectonic evolution pattern with three stages for the east and west sag belts in the deep-water area of the Qiongdongnan Basin, i.e. faulted-depression stage, thermal subsidence stage and neotectonic stage (Fig. 5).

(1) Faulted-depression stage (about 23.3 Ma, the deposition period of the Yacheng Formation and the Lingshui Formation): the subsidence and deposition centers of the Songnan Sag were developed in the No.2 Fault. The activity rates of boundary faults were higher than that of the sag subsidence and deposition rates. The subsidence and deposition centers of the Ledong sag, Lingshui Sag and Baodao-Changchang sags were developed in the middle of the sags, and the activity rates of boundary faults were lower than that of the sag subsidence and deposition rates.

(2) Thermal subsidence stage (23.3–11.5 Ma, the deposition period of the Sanya Formation and the Meishan Formation): the depositional thickness of marine strata is generally small, and thermal subsidence was beneficial to the stable development of shelf slope break zones.

(3) Neotectonic stage (11.5 Ma to now, the deposition period of the Huangliu Formation and younger strata): the deep-water area developed the Yingqiong bimodal multistage fan. The Ledong Sag developed very thick strata being much thicker than that during the thermal subsidence period, with fluid diapirs related to overpressure caused by very thick strata.

5.2 *East-west differences*

The genetic mechanism of the “east–west blocking” in the deep-water area of the Qiongdongnan Basin was a focus in previous studies. It was believed that the genetic mechanism is related to the faulting process. One view held that the hidden NW-trending faults are the main controlling factor, while the other indicated that the NW-trending No.1 Fault and No.14 Fault are the main factors controlling the “east–west blocking” of the basin. This research considers that the key to the genetic mechanism of the “east–west differentiation” in the central depression belt lies in the nature of the Songnan low bulge, and the early paleo-bulges or the later diapir structures also determine the significant differences in structures, deposits and hydrocarbon accumulation between the east and west sides of the Songnan low bulge.

The Songnan low bulge, a paleo-bulge, divides the central depression belt in the deep-water area of the Qiongdongnan Basin into two sag zones (Fig. 3). This has been proved by four evidences.

(1) Gravity and magnetic data show that the Songnan low bulge has high gravity anomaly and low magnetic anomaly, similar to crystalline basement in nature. The thickness of the crystalline crust in the Songnan low bulge is 15–10 km. According to the calculation result of the tension factor for the deep-water area, the Songnan low bulge divides the deep-water area of the Qiongdongnan Basin into two thinning centers in east and west.

(2) Seismic sections through the Songnan Sag, Songnan low bulge and Lingshui Sag show that the Yacheng Formation onlaps the crystalline basement of the Songnan low bulge at a certain angle (Fig. 6), indicating that the Songnan low bulge was an paleo-uplift during the sedimentary period of the Yacheng Formation. The near SN seismic sections through the Songnan Sag,

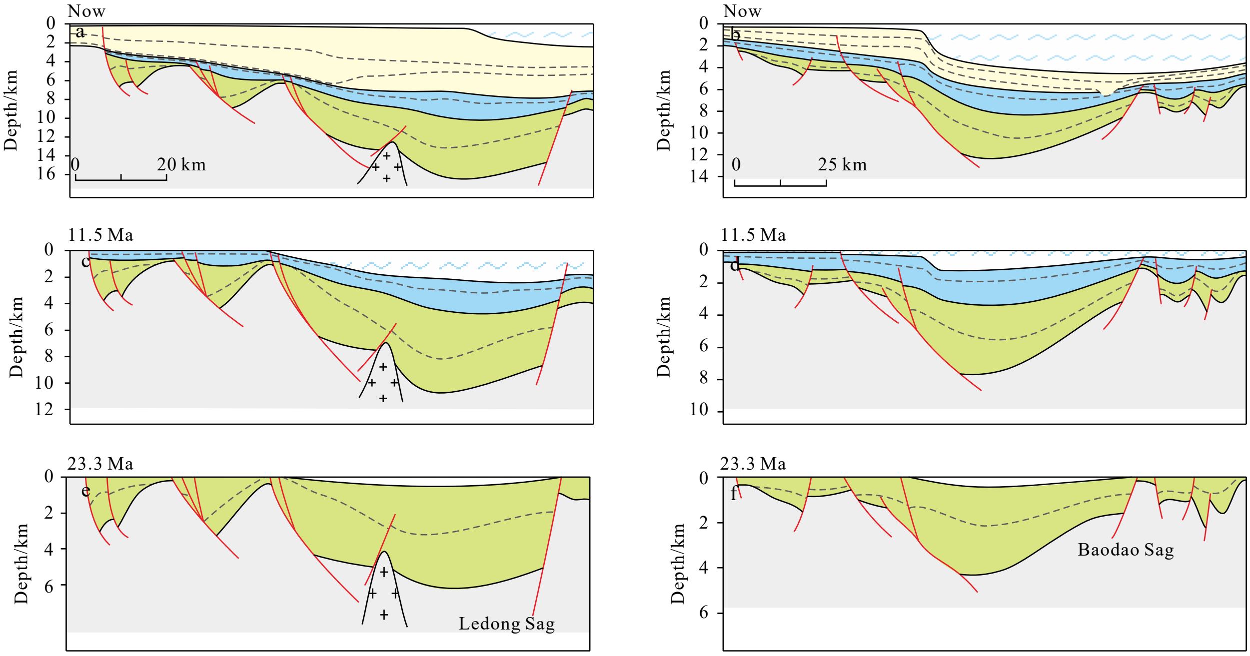


Fig. 5. Tectonic evolution models of the Ledong Sag (a, c, and e) and Baodao Sag (b, d, and f).

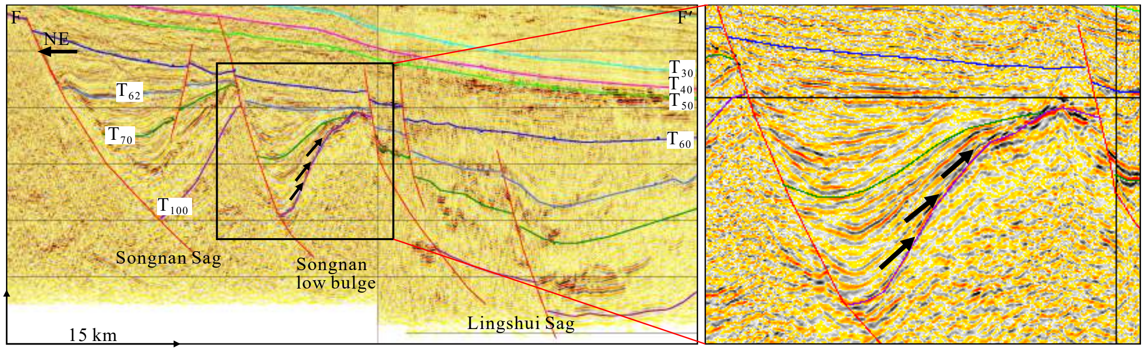


Fig. 6. Typical onlap seismic section at the bottom of Yacheng Formation in the Songnan low bulge.

Songnan low bulge, Lingshui Sag and Beijiao Sag show that the Songnan low bulge acted as separation during the sedimentary period of the Yacheng Formation. On the seismic sections through the Ledong-Lingshui sags, Songnan low bulge, and Songnan-Baodao sags, the Songnan low bulge divides the deep-water area of the Qiongdongnan Basin into two major sedimentary centers.

(3) In terms of regional structure, the Songtao Uplift is located in the Lingshui section and Songnan section of the No.2 Fault. The middle part of two boundary faults controlling sags is exactly the fault transition zone, and it is a favorable part for the development of crystalline basement uplift and also an effective path for provenance dispersion (Morley et al., 1990; Lambias, 1991; Feng and Xu, 2006; Lin et al., 2000, 2010) (Fig. 7).

(4) For deposition, on the seismic section through the No.2 Fault transition belt, the marginal facies zone is observed within the Yacheng Formation, also indicating the existence of the provenance area of the paleo-uplift (Fig. 7).

The separation and shielding of the Songnan paleo-bulge played an important role in controlling basin subsidence and sedimentation. Thus, the Ledong-Lingshui sags can be merged to the west sag belt, and the Songnan-Baodao-Changchang sags to the east sag belt.

According to the stratum sedimentary thickness, the depositional thickness of the west sag belt was large during the faulted-depression stage (up to 6 800 m) and neotectonic stage (up to 5 900 m). A near SN seismic section through the Yabei-Yanan-Ledong sags shows that the sedimentary thicknesses of the strata in the Ledong Sag varied in a pattern of thick–thin–thick during the faulted-depression stage, thermal subsidence stage and neotectonic stage (Fig. 8). A near SN seismic section through the Songdong-Baodao-Changchang sags shows that the sedimentary thicknesses of the strata in the Baodao Sag varied in a pattern of thick–thin–thin during the faulted-depression stage, thermal subsidence stage and neotectonic stage (Fig. 8). According to the stratum thickness statistics, the west sag belt is the inherited deep and large sag zone of the Qiongdongnan Basin, and the stratum thickness of the Ledong Sag can reach 15 000 m.

Diapir structures are different between the east and west sag belts–fluid diapirs in the west sag belt and submarine volcanic diapirs in the east sag belt (Fig. 9). In the west sag belt, due to rapid subsidence and deposition, pore fluids in mudstone cannot be drained smoothly, and overpressure system is formed under the action of undercompaction, clay mineral dehydration, or-

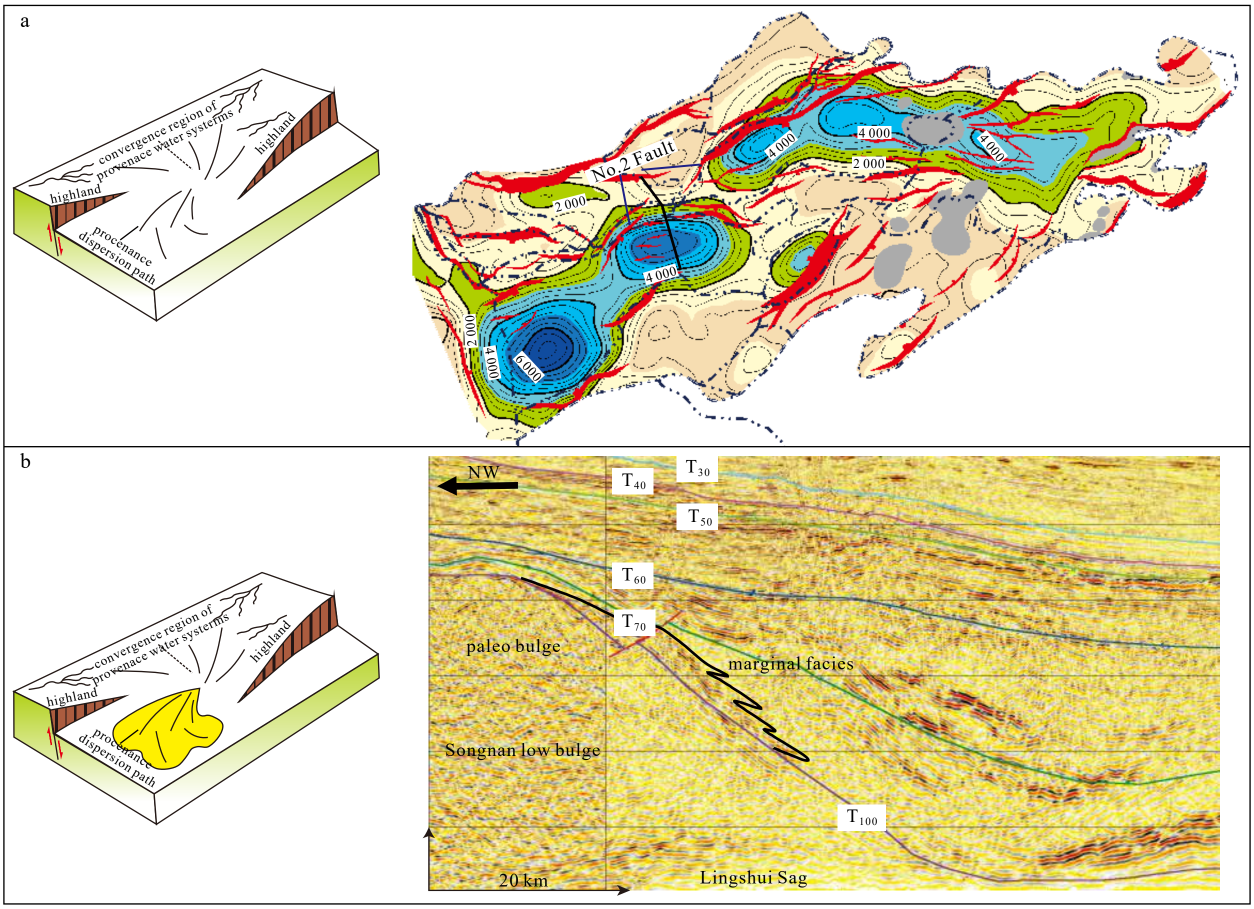


Fig. 7. Transition zone model of No.2 Fault in the central depression belt of the Qiongdongnan Basin.

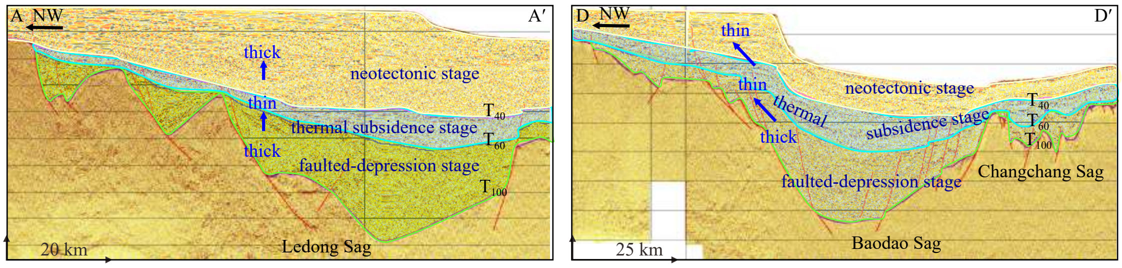


Fig. 8. Typical sections of stratum thickness variation of tectonic evolution in the central depression belt in the deep-water area of the Qiongdongnan Basin.

ganic hydrocarbon generation and thermal pressurization. When the abnormal pressure of tectonic activity or pore fluid is greater than the critical broken pressure value of seal layers, abundant faults and micro-fissures can be generated, then hydrocarbons and other fluids accompanied by shale plastic fluids upwarp and penetrate through the overlying strata along the faults and micro-fissures in miscible flashy flow to form fluid diapirs (Wang et al., 2006; Man et al., 2018; Yang et al., 2018) (Fig. 9). In the east sag belt, near the northwest sub-basin of the South China Sea, a large number of submarine volcanoes related to magmatic activities are developed (Fig. 9).

It can be seen from the present landforms of the east and west sag belts that the Ledong Sag and Lingshui Sag in the west sag belt are separated by bulge to a limited extent, while the Baodao Sag and Changchang Sag in the east sag belt are separated by submarine volcanoes. On the seismic section through the Ledong-Lingshui sags, the maximum sedimentary thickness is observed in the middle of the sag, suggesting the long-term existence of paleo-bulge. According to the palaeogeomorphic restoration, the Ledong-Lingshui sags are partially separated by paleo-bulge, showing a semi-connected pattern (Fig. 10). On the seismic section through the Baodao-Changchang sags, the maximum sedimentary thickness is recorded at the junction of the sags if the influence of late submarine volcanoes is neglected, suggesting that the Baodao-Changchang sags were a connected sag. According to the palaeogeomorphic restoration, the Baodao-Changchang sags present as a unified connected sag if the influence of late submarine volcanoes is neglected (Fig. 10).

5.3 *Hydrocarbon discovery of Songnan low bulge*

The structural and sedimentary differences between the east and west sag belts above further determine the different hydro-

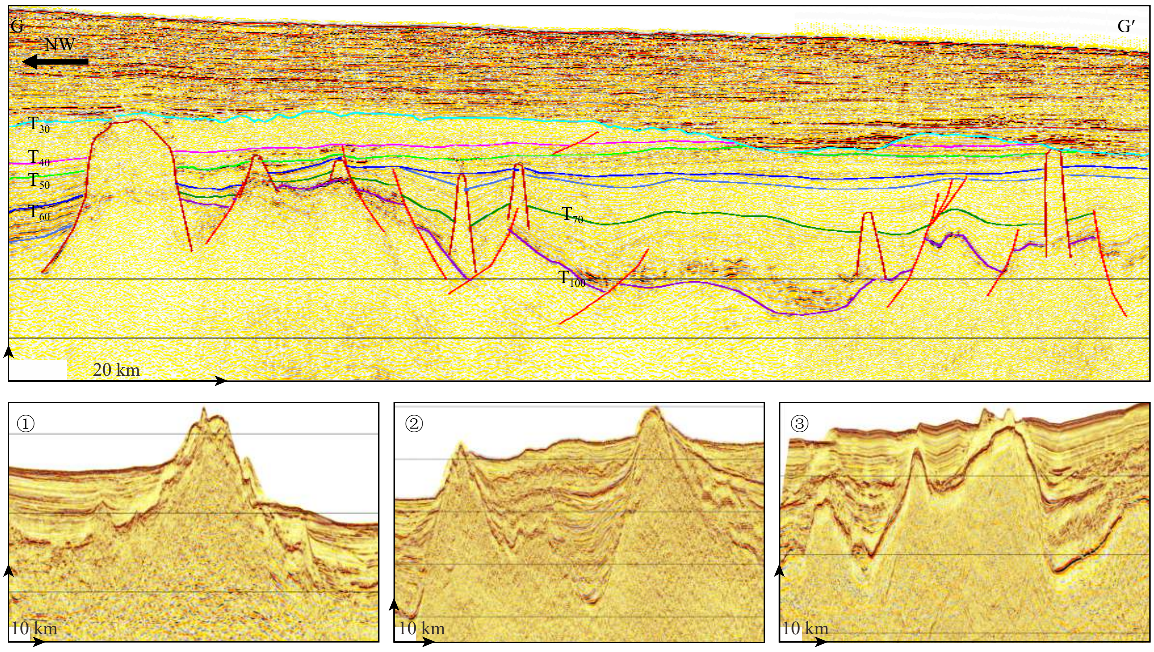


Fig. 9. Typical seismic sections of diapirs in the central depression belt in the deep-water area of the Qiongdongnan Basin. ①②③ are diapirs of Changchang Sag shown in Fig. 3a.

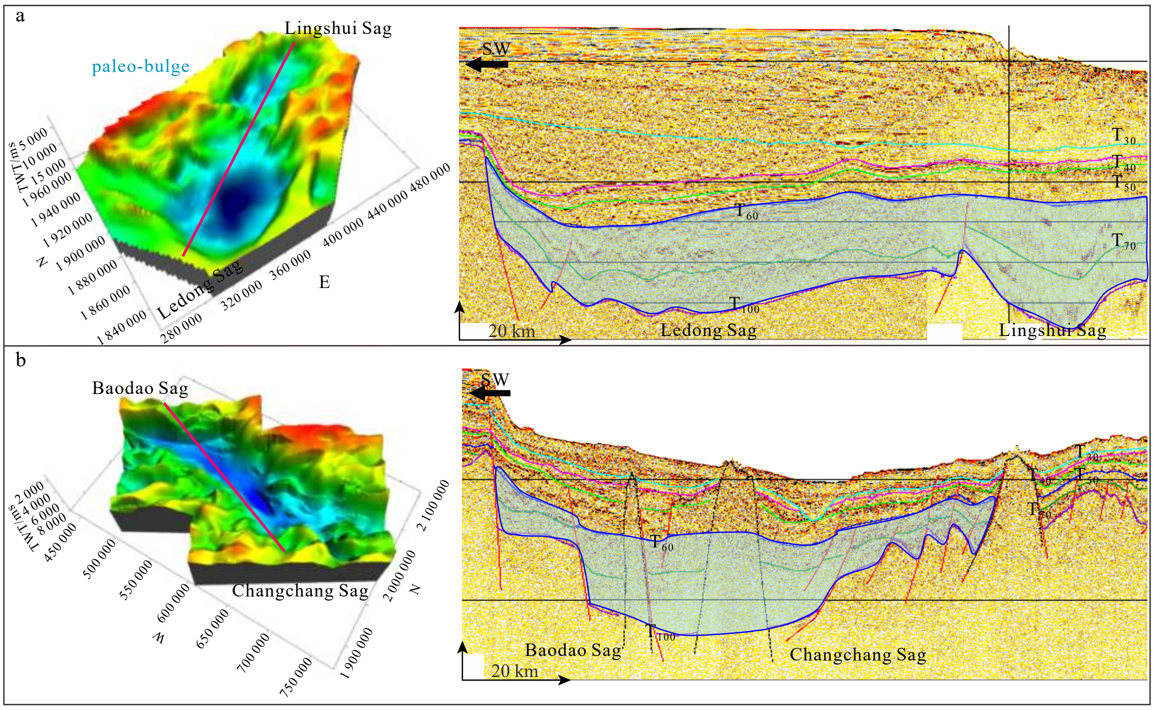


Fig. 10. Palaeogeomorphic restoration maps of the Ledong-Lingshui sags and the Baodao-Changchang sags.

carbon accumulation conditions in the east and west sag belts. In terms of sedimentary environment and source conditions, during the sedimentary period of the Yacheng Formation, the water body in the west sag belt was more closed due to the shielding effect of the Songnan paleo-bulge, corresponding to a coastal plain–delta–littoral shallow sea sedimentary system; the east sag belt was locally connected with the ancient South China Sea, contained littoral and shallow sea sedimentary system. The source rocks in the deep-water area of the Qiongdongnan Basin are mainly terrigenous marine mudstone and coal measures, while the kerogen is mainly type II_2–III. They generate gas with high maturity and oil with low maturity: the west sag belt chiefly generates gas, and the east sag belt generates both oil and gas (Huang et al., 2012, 2014; Li et al., 2013; Zhang et al., 2016). From the view point of hydrocarbon migration and accumulation, the west sag belt is dominated by the "channel sand + diapir + overpressure" structural lithologic complex trap model of "central canyon" (Yao et al., 2015; Zhang et al., 2016; Xie et al., 2016a, 2016b), while the east sag belt is dominated by the structural trap model with hydrocarbon migration along fault.

The Songnan low bulge is souced by surrounding sags, and the reservoir properties are superior. There are developed several types of hydrocarbon accumulation combination, such as, the pre-Paleogene buried hill trap, Paleogene draped anticline and stratigraphic onlap trap, and the Sanya Formaion channel lithologic trap (Yang et al., 2019). The Songnan low bulge is located on the favorite pathways of focusing gas migration along platform marginal faults, Paleogene unconformities and structural ridge, and therefore has a large exploration potential (Zhang et al., 2019). The YL 8 area, located in the southwestern high part of the Songnan low bulge, is a favorable target for the future gas exploration (Yang et al., 2019). The Well 8-1-1 was drilled in August 2018 and obtained potential business discovery, and the Well YL8-3-1 was drilled in July 2019 and obtained the business discovery.

6 Conclusions

It has unique and complex fault characteristics, sag architecture and tectonic evolution history. The key to the genetic mechanism of the “east-west differentiation” in the central depression belt lies in the nature of the Songnan low bulge. The early paleobulges or later diapir structures determine the significant differences in structures, deposits and hydrocarbon accumulation between the east and west sides of the Songnan low bulge. This study can draw the conclusions as follows:

(1) The faults were mainly developed during the Paleogene, striking in NE–SW, E–W and NW–SE directions. The NE–SW faults are large, represented by the No.2 Fault. The E–W faults are mainly developed in the Baodao Sag and Changchang Sag, represented by the No.15 Fault. The NW–SE faults are represented by the No.14 Fault.

(2) The architectures of the sags in the deep-water area of the Qiongdongnan Basin change regularly from west to east, being (asymmetric) grabens in the Ledong Sag, western Lingshui Sag, eastern Baodao Sag and western Changchang Sag, and half-grabens in the Songnan Sag, eastern Lingshui Sag and eastern Changchang Sag.

(3) The structural evolution of the Qiongdongnan Basin is affected by a series of tectonic events, such as the subduction of the Pacific-Philippine Plate, collision of the India-Eurasia Plate, expansion of the South China Sea, and strike-slipping of the Red River Fault. The tectonic evolution in the deep-water area can be divided into three stages, i.e. faulted-depression stage, thermal subsidence stage, and neotectonic stage.

(4) The deep-water area of the Qiongdongnan Basin is divided into the east sag belt and west sag belt by the Songnan paleo-bulge, which are significantly different in deposit filling, diaper genesis, and sag connectivity. The west sag belt is characterized by high maturity, well-developed fluid diapirs and channel sand bodies, indicative of superior conditions for oil and gas migration and accumulation. The east sag belt contains a large quantity of resources, and generates both oil and gas.

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