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Formation and evolution of the South China Sea since the Late Mesozoic: A review

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ABSTRACT

The existing genetic models of the South China Sea (SCS) include an extrusion model of the Indochina Peninsula, a back-arc extension model, and a subduction and dragging model of the Proto-South China Sea (PSCS). However, none of these models has been universally accepted because they do not fully match a large number of geological phenomena and facts. By examining the regional tectonics and integrating them with measured data for the SCS, in this study, a back-arc spreading-sinistral shear model is proposed. It is suggested that the SCS is a back-arc basin formed by northward subduction of the PSCS and its formation was triggered by left-lateral strike-slip motion due to the northward drift of the Philippine Sea Plate. The left-lateral strike-slip fault on the western margin caused by the Indo-Eurasian collision changed the direction of the Southwest Sub-basin's spreading axis from nearly E−W to NE−SW, and subduction retreat caused the spreading ridge to jump southward. This study summarizes the evolution of the SCS and adjacent regions since the Late Mesozoic.

1. Introduction

The West Pacific Margin is one of the largest and most complex plate boundaries in the world today, and a series of marginal seas have developed in this area. Among them, the South China Sea (SCS) is located at the conjunction of the NE and NNW basin chains, which formed in a complex tectonic environment involving the interactions between the Eurasian, Philippine Sea, and Australian plates (Pubellier M and Meresse F, 2013; Yuan XB and Fang NQ, 2019; Li XJ et al., 2017, 2020; Hong WT et al., 2020; Wang LJ et al., 2020; Shang LN et al., 2020).

In recent decades, the SCS has been of continuous interest to many geologists, and a large number of basic geological surveys and studies have been conducted, including 1∶1000000 marine geological and resource surveys and three Ocean Drilling Program-International Ocean Discovery Program (ODP-IODP) drilling expeditions. The National Natural Science Foundation of China (NSFC) has supported the Major Research Program "Deep Sea Processes and Evolution of the South China Sea" (the SCS Deep) since 2010, which has focused on the northern SCS and the related sea basins and investigated the deep-sea processes and evolution in the SCS from a multi-disciplinary perspective. This program has achieved great results.

The northern margin of the SCS is mainly affected by an extensional tectonic regime, resulting in the formation of extensional basins, including the Beibu Gulf Basin (BBGB), the Qiongdongnan Basin (QDNB), and the Pearl River Mouth Basin (PRMB). The northern part of the southern margin has mainly formed in an extensional setting, while the southern part is a subduction-collision zone. The western margin is dominated by a transtensional fault system, which formed the QDNB and Yinggehai Basin (YGHB). The eastern margin is the Manila subduction zone. The central basin is a seafloor spreading area with clear magnetic anomalies. After IODP Expedition 349, the spreading time of each basin was dated. The earliest spreading of the East Sub-basin initiated at about 33 Ma. At 23.6 Ma, the spreading axis jumped southward and the spreading of the Southwest Sub-basin began. The spreading of the East Sub-basin ended at about 15 Ma, and the spreading of the Southwest Sub-basin ended at about 16 Ma (Li CF et al., 2015; Li CF et al., 2014).

The SCS has been studied in depth and is considered to be the most studied marginal sea in the Western Pacific Ocean. However, there are still many difficulties in understanding the

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origin of the SCS due to its unique tectonic setting, as well as the fact that the structures of the eastern and southern margins significantly changed after the formation of the SCS. Therefore, the formation and evolution of the SCS remain controversial, resulting in the coexistence of various genetic models, which will be summarized in the following section.

2. Overview of previous models

Many different models of the formation and evolution of the SCS have been proposed, including an extrusion model (Tapponnier P et al., 1990; Briais A et al., 1993; Replumaz A and Tapponnier P, 2003), a back-arc spreading model (Hilde TWC et al., 1977; Sun WD, 2016), an Atlantic-type spreading model (Ben-Avraham Z and Uyeda S, 1973; Yao BC, 1997), a subduction slab-pull model of the Proto-South China Sea (PSCS) (Holloway NH, 1982; Taylor B and Hayes DE, 1982; Hall R, 1996), a mantle plume model (Deng JF et al., 1992), a dextral strike-slip pull-apart model (Xu JY and Zhang LY, 2000; Li SZ et al., 2012; Wang PC et al., 2017, 2021), a passive spreading under combined effects (Luan XW and Zhang L, 2009), and a hybrid model combining the PSCS slab-pull and Indochina Peninsula extrusion models (Morley CK, 2002; Zhou D, 2002; Sun Z et al., 2006). However, none of these genetic models has been universally accepted because they do not fully match a large number of geological phenomena and facts. Overall, the extrusion and subduction-drag models are the most influential models.

2.1. Extrusion model

Based on physical experiments and geological observations, Tapponnier P et al. (1982, 1990), Briais A et al. (1993), and others have proposed that the collision between India and Eurasia led to the southward extrusion of more than 700 km of the Indochina Peninsula along the left-lateral Ailao Shan-Red River Fault (ASRRF), causing the opening of the SCS (Fig. 1a). This model seems to be reasonable and has been widely cited and supported in China (Xia B et al., 2004; Xie JH et al., 2005). However, many doubts persist. According to Morley CK (2002), extensional structures on the margin of the SCS developed in the Late Cretaceous and Paleogene and the ASRRF developed in the Oligocene, which indicates that the ASRRF was superimposed on the existing extensional structures, so the impact of the fault zone on the continental margin may be a secondary effect rather than a major driving factor of the extension. A similar situation in Thailand suggests that some major faults related to the Oligocene escape tectonics were active before the Oligocene (Watkinson I et al., 2008).

Through a large number of geological surveys, however, it has been found that there are many problems with this model, which makes it inconsistent with the geological phenomena.

(i) The spreading of the SCS was the result of the long-term rifting of the South China continental margin since the Late Cretaceous. The development of these rifts occurred much earlier than the onset of the strike-slip motion on the ASRRF at about 40 Ma, which was followed by the seafloor spreading in the SCS basin at 32 Ma (Taylor B and Hayes DE, 1982; Liang HY et al., 2007). This means that the timings of the two tectonic processes are not consistent.

(ii) If the extrusion of the Indochina Peninsula along the ASRRF and the sinistral motion on the western margin fault (WMF) were the main causes of the spreading of the SCS, the spreading should have developed eastwards, but the actual situation is just the opposite.

(iii) The sinistral movement on the WMF extends southwards and terminates at the Tuy Hoa fault, while the East Wan’An fault to the south becomes dextral. The Tuy Hoa fault is still located in the northern part of the Southwest Sub-basin, which is insufficient to cause the breakup of the SCS. Moreover, the transtensional basins in the western margin of the SCS are filled with Neogene strata, which suggests a smaller magnitude of strike-slip movement on the western margin during the Paleogene.

(iv) The strike-slip displacement on the ASRRF zone was much smaller than that required by a full extrusion tectonic model, and it was mainly accommodated by the YGHB (Searle MP, 2006); therefore, this displacement was insufficient to cause the opening of the SCS by itself.

(v) In the experiment of Tapponnier P et al. (1982), the

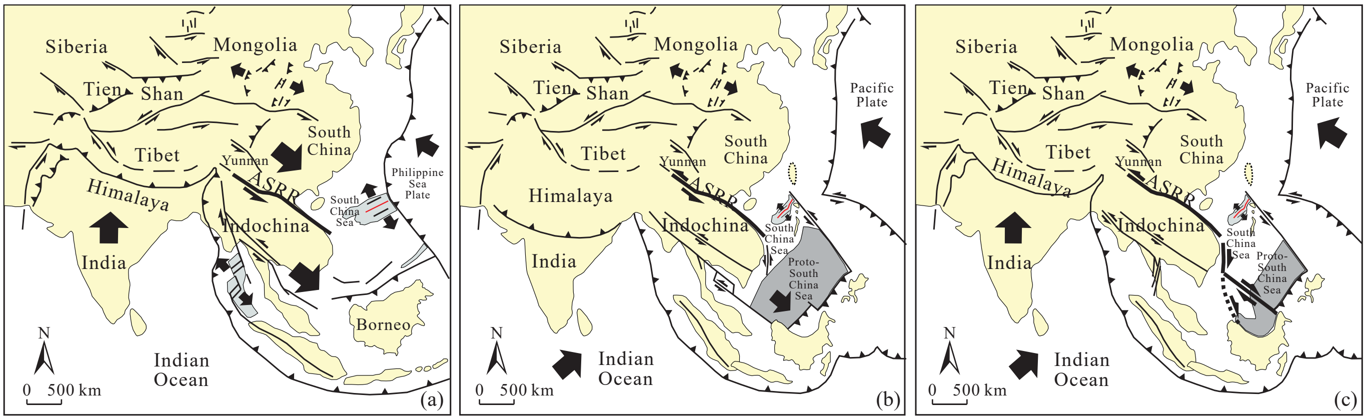

Fig. 1. Map showing the main models of the genesis of the SCS (after Sun WD, 2016). a–Extrusion model; b–PSCS subduction-slab pull model; c–Hybrid model.

southern and eastern sides of the Indochina Peninsula were set as free boundaries, which is different from the facts, i.e., that there are different plates around the Indochina Peninsula and the SCS and there are complex tectonic boundaries and interactions between the different plates, such as the Pacific Plate to the east and the extinct Neo-Tethys and PSCS to the south.

The extrusion model is too simple to explain the geometry, timing and complexity of the development of the SCS. The effect of the Tibetan-Himalayan gravity potential does not extend as far southwards as Southeast Asia (Pubellier M and Meresse F, 2013).

2.2. PSCS subduction-slab pull model

The PSCS subduction-slab pull model (Fig. 1b) hypothesizes that the PSCS once existed on the southern side of the SCS, and the southward subduction-slab pull towards Borneo led to the extension and rifting of the South China continental margin and the opening of the SCS (Hall R, 1996; Zhang GC et al., 2015).

Because the PSCS has been subducted, the key to supporting this hypothesis is to determine the existence and scale of the PSCS. The existence of the PSCS and the hypothesis are supported by the ophiolite suite and the Rajang-Crocker collisional accretion zone along the line from Natuna Island through northern Borneo to the central and southern parts of Palawan Island. It is believed that the Rajang Group and the Crocker Formation are deep-sea deposits formed in the PSCS, which subducted southward along the Lupar Line, forming an accretionary wedge. Therefore, the existence of the PSCS can be confirmed, but there are still potential problems in the model.

(i) The sedimentation of the deepwater Rajang Group in Sarawak, northwestern Borneo, ended in the Middle or Late Eocene, which constitutes the Sarawak Orogen (Cullen A, 2014). Consequently, the PSCS to the west of the Tinjar Line had been subducted, and the Zengmu Block had collided with Borneo and uplifted before the opening of the SCS. Thus, the spreading of the SCS was not relevant to the PSCS to the west of the Tinjar Line.

(ii) The age of the deepwater Crocker Formation in northeastern Borneo may extend into the Middle Miocene, indicating that the closure of the PSCS gradually propagated eastwards, which caused the age of the Rajang-Crocker collision accretionary zone to decrease in the same direction. Therefore, the opening of the SCS should have developed eastwards; however, this is inconsistent with the facts.

(iii) The possibility that the dynamic mechanisms of the southward subduction of the relatively thin PSCS oceanic crust led to the extension of the relatively thick South China continental lithosphere and the spreading of the SCS is doubtful. Sun WD (2016) suggested that the distribution of the existing residual ophiolites is limited, and it is impossible to pull apart the thick South China lithosphere.

(iv) The tomography reveals that only part of the PSCS slab is subducted southward under Borneo, and most of the slab is subducted northward under nearly the entire present SCS area (Wu J et al., 2016; Wu J and Suppe J, 2018).

2.3. Earlier SW Sub-basin spreading model

Based on detailed studies of the tectonic characteristics of the South China Block, it has been found that the NE-trending structures are predominantly older than the nearly EW-trending structures. Yao BC (1997) and Yao BC et al. (2004) proposed that the SCS basin was formed through two stages of spreading. The first occurred from the Late Eocene to the Early Oligocene, with an NW–SE spreading direction, resulting in the formation of the southwest and northwest sub-basins in the SCS. The second occurred from the Late Oligocene to the Early Miocene, and the spreading direction was NS, resulting in the formation of the central basin in the SCS. It is also believed that the SCS experienced Atlantic-type spreading, which included the entire process of continental rifting, continental separation, and seafloor spreading.

Through the IODP drilling expeditions in the SCS, the seafloor spreading evolution was dated (Li CF et al., 2014), and thus the model involving the earlier spreading of the Southwest Sub-basin is not consistent with the facts.

2.4. Plume model

According to the plume model, the spreading in the SCS was the result of plume activity (Yan QS and Shi XF, 2007; Xu YG et al., 2012). Deng JF et al. (1992) considered that three plumes under the East Asian continent led to the formation of the SCS, the Japan Sea, and the Okhotsk Sea, and large areas of Cenozoic rift basalts formed in the three marginal seas and on the continents to the west of these seas. Based on studies conducted on the tectonic-sedimentary filling, thermal structure, and deep background of the BBGB, the YGHB, the QDNB, and the PRMB since the Tertiary, Li ST et al. (1998) suggested that the SCS plume and lateral mantle flow are the most reasonable factors in explaining the formation and evolution of the SCS and its marginal basins in the future.

On the seismic tomography beneath Hainan Island, Zhao DP (2007) suggested that a plume may exist under the SCS, which extends down to the 660 km seismic discontinuity and continues to a depth of about 1900 km. Yan QS and Shi XF (2007) established a model of the formation of the SCS caused by the Hainan plume. However, this hypothesis is not supported by most scholars due to a lack of large-scale magmatism with typical plume head characteristics in the SCS and its surrounding areas.

2.5. Back-arc spreading model

Back-arc spreading is the main genetic model for the marginal seas in the western Pacific, and it is also one of the earliest models for understanding the SCS. In early research, the SCS was regarded as a subducting back-arc basin of the

Philippine Sea (Ben-Avraham Z and Uyeda S, 1973; Guo LZ et al., 1983). As the understanding of the western Pacific Ocean has improved, it has been suggested that the Philippine Arc drifted northward and was gradually emplaced due to the spreading of the Philippine Sea, and it was irrelevant to the formation of the SCS.

Hilde TWC et al. (1977) proposed that the SCS was formed as a back-arc basin during the subduction of the Neo-Tethys Ocean between Australia and Eurasia. According to this model, the northward subduction of the Neo-Tethys Ocean may have started at about 125 Ma, and the spreading of the SCS may have initiated at about 100 Ma. This is not consistent with the actual situation because all of South China was mainly compressed at 100 Ma (Li CF et al., 2014; Sun WD, 2016).

Ren JY and Li ST (2000) suggested that the eastward and southeastward mantle flow induced by the India-Eurasia collision may have resulted in the retreat of the subduction zones on the eastern and southern sides of the East Asian continent and may have triggered back-arc spreading and the formation of the SCS and the Sulu Sea. Sun WD (2016) improved the back-arc spreading model of the SCS and considered that the SCS was formed by the back-arc spreading caused by the northward subduction of the Neo-Tethys Plate between Australia and Eurasia. They proposed a more comprehensive model suggesting that (1) the northward subduction of the Neo-Tethys between Australia and Eurasia may have begun at about 125 Ma. (2) When the Tethys spreading ridge began to subduct, the tectonic mechanism changed from extension to compression, which may have triggered or promoted the subduction of the PSCS. (3) As the northward subduction continued, the PSCS was consumed, north-south back-arc extension began in the north, and the seafloor spreading that formed the SCS began at 33 Ma. However, it remains unclear why the Tethys began to subduct at about 125 Ma but the spreading of the SCS did not initiate until 33 Ma and whether the back-arc spreading of the SCS could occur while the spreading axis was far away from the Neo-Tethys.

2.6. Hybrid model

The hybrid model combines several events, including the combination of the mantle flow generated by the PSCS subduction/traction and India-Eurasia collision (Sun Z et al., 2006), the combination of the PSCS subduction/traction and the southward extrusion of the Indochina Peninsula (Fig. 1c; Morley CK, 2002), and the subduction, shearing, and collision of several plates. In addition, there are other different understandings and models (Lin CS et al., 2006; Cai ZR et al., 2008; Li SZ et al., 2012). However, due to many problems with the hybrid model and other views, they are not widely accepted.

3. Regional tectonic setting

The SCS and its surrounding areas were primarily affected by the movement and reconstruction of three major plates in the Cenozoic. In the west, the Indian Plate drifted northward and collided with the Eurasian Plate. In the middle, the Australian Plate drifted northward and collided with Southeast Asia (Sundaland). In the east, the Paleo-Pacific Plate moved northwestward, and the Philippine Sea Plate formed, drifted northward, and rotated. The SCS developed in this regional tectonic setting, and the interactions between these three plates need to be comprehensively considered to better understand the origin of the SCS (Fig. 2).

3.1. Movement of the Indian Plate and its collision with the Eurasian Plate in the east

Since the Early Cretaceous (125–130 Ma), the Indian and Australian plates have successively separated from the Antarctic Plate and drifted northward by 60° and 40°, respectively (Mcelhinny MW et al., 1974; Sun WD, 2016). The Indian Plate in the west drifted northward rapidly after splitting from the Antarctic Plate during the Cretaceous and collided with the Eurasian Plate in the Eocene (about 55–34 Ma) (Wang EQ, 2017); this led to the extrusion of the Indochina Block and its southern areas along the ASRRF zone to the southeast for hundreds of kilometers (Lee TY and Lawver LA, 1995; Replumaz A and Tapponnier P, 2003). Based on thermochronological evidence, it is generally believed that the sinistral movement on the ASRRF zone began in the Eocene to Early Oligocene or the Late Oligocene to Miocene (Fyhn MBW et al., 2009).

The ASRRF zone extends eastward into the YGHB. A previous study reported that the boundary fault of the YGHB experienced obvious sinistral movement and extension in the Paleogene, and the amount of sinistral movement may have been quite large (Fyhn MBW et al., 2009). The sinistral boundary fault extends southward to the Zhongjiannan Basin and then terminates at the Tuy Hoa Fault Zone. The Wanan East Fault on the south side is mainly dextral (Clift PD et al., 2008).

A series of sedimentary basins controlled by a strike-slip movement developed in the western margin of the SCS, including the YGHB, QDNB, and Wanan Basin from north to south. According to the thickness of the Cenozoic sedimentary strata in the western SCS, the WMF controlled the sedimentary basins and sedimentary thickness (Fig. 3a). Among them, the thickness of the Paleogene strata is relatively small (Fig. 3b) and the thickness of the Neogene strata is large (Fig. 3c), which could indicate that the impact of the WMF mainly occurred in the Neogene. In addition, the rapid northward movement of the Indian Plate and the northward subduction and compression of the Neo-Tethys have resulted in an extensional environment in the eastern part of the South China continental margin since the Early Cenozoic.

3.2. Movement of the Australian Plate and formation of the PSCS in the central area

In the central area, the Australian Plate and the Indian Plate separated from the Antarctic Plate at roughly the same

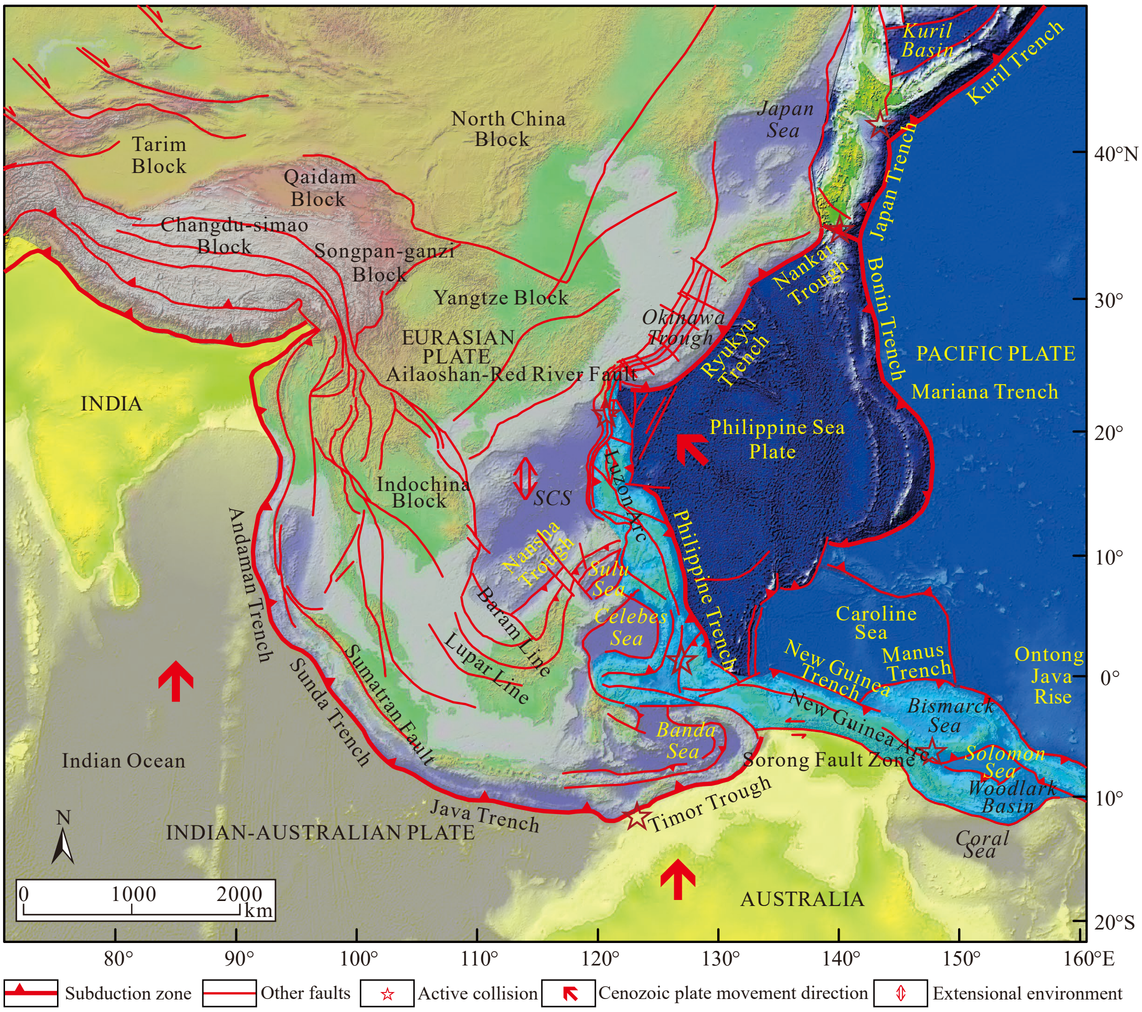

Fig. 2. Map showing the tectonic setting of the SCS and its adjacent areas.

time, and the Neo-Tethys, which was located between the Australian and Eurasia plates, began to subduct northward at about 125 Ma (Sun WD, 2016). However, its movement was much slower than that of the Indian Plate, which was mainly due to the northward subduction of the Neo-Tethys under Borneo, resulting in back-arc spreading in the north and the formation of the PSCS. The spreading of the PSCS and the northward subduction and consumption of the Neo-Tethys offset each other, making the northward movement of the Australian Plate extremely slow.

The western part of Borneo is underlain by the Paleozoic basement, and the Paleozoic strata in southwestern Borneo mainly consist of Carboniferous to Permian metamorphic rocks. The northwestern Kalimantan region contains fossil-bearing Carboniferous limestones, Permian-Triassic granites, Triassic marine shales, Jurassic ammonite-bearing sedimentary rocks, and Cretaceous melanges. In Sarawak, the Triassic flora with a Cathaysian affinity is comparable to that in the Indochina (Hall R et al., 2008; Hall R, 2013).

The Neo-Tethys, which was located on the northern side of Australia, subducted northward under Borneo, forming an island arc in the Schwaner Mountains where granite intrusions were emplaced in the Cretaceous (Galin T et al., 2017). Hall R (2012) suggested that the NE-SW trending Meratus suture from Western Java to the Meratus Mountains in SE Borneo (Fig. 4) is the southeastern boundary of the Cretaceous Sunda continental crust. Java and southeastern Borneo, which lie to the southeast of this line, are composed of ophiolites, island arc strata, and high-pressure and low-temperature metamorphic rocks, which represent the subduction zone formed by the subduction of the Neo-Tethys toward Sunda in the Early Cretaceous. The collisional-accretionary system includes tectonic units representing seafloor spreading, island-arc volcanism, oceanic and forearc sedimentation, and metamorphism (Wakita K, 2000). The Luk Ulo Complex in Central Java consists of serpentinized ultramafic rocks, basalts, chert, limestone, siliceous shales, shales, volcanic breccias, and low temperature and ultra-high pressure metamorphic rocks (Wakita K, 2000).

Based on K-Ar dating of the metamorphic rocks in Java, the HP-LT metamorphism in this suture occurred at 117–124 Ma, and the radiolarians associated with the pillow lavas in Luk Ulo have been dated as Early Cretaceous (Hall R, 2012). The suture line should be the product of the subduction of the Neo-Tethys, which led to back-arc spreading on its northern side and the formation of the PSCS in the late Early Cretaceous-early Late Cretaceous.

According to recent tomography studies, the PSCS

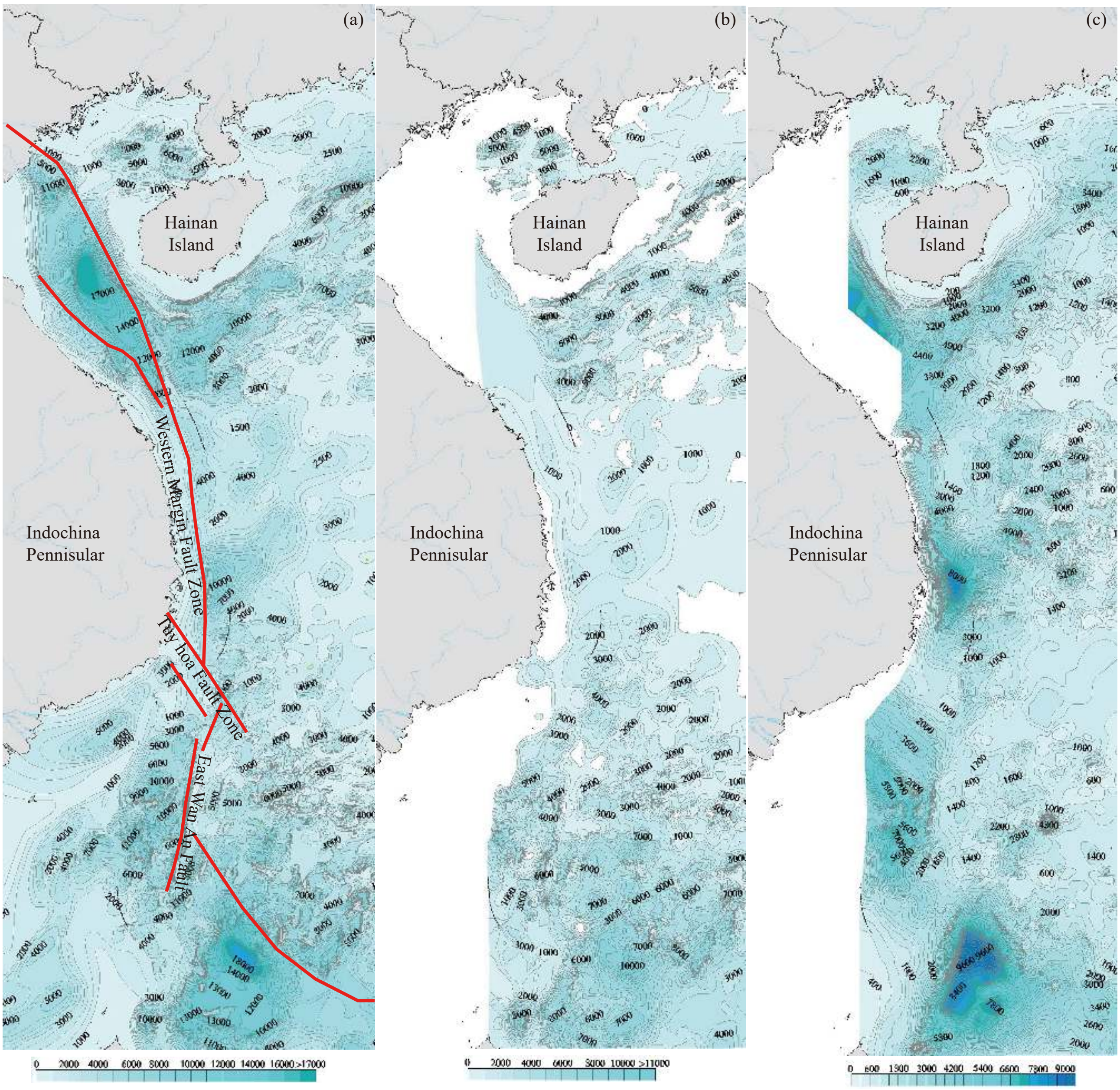

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Fig. 3. Western Margin Fault (WMF) of the SCS and sedimentary thickness. (a)–Cenozoic thickness; (b)–Paleogene thickness; (c)–Neocene-Quaternary thickness.

subducted both southward and northward, although it is generally believed that the PSCS subducted southward (Clift PD et al., 2008; Hutchison CS, 2010). This is similar to the present Molucca Sea Plate, which is subducting both eastward and westward. The south-north length of the PSCS slab was 1600 km (Wu J et al., 2016), and its southwestern part (the PSCS slab) was subducted southward under northern Borneo along the Lupar Line, which led to the collision of the Zengmu Block and northern Borneo.

The southward subduction of the PSCS along the Lupar Line is confirmed by the widespread accretion, ophiolite emplacement, volcanic activity, compressive deformation, uplift, and crustal thickening in northern Borneo (Fyhn MBW et al., 2009; Madon M et al., 2013). The ophiolite and ophiolitic melange along the Lupar Line are exposed along the line from Natuna Island through the northern part of Kalimantan Island to the southern part of Palawan Island (Fig. 3). In the Eocene, the Zengmu Block collided with Borneo and uplifted at about 43 Ma, forming the Sarawak orogenic belt (Lu BL et al., 2014). In the offshore area, the T_8 unconformity, which represents the Xiwei movement, is also clear (Yang MZ et al., 1996).

In addition, the northern slab of the PSCS has subducted northward beneath Nansha and northern Palawan since approximately the Eocene. The subducted northern slab of the PSCS (up to 900 km in length, Figs. 5–6) existed beneath almost the entire SCS, and the SCS was generally consistent with the eastern margin of the PSCS slab, indicating that they

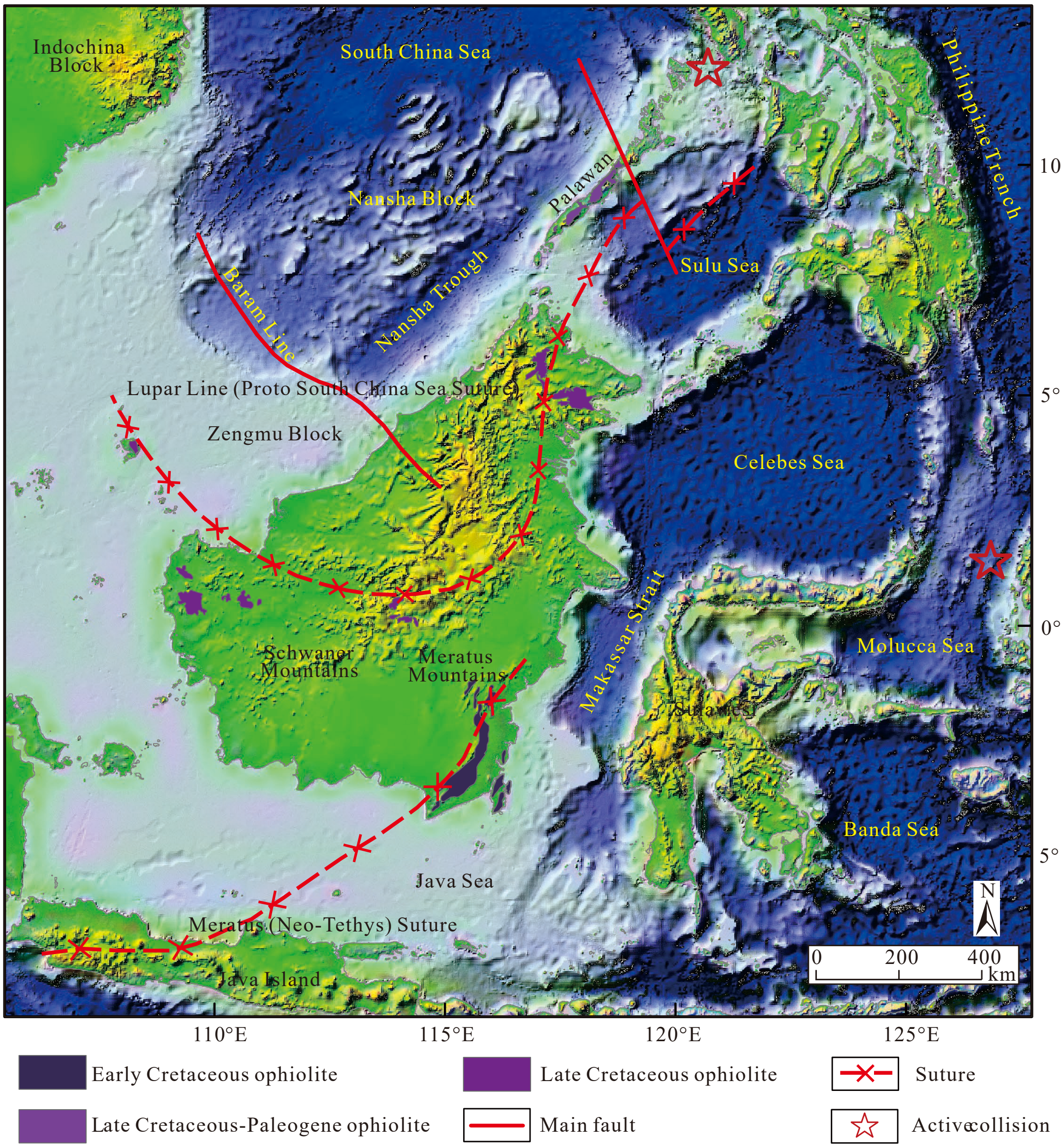

Fig. 4. Distribution of ophiolite and suture lines in southern SCS (Modified from MGBP, 2010; Aurelio MA et al., 2014; Galin T et al., 2017; Hutchison CS, 2010; Hall R, 2013; Pubellier M et al., 2004; Hall R et al., 2008; Lu BL et al., 2014).

were closely related. Therefore, it can be inferred that the northward subduction of the PSCS led to the back-arc spreading that formed the SCS (Wu J et al., 2016; Wu J and Suppe J, 2018).

Palawan Island is divided into northern Palawan and central-southern Palawan. The oldest stratum in North Palawan is Permian, and the Triassic to Jurassic stratigraphic section is characterized by deep-water chert silicalite. The oldest rocks dredged from the Reed Bank are dense, gray-black, laminated Middle Triassic siliceous rocks, which is comparable in age to the radiolarians in the Middle Triassic chert bands exposed in northern Palawan and on Calamian Island. It is generally believed that the North Palawan and Nansha blocks are micro-continental blocks separated from South China during the spreading of the SCS (Yumul GP et al., 2008; Aurelio MA et al., 2012).

Central-southern Palawan is an orogenic belt that is mainly composed of ophiolites and mélanges, which originated in an ocean basin formed during the Cretaceous (Rangin C et al., 1990). The ophiolites in central Palawan have been dated to 40–42 Ma (Raschka H et al., 1985). The ^{39}Ar/^{40}Ar age of the southern Palawan pillow basalt is 34 Ma (Encarnación J, 2004). The ophiolite thrust structure developed in central and southern Palawan was formed by the subduction and collision between the Cagayan Ridge and the Nansha-North Palawan Block (Liu WN et al., 2014). The ophiolite is Oligocene in age (33–23 Ma) and was thrust onto turbidite deposits (Aurelio MA et al., 2014).

The collision orogenic belt in central-southern Palawan is the eastward extension of the Sabah orogenic belt. The northwestern boundary of this belt is the frontal thrust fault zone at the Palawan shelf margin, and the southeastern boundary is the arc-continent collision suture between the Cagayan arc and the Nansha Block. The suture extends northeastward, gradually approaches the Calamian micro-continental block, and eventually meets at the southern end of

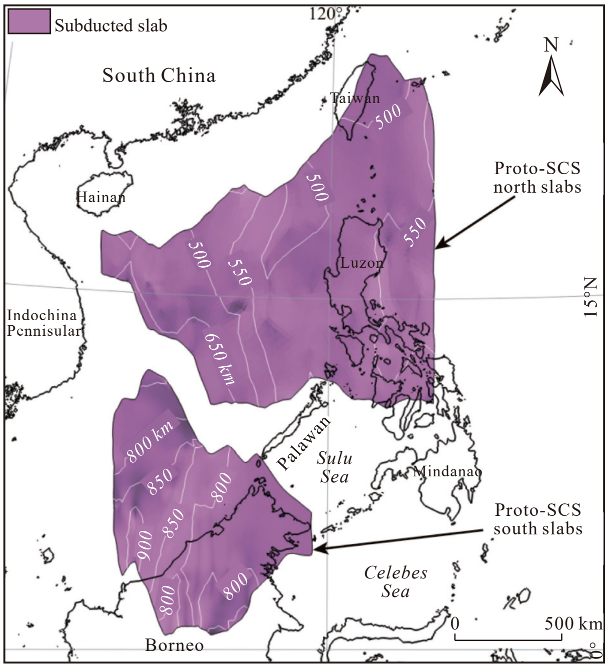

Fig. 5. Distribution of the PSCS slabs (Modified from Wu J and Suppe J, 2018).

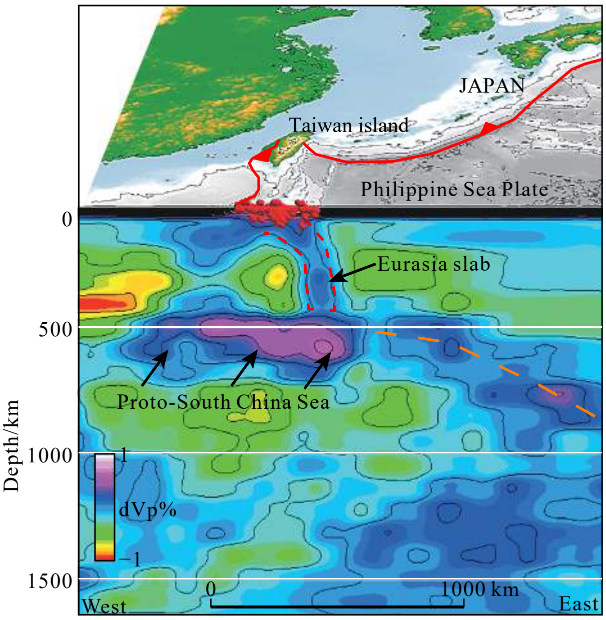

Fig. 6. Tomographic cross-section showing the PSCS slabs beneath the SCS (Modified from Wu J and Suppe J, 2018).

the Philippine mobile belt. The suture connects with the Lupar Line in the west and constitutes the integrated suture of the PSCS.

3.3. Subduction of the Paleo-Pacific Plate and evolution of the Philippine Sea Plate in the east

The Philippine Sea Plate is surrounded by subduction zones. The northern part of the Philippine Sea Plate was subducted under the Eurasian Plate along the Ryukyu Trench and the Nankai Trough, and the western part was subducted towards the Philippine Island Arc along the Philippine Trench. The eastern part is the Mariana Trench and the Izu-Bonin Trench, and the southwestern part is the Yap Trench (Fig. 2).

The Philippine Sea Plate consists of several Cenozoic sub-basins, including the West Philippine Basin, the Shikoku Basin, the Parece Vela Basin, and the Mariana Basin. The seafloor spreading in the West Philippine Basin began in the Early Cenozoic (about 58–51 Ma) (Hilde TWC and Lee CS, 1984; Deschamps A and Lallemand S, 2002; Ishizuka O et al., 2013) and ended at 34–36 Ma or 33–30 Ma (Deschamps A and Lallemand S, 2002). The spreading of the Shikoku and Parece Vela basins began at about 30 Ma and continued until about 15 Ma (Sdrolias M et al., 2004). The seafloor spreading in the Mariana Trough began at the end of the Miocene (about 7 Ma) and continues at present, forming the Mariana Basin (Yamazaki T et al., 2003; Wu J et al., 2016).

Paleomagnetic studies have revealed that the Philippine Sea Plate experienced large-scale northward movement and clockwise rotation in the past (Hall R et al., 1995; Hall R, 2002). The Philippine Sea Plate was located near the equator at the beginning of its formation, but later moved northward by about 20° latitudinally (Queano KL et al., 2007; Yamazaki T et al., 2010). Since 40 Ma, the northward movement rates of the Indian-Australian Plate and the Philippine Sea Plate have been similar. Paleo-latitude studies in the North Philippine Sea have revealed that the northward movement of the Philippine Sea Plate mainly occurred before 25 Ma, but a small amount of northward movement occurred after 15 Ma (Wu J et al., 2016).

Hall R (2002) concluded that the Philippine Sea Plate rotated about 50° during 55–45 Ma; no obvious rotation occurred during 40–25 Ma; 34° clockwise rotation occurred during 25–5 Ma; 5.5° clockwise rotation occurred during 5–0 Ma. This suggests that the Parece Vela and Shikoku basins formed during the non-rotation (28–25 Ma) to clockwise rotation (25 Ma) periods of the Philippine Sea Plate, and spreading ceased at 15 Ma (Sdrolias M et al., 2004).

The Philippine Sea Plate moved northward significantly, and a large-scale sinistral strike-slip fault formed on its western margin (Fig. 7). In a mainly back-arc spreading environment, this strike-slip fault would trigger north-south extension from east to west, leading to seafloor spreading. Compared with the rotation of the Philippine Sea Basin, the spreading period of the SCS coincided with the period during which the Philippine Sea Plate did not experience obvious rotation, and pure translational shear may have been more likely to trigger extension.

4. Back-arc spreading-sinistral shear model

The above analysis shows that there are obvious defects in many of the existing genetic models of the SCS, which are not consistent with the actual observations. The authors believe that the formation of the SCS was mainly controlled by three factors: (1) The northward drift of the Indian Plate to the west and the extrusion of the Indochina Block; (2) the northward movement of the Australian Plate and the subduction of the Neo-Tethys in the central region led to the formation of an extensional environment in Southern China and; and (3) the formation and northward movement of the Philippine Sea Plate in the east since the Eocene led to large-scale left-lateral strike-slip activity on its western margin. Based on the available data, the authors suggest that the back-arc spreading caused by the subduction of the PSCS was key to the formation of the SCS. The left-lateral shear caused by the northward movement of the Philippine Sea Plate triggered the spreading. The collision between India and Asia led to the extrusion of the Indochina Peninsula, and the sinistral strike-slip movement caused the spreading axis in the southwestern SCS basin to transform from nearly EW to NE. The specific evolution is described below and is illustrated in Figs. 8–9.

(i) In the Early Cretaceous (about 125 Ma), the Australian Plate separated from the Antarctic Plate and drifted northward, and the Neo-Tethys between Australia and Eurasia subducted northwards along the Meratus line, resulting in back-arc spreading in the north and the formation of the PSCS. Therefore, it is speculated that the PSCS may have formed in the Early Late Cretaceous to Paleocene (about 100–60 Ma), which is roughly consistent with the age of the ophiolite found in the Lupar fault zone in northern Borneo (Wakita K, 2000; Hall R, 2012).

(ii) From the latest Cretaceous to the Eocene, with the continued northward subduction of the Australian Plate, northern Australia began to be compressed and the PSCS began to subduct northwards and southwards successively. The southwestern PSCS was subducted southwards under northern Borneo along the Lupar Line; and most of the PSCS was subducted northwards under the Nansha-North Palawan blocks to the east of the Tinjar Line, resulting in a back-arc extensional environment in the South China continental margin and a rifting continental margin.

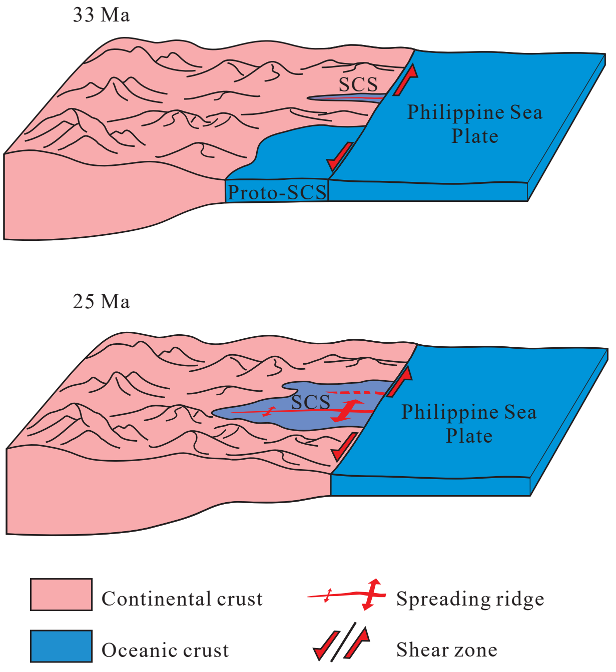

Fig. 7. Schematic diagram of the strike-slip boundary in the eastern SCS.

(iii) In the Middle-Late Eocene (about 45 Ma), India collided with Eurasia, resulting in the extrusion of the Indochina Peninsula. During this period, the direction of the subduction of the Pacific Plate toward the East Asian continental margin changed from NNW to NWW. The convergence from both sides enhanced the north-south extension of South China. Thereafter, the PSCS subducted northward during 43–38 Ma, and the Zengmu Block collided with northern Borneo along the Lupar suture zone from west to east, forming the Sarawak orogenic belt, which is shown as the Xiwei movement in the offshore area.

(iv) After the Eocene, the Philippine Sea Plate formed in the east and moved northward, accompanied by clockwise rotation (Hall R et al., 1995), resulting in large-scale sinistral strike-slip motion on its western margin. As a result, in the Early Oligocene (32–33 Ma), sea-floor spreading began in the earlier rift, and the SCS opened in a scissor-like manner from east to west.

(v) Under the effects of the westward propagation of the spreading of the SCS and the retreat of the subduction zone, the spreading center jumped southward by the end of the Oligocene (about 24 Ma). At the same time, due to the extrusion of the Indochina Peninsula caused by the India-Eurasia collision, the direction of the spreading axis gradually changed from nearly E–W to NE–SW.

(vi) In the late Early Miocene (about 16 Ma), the spreading of the SCS ceased due to the collision between the Nansha-North Palawan Block and the Cagayan Ridge, which was named the Sabah orogeny by Hutchison CS (2010).

5. Discussion

The back-arc spreading-sinistral shear model considers the regional tectonics and the evolution of the South China Sea and its surrounding areas since the end of the Mesozoic, including the subduction and consumption of the Neo-Tethys and Proto South China Sea due to the northward drift of Australia in the central area; the northwestward movement of the Paleo-Pacific in the east, especially the formation of the Philippine Sea Plate and its northward drift and rotation; the northward drift of the Indian Plate and its collision with the Eurasian Plate in the west, this resulted in the extrusion of the Indochina Block. With more comprehensive consideration of the regional tectonic controls on the formation of the South China Sea, this model is more reasonable than previous models, including the extrusion model (Tapponnier P et al., 1982, 1990) and the PSCS subduction-slab pull model (Hall R, 1996; Zhang GC et al., 2015).

According to the current understanding, the Japan Sea, Okinawa Trough, and Mariana Trough in the West Pacific Margin all have a back-arc spreading origin. The surrounding tectonic environment did not change significantly after their formation and the trench-arc-basin system remained intact, which is the key to understanding their origin.

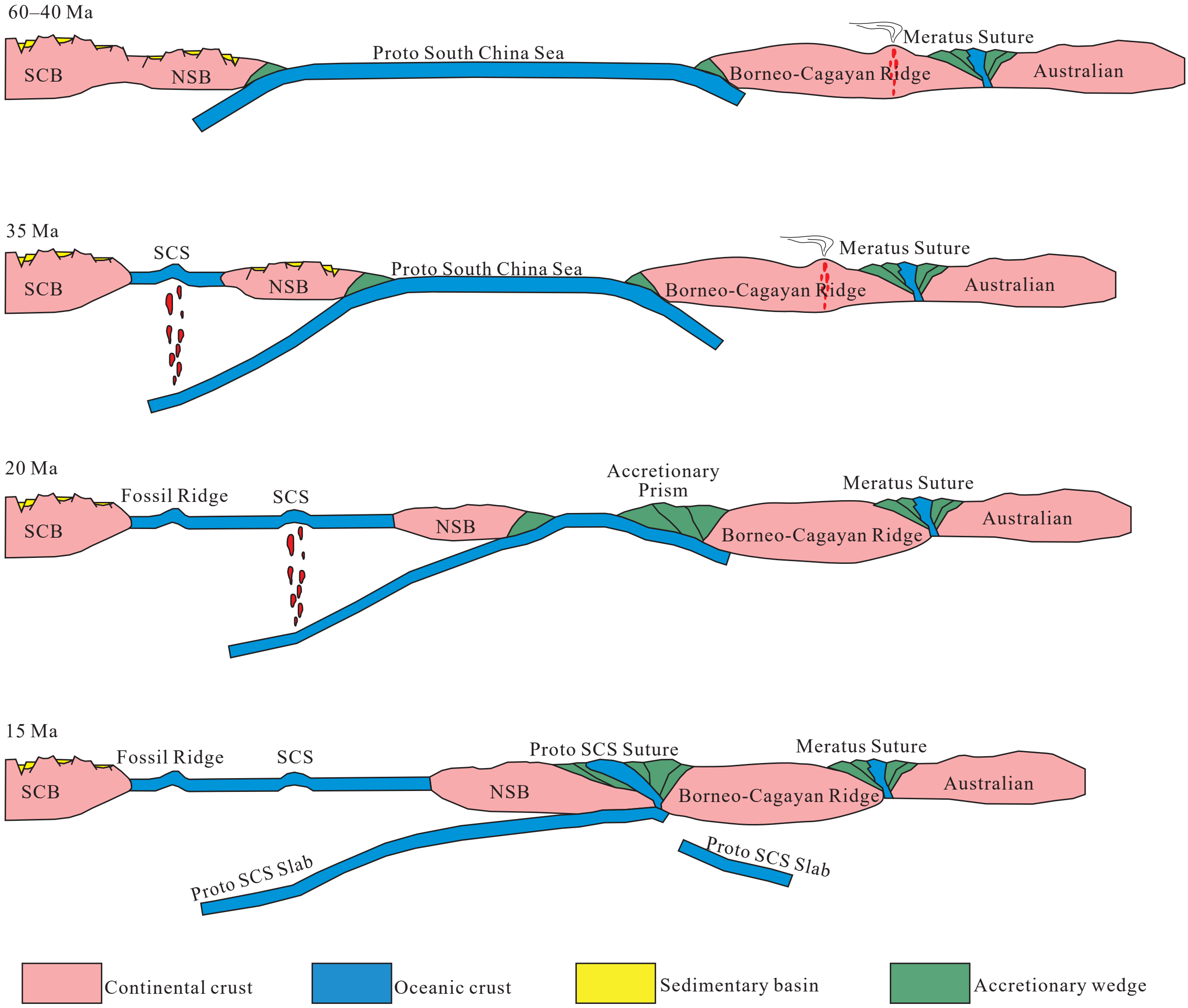

Fig. 8. Cross-sectional model showing the evolution of the SCS.

In contrast, the surrounding tectonic environment changed a great deal after the formation of the South China Sea, the Sulu Sea, and the Celebes Sea in the central section of the West Pacific Margin (Li XJ et al., 2017). For example, the formation and emplacement of the Philippine Sea Plate in the east completely changed the characteristics of the eastern margin, and the changes were more complex in the southern margin and southeastern margin. In addition, the oceanic crust of these marginal seas was subducted differentially. All of these factors increase the difficulty of understanding the formation of the South China Sea while providing a reference for many other different hypotheses.

After fully analyzing these tectonic factors, it is natural to assume that the tectonic environment and the timing of the formation of the Cenozoic marginal seas in the western Pacific were similar to a certain extent, and perhaps there is a similar genetic mechanism. Since the end of the Mesozoic, the Australian Plate has been drifting northward, and the subduction and disappearance of the Neo-Tethys domain are bound to occur on its north side. However, it is difficult to recognize the traces of the subduction and disappearance due to the later reworking. The Sabah Ophiolite in the northeastern part of Kalimantan and the central-southern Palawan Ophiolite may be evidence of the consumption of the Neo-Tethys, but the central-southern Palawan Ophiolite was subjected to a later thrust event and overlies Eocene strata (Aurelio MA et al., 2014).

After IODP Expedition 349, the timing of the spreading of the South China Sea was basically indisputable, and it was determined that the eastern sub-basin began to spread earlier (about 32–33 Ma), the spreading center jumped southward at 24 Ma when the Southwest Sub-basin developed, and the spreading of the two sub-basins ended concurrently at about 16–17 Ma (Li CF et al., 2014). The spreading propagated from east to west, which also indicates that the tectonic evolution of the east side of the South China Sea played a more important role in the formation of the South China Sea than that of the west side. After its formation in the Eocene, the Philippine Sea Plate, which was located on the eastern margin of the South China Sea, moved northward by about 2000 km (Hall R, 2002), and a large sinistral strike-slip fault may have formed along its western margin. The tomography

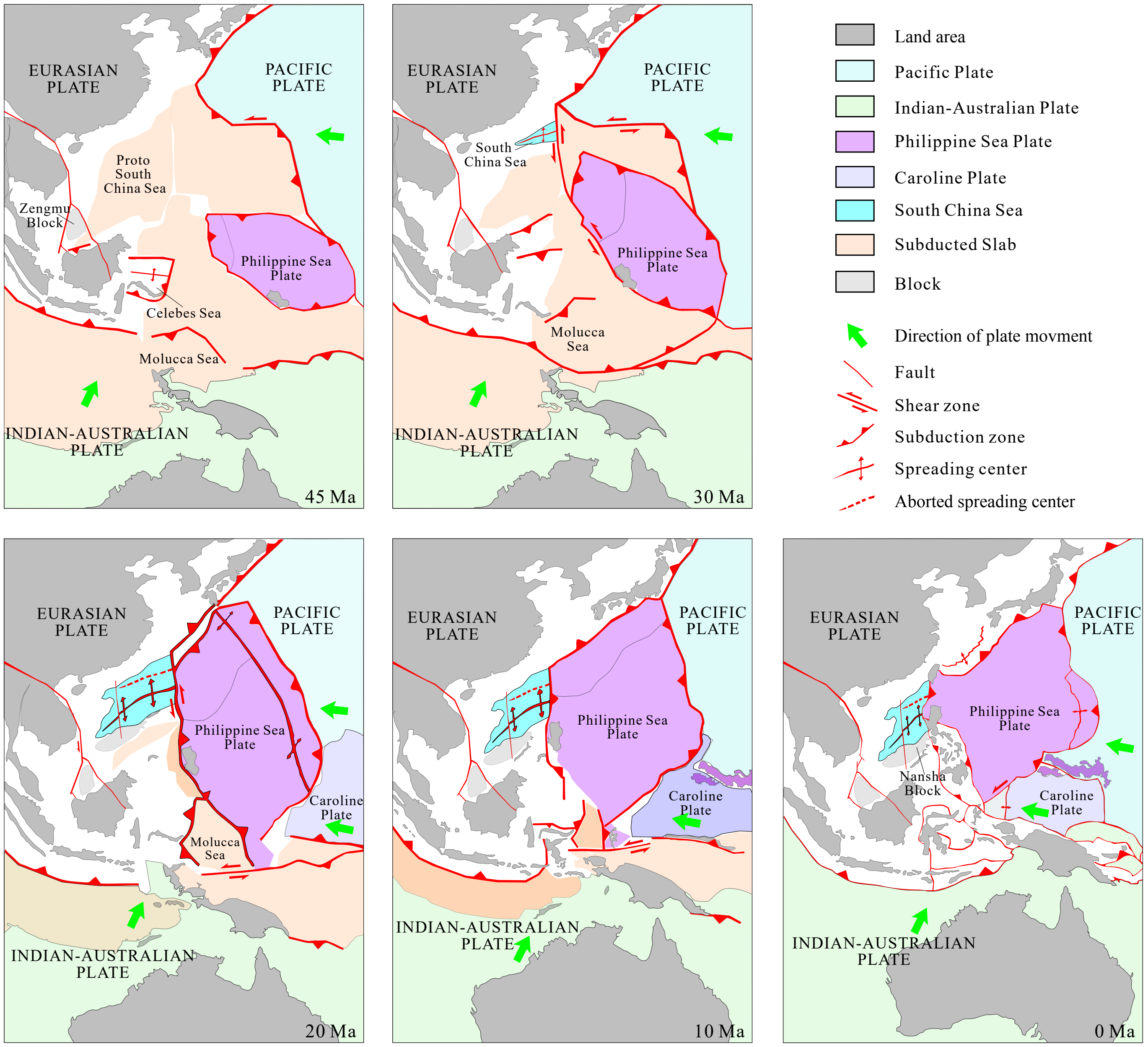

Fig. 9. Schematic map showing the evolution of the SCS and its surrounding areas (the regional tectonic evolution is based on Wu J et al., 2016).

also reveals that the eastern margin of the South China Sea was roughly coincident with the western margin of the Philippine Sea Plate when the South China Sea was formed (Wu J et al., 2016; Wu J and Suppe J, 2018). This fault could trigger the expansion of the South China Sea.

The southward jump of the spreading ridge of the South China Sea is not reasonably explained by the extrusion model, the PSCS subduction-slab pull model, or the mantle plume model, while the model in which the subduction retreat causes back-arc spreading is very reasonable. The spreading ridge developed southwestward and its trend changed from nearly east–west to the northeast, which is difficult to explain using the previously proposed models. The authors believe that this may be the result of the southward movement of the Indochina Block due to the India-Asia collision.

6. Conclusion

The surrounding tectonic environment of the SCS has undergone a complex evolution process since its formation, this resulted in the origin of the SCS being the focus of long-term controversy. In recent years, several investigations have been conducted on the SCS and substantial survey data have been accumulated. Furthermore, in-depth studies have been carried out from different perspectives and a variety of genetic evolution models have been proposed. However, none of these models has been widely accepted.

Based on the interactions between the three major plates since the Late Mesozoic and the measured data for the SCS, this paper proposed a back-arc spreading-sinistral shear model for the formation of the SCS. The back-arc spreading caused by the subduction of the PSCS was critical to the formation of the SCS. Additionally, the sinistral shear caused by the northward movement of the Philippine Plate was the trigger of the spreading. The India-Asia collision, the extrusion of the Indochina Peninsula, and the sinistral strike-slip motion caused the direction of the spreading axis of the southwestern SCS to change from nearly E–W to NE. Moreover, the subduction retreat caused the spreading ridge to jump southward.

CRediT authorship contribution statement

Xue-Jie Li conceived the presented idea. Xue-Jie Li and Zhe Wang contributed to the interpretation of the results. All of the authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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