

The Cenozoic activities of Yangjiang-Yitongdong Fault: insights from analysis of the tectonic characteristics and evolution processes in western Zhujiang (Pearl) River Mouth Basin

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Abstract

The Yangjiang-Yitongdong Fault (YJF) is an important NW-trending regional fault, which divides the Zhujiang (Pearl) River Mouth Basin (ZRMB) into western and eastern segments. In Cenozoic, the northern continental margin of the South China Sea (SCS) underwent continental rifting, breakup, seafloor spreading and thermal subsidence processes, and the Cenozoic activities of YJF is one part of this series of complex processes. Two long NW-trending multichannel seismic profiles located on both sides of the YJF extending from the continental shelf to Continent-Ocean Boundary (COB) were used to study the tectonic and sedimentary characteristics of western ZRMB. Using the 2D-Move software and back-stripping method, we constructed the balance cross-section model and calculated the fault activity rate. Through the comprehensive consideration of tectonic position, tectonic evolution history, featured structure, and stress analysis, we deduced the activity history of the YJF in Cenozoic. The results showed that the YJF can be divided into two segments by the central uplift belt. From 65 Ma to 32 Ma, the YJF was in sinistral motion as a whole, inherited the preexisting sinistral motion of Mesozoic YJF, in which, the southern part of YJF was mainly in extension activity, controlling the formation and evolution of Yunkai Low Uplift, coupled with slight sinistral motion. From 32 Ma to 23.8 Ma, the sinistral motion in northern part of YJF continued, while the sinistral motion in southern part began to stop or shifted to a slightly dextral motion. After 23.8 Ma, the dextral motion in southern part of YJF continued, while the sinistral motion in northern part of YJF gradually stopped, or shifted to the slightly dextral motion. The shift of the YJF strike-slip direction may be related to the magmatic underplating in continent-ocean transition, southeastern ZRMB. According to the analysis of tectonic activity intensity and rift sedimentary structure, the activities of YJF in Cenozoic played a regulating role in the rift extension process of ZRMB.

Key words: Yangjiang-Yitongdong Fault, Zhujiang (Pearl) River Mouth Basin, tectonic evolution, strike slip movement, Cenozoic

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1 Introduction

The South China Sea (SCS) is the largest marginal sea along the Southeast Asia continent, and it is a natural laboratory to study the marginal sea tectonic-sedimentary process. As this area is rich in oil and gas resources, it has attracted the attention of many researchers. The Zhujiang (Pearl) River Mouth Basin (ZRMB), located on the northern SCS continental margin, is a Cenozoic sedimentary basin that has undergone multiple extension episodes during late Cretaceous to Oligocene (Ru et al., 1994; Dong et al., 2008; Wu et al., 2016). We have already got abundant geological knowledge in this area due to many years of oil and gas exploration.

The Yangjiang-Yitongdong Fault (YJF) is an important NW-trending strike-slip fault in western ZRMB, with the total length

of over 400 km (Fig. 1). The YJF was formed before the Cenozoic. Some former researchers studied the Mesozoic NE-SW-trending subduction-accretion zone in northern SCS continental margin and identified that some NW-trending sinistral strike-slip faults which cut off the subduction-accretion zone (Zhou et al., 2006; Chen et al., 2005). While the YJF is the only NW-trending through-going fault and offsets the NE-trending fault in ZRMB (Sun et al., 2010), thus we mainly focus on the western ZRMB and Cenozoic activities of YJF. We recognized the YJF is an important tectonic boundary of the northern SCS through the comparison on both sides of the YJF in crustal structure, basement lithology, sedimentary facies, and basin structure (Fig. 1b). About crustal structure, in southern ZRMB, the YJF shows a sharp variation of the Moho surface isoline, which is the western boundary of the

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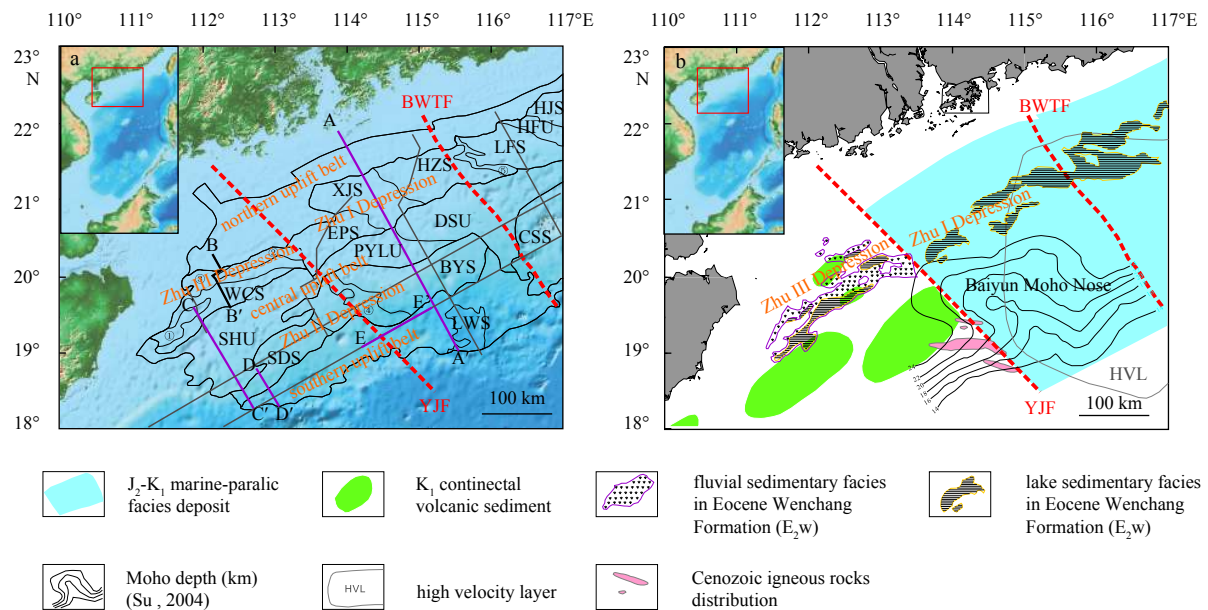


Fig. 1. Tectonic division of the Zhujiang River Mouth Basin with the locations of seismic profiles used in this study (a, after Wang et al., 2015; Liu et al., 2013); and geological contrast between the east and west sides of the PRMB (b, after Hu et al., 2009; Guo et al., 2016; Sun et al., 2014; Lu et al., 2011; Zhang et al., 2014). The red dotted lines represent the locations of the large NW-trend strike-slip faults. The black solid lines represent the tectonic boundaries. The purple solid lines represent the seismic profiles which interpret in this study. The brown solid lines represent the reference seismic profiles. YJF: Yangjiang-yitongdong Fault; BWTF: Beiweitai Fault; WCS: Wenchang Sag; EPS: Enping Sag; XJS: Xijiang Sag; HZS: Huizhou Sag; LFS: Lufeng Sag; HFU: Haifeng Uplift; HJS: Hanjiang Sag; SHU: Shenhu Uplift; PYLU: Panyu Low Uplift; DSU: Dongsha Uplift; SDS: Shunde Sag; KPS: Kaiping Sag; BYS: Baiyun Sag; CSS: Chaoshan Sag; LWS: Liwan Sag; ①: QHU, Qionghai Uplift; ②: YJS, Yangjiang Sag; ③: YJLU, Yangjiang Low Uplift; ④: YKLP, Yunkai Low Uplift; ⑤: HLLU, Huilu Low Uplift.

Baiyun Moho Nose (Hu et al., 2009). In the Continent-Ocean Transition zone (COT), the high-velocity layer (HVL) in the lower crust is mainly distributed in the east side of YJF, and there is no HVL in the west side (Guo et al., 2016). About basement lithology, the east side of YJF is dominated by marine and transitional sedimentary facies while the west side is dominated by the early Cretaceous continental volcanism sedimentary facies (Sun et al., 2014; Zhu et al., 2017). Meanwhile, the east side of YJF has the complete three-layer pre-Cenozoic basement structure, with rock ages ranging from Proterozoic to Mesozoic, but the west side is an incomplete three-layer structure that has the complete Proterozoic and Paleozoic layers with Mesozoic rocks in a scattered distribution (Lu et al., 2011). All of these geological facts indicate that the ancient-YJF has a control of crustal structure and basement lithology on the northern SCS continental margin, showing crustal-scale fault characteristics.

However, except from some researches and speculations on the pre-Cenozoic fault movement based on the gravity and magnetic data combined with the regional tectonic movement (Zhou et al., 2002, 2006; Chen et al., 2005), both the Cenozoic extensional geometry characteristics and the nature, scale and rate of the Cenozoic movement of YJF are not getting enough attention. There are many geological differences between the east and west sides of the ZRMB separated by the YJF in the shallow crust (Xia et al., 2016). Liu et al. (2013) found that the east-west difference of sedimentary characteristics of Wenchang Formation in the northern depression zone of the ZRMB is affected by the Cenozoic activities of YJF. The Zhu I depression located on east side of the YJF is mainly composed of shallow to deep lake sedimentary facies, but to the west, the Zhu III depression is mainly of fluvial

facies (Fig. 1b). From the west side to the east side crossing the YJF, the strike of extensional normal fault and the rift in ZRMB show a certain degree of clockwise rotation (Sun et al., 2008; Zhong et al., 2014). In addition, the Cenozoic activities of YJF controlled the distribution of magma activities in Shenhu area, that igneous rocks are distributed along the southern part of YJF (Zhang et al., 2014) (Fig. 1b). Does the activities of YJF in Cenozoic control the extensional fault and rift distribution as well as sedimentary characteristics of the Cenozoic ZRMB? Some analogue modeling experiments proved this controlling effect in a way (Sun et al., 2010), but it is still questionable because of ambiguity about the Cenozoic activities of YJF. Clarifying the Cenozoic activity characteristics of YJF, the important ancient regional fault, should be conducive to our understanding of the tectonic-sedimentary process of the ZRMB.

2 Geological setting

The SCS is located at the junction of the Eurasian Plate, Pacific Plate, and India-Australian Plate (Tapponnier et al., 1982; Hall, 1996; Briaies et al., 1993). It was influenced by Pacific and Tethyan tectonic domains during the Mesozoic era (Liu et al., 2011; Zhou et al., 2008a). An incomplete Wilson Cycle terminated before adulthood period has occurred in SCS since late Mesozoic period (Zhou et al., 2002; Sun et al., 2010; Bai et al., 2015; Li et al., 2014; Briaies et al., 1993). The seafloor spreading of SCS started at 32 Ma or 33 Ma, and the ridge jumped southward at 23.5 Ma (Barckhausen et al., 2014; Li et al., 2014; Briaies et al., 1993). The extensional rift period occurred after the onset of SCS seafloor spreading, up to 23 Ma, and the thermal subsidence period started after the ridge jump occurred (Dong et al., 2008;

Cameselle et al., 2017). The cessation time of seafloor spreading was at about 16–15 Ma (Chang et al., 2015; Li et al., 2014; Briais et al., 1993), and other researchers think that the SCS stopped seafloor spreading at about 20.5 Ma (Barckhausen et al., 2014, 2015). In addition, the dynamic mechanism of the SCS seafloor spreading remains a controversy, and the proposed candidates may include the back-arc spreading pattern (Li et al., 2007; Karig, 1971; Ben-Avraham and Uyeda, 1973); the mantle upwelling pattern (Tamaki, 1995; Chen et al., 2017); the right-lateral transtensional pattern (Zhou et al., 2002); Indochina extrusion pattern (Tapponnier et al., 1982, 1990; Briais et al., 1993); the slab pull pattern caused by subduction of the proto-SCS (Hollway, 1982; Hall, 2002).

During the Jurassic to early Cretaceous period, as an active continental margin, the northern part of the SCS region was a subduction zone where a part of the Paleo-Tethys in East-Asia margin subducted under the Eurasian plate (Zhou et al., 2006; Karig, 1971). During the late Eocene, the India-Australian plate collided with the Eurasian plate in NNE-SSW direction (Hall, 2012). With the oceanward retreat of the Pacific subduction zone, the compressive stress of the South China continental margin gradually relaxed (Taylor and Hayes, 1980, 1983; Hall, 2012; Yan et al., 2014), and the first rifting episode started, which is named the Shenhu Event (Pang et al., 2004; Sun et al., 2008), the reflector of Shenhu Event in seismic profile is T_9 (Fig. 2). The Shenhu

Formation was formed in this period, and sedimentary facies are mainly composed of the fluvial and alluvial fan, controlled by NNE-NE trending faults of this period. During early to middle Eocene, in the second rifting episode, named the First Episode of Zhuqiong Event (Pang et al., 2004; Sun et al., 2008), the Wenchang Formation was mainly of deep lake sedimentary facies (Fig. 2). The seismic reflector of Zhuqiong Event I is T_9 . Due to the difficulty still exists in defining and interpreting seismic reflector T_9 in our seismic profile, we cannot divide Shenhu Formation (E_{1s}) and Wenchang Formation (E_{2w}) definitely. In this case, we merged Shenhu Formation and Wenchang Formation as a whole. Rifts developed during this stage trended NE to NEE. The direction of principal extension stress was NNW-SSE, and its dynamic source may be related to the retreat of subduction zone of the western Pacific Plate (Zhong et al., 2014; Wu et al., 2016). From late Eocene to early Oligocene, in the third rifting episode named the Second Episode of Zhuqiong Event (Pang et al., 2004; Sun et al., 2008), the reflector of Zhuqiong Event II in seismic profile is T_8 . In this period, the rift basin trending NEE to EW was controlled by several factors including the collision between the India-Australian Plate and Eurasian Plate, the direction change of western Pacific subduction zone and eastward expansion of the Philippine Ocean (Wu et al., 2016). The sedimentary stratum is mainly Enping Formation in marshy sedimentary facies (Fig. 2). In this period, the dynamic source may come from the south-

Chrono-stratigraphy	Age/Ma	Formation	Seismic reflector	Tectonic events	Sedimentary facies	Stages	Regional tectonic setting			
							I-A plate	SCS	RRF	Philippine Plate
Quaternary	1.75		T_0							
Neogene	Pliocene	Wanshan (N_2w)			marine	neo-tectonic stage			dextral motion 5 Ma	
		Yuehai (N_1y)		Dongsha Event						
	Miocene					post rift subsiding stage				
		Upper	10.2							
		Middle	16.3		neritic bathyal					
		Lower	18.5		delta marine					
Paleogene	Oligocene		23.8							
		Zhujiang (N_1z)	T_6							
	Middle									
		Zhuhai (E_3z)			shoreside					
	Lower		32							
		Euping (E_3e)	T_7	Naihai Event						
	Eocene		39.5			marginal rifting stage				
		Middle			marshy					
		Lower	49							
	Lower									
		Wenchang (E_2w)	T_8	Zhuqiong Event II	lacustrine					
Paleocene										
		Shenhu (E_{1s})		Zhuqiong Event I						
Cretaceous	65		T_9	Shenhu Event	fluvial alluvial fan					

Fig. 2. The stratigraphy and tectonic events comprehensive column of the Zhujiang River Mouth Basin (modified from Sun et al., 2008; Hall, 2012; Li et al., 2014; Briais et al., 1993; Gilley et al., 2003; Leloup et al., 1995). I-A plate: India-Australian Plate; SCS: South China Sea; RRF: Red River Fault. From bottom to top, the Cenozoic stratigraphic sequence of the PRMB is consist of the Palaeocene Shenhu Formation (E_{1s}) and Eocene Wenchang Formation (E_{2w}) (65–39.5 Ma), Oligocene Enping Formation (E_{3e}) (39.5–32 Ma), Oligocene Zhuhai Formation (E_{3z}) (32–23.8 Ma), Miocene Zhujiang Formation (N_1z) (23.8–16.3 Ma), Miocene Hanjiang Formation (N_1h) (16.3–10.5 Ma), Miocene Yuehai Formation (N_1y) and Pliocene Wanshan Formation (N_2w) (after 10.5 Ma).

ward subduction of Proto-SCS and the Indochina Block clockwise rotation and extrusion after the India-Australian Plate collided and sutured with the Eurasian Plate (Zhong et al., 2014; Wu et al., 2016; Ru et al., 1994), and the principal stress direction of extension was N-S.

The Nanhai Event occurred in late Oligocene, which is sign of the shift from rifting to drifting (Pang et al., 2004; Sun et al., 2008), the seismic reflector of Nanhai Event is T_7 . The sedimentary facies of ZRMB transformed into marine thereafter and the SCS started seafloor spreading (Fig. 2). During SCS spreading period, the seismic reflector T_6 , T_5 , T_4 represent the boundary of Zhuhai/Zhujiang Formation (23.8 Ma), Lower/Upper Zhujiang Formation (18.5 Ma) and Zhujiang/Hanjiang Formation (16.3 Ma), respectively. After the Miocene, the SCS entered into the thermal subsidence period (Clift et al., 2002; Xie et al., 2006). From 10 Ma to 5 Ma, the Dongsha Event led to the fault-block movement in the eastern ZRMB as well as uplifting and erosion in some areas, the seismic reflector is T_2 correspondingly. It is supposed to be caused by the subduction of the Philippine plate under the Eurasian plate (Sun et al., 2008) (Fig. 2). Since we need not do particularly refined studies of the sedimentary layers formed in subsidence period which has low tectonic activities, especially in the Pliocene, we merged Yuehai Formation (N_{1y}) and Wanshan Formation (N_{2w}) as a whole.

Through a series of tectonic events in Mesozoic and Cenozoic, the SCS formed the tectonic framework that has extensional continental margin in the north, thrust nappe structure in the south (Borneo and southern Palawan), Red River-Yuedong strike-slip boundary in the west, Manila Trench subduction boundary in the east, and central oceanic crust basin in the middle (Liu et al., 2002). The ZRMB can be divided into several segments in E-W direction, and several belts in N-S direction, including the northern uplift belt, the northern depression belt, the central uplift belt, the southern depression belt and the southern uplift belt (Shi et al., 2005; Xie et al., 2014) (Fig. 1a). The northern depression belt consists of the Zhu I Depression (Enping Sag, Xijiang Sag, Huizhou Sag, Lufeng Sag and Hanjiang Sag) and the Zhu III Depression (Wenchang Sag, Yangchun Sag, Qionghai Sag and Yangjiang Low Uplift). The central uplift belt consists of Shenhu Uplift, Panyu Low Uplift and Dongsha Uplift from west to east. The southern depression belt consists of the Zhu II Depression (Shunde Sag, Kaiping Sag, Yunkai Low Uplift and Baiyun Sag) and Chaoshan Depression (Fig. 1a). The sags and uplifts in ZRMB are mainly NE-NEE-trending. The faults developed in the ZRMB during Cenozoic are mainly composed of NE to EW-trending normal faults and NW-trending shear faults. The NW-trending faults, such as YJF and Beiweitan Fault (BWTF) in Fig. 1, may have been formed and activated since Mesozoic, which offset the Mesozoic subduction-accretion zone in northern SCS (Zhou et al., 2006). These NW-trending faults have only been identified by maps of gravity and magnetic anomalies (Chen et al., 2005). Contrast with the YJF, the BWTF does not have such obvious boundary characteristics. Both sides of BWTF does not have such difference in crustal structure (Gao, 2008) and basement lithology (Liu et al., 2013; Lu et al., 2011). And the BWTF is even not the boundary of sub-basin (Fig. 1a), thus we cannot confirm if it has activities in Cenozoic.

3 Data and methods

In order to compare the tectonic-sedimentary framework of the basin on both sides of the YJF, we selected two long multichannel seismic Profiles A-A' and C-C', located in both sides of the YJF, and extending from the continental shelf to Continent-

Ocean Boundary (COB) for geological interpretation (Fig. 1a). We tried to clarify the tectonic-stratigraphy situation in Shunde Sag and southern depression belt, so we interpreted the D-D' seismic profile to supplement the breezing section in Southern C-C'. In addition, the E-E' seismic profile which across the YJF was interpreted. The seismic profile data were derived from CNOOC. The long 2D profiles were mostly collected by 7.5 km long cable with a 13.0 m trace interval.

It is necessary to make a time-depth conversion for the construction of balanced cross-section and the calculation of fault activity rate. Abundant strata velocity data from ZRMB are available, such as far offset refracted wave (Chen et al., 2014), two-ship expanding spread profiles (ESPs) (Nissen et al., 1995), Ocean Bottom Seismometer (OBS) presumption velocity (Huang et al., 2005). However, these data have a big difference in detection methods, and the data process might encounter subjectivity and difficulty because it contains so huge data that we need to divide the long seismic profile into several segments. Therefore, we tentatively use power function for the time-depth conversion. If we apply the cubic polynomial function, it will make velocity inverse. And the quadratic polynomial leads to an overestimation of depth in deep-seated strata. Only the power between 1 and 2 can be the most reasonable to achieve the time-depth conversion. Thus we used power function to make the time-depth conversion for A-A', B-B', C-C', D-D' profiles (Zhou et al., 2008b):

$$D = 946 \times (t - t_w)^{1.477} + 750 \times t_w, \quad (1)$$

where D is the depth; t is the TWT from seabed; and t_w is the TWT from sea level to seabed.

We used the 2D-Move software and back-stripping method to establish the balance cross-section model on both sides of the YJF with nearly parallel direction and analyzed the tectonic-sedimentary evolution of these two cross-sections in different periods. The fault activity rate was calculated by the formula:

$$V_f = (H_d - H_u) / T, \quad (2)$$

where V_f is fault activity rate; H_d is the thickness of downthrown block; H_u is the thickness of upthrown block; and T is the deposition time (Li et al., 2000).

4 Results

4.1 Geological characteristics

4.1.1 The tectonic-sedimentary framework on the east side of YJF

On the east side of YJF, the northern uplift belt, Xijiang Sag, and Panyu Low Uplift are all located on the continental shelf (Fig. 3). The northern uplift belt is mainly composed of small half grabens in the northern part and fault terrace zone in the southern part. The sedimentary layers gradually thicken seaward, and it is bounded by a large southward dipping normal fault with Xijiang Sag (F1 in Fig. 3). The Xijiang Sag shows a compound graben style composed of several grabens and half grabens in the profile. The sedimentary thickness of the northern part is slightly larger than that of the south. In the southernmost, the Xijiang Sag is bounded by a negative flower structure with Panyu Low Uplift (F3 in Fig. 3). The northern part of Panyu Low Uplift shows slight uplift due to the pre-existing high basement. The southern part is mainly composed of the uplifted tilted fault block, and the faults feature a series of consistently north-dipping listric normal fault.

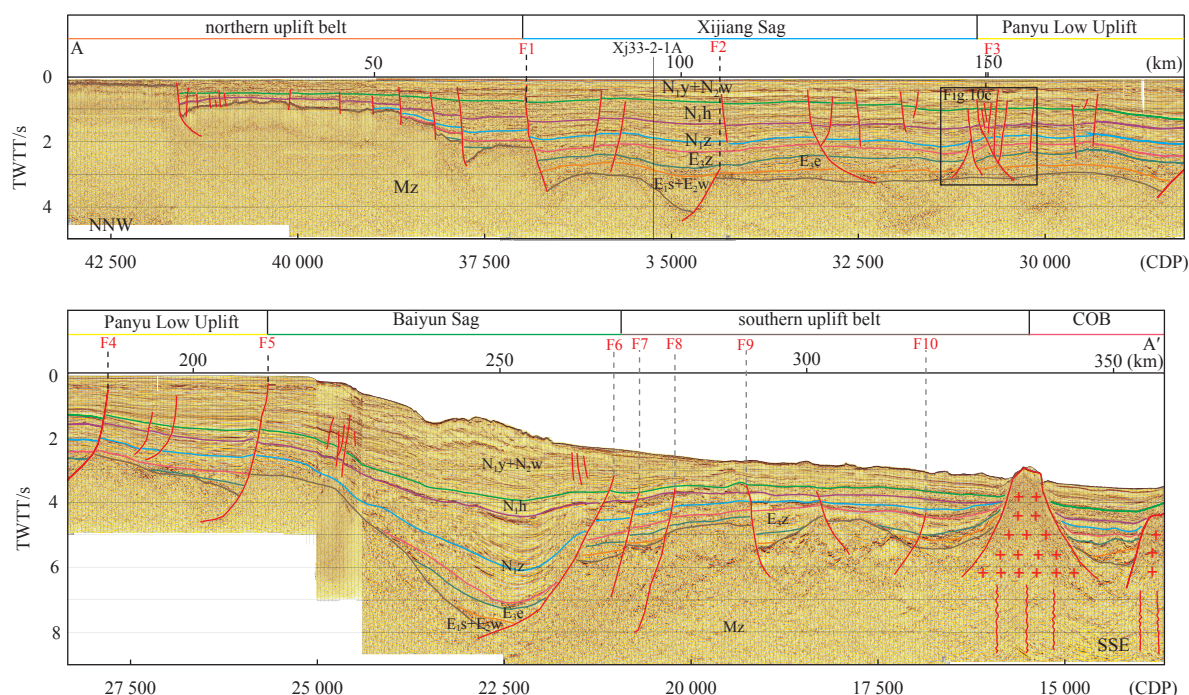


Fig. 3. Interpreted seismic Profile A-A' across the Zhujiang River Mouth Basin showing the tectonic-sedimentary framework in the east side of Yangjiang-Yitongdong Fault, the northern South China Sea margin (see Fig. 1 for line location). COB: continental-ocean boundary.

The Panyu Low Uplift is bounded by a north-dipping listric normal fault (F5 in Fig. 3) and a part of the uplift basement with Baiyun Sag. The Baiyun Sag is a large half graben controlled by a long north-dipping listric normal fault (F6 in Fig. 3), which is the boundary along the southern uplift belt. The sedimentary thickness is huge, showing the characteristics of lapout from the ocean to the land. The southern uplift belt has a complicated structural style, which consists of the north-dipping step type fault block, horst and destroyed buried hill. In addition, the southernmost of Profile A-A' shows that there is a young intrusion of magma at the COB (Fig. 3).

4.1.2 The tectonic-sedimentary framework on the west side of YJF

The basin structure on the west side of YJF is characterized by narrow sub-basin and wide uplift in comparison with the east side. On the continental shelf, the Qionghai Uplift shows a basement uplift in a buried-hill form, and the sedimentation in Wenchang Sag was controlled by a large north-dipping plate-like and listric fault (F11 in Fig. 4), showing a large half-graben that contains thick sedimentary layers. The Shenhu Uplift to the south of the Wenchang Sag shows a flat basement with a few faults and a series of fault terraces. The Shunde Sag is located on the continental slope, and the structure style shows two wide graben intervals, two narrow horsts and one narrow graben with thin sediments. The southern uplift belt is formed by the fault block uplift.

4.2 Tectonic evolution

The balance cross-sections on the east and west side of YJF are shown in Fig. 5 and Fig. 6, which are based on the time-depth converted profiles shown in Fig. 3 and Fig. 4, respectively.

4.2.1 Tectonic evolution on the east side of YJF

During Paleocene to the middle Eocene (65–39.5 Ma), the east side of YJF formed two independent rifting sags named Xijiang

Sag and Baiyun Sag (Fig. 5g). The deposition of the Shenhu Formation (E_1s) and Wenchang Formation (E_2w) of northern Xijiang Sag is relatively thick, which is controlled by two opposite faults (F1 and F2 in Fig. 5g). In this case, the north-dipping fault is the main controlling fault, which has a large activity rate (Fig. 7a) and deep cuts into the basement. The structural style of Baiyun Sag is a half-graben controlled by a homogeneous north-dipping fault (F6 in Fig. 5g), with moderate fault activity (Fig. 7c) and little deposition. In this period, there were scattered deposits in the Panyu Low Uplift and southern uplift belt. The Panyu Low Uplift has mainly developed some north-dipping faults, and the southern uplift belt features some horsts bounded by the opposite dip faults. The sedimentary facies of Wenchang Formation and Shenhu Formation are mainly fluvial and shallow lacustrine (Sun et al., 2008).

During the deposition time of the Enping Formation (E_3e , 39.5–32 Ma) (Fig. 5f), the rifting in Xijiang Sag and Baiyun Sag continued. The fault activity slowed down in northern Xijiang Sag but strengthened in Baiyun Sag (Figs 7a, c), and the depocenter of Baiyun Sag was still in the north. The Panyu Low Uplift has shown a preliminary structural style of faulted uplift, which was controlled by two north-dipping normal faults (F4 and F5 in Fig. 5f). In the north part of the southern uplift belt, two north-dipping normal faults continuously developed (F7 and F8 in Fig. 5f), and the horst shows a north-facing step-type faulted uplift. The southern part of southern uplift belt shows a broken hill structural style held by opposite-dipping faults (F9 and F10 in Fig. 5f), and the fault activity was not strong (Fig. 7d).

The SCS started seafloor spreading and entered the transitional period between rifting and depressing during the time of deposition of the Zhuhai Formation (E_3z , 32–23.8 Ma) (Fig. 5e). The fault activity in Xijiang Sag tended to stagnate (Fig. 7a). However, the biggest controlling fault in Baiyun Sag (F6 in Fig. 5e) was still active. The sag constantly expanded but was not connec-

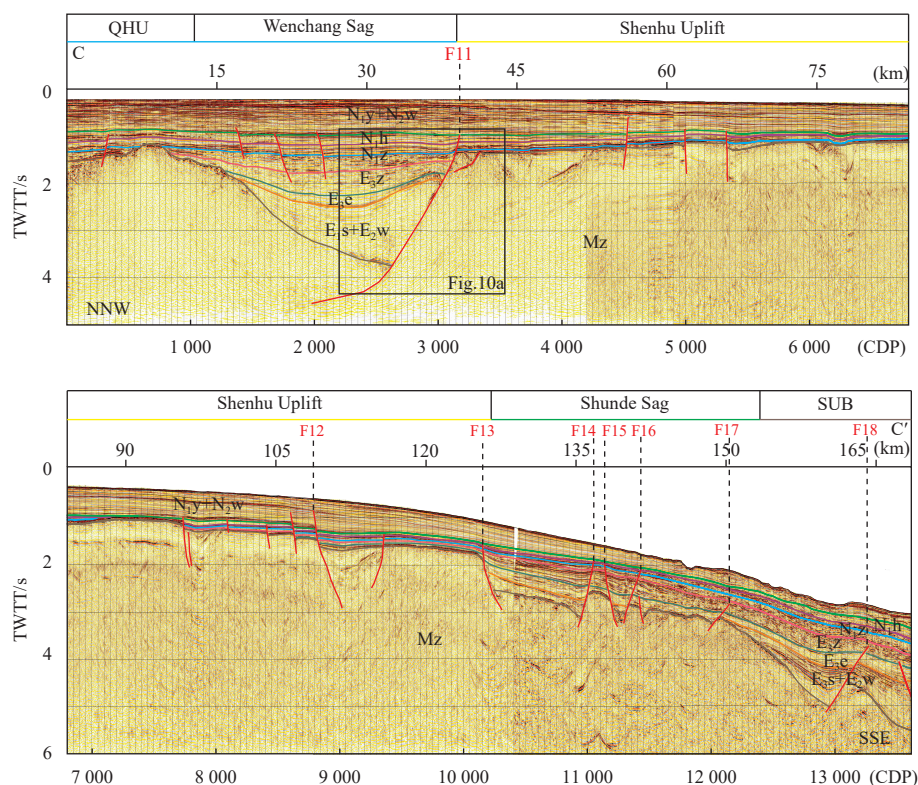


Fig. 4. Interpreted seismic Profile C-C' across the Zhujiang River Mouth Basin showing the tectonic-sedimentary framework in the west side of Yangjiang-Yitongdong Fault, the northern South China Sea margin (see Fig. 1 for line location). QHU: Qionghai Uplift; SUB: southern uplift belt.

ted to the northern sag. The depocenter was still located in the north. The southern boundary fault of Panyu Low Uplift was still active (F5 in Fig. 5e). The basement uplift looks like a ladder from north to south. At the southern boundary of southern uplift belt horst (F9 in Fig. 5e), the fault activity rate increased, resulting in a combination of unsymmetrical horst and buried hills.

The northern boundary of Xijiang Sag was slightly active (F1 in Figs 5c, d) during the time of deposition of the Zhujiang Formation (N_{1z} , 23.8–16.3 Ma). An inverse “y” type fault, located at the southern boundary of Xijiang Sag (F3 in Figs 5c, d), spreads upward and forms a flower structure, which is speculated as a result of the tensional-torsional stress. The control fault activity of Baiyun Sag (F6 in Figs 5c, d) further strengthened. A dustpan-like half graben structure controlled by the listric fault F6 is fully revealed, while the depocenter began to move to the central part of the sag. The fault activity in Panyu Low Uplift tended to stop, while some vertical linear faults were formed in the north, and some small north-dipping listric normal faults were also developed between two large listric faults (F4 and F5 in Figs 5c, d). We speculate that they may be formed by the balanced stress after the large faults stopped the activity. In the southern uplift belt, the fault activity of the northern horst zone exceeded that of the south. The fault activity on the anticlinal core (between F9 and F10) led to the destruction of buried hills. From this period, the southern uplift belt formed the composite structural style composed of horsts, tilted fault blocks and single broken hills from north to south. At the end of early Miocene, except that the Baiyun Sag still had large fault activity (also began to reduce), the faults of the Xijiang Sag, Panyu Low Uplift, and the southern uplift belt were inactive, and these areas came to the thermal subsidence period.

The basin began to accept abundant deposition after middle Miocene (16.3–0 Ma) (Figs 5a, b). Several small faults were developed in Baiyun Sag after 10.5 Ma, which may be related to the Dongsha Movement.

4.2.2 Tectonic evolution on the west side of YJF

The west side of YJF formed a half-graben named Wenchang Sag in the northern area during the deposition of the Shenhu Formation (E_{1s} , 65–49 Ma) and Wenchang Formation (E_{2w} , 49–39.5 Ma) (Fig. 6g), which was controlled by a north-dipping listric fault (F11 in Fig. 6g). The depocenter was mainly located in the southern part of the sag. Some scattered rifts formed in the south, and they were mainly in the structure of symmetrical graben and horst controlled by two opposite dipping faults (F13 and F14, F15 and F16 in Fig. 6g). Some tilted fault blocks formed in the southernmost of Profile C-C'. A huge half-graben controlled by a main plate-like fault (F18 in Fig. 6g) covered the tilted fault blocks. The average fault activity rate of Qionghai Uplift and Wenchang Sag as well as the western part of southern uplift belt achieved the maximum values of 156.0 m/Ma and 35.0 m/Ma, respectively (Figs 7a, d). The sedimentary facies were mainly fluvial and shallow lacustrine in this period.

During the deposition time of the Enping Formation (E_{3e} , 39.5–32 Ma), the sedimentary thickness of Shunde Sag and the southern uplift belt was larger than that of the Wenchang Sag (Fig. 6f). The average fault activity rate decreased to 31.2 m/Ma in Wenchang Sag, and 14.9 m/Ma in the western part of the southern uplift belt (Figs 7a, d). The deposits covered all Shunde Sag in this period that the sub-basin extended to the south (F13 to F17), and a broader graben formed in Shunde Sag.

The fault activity of Wenchang Sag began to strengthen again

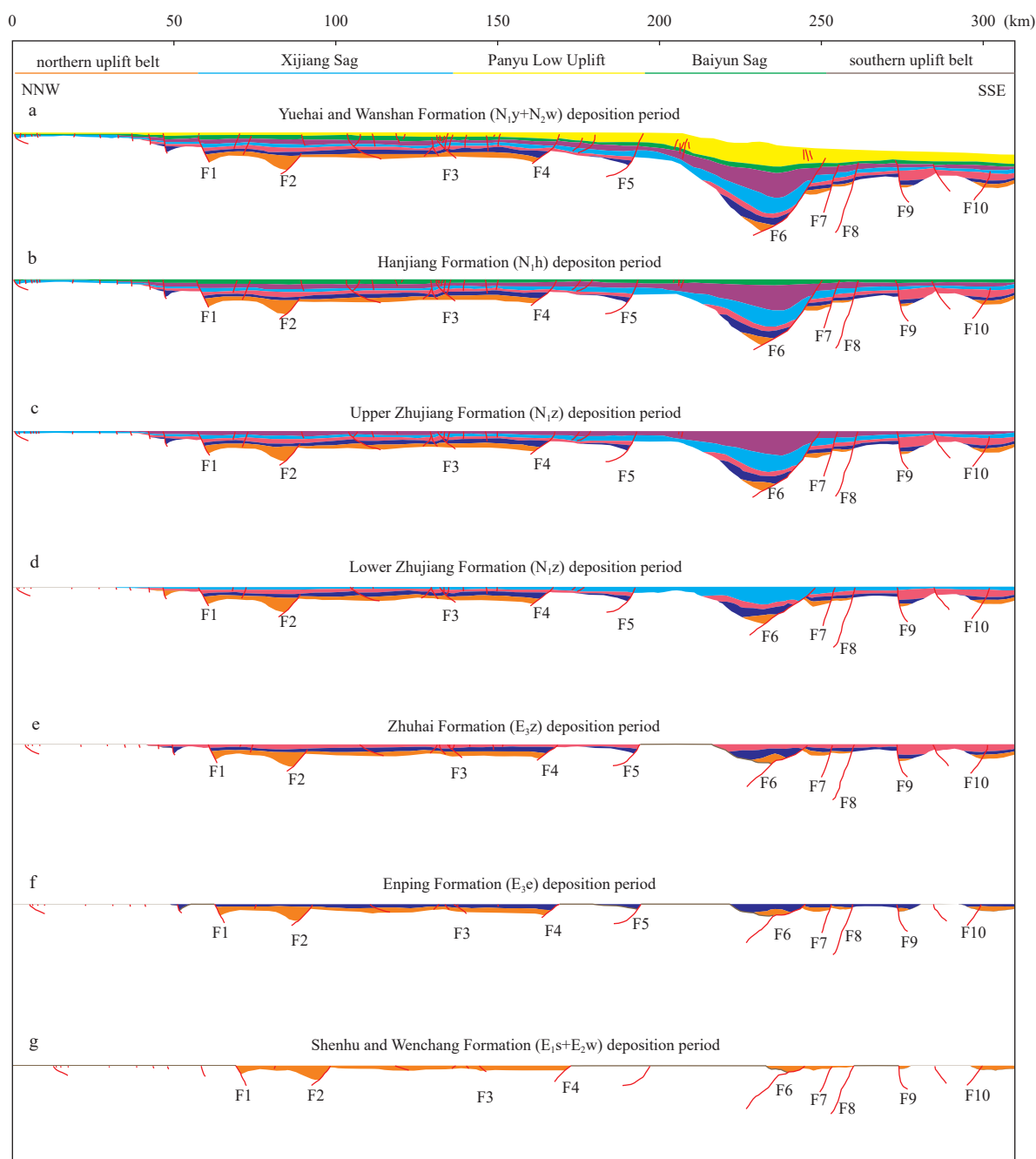


Fig. 5. The balanced cross-section in the east side of Yangjiang-Yitongdong Fault, Zhujiang River Mouth Basin (the modern seismic profile is Fig. 3). The time limit of each formation can be seen in Fig. 2. The Shenhu Formation (E_{1s}) and Wenchang Formation (E_{2w}) are merged into one deposition period because of the difficulty in identification of the formation interface. The similar situation happened in Yuehai Formation (N_{1y}) and Wanshan Formation (N_{2w}).

during the deposition of the Zhuhai Formation (E_{3z} , 32–23.8 Ma) (Fig. 6e and Fig. 7a), and the depocenter gradually moved to the center of the sag. In the south, the deposit area further expanded to the continent (to F12 in Fig. 6e). The sedimentary facies were mainly lacustrine and marshy.

The southern boundary fault of Wenchang Sag developed a subbranch at the top (F11 in Fig. 6d) during the deposition of the Zhujiang Formation (N_{1z} , 23.8–16.3 Ma) (Figs 6c and d). The basin began to enter the thermal subsidence period. The whole area started to subside and accepted the sediments, but the sediment thickness was small. The fault activity in the whole area

tended to stop in this period, and the sedimentary facies were mainly delta and marine.

The sedimentary characteristics of the west side of YJF were in a moderate aggradation rate after middle Miocene (16.3–0 Ma) (Figs 6a and b). The basin to the west side of YJF came into the thermal subsidence period, and the sedimentary facies were mainly neritic, bathyal and marine.

4.3 The fault dip angle of the western ZRMB

The rose diagrams of fault dips show the difference in northern depression belt between Qionghai Uplift/Wenchang Sag and

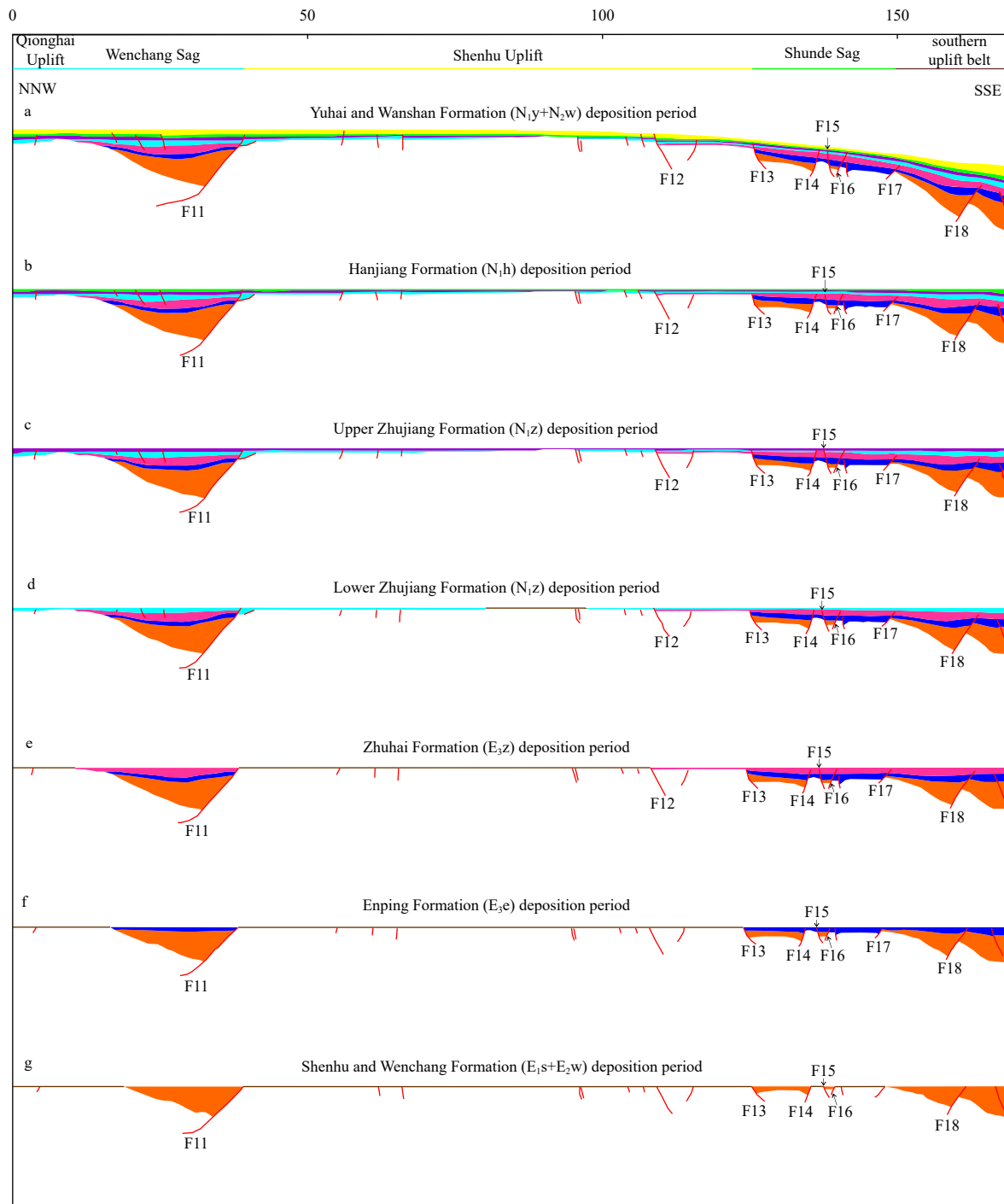


Fig. 6. The balanced cross-section in the west side of Yangjiang-Yitongdong Fault, Zhujiang River Mouth Basin (the modern seismic profile is Fig. 4). The relevant illustration is the same as Fig. 5.

Xijiang Sag (Figs 8a and b). The fault dips on the east side of YJF (Xijiang Sag) is almost between 50° to 70° , greater than 30° to 45° of the west side of YJF (Qionghai Uplift and Wenchang Sag).

In the central uplift belt, the fault dips in the west side of YJF (Shenhu Uplift) is almost between 65° – 70° , south dipping. In the east side of YJF (Panyu Low Uplift) is almost between 25° – 45° , north dipping (Figs 8c and d). However, the fault dips in the east side of YJF is slightly larger than west side in southern depression belt and southern uplift belt, such as 55° – 65° , north dipping in Shunde Sag versus 65° – 85° , south dipping in Baiyun Sag (Figs 8e

and f), and 45° – 50° , north dipping in the west part of the southern uplift belt versus 60° – 65° , north dipping in the east part (Figs 8g and h).

5 Discussion

5.1 The regulating effect of YJF in ZRMB

We counted the fault strike on both sides of YJF, and the results show an obvious difference that the fault strike in the east side of YJF is mainly E-W direction, while the west side is mainly

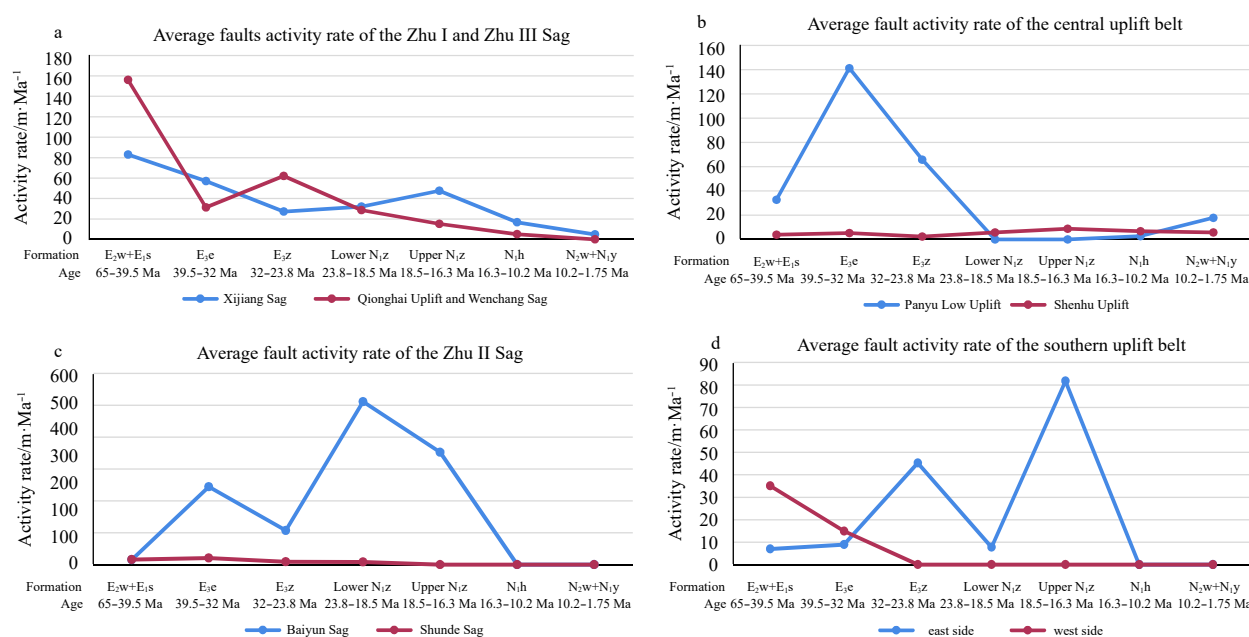


Fig. 7. The same tectonic belt comparison between fault activity rates of the east and west sides of Yangjiang-Yitongdong Fault in the northern South China Sea margin. The strategy of stratigraphic subdivisions is the same as Fig. 5 and Fig. 6.

50°–65°N (Fig. 9). Similarly, the strike of the Cenozoic rifts on the west side of YJF is NE-SW, but NEE-SWW to E-W on the east side (Sun et al., 2008; Zhou et al., 2002; Ru et al., 1994). In addition, it can be seen in seismic Profiles A-A', B-B', C-C' and D-D' that the rifts are wide on the east side of YJF but narrow on the west side (Figs 3 and 4). The YJF acted as a distinct tectonic boundary between these differences in ZRMB.

The obvious structural and morphological variations in the F_1 , the southern boundary fault of northern depression belt, from west to east have been noticed, and this variation may reflect the variation of stress in each position of different periods. In the westernmost, the boundary fault of the Wenchang Sag and Shenhu Uplift (see Fig. 1a C-C' for location) shows a complete large listric and plate-like normal fault style and has a small branch only at the top (Fig. 10a). To the eastward in B-B' profile, the boundary fault of Wenchang Sag and Shenhu Sag showed extensional normal fault properties at the early period and subsequently transferred to the negative flower structure which was in tensional-torsional properties (Fig. 10b). The extensional normal fault cuts the Shenhu Formation (E_1s) to the Zhuhai Formation (E_3z), showing dominance during T_6 to T_8 sedimentary period (65–23.8 Ma). After 23.8 Ma, the extensional normal faults were inactive and the negative flower structure strongly developed. Therefore, the transformation time of the fault property in Fig. 10b was about 23.8 Ma. To the easternmost A-A' profile, the boundary fault of Xijiang Sag and Panyu Low Uplift shows a negative flower structure which was of tension-torsional properties. This fault had merely extensional normal fault properties before T_8 sedimentary period (39.5 Ma) (Fig. 10c). According to the structural and morphological differences in the southern boundary fault of northern depression belt from west to east, and combined with the regional tectonic background, it is interpreted that the western and eastern segments were subjected to the main extension stress of NW before 39.5 Ma, and the F_1 was characterized by normal fault properties in this period. During 39.5–23.8 Ma, the east segment shifted to the main extension stress of N-S related to the force which led to the early seafloor spreading of SCS

(Li et al., 2007, 2014; Sibuet et al., 2016). The extension stress of NW was reduced at the same time, therefore the negative flower structure formed in the east part earlier. After 23.8 Ma, the extension stress in west segment weakened due to the development of southwest sub-basin seafloor spreading (Li et al., 2007, 2014; Sibuet et al., 2016), and the F_1 in the west segment also began to form negative flower structure. Under the regional geotectonic background of the hard crust of Cathaysia located in the north and the continent marginal crust block drifted to southward (Hall, 2012; Yan et al., 2014), we believe that an NW-striking fault adjusted the tectonic stress difference between the east and west sides of YJF.

All these characteristics demonstrated that the NE-EW-trending normal faults controlled the development of rift and sedimentation in ZRMB, the tectonic stress difference affected the rift development between the two sides of YJF, and the activity of YJF in Cenozoic is likely to play a regulating role.

5.2 The Cenozoic activities of YJF and its controlling factor

5.2.1 Before Eocene: inherited preexisting sinistral motion

On the seismic Profile E-E', the YJF shows an extension normal fault style before the deposition of Zhuhai Formation (before 32 Ma) (Fig. 11), and the Yunkai Low Uplift formed in NW-SE direction along the east side of YJF, indicating that the south segment of YJF was mainly under extension in this period (Fig. 12b).

From the analysis of morphological variations of F_1 from east to west, we can conclude that this variation was mainly caused by the NW-trending extension stress gradually released from east to west. This NW-trending extension stress is interpreted to be a manifestation of the First Episode of Zhuqiong Event (Ru et al., 1994; Zhong et al., 2014). The morphological difference between the east and west segment of F_1 indicates that the NW-SE extension stress on the west side of YJF was larger than that on the east side in northern ZRMB. If the Cathaysia located on the north remain stationary, the larger stress on the east side means the YJF should keep sinistral motion to regulate the strain difference.

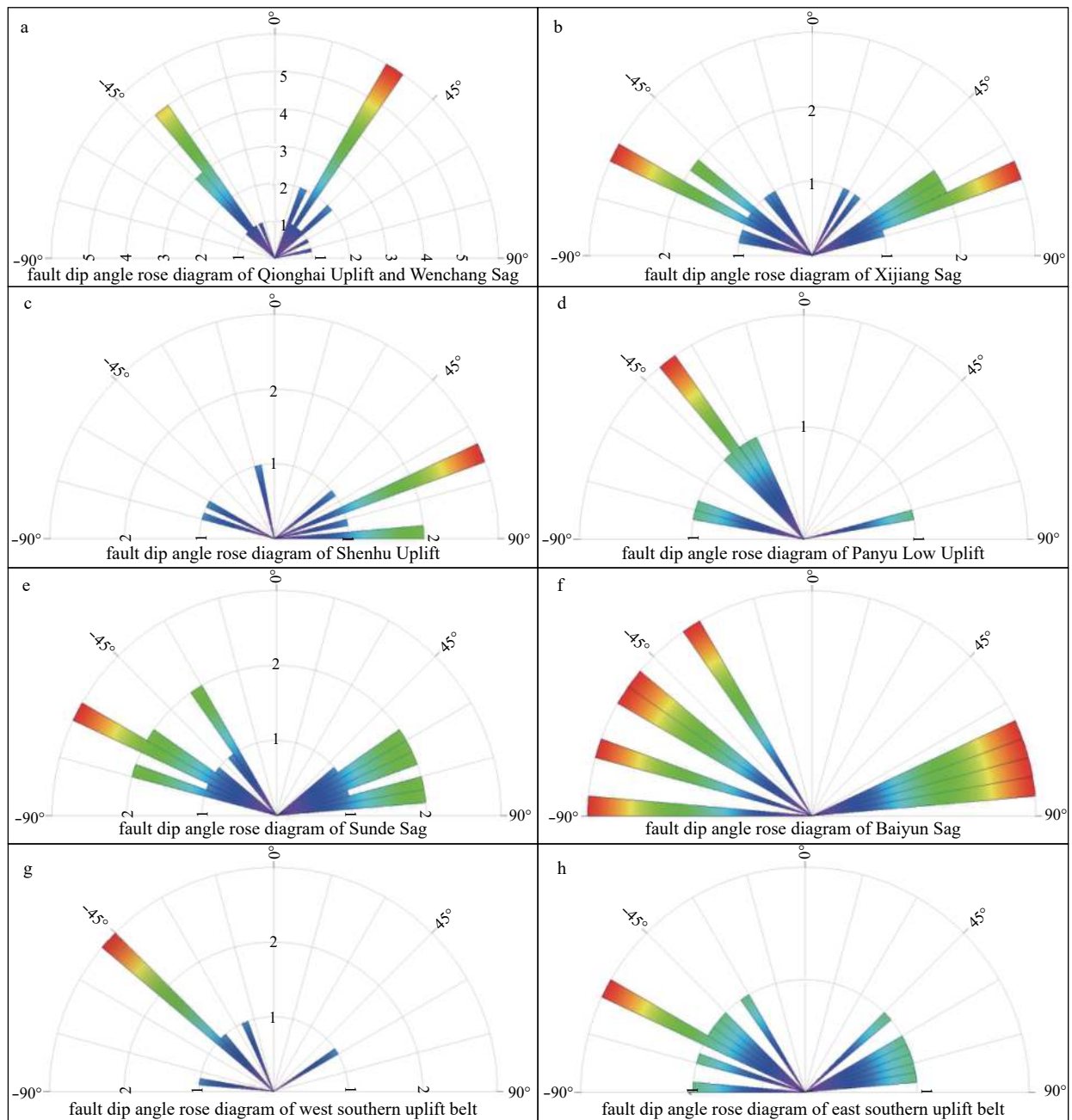


Fig. 8. The fault dip angle rose diagram of the tectonic region in west and east sides of Yangjiang-Yitongdong Fault, northern South China Sea margin. The left column is the fault dip angle rose diagrams of the west side of Yangjiang-Yitongdong Fault. The right column is the fault dip angle rose diagrams of the east side of Yangjiang-Yitongdong Fault.

Therefore, we conclude that the northern segment of YJF kept sinistral motion before 23.8 Ma (Figs 12b and c).

During the Paleocene to Eocene (65–39.5 Ma), the rifting scale in the southern part of the basin was tiny, and the rifting activity has mainly proceeded in the northern part. Although the structural styles of Xijiang Sag and Wenchang Sag were different, the average fault activity rate of these two sags reached the maximum (82.9 m/Ma and 156.0 m/Ma, respectively) among the basin scale (Fig. 7a). The fault activity in the west part of southern uplift belt reached the maximum of 35.0 m/Ma, which was larger than that of the east part. The tectonic activity of the west side of YJF was stronger than that of the east side in this period, which was consistent with the results of full-fit reconstruction of

the SCS conjugate margins (Bai et al., 2015) and the continental crustal extension (Hayes and Nissen, 2005), all of which indicated that the northern SCS continental margin crust had greater extension in the west segment than east before the SCS seafloor spreading. The results of tectonic activity intensity are coincident with the transfer time in tectonic deformation, we can also get the conclusion that the YJF kept sinistral strike-slip motion during 65–39.5 Ma (Fig. 12b). The initial sinistral strike-slip motion of YJF probably inherited the sinistral motion of the Mesozoic period revealed by gravity and magnetic anomalies (Zhou et al., 2006) (Fig. 12a).

In the late Eocene (39.5–32 Ma), the rate of rifting in the northern depression belt was in a consistently decreasing trend

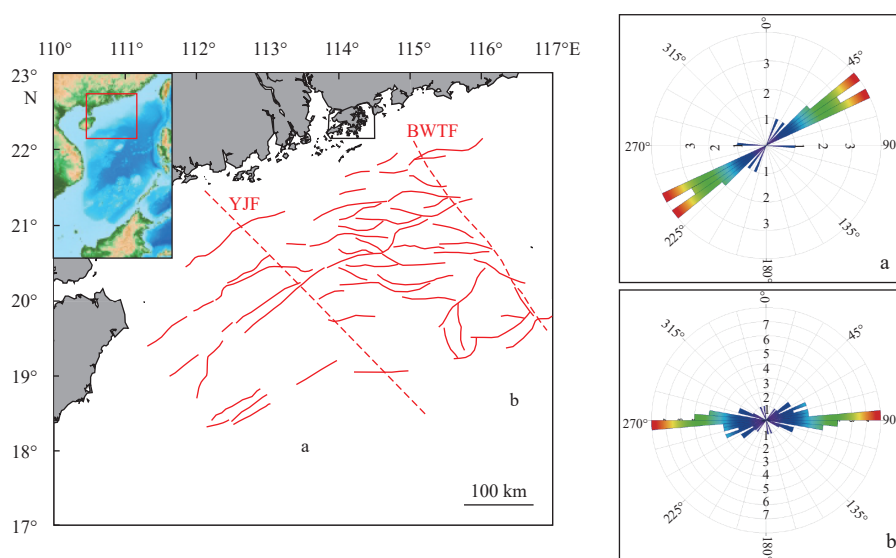


Fig. 9. Main Cenozoic extensional faults in the Zhujiang River Mouth Basin and their fault strike rose diagrams (after Yang et al., 2015). a. The fault strike rose diagram of the west side of the Yangjiang-Yitongdong Fault, Zhujiang River Mouth Basin; and b. the fault strike rose diagram of the east side of the Yangjiang-Yitongdong Fault, Zhujiang River Mouth Basin.

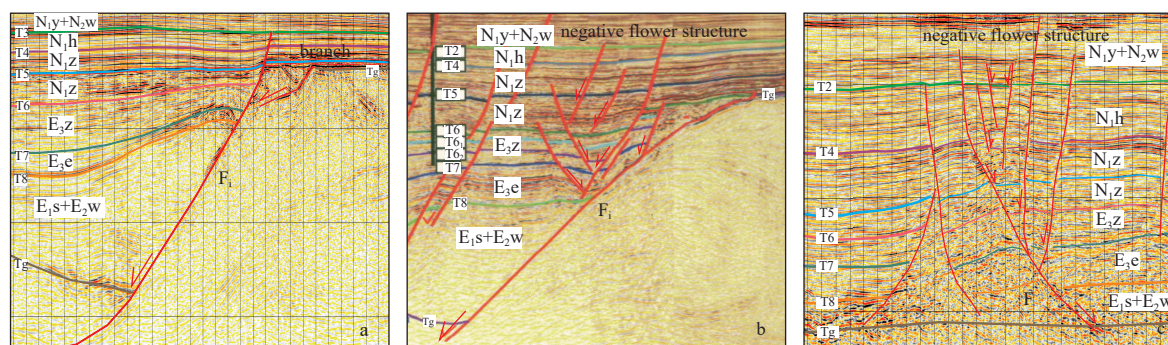


Fig. 10. The structural morphological variation of the mark fault F_i , which located in the southern boundary of the northern depression belt. a. The boundary fault of Wenchang Sag and Shenhu Uplift (see Fig. 4 for location); b. the boundary fault of Wenchang Sag and Shenhu Uplift (see B-B' seismic profile in Fig. 1 for location, modified from Zhu and Mi (2011)); and c. the boundary fault of Xijiang Sag and Panyu Low Uplift (see Fig. 3 for location).

on both sides of YJF (Fig. 7a). The fault activity rate in other areas of the basin increased. For example, the fault activity rate in Panyu Low Uplift reached the maximum of 141.2 m/Ma. The reason for this high fault activity rate is that the Panyu Low Uplift belonged to the large sub-basin connected to Xijiang Sag in this period, and the northern Panyu Low Uplift was even depocenter (Fig. 7b). The fault activity increased but still tiny in Shenhu Uplift (Fig. 7b), and sharply increased in Baiyun Sag, reaching 244.1 m/Ma (Fig. 7c). In addition, the fault activity rate in Shunde Sag reached a maximum of 20.9 m/Ma (Fig. 7c) during 39.5–32 Ma. In the southern uplift belt, the east side of YJF showed a step type faulted block in the north and a broken hill structural style bounded by opposite dipping faults (Fig. 5), and the west side of YJF showed tilted faulted block and single broken hill structural style (Fig. 6). Fault activity and structural style characteristics indicate that the extension stress of this stage was gradually diffused from the north to the whole basin and the sinistral motion weakened.

5.2.2 From Oligocene: shift to dextral motion gradually

In the Oligocene period (32–23.8 Ma), except for the east part

of the southern uplift belt and the Wenchang Sag, the fault activity of other areas in ZRMB was in different degrees of weakening compared with the previous period (Fig. 7). The SCS started seafloor spreading in this period (Li et al., 2014; Barckhausen et al., 2014), and the extension stress of the ZRMB may be gradually released together with the activity of the SCS (Sun et al., 2010). From the balanced cross-section, we can see that the tectonic activity in southern part, east side of YJF was more intensive than that in other regions, showing a strong stress concentration (Fig. 5). The probable reason is that the deep magmatic underplating in the vicinity of the COB (Li et al., 2007, 2008; Guo et al., 2016), which was related to the opening of SCS and led to the accelerated basin subsidence. The regional extension stress was likely large enough to adjust the difference of the structural strain in the west side of YJF, therefore, the sinistral motion in the southern section of YJF would have stopped or transferred to a slight dextral motion in this period (Fig. 12c). In northern depression belt, the tectonic activity on the west side of YJF was stronger than that of the east side, indicating that sinistral motion still existed in the northern section of YJF.

During the early Miocene (23.8–16.3 Ma), on the east side of

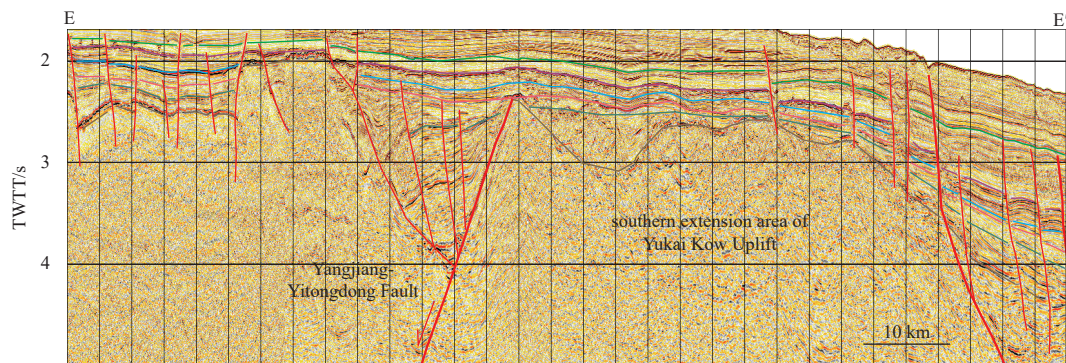


Fig. 11. The Yangjiang-Yitongdong Fault showed extensional fault property in the early period (see E-E' seismic profile in Fig. 1 for location).

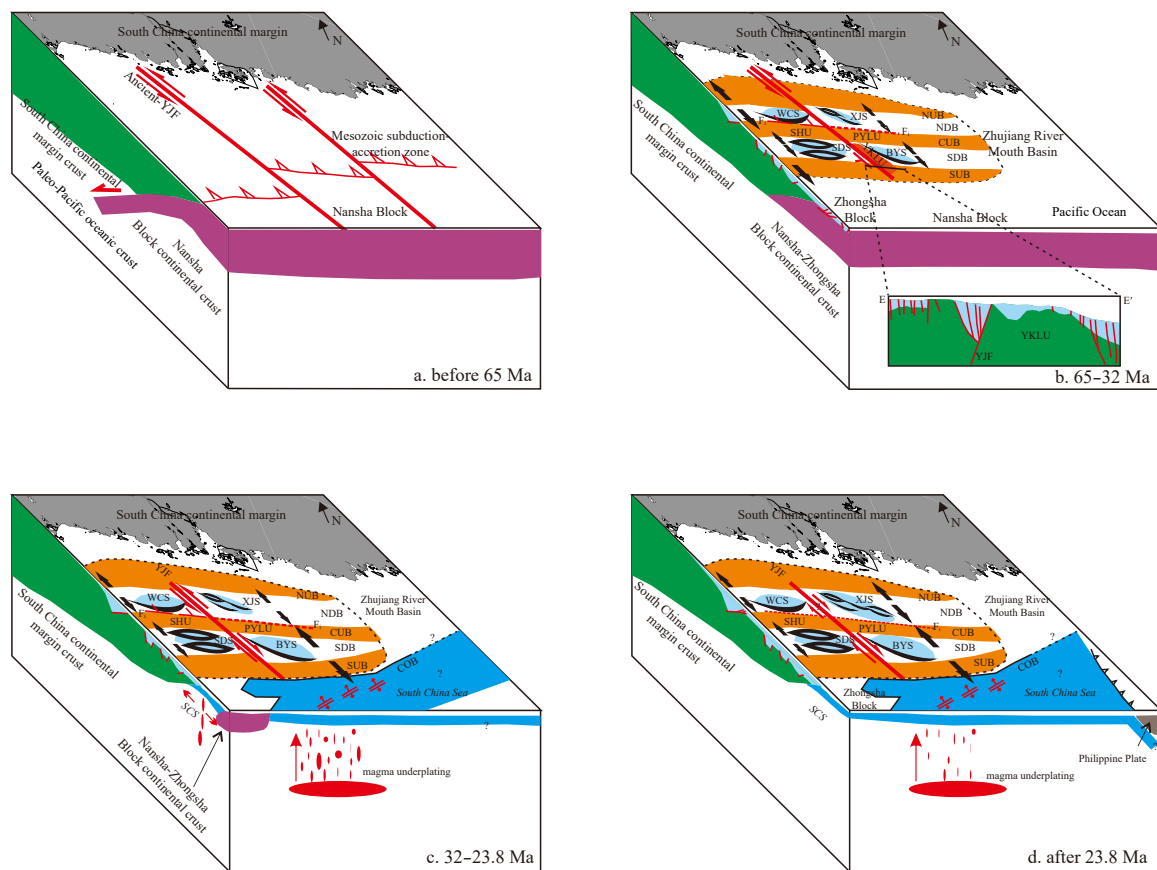


Fig. 12. Regional tectonic evolution process and the Cenozoic activity of the Yangjiang-Yitongdong Fault. The red dotted line represents the negative flower structure of the mark fault Fi. NUB: northern uplift belt; NDB: northern depression belt; CUB: central uplift belt; SDB: southern depression belt; SUB: southern uplift belt. See Fig. 1 for other annotations.

YJF, the rifting activity of Baiyun Sag and southern uplift belt continued to strengthen, and the fault activity rate of Baiyun Sag reached a maximum of 510.8 m/Ma at about 18.5 Ma (Fig. 7c). On the west side of YJF, the fault activity of Shunde Sag was almost stagnant, and it entered the complete thermal subsidence period (Pang et al., 2004; Sun et al., 2008) (Fig. 7c). To regulate such a large difference in tectonic intensity, the YJF continued the dextral motion in the south segment. While in the north segment, the fault activity rate in Xijiang Sag was higher than that of Qionghai Uplift and Wenchang Sag, and both of them were minor with time (Fig. 7a). This shift indicates that the north segment of YJF was speculated to transfer to a slight dextral motion

or that sinistral motion became stagnant under the influence of the dextral motion in the south segment of YJF (Fig. 12d).

After Miocene (16.3–0 Ma), the SCS stopped the seafloor spreading (Li et al., 2014), the whole region entered into a period of thermal subsidence (Pang et al., 2004; Sun et al., 2008) (Fig. 7). In this period, the activity of YJF maintained the previous dextral motion and the activity intensity decreased. The fault dip angle in the east side of YJF is larger than the west of that except in the central uplift belt (Fig. 8), hinting that the YJF had more dextral motion quantity than sinistral motion in Cenozoic.

Regarding the reason for the shift of activities of YJF and rift development in ZRMB, we speculate that the beginning of SCS

seafloor spreading and interrelated magmatic underplating are the crucial factors. The first episode of Zhuqiong Event dominated the sinistral motion in early Cenozoic, and the sinistral motion weakened during the second episode of Zhuqiong Event. Although the extension stress during the second episode of Zhuqiong Event was mainly in NNW to NS direction, and formed NEE to EW-trending rift (Pang et al., 2004; Zhong et al., 2014), the sinistral motion was only been inversed until the SCS seafloor spreading started. From the sedimentary pattern acquired from the seismic profile (Figs 3 and 4), we can find that the thick sediments after T_6 in the east side of YJF are mainly attributed to thermal subsidence especially in Baiyun Sag. The magmatic underplating took place at the COT zone of the southern ZRMB (Li et al., 2007; Guo et al., 2016), which caused ductile thinning and extension of the crust in Baiyun Sag (Sun et al., 2005). The magmatic underplating led to the strengthening of tectonic activity on the east side of YJF, therefore, the shift in the strike-slip direction of YJF is probably the response of magmatic underplating in the east side of YJF, related to the beginning of SCS seafloor spreading. If we consider the dynamic mechanism from a larger scale, such as the retreat of the Pacific subduction zone, the subduction of proto-SCS or Indian-Eurasian collision, they are possible to become the source of the shift of YJF strike-slip direction. However, there is no compelling evidence can verify which project led the tectonic stress shift. The most critical thing is that these dynamic mechanisms are hard to explain why the northern segment of YJF does not shift to dextral motion synchronize with the southern segment. A further research is needed to solve this problem.

6 Conclusions

In this study, we compared the tectonic-sedimentary characteristics and evolution process on both two sides of YJF, interpreted the featured structure and analyzed the Cenozoic activities of YJF. The seismic profiles and basin rift structure show that the sedimentary process and rift development were mainly controlled by the NE-EW-trending normal faults in ZRMB. On the basis of the analysis of tectonic activity intensity and deformation characteristics, we found that the tectonic stress difference in rifts does exist between the two sides of YJF in Cenozoic, and which makes YJF likely to play a regulating role in the E-W trend difference of tectonic and sedimentary in ZRMB. Before 32 Ma, the YJF played the main role in forming and rift development process of the NW-SE-trending Yunkai Low Uplift and its vicinity area.

Through the comparison of structural style and tectonic evolution history between the two sides of YJF and combined with the geotectonic background, we divided the YJF into the north and south segments with the boundary of the central uplift belt. The activity of YJF in Cenozoic can be concluded as three stages: (1) 65–32 Ma, the YJF was entirely in sinistral motion. The south segment of YJF was mainly under extension activity, with a slight sinistral motion. This stage may be related to the inheritance of the ancient-YJF sinistral motion in Mesozoic and the development of the first episode of Zhuqiong. (2) 32–23.8 Ma, the north segment of YJF kept the sinistral motion, while the south segment began to stop sinistral motion or turn to a slightly dextral motion. The shift in strike-slip might be caused by the magmatic underplating into the south boundary area of the east side of YJF before the continental breakup. (3) After 23.8 Ma, the fault activity in the north segment of YJF turned to stagnate or a slight dextral motion, while the dextral motion of the south segment of YJF continued, with weak activity quantity. The ZRMB entered into the thermal

subsidence stage gradually, and the tectonic activities tended to be weakened.

References

- Bai Yongliang, Wu Shiguo, Liu Zhan, et al. 2015. Full-fit reconstruction of the South China Sea conjugate margins. *Tectonophysics*, 661: 121–135, doi: [10.1016/j.tecto.2015.08.028](https://doi.org/10.1016/j.tecto.2015.08.028)
- Barckhausen U, Engels M, Franke D, et al. 2014. Evolution of the South China Sea: revised ages for breakup and seafloor spreading. *Marine and Petroleum Geology*, 58: 599–611, doi: [10.1016/j.marpetgeo.2014.02.022](https://doi.org/10.1016/j.marpetgeo.2014.02.022)
- Barckhausen U, Engels M, Franke D, et al. 2015. Reply to Chang et al., 2014, Evolution of the South China Sea: revised ages for breakup and seafloor spreading. *Marine and Petroleum Geology*, 59: 679–681, doi: [10.1016/j.marpetgeo.2014.09.002](https://doi.org/10.1016/j.marpetgeo.2014.09.002)
- Ben-Avraham Z, Uyeda S. 1973. The evolution of the China Basin and the Mesozoic paleogeography of Borneo. *Earth and Planetary Science Letters*, 18(2): 365–376, doi: [10.1016/0012-821X\(73\)90077-0](https://doi.org/10.1016/0012-821X(73)90077-0)
- Briaies A, Patriat P, Tapponnier P. 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: implications for the tertiary tectonics of Southeast Asia. *Journal of Geophysical Research*, 98(B4): 6299–6328, doi: [10.1029/92JB02280](https://doi.org/10.1029/92JB02280)
- Cameselle A L, Ranero C R, Franke D, et al. 2017. The continent-ocean transition on the northwestern South China Sea. *Basin Research*, 29(S1): 73–95
- Chang J H, Lee T Y, Hsu H H, et al. 2015. Comment on Barckhausen et al., 2014—evolution of the South China Sea: revised ages for breakup and seafloor spreading. *Marine and Petroleum Geology*, 59: 676–678, doi: [10.1016/j.marpetgeo.2014.09.003](https://doi.org/10.1016/j.marpetgeo.2014.09.003)
- Chen Hanzong, Wu Xiangjie, Zhou Di, et al. 2005. Meso-cenozoic faults in Zhujiang River Mouth Basin and their geodynamic background. *Journal of Tropical Oceanography (in Chinese)*, 24(2): 52–61
- Chen Jiangxin, Zhang Baojin, Song Haibin. 2014. Far offset refractive velocity properties of the Cenozoic strata in the northern South China Sea. *Chinese Journal of Geophysics (in Chinese)*, 57(7): 2223–2234
- Chen Lin, Hu Jiwei, Yang Dinghui, et al. 2017. Kinematic models for the opening of the South China Sea: An upwelling divergent flow origin. *Journal of Geodynamics*, 107: 20–33, doi: [10.1016/j.jog.2017.03.002](https://doi.org/10.1016/j.jog.2017.03.002)
- Clift P, Lin Jian, Barckhausen U. 2002. Evidence of low flexural rigidity and low viscosity lower continental crust during continental break-up in the South China Sea. *Marine and Petroleum Geology*, 19(8): 951–970, doi: [10.1016/S0264-8172\(02\)00108-3](https://doi.org/10.1016/S0264-8172(02)00108-3)
- Dong Dongdong, Wu Shiguo, Zhang Gongcheng, et al. 2008. Rifting process and formation mechanisms of syn-rift stage prolongation in the deepwater basin, northern South China Sea. *Chinese Science Bulletin*, 53(23): 3715–3725, doi: [10.1007/s11434-008-0326-1](https://doi.org/10.1007/s11434-008-0326-1)
- Gao Hongfang. 2008. Comparing the basement characteristics of Cenozoic sedimentary basins on the eastern and western margins of the northern South China Sea. *Geological Research of South China Sea (in Chinese)*, 23–34
- Guo Lingli, Li Sanzhong, Zhao S J, et al. 2016. Final breakup of continental block and opening of oceanic lithosphere: insights from deep crustal structure and tectonic evolution of the ocean-continent transition zone in the northern South China Sea. *Geological Journal*, 51(S1): 318–330
- Gilley L D, Harrison T M, Leloup P H, et al. 2003. Direct dating of left-lateral deformation along the Red River shear zone, China and Vietnam. *Journal of Geophysical Research*, 108(2): 2127
- Hall R. 1996. Reconstructing Cenozoic SE Asia. In: Hall R, Blundell D J, eds. *Tectonic evolution of Southeast Asia*. London: Geological Society Special Publication, 153–184
- Hall R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. *Journal of Asian Earth Science*, 20(4):

- 353–431, doi: [10.1016/S1367-9120\(01\)00069-4](https://doi.org/10.1016/S1367-9120(01)00069-4)
- Hall R. 2012. Late Jurassic-Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics*, 570–571: 1–41, doi: [10.1016/j.tecto.2012.04.021](https://doi.org/10.1016/j.tecto.2012.04.021)
- Hayes D E, Nissen S S. 2005. The South China Sea margins: implications for rifting contrasts. *Earth and Planetary Sciences Letters*, 237(3–4): 601–616, doi: [10.1016/j.epsl.2005.06.017](https://doi.org/10.1016/j.epsl.2005.06.017)
- Hollway N H. 1982. The stratigraphic and tectonic evolution of Reed Bank, North Palawan and Mindoro to the Asian mainland and its significance in the evolution of the South China Sea. *AAPG Bulletin*, 66: 1357–1383
- Hu Dengke, Zhou Di, Wu Xiangjie, et al. 2009. Crustal structure and extension from slope to deepsea basin in the northern South China Sea. *Journal of Earth Science*, 20(1): 27–37, doi: [10.1007/s12583-009-0003-6](https://doi.org/10.1007/s12583-009-0003-6)
- Huang Chunju, Zhou Di, Chen Changmin, et al. 2005. Deep crustal structure of Baiyun Sag, northern South China Sea revealed from deep seismic reflection profile. *Chinese Science Bulletin*, 50(11): 1131–1138, doi: [10.1360/04wd0207](https://doi.org/10.1360/04wd0207)
- Karig D E. 1971. Origin and development of marginal basins in the western Pacific. *Journal of Geophysical Research*, 76(11): 2542–2561, doi: [10.1029/JB076i011p02542](https://doi.org/10.1029/JB076i011p02542)
- Leloup P H, Lacassin R, Tapponnier P, et al. 1995. The Ailao Shan-Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina. *Tectonophysics*, 251(1–4): 3–10
- Li Qinying, Luo Fengzhi, Miao Cuizhi. 2000. Research on fault activity ratio and its application. *Fault-Block Oil & Gas Field (in Chinese)*, 7(2): 15–17
- Li Chunfeng, Xu Xing, Lin Jian, et al. 2014. Ages and magnetic structures of the South China Sea constrained by deep tow magnetic surveys and IODP Expedition 349. *Geochemistry, Geophysics, Geosystems*, 15(12): 4958–4983, doi: [10.1002/2014GC005567](https://doi.org/10.1002/2014GC005567)
- Li Chunfeng, Zhou Zuyi, Li Jiabiao, et al. 2007. Structures of the northeasternmost South China Sea continental margin and ocean basin: geophysical constraints and tectonic implications. *Marine Geophysical Researches*, 28(1): 59–79, doi: [10.1007/s11001-007-9014-9](https://doi.org/10.1007/s11001-007-9014-9)
- Li Chunfeng, Zhou Zuyi, Li Jiabiao, et al. 2008. Magnetic zoning and seismic structure of the South China Sea ocean basin. *Marine Geophysical Researches*, 29(4): 223–238, doi: [10.1007/s11001-008-9059-4](https://doi.org/10.1007/s11001-008-9059-4)
- Liu Hailing, Guo Lingzhi, Sun Yan, et al. 2002. Study on Fault System in Nansha Block (South China Sea) and the Block's Lithospheric Dynamics (in Chinese). Beijing: Science Press, 8–19
- Liu Hailing, Zheng Hongbo, Wang Yanlin, et al. 2011. Basement of the South China Sea: tracing the Tethyan Realm. *Acta Geologica Sinica*, 85(3): 637–655, doi: [10.1111/acgs.2011.85.issue-3](https://doi.org/10.1111/acgs.2011.85.issue-3)
- Liu Zhifeng, Wang Shenglan, Yin Binhao, et al. 2013. Different distribution of lacustrine facies and its controlling factors during rifting stage, Zhu I and Zhu III Depressions, Pearl River Mouth Basin. *Petroleum Geology and Experiment (in Chinese)*, 35(5): 523–527
- Lu Baoliang, Wang Pujun, Zhang Gongcheng, et al. 2011. Basement structures of an epicontinental basin in the northern South China Sea and their significance in petroleum prospect. *Acta Petrolei Sinica (in Chinese)*, 32(4): 580–587
- Nissen S S, Hayes D E, Buhl P, et al. 1995. Deep penetration seismic soundings across the northern margin of the South China Sea. *Journal of Geophysical Research*, 100(B11): 22407–22433, doi: [10.1029/95JB01866](https://doi.org/10.1029/95JB01866)
- Pang Xiong, Yang Shaokun, Zhu Ming, et al. 2004. Deep-water fan systems and petroleum resources on the northern slope of the South China Sea. *Acta Geologica Sinica*, 78(3): 626–631
- Ru Ke, Zhou Di, Chen Hanzong. 1994. Basin evolution and hydrocarbon potential of the northern South China Sea. In: Zhou Di, Liang Yuanbo, Zeng Chengkui, eds. *Oceanology of China Seas*. Dordrecht: Springer, 361–372
- Shi Xiaobin, Burov E, Leroy S, et al. 2005. Intrusion and its implication for subsidence: a case from the Baiyun Sag, on the northern margin of the South China Sea. *Tectonophysics*, 407(1–2): 117–134, doi: [10.1016/j.tecto.2005.07.004](https://doi.org/10.1016/j.tecto.2005.07.004)
- Sibuet J C, Yeh Y C, Lee C S. 2016. Geodynamics of the South China Sea. *Tectonophysics*, 692: 98–119, doi: [10.1016/j.tecto.2016.02.022](https://doi.org/10.1016/j.tecto.2016.02.022)
- Su Daquan. 2004. Geological and geophysical complimentary survey and evaluation on mineral resources (in Chinese). Beijing: China Oceanic Press, 132
- Sun Zhen, Pang Xiong, Zhong Zhihong, et al. 2005. Dynamics of tertiary tectonic evolution of the Baiyun Sag in the Pearl River Mouth Basin. *Earth Science Frontiers (in Chinese)*, 12(4): 489–498
- Sun Xiaomeng, Zhang Xuqing, Zhang Gongcheng, et al. 2014. Texture and tectonic attribute of Cenozoic basin basement in the northern South China Sea. *Science China Earth Sciences*, 57(6): 1199–1211, doi: [10.1007/s11430-014-4835-2](https://doi.org/10.1007/s11430-014-4835-2)
- Sun Zhen, Zhong Zhihong, Zhou Di, et al. 2008. Dynamics analysis of the Baiyun Sag in the Pearl River Mouth Basin, North of the South China Sea. *Acta Geologica Sinica*, 82(1): 73–83
- Sun Zhen, Zhou Di, Sun Longtao, et al. 2010. Dynamic analysis on rifting stage of Pearl River Mouth basin through analogue modeling. *Journal of Earth Science*, 21(4): 439–454, doi: [10.1007/s12583-010-0106-0](https://doi.org/10.1007/s12583-010-0106-0)
- Tamaki K. 1995. Upper mantle extrusion tectonics of Southeast Asia and formation of the western Pacific back-arc basins. In: Le Pichon X, Rangin C, Tapponnier P, eds. *International Workshop: Cenozoic Evolution of the Indochina Peninsula*. Hanoi-Do Son, Abstract with Program, 89
- Tapponnier P, Lacassin R, Leloup P H, et al. 1990. The Ailao Shan/Red River metamorphic belt: Tertiary left-lateral shear between Indochina and South China. *Nature*, 243(6267): 431–437
- Tapponnier P, Peltzer G, Le Dain A Y, et al. 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology*, 10(12): 611–616, doi: [10.1130/0091-7613\(1982\)10<611:PETIAN>2.0.CO;2](https://doi.org/10.1130/0091-7613(1982)10<611:PETIAN>2.0.CO;2)
- Taylor B, Hayes D E. 1980. The tectonic evolution of the South China Basin. In: Hayes D E, ed. *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands*. Washington, DC: American Geophysical Union, 89–104
- Taylor B, Hayes D E. 1983. Origin and history of the South China Sea basin. In: *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, II*. Washington, DC: American Geophysical Union, 23–56
- Wang Zhangshi, Zhu Weilin, Zhong Kai, et al. 2015. Late cretaceous tectonic thrusting and its genesis in northern slope of the South China Sea (in Chinese). *Earth Science-Journal of China University of Geosciences*, 40(9): 1505–1516 doi: [10.3799/dqkx.2015.135](https://doi.org/10.3799/dqkx.2015.135)
- Wu Zhe, Zhu Weilin, Shao Lei, et al. 2016. Sedimentary facies and the rifting process during the late Cretaceous to early Oligocene in the northern continental margin, South China Sea. *Interpretation*, 4(3): SP33–SP45, doi: [10.1190/INT-2015-0163.1](https://doi.org/10.1190/INT-2015-0163.1)
- Xie Xinong, Müller R D, Li Sitian, et al. 2006. Origin of anomalous subsidence along the Northern South China Sea margin and its relationship to dynamic topography. *Marine and Petroleum Geology*, 23(7): 745–765, doi: [10.1016/j.marpetgeo.2006.03.004](https://doi.org/10.1016/j.marpetgeo.2006.03.004)
- Xia Zhongyu, Wan Zhifeng, Wang Xianqing, et al. 2016. The tectonic differences between the east and the west in the deep-water area of the northern South China Sea. *Acta Oceanologica Sinica*, 35(1): 86–95, doi: [10.1007/s13131-016-0799-8](https://doi.org/10.1007/s13131-016-0799-8)
- Xie Hui, Zhou Di, Li Yuanping, et al. 2014. Cenozoic tectonic subsidence in deepwater sags in the Pearl River Mouth Basin, northern South China Sea. *Tectonophysics*, 615–616: 182–198, doi: [10.1016/j.tecto.2014.01.010](https://doi.org/10.1016/j.tecto.2014.01.010)
- Yan Quanshu, Shi Xuefa, Castillo P R. 2014. The late Mesozoic-Cenozoic tectonic evolution of the South China Sea: a petrologic perspective. *Journal of Asian Earth Sciences*, 85: 178–201, doi: [10.1016/j.jseas.2014.02.005](https://doi.org/10.1016/j.jseas.2014.02.005)
- Yang Shengxiong, Qiu Yan, Zhu Benduo, et al. 2015. *Atlas of Geology and Geophysics of the South China Sea*. Tianjin: China Navigation Publications
- Zhang Bingkun, Li Sanzhong, Xia Zhen, et al. 2014. Distribution of

- Cenozoic igneous rocks and its relation to submarine geological hazards in the deepwater area of the northern South China Sea. *Haiyang Xuebao* (in Chinese), 36(11): 90–100
- Zhong Zhihong, Shi Hesheng, Zhu Ming, et al. 2014. A discussion on the tectonic-stratigraphic framework and its origin mechanism in Pearl River Mouth Basin. *China Offshore Oil and Gas* (in Chinese), 26(5): 20–29
- Zhou Di, Chen Hanzong, Wu Shimin, et al. 2002. Opening of the South China Sea by dextral splitting of the East Asian continental margin. *Haiyang Xuebao* (in Chinese), 76(2): 180–190
- Zhou Di, Hu Dengke, He Min, et al. 2008a. The selection of fitting curve in time-depth transformation of deep-seated strata and crust. *Earth Science-Journal of China University of Geosciences* (in Chinese), 33(4): 531–537, doi: [10.3799/dqkx.2008.067](https://doi.org/10.3799/dqkx.2008.067)
- Zhou Di, Sun Zhen, Chen Hanzong, et al. 2008b. Mesozoic paleogeography and tectonic evolution of South China Sea and adjacent areas in the context of Tethyan and Paleo-Pacific interconnections. *Island Arc*, 17(2): 186–207, doi: [10.1111/j.1440-1738.2008.00611.x](https://doi.org/10.1111/j.1440-1738.2008.00611.x)
- Zhou Di, Wang Wanyin, Wang Jialin, et al. 2006. Mesozoic subduction-accretion zone in northeastern South China Sea inferred from geophysical interpretations. *Science in China Series D*, 49(5): 471–482, doi: [10.1007/s11430-006-0471-9](https://doi.org/10.1007/s11430-006-0471-9)
- Zhu Weilin, Mi Lijun. 2011. *Atlas of Oil and Gas Basins, China Sea* (in Chinese). Beijing: Petroleum Industry Press, 1–316
- Zhu Weilin, Xie Xinong, Wang Zhenfeng, et al. 2017. New insights on the origin of the basement of the Xisha Uplift, South China Sea. *Science China Earth Sciences*, 60(12): 2214–2222, doi: [10.1007/s11430-017-9089-9](https://doi.org/10.1007/s11430-017-9089-9)