Acta Oceanol. Sin., 2021, Vol. 40, No. 9, P. 33–42
https://doi.org/10.1007/s13131-021-1898-8
http://www.aosocean.com
E-mail: ocean2@hyxb.org.cn

Tectonic unit divisions based on block tectonics theory in the South China Sea and its adjacent areas

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Received 8 January 2021; accepted 20 May 2021

Abstract
Identifying distinct tectonic units is key to understanding the geotectonic framework and distribution law of oil and gas resources. The South China Sea and its adjacent areas have undergone complex tectonic evolution processes, and the division of tectonic units is controversial. Guided by block tectonics theory, this study divide the South China Sea and its adjacent areas into several distinguished tectonic units relying on known boundary markers such as sutures (ophiolite belts), subduction-collision zones, orogenic belts, and deep faults. This work suggests that the study area is occupied by nine stable blocks (West Burma Block, Sibumasu Block, Lanping-Simao Block, Indochina Block, Yangtze Block, Cathaysian Block, Qiongnan Block, Nansha Block, and Northwest Sulu Block), two suture zones (Majiang suture zone and Southeast Yangtze suture zone), two accretionary zones (Sarawak-Sulu accretionary zone and East Sulawesi accretionary zone), one subduction-collision zone (Rakhine-Java-Timor subduction-collision zone), one ramp zone (Philippine islands ramp zone), and six small oceanic marginal sea basins (South China Sea Basin, Sulu Sea Basin, Sulawesi Sea Basin, Banda Sea Basin, Makassar Basin, and Andaman Sea Basin). This division reflects the tectonic activities, crustal structural properties, and evolutionary records of each evaluated tectonic unit. It is of great theoretical and practical importance to understand the tectonic framework to support the exploration of oil and gas resources in the South China Sea and its adjacent areas.

Key words: South China Sea, block tectonics, tectonic units, suture zone

Citation: Yin Zhengxin, Cai Zhourong, Zhang Cheng, Huang Xiaofeng, Huang Qianru, Chen Liang. 2021. Tectonic unit divisions based on block tectonics theory in the South China Sea and its adjacent areas. Acta Oceanologica Sinica, 40(9): 33–42, doi: 10.1007/s13131-021-1898-8

1 Introduction

The South China Sea and its adjacent areas have long been subjected to tectonic movements caused by interactions with the Eurasian Plate, the Philippine Sea-Pacific Plate, and the Indo-Australian Plate (Fig. 1). Influenced by different tectonic stresses, many phases of Cenozoic tectonic processes, such as tension, rupture, convergence, and collision, result in the formation of various crustal and lithospheric fragments in these areas (Yin et al., 2015; Liu et al., 2002a; Yao et al., 2012). A large number of geotectonic units and the diversity of crustal properties complicate our understanding of both the tectonic history of the South China Sea and the location of the oil and gas resources in these areas. Accurate demarcation of the different tectonics is an effective way to understand the distribution law of oil and gas resources. Previous studies have attempted to divide the different tectonic units in the South China Sea and its adjacent areas based on the theory of faulted block tectonics, plate tectonics, layered block tectonics, microblock tectonics and historical geotectonics (Zhang, 1984; Liu, 1993; Li et al., 2018, 1995a; Wu, 1998; Liu et al., 2002a, 2004a, 2018; Yao et al., 2010; Metcalfe, 2013; Yang et al., 2015; Zhang et al., 2018). These division schemes have different emphases and reflect different geotectonic perspectives within a certain historical period. However, they also have certain limitations because the tectonic unit often mixes stable zones and active zones in these schemes. It is difficult to distinguish the differences in the tectonic activities, crustal tectonic properties and evolutionary history of the region. This study utilizes a new scheme for the tectonic unit division of the South China Sea and its adjacent areas (approximate research scope: 10°S–25°N, 90°–130°E) based on block tectonic theory.

The term “block” was formerly used to describe the mass of a surface unit, such as an avalanche or a landslide. The concept of blocks or terranes was first proposed in an early study of continental tectonics (William, 1972). Zhu (1983) and Liu (1993) defined blocks as stable geotectonic units that share similar evolutionary histories. Conversely, suture zones or active zones are defined as geotectonic units that have undergone multiple tectonic movements and are typically distributed along the borders

Foundation item: The National Natural Science Foundation of China under contract Nos 41706055, 41776072, 41602092, 4106035 and 41776072; the Natural Science Foundation of Guangdong Province under contract Nos 2018A030313168 and 2018B030311030; the National Marine Geology Special Project under contract Nos DD20160147 and DD20189643.
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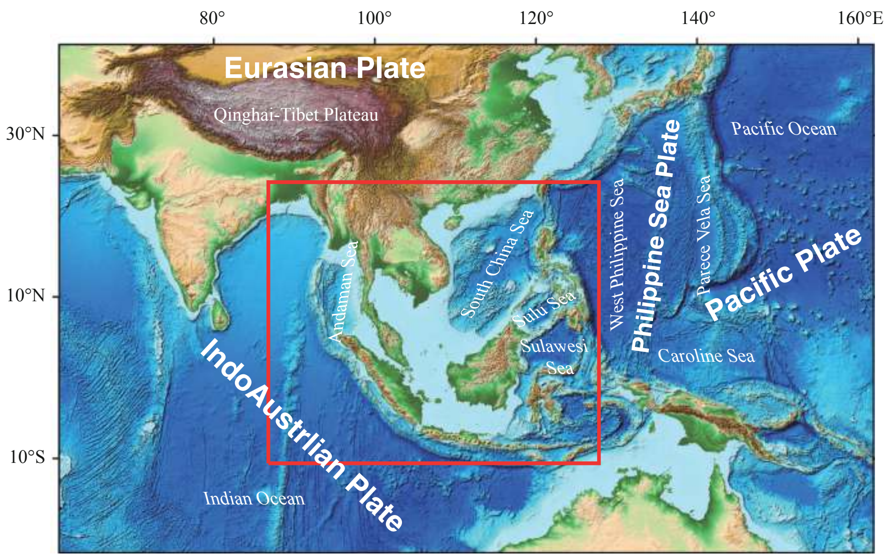

Fig. 1. Study area (red rectangular frame) and topographic features.

of such blocks. Therefore, the block and the active zone are the secondary tectonic units of the lithospheric plate. After further refinement by later geologists, block tectonics theory was eventually established (Zhang et al., 2009, 2010; Zhang and Guo, 2014; Guo et al., 2014; Wen et al., 2014; Gao et al., 2014). Li et al. (2018) proposed the microblock tectonics theory and systematically summarized the genetic classification, boundary type, formation environment and dynamic mechanism of microblocks. Microblock tectonics theory is similar to block tectonics theory, but the latter places more emphasis on the stability of the block and the activity of the suture zone around the block. This theory represents a new development of and complements plate tectonics theory. The core content of block tectonics theory is as follows: within a lithospheric plate, the relatively stable tectonic unit is called a block, while the active zones represent the areas between the blocks. Each block has a unique size, shape, thickness, structure, and tectonic evolution history. This theory plays an important role in understanding the tectonic evolution within a plate. Furthermore, the properties of block tectonics and the intensity of tectonic activity are incorporated. Guided by the tenets of block tectonics theory, this study can better partition the tectonic units of the South China Sea and its adjacent areas with complex tectonic backgrounds.

2 Discriminant markers at block unit boundaries

Since block tectonic theory is based on plate tectonic theory, the identification of block units first requires the identification of tectonic plates. Our study area is mainly located on the Eurasian Plate, bounded by the Philippine Sea Plate subduction zone to the east and the Indo-Australian Plate subduction zone to the southwest. The objective of tectonic unit division is to find markers that allow us to distinguish the stable zones from the active zones, as well as identify changes in the tectonic properties and evolutionary histories of the unit. These markers include sutures (ophiolite belts), subduction-collision zones, deep faults, and orogenic belts. The paleogeography, paleocommunity, and paleoclimate of the study area may also provide valuable information about the boundaries of different blocks.

2.1 *Sutures (ophiolite belts)*

Ophiolites represent the remnants of oceanic lithosphere and are one of the most important markers available for identifying paleoconvergent plate boundaries. Ophiolite belts are often a reliable basis for judging the ocean–continent, arc–continent, or continent–continent collisions of paleoconvergent plates. Because the units on either side of the ophiolite suture often have different tectonic properties and histories, ophiolites can be used as important markers of the boundary of block tectonic units. Our study area is located in the front zone of the interaction between the Tethys tectonic domain and Pacific tectonic domain. The ophiolite and ophiolite mélanges (Maury et al., 2004; Yumul, 2007; Zhang and Liu, 2011; Dimalanta et al., 2020), which have been accruing since the Paleozoic, contain key information about the interaction between the Tethys tectonic domain and Pacific tectonic domain; they also provide key geological information affecting the tectonic evolution of Southeast Asia. This study collected data on almost all ophiolite outcrops in the study area and found that most of the exposed ophiolites were formed at convergent margins, specifically in back-arc and island-arc environments. The Paleozoic and Mesozoic ophiolites developed at the margins of the Indochina Block (which is part of the Eurasian Plate) and the Indo-Australian Plate. These ophiolite belts may also be related to the formation and evolution of the Paleo- and Meso-Tethys Oceans. The Mesozoic and Cenozoic ophiolites, which are closely related to the formation and evolution of the Meso- and Neo-Tethys Oceans, were initially located on the eastern Philippine island arc of Southeast Asia, Kalimantan Island, and the southeastern part of Southeast Asia. These ophiolite belts are important diagnostic tools that can aid in the identification of different block unit boundaries (Table 1 and Fig. 2).

2.2 *Subduction-collision zones*

The trench-arc-basin system is the most influential tectonic system in Southeast Asia. Our study area is located in this system and was created during the subduction-collision of various plates, including the western Philippine Sea Plate, the Indo-Australian Plate, and the Eurasian Plate. The Philippine Trench subduction zone represents the boundary between the western Philippine Sea Plate and the Eurasian Plate, while the Indian-Australian Plate and the Eurasian Plate are connected by the Rakhine-Andaman-Sumatra-Java-Timor subduction-collision zone. These

Table 1. Properties of the exposed sutures (ophiolite belts) in the study area

Location	Number of ophiolites (or ophiolitic belts)	Names of ophiolites (or ophiolitic belts)	Age of formation	Age of emplacement	Tectonic setting	References (include their cited papers)
Indochina Peninsula	①	Jinshajiang-Ailaoshan-Majiang	C_1-T_3	C_2-T_3	Palae-Tethys marginal oceanic basin	Chen et al. (2010), Hutchison (1989)
	②	Changning-Menglian-Chiang Mai-Chanthaburi-Benton-Raub	D-T	T	Paleo-Tethys major oceanic basin	Chen et al. (2010), Hutchison (1989)
	③	Dien Bien Phu-Nan-Uttaradit	C-T	T_2	palae-Tethys marginal oceanic basin	Chen et al. (2010), Hutchison (1989)
	④	Mandalay-Jade Mines	–	K_2	Meso-Tethys oceanic basin	Hutchison (1989)
	⑤	Naga hills	–	K_2-E	Neo-Tethys oceanic basin	Hutchison (1989)
	⑥	Andaman-Nicobar islands	–	K_2-E_2	Neo-Tethys oceanic basin	Hutchison (1989)
Philippines	⑦	Ilocos Norte	J_3-K_1	–	MOR and SSZ, marginal basin	Pubellier et al. (2004), Maury et al. (2004)
	⑧	Lepanto-Pugo	K-E_2	–	MOR, arc-marginal basin	Pubellier et al. (2004), Maury et al. (2004)
	⑨	Zambales, Luzon	E_2	–	SSZ, marginal basin	Pubellier et al. (2004), Maury et al. (2004)
	⑩	Angat, Central Luzon	K_2	–	SSZ	Pubellier et al. (2004), Maury et al. (2004)
	⑪	Mangyan, Mindoro Island	K_2	–	SSZ	Pubellier et al. (2004), Maury et al. (2004)
	⑫	Amnay, Mindoro Island	E_1	–	SSZ	Pubellier et al. (2004), Maury et al. (2004)
	⑬	Antique, Panay Island	K_2	–	SSZ, island arc	Pubellier et al. (2004), Maury et al. (2004)
	⑭	Cebu, Cebu Island	K_1	–	SSZ, marginal sea	Pubellier et al. (2004), Maury et al. (2004)
	⑮	Southeast Bohol, Bohol Island	K_1	–	SSZ, marginal basin and island arc	Pubellier et al. (2004), Maury et al. (2004)
	⑯	Polanco, Northeastern, Zamboanga	K	–	SSZ	Pubellier et al. (2004), Maury et al. (2004)
	⑰	Titay, Central Zamboanga	K_2	–	SSZ	Yumul (2007)
	⑱	Palawan, SouthwesternPalawan Island	K_2-E_2	–	SSZ, marginal sea	Yumul (2007)
	⑲	Casiguran/Isabela, Eastern Luzon	K_2	–	SSZ, marginal sea	Yumul (2007)
	⑳	Camarines Norte, Southeastern Luzon	K_1	–	SSZ, marginal sea	Yumul (2007)
	㉑	Lagonoy, Southeastern Luzon	Pre- K_2	–	SSZ	Yumul (2007)
	㉒	Rapu-Rapu, Southeastern Luzon	Pre- K_2	–	SSZ	Yumul (2007)
	㉓	Tacloban, Leyte Island	K_1	–	SSZ	Yumul (2007)
	㉔	Samar, Samar Island	K_1- K_2	–	SSZ, marginal sea	Yumul (2007)
	㉕	Malibog/Panaon, Leyte Island	K_2	–	SSZ	Yumul (2007)
	㉖	Dinagat, Dinagat Island	J-k_2	–	SSZ	Yumul (2007)
	㉗	Surigao, Northeastern Mindanao	K?	–	SSZ	Yumul (2007)
	㉘	Pujada, Southeastern Mindanao	K_2	–	SSZ	Yumul (2007)
	㉙	Sibuyan	J-k	–	MOR	Yumul et al. (2020)
	㉚	NE Zamboanga	Late E_3 to early N_1	–	arc-marginal sea (?)	Pubellier et al. (2004)
	㉛	SW Zamboanga	K_2	–	arc-marginal sea (?)	Pubellier et al. (2004)
Kalimantan	㉜	Lupar Line-Boyan	J-K	Early E_2	marginal sea	Hutchison (1989)
	㉝	Darval Bay-Labuk-Palawan	K_1, K_2-E	Late E_3-early N_1	–	
	㉞	Sabah (Darvel Bay)	K_2	E_2	arc-marginal sea (?)	Pubellier et al. (2004)
	㉟	Tatao-Mersing line	E_1-E_2	–	–	Hutchison (1989)
	㊱	Adio belt	J_3-K_1	–	–	Hutchison (1989), Zhou et al. (2008)
	㊲	Meratus (southeast Kalimantan)	K_1	K_2	arc–marginal basin	Pubellier et al. (2004)
	㊳	Laut Island (SE Kalimantan)	–	–	–	Pubellier et al. (2004)
Sulawesi	㊴	Balantak and central Sulawesi	E_2	E_3	marginal basin	Pubellier et al. (2004)
	㊵	Lamasi (central Sulawesi)	–	–	marginal basin	Pubellier et al. (2004)
	㊶	Kabaena (South Sulawesi)	–	–	–	Pubellier et al. (2004)
	㊷	Buton Island (South Sulawesi)	–	N_1	–	Pubellier et al. (2004)
Sumatra-Java Arc	㊹	Gumai, Garba and Aceh Line	–	–	Neo-Tethys Ocean	Pubellier et al. (2004)
	㊺	Nias	Cenozoic	–	Indian Ocean	Pubellier et al. (2004)

Note: MOR , Mid-Ocean Ridge; SSZ, supra-subduction zone; –, no data.

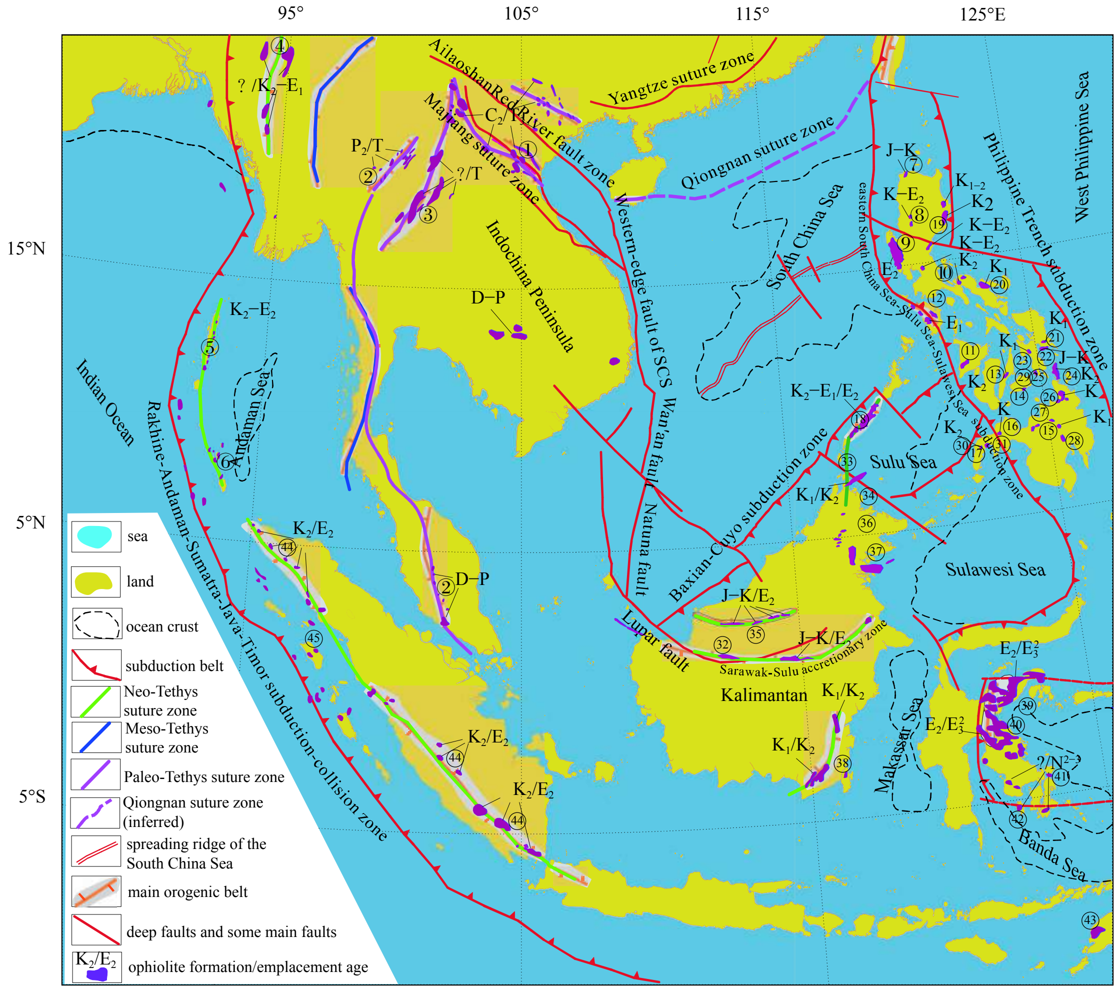

Fig. 2. Tectonic map of the main sutures (ophiolite belts), subduction-collision zones, deep faults, and orogenic belts in the study area. Numbers in the cycles, such as①②③, denote the number of ophiolites (or ophiolitic belts), as shown in Table 1.

modern subduction zones can serve as clear boundaries between plates or blocks. The South China Sea and its adjacent areas are dotted with small ocean basins that are also bounded by subduction-collision zones. For example, the subduction zone located on the eastern South China Sea-Sulu Sea-Sulawesi Sea (Cai et al., 2016) represents the eastern border of the South China-Sulu-Sulawesi Sea; it starts in Taiwan and extends southward along the Manila Trench. After crossing the Mindoro thrust fault zone, it joins the Negros Trench on the eastern margin of the Sulu Basin and then connects with the Cotabato Trench via the Zamboanga thrust fault zone. The dividing line between the South China Sea and Kalimantan Island is also known as the Baxian-Cuyo subduction zone. The area encompassed by this subduction zone is characterized as a stable block in the north and an active collisional accretionary zone in the south. According to previously published geophysical data, modern trench subduction zones have also developed in the southern part of the Sulu Sea and the Sulawesi Sea (Figs 2 and 3). Because the tectonic units on either side of subduction-collision zones have different tectonic properties and evolutionary histories, these subduction-collision zones can help us to discern the different block tectonic units.

2.3 *Deep faults*

Because deep faults cut through the lithosphere, they are an important controlling factor in the flow and migration of lithospheric mantle and crustal material, which in turn affects the geological structure of the tectonic units on both sides of the deep fault. As such, the presence of deep faults is another indicator of the block boundary. Lithospheric faults are often categorized as normal faults, thrust faults, or strike-slip faults. The spreading that occurs at mid-ocean ridges is typically accommodated by normal faults and strike-slip faults, while thrust faults are usually associated with subduction trenches and accretionary collision zones and often overlap with modern subduction-collision zones, orogenic belts and ophiolite belts. For example, the Manila Trench in the eastern South China Sea is also a deep and large fault. Deep and large strike-slip faults usually have deeper cutting depths, which is also an important marker to judge the boundaries of blocks. The giant fault zone system on the western margin of the South China Sea, consisting of the Ailaoshan–Red River fault zone and its southward extension to the western edge of the South China Sea, Wan'an fault, Natuna fault, and Lupar fault, is a deep continuous strike-slip fault (Liu et al., 2015). The fault zone defines some of the boundaries for the Indochina Block, the Cathaysian Block, the Qiongnan Block, and the Nansha Block (Figs 2 and 3).

2.4 *Orogenic belts*

An orogenic belt is a narrow structural deformation zone caused by the compression and contraction of the Earth's crust.

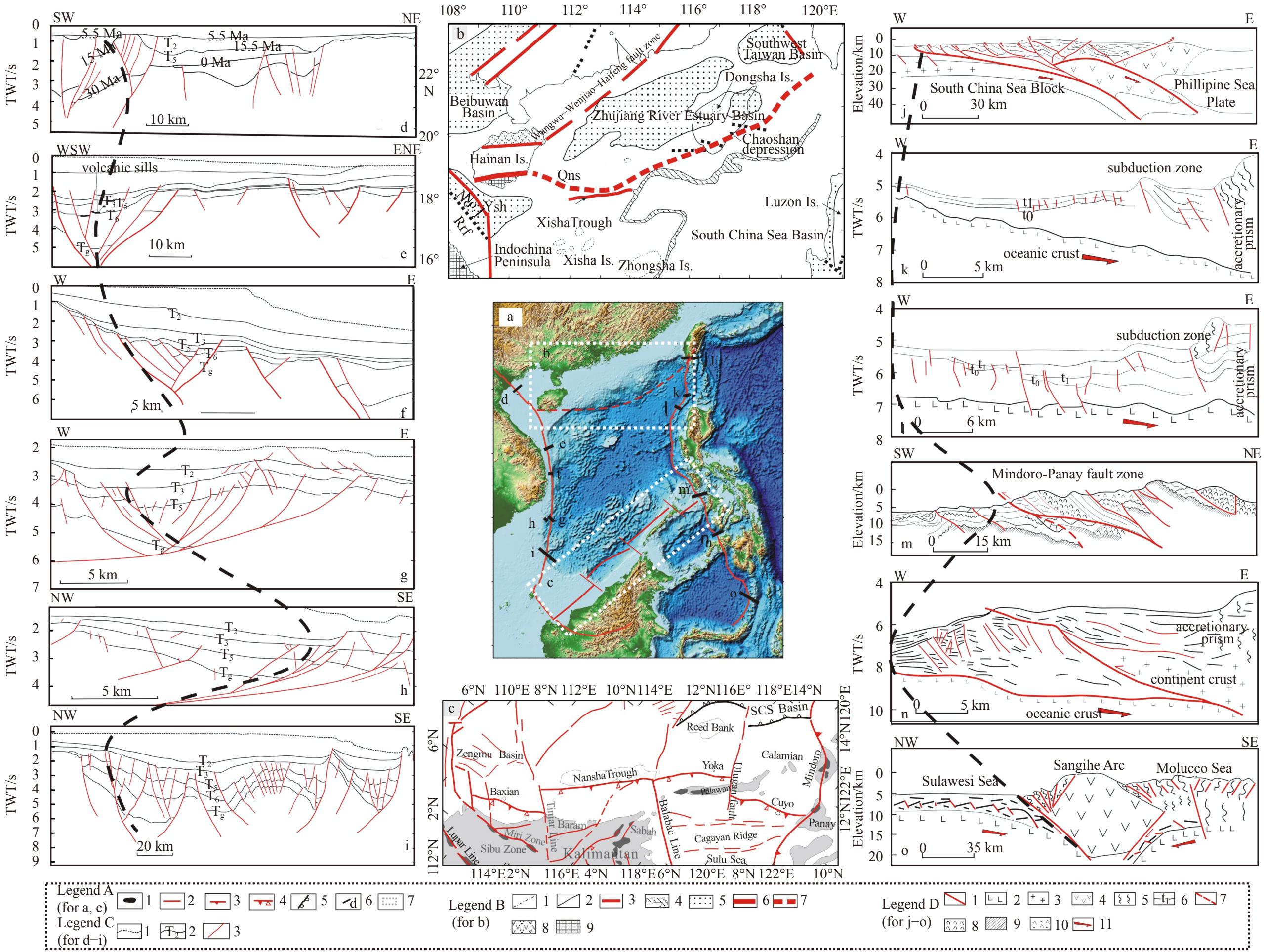

Fig. 3. Characteristic tectonic boundary properties of the South China Sea region (b modified from Liu et al. (2002b), c from Liu et al. (2006); d from Rangin et al. (1995); e and f from Vu et al. (2017); g and h from Fyhn et al. (2009); i from Tuan et al. (2016); j–o from Cai et al. (2016) and its cited articles). This region is bounded by a paleo suture zone (Qiongnan suture zone) to the north, subduction-collision zones to the east and south, and a strike-slip deep fault to the west. Legend A: 1 represents ophiolite, 2 faults, 3 active subduction zone, 4 subduction-thrust zone, 5 boundary of South China Sea Basin, 6 location of section d–o, 7 location of b and c. Legend B: 1 represents boundary of Chaoshan depression, 2 tectonic boundary, 3 crustal fault, 4 ocean-continental boundary, 5 Cenozoic sedimentary basin, 6 South Hainan suture zone, 7 South Hainan suture zone (inferred), 8 basalt, 9 pre-Cambrian basement; Rrf represents Red River fault, Qns South Hainan suture zone, Ysh Yinggehai and Southeast Hainan Basins; No.1 represents No.1 fault in Yinggehai basin. Legend C: 1 represents sea bed, 2 stratigraphy, 3 faults; T_2 represents the bottom of Pliocene, T_3 the bottom of Upper Miocene, T_5 Middle Miocene, T_6 Lower Miocene, T_7 Middle Oligocene. Legend D: 1 represents fault, 2 oceanic crust, 3 continent crust, 4 arc, 5 fold, 6 seismic reflection interface, 7 inferred fault, 8 ophiolite or meta-ophiolite, 9 undifferentiated metamorphic basement, 10 volcaniclastics, 11 movement direction of the crust; t_0 represents the base of the trench turbidity current deposition system, t_1 represents the sequence of turbidity current deposition.

Generally, the tectonic process caused by collision between two continental blocks is considered collisional orogeny, and the continental growth process in which magmatic arcs develop on the continental margin or island arcs accrete to the continental margin is considered accretive orogeny (Xiao et al., 2010, 2019; Zheng et al., 2015; Xu et al., 2019). As the junctional zone between the two land masses after the subduction of the ancient ocean, the orogenic belt still experiences strong tectonic activity. Ophiolite belts and deep faults are commonly visible in orogenic zones, so these divisional signs often overlap with each other, but the orogenic belt is wider in scope. Since the Paleozoic, tectonic events such as subduction, arc-continent collision, and continent-continent collision have created a series of broad orogenic belts among the various plates and blocks of the South China Sea and its adjacent areas. Some of these orogenic belts include the Majiang suture zone (located between the Cathaysian Block and the Indochina Block), the Yangtze suture zone (located between the Yangtze Block and the Cathaysian Block), and the Sarawak-Sulu accretionary zone (located along the northern boundary of Borneo) (Fig. 2). Although some Tethys suture zones are also orogenic in nature, they are relatively small and are classified as markers of ophiolites and deep faults.

2.5 *Other discriminant markers*

We also considered the development of ocean basins with oceanic crust as part of the block boundary identification process. These basins, such as the South China Sea, the Sulu Sea, the Sulawesi Sea, the Banda Sea, the Andaman Sea, and the Makassar Sea, formed because of collision, subduction, or plate retreat processes. Since the Cenozoic, oceanic basins experience strong tectonic activity, such as expansion, subduction and volcanism, which are special tectonic units in addition to stable block tectonic units.

One further piece of evidence we included in our tectonic block assessment is previously published paleontological and paleogeographical data. For example, evidence of the Cathaysia flora is found in the Baoshan-Shan Thai, Lanping-Simao, Qiongnan, and Nansha Blocks, while traces of Angolan flora are found in the Indochina, Yangtze, and Cathaysian Blocks (Li et al., 1995b).

3 Division project of block tectonic units

3.1 *Division project*

Based on block tectonics theory and knowledge of the markers of block boundaries, we divided the South China Sea and its adjacent areas into three primary tectonic units at the plate level: the Indian-Australian Plate, the Pacific (Philippine Sea) Plate, and the Eurasian Plate. We then divided these plates into secondary tectonic units, including nine blocks, two suture zones, two accretionary zones, one subduction-collision zone, one ramp zone, and six marginal sea basins (Table 2 and Fig. 4).

3.2 *Characteristics of main tectonic units*

3.2.1 *Characteristics of the blocks*

(1) West Burma Block

The West Burma Block, which also includes part of Sumatra, is bounded by the Meso-Tethys ophiolite suture zone to the east and the Neo-Tethys ophiolite suture, the Yarlung Zangbo River-Naga-Rakhine suture zone, and the Rakhine-Java-Timor subduction-collision zone to the west. On its northern boundary lies the eastern syntaxis, where the Indian Plate collides with the Lhasa-Bomi Block, while the southern part of the block is submerged beneath the Andaman Sea. The West Burma Block formed after the subduction of the Meso-Tethys Ocean. Before the Triassic, this block was characterized by exotic metamorphic rocks and sedimentary discontinuities. In the Late Jurassic, the West Burma Block resided within the active Indian continental margin. By the Cretaceous, marine carbonate rocks, presumably Neo-Tethys sedimentary layers, had developed on the western side of this block.

(2) Sibumasu Block

The Sibumasu Block is located on the Shan Plateau between the Bangong-Nujiang suture zone (Meso-Tethys Ocean) and the Changning-Menglian suture zone (Paleo Tethys Ocean). These suture zones are characterized by residual Paleo-Tethys sedimentary formations (Liu et al., 2004c; Chen et al., 2010). The lower Permian biostratigraphic assemblages found in this block indicate that this block may have been sourced from Gondwana (Zhong, 1998); the Sibumasu Block, as a microplate, may have drifted for a long time in the proto-Paleo-Tethys Ocean, where it eventually migrated towards the Gondwanan continent in the late Paleozoic (Li et al., 1999).

(3) Lanping-Simao Block

The Lanping-Simao Block is bounded by the Changning-Menglian-Chiang Rai-Chiang Mai suture zone (Lancangjiang suture zone) to the west and the Ailaoshan deep metamorphic zone and the Nan-Uttaradit ophiolite zone to the east. The block margins are clearly delineated by Paleo-Tethys ophiolite sutures. This block is characterized by late Paleozoic Cathaysia biota (Zhong, 1998). During the subduction of the Lancangjiang and Jinshajiang suture zones, the Paleozoic strata experienced strong deformation and metamorphism, while the Mesozoic and Cenozoic strata were only weakly metamorphosed. As a result, the fold structures in this block are well developed, and volcanic rocks are

Table 2. Division of tectonic units in the South China Sea and its adjacent areas

First-order tectonic units	Secondary tectonic units	
Indo-Australia Plate	–	–
Pacific (Philippine Sea) Plate	–	–
Eurasian Plate	blocks	West Burma Block
		Sibumasu Block
		Lanping-Simao Block
		Indochina Block
		Yangtze Block
		Cathaysian Block
		Qiongnan Block
		Nansha Block
		Northwest Sulu Block
	subduction-collision zone	Rakhine-Java-Timor subduction-collision zone
	suture zones	Majiang suture zone
		Southeast Yangtze suture zone
	accretionary zones	Sarawak-Sulu accretionary zone
		East Sulawesi accretionary zone
	ramp zone	Philippine archipelago ramp zone
	marginal sea basin	South China Sea Basin
		Sulu Sea Basin
		Sulawesi Sea Basin
		Banda Sea Basin
		Makassar Sea Basin
		Andaman Sea Basin

Note: – represents the items not listed here.

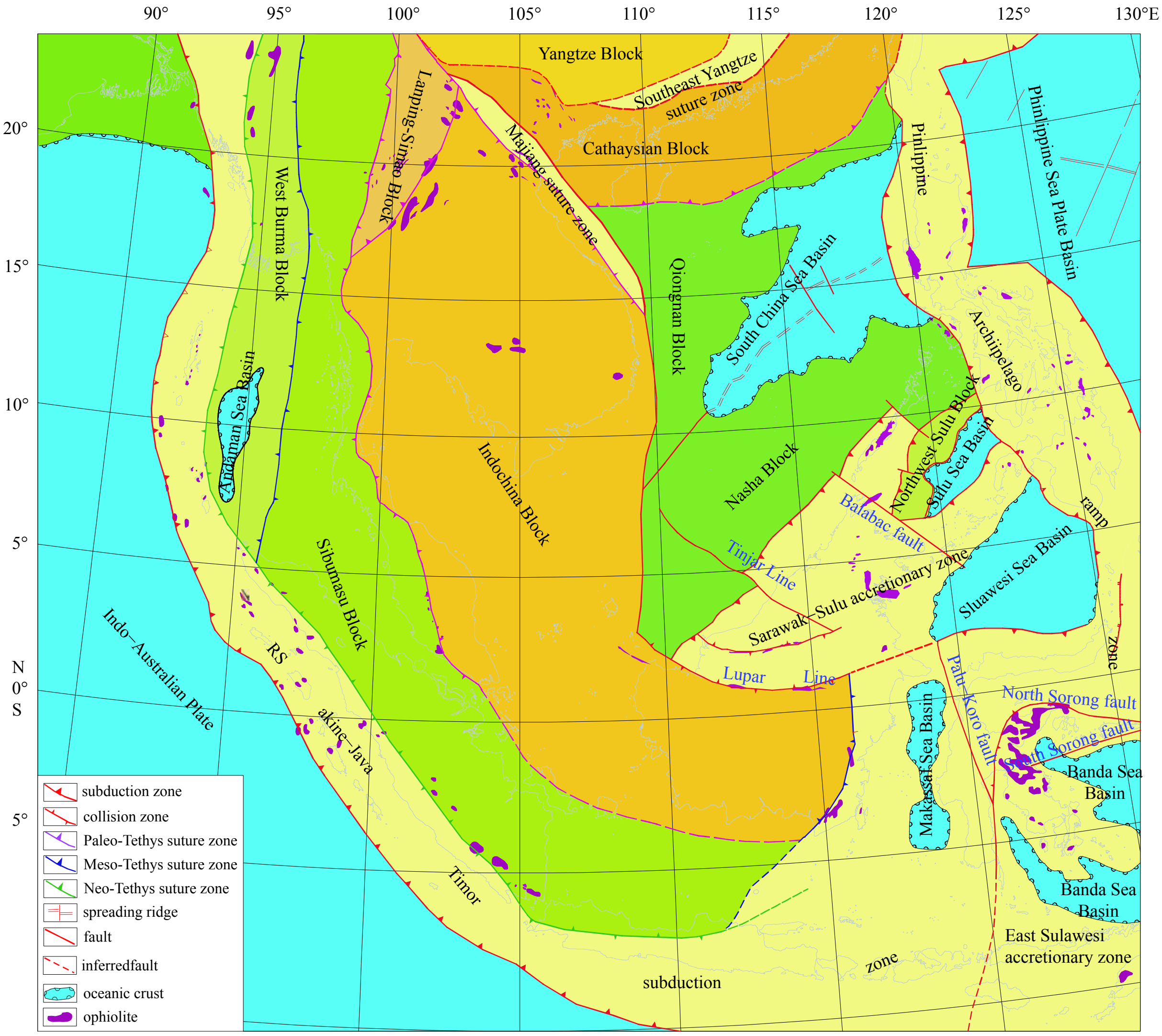

Fig. 4. Distribution and boundary properties of the block tectonic units in our study area.

sporadically distributed.

(4) Indochina Block

The Indochina Block includes the main body of the Indochina Peninsula, as well as parts of the Malay Peninsula, Sumatra Island, and Kalimantan Island. In the northwest, the Indochina Block is separated from the Lanping–Simao Block by the Dien Bien Phu–Nan–Uttaradit suture zone (Paleo-Tethys Ocean); in the northeast, it is connected to the Cathaysian Block by the Majiang suture (Paleo-Tethys Ocean). The Indochina Block is bounded by the Chanthaburi–Shalajiao–Bentong–Raub suture zone (Paleo-Tethys Ocean) to the west and the deep fault system known as the Ailaoshan–Red River–Western-edge fault of the South China Sea–Wan'an fault –Natuna fault-Lupar fault to the east (Cai et al., 2015). While the southwestern edge of the Indochina Block is more difficult to define, this study tentatively placed it along the Meratus ophiolite belt. Structurally, the Indochina Block consists of crystalline schist and gneiss basement rocks from the Archean and Proterozoic eonothems. Li et al. (1982) speculated that these basement rocks are similar to those of the Yangtze Block. During the Hercynian tectonic movement, many fold belts developed in the Indochina Block. The Upper Triassic continental sediments found in the Indochina Block are similar to those of the Yangtze and Cathaysian Blocks.

(5) Yangtze Block

The Yangtze Block is distributed within a large area east of the Ailaoshan deep metamorphic belt, south of the Qinling-Dabie orogenic belt, and north of the Nanling region. The main area visible in the study area is only a small part of the southwestern part of the block. This block is bounded by the Lanping-Simao Block and the Ailaoshan suture zone to the southwest and the Shizong-Mile fault zone to the south. The western boundary of the block is the ophiolitic suture, which is clear. However, due to the thick sedimentary cover, no ophiolite sutures or deep faults and other structural signs, the exact location of the southwestern and southern boundaries is not well known and is a speculative boundary. The Yangtze Block is an ancient continental block that is composed of pre-Sinian basement rocks and Sinian and above caprocks.

(6) Cathaysian Block

The northern (Zhenghe-Dafu and Lianhuashan faults) and western (Majiang ophiolite suture) boundaries of the Cathaysian Block are clearly defined. The Cathaysian Block is bounded to the south by the Qiongnan suture; this suture is a rift-type Caledonian active belt that includes the Qinzhou Hercynian fold belt and the late Paleozoic sea shelf (Wang, 1982). The Guangxi movement in the late early Paleozoic welded the Cathaysian Block and the Yangtze Block together, resulting in a period of relative stability.

(7) Qiongnan Block

The Qiongnan Block is bounded by the Qiongnan suture zone (Liu et al., 2006, 2009; Zhou et al., 2016; Shen et al., 2016) to the north and the western margin of the South China Sea to the west. The Qiongnan Block consists of many smaller tectonic blocks, including the Sanya, Xisha, Zhongsha, and Zhongshabei microblocks. The Qiongnan Block is characterized by Precambrian folded basement rocks that were subjected to intense regional metamorphism in the late Mesozoic (Zhu et al., 2017) and uplifted for a long time. Reef limestones eventually developed in the Qiongnan Block during submersion beneath the sea water until the Miocene.

(8) Nansha Block

The Nansha Block is bounded by the Changlong-Huangyan ocean ridge fault zone to the north and the Kalimantan landmass to the south. Because this block also connects the Luzon-Panay island arc on the east and the Indochina-Sunda shelf on the west, the Nansha Block is defined as a complex mix of continental crust areas, transitional crust areas, oceanic crust areas, extensional divergent margins, transpressional convergent margins, transtensional pull-apart margins, and subduction-nappe margins (Liu et al., 2002c, 2004b, 2004c, 2009, 2017; Yao et al., 2012; Li et al., 2019; Zhu et al., 2018).

(9) Northwest Sulu Block

Separated from the Nansha Block by the northwestern Sulu nappe accretionary zone, the Northwest Sulu Block is located in the northeastern Sarawak-Sulu accretionary zone. This block also includes the Cagayan split continental arc ridge, and the block spreads in the NE direction. On its southeast side is the southeast Sulu oceanic back-arc basin with oceanic crusts, and the boundary between this basin and the Northwest Sulu Block is a regional SE-trending tensional detachment fault in the NE direction (Hutchison, 1975; Hamilton, 1979; Rangin and Silver, 1990; Liu et al., 1998; Li et al., 2020).

3.2.2 *Features of non-block tectonic units*

This study also identified several nonblock tectonic units, including two suture zones (the Majiang and Yangtze suture zones), two accretionary zones (the Sarawak-Sulu and East Sulawesi accretionary zones), one subduction-collision zone (the Rakhine-Java-Timor subduction zone), one ramp zone (the Philippine island arc ramp zone), and six marginal seas or small ocean basins (the South China Sea, Sulu, Sulawesi, Banda, Makassar, and Andaman Basins). These tectonic units are surrounded by deep faults and have experienced intense tectonic activity such as faulting, thrust nappe development, collision, subduction, expansion, and volcanic activity since the Neotectonic period. For example, the boundary between the Philippine island arc ramp zone and the Rakhine-Java-Timor subduction zone is the Palu-Koro fault, and the boundary between the Sarawak-Sulu accretionary zones and the Rakhine-Java-Timor subduction zone is the eastern extension of the Lupar line. These tectonically active zones are also areas where tectonic earthquakes are frequent.

4 Discussion

The division of tectonic units is a concentrated expression of geotectonic ideas and represents a certain tectonic perspective. The geoscale-platform theory developed in the middle of the 19th century, the five major Chinese tectonic schools formed in the early 20th century, and the plate tectonic theory that began in the 1960s all demonstrate our ever-deepening understanding of the tectonics, evolutionary records, and tectonic mechanisms of the Earth's lithosphere (Wang, 1982; Li et al., 1982). Block tectonics theory is the development product and supplement of plate tectonic theory (Zhang et al., 2009; Zhang and Guo, 2014; Guo et al., 2014). Our division of tectonic units in the South China Sea and its adjacent areas fully refers to previous geotectonic understanding. Through the recognition and redefinition of the boundary of a series of tectonic units, block tectonics theory emphasizes the activity structure in plate tectonic theory. The tectonic properties of the units, as well as their boundary characteristics and evolutionary histories, are more clearly understood. Two Paleo-Tethys sutures, located on the boundaries of the Lanping-Simao and Indochina Blocks, may indicate that these two blocks were located on the northern margin of the earliest Tethys Ocean (Chen et al., 2010). Therefore, the Lanping-Simao Block, the Indochina Block, the Yangtze Block, and the Cathaysian Block were part of Laurasia before the Mesozoic, while the West Burma Block, the Sibumasu Block, the Qiongnan Block, the Nansha Block, and the Northwest Sulu Block were located between the Neo-Tethys Ocean suture and the Paleo-Tethys suture (Hutchison, 1975, 1989; Zhu, 1983). During the evolution of the Tethys Ocean, these blocks may have been landmasses floating in the ocean basin and likely belonged to the pan-Cathaysian continental group (Li et al., 1995b). From the crustal structural properties, development records, evolution laws and boundary characteristics of block tectonic units, the tectonic evolution of the South China Sea and adjacent areas is much clearer. In pre-Cenozoic times, the Tethyan tectonic domain and the Paleo-Pacific tectonic domain interacted, which caused the Indochina, Lanping-Simao, Baoshan-Shan Thai, West Burma, Qiongnan, and Nansha Blocks to be sutured together and accreted onto the southeast margin of the Eurasian Plate. In the Cenozoic, the Pacific Plate and the Indian-Australian Plate both collided with the Eurasian Plate, which resulted in the creation of several subduction-collision zones, accretion zones, and marginal sea basins on the eastern, western, and southern margins of the study area (Liu et al., 2004b; Pubellier et al., 2004).

Oil and gas resources tend to concentrate in stable blocks, such as the Cathaysian Block, Qiongnan Block and Nansha Block (Zhang et al., 2018); solid mineral resources are mainly distributed in nonblock tectonic units, such as collision zones and accretionary zones. Therefore, our division of tectonic units in the South China Sea and its adjacent areas provides useful insight into locating oil and gas resources.

5 Conclusions

(1) Block tectonics theory represents a refinement of plate tectonics theory, and it emphasizes the role that stable and active regions play in identifying different tectonic units. Guided by this theory, this study used discriminant markers such as sutures (ophiolite), modern subduction-collision zones, deep faults, and orogenic belts to reliably divide the South China Sea and its adjacent areas into discrete tectonic blocks.

(2) This study ultimately divided the South China Sea and its adjacent areas into nine block tectonic units (the West Burma, Baoshan-Shan Thai, Lanping-Simao, Indochina, Yangtze, South China, Qiongnan, Nansha, and Northwest Sulu Blocks), two suture zones (the Majiang and Southeast Yangtze suture zones), two accretionary zones (the Sarawak-Sulu and East Sulawesi accretionary zones), a subduction-collision zone (the Rakhine-

Java-Timor subduction zone), a ramp zone (the Philippine island arc ramp zone), and six marginal seas or small ocean basins (the South China Sea, Sulu Sea, Sulawesi Sea, Banda, Makassar Sea, and Andaman Sea Basins).

(3) By analysing the crustal tectonic properties, evolutionary history, and boundary characteristics of each block tectonic unit in the South China Sea and its adjacent areas, this study proposed that the Lanping-Simao Block, the Indochina Block, the Yangtze Block, and the Cathaysian Block belonged to Laurasia before the Mesozoic, while the remaining blocks belonged to the Pan-Cathaysian landmass group. The division of block tectonic units plays an important role in building the regional tectonic framework and clarifying the distribution pattern of oil and gas resources in the South China Sea.

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