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Texture and tectonic attribute of Cenozoic basin basement in the northern South China Sea

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Based on the drilling data, the geological characteristics of the coast in South China, and the interpretation of the long seismic profiles covering the Pearl River Mouth Basin and southeastern Hainan Basin, the basin basement in the northern South China Sea is divided into four structural layers, namely, Pre-Sinian crystalline basement, Sinian-lower Paleozoic, upper Paleozoic, and Mesozoic structural layers. This paper discusses the distribution range and law and reveals the tectonic attribute of each structural layer. The Pre-Sinian crystalline basement is distributed in the northern South China Sea, which is linked to the Pre-Sinian crystalline basement of the Cathaysian Block and together they constitute a larger-scale continental block—the Cathaysian-northern South China Sea continental block. The Sinian-lower Paleozoic structural layer is distributed in the northern South China Sea, which is the natural extension of the Caledonian fold belt in South China to the sea area. The sediments are derived from southern East China Sea-Taiwan, Zhongsha-Xisha islands and Yunkai ancient uplifts, and some small basement uplifts. The Caledonian fold belt in the northern South China Sea is linked with that in South China and they constitute the wider fold belt. The upper Paleozoic structural layer is unevenly distributed in the northern South China. In the basement of Beibu Gulf Basin and southwestern Taiwan Basin, the structural layer is composed of the stable epicontinental sea deposit. The distribution areas in the Pearl River Mouth Basin and the southeastern Hainan Basin belong to ancient uplifts in the late Paleozoic, lacking the upper Paleozoic structural layers. The stratigraphic distribution and sedimentary environment in Middle-Late Jurassic to Cretaceous are characteristic of differentiation in the east and the west. The marine, paralic deposit is well developed in the basin basement of southwestern Taiwan but the volcanic activity is not obvious. The marine and paralic facies deposit is distributed in the eastern Pearl River Mouth Basin basement and the volcanic activity is stronger. The continental facies volcano-sediment in the Early Cretaceous is distributed in the basement of the western Pearl River Mouth Basin and Southeastern Hainan Basin. The Upper Cretaceous red continental facies clastic rocks are distributed in the Beibu Gulf Basin and Yinggehai Basin. The NE direction granitic volcanic-intrusive complex, volcano-sedimentary basin, fold and fault in Mesozoic basement have the similar temporal and spatial distribution, geological feature, and tectonic attribute with the coastal land in South China, and they belong to the same magma-deposition-tectonic system, which demonstrates that the late Mesozoic structural layer was formed in the background of active continental margin. Based on the analysis of basement structure and the study on tectonic attribute, the paleogeographic map of the basin basement in different periods in the northern South China Sea is compiled.

northern South China Sea, basin basement, structural layer, tectonic attribute

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The distribution range of the northern South China Sea studied in this paper is located in 15°30′–26°00′N, 107°–122°E sea area and the research focuses on the Cenozoic basin basement of southwestern Taiwan, Pearl River mouth, southeastern Hainan, Beibu Gulf, and Yinggehai (Figure 1). Since the beginning of the 1980s, using the method of comprehensive analysis of geophysical data, drilling core and comparison between the sea area and the land area, some geologists have studied the tectonic attribute of the basin basement in succession and divided the basin basement into the Precambrian folded basement, Caledonian folded basement, Hercynian-Indochina folded basement, and Yanshan folded basement in chronological order (Wang et al., 1992; Liu and Zhan, 1994; Liu et al., 2002). Using gravity and magnetic interpretation, Wang et al. (2002) divided the Pearl River Mouth Basin into the west and the east, the west of which is the distribution area of Paleozoic metamorphic rocks and the extension of Caledonian and Hercynian fold belt in South China to the sea area, and the east of which is the distribution area of Mesozoic intermediate-acid magmatic rocks and sedimentary rocks. Based on the geophysical interpretation and the comparison with land, Zhou et al. (2006) believed that the west section of Pre-Cenozoic basin basement in the northern South China Sea belongs to Caledonian fold belt, the middle and the east sections of which belong to Yanshan fold belt, composed of the Cretaceous granites, but Jurassic(?)-Early Cretaceous marine deposit is well developed in the Southwestern Taiwan Basin. He et al. (2008) divided the Pearl River Mouth Basin and Southwestern Taiwan Basin basement into the northwestern Caledonian folded basement, central Hercynian-Indochina folded basement, and southeastern Yanshan folded basement and also believed that Beibu Gulf Basin basement belongs to the extension of Yunkai block to the sea area. The Yinggehai Basin basement is composed of the fold belt between Indochina block and Cathaysian block and

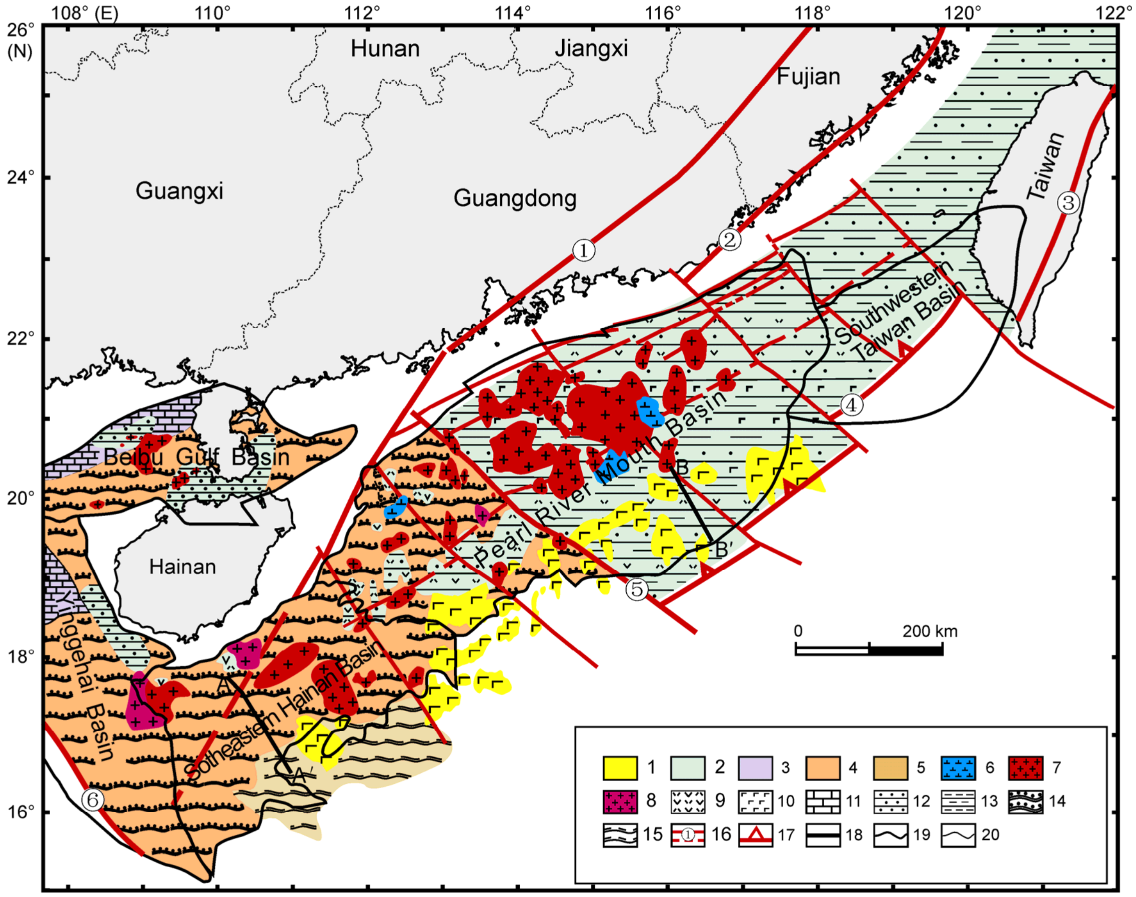

Figure 1 Geological map of the basin basement in the northern South China Sea (after Lu et al., 2011b; Zhou et al., 2002; 2006; Xu, 1988[1)]). 1. Cenozoic; 2. Mesozoic; 3. upper Paleozoic; 4. Sinian-lower Paleozoic; 5. Pre-Sinian crystalline basement; 6. Cretaceous diorite; 7. Cretaceous granite; 8. Triassic-Jurassic granite; 9. intermediate-acid volcanic rock; 10. basalt; 11. carbonate rock; 12. sandstone; 13. mudstone; 14. low-grade metamorphic sandstone and conglomerate; 15. gneiss; 16. measured /speculated fault; 17. Mesozoic subduction zone; 18. seismic profiles; 19. basin boundary; 20. land boundary. ① Lianhuashan fault; ② Changle-Nan'ao fault; ③ huge canyon fault of eastern Taiwan; ④ Mesozoic subduction zone in the northern South China Sea; ⑤ Yangjiang-Yitong shoal fault; ⑥ western edge fault in Yinggehai Basin.

1) Xu Y X. 1988. The basin basement speculate figure of the Beibu Gulf Basin.

Southeastern Hainan Basin basement is composed of the Precambrian crystalline basement, Paleozoic, and Mesozoic.

In the basin basement study, academia and the oil companies pay more attention to the Mesozoic residual basins. Many scholars conducted special studies on paleontology, formation, lithofacies paleogeography, magmatic rocks, fracture, and hydrocarbon generation capacity of the Mesozoic basement (Matsumoto et al., 1965; Mastumoto, 1979; Huang, 1978; Wu et al., 2007; Su et al., 1995; Wang et al., 2000; Yang et al., 2002; Wang et al., 2002; Hao et al., 2004, 2009a; Zhou, 2002; Zhou et al., 2005a; Zhou and Yao, 2009; Shao et al., 2007; Zhong et al., 2007, 2011; Pang et al., 2007; Gong et al., 1997; Li et al., 1998; He et al., 2008) and obtained a series of important results. In recent years, some scholars proposed that the Mesozoic residual basins in the deep water area of the northern South China Sea are the new important area of oil and gas exploration (Liu et al., 1999; Liu, 2011; Yang et al., 2002; Cai et al., 2004; Zhang et al., 2011; Liu and Liu, 2011), which highlights the importance of the basement study. On the basis of comprehensive study on strata, lithology, metamorphism, and lithofacies paleogeography, the previous researchers also compiled the geological map of the basin basement in the northern South China Sea (Wang et al., 1992; Pang et al., 2007; Lu et al., 2011b) and studied the Pre-Cenozoic tectonic evolution of the South China Sea (Zhou et al., 2005a, 2005b; Metcalfe, 2006, 2011). These results have laid a good foundation and broadened the research for the further study of the basin basement.

However, due to the factors of buried depth of the basement, the drilling depth into the basement, and the seismic acquisition and the processing technique for physical parameters, the basement nature and its structural and stratigraphic distribution are unclear (Zhu et al., 2012). For example, is there any Precambrian crystalline basement in the Pearl River Mouth Basin, Southwestern Taiwan Basin, Beibu Gulf Basin, and Yinggehai Basin? How large is the distribution range of Sinian to lower Paleozoic structural layers in the northern South China Sea? Where is the sediment derived? Is the upper Paleozoic structural layer widely distributed? Is it composed of low-grade metamorphosed Hercynian fold belt with flysch formation feature or is it composed of unmetamorphosed, neritic facies sedimentary rocks? What are the characterization and distribution law of the Mesozoic strata, sedimentary facies, magmatic rock, and structure? What are the genetic connections between each structural layer in the basin basement and Cathaysian block? These unanswered questions have directly hampered the study on the division of the structural layer, the determination of the tectonic attribute of the basin basement, the constraint of the basement on the Cenozoic basin, and the hydrocarbon prospect evaluation.

We selected the stratigraphic section of different ages in Guangdong and Fujian coasts, Hainan and Taiwan of China, and northern Vietnam for observation, collected more than 500 rock samples that may appear in the basin basement, determined the density and magnetic susceptibility, established various lithology densities-magnetic susceptibility intersection plate, and completely collected, and sorted out lithology, dating data, and geophysical data of the basin basement in more than 180 drillings into each basin basement. By using the seismic-gravity and magnetic interpretation method constrained by basin margin geological characteristics and the basin drilling data, we comprehensively interpreted about the 104 strips of geological and geophysical contiguous seismic profiles of 2.1×10^4 km in length and gravity and magnetic data covering the entire Pearl River Mouth Basin and Southeastern Hainan Basin. Meanwhile, using the previous drilling data, we put the constraint on the basement structure and composition in the Southwestern Taiwan Basin, Beibu Gulf Basin, and eastern Yinggehai Basin. On the basis of the above, the whole basin basement texture in the northern South China Sea is divided into four structural layers, the distribution range and the law of each structural layer are discussed, and the attributes of each structural layer are revealed. At the same time, paleogeographic maps (Figure 2) of the basin basement of different period in the northern South China Sea are compiled, which lays a good foundation of investigating the influence of the basement on the hydrocarbon generation, accumulation, and distribution law.

The basin basement texture in the northern South China Sea is divided into four structural layers in chronological order, namely, the Pre-Sinian crystalline basement, Sinian to lower Paleozoic, upper Paleozoic, and Mesozoic structural layers, which are composed of the different sedimentary facies or metamorphic grade rocks and the layers possess different structure attributes.

1 The tectonic attribute of the Pre-Sinian crystalline basement

The granitic gneiss, gneiss, and gneissic granite were drilled in 1279–1384.6 m of Xiyong drilling 1 in the Xisha sea area, the Rb-Sr isochron age of granitic gneiss is 1465 Ma (Qin, 1987). On the basis of the gravity and magnetic anomalies, He (1987) and Liu et al. (1994) identified that the Proterozoic crystalline basement exists in the Zhongsha and Xisha islands. Based on the new magnetic data and the anomalies of magnetic basement, Hao et al. (2009b) believed that Zhongsha and Xisha areas are the long-term uplift areas composed of the Precambrian metamorphic basement. At present, some scholars limited the distribution area of the Precambrian crystalline basement to the southern edge of the Hainan island, the Southeastern Hainan Basin, the Zhongsha and Xisha islands, and the Kontum in Vietnam and believed that the Precambrian crystalline basement belongs to residual fragments of the ancient South China Sea-Kontum block (He et al., 1987; Wang et al., 1992; Yao et al.,

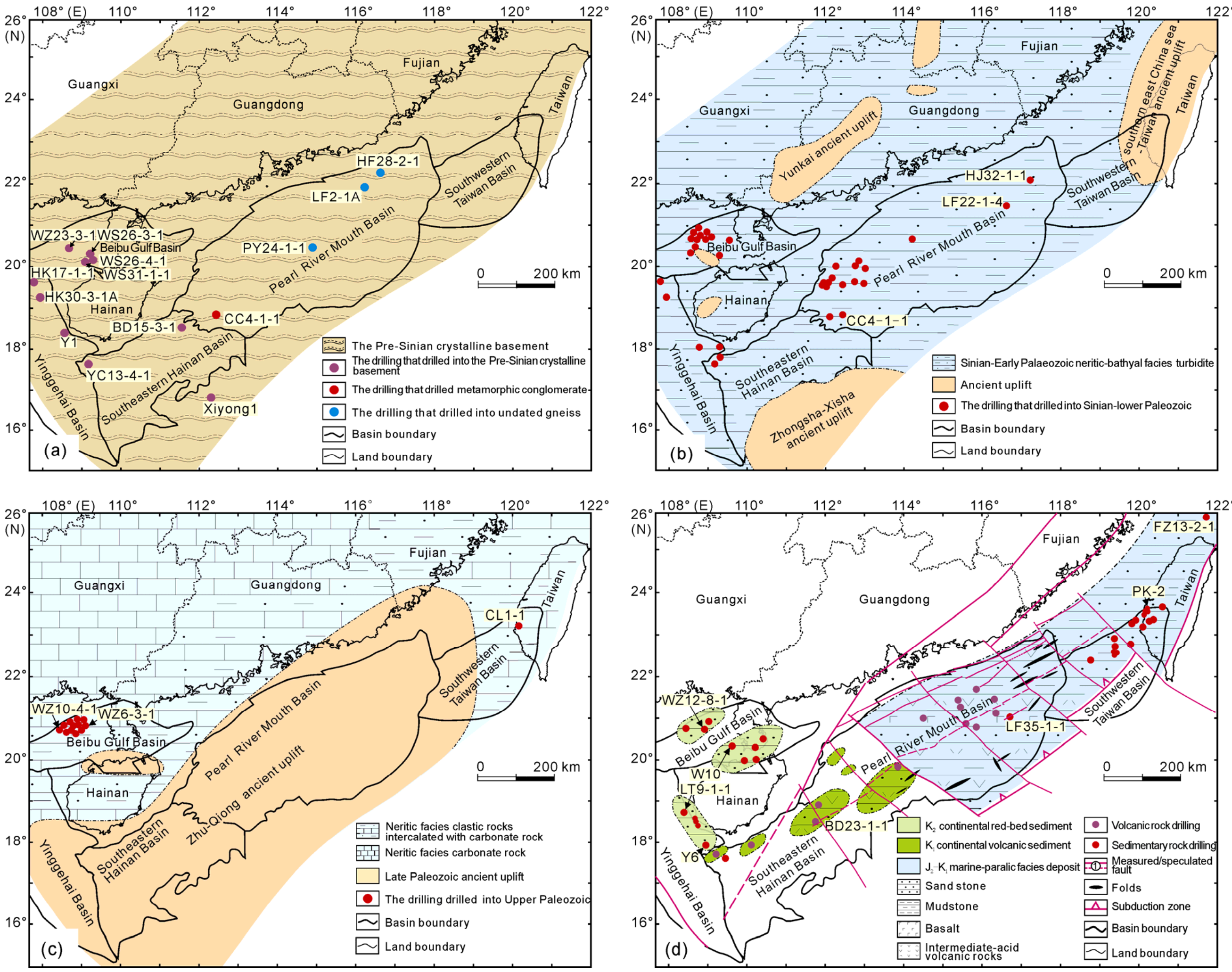

Figure 2 Paleogeographic map in different periods of basin basement in the northern South China Sea. (a) Paleogeographic map in Pre-Sinian; (b) lithofacies-paleogeographical map in early Paleozoic; (c) lithofacies-paleogeographical map in late Paleozoic; (d) tectonic paleogeographical map in Mesozoic.

2006; He, 2008). However, there is no systematic study on whether there exists the Pre-Sinian crystalline basement in the Beibu Gulf Basin, Yinggehai Basin, and Pearl River Mouth Basin. We have checked almost all of drilling data on the basement in the study area[2)] and found the important information that can prove the existence of the Pre-Sinian crystalline basement. In the drillings of HK17-1-1 and HK30-3-1A in the Yinggehai Basin, granite- gneiss was drilled under the quartzite and metamorphic sandy conglomerate of the Sinian to lower Paleozoic, which accurately demonstrates the superposed relationship of the two upper and lower structural layers (Figure 2(a)). In the drillings of WZ23-3-1, WS31-1-1, and WS26-4-1 in the Beibu Gulf Basin, granite-gneiss was drilled. In the drilling of WS26-3-1, gneiss with augen structure rich in pyroxene was drilled, which is composed of mica, quartz, and feldspar (mica schist was named in the original log report). In the drillings of WZ22-3-1 and WZ22-2-1 close to the north and south sides of WZ23-3-1 drilling, low-grade metamorphic rocks in the lower Paleozoic were drilled, which indicates that the gneiss is located under the Sinian to lower Paleozoic. In the drilling of CC4-1-1 in the Pearl River Mouth Basin (Figure 2(a)), the lowest part of metamorphic conglomerate in the Sinian to lower Paleozoic contains gneiss gravels, which illustrates this drilling is close to the Zhongsha and Xisha block, and the Pre-Sinian crystalline basement in Zhongsha and Xisha probably extends under the Pearl River Mouth Basin. In the drilling of BD15-3-1 in the Southeastern Hainan Basin, the low-grade metamorphic rocks were drilled on the top part of the basement and variegated metamorphic rocks are under it. The cuttings in YC13-4-1 drilling contain both the low-grade metamorphic slate and

2) The drilling data in this paper are quoted from *The Basic Data Manual of China National Offshore Oil Wells* by Xu Qingmei, Research Center of China National Offshore Oil Co., Ltd., 2008. 1–60.

the medium high grade metamorphic gneiss, which indicates the existence of the two structural layers. The two drillings are located between the Hainan island and Xisha islands, which provides the important information for the interconnection of the Pre-Sinian crystalline basement under the Southeastern Hainan Basin in both areas. In Lingfeng drilling 1 in the East China Sea adjacent to the northern South China Sea, the Rb-Sr isochron age of biotite amphibole plagioclase gneiss drilled is 1680 Ma (Liu, 1988). In addition, the data of seismic and gravity-magnetic inversion also reveal the existence of the Proterozoic ancient uplift in the southern East China Sea (Li et al., 2012). These sea area drilling data indicate that the Pre-Sinian crystalline basement is distributed in many parts of the northern South China Sea. It should be noted that although the previous researchers obtained gneiss in the drillings of HF28-2-1, LF2-1A, and PY24-1-1 in the Pearl River Mouth Basin, at present, we cannot distinguish whether it is the product of the Pre-Sinian crystalline basement or tectonometamorphism in late stage, due to the lack of the high precision dating or the basis of the stratigraphic sequence.

In the Pearl River Mouth Basin, there is yet no drilling that can accurately drill into the Pre-Sinian crystalline basement, and we can only make inferences by geophysical methods. However, because the buried depth of the basement, the poor quality of seismic reflection data, the severe damage to the basement structure caused by the magmatic intrusion, and superimposed effects of the strong magnetic field caused by granites and volcanic rocks on the basement magnetic field, it is difficult for us to identify the basement structure and the material composition. Although we adopt the seismic data collected and processed in recent years by China National Offshore Oil Corporation and the quality of the deep seismic reflection data is improved, we still can roughly identify that there exists the Pre-Sinian crystalline basement in the Southeastern Hainan Basin and the southern uplift of the Pearl River Mouth Basin (Figures 3, 4). Based on the magnetic anomaly, Wang et al. (2002) identified the magnetosphere was deeply buried in 11–14.5 km in the southern Dongsha islands, the northern and southern Yitung shoal uplift and the southeastern Hainan island and believed that its main part is the reflection of the metamorphic magnetic basement. Based on the latest gravity and magnetic data in the South China Sea, Hao et al. (2011) speculated that there exist the Precambrian bedrock and the magmatic rock uplift between the southern uplift area and the central basin in the South China Sea. From one side, these gravity and magnetic interpretations corroborate the probability of the existence of the Pre-Sinian crystalline basement in the Southeastern Hainan Basin and the southern Dongsha uplift in the Pearl River Mouth Basin. Due to the invasion of a huge amount of granite (Figure 1), the original basement structure was damaged in the northwestern Dongsha uplift. At present, its main behavior is volcanic arc of late Mesozoic with high magnetic anomaly zone (Zhou et al., 2006). Using seismic and gravity-magnetic research method, the previous

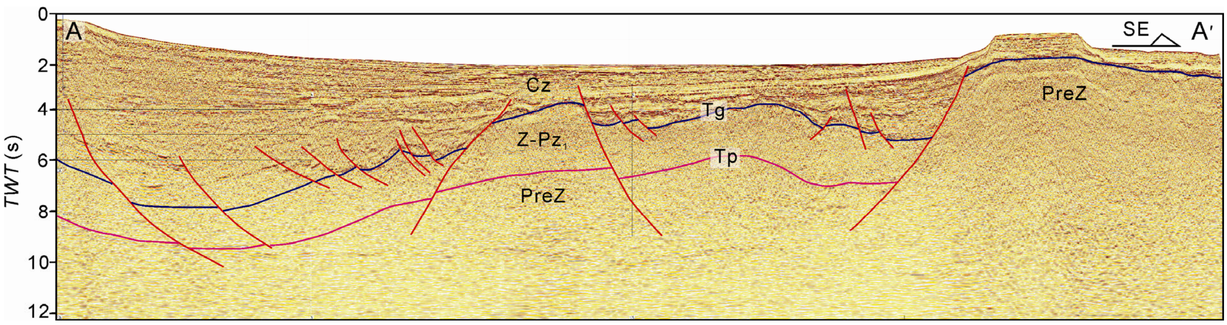

Figure 3 The interpretation for the basement structural layers of A-A′ seismic profile in Southeastern Hainan Basin. The profile location is seen in Figure 1. PreZ, Pre-Sinian crystalline basement; Z-Pz$_1$, Caledonian fold belt; Cz, Cenozoic; Tp, Sinian bottom boundary; Tg, Cenozoic bottom boundary.

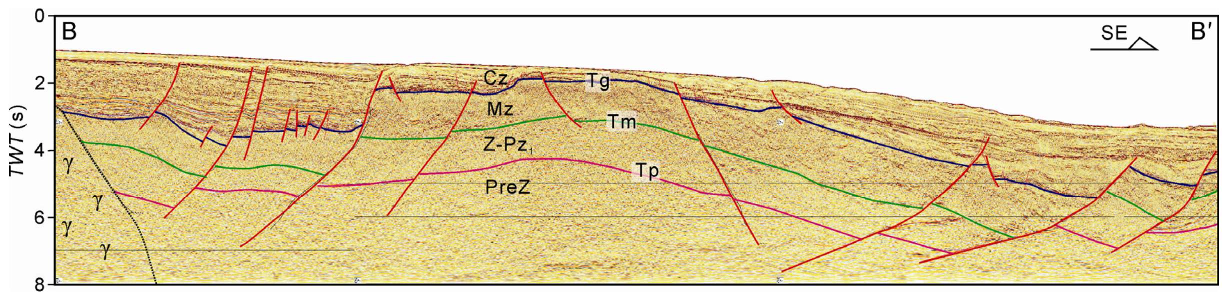

Figure 4 The interpretation for the basement structural layers of B-B' seismic profile in Pearl River Mouth Basin. The profile location is seen in Figure 1. PreZ, The Pre-Sinian crystalline basement; Z-Pz$_1$, Caledonian fold belt; Mz, Mesozoic; Cz, Cenozoic; Tp, Sinian bottom boundary; Tm, Mesozoic bottom boundary; Tg, Cenozoic bottom boundary.

researchers identified the Proterozoic relicts separated by granite in Zhu 1 depression (Lu et al., 2011a). Although the Cathaysian block was invaded and reformed by a huge amount of granite in Hercynian, Indochina, and Yanshanian epochs, it was a whole block in Proterozoic with the uniform crystalline basement (Shu, 2012). Taking all the above factors into consideration, we speculate that the Pre-Sinian crystalline basement probably exists in the northwestern Pearl River Mouth Basin, but it is severely damaged and reformed by the Mesozoic granite.

The above drillings and the data of seismic reflection and gravity-magnetism preliminarily reveal that the Pre-Sinian crystalline basement is widely distributed in the basement of the Yinggehai Basin, Beibu Gulf Basin, Southeastern Hainan Basin, and Southwestern Taiwan Basin. According to the information of the southern East China Sea and the Taiwan Pre-Sinian crystalline basement, it is speculated that the structural layer is probably distributed in the southwestern Taiwan Basin basement. To the south, the structural layer is linked to the Zhongsha-Xisha block and constitutes a larger-scale continental block in the sea area, namely, the northern South China Sea block.

Apart from the sea area data, the abundant isotope evidence of the Pre-Sinian crystalline basement has been accumulated in the land area around the northern South China Sea. According to the Pre-Sinian isotopic dating data collected from 61 sets, Shu (2006, 2012) combined the data with the statistical analysis of more than 900 sets of detrital zircon U-Pb ages in the Ordovician and Devonian sandstone (Yao et al., 2011b; Xiang and Shu, 2010) and believed that the Cathaysian block is the Pre-Nanhuan basement mainly consisting of the Neoproterozoic rock. There probably exist middle Archean to Paleoproterozoic geological bodies, which are composed mainly of schist, gneiss, and migmatite. The zircon U-Pb ages and Hf isotope test data obtained by Yu et al. (2006, 2007) and Zheng et al. (2007) also suggested that the Cathaysian block is composed mainly of the Neoproterozoic sedimentary rock, containing the ancient components of late Archean to Paleoarchaean, which reveals that there once existed more ancient old land or continental crust relicts. Jahn et al. (1986) obtained 1000–1700 Ma zircon U-Pb ages in the granite of Tananao Group in Taiwan of China. Wang et al. (1997) obtained two formations of 1295 and 1589 Ma zircon U-Pb ages in gneissic granite of Xipan in Taiwan, all of which suggest that there exists the Pre-Sinian crystalline basement in Taiwan and that the Pre-Sinian structure attribute in Taiwan belongs to the eastern edge of the Cathaysian old land. Through the study on the geochemistry and Sm-Nd isotope of the metamorphic sedimentary rock of Baoban group on Hainan island and the SHRIMP U-Pb zircon dating of the granitic rock, Xu et al. (2002, 2006) demonstrated that there exists the middle Paleoproterozoic or more ancient crystalline basement on Hainan island, and believed that the Pre-Sinian structure attribute is much more similar to the Cathaysian Block. Through the analysis of Sm-Nd isotopic characteristics of crustal rocks on Hainan island, Lei et al. (2005) suggested that the history of crustal growth in the north of Jiusuo-Lingshui fault is similar to the Cathaysian old land and its basement is a part of the Cathaysian old land. These studies show that the Pre-Sinian crystalline basement is widely distributed in peripheral land areas of the northern South China Sea.

While exploring the structure attribute of the Pre-Sinian crystalline basement in the northern South China Sea, we inevitably encounter the term "Cathaysian old land". Grabau (1924) proposed that the Cathaysian old land refers to a set of regional metamorphic rocks exposed in vast areas of the southeastern China and its neighbors. There have been scores of years since Grabau named it, and the term continued to be used in both Chinese and foreign literature, but there has been a strong disagreement on its tectonic implication and geographical distribution (Huang, 1945, 1960; Ren 1964, 1990; Shui, 1988; Chen et al., 1995; Cheng and Wang, 2006; Lu, 2006; Rong et al., 2010; Shu, 2012). This paper adopts the widely-used term Cathaysian Block and its distribution scope and implication are adopted from the idea of Shu (2006, 2012).

Because of the existence of a crystalline basement which experiences middle- to high-grade metamorphic and is older in age under the Caledonian fold belt in South China (Ren,1990), the crystalline basement can contrast geologic era, lithology, and metamorphic grade with those of the Pre-Sinian crystalline basement in the northern South China Sea. Therefore, the Pre-Sinian crystalline basement in South China has extended to the northern South China Sea and constituted a larger-scale continental block with the unified Pre-Sinian crystalline basement. The continental block contains both the Cathaysian block and northern South China Sea block, and both blocks are referred to as the Cathaysian-northern South China Sea continental block by us. In recent years, Shu (2006, 2012) pointed out that the existence of the Jiangnan orogenic belt indicates that there is a larger-scale continental block in the east of ancient South China ocean; otherwise, it is difficult to explain the formation of the Jiangnan orogenic belt, which extends to 1500km and is hundreds of thousand meters in width. It is also difficult to understand the formation of S-type granite with the same extending length. The wide distribution of the Pre-Sinian crystalline basement of the Cathaysian-northern South China Sea continental block sustains the idea.

Based on the geographical distribution of plate junction and fault of the continental block periphery in Cathaysian-northern South China Sea, the continental block scope is limited to the east of Jiangnan orogenic belt, to the west of the huge canyon in eastern Taiwan Mesozoic subduction zone of the northern South China Sea (Zhou et al., 2006; Zhou and Yao, 2009) and to the north of Ailao Mountain-Song Ma orogenic belt (Lepvrier et al., 2008；Thanh et al., 2011). The Indochina block also possesses the Pre-Sinian crystalline basement; however, because there existed the Paleo-Tethys ocean between the Indochina block and Cathaysian block in Paleozoic, the ocean basin eventually disappeared in the Triassic/Permian boundary (Zhong, 2000; Sun and Jian, 2004; Metcalfe, 2006, 2011; Jian et al., 2009a; 2009b), which indicates that the two blocks were not linked together before Mesozoic. Therefore, the continental block of Cathaysian-northern South China Sea does not contain the Kontum block of Indochina peninsula.

2 The tectonic attribute of Sinian to lower Paleozoic

Based on a small amount of drilling data of the low-grade metamorphic rock of Sinian to lower Paleozoic and combined with the comprehensive study on the characteristics of gravity and magnetic field, the previous researchers believed that there existed the Caledonian folded basement in the basin of the northern South China Sea and speculated that it is the extension of the Caledonian fold belt of the land area to the sea area (Liu and Zhan, 1994; Gong et al., 1997; Wang et al., 2002; Liu et al., 2002; Pang et al., 2007; Wan et al., 2009). This cognition lays an important foundation for the study on structural layers of the basin basement in the northern South China Sea. However, because of the limited drilling data adopted, the previous researchers had no systematic study and clear understanding of its distribution arrange and sedimentary source in the sea area.

Based on the original data of more than 180 drillings into the basin basement, excluding the drillings into contact metamorphic rocks, 35 drillings are eventually selected (Table 1, Figure 2(b)). The lithology seen in the drillings mainly contains low-grade metamorphic conglomerate, sandstone, fine sandstone, siltstone, slate, phyllite, and quartzite, which can be compared with the regional low-grade Sinian-Ordovician metamorphic rocks in the southwestern Fujian, eastern Guangdong, central Guangdong, and Hainan. (Li et al., 1997; Nan et al., 1996; Chen et al., 1997; Shu et al., 2008b). The drillings are spread among the Yinggehai, Beibu Gulf, southeastern Hainan, and Pearl River Mouth Basins, which confirms that there widely exists the Sinian to lower Paleozoic structural layer composed of the regional low-grade metamorphic rocks in the northern South China Sea. Furthermore, under the constraints of the drilling data, we also identify the structural layer in the seismic profiles of the Pearl River Mouth Basin and Southeastern Hainan Basin (Figures 3, 4).

In the southwestern Pearl River Mouth Basin, the lithology of lower Paleozoic has significant variations, namely, the lithology of Yangjiang low uplift is composed of metamorphic silty mudstone and metamorphic sandstones of fine texture, the lithology extended south to the Qionghai uplift, the Wenchang sag, and Kaiping sag, and the clastic diameter became large, which contains both metamorphic sandstones and metamorphic conglomerate. Further south to the Changchang sag, the clastic diameter became larger, which is mainly metamorphic conglomerate. The gravel has angular and subrounded shapes, which shows that the water of the south is shallower than that of the north in the deposit. Especially, CC4-1-1 drilling close to Xiyong drilling 1 contains metamorphic conglomerate with gneiss gravel, which indicates that provenance comes mainly from the Zhongsha-Xisha ancient uplift area composed of gneiss (Table 1, Figure 2(b)). In the northwestern Pearl River Mouth Basin, metamorphic sandstones, fine sandstone, and siltstone are drilled mainly in LF22-1-4 and HJ32-1-1 drillings. Because there are both the Pre-Sinian crystalline basement and the upper Paleozoic basement, Mesozoic and Cenozoic in Taiwan, only lacking Sinian to lower Paleozoic (Wang et al., 1997; Huang et al., 1996), Sinian to early Paleozoic of Taiwan is the ancient uplift, which links together to the Proterozoic ancient uplift in the southern East China Sea, and provides the provenance for the Sinian to early Paleozoic deposit in the northeastern Pearl River Mouth Basin (Figure 2(b)), which shows that sediments in the Sinian to lower Paleozoic basement of the Beibu Gulf Basin, Yinggehai Basin, southeastern Hainan basin and western Pearl River Mouth Basin came from the Yunkai ancient uplift, Zhongsha-Xisha ancient uplift, and small ancient uplifts in the Beibu Gulf Basin basement and the Hainan island separately.

The study shows that the northern South China Sea formed rift because of the breakup of Rodinia super-continent in Cryogenian, which was the same rift as that in Sinian to early Paleozoic of South China, and received unified rift type sediment. The provenance of rift in the northern South China Sea mainly came from three ancient uplifts of the southern East China Sea-Taiwan, Zhongsha-Xisha and Yunkai and some small ancient uplifts. After the tectonic heat event in the Caledonian period, the sediments in the rift suffered unified folding and metamorphism and formed widely-distributed low green schist facies metamorphic rocks. Therefore, the tectonic attribute of the structural layer is the Caledonian fold belt, which links to the fold belt of the same period in South China and constitutes a wider fold belt. The breakup in Neoproterozoic to early Paleozoic only occurred in the crust without the growth and extinction of the oceanic crust (Shu, 2006, 2012; Shu et al., 2008b). Therefore, it did not damage the completeness of the Cathaysian-northern South China Sea continental block. The recognition also confirms the existence of the unified Pre-Sinian crystalline basement of Cathaysian-northern South China Sea. It is the unified Pre-Sinian crystalline basement that can lay the basic platform for the formation and deposit of the rift.

3 The tectonic attribute of upper Paleozoic

The previous researchers held two entirely different views

Table 1 Sinian to lower Paleozoic low-grade metamorphic rocks in the basin basement of the northern South China Sea

Basin	Drilling No.	Bedrock buried depth (m)	Well completion depth (m)	Thickness (m)	Lithology
Pearl River Mouth Basin	HJ32-1-1	1696	1719	23	metamorphic sandstone
	LF22-1-4	1725	1745	20	metamorphic fine sandstone and siltstone
	PY14-5-1	3786.5	3817	30.5	quartzite
	YJ32-1-1	2367.5	2502	134.5	quartzite
	YJ35-1-1	4341	4345	4	metamorphic silty mudstone
	YJ36-1-1	2898	3582	684	metamorphic sandstone
	WC8-2-1	2682	2730	48	metamorphic conglomerate
	WC13-1-2	1588	1603	15	quartzite
	WC13-2-1	1379	1394	15	metamorphic conglomerate
	WC13-2W-1	1560	1563.7	3.7	metamorphic fine sandstone
	WC13-2-2	1426	1453	27	metamorphic sandstone and conglomerate
	WC17-1-1	2174	2219.6	45.6	metamorphic sandstone
	KP1-1-1	1884	1906.8	22.8	metamorphic sandy mudstone
	QH18-1-2	1262	1283	21	metamorphic sandstone
	QH18-1-3A	1296	1341	45	metamorphic rock
	QH18-4-1	1388	1423	35	metamorphic sandstone and conglomerate
	CC1-1-1	1173	1181.8	8.8	metamorphic sandstone and conglomerate
	CC4-1-1	873	887	14	metamorphic conglomerate, contains gneiss gravels
Southeastern Hainan Basin	YC13-4-1	2960	3001	41	slate, quartzite, gneiss
	BD15-3-1	2312.0	2343.0	31	The top is low grade metamorphic argillaceous limestone, the under is variegated metamorphic rock
Beibu Gulf Basin	W5	1127.99	1501.69	373.7	metamorphic fine sandstone and siltstone
	WZ5-8-1	924	954	30	metamorphic sandstone
	WZ11-4-A1	1161.54	1189.69	28.15	slate
	WZ11-4-1	1364	1462	98	mica schist with sandstone interbed
	WZ11-4N-1	2670	2718	48	slate and phyllite, sericite-schist
	WZ11-4N-3	3069	3112	43	phyllite
	WZ11-4N-5	2497.5	2530	32.5	metamorphic sandstone
	WZ11-7-3	2459	2530	71	slate and phyllite
	WZ22-2-1	2753	2786	33	low grade metamorphic rock
	WZ22-3-1	2652	2685	33	metamorphic sandstone and mudstone
	WS16-3-1	1869.5	1922	52.5	slate
Yinggehai Basin	HK17-1-1	1495	1525	30	Metamorphic limestone, quartzite, gneiss are from shallow part to deep part
	HK30-3-1A	1982	2029	47	The upper is metamorphic sandstone and conglomerate, the lower is granitic gneiss
	LT15-1-1	1175	1353.78	178.78	metamorphic sandstone and conglomerate
	YX32-1-1	658	680	22	quartzite

on the distribution of upper Paleozoic. One view, based mainly on geophysical data, held that there was the Hercynian-Indochina fold belt in the center of the Pearl River Mouth Basin and that the belt was composed of the low-grade metamorphic flysch formation and overlaid above the Caledonian fold belt (Liu et al., 2002; He et al., 2008; Liu and Zhan, 1994). The other view held that the area was in the state of uplifting after the Caledonian orogeny, no exact upper Paleozoic was seen, and there was no Hercynian-Indochina "geosyncline" (Yao et al., 2006).

The abundant drilling data show that the Cenozoic and Mesozoic directly cover the low-grade metamorphic rock of Sinian to lower Paleozoic in the Pearl River Mouth Basin and Southeastern Hainan Basin, which confirms that the area lacks the upper Paleozoic (Figures 1, 2(c)). Obviously, if there was the Hercynian-Indochina fold belt, over 20 drillings into lower Paleozoic inevitably penetrated it first, which is the fundamental reason why Paleozoic cannot be divided into two upper and lower structural layers according to seismic profiles. There are two probabilities controlling the factors of lacking the upper Paleozoic structural layers. One is that there was the late Paleozoic deposit and then it was completely denudated while experiencing tectonic uplift. The other is that it then belonged to old land and did not receive any deposit. To which tectonic paleogeography it belongs needs to be confirmed by taking advantage of the comprehensive analysis of lithofacies and paleogeographic characteristics of the coastal land in South China. In Late Devonian or Early Carboniferous to Middle Triassic, South China was basically in a stable, littoral and neritic environment, which is characteristic of platform facies and epicontinental sea facies deposit. (Ren et al., 1990; Shu et al., 2008a; Shu, 2012), In the stratigraphic divisions of the southwestern Fujian province and Dongjiang in Guangdong province, the depositional thickness of clastic rock and carbonate rock of the littoral and neritic facies in late Paleozoic to Middle Triassic is large, and the maximum cumulative thickness is larger than 4000 m. In the Yunkai stratigraphic division at the junction of Guangdong and Guangxi, the maximum cumulative thickness of paralic facies and neritic facies sediments of the Permo-Carboniferous is larger than 3600 m. In the stratigraphic division of Wuzhi Mountain on Hainan Island, the Permo-Carboniferous is composed mainly of neritic facies sandstone, mudstone, and limestone, and the maximum cumulative thickness is larger than 1547m (Li et al., 1997; Nan et al., 1996; Chen et al., 1997; Yin et al., 1997). The above regional stratigraphic data verify that the upper Paleozoic structural layers are widely distributed in South China, and are composed mainly of thicker littoral and neritic facies sediments with rich corals, brachiopods, bivalves, fusulinids, and foraminifera fossils, unconformably overlying the low-grade metamorphic Caledonian fold belt. However, no late Paleozoic sediments were received in the basement of the Pearl River Mouth Basin, Southeastern Hainan Basin and the southern Hainan Island. It can be imagined that if the upper Paleozoic with thousands of meters in thickness in the land area extends to these areas and is completely denuded in later period, which needs a long uplift history or intensive uplift amplitude. The study shows that tectonic uplift period of late Paleozoic-Triassic in South China occurred mainly in the Late Triassic, which was caused by the closure of Paleo-Tethys ocean of Jinsha River-Ailao Mountain-Song Ma and Changning-Menglian-Qingmai and the collision of the Indochina block with the Yangtze-South China plate (Zhong, 2000; Sun and Jian, 2004; Lepvrier et al., 2004; Liu et al., 2011). The uplift is short in time and the uplift amplitude is small, which had little impact on South China, did not cause large-scale missing of Devonian to Middle Triassic, and only formed the unconformable contact between Middle Triassic and Upper Triassic (Shu, 2012). Therefore, the basic cause of lacking structural layers of the upper Paleozoic in basement of the Pearl River Mouth Basin and Southeastern Hainan Basin is the ancient uplift, not the late erosion.

It was reported that in the northwestern Beibu Gulf Basin, over 10 drillings (WZ10-3N-1, WZ10-3N-2, WZ10-4-1, WZ11-1-1, WZ11-1-2, WZ10-3N-3, WZ5-2-1, WZ6-1-1, WZ6-1-2, WZ6-1-3, WZ6-3-1, W2, W4, and W9) were drilled into the Carboniferous neritic facies carbonate rocks. It was also reported the drillings into the Permian crystalline limestone in the Southwestern Taiwan Basin (Jahn et al., 1992; Zhou, 2002), which is the natural extension of the littoral and neritic facies deposits in coastal land to the sea area.

The facts have confirmed that the structural layers in upper Paleozoic take on the uneven distribution. The basement of the Beibu Gulf Basin and Southwestern Taiwan Basin is composed of stable epicontinental sea facies deposit. The basement of the Pearl River Mouth Basin and the Southeastern Hainan Basin basement belong to the ancient uplift in late Paleozoic, lacking the upper Paleozoic structural layers, which is called the Zhu-Qiong ancient uplift for short in this paper (Figure 2(c)). Obviously, there is no Hercynian fold belt composed of low-grade metamorphic rocks in the area.

4 The Mesozoic tectonic attribute

Based on the seismic profiles, gravity and magnetic interpretation, and drilling data, many researchers have reported that the Mesozoic marine facies sedimentary layers exist in the Pearl River Mouth Basin basement (Su et al., 1995; Wang et al., 2000; Yang et al., 2002; Wang, 2002; Yu, 2012). They combined the Late Triassic-Cretaceous formation and sedimentary facies of the coastal area in the South China and concluded that the Mesozoic in the northern South China Sea experienced transgression and marine regression sedimentary cycles twice. They also drew lithofacies paleogeography maps of Late Triassic-Early Jurassic, Late Jurassic-Early Cretaceous (Hao et al., 2001, 2004; Zhou et al., 2005a; Zhong et al., 2007, 2011). However, the Upper Triassic-Lower Jurassic in the Pearl River Mouth Basin is obtained mainly by the deduction of coeval strata in South China and there is no drilling evidence so far. The Chaoshan depression is the most representative of the Mesozoic residual depression in the Pearl River Mouth Basin. At the beginning of this century, the previous researchers interpreted that there was the Upper Triassic-Lower Jurassic in the seismic profiles of the Chaoshan depression, which was later confirmed as the Middle Jurassic to Cretaceous by LF35-1-1 drilling (Shao et al., 2007; Wu et al., 2007; Hao et al., 2009a). Therefore, whether early Mesozoic strata exist in the Pearl River Mouth Basin is unclear. Under this circumstance, there is no basis of discussing the early Mesozoic sedimentary environment in the northern South China Sea. Therefore, this paper only demonstrates the late Mesozoic stratigraphic distribution, sedimentary environment, magmatic rock, and structural characteristics.

The previous scholars' study shows that the Jurassic (?) in Southwestern Taiwan Basin is composed mainly of the bathyal-abyssal facies environment, and the Beigang uplift is in the paralic facies or lake facies environment. The land-sea distribution in the Early Cretaceous changed greatly, the

Southwestern Taiwan Basin in Aptian period to early Albian period was in inland lake environment, and the Beigang uplift in Aptian period was in the paralic facies and neritic facies environment (Matsumoto et al., 1965; Matsumoto, 1979; Huang, 1978; Zhou, 2002). Residual Mesozoic is generally distributed in the eastern Pearl River Mouth Basin and the maximum thickness of Mesozoic is 5000 m (Zhong et al., 2011). The micropaleontology, rock association, and sedimentary characteristics in LF35-1-1 drilling suggest that this area experienced the sedimentary cycle of littoral neritic facies-abyssal facies in the Mid-Late Jurassic and then marine-continental transitional facies in Early Cretaceous and finally continental facies in late Cretaceous, companied by the based and acid volcanic eruption (Shao et al., 2007). In the basement of the western Pearl River Mouth Basin and Southeastern Hainan Basin, the Mesozoic is in the state of isolated island, situated on the low-grade metamorphic rock of lower Paleozoic, which is composed of the continental volcanic-sedimentary rock in the Early Cretaceous. In the basement of the Beibu gulf and Yinggehai Basins, most of the stratigraphy and lithology seen in more than 10 drillings, such as W10, WZ128-1, LT9-1-1, and Yin6, are the Upper Cretaceous continental facies red clastic rocks (Figures 1, 2(d)). This shows that the late Mesozoic stratigraphic distribution and sedimentary environment in the northern South China Sea is characteristic of differentiation in the east and west. The Middle Jurassic to Cretaceous marine and paralic faces deposits develop in the Southwestern Taiwan Basin and the volcanic activity is not obvious. The Middle Jurassic to Early Cretaceous marine and marine-continental transitional facies deposits are distributed mainly in the eastern Pearl River Mouth Basin and the volcanic activity is stronger. The Early Cretaceous continental volcano-sediment is distributed mainly in the western Pearl River Mouth Basin and Southeastern Hainan Basin, which is in the state of isolated island and oddly scattered. The red clastic rock deposit of the continental facies in the Upper Cretaceous is distributed mainly in the Beibu Gulf and Yinggehai Basins.

The granite, granodiorite, and quartz diorite were drilled in 77 drillings in the basement of the Pearl River Mouth Basin and Southeastern Hainan Basin. The distribution area of intermediate-acid intrusive rocks, which are composed mainly of granite, approximately accounts for one fourth of the basin area (Figure 1). According to incomplete statistics, isotopic age data of 21 intrusive rocks are distributed in 130–70.5 Ma (Pang et al., 2007; Gong et al., 1997; Li et al., 1998; Shao et al., 2007; He et al., 2008), which shows that they were formed mainly in the Cretaceous. In addition, volcanic rocks were drilled in more than 10 drillings and the rock associations are mainly rhyolite, volcanic breccia, tuff, and sedimentary clastic rock, and secondarily andesite and andesitic brecciated tuff. The Cretaceous intermediate-acid intrusive rocks are large-scaled and widely distributed, occurring mostly in the form of batholith and often accompanied by the contemporary volcanic-sedimentary basin. The rock association and distribution characteristics of intrusive rocks and extrusive rocks are similar to granitic volcanic-intrusive complex in the coastal areas of South China (Wang and Shu, 2012; Wang and Zhou, 2002; Zhou et al., 2007; Shu, 2012), which shows that they have the same tectonic background.

The seismic profiles, gravity, and magnetic interpretation identified that the NE and NW-direction faults are widely distributed in the Mesozoic basement of the Pearl River Mouth Basin and Southeastern Hainan Basin (Figure 2(d)). The NE direction faults are arranged parallel to a series of NE-direction ductile shear zone of Changle-Nan'ao and Lianhua Mountain, South China, the NW-direction levorotatory faults cut the NE-direction faults, and many NW-direction faults reach the coastline and link NW-direction fault in South China. In addition, a series of large, wide, and long axis folds are identified, whose axial line spreads in the NE direction, the anticlinal core is accompanied by a small amount of thrust fault, and the fault overthrust from the SE to the NW-directions, which shows that the compressive stress came from the SE-direction (Hao et al., 2004; Yao et al., 2011a).

The above NE direction granitic volcanic-intrusive complex, volcano-sedimentary basin, fold and the fault in the late Mesozoic basement have the similar temporal and spatial distribution, geological feature, and tectonic attribute with those of the coastal land in South China, which belong to the same magma-deposition-tectonic system whose cause can be interpreted by the Paleo-Pacific plate subducting under the Eurasian continental margin (Isozaki, 1997; Maruyama and Seno, 1986; Maruyama et al., 1997; Wang and Shu, 2012). In the study area, the Paleo-Pacific subduction zone, which is distributed mainly in the Southwestern Taiwan Basin and the northern margin of deep-sea basin in the South China Sea, is a NE direction Mesozoic subduction-accretion zone (Zhou et al., 2006; Zhou and Yao, 2009). That Pacific plate subducted along the zone to the northern South China Sea-Cathaysian block caused the formation of the NE direction folds and faults in the northern South China Sea and of the NE direction magmatic arc in the Pearl River Mouth Basin, which demonstrates the structural layer in the late Mesozoic was formed in the background of active continental margin. In Late Cretaceous, the subduction zone of the Pacific plate dramatically retreated eastward and the southeastern China was generally in the extensional environment. Being affected by the intra-continental extensional tectonism, tensile rifting occurs again in South China, which formed the Late Cretaceous continental rift basin (Shu et al., 2004).

5 Conclusions

(1) The Pre-Sinian crystalline basement in the northern

South China Sea is distributed not only in the Southeastern Hainan Basin and the Zhongsha-Xisha islands, but also in the basement of the Beibu Gulf Basin, Yinggehai Basin, and Pearl River Mouth Basin, which is linked to the Pre-Sinian crystalline basement in Cathaysian block and composed of the larger-scale continental block—Cathaysian-northern South China Sea continental block.

(2) The Sinian to lower Paleozoic is widely distributed in the northern South China Sea, which is the natural extension of the Caledonian fold belt in South China to the sea area. The Sinian to lower Paleozoic in both land area and sea area is composed of the larger-scale Caledonian fold belt and its sediments are derived from the southern East China Sea-Taiwan, Zhongsha-Xisha islands, the Yunkai ancient uplift, and some small basement uplifts.

(3) The upper Paleozoic structural layers are unevenly distributed in the northern South China Sea. In the basement of the Beibu Gulf Basin and Southwestern Taiwan Basin, the upper Paleozoic structural layers are composed of the stable epicontinental sea sediments. The basement in the Pearl River Mouth and Southeastern Hainan Basins belongs to the late Paleozoic ancient uplift, lacking the upper Paleozoic structural layers. There is no Hercynian fold belt composed of low-grade metamorphised rocks.

(4) The stratigraphic distribution and sedimentary environment in Middle-Late Jurassic to Cretaceous is characteristic of differentiation in the east and the west. The marine deposit and paralic faces deposit develop in the Beigang uplift and the Southwestern Taiwan Basin, and the volcanic activity is not obvious. The marine and marine-continental transitional facies sediment is distributed mainly in the eastern Pearl River Mouth Basin and the volcanic activity is stronger. The continental volcano-sediment in Early Cretaceous is distributed mainly in the western Pearl River Mouth Basin and Southeastern Hainan Basin. The Late Cretaceous red continental clastic rocks are distributed mainly in the Beibu Gulf Basin and Yinggehai Basin. The NE direction granitic volcanic-intrusive complex, volcano-sedimentary basin, fold and fault in the Mesozoic basement have the similar temporal and spatial distribution, geological features, and tectonic attribute with those of the coastal land in South China, belonging to the same magma-deposition-tectonic system, which demonstrates the late Mesozoic structural layer was formed in the background of the active continental margin.

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