Acta Geochim (2016) 35(3):215–225
DOI 10.1007/s11631-016-0110-x

ORIGINAL ARTICLE

Initiation and evolution of the South China Sea: an overview

Weidong Sun[1,2]

Received: 23 February 2016 / Revised: 4 May 2016 / Accepted: 16 May 2016 / Published online: 3 June 2016

Abstract Different models have been proposed for the formation and tectonic evolution of the South China Sea (SCS), including extrusion of the Indochina Peninsula, backarc extension, two-stage opening, proto-SCS dragging, extension induced by a mantle plume, and integrated models that combine diverse factors. Among these, the extrusion model has gained the most attention. Based on simplified physical experiments, this model proposes that collision between the Indian and Eurasian Plates resulted in extrusion of the Indochina Peninsula, which in turn led to opening of the SCS. The extrusion of the Indochina Peninsula, however, should have led to preferential opening in the west side of the SCS, which is contrary to observations. Extensional models propose that the SCS was a backarc basin, rifted off the South China Block. Most of the backarc extension models, however, are not compatible with observations in terms of either age or subduction direction. The two-stage extension model is based on extensional basins surrounding the SCS. Recent dating results indeed show two-stage opening in the SCS, but the Southwest Subbasin of the SCS is much younger, which contradicts the two-stage extension model. Here we propose a refined backarc extension model. There was a wide Neotethys Ocean between the Australian and Eurasian Plates before the Indian-Eurasian collision. The ocean floor started to subduct northward at ~125 Ma, causing backarc extension along the southern margin of the Eurasian Plate and the formation of the proto-SCS. The Neotethys subduction regime changed due to ridge subduction in the Late Cretaceous, resulting in fold-belts, uplifting, erosion, and widespread unconformities. It may also have led to the subduction of the proto-SCS. Flat subduction of the ridge may have reached further north and resulted in another backarc extension that formed the SCS. The rollback of the flat subducting slab might have occurred ~90 Ma ago; the second backarc extension may have initiated between 50 and 45 Ma. The opening of the Southwest Subbasin is roughly simultaneous with a ridge jump in the East Subbasin, which implies major tectonic changes in the surrounding regions, likely related to major changes in the extrusion of the Indochina Peninsula.

Keywords South China Sea · Neotethys · Plate subduction · Ridge subduction · Indochina Peninsula extrusion · Backarc extension · Multiple plate interactions · Proto-South China Sea

1 Introduction

The South China Sea (SCS) is the largest marginal sea in the world, with an area of about 3.5 million km^2, and has been a hot topic among geologists in China and western countries (Sun et al. 2011; Zhou et al. 2011; Xu et al. 2012; Huang et al. 2013; Li et al. 2014a; Liu et al. 2014; Tang et al. 2014; Clift et al. 2015; Lei et al. 2015). Tectonically, the SCS is located at the junction of the Eurasian, Indian, Australian, and Pacific Plates and its formation is commonly attributed to interactions among these plates (Sun et al. 2006; Xia et al. 2006). The details of the formation

✉ Weidong Sun
weidongsun@gig.ac.cn

[1] CAS Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

[2] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China

and evolution of the SCS have been hotly debated due to its special tectonic setting and multiple plate interactions (Taylor and Hayes 1980, 1982; Tapponnier et al. 1982; Briais et al. 1993; Zhou et al. 1995, 2002, 2008; Chung et al. 1997; Sun et al. 2006, 2009, 2011). Here we discuss major models on the origin and evolution of the SCS. Based on the drifting history of the Indian, Australian, and Pacific Plates since the Cretaceous, we propose that the initiation of the SCS was controlled by backarc extension associated with the northward subduction of the Neotethys. Southward extrusion of the Indochina Peninsula was not the controlling factor.

2 Brief description of different models of the South China Sea

A variety of models have been proposed for the initiation, formation, and evolution of the SCS, including the extrusion model (Tapponnier et al. 1990; Briais et al. 1993), backarc extension model (Hilde et al. 1977), two-stage rifting model (Yao 1999), proto-SCS dragging model (Holloway 1982; Taylor and Hayes 1982; Hall 1996), models that involve extension induced by mantle plume (Flower et al. 1998), combinations of proto-SCS pull and extrusion of the Indochina Peninsula, and/or mantle flows (Tamaki 1995; Morley 2002; Zhou et al. 2002; Sun et al. 2006), etc.

2.1 The extrusion model of the Indochina Peninsula

The most famous model for the formation of the SCS is the extrusion model proposed by Tapponnier et al. based on physical modeling experiments (Fig. 1) (Tapponnier et al. 1982, 1990; Briais et al. 1993). According to this model, collision between the Indian and Eurasian continents resulted in major deformation in the Eurasian crust, leading to >700 km of southward extrusion of the Indochina Peninsula along the Ailaoshan–Red River sinistral fault. The model is based mainly on physical experiments with plasticine, on structural data of the crustal-scale Ailaoshan–Red River fault, and on the spreading history of the SCS (Tapponnier et al. 1990). The synchronicity between the strike-slip movement of the fault (Tapponnier et al. 1990; Leloup et al. 1993) and the spreading of the SCS (Taylor and Hayes 1980, 1982) was initially viewed as key evidence. However, as study on the SCS continued, problems emerged with the extrusion model:

(1) Age discrepancy. Ocean floor magnetic anomalies provide an efficient method for dating the ocean floor. The accuracy of this method, however, requires that the absolute age of at least one point is well known. Therefore, this method is most reliable for dating ocean floors with active spreading centers, i.e., with a starting age of zero. It was once thought that the SCS is no longer spreading. Therefore, magnetic anomaly dating of the SCS was governed by an estimate of the initiation time of the SCS. The widely cited age of 32 Ma was estimated based on sedimentary records in the northern part of the SCS (Taylor and Hayes 1980, 1982). Combined with analyses of deep-tow magnetic anomalies, it is inferred that the initial seafloor spreading started around 33 Ma in the northeastern SCS, with a 1 to 2 Myr variation along the northern continent-ocean boundary. Recently collected International Ocean Discovery Program

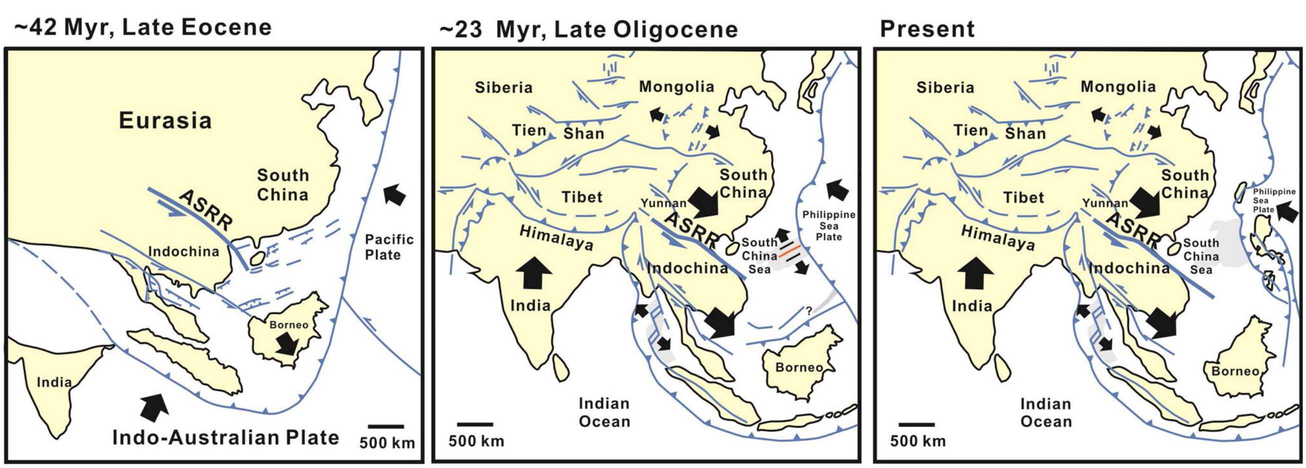

Fig. 1 The extrusion model of Tapponnier. According to this model, the collision between the Indian and Eurasian Plates resulted in sinistral stike-slip movement of the Ailaoshan–Red River fault (ASRR), and consequently the southward extrusion of the Indochina Peninsula, leading to the opening of the SCS (Tapponnier et al. 1982, 1990; Briais et al. 1993; Leloup et al. 1993)

(IODP) Expedition 349 cores show the terminal age of seafloor spreading to be ~15 Ma in the East Subbasin and ~16 Ma in the Southwest Subbasin (Li et al. 2014a), which is consistent with the collision unconformity in Nansha (Sun et al. 2011). In contrast, the initiation time of the Ailaoshan–Red River fault is ~40 Ma, about 6–8 Myr earlier than previous results (Taylor and Hayes 1980, 1982; Chung et al. 1998; Liang et al. 2007). This makes the oldest oceanic crust in the SCS younger than the initiation of extension and continent breakup. Therefore, the ages of the SCS do not support the extrusion model.

Moreover, there was a southward ridge jump at ~23.6 Ma in the East Subbasin, which was coeval to the onset of seafloor spreading in the Southwest Subbasin (Li et al. 2014a). This cannot be plausibly explained by extrusion along the Ailaoshan–Red River shear zone.

(2) Drillhole samples from Reed Bank show an obvious unconformity corresponding to >65 Ma (Fig. 2). This unconformity is actually widely distributed around the SCS (Taylor and Hayes 1982). Moreover, geophysical data show well-developed folds below this unconformity (Yan and Liu 2004), which indicate collision/compression before the extension of the SCS. Paleocene marine sediments are in direct contact with Early Cretaceous sediments in the Nansha Islands (Schluter et al. 1996), suggesting that collision was followed by extension in or before the Paleocene. Taylor and Hayes (1982) proposed that the extension in the SCS occurred at 65 ± 10 Ma, i.e. before the collision between the Indian and the Eurasian continents (Chung et al. 1998, 2005; Wu et al. 2010; Yin 2010). Given that the extrusion of the Indochina block was much later, the collision between the Indian and Eurasian continents was not likely the primary driving force of extension in the SCS.

(3) Both the south and east sides were set as free boundaries in the physical experiment of Tapponnier et al. (1982). This is not realistic as shown by later plate reconstruction results (Lee and Lawver 1994; Hall 1996). There were several plate subductions around the SCS: the Pacific Plate in the east, and the now vanished Neotethys and proto-SCS plates in the south.

Subducting plates may interact intensively with obducting plates. Major orogens may form particularly during flat subduction, as along the Andes where the Pacific pPlate is subducting underneath the American continent (Sobolev and Babeyko 2005). The unconformity and folds before ~65 Ma likely resulted from the interaction between subducting plates and the Eurasian continent due to a changed subduction regime, such as the subduction of the Neotethys spreading ridge. Therefore, experiments with free boundaries cannot reflect the real geodynamic conditions.

(4) The laboratory experiments with plasticine cannot precisely simulate the physical properties of rocks,

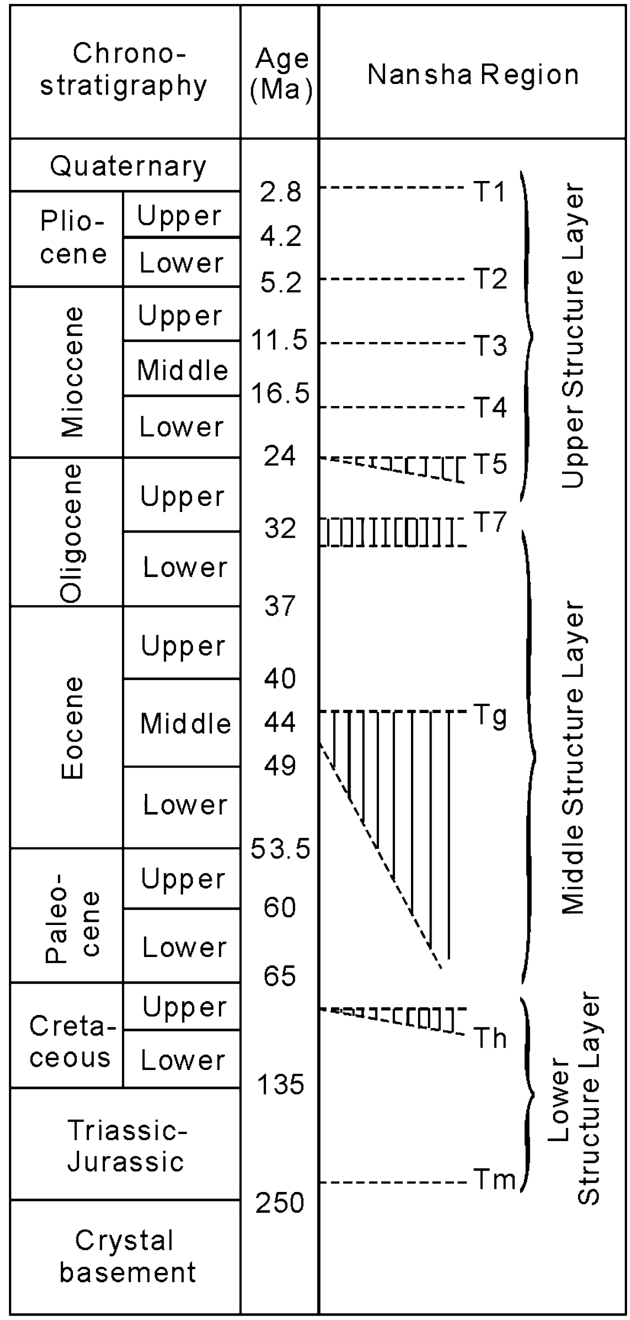

Fig. 2 Simplified strata of the Nansha terrane, modified after (Yan and Liu 2004), established by seismic data and published stratigraphy schemes. Nine reflectors were established, T1–T5, T7, Tg, Th, and Tm Note: Th and Tm are well-observed in the pre-rift formations around the SCS by seismic methods, which place initiation time of the spreading of the SCS at 65 ± 10 Ma (Taylor and Hayes 1982)

especially the long-term geodynamic properties and behaviors of the crust and the lithosphere scales of over 1000 km (Tapponnier et al. 1982). In addition, the results of Tapponnier et al.'s physical experiments were not reproduced by either Xia et al.'s (2006) numerical modeling or by Sun et al.'s (2006) physical experiments with different boundary conditions (Sun et al. 2009, 2010, 2011).

(5) The extrusion of the Indochina Peninsula along the Ailaoshan–Red River fault may have indeed changed the stress of the SCS, but since the main force of the extrusion was concentrated along the western margin of the SCS, the corresponding extension should be better developed in the west. In contrast, the spreading center of the SCS is wider in the east than in the west, which cannot be directly explained by the extrusion model.

2.2 Backarc extension

The backarc extension model proposes that the SCS was a backarc basin rifted from the passive margin of the Eurasian continent. While the subduction of the Philippine Sea pPlate was originally taken as the primary driving force (Karig 1971; Benavrah and Uyeda 1973; Guo et al. 1983), the subduction direction of the Philippine Sea and the Pacific Plate is not compatible with the extension direction of the SCS. Alternatively, SCS was interpreted as a backarc basin related to subduction of the Neotethys Plate between the Australian and Eurasian continents (Hilde et al. 1977). The subduction direction of the Neotethys and extension direction of the SCS match with each other quite well. According to this model, the extension of the SCS started at 100 Ma (Fig. 3) (Hilde et al. 1977; Stern and Bloomer 1992). There is no evidence, however, for such an early extension in the SCS. Instead, there was major compression in the whole south China around 100 Ma (Li et al. 2014b).

Interestingly, paleomagnetic studies show that several of the islands near the southern margin of the SCS were located close to the Eurasian continent at 65 Ma (Lee and Lawver 1995). The Late Cretaceous southward extension along the south margin of the Cathaysia block is called the "Shen Hu movement" (Yao et al. 1994) and may have started ~80 Ma. Such early extension may have formed the proto-SCS. All these studies provide constraints on the extension model. (See details in Sect. 3)

2.3 Two-stage extension model

The two-stage extension model proposes two extension events in the SCS, based on geophysical features; in particular: water depths, extensional basins surrounding the SCS, and magnetic anomalies in the Southwest Subbasin of the SCS. According to this model, the first extension, which occurred in the Late Eocene to Early Oligocene (42–35 Ma), formed the southwest-northeast trending Southwestern Subbasin. The magnetic anomalies correspond to No. 18-13 in the international magnetic age table. The second extension occurred in the Late Oligocene to Early Miocene, resulting in the east–west trending East/Main Subbasin (Fig. 4) (Yao 1999). This model is mainly based on the two sets of extensional basins surrounding the SCS. The Late Eocene to Early Oligocene basins display northwest-southeast extension followed by north–south extension. The former are roughly parallel to the Southwest Subbasin of the SCS, whereas the latter are parallel to the main basin (Yao 1999). This model, however, did not provide any driving force for the opening of the SCS.

Recent dating results indeed show two-stage opening of the SCS, but the timing is not consistent: the Southwest Subbasin propagated for about 400 km southwestward from ~23.6 to ~21.5 Ma and ended at 16 Ma (Li et al. 2014a). The opening of the Southwest Subbasin is roughly simultaneous with a ridge jump in the East Subbasin, likely suggesting major changes in tectonic settings and/or driving forces. These do not support the two-stage extension model.

2.4 Proto-South China Sea dragging model

The dragging model posits that a proto-SCS to the south of the current SCS vanished through southeastward subduction beneath the Luzon and Sulu islands in the Late Cretaceous to Paleocene (Holloway 1982; Taylor and Hayes 1982; Lee and Lawver 1994, 1995). Subduction of the proto-SCS resulted in extension and rifting along the southeast margin of the South China Block and the formation of the SCS (Fig. 5) (Holloway 1982; Taylor and Hayes 1982; Hall 1996). Although this model is seemingly supported by abundant ophiolites in the Luzon and Sulu islands (Yumul 2007), paleomagnetic results show that the proto-SCS was very small (Lee and Lawver 1994). It is not likely to have pulled apart the thick continental lithosphere of South China.

The formation of the proto-SCS is not explained by these models. Based on current knowledge of backarc extension, we propose that the proto-SCS was formed through backarc extension during the closure of the Neotethys. (See details in Sect. 3.)

2.5 Extension induced by mantle plume

A mantle plume has also been proposed as the driving force for the formation of the SCS (Flower et al. 1998; Xu et al. 2012). This model is seemingly supported by seismic

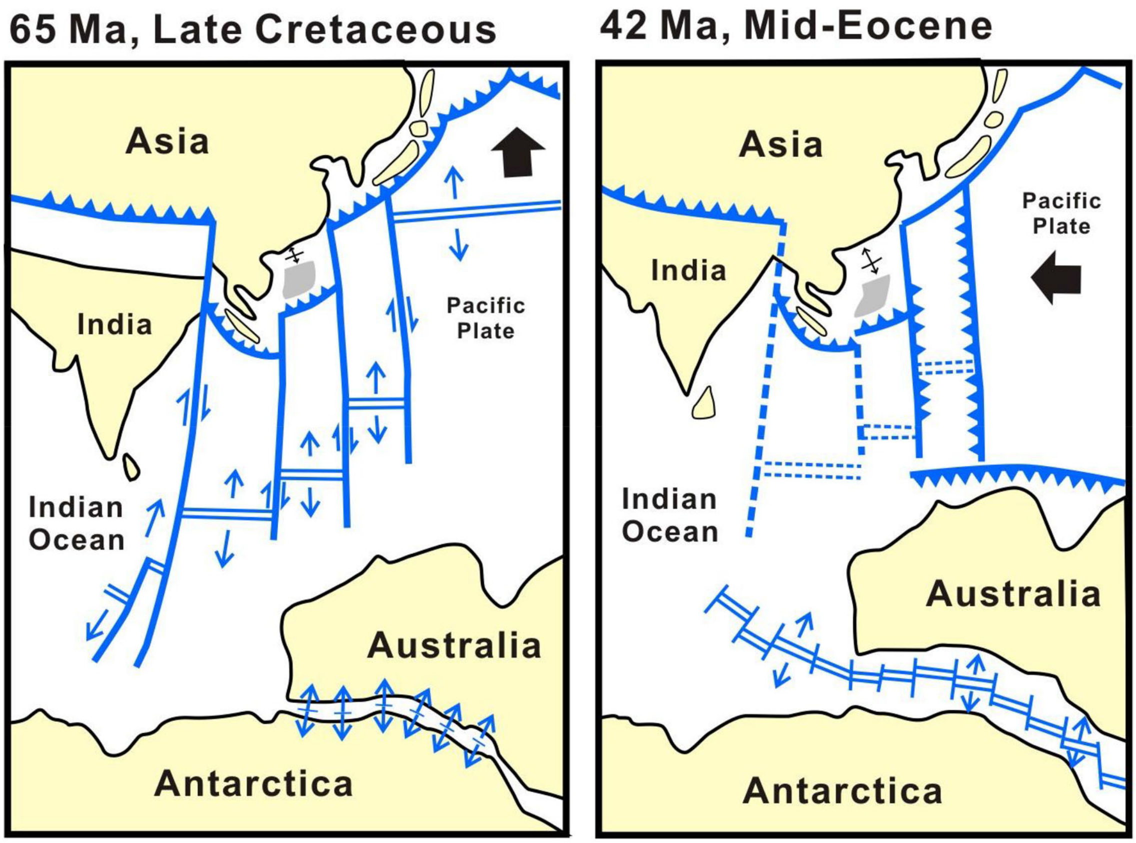

Fig. 3 Backarc extension model, modified after (Stern and Bloomer 1992). According to this model, the SCS initiated at ~100 Ma and formed as the backarc basin of the Neotethys Plate subduction (Hilde et al. 1977)
Note: the collision between the Indian and Eurasian continents and the position of the Neotethys ridge in this model are not consistent with current understanding

tomography, which shows high temperature anomalies beneath the SCS (Huang and Zhao 2006; Zhao 2007). Geochemical data on some basaltic rocks are arguably consistent with the mantle plume model (Yan et al. 2008; Zou and Fan 2010; Xu et al. 2012; Huang et al. 2013). However, the same type of alkalic basalts are common at the eastern margin of the Eurasian continent, which is mostly much younger than the SCS. Plume heads may initiate plate drifting (Griffiths and Campbell 1991); large-scale magmatism, which is typical of mantle plume heads, however, is absent in the SCS and surrounding regions. We argue that, although there are volcanic rocks that are seemingly plume related, most of those plume-type volcanic rocks are much younger than the SCS. Therefore, a mantle plume is not likely to be the main driving force that initiated the SCS. Instead, the Hainan plume may have been initiated by the subducted Neotethys Plate.

2.6 Integrated models

Integrated models attribute the opening of the SCS to a combination of several events, e.g., proto-SCS subduction/pull plus mantle flow induced by collision between the Indian and Eurasian continents (Sun et al. 2006); proto-SCS subduction/pull plus southward extrusion of the Indochina Peninsula (Morley 2002); or multiple plate subduction, shearing, and collisions (Tamaki 1995; Zhou et al. 2002). For example, Morley (2002) proposed that both the southward extrusion of the Indochina Peninsula and the subduction of the proto-SCS contributed to the formation of the SCS (Fig. 6). According to this model, the Ailaoshan–Red River fault is connected to the subduction zone of the proto-SCS, with southward extrusion having enhanced the subduction of the proto-SCS and the opening of the SCS. However, as discussed above, neither extrusion nor proto-SCS subduction/pull can explain the formation of the SCS. Nor can it explain the two-stage extension.

Some of the multiple plate interaction models take the Japan Sea/East Korean Sea as an analog of the SCS, which suggests the dextral faulting along the eastern margin of the Eurasian continents was due to eastward mantle flow resulting from the India-Eurasia collision and NNW drift of the Australian Plate (Zhou et al. 2002). The problem is that the SCS is located in the southeast margin of the Eurasian

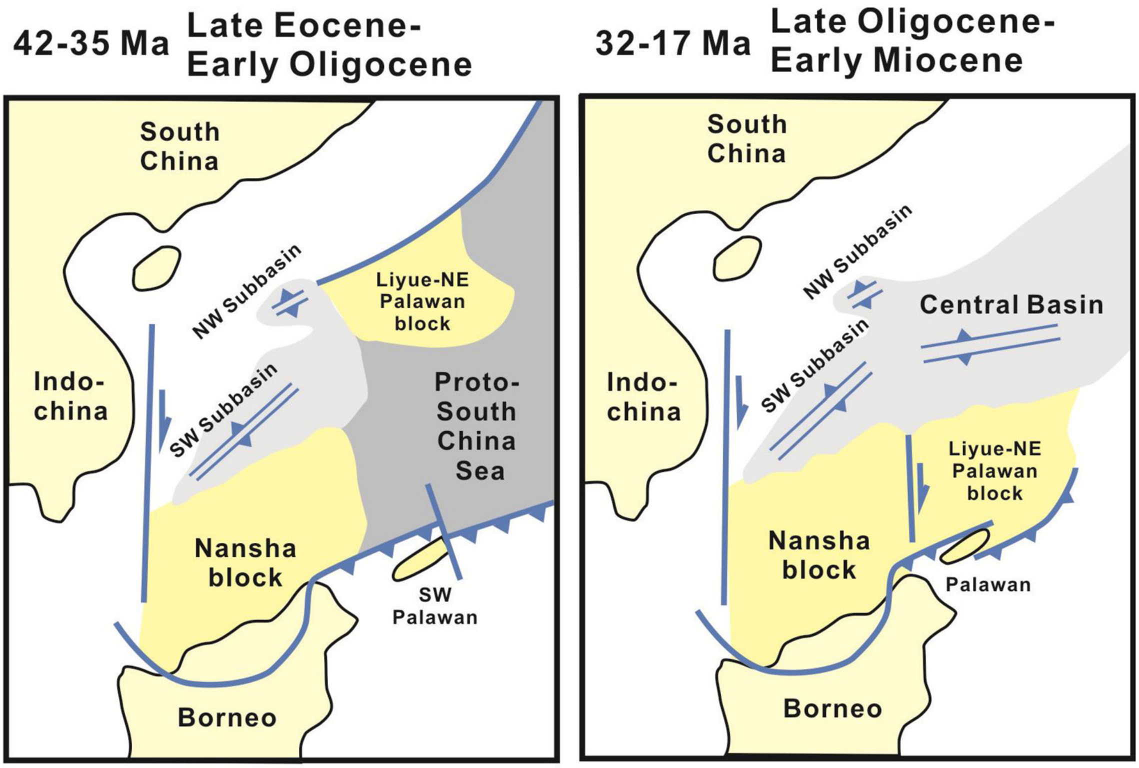

Fig. 4 Two-stage extension model, suggesting that the southwest and northwest subbasins formed early (42–35 Ma), whereas the central SCS basin formed much later of (32–17 Ma). Note: the extension directions of the two extensions are different (Yao 1999). New dating results show a much younger Southwest Subbasin, which does not support the two-stage extension model (Li et al. 2014a)

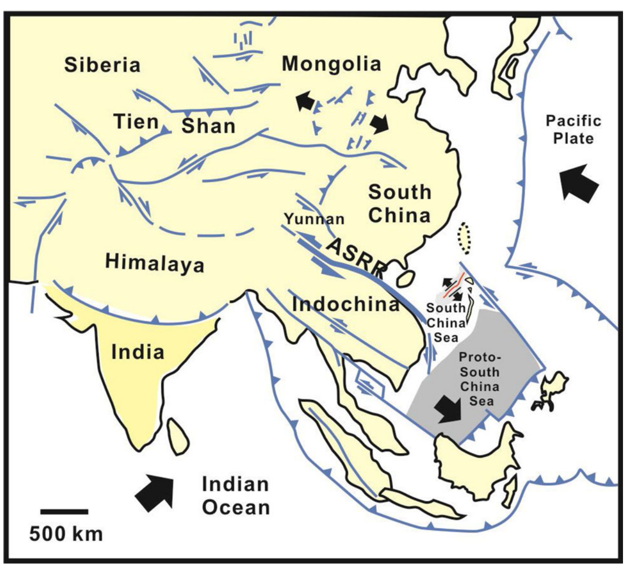

Fig. 5 Proto-SCS dragging model suggests that the SCS resulted from the southeastward subduction of the proto-SCS (Holloway 1982; Taylor and Hayes 1982; Hall 1996)

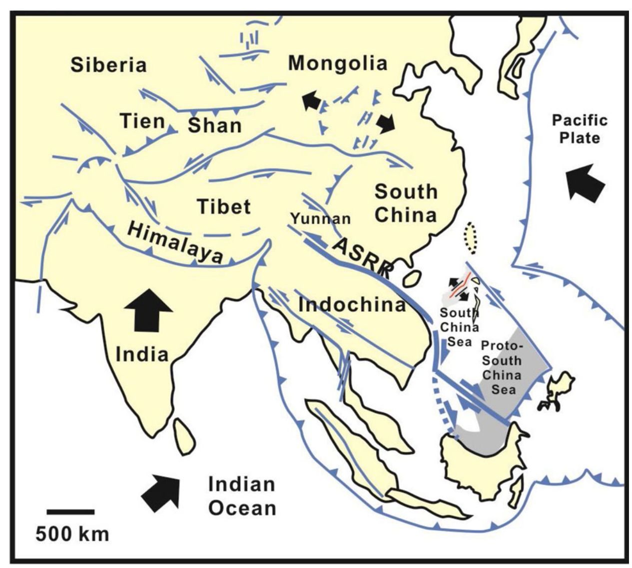

Fig. 6 The integrated model, which proposed that both the southward extrusion of the Indochina Peninsula and subduction of the proto-SCS were responsible for the formation of the SCS (Morley 2002)

continent, which is dramatically different from the Japan Sea/East Korean Sea.

The Japan Sea/East Korean Sea was once attributed to back arc extension controlled by large intracontinental strike-slip faults likely induced by the India-Asia collision (Jolivet et al. 1994). A later study suggested that "opposite rotational torques," which led to opposite terrane rotations, could have been caused by rollback of a curved trench hingeline or by the divergent slab-sinking forces of the Pacific and Philippine Sea Plates (Martin 2011). Alternatively, it was proposed that backarc basins around the Eurasian continent, opened at 32–17 Ma, were induced by either rapid eastward migration of the western Pacific trench system or by oblique subduction of the Pacific Plate beneath Asia (Yin 2010). The Pacific Plate was subducting roughly northward between 100 and 50 Ma (Sun et al. 2007, 2013), which was likely responsible for the north–south extension of the Japan Sea/East Korean Sea and the Philippine Sea. Nevertheless, the subduction regime associated with the SCS was quite different from that of the Japan Sea/East Korean Sea.

3 Refined backarc extension model

Based on observations currently available and detailed analyses on previous models, we favor a refined backarc extension model (Fig. 7). We propose that the SCS formed through backarc extension associated with the northward subduction of the Neotethys oceanic plate, which was located between Australia and Eurasia.

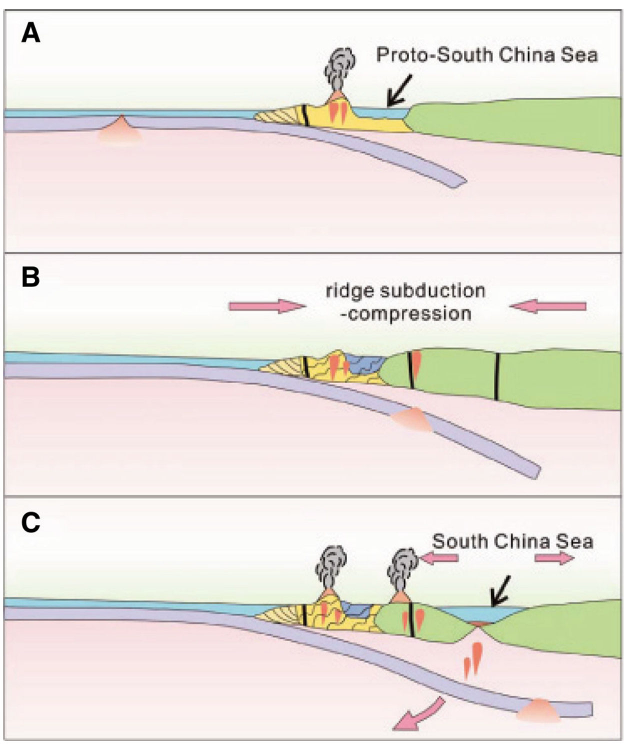

Fig. 7 Refined backarc extension model. **A**. Northward subduction of the Neotethys oceanic plate probably resulted in formation of the proto-SCS in the Early Cretaceous in response to backarc extension, which vanished through southward subduction. **B**. Ridge subduction resulted in collision and compression. **C**. The SCS was initiated due to backarc extension under a changed subduction regime

(1) The northward subduction of the Neotethys between the Australian and Eurasian Plates may have started at ~125 Ma. Early on, the northward subduction of the Neotethys was probably normal (with an angle of ~40°) or steep subduction. In both case, there should have been backarc extension, which was probably responsible for the formation of the proto-SCS. The whole Pacific Plate started to drift northward at ~100 Ma (Sun et al. 2007), coupled with accelerated northward drifting of the Australian, African, and Indian Plates (Scotese 2004), which intensified the northward drifting of the Australian Plate.

(2) The tectonic regime changed from extension to compression when the spreading ridge of the Neotethys started to subduct, forming folds and unconformities, as shown in Fig. 2. This process may have triggered and promoted the subduction of the proto-SCS. Given that major compression occurred across south China as shown by discontinuities at ~100 Ma (Li et al. 2014b), it is likely that the ridge subduction started around this time. Adakites of ~100 Ma in south China are likely due to this ridge subduction.

(3) As the northward subduction continued, the proto-SCS disappeared; meanwhile, north–south backarc extension started in the north and migrated southward. There was a southward extension in the Late Cretaceous along the southern margin of the Cathaysia Block—the so-called "Shen hu Movement" (Yao et al. 1994). Based on the ages of A-type granites associated with adakite, this extension may have started at ~80 Ma. Extension in the whole SCS region may have started between ~50 and 45 Ma, after ridge subduction and bending between the Emperor-Hawaii island chains (Sun et al. 2007). Sea floor appeared in the SCS at 33 Ma, ~12 to 17 Ma after the initiation of continent breakup and extension (Fig. 7).

(4) The Indian and Eurasian Plates collided at ~50 to 65 Ma, leading to uplift of the Tibetan Plateau (Ji et al. 2009; Yin 2010; Chu et al. 2011; Liu et al. 2011; Meng et al. 2012). As collision continued, the Tibetan Plateau rose to a critical point and started to extrude eastward at about ~40 Ma (Liang et al. 2007; Wang et al. 2010). This was accompanied by magmatism (Liang et al. 2007; Wang et al. 2010) and was followed by southward extrusion of the Indochina Peninsula (Tapponnier et al. 1990), which had a significant influence on backarc extension.

(5) The southward extrusion of the Indochina Peninsula may have promoted the extension of the Northwest Subbasin, and hindered development of the backarc basins in the southwest (i.e. Southwest Subbasin). The extension of the Southwest Subbasin is likely due to changes in the extrusion of the Indochina Peninsula.

4 Discussion

4.1 Ridge subduction and extension

The Australian, Indian, and Antarctic Plates separated from each other in the Early Cretaceous (~125 to 130 Ma), likely triggered by the Kurgelen mantle plume (Acharyya 2000; Scotese 2004). Both the Australian and Indian Plates moved northwards, by 40° and 60°, respectively (Mcelhinny et al. 1974). The Australian Plate has drifted ~4500 km northward since ~125 Ma. Given that there is no contemporaneous oceanic plate to the north of the Neotethys, the northward drifting implies the initiation of the northward subduction occurred shortly after 125 Ma and that more than 4500 km of the Neotethys oceanic plate was subducted northward, even if the Neotethys spreading ridge stopped during the northward subduction. This is sufficient to form backarc basins. A more realistic scenario is that the ridge of the Neotethys also moved northward as a result of single-side subduction.

The first stage of plate subduction was normal, with older oceanic crust closer to the subduction zone. Such subduction forms normal backarc extension. The likely result was the proto-SCS.

Compression occurred when the Neotethys ridge started to subduct, leading to discontinuities in sedimentary rocks (Fig. 2) and major compression across the whole of south China around 100 Ma (Li et al. 2014b). This is likely to be the causal mechanism that initiated the southward subduction of the proto-SCS.

During ridge subduction, young hot slab is subducted at a low angle, or even flat, which may affect intra-plate regions far from the subduction zone, and induce slab rollback (Coney and Reynolds 1977; Li and Li 2007; Sun et al. 2012). The Neotethys ridge might have been subducted beneath what is now southern Canton province. The rollback of this slab might have commenced at ~90 Ma, causing extension and rifting, starting from the far north.

Consistently, paleomagnetic data show that Palawan Island was located near the southern margin of the Eurasian continent at 65 Ma, and had drifted ~100 km southward by 45 Ma. This indicates that the initiation of the SCS occurred between 65 and 45 Ma (Lee and Lawver 1995). Backarc extension also plausibly explains the migration of extension centers from north to south.

4.2 Backarc extension

Backarc extension started at regions much closer to the subduction zone after slab rollback. In the case of the SCS, backarc extension may have started after the steering of the whole Pacific Plate from northward drifting to northwestward at ~50 Ma (Sharp and Clague 2006; Sun et al. 2007, 2013), because the major change in the drifting direction of the Pacific Plate was coupled with a dramatic decrease in northward compression of the tectonic regime of the SCS region.

The extension of the SCS is not symmetric. The spreading center migrated southward through ridge jump at ~26 Ma (Briais et al. 1993; Li et al. 2003) or 23.6 Ma (Li et al. 2014a). In most ocean basins, ridge jump is usually associated with mantle plumes or hot spots, due to ridge suction. It has been proposed that there is a mantle plume in the Hainan Island, which is located to the north of the ridge. No plume has been confirmed to the south of the SCS ridge. Ridge-plume interaction would have resulted in northward ridge jump.

In contrast, the southward ridge jump is consistent with backarc extension, i.e., ridges in backarc basins jump toward the subduction zone. This kind of asymmetric ridge jump is common in southwest Pacific backarc basins, including the backarc extension in the Philippine Plate since 33 Ma. These phenomena can best be explained by backarc extension associated with slab rollback of the northward subducting Neotethys Plate (Fig. 7).

4.3 Ophiolite and Proto-South China Sea

Ophiolites in the Luzon and Sulu Islands reflect the history of plate subduction surrounding the SCS. Four ophiolite belts, with ages from Jurassic to Eocene, have been recognized (Fig. 8) (Yumul 2007). All these ophiolites are located along the Manila trench, implying connections to the SCS or proto-SCS. Given that the oldest oceanic crust of the SCS is 33 Ma (Li et al. 2014a), these ophiolites are most likely related to the proto-SCS, and even the Neotethys.

4.4 The relation between the Tibetan Plateau and the South China Sea

At ~40 Ma, the Tibetan Plateau reached a critical point at which the lithosphere was not able to sustain gravitational forces and east–west extension and extrusion ensued. The Indochina Peninsula extruded southward along the Ailaoshan–Red River belt. Such extrusion hindered the

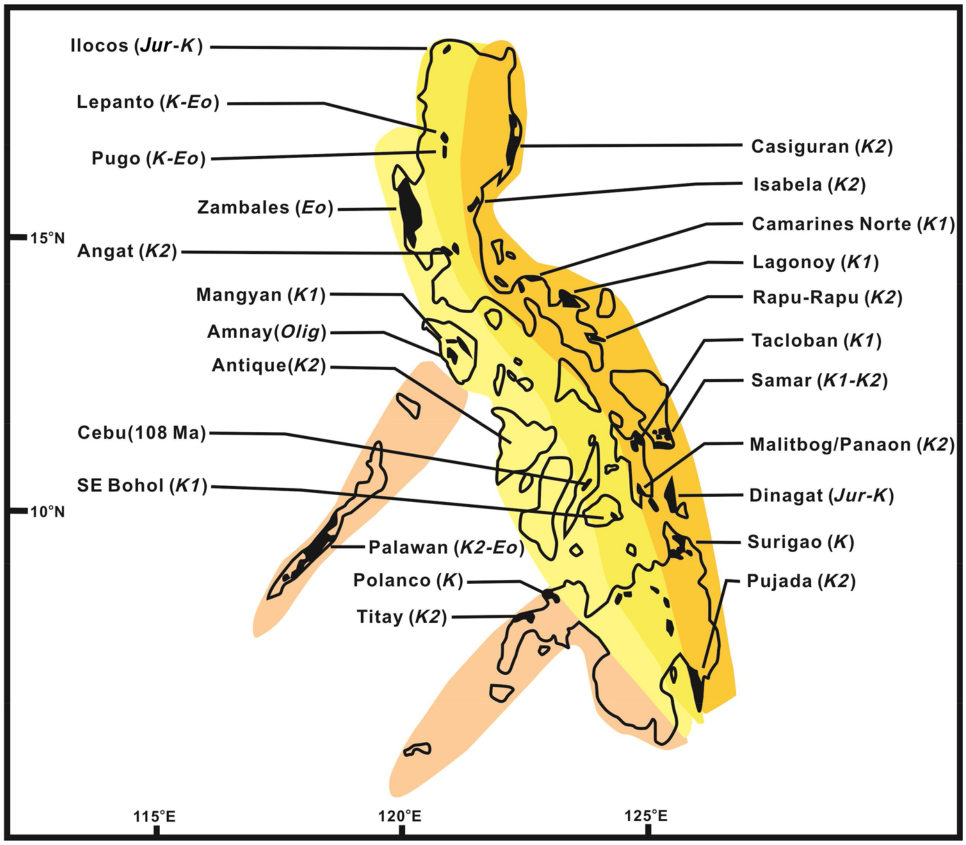

Fig. 8 Distribution of ophiolites in Luzon and Sulu Islands (Yumul 2007). *Jur* Jurassic, *K* Cretaceous, *K1* Early Cretaceous, *K2* Late Cretaceous, *Eo* Eocene, *Olig* Oligocene

development of backarc basins to the south of the Indochina Peninsula, and probably was partially responsible to the narrowing of the SCS in the west. The southward extrusion of the Indochina Peninsula decreased dramatically at ~23 Ma. As a result, backarc extension in the west was influenced and the extension of the Southwest Subbasin started. This may plausibly explain the two-stage opening of the SCS. The extension of the whole SCS terminated when the Australian Plate collided with the Indonesian arc.

5 Conclusion

Here we propose a model, involving two-stage backarc extension, induced by northward subduction of the Neotethys Plate—normal subduction followed by ridge subduction/flat subduction. The first backarc extension was responsible for the formation of the proto-SCS, whereas the second extension was responsible for the Shenhu event and ultimately the formation of the SCS.

Acknowledgments This is contribution No. IS-2248 from GIGCAS, which is supported by the NSFC (No. 91328204, 41421062) and the Chinese Academy of Sciences (KZCX1-YW-15).

References

Acharyya SK (2000) Break up of Australia-India-Madagascar block, opening of the Indian Ocean and continental accretion in Southeast Asia with special reference to the characteristics of the peri-Indian collision zones. Gondwana Res 3(4):425–443

Benavrah Z, Uyeda S (1973) Evolution of China basin and mesozoic paleogeography of Borneo. Earth Planet Sci Lett 18(2):365–376

Briais A, Patriat P, Tapponnier P (1993) Updated interpretation of magnetic-anomalies and sea-floor spreading stages in the South China Sea—implications for the tertiary tectonics of southeast-Asia. J Geophys Res 98(B4):6299–6328

Chu MF, Chung SL, O'Reilly SY, Pearson NJ, Wu FY, Li XH, Liu DY, Ji JQ, Chu CH, Lee HY (2011) India's hidden inputs to Tibetan orogeny revealed by Hf isotopes of Transhimalayan zircons and host rocks. Earth Planet Sci Lett 307(3–4):479–486. doi:10.1016/j.epsl.2011.05.020

Chung SL, Lee TY, Lo CH, Wang PL, Chen CY, Yem NT, Hoa TT, Wu GY (1997) Intraplate extension prior to continental extrusion along the Ailao Shan Red River shear zone. Geology 25(4):311–314

Chung SL, Lo CH, Lee TY, Zhang YQ, Xie YW, Li XH, Wang KL, Wang PL (1998) Diachronous uplift of the Tibetan plateau starting 40 Myr ago. Nature 394(6695):769–773

Chung SL, Chu MF, Zhang YQ, Xie YW, Lo CH, Lee TY, Lan CY, Li XH, Zhang Q, Wang YZ (2005) Tibetan tectonic evolution inferred from spatial and temporal variations in post-collisional magmatism. Earth Sci Rev 68(3–4):173–196

Clift PD, Brune S, Quinteros J (2015) Climate changes control offshore crustal structure at South China Sea continental margin. Earth Planet Sci Lett 420:66–72. doi:10.1016/j.epsl.2015.03.032

Coney PJ, Reynolds SJ (1977) Cordilleran benioff zones. Nature 270(5636):403–406. doi:10.1038/270403a0

Flower MFJ, Tamaki K, Hoang N (1998) Mantle extrusion: a model for dispersed volcanism and DUPAL-like asthenosphere in east Asia and the western Pacific. In: Flower MEJ, Chung SL, Lo C H (eds) Mantle dynamics and plate interactions in east Asia, vol 27. AGU, Geodynamics, pp 67–88

Griffiths RW, Campbell IH (1991) On the dynamics of long-lived plume conduits in the convecting mantle. Earth Planet Sci Lett 103(1–4):214–227. doi:10.1016/0012-821x(91)90162-B

Guo LZ, Shi YS, Ma RS (1983) The formation and evolution of Mesozoic and Cenozoic active continental margins and island arcs in the western Pacific. Acta Geol Sin 57(1):11–21

Hall R (1996) Reconstructing cenozoic SE Asia. In: Hall R, Blundell DJ (eds) Tectonic evolution of southeast Asia, vol 106., Geol Soc Lond Spec Publ, London, pp 203–224

Hilde TWC, Uyeda S, Kroenke L (1977) Evolution of the western Pacific and its margin. Tectonophysics 38(1–2):145–165. doi:10.1016/0040-1951(77)90205-0

Holloway NH (1982) North Palawan Block, Philippines—its relation to Asian Mainland and role in evolution of South China Sea. AAPG Bull 66(9):1355–1383

Huang JL, Zhao DP (2006) High-resolution mantle tomography of China and surrounding regions. J Geophys Res. doi:10.1029/2005jb004066

Huang XL, Niu YL, Xu YG, Ma JL, Qiu HN, Zhong JW (2013) Geochronology and geochemistry of Cenozoic basalts from eastern Guangdong, SE China: constraints on the lithosphere evolution beneath the northern margin of the South China Sea. Contrib Miner Pet 165(3):437–455. doi:10.1007/s00410-012-0816-7

Ji WQ, Wu FY, Chung SL, Li JX, Liu CZ (2009) Zircon U-Pb geochronology and Hf isotopic constraints on petrogenesis of the Gangdese batholith, southern Tibet. Chem Geol 262(3–4):229–245. doi:10.1016/j.chemgeo.2009.01.020

Jolivet L, Tamaki K, Fournier M (1994) Japan sea, opening history and mechanism—a synthesis. J Geophys Res 99(B11):22237–22259

Karig DE (1971) Origin and development of marginal basins in Western Pacific. J Geophys Res 76(11):2542–2561

Lee TY, Lawver LA (1994) Cenozoic plate reconstruction of the South China Sea region. Tectonophysics 235(1–2):149–180

Lee TY, Lawver LA (1995) Cenozoic plate reconstruction of Southeast Asia. Tectonophysics 251(1–4):85–138. doi:10.1016/0040-1951(95)00023-2

Lei C, Ren JY, Sternai P, Fox M, Willett S, Xie XL, Clift PD, Liao JH, Wang ZF (2015) Structure and sediment budget of Yinggehai-Song Hong basin, South China Sea: implications for Cenozoic tectonics and river basin reorganization in southeast Asia. Tectonophysics 655:177–190. doi:10.1016/j.tecto.2015.05.024

Leloup PH, Harrison TM, Ryerson FJ, Chen WJ, Li Q, Tapponnier P, Lacassin R (1993) Structural, petrological and thermal evolution of a Tertiary ductile strike-slip shear zone, Diancang Shan, Yunnan. J Geophys Res 98(B4):6715–6743

Li ZX, Li XH (2007) Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: a flat-slab subduction model. Geology 35(2):179–182

Li XH, Wei GJ, Shao L, Liu Y, Liang XR, Han ZM, Sun M, Wang PX (2003) Geochemical and Nd isotopic variations in sediments of the South China Sea: a response to Cenozoic tectonism in SE Asia. Earth Planet Sci Lett 211(3–4):207–220

Li CF, Xu X, Lin J, Sun Z, Zhu J, Yao YJ, Zhao XX, Liu QS, Kulhanek DK, Wang J, Song TR, Zhao JF, Qiu N, Guan YX, Zhou ZY, Williams T, Bao R, Briais A, Brown EA, Chen YF, Clift PD, Colwell FS, Dadd KA, Ding WW, Almeida IH, Huang XL, Hyun SM, Jiang T, Koppers AAP, Li QY, Liu CL, Liu ZF, Nagai RH, Peleo-Alampay A, Su X, Tejada MLG, Trinh HS, Yeh YC, Zhang CL, Zhang F, Zhang GL (2014a) Ages and magnetic structures of the South China Sea constrained by deep tow magnetic surveys and IODP expedition 349. Geochem Geophys Geosyst 15(12):4958–4983. doi:10.1002/2014gc005567

Li JH, Zhang YQ, Dong SW, Johnston ST (2014b) Cretaceous tectonic evolution of South China: a preliminary synthesis. Earth Sci Rev 134:98–136. doi:10.1016/j.earscirev.2014.03.008

Liang HY, Campbell IH, Allen CM, Sun WD, Yu HX, Xie YW, Zhang YQ (2007) The age of the potassic alkaline igneous rocks along the Ailao Shan-Red River shear zone: implications for the onset age of left-lateral shearing. J Geol 115(2):231–242

Liu CZ, Wu FY, Chung SL, Zhao ZD (2011) Fragments of hot and metasomatized mantle lithosphere in Middle Miocene ultrapotassic lavas, southern Tibet. Geology 39(10):923–926. doi:10.1130/G32172.1

Liu ET, Wang H, Li Y, Zhou W, Leonard ND, Lin ZL, Ma QL (2014) Sedimentary characteristics and tectonic setting of sublacustrine fans in a half-graben rift depression, Beibuwan Basin, South China Sea. Mar Pet Geol 52:9–21. doi:10.1016/j.marpetgeo.2014.01.008

Martin AK (2011) Double saloon door tectonics in the Japan Sea, Fossa Magna, and the Japanese Island Arc. Tectonophysics 498(1–4):45–65. doi:10.1016/j.tecto.2010.11.016

Mcelhinny MW, Haile NS, Crawford AR (1974) Paleomagnetic evidence shows Malay Peninsula was not a part of Gondwanaland. Nature 252(5485):641–645

Meng J, Wang CS, Zhao XX, Coe R, Li YL, Finn D (2012) India-Asia collision was at 24 degrees N and 50 Ma: palaeomagnetic proof from southernmost Asia. Sci Rep-Uk 2. doi 10.1038/Srep00925

Morley CK (2002) A tectonic model for the tertiary evolution of strike-slip faults and rift basins in SE Asia. Tectonophysics 347(4):189–215

Schluter HU, Hinz K, Block M (1996) Tectono-stratigraphic terranes and detachment faulting of the South China Sea and Sulu Sea. Mar Geol 130(1–2):39–51. doi:10.1016/0025-3227(95)00137-9

Scotese CR (2004) A continental drift flipbook. J Geol 112(6):729–741

Sharp WD, Clague DA (2006) 50-Ma initiation of Hawaiian-emperor bend records major change in Pacific pPlate motion. Science 313(5791):1281–1284. doi:10.1126/science.1128489

Sobolev SV, Babeyko AY (2005) What drives orogeny in the Andes? Geology 33(8):617–620. doi:10.1130/G21557

Stern RJ, Bloomer SH (1992) Subduction zone infancy—Examples from the Eocene Izu-Bonin-Mariana and Jurassic California Arcs. Geol Soc Am Bull 104(12):1621–1636

Sun Z, Zhou D, Zhong ZH, Xia B, Qiu XL, Zeng ZX, Jiang JQ (2006) Research on the dynamics of the South China Sea opening: evidence from analogue modeling. Sci China D 49(10):1053–1069. doi:10.1007/s11430-006-1053-6

Sun WD, Ding X, Hu YH, Li XH (2007) The golden transformation of the Cretaceous plate subduction in the west Pacific. Earth Planet Sci Lett 262(3–4):533–542

Sun Z, Zhong ZH, Keep M, Zhou D, Cai DS, Li XS, Wu SM, Jiang JQ (2009) 3D analogue modeling of the South China Sea: a discussion on breakup pattern. J Asian Earth Sci 34(4):544–556. doi:10.1016/j.jseaes.2008.09.002

Sun Z, Zhou D, Sun LT, Chen CM, Pang X, Jiang JQ, Fan H (2010) Dynamic analysis on rifting stage of pearl river mouth basin through analogue modeling. J Earth Sci 21(4):439–454. doi:10.1007/s12583-010-0106-0

Sun Z, Zhao ZX, Li JB, Zhou D, Wang ZW (2011) Tectonic analysis of the breakup and collision unconformities in the Nansha. Chin J Geophys 54(12):3196–3209. doi:10.3969/j.issn.0001-5733.2011.12.019

Sun WD, Yang XY, Fan WM, Wu FY (2012) Mesozoic large scale magmatism and mineralization in South China: preface. Lithos 150:1–5. doi:10.1016/j.lithos.2012.06.028

Sun WD, Li S, Yang XY, Ling MX, Ding X, Duan LA, Zhan MZ, Zhang H, Fan WM (2013) Large-scale gold mineralization in eastern China induced by an early Cretaceous clockwise change in Pacific pPlate motions. Int Geol Rev 55(3):311–321. doi:10.1080/00206814.2012.698920

Tamaki K (1995) Opening tectorfic of the Japan Sea. Plenum Press, New York

Tang XY, Chen L, Hu SB, Yang SC, Zhang GC, Shen HL, Rao S, Li WW (2014) Tectono-thermal evolution of the Reed Bank Basin, Southern South China Sea. J Asian Earth Sci 96:344–352. doi:10.1016/j.jseaes.2014.09.030

Tapponnier P, Peltzer G, Ledain AY, Armijo R, Cobbold P (1982) Propagating extrusion tectonics in Asia—new insights from simple experiments with plasticine. Geology 10(12):611–616. doi:10.1130/0091-7613(1982)10<611:petian>2.0.co;2

Tapponnier P, Lacassin R, Leloup PH, Scharer U, Zhong DL, Wu HW, Liu XH, Ji SC, Zhang LS, Zhong JY (1990) The Ailao Shan Red River metamorphic belt—tertiary left-lateral shear between Indochina and South China. Nature 343(6257):431–437

Taylor B, Hayes DE (1980) The tectonic evolution of the South China Basin. In: Hayes DE (ed) The tectonic and geologic evolution of Southeast Asian seas and islands, Part 1, vol 23., American Geophysical UnionGeophysical Monograph, Washington, DC, pp 89–104

Taylor B, Hayes DE (1982) Origin and history of the South China Sea Basin. In: Hayes DE (ed) The tectonic and geologic evolution of Southeast Asian seas and islands, Part 2, vol 27., American Geophysical UnionGeophysical Monograph, Washington, DC, pp 23–56

Wang Q, Wyman DA, Li ZX, Sun WD, Chung SL, Vasconcelos PM, Zhang QY, Dong H, Yu YS, Pearson N, Qiu HN, Zhu TX, Feng XT (2010) Eocene north-south trending dikes in central Tibet: new constraints on the timing of east-west extension with implications for early plateau uplift? Earth Planet Sci Lett 298(1–2):205–216. doi:10.1016/j.epsl.2010.07.046

Wu FY, Ji WQ, Liu CZ, Chung SL (2010) Detrital zircon U-Pb and Hf isotopic data from the Xigaze fore-arc basin: constraints on Transhimalayan magmatic evolution in southern Tibet. Chem Geol 271(1–2):13–25. doi:10.1016/j.chemgeo.2009.12.007

Xia B, Zhang Y, Cui XJ, Liu BM, Xie JH, Zhang SL, Lin G (2006) Understanding of the geological and geodynamic controls on the formation of the South China Sea: a numerical modelling approach. J Geodyn 42(1–3):63–84

Xu YG, Wei JX, Qiu HN, Zhang HH, Huang XL (2012) Opening and evolution of the South China Sea constrained by studies on volcanic rocks: preliminary results and a research design. Chin Sci Bull 57(24):3150–3164. doi:10.1007/s11434-011-4921-1

Yan P, Liu HL (2004) Tectonic-stratigraphic division and blind fold structures in Nansha Waters, South China Sea. J Asian Earth Sci 24(3):337–348

Yan QS, Shi XF, Wang KS, Bu WR, Xiao L (2008) Major element, trace element, and Sr, Nd and Pb isotope studies of Cenozoic basalts from the South China Sea. Sci China D 51(4):550–566. doi:10.1007/s11430-008-0026-3

Yao BC (1999) Spreading of the southwest basin of the South China Sea and its tectonic significance. South China Sea Geol 9:20–36 **(in Chinese with English abstract)**

Yao BC, Zeng W, Chen Y, Zhang X, Hayes DE, Diebold J, Buhl P, Spangler S (1994) The Geological Memoir of South China Sea surveyed jointly by China and USA (in Chinese). vol. China Univ. of Geosci. Press, Wuhan, pp 1–204

Yin A (2010) Cenozoic tectonic evolution of Asia: a preliminary synthesis. Tectonophysics 488(1–4):293–325

Yumul GPJ (2007) Westward younging disposition of Philippine ophiolites and its implication for arc evolution. Isl Arc 16:306–317

Zhao DP (2007) Seismic images under 60 hotspots: search for mantle plumes. Gondwana Res 12(4):335–355. doi:10.1016/J.Gr.2007.03.001

Zhou D, Ru K, Chen HZ (1995) Kinematics of Cenozoic extension on the South China Sea continental margin and its implications for the tectonic evolution of the region. Tectonophysics 251(1–4):161–177. doi:10.1016/0040-1951(95)00018-6

Zhou D, Chen HZ, Wu SM (2002) The formation of the South China Sea by dextral strike-slip along continental margins. Acta Geol Sin 76(2):180–190 **(in Chinese with English abstract)**

Zhou D, Sun Z, Chen HZ, Xu HH, Wang WY, Pang X, Cai DS, Hu DK (2008) Mesozoic paleogeography and tectonic evolution of South China Sea and adjacent areas in the context of Tethyan and Paleo-Pacific interconnections. Isl Arc 17(2):186–207. doi:10.1111/j.1440-1738.2008.00611.x

Zhou D, Zhao ZX, Liao J, Sun Z (2011) A preliminary assessment on CO_2 storage capacity in the Pearl River Mouth Basin offshore Guangdong, China. Int J Greenh Gas Con 5(2):308–317. doi:10.1016/j.ijggc.2010.09.011

Zou HB, Fan QC (2010) U-Th isotopes in Hainan basalts: implications for sub-asthenospheric origin of EM2 mantle endmember and the dynamics of melting beneath Hainan Island. Lithos 116(1–2):145–152. doi:10.1016/j.lithos.2010.01.010