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RESEARCH PAPER

Distribution of the Mesozoic in the continental margin basins of the South China Sea and its petroliferous significance

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Abstract: Based on 40 wells encountering the Mesozoic sedimentary rocks, 52 thousands kilometers of seismic profiles covering most parts of the South China Sea (SCS) and the latest collection of gravity and magnetic data, the distribution of the Mesozoic in the continental margin of South China Sea and the oil and gas exploration prospect are studied. The Mesozoic is distributed in three main areas in the SCS: (1) the area of eastern Pearl River Mouth Basin and Southwest Taiwan Basin, where the Mesozoic buried at 1–3 km deep and 2–8 km thick, is thickest in the Chaoshan Depression and east Dongsha Uplift, and there is a long axis gentle fold in the east of the Pearl River Mouth Basin; (2) Liyue-Palawan Basin area, where the Mesozoic, 2–4 km deep and 2–5 km thick, is thickest in the south depression of the Liyue Basin; (3) Zhongjiannan-Wan'an-western Nanwei Basin area, where the Mesozoic is 3–5 km deep and 2–3 km thick. According to the spatial location relationship between the Mesozoic distribution and deep faults, it is inferred that the Mesozoic distribution is controlled by the eastern Yangjiang-Yitong Shoal fault, Balabac fault and YueDong-Wan'an fault, and affected by the uneven base uplifting and block faulting caused by the Mesozoic Pacific plate subduction to the East Asian continent. The study on the distribution of residual Mesozoic strata, structural traps and source rocks concludes that there are two favorable areas for the Mesozoic hydrocarbon exploration, namely, Chaoshan Depression and Dongsha Uplift in the east of Pearl River Mouth Basin, and south depression in the Liyue Basin. However, the exploration prospect of the Zhongjiannan-Wan'an-western Nanwei Basin area needs further investigation.

Key words: South China Sea; continental margin; Mesozoic; fold; source rock; petroleum prospect

Introduction

Since the 1990s, the Pre-Cenozoic residual basins, especially the Mesozoic residual basins in China, have drawn high attention from researchers in China [1-6] who all considered that the Mesozoic residual basins are a new domain and strategic replacement for oil and gas exploration in China's future. Because offshore oil and gas exploration in Chinese Pre-Cenozoic residual basins is very difficult, the exploration and geological research level there is low [1–2]. In view of this, we systematically collected the data of 40 wells encountering the Mesozoic and 2 trawl samples revealing the Mesozoic sedimentary rocks, and 52 thousands kilometer seismic data covering the whole South China Sea basin and gravity and magnetic data in a large scale. On the basis of previous research findings, and by processing, analyzing and interpreting drilling, trawling, seismic and gravity and magnetic data, we have examined the distribution range, depth and thickness of the Mesozoic in the South China Sea continental margins, and predicted favorable Mesozoic areas for oil and gas exploration according to the previous research of the Mesozoic source rocks and hydrocarbon conditions.

1 Basic data

There are 40 wells and 2 trawl samples encountering the Mesozoic sedimentary rocks in the South China Sea margin basins, which are mainly concentrated in Southwest Taiwan Basin, Pearl River Mouth Basin in the northern South China Sea, and Liyue Basin, Palawan Basin, and 52 thousands kilometers of seismic lines covering most of the South China Sea areas (Fig. 1, Tables 1 and 2).

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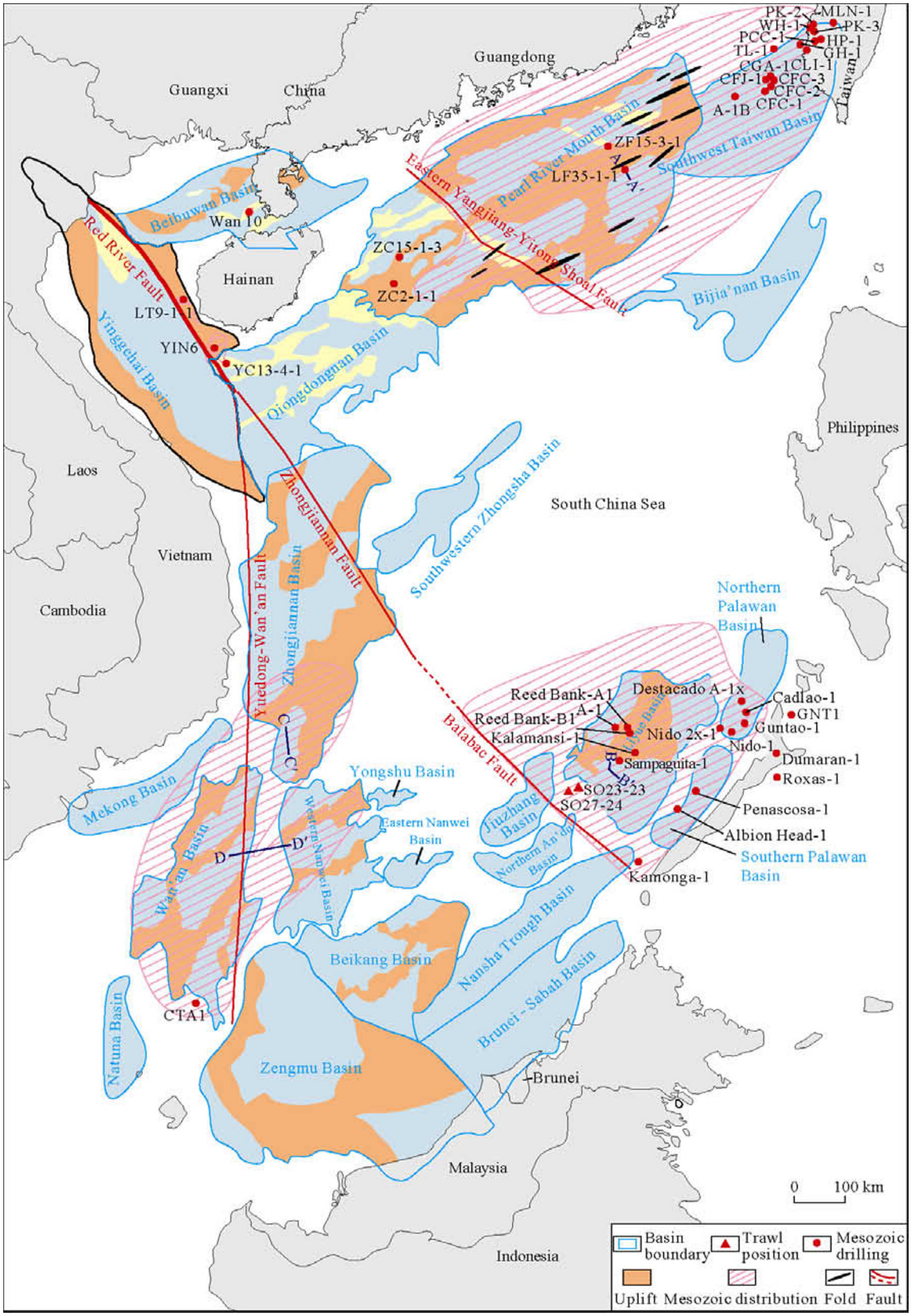

Fig. 1 Schematic diagram of South China Sea Basin and predicted Mesozoic distribution

Twenty-three wells drilled the Mesozoic in the northern marginal basins of South China Sea, including Beibuwan Basin, Yinggehai Basin, Qiongdongnan Basin, Pearl River Mouth Basin and Southwest Taiwan Basin (Table 1). The southern central marginal basins in South China Sea include over 10 basins like Wan'an Basin, Liyue Basin and Palawan Basin etc, where 17 wells and 2 trawl samples encounter the Mesozoic sedimentary rocks (Table 2). The Mesozoic deposits are mainly shale and conglomerate rocks, but also contain a small amount of limestone, mudstone, chert and claystone,

Table 1 Mesozoic lithology and period features revealed by drilling in the northern margin of the South China Sea

Basin name	Structural unit	Well name	Total depth/m	Thickness of Mesozoic/m	Lithology	Period	References
Beibuwan	Liusha Salient	Wan10	1 586.5	154.5	Red clastic rock	K	[7]
Yinggehai	Yingdong Slope	YIN6	1 768.0	732.0	Tuffaceous sandstone	K	[7]
	Central Depression	LT9-1-1	1 160.0	40.0	Continental facies red argillaceous sandstone, sandy mudstone	K	[4]
Qiongdongnan	Yacheng Salient	YC13-4-1	2 971.0	30.0	Feldspar quartz sandstone, argillaceous sandstone and conglomerate	Mz	[4]
Pearl River Mouth	Shenhu Uplift	ZC2-1-1	1 050.0	84.0	Sandstone, conglomerate, mudstone	Mz	
		ZC15-1-3	1 458.0	22.0	Middle-upper limestone, basal granite	Mz	
	Dongsha Uplift	ZF15-3-1	2 160.0	38.0	Massive sandstone	Mz	
	Chaoshan Depression	LF35-1-1	977.0	1 446.0	Mudstone, sandstone, radiolarian chert with limestone	J—K	[8-9]
Southwest Taiwan Basin	Cental Uplift	A-1B			Sandstone, mudstone, shale	K_1	[10]
		CFC-1	3 252.0	298.0	Sandstone, shale	J—K_1	[10]
		CFC-2			Marine sandstone and shale	K_1	[10]
		CFC-3			Sandstone, mudstone, shale	K_1	[10]
		CFJ-1			Marine sandstone and shale	K_1	[10]
		CGA-1			Marine sandstone and shale	K_1	[10]
		CLI-1	4 612.0	800.0	Limestone	K_1	[11]
		MLN-1	3 873.0	452.0	Shale, sandstone and siltstone, fine-grained sandstone	K_1	[10]
	Beigang Uplift	GH-1			Marine sandstone and shale	K_1	[12]
		HP-1	4 025.0	87.0	Sedimentary rock	K_1	[12]
		PCC-1			Marine sandstone and shale	K_1	[10]
		PK-2	1 590.0	530.0	Basal conglomerate, fine sandstone, shale	K_1	[12]
		PK-3	1 962.0	53.0	Tuffaceous sedimentary rock	K_1	[12]
		WH-1	1 425.0	1 534.0	Sandstone , shale and limestone	K_1	[12]
	Tong Liang	TL-1	2 959.0	44.0	Marine sandstone and shale	K_1	[10]

Table 2 Mesozoic lithology and period features revealed by trawl samples and drilling in the southern margin of the South China Sea

Basin name	Structural unit	Well name	Total depth/m	Thickness of Mesozoic/m	Lithology	Period	References
Wan'an	Southern Depression	CTA-1			Clastic rock	K	[13]
Liyue Basin and its adjacent areas	Central Uplift	Kalamansi-1	4 365.9		Siltstone	K	[14]
		Reed Bank-A1	2 776.1		Shallow marine clastic rock	K_1	[14]
		Reed Bank-B1	3 734.4		Shallow marine clastic rock	K_1	[14]
		Sampaguita-1	4 032.4		Sandstone and shale with thin limestone	K_1	[15]
	Northwest Depression	A-1	2 155.0		Clastic rock	K_1	[10]
	Southwest Reed Bank	SO23-23			Sandstone and siltstone, shale	T_3—J_1	[16]
		SO27-24			Siliceous shale	T_2	[16]
Palawan Basin and its adjacent areas		Albion Head-1	3 776.5		Clastic rock	K	[14]
		Cadlao-1	3 191.2		Tuffaceous sandstone, Sandy shale, sandstone	J_3—K_1	[14]
		Destacado A-1x	3 236.5		Calcareous silty shale, sandstone	K_1	[14]
		Dumaran-1	2 033.0		Sandstone , shale and siltstone	K_2	[14]
		GNT1			Limestone	J_3	[17]
		Guntao-1	2 235.1		Limestone	J_3—K_2	[14]
		Kamonga-1	1 635.3		Clastic rock	K	[14]
		Nido 2x-1	4 130.6		Limestone	K	[14]
		Nido-1	2 773.7		Shallow marine clastic rock	K_1	[14]
		Penascosa-1	4 207.2		Shale	K_1	[14]
		Roxas-1	1 912.1		Sandstone, shale and siltstone	K_2	[14]

which were mainly deposited in the Cretaceous, followed by the Jurassic and the Triassic.

2 Distribution and geophysical identification of the Mesozoic in the continental margin basins of South China Sea

We have identified four reflection interfaces and three structural layers (Figs. 2 and 3) in the Mesozoic on the seismic sections according to the comparative study of drilling profile and seismic profile. The four reflection interfaces are Cenozoic bottom interface (Tg), Cretaceous bottom interface (Tk), Jurassic bottom interface (Tj) and Mesozoic bottom interface (Tm). The three structural layers are Cretaceous structural layer (Tg-Tk), Jurassic structural layer (Tk-Tj) and Triassic structural layer (Tj-Tm).

2.1 Northern continental margin of South China Sea

The seismic section in Fig. 2 is located in the eastern Pearl River Mouth Basin, where Well LF35-1-1 encountered the Mesozoic of about 1500 m thick, which reveals that the middle Jurassic was in littoral-neritic sedimentary environments, the upper Jurassic was in deep see environments, the lower Cretaceous was in terrestrial deep transitional environments to humid continental environments and the upper Cretaceous was in drought, hot continental sedimentary environments[8,9]. Four reflection interfaces (Tg, Tk, Tj, Tm) and three structural layers (Tg-Tk, Tk-Tj, Tj-Tm) have been identified according to the stratigraphic data of Well LF35-1-1 and features of the seismic reflection section.

The top interface of Tg-Tk structural layer is a regional angular unconformity. This structural layer overlaps and truncates the underlying strata. The seismic reflection characteristics of the layer are middle to low frequency, medium-weak amplitude, medium - poor continuity, subparallel and wave-like reflection.

The top interface of Tk-Tj structural layer is a regional unconformity surface, which onlaps on the underlying strata. The seismic reflection characteristics of the layer are high frequency, high amplitude, good continuity, subparallel, and disorder reflection.

The top interface of Tj-Tm structural layer is an unconformity interface, while the bottom interface of the layer is a discontinuous wave impedance interface with toplap and truncation. The reflection characteristics of the layer are medium-low frequency, medium-weak amplitude, medium-poor continuity, subparallel, desultory and intermittently wave-like reflection.

Few faults and the developed broad folds are the main tectonic features of the Mesozoic in the northeast of the South China Sea, and they are an important sign to distinguish from the Cenozoic. The subduction of the Pacific plate to the Eurasian plate led to the regional compression of the Pearl River Mouth Basin in the Late Cretaceous, giving rise to a series of NE-trending broad and gentle folds. The angular unconformity interface Tg reflects uplift and denudation. The Mesozoic on seismic profiles is shown as parallel to subparallel and continuous reflection, with low reflection frequency, poorer continuity than the Cenozoic. The reflection is stable over a large scope, with local onlap and downlap. The Mesozoic is in angular unconformity with the Cenozoic.

2.2 Southern continental margin of South China Sea

The seismic profile in Fig. 3 is located in the south de-

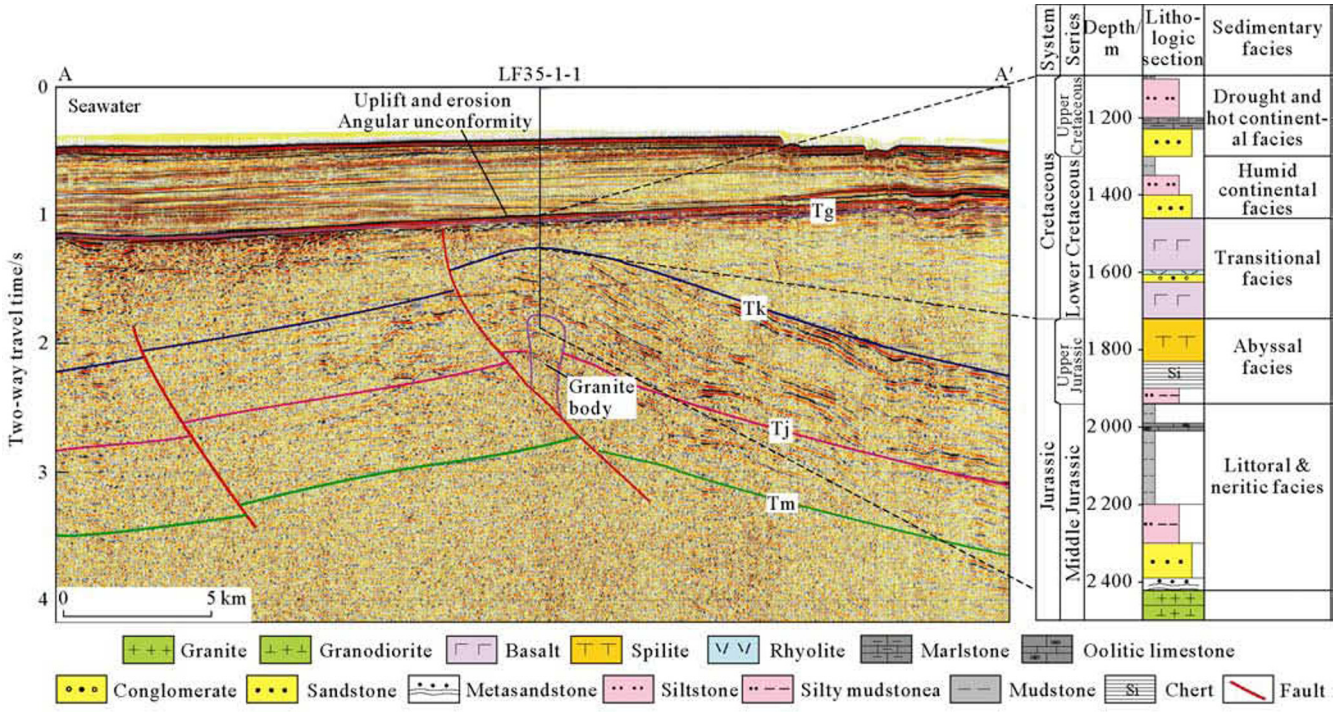

Fig. 2 Seismic reflection characteristics of Mesozoic in Pearl River Mouth Basin (Location of the section is shown in Fig. 1. Drilling histogram is from references [8,9])

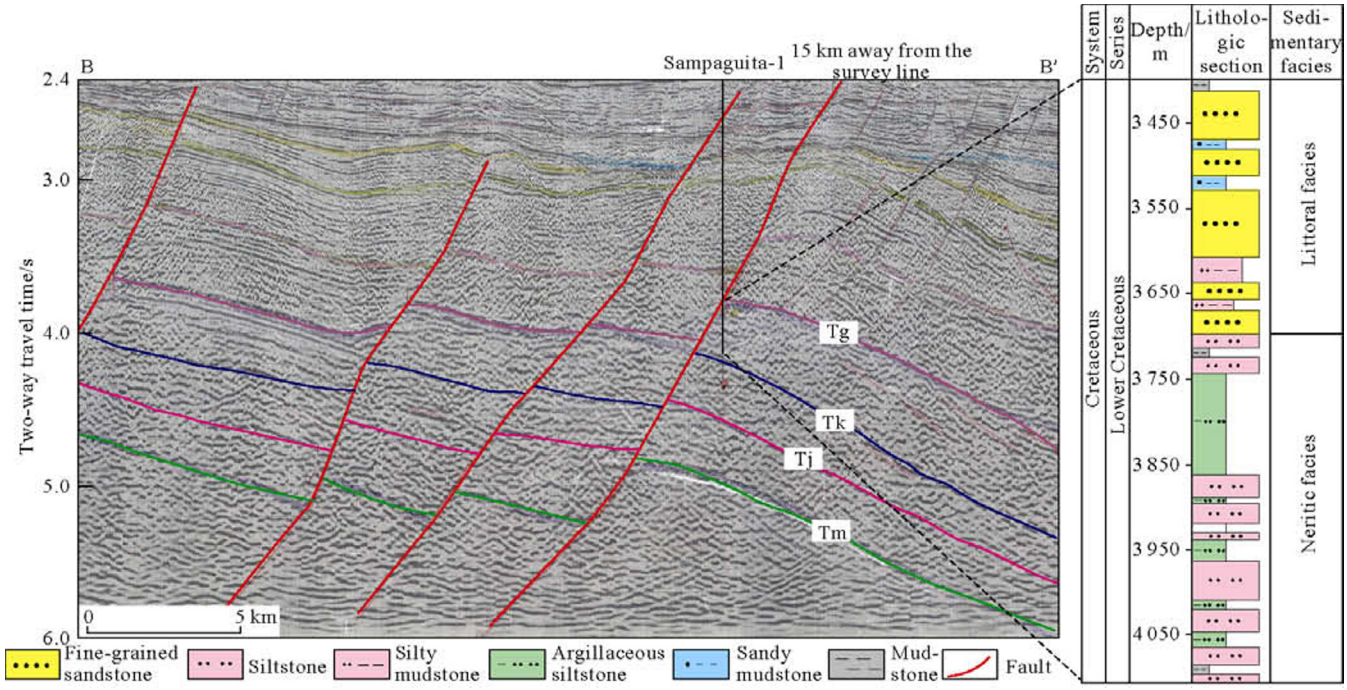

Fig. 3 Seismic reflection characteristics of Mesozoic in Liyue Basin (Location of the section is shown in Fig. 1. Drilling histogram according to reference [15])

pression of Liyue Basin, the lower Cretaceous was revealed in Well Sampaguita-1 drilled 15 km distance to the northeast of the seismic profile, indicating that the area was in a littoral shallow sea environment in the early Cretaceous, while the upper Cretaceous was missing [15]. We have identified four reflection interfaces (Tg, Tk, Tj, Tm) and three structural layers (Tg-Tk, Tk-Tj, Tj-Tm) on the seismic section according to the stratigraphic data of Well Sampaguita-1 and the trawl outcrop data of adjacent regions and the reflection characteristics on seismic section.

The top interface of Tg-Tk structural layer is an angular unconformity surface, while truncation can be seen on its bottom interface. The upper Cretaceous is seriously denuded. The seismic reflection characteristics inside the layer are featured by low frequency, medium-weak amplitude, medium-poor continuity, some disorder reflection, and stable thickness. Seismic facies show big dip and distorted parallel reflection structure.

The top interface of Tk-Tj structural layer is an angular unconformity surface, while the bottom interface of the layer has truncation. The seismic reflection characteristics inside the layer are medium frequency, medium-high amplitude, medium continuity, subparallel and disorder reflection.

The top interface of Tj-Tm structural layer is an angular unconformity surface, while the bottom interface of the layer is a discontinuous wave impedance interface. The seismic reflection characteristics inside the layer are medium-low frequency, medium-weak amplitude, medium-poor continuity, subparallel and disorder reflection.

Dipping south-southeast on the whole, the Mesozoic is tilted by a series of reverse extensional Cenozoic normal faults.

Since there is no drilling data to be correlated in the Zhongjiannan-Wan'an-Western Nanwei basins and their adjacent sea areas, the specific sedimentary period of the strata cannot be confirmed, so the study of the Mesozoic there mainly relies on the seismic data. Most of the seismic sections cannot show internal structural layers of the Mesozoic, but can tell the massive Mesozoic clearly (Figs. 4 and 5).

The Mesozoic is unconformable contact with its overlying Cenozoic according to the characteristics of seismic reflection in the south of the Zhongjiannan Basin and Wan'an Basin, its bottom interface with truncation is an obvious discontinuous wave impedance interface. The seismic reflection characteristics inside the layer are medium-low frequency, medium-weak

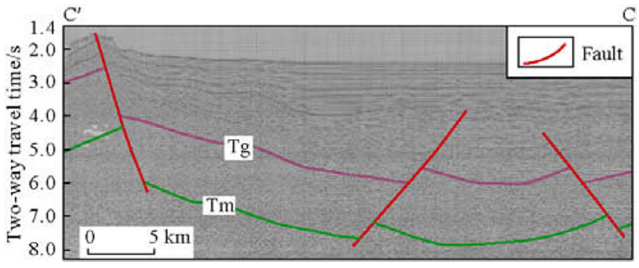

Fig. 4 Seismic reflection characteristics of the Mesozoic in the Zhongjiannan Basin (Location of the section is shown in Fig. 1)

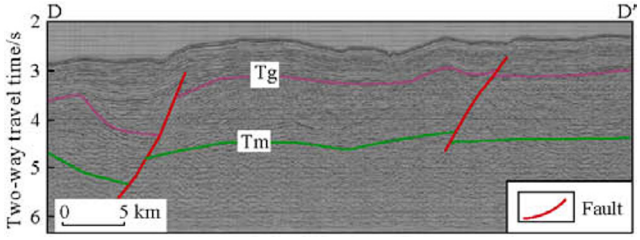

Fig. 5 Seismic reflection characteristics of the Mesozoic in the Wan'an Basin (Location of the section is shown in Fig. 1)

amplitude, intermittent and local continuity reflecting layers, with parallel-subparallel reflection (Fig. 4).

On seismic facies, the sequence layer under the Cenozoic show features such as weak fold deformation, high frequency, medium-weak amplitude, medium continuity, stable thickness, and oblique layer form in the Western Nanwei Basin, which is speculated to be the Mesozoic and the stratification in local structural layers is good (Fig. 5).

2.3 Distribution characteristics of the Mesozoic at the continental margin of the South China Sea Basin

Based on comprehensive interpretation of drilling, trawl sampling, seismic, gravity and magnetic data and Mesozoic stratigraphic correlation, we infer that the Mesozoic at the continental margin of the South China Sea Basin is mainly distributed in three areas (Fig. 1):

(1) Eastern Pearl River Mouth Basin to Southwest Taiwan Basin. The Mesozoic is mainly distributed in Zhu I depression, most of the Zhu II depression, Chaoshan depression, northern uplift, Panyu low uplift, Dongsha uplift and the east of southern uplift east of eastern Yangjiang-Yitong shoal fault in the Pearl River Mouth Basin, and in the central uplift belt, Beigang uplift in Southwest Taiwan Basin. Broad long axis folds are developed well in eastern Pearl River Mouth Basin. The Mesozoic in this area, buried at about 1 to 3 km deep and about 2 to 8 km thick, is thickest in Chaoshan depression and the east of Dongsha uplift.

(2) Liyue Basin to Palawan Basin. The Mesozoic is mainly distributed in Liyue Basin, north of Jiuzhang Basin, south of north Palawan Basin, south Palawan Basin and their adjacent sea areas. In this belt, the Mesozoic, about 2 to 4 km deep, and 2 to 5 km thick, is thickest in the south depression in Liyue Basin.

(3) Zhongjiannan-Wan'an-Western Nanwei basins. The Mesozoic is mainly distributed in the southern upwarping folded zone in Zhongjiannan Basin, Wan'an Basin, the north uplift of Western Nanwei Basin, the central depression of Western Nanwei Basin, the west to central depression of Western Nanwei Basin. There the Mesozoic is about 3 to 5 km deep, and 2 to 3 km thick.

Based on the analysis of the Mesozoic distribution areas and basement fault location, it is inferred that the stratigraphic distribution is controlled by the eastern Yangjiang-Yitong Shoal fault, Balabac fault and Yuedong – Wan'an fault. The distribution of Mesozoic is scattered in Pearl River Mouth Basin, Yinggehai Basin and Beibuwan Basin west of the eastern Yangjiang-Yitong Shoal fault, and the upper Cretaceous is missing in Liyue Basin of Nansha region, which are related to uneven uplift of the basement and block faulting caused by Pacific plate subduction to East Asian continent in the Mesozoic.

3 Source rock conditions and petroleum geological significance

Synthesizing the previous studies on Mesozoic petroleum geology of the South China Sea, we collected the geochemical data of hydrocarbon source rocks of different Mesozoic strata in Southwest Taiwan Basin, Pearl River Mouth Basin, Liyue Basin, Mindoro Island and southeastern China (Table 3), and compared them with Mesozoic source rocks in sea areas, which lead us to the conclusion that the Mesozoic in South China Sea has moderate - good potential of gas generation. Lower Cretaceous black shales and mudstones are a major suite of source rock in which organic matter is dominated by type III kerogen with high thermal evolution degree. The Upper Triassic - Lower Jurassic source rocks are higher in TOC and high in maturity, but over-mature in most areas.

In the late Mesozoic, the Pearl River Mouth Basin region underwent major uplift and erosion, which led to the different preservation degrees of the Mesozoic strata, but still well-developed thick dark shale. In the eastern Pearl Mouth River Basin, the broad and gentle folds formed a series of anticlines and faulted anticlines, which provide good conditions for hydrocarbon accumulation. Through the comprehen-

Table 3 Hydrocarbon parameters of Mesozoic sedimentary rocks in South China Sea and adjacent areas

Strata	Area	Sedimentary facies	*TOC*/%	R_o/%	Kerogen type
Cretaceous	Guangdong Province	continental facies	0.7–1.0	0.92	Mainly type III, minor type II_2
	Peng Chau Island, Hongkang	continental facies—littoral facies	0.88–4.26	1.11	
	Southwest Taiwan Basin	littoral facies	0.60–0.95, max: 2.5	0.6–1.0	type III
	Chaoshan Depression	fluvial—lacustrine facies	0.05–0.54	>2.0	type III mainly, minor type II_2
	Liyue Basin	neritic facies	1.5–2.0	1.0–2.5	type III
Jurassic	Guangdong Province	littoral-neritic facies	0.5–2.0	2.69–3.75	type III
	Chaoshan Depression	littoral-neritic facies	0.50–1.48	>2.0	type III mainly, minor type II_2
	Southwest Taiwan Basin	littoral-neritic facies	0.6–1.8	1.00–1.38	type III
Triassic	Guangdong Province	littoral-neritic facies	0.35–6.75	1.11–1.59	type III
	Mindoro Island	neritic—bathyal facies		0.54–0.88	type III
	Liyue Basin	littoral-neritic facies		1.0–2.5	type III

Note: the data is from references [7, 20-24].

sive analysis of Mesozoic thickness, source rocks conditions and structural traps, we predicted that Chaoshan depression, eastern Dongsha uplift and the junction of Dongsha uplift-Huilu low uplift-Lufeng sag are favorable oil and gas exploration areas of the Mesozoic [19].

The source rocks in Liyue Basin have mainly type III organic matter, and high hydrocarbon maturity, and medium-high hydrocarbon potential. Multiple wells reveal upper Jurassic-lower Cretaceous marine clastic, mainly sandstone and shale in northern Liyue Basin, and limestone found in the southern. The lithology in the southeastern margin of the basin is mainly middle Triassic bathyal siliceous shales and upper Triassic-Lower Jurassic deltaic sandstone and siltstone. Affected by regional faults, the Mesozoic in Liyue Basin is changed greatly in distribution and thickness. Southern depression, where the Mesozoic is most developed, is also the most favorable area of oil and gas exploration in Liyue Basin.

Lack of drilling data, the type of organic matter is not yet conclusive in the Zhongjiannan-Wan'an-Western Nanwei Basin area. The Mesozoic can only be identified on seismic profiles, and the exploration prospect needs further investigation.

4 Conclusions

The comprehensive study shows that there are three main distribution areas of the Mesozoic strata in the South China Sea Basin: (1) the eastern part of Pearl River Mouth Basin and Southwest Taiwan Basin, where the Mesozoic is mainly distributed in Zhu I Depression, most part of Zhu II Depression, Chaoshan Depression, North uplift, Panyu low uplift, Dongsha uplift in Pearl River Mouth Basin, and central uplift, Beigang uplift in Southwest Taiwan Basin. In addition, broad and gentle folds are developed in the eastern Pearl Mouth River Basin; (2) Liyue-Palawan Basin area, where the Mesozoic is mainly distributed in Liyue Basin, northern Jiuzhang Basin, Southern north Palawan Basin, south Palawan Basin and its adjacent areas; (3) Zhongjiannan-Wan'an-Western Nanwei Basin area, where the Mesozoic is distributed primarily in southern fold belt of Zhongjiannan Basin, Wan'an Basin and northern uplift, central Depression and western central uplift of Western Nanwei Basin. The Mesozoic is mainly distributed in the three areas andsporadic in the west of Pearl River Mouth Basin, Yinggehai Basin, North Bay Basin, and the upper Cretaceous is missing in Liyue Basin,which are related to uneven base uplift and block faulting caused by Mesozoic Pacific plate subduction to the East Asian continent. Based on the distribution of the residual Mesozoic strata, structural traps and source rocks, we consider that there are two favorable areas of Mesozoic hydrocarbon exploration, Chaoshan Depression and east Dongsha Uplift in Pearl River Mouth Basin, and south depression in Liyue Basin. In contrast, the exploration prospect of the Zhongjiannan-Wan'an-Western Nanwei Basin area needs further investigation.

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