A Summary of the South China Sea Evolution

Lachit S. Ningthoujam and Dhananjai K. Pandey

Abstract The South China Sea offers a special site for studying continental break-up, sedimentary basin formation, mantle and lithosphere evolution and other land-ocean interactions because of its location and its well-preserved evolutionary records. It behaves as a natural laboratory for understanding of different plate boundaries in a small region. The SCS has got important attention for its international marine transportation and navigation, its rich marine biodiversity and rich oil and gas resources. As the largest marginal sea separating Asia, the largest continent from Pacific, the largest ocean, the SCS plays a key role in land-sea interactions of the Earth system. From the tectonics perspective, there have been several controversies and challenges for understanding the tectonics and evolution of the South China Sea. Here, we present a brief overview on the evolution and formation of the South China Sea.

Keywords South China Sea · Evolution · Marginal sea

1 Introduction

The South China Sea (SCS), which spans from Singapore and the Malacca Strait in the south to the Strait of Taiwan in the north, and from Borneo and the Philippines on the east to Vietnam and south-eastern China on the west, is one of the largest marginal seas in the world. It is located at the convergence of three major plates (the Eurasian, Pacific-Philippine and Indo-Australian plates) along two super-convergent zones (the circum-Pacific and Tethyan zones) (Wang et al. 2000; Li et al. 2013; Zhou and Yao 2009). It is surrounded by passive margins (rifting) in the north and south, an active margin (subduction) in the east, and a transform margin in the west. Hence the evolution of SCS can be thought of as an integrated result of a complex tectonic

L. S. Ningthoujam (✉) · D. K. Pandey
National Centre for Polar and Ocean Research, Vasco da Gama, Goa, India
e-mail: lachit@ncpor.res.in

D. K. Pandey
e-mail: pandey@ncpor.res.in

D. K. Pandey et al. (eds.), *Dynamics of the Earth System: Evolution, Processes and Interactions*, Society of Earth Scientists Series,
https://doi.org/10.1007/978-3-030-40659-2_11

history. Here, the SCS refers a collective feature which includes the deep-sea plain and surrounding slopes and shelves (Fig. 1).

The SCS developed from magma-poor continental margin rifting to subsequent seafloor spreading in the latest Cretaceous to Early Paleocene (Taylor and Hayes 1983; Cullen et al. 2010; Franke 2013) and thus oceanic crust covers the central portion of the basin. Evolution of the SCS is largely believed to be induced by the India-Eurasia collision to the northwest (Morley 2002; Tapponnier et al. 1986), the subduction of the Pacific plate and then the compression from the Philippine sea plate in the east (Li 1994; Zhou et al. 2002), as well as the slab-pull of the proto-South China Sea in the south (Hall 1996; Morley 2002; Taylor and Hayes 1983).

The SCS oceanic basin formed during the early Oligocene to middle Miocene (32–15 Ma) (Li et al. 2015; Taylor and Hayes 1983). Its age is mature enough to experience the entire history of marginal sea development as well as young enough to preserve and exhibit the complete evolutionary records from being distorted (Zhou, and Yao 2009) and moreover it is relatively small so the entire basin is easily accessible. Thus, the basin is considered to be a key site and natural laboratory for studying continental break-up, sedimentary basin formation, mantle and lithosphere evolution, Asian monsoonal climate dynamics and other land-ocean interactions (Li et al. 2012). The lack of salt and Seaward Dipping Reflector (SDRs) and its potential for oil and gas have caught more attention for studying the transition between highly stretched continental and oceanic crust.

Even though studies had been focused primarily on the sea-floor dating and tectonic evolution through modelling (Taylor and Hayes 1980, 1983; Briais et al. 1993; Barckhausen and Roeser 2004), the evolutionary history of the SCS has been in debate for decades (Barckhausen et al. 2014; Briais et al. 1993; Cullen et al. 2010; Franke et al. 2013; Li et al. 2012; Taylor and Hayes 1980, 1983; Zhou et al. 1995). However, in the recent years, with different geophysical data the basin has been well-imaged and scientific drilling expeditions (ODP Leg 184; IODP-349, 367, 368 and 368X) (Wang et al. 2000; Li et al. 2015; Sun et al. 2018 and Childress 2018) have provided crucial clues in constraining the processes of rifting and eventual rupturing of the continental crust during breakup, at this magma-poor rifted margin (drilling locations are shown in Fig. 1). In this paper, we would like to highlight a glimpse of the present scenario of our understanding on the evolution of SCS.

2 Regional Geological Setting

The SCS basin is a 'V'-shaped basin (characteristic of a propagation opening; Courtillot 1982; Taylor et al. 1999) and shows an irregular triangular shape with the major apex towards south-west which reveals a propagating rift (Huchon et al. 2001). The SCS basin has been subdivided into an eastern sub-basin (ESB), northwest sub-basin (NWSB) and southwest sub-basin (SWSB) (Hutchison 1989; Li et al. 2008) (Fig. 1.). The ESB is separated from the SWSB by Zhongnan Fault Zone (Sun et al. 2009) (Figs. 1 and 2). Briais et al. (1993) proposed that the SWSB and the ESB began to

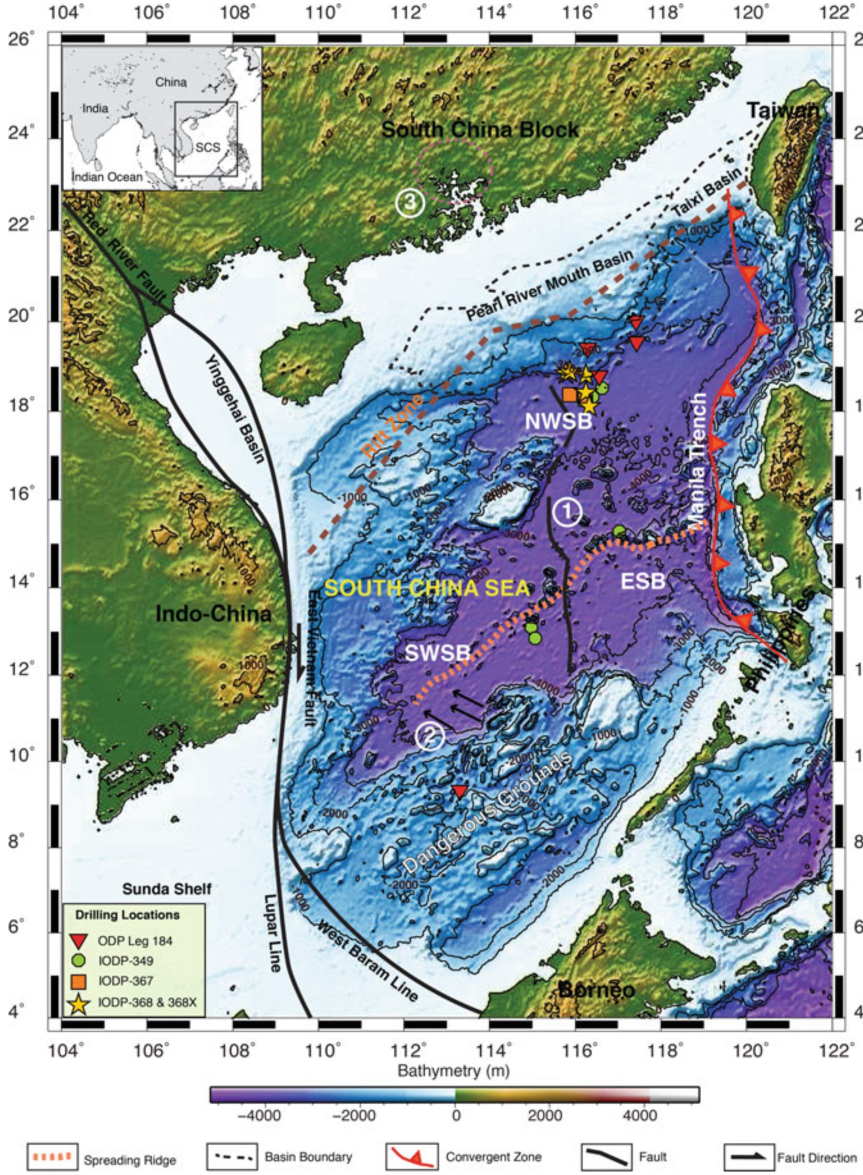

Fig. 1 Map depicts major structures in and around the South China Sea Basin (modified after Sun et al. 2009). Sub-basins in the SCS basin are shown (ESB; East sub-basin, NWSB: North-west sub-basin and SWSB: South-west sub-basin). Location of Zhongnan fault is plotted after Ziying et al. 2019 (indicated as No. 1). In the SWSB, ribbon like structures (indicated as No. 2) are highlighted with arrow-head line segments which implies a decollement (Hayes et al. 1995; Ding et al. 2013). The round shapes (indicated as No. 3) in the northern margin are also highlighted with a dotted circle, these structures are compared to the large granitic bodies cropping out onland in China and Vietnam (Savva et al. 2014). Distinct delineation of the basin is marked by large gradient in the bathymetry

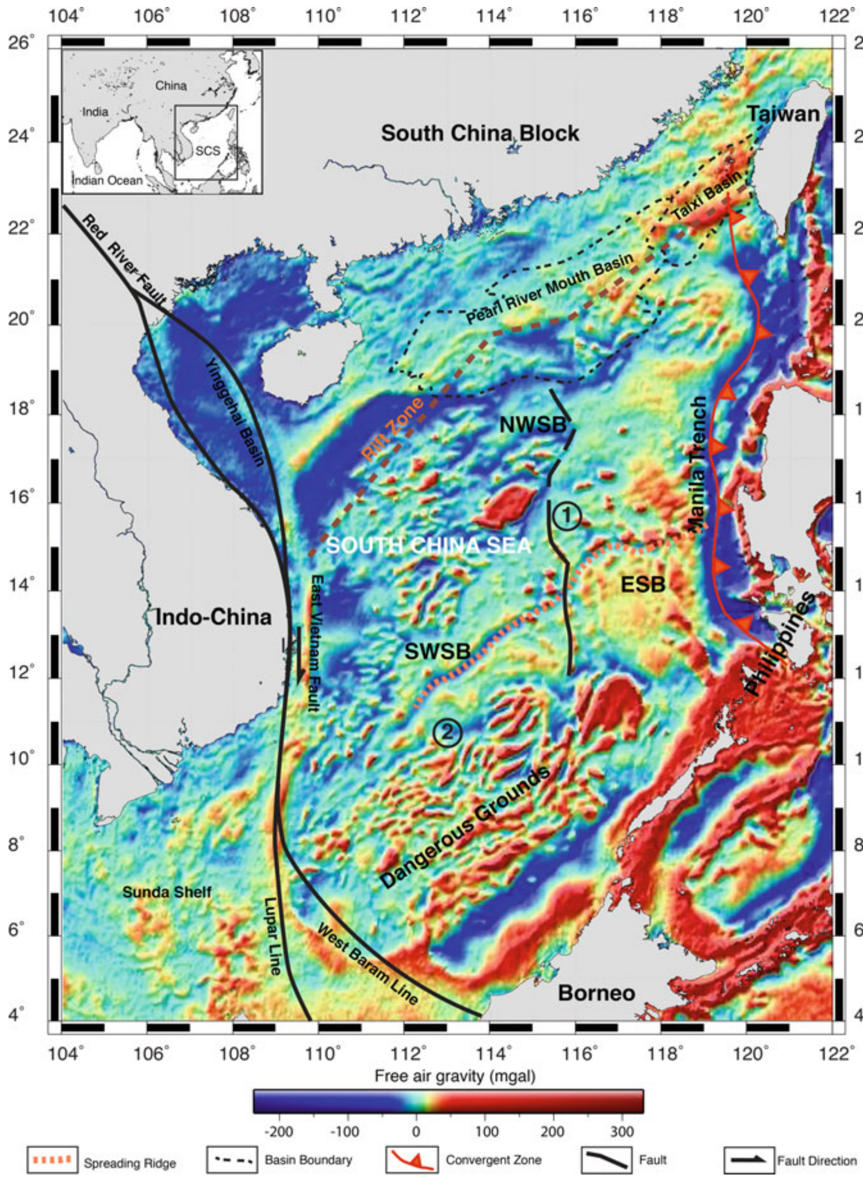

Fig. 2 It shows the free-air gravity anomaly variation in the South China Sea Basin in which major features are highlighted. Zhongnan fault (indicated as No. 1) is distinctly visible. The map reflects high gravity anomalies in the oceanic basin and lows in the surrounding islands (after Yu et al. 2017). The region of ribbon like structures is indicated as No. 2

spread in a N-S orientation at 30 Ma after which the spreading ridge jumped towards south where the spreading episode lasted from 25 to ~16 Ma and the spreading appears to propagate from northeast to southwest.

The conjugate margins of the SCS exhibit various morphological features (Yu et al. 2017) which are shown in Fig. 1. The bottom of the basin is fairly flat with seamounts, sea knolls and depressions of varying sizes. The elongation direction of the seamounts is mainly in E-W (Yu et al. 2017). In the deep area of the SCS, there are more than 50 seamounts that are over 500 m above the seafloor. Compared with those in the central basin, the seamounts in the southwest sub-basin are much smaller and their sails are relatively small.

The south-western part of the SCS shows ribbon like structures (Hayes et al. 1995; Ding et al. 2013) distributed over a wide “Basins and Range-like” province which implies a decollement level in the crust (Gilder et al. 1991; Franke 2013; Pichot et al. 2014) (Fig. 2). The central parts of both the northern and southern margins display a different morphology underlined by large round shapes of around 50–100 km in size. The round shapes in the northern margin may be compared to the large granitic bodies cropping out onland in China and Vietnam (Savva et al. 2014) (Fig. 1). Zhongnan Fault Zone is a striking feature in the middle part of the SCS basin.

Across the South China Sea, the crustal thickness varies significantly (Nissen et al. 1995; Qui et al. 2011; Pichot et al. 2014). The northern margin has an average of 30 km (Nissen et al. 1995) which generally thins towards the South with 10–15 km thick (Qui et al. 2011; Pichot et al. 2014). The coastal zone of the northern margin is marked by a much rougher morphology with elongated flakes composed of granite and Palaeozoic sediments (Shen 2008; Pichot et al. 2014). Basin portions closer to COT boundaries are composed of a thinner crust (between 3 and 5 km on the northern margin and 3 km on the southern side) (Savva et al. 2014).

Satellite gravity images clearly reflect most of the primary tectonic features and many other secondary structural details in the basin (Fig. 2). The gravity map depicts high gravity anomalies in the oceanic basin and lows in the surrounding islands, indicating that the crust of the basin is very thin and characteristic of typical oceanic crust. NE-trending low-intensity anomaly stripes are observed in the high-gravity background of the southwest sub-basin (Yu et al. 2017). The region of dangerous grounds is marked by elongated gravity high and low anomalies.

3 Evolution History

The south-west tapered South China Sea is a backarc basin rifted off the South China Block (Sun 2016) which resulted from the late Cretaceous to Paleogene rifting, late Eocene to middle Miocene seafloor spreading, and post-spreading subduction and closing since the late Miocene. The complex geological evolution of the SCS resulted in a variety of structures across the basin, including the abundant extensional structures and limited magmatic activity that developed in the northern margin of the SCS during and after the rifting and seafloor spreading (Franke et al. 2013). The opening of the SCS was mainly induced by the extrusion of Indochina subcontinent due to Tibet uplift and slab pull due to subduction of the Asian continental crust into the Philippine Sea Plate. Sun et al. (2009) viewed that a Proto-SCS existed before rifting and spreading occurred mainly along the present south-eastern margin although its size and connection with other paleo-oceans are not clear. Based on sea floor spreading magnetic anomaly data from the northeast, the SCS first opened at ~37 Ma, in the late Eocene. IODP Expedition 349 core (Li et al. 2014) shows that initial seafloor spreading started around 33 Ma in the northeastern South China Sea (SCS), but varied slightly by 1–2 Ma along the northern continent-ocean boundary (COB), and the terminal age of seafloor spreading is ~15 Ma in the East sub-basin and ~16 Ma in the Southwest sub-basin. Larsen et al. (2018) also proposed that narrow and fast rift-to-drift transitions along the northern SCS has resulted due to major rifting events within thin lithosphere permitting mantle upwelling, yielding abundant MORB-type melts during final breakup and early seafloor spreading.

The rift stages (in which the basin rifted from the South China Block) that resulted in the formation of the SCS started with an initial uplift of the rift shoulders accompanied by widespread erosion and peneplanation in the Late Cretaceous to Early Paleocene (Taylor and Hayes 1980, 1983; Ru and Pigott 1986; Schlüter et al. 1996; Pubellier et al. 2003). According to Sun et al. (2009), the proto-margins of the SCS experienced three main stages of deformation as the rifting propagated from North to South and then from East to West. By the end of rifting of the NE part of the SCS, spreading began and propagated gradually toward the SW. In the north eastern portion of the SCS, Hsu et al. (2004) and Yeh et al. (2010) interpreted Late Eocene/Early Oligocene oceanic crust and seafloor spreading (37.8–30.1 Ma). However, the nature of the crust there is ambiguous as McIntosh et al. (2013) proposed a hyper-extended crust with a possible mantle exhumation. The timing of seafloor spreading in the central South China Sea has been revised to 32–20.5 Ma (Barckhausen and Roeser 2004) from 32 to 15.5 Ma (Taylor and Hayes 1980; Briais et al. 1993). The post Middle Miocene evolution is considered to be devoid of important tectonic activity except for the Northwest Borneo wedge vertical motions (Sapin et al. 2011).

In the south, rifting delayed until the Eocene-Miocene and often a breakup unconformity of 3–5 Ma is observed underlying strata of 16 Ma and older ages. Since the middle Miocene, the eastern margin has been subducting, subsequently causing the closure of the sea basin and rise of Taiwan in the last 5 Ma (Li et al. 2013).

4 Dynamics of the South China Sea

Researchers have given considerable attention to understand the dynamics and related mechanisms for the evolution of the SCS. Different models have been proposed (Sun 2016) for the evolution of SCS. Of these the models that are widely accepted include (a) Tectonic extrusion model (Tapponnier et al. 1990; Briais et al. 1993); (b) Backarc extension model (Hilde et al. 1977); (c) Two-stage rifting model (Yao 1999); (d) Proto-SCS dragging model (Holloway 1982; Taylor and Hayes 1983; Hall 1996), (e)

Models that involve extension induced by mantle plume (Tamaki and Hoang 1998); and (f) 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.

4.1 The Tectonic Extrusion Model

This model is based on physical modelling experiments (Tapponnier et al. 1990; Briais et al. 1993) and considered to be the most famous model. The model depicts the major deformation in the Eurasian crust due to the collision between the Indian and Eurasian continents, leading to southward extrusion of the Indo-China Peninsula along the Ailaoshan-Red River sinistral fault. The model was supported by the synchronicity between the strike-slip movement of the fault (Tapponnier et al. 1990) and the spreading of the SCS (Taylor and Hayes 1980, 1983). However, problems emerged with the extrusion model in terms of age discrepancy, compression and extension of the SCS, failing to reflect the real geodynamic conditions and failing to explain the wider spreading in the east of SCS than in the west.

4.2 Backarc Extension Model

This model (Hilde et al. 1977) proposes that the SCS was a back-arc basin rifted from the passive margin of the Eurasian continent. In the model, the subduction direction of the Philippine Sea and the Pacific Plate is not compatible with the extension direction of the SCS even though the subduction of the Philippine Sea Plate was taken as the primary driving force (Karig 1971; Ben-Avraham and Uyeda 1973; Guo et al. 1983). Also, the SCS was assumed as a backarc basin related to subduction of the Neotethys Plate between the Australian and Eurasian continents (Hilde et al. 1977). The model shows that the extension of the SCS started at 100 Ma (Hilde et al. 1977; Stern and Bloomer 1992) without any evidence.

4.3 Two-Stage Rifting Model

Considering geomorphological/geophysical features like water depths, extensional basins surrounding the SCS, and magnetic anomalies in the SWSB of the SCS, this model proposes two extension events in the SCS-the first extension, which occurred in the Late Eocene to Early Oligocene (42–35 Ma), formed the southwest-northeast trending SWSB and the second extension occurred in the Late Oligocene to Early Miocene, resulting in the formation of east–west trending ESB (Yao 1999). Despite the two-stage opening of the SCS predicted by this model is confirmed by recent dating results, the timing is not consistent (Li et al. 2014).

4.4 Proto-SCS Dragging Model

According to this model, a proto-SCS existed south of the current SCS and disappeared through south-eastward subduction beneath the Luzon and Sulu islands in the Late Cretaceous to Paleocene (Holloway 1982; Taylor and Hayes 1983; Lee and Lawver 1994, 1995) which resulted in extension and rifting along the southeast margin of the South China Block and the formation of the SCS (Holloway 1982; Taylor and Hayes 1983; Hall 1996). But, paleomagnetic results suggest that the proto-SCS was very small (Lee and Lawver 1994) to have pulled apart the thick continental lithosphere of South China.

4.5 Models that Involve Extension Induced by Mantle Plume

In this model, a mantle plume is considered as the driving force for the evolution of the SCS (Tamaki and Hoang 1998) which is apparently supported by seismic tomography showing high temperature anomalies beneath the SCS (Huang and Zhao 2006; Zhao 2007). However, absence of large scale magmatism and other geochemical data on some basaltic rocks (Yan et al. 2008; Zou and Fan 2010; Xu et al. 2012; Huang et al. 2013) are against this plume induced model.

4.6 Combined Model

In this model, several events/features like 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) are put together to explain the opening of the SCS. However, neither extrusion nor proto-SCS subduction/pull can explain the formation of the SCS nor can it explain the two-stage extension. As of now, this model is more widely used than the other models.

Remarks
From various perspectives the SCS has been an interesting region for geoscience researchers. Existence of different types of geological features which preserves the complete evolutionary records of the SCS makes it a fascinating area for understanding the geological journey that was taken by a rifted marginal sea which has been

influenced by various plate tectonic processes. Studies with the help of integrated geophysical and geological data would be able to find a conclusive mechanism for the initiation, evolution and formation of the South China Sea.

Acknowledgements This short article is based on the available literatures. We thank the director of NCPOR, Goa. The authors gratefully acknowledge all authors of the research articles which have been referred to compile this article.

References

Barckhausen U, Roeser HA (2004) Seafloor spreading anomalies in the South China Sea revisited. In: Continent-ocean interactions within East Asian marginal seas, vol 149. AGU, Washington, DC, pp 121–125

Barckhausen U, Engels M, Franke D, Ladage S, Pubellier M (2014) Evolution of the South China Sea: revised ages for breakup and seafloor spreading. Mar Pet Geol 58:599–611

Ben-Avraham Z, Uyeda S (1973) The evolution of the China Basin and the 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 seafloor spreading stages in the South China Sea: implications for the tertiary tectonics of Southeast Asia. J Geophys Res: Solid Earth 98(B4):6299–6328

Childress L (2018) The expedition 368X scientists. Int Ocean Discov Program, Exped 368X Prelim Rep: IODP Publ

Courtillot V (1982) Propagating rifts and continental breakup. Tectonics 1(3):239–250

Cullen A, Reemst P, Henstra G, Gozzard S, Ray A (2010) Rifting of the South China Sea: new perspectives. Pet Geosci 16(3):273–282

Ding W, Franke D, Li J, Steuer S (2013) Seismic stratigraphy and tectonic structure from a composite multi-channel seismic profile across the entire dangerous grounds, South China Sea. Tectonophysics 582:162–176

Franke D (2013) Rifting, lithosphere breakup and volcanism: comparison of magma-poor and volcanic rifted margins. Mar Pet Geol 43:63–87

Franke D, Savva D, Pubellier M, Steuer S, Mouly B, Auxietre JL, Meresse F, Chamot-Rooke N (2013) The final rifting evolution in the South China Sea. Mar Pet Geol 58:704–720

Gilder SA, Keller GR, Luo M, Goodell PC (1991) Timing and spatial distribution of rifting in China. Tectonophysics 197:225e243

Guo LZ, Shi YS, Ma R (1983) On the formation and evolution of the mesozoic-cenozoic active continental-margin and island-arc tectonics of the western Pacific-Ocean. Acta Geol Sin 57(1):11–21

Hall R (1996) Reconstructing cenozoic SE Asia. Geol Soc Lond Spec Publ 106(1):153–184

Hayes DE, Nissen SS, Buhl P, Diebold J, Bochu Y, Zeng W, Chen Y (1995) Throughgoing crustal faults along the northern margin of the South China Sea and their role in crustal extension. J Geophys Res: Solid Earth 100(B11):22435–22446

Hilde TW, Uyeda S, Kroenke L (1977) Evolution of the western Pacific and its margin. Tectonophysics 38(1–2):145–165

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

Hsu SK, Yeh YC, Doo WB, Tsai CH (2004) New bathymetry and magnetic lineations identifications in the northernmost South China Sea and their tectonic implications. Mar Geophys Res 25(1–2):29–44

Huang J, Zhao D (2006) High-resolution mantle tomography of China and surrounding regions. J Geophys Res: Solid Earth 111(B9)

Huang XL, Niu Y, 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 Min Pet 165(3):437–455

Huchon P, Nguyen TNH, Chamot-Rooke N (2001) Propagation of continental break-up in the southwestern South China Sea. Geol Soc Lond Spec Publ 187(1):31–50

Hutchison CS (1989) Geological evolution of South-east Asia, vol 13. Clarendon Press, Oxford, p 368

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

Larsen HC, Mohn G, Nirrengarten M, Sun Z, Stock J, Jian Z, Klaus A, Alvarez-Zarikian CA, Boaga J, Bowden SA, Briais A, Chen Y, Cukur D, Dadd K, Ding W, Dorais M, Ferré EC, Ferreira F, Furusawa A, Gewecke A, Hinojosa J, Höfig TW, Hsiung KH, Huang B, Huang E, Huang XL, Jiang S, Jin H, Johnson BG, Kurzawski RM, Lei C, Li B, Li L, Li Y, Lin J, Liu C, Liu C, Liu Z, Luna AJ, Lupi C, McCarthy A, Ningthoujam L, Osono N, Peate DW, Persaud P, Qiu N, Robinson C, Satolli S, Sauermilch I, Schindlbeck JC, Skinner S, Straub S, Su X, Su C, Tian L, van der Zwan FM, Wan S, Wu H, Xiang R, Yadav R, Yi L, Yu PS, Zhang C, Zhang J, Zhang Y, Zhao N, Zhong G, Zhong L (2018) Rapid transition from continental breakup to igneous oceanic crust in the South China Sea. Nat Geosci 11(10):782

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

Li CF, Li J, Ding W, Franke D, Yao Y, Shi H, Pang X, Cao Y, Lin J, Kulhanek DK, Williams T (2015a) Seismic stratigraphy of the central South China Sea basin and implications for neotectonics. J Geophys Res: Solid Earth 120(3):1377–1399

Li CF, Lin J, Kulhanek DK (2013) South China Sea tectonics: opening of the South China Sea and its implications for southeast Asian tectonics, climates, and deep mantle processes since the late Mesozoic. Int Ocean Discov Program Sci Prospect 349:1–111

Li C-F, Lin J, Kulhanek DK (2015) The Expedition 349 Scientist. Proc Int Ocean Discov Program: IODP Publ 349

Li CF, Wang P, Franke D, Lin J, Tian J (2012) Unlocking the opening processes of the South China Sea. Sci Drill 14:55–59

Li CF, Xu X, Lin J, Sun Z, Zhu J, Yao Y, Zhao X, Liu Q, Kulhanek DK, Wang J, Song T (2014) 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

Li CF, Zhou Z, Hao H, Chen H, Wang J, Chen B, Wu J (2008) Late Mesozoic tectonic structure and evolution along the present-day northeastern South China Sea continental margin. J Asian Earth Sci 31(4–6):546–561

Li PL (1994) Structural features and oil-and-gas accumulation in Pearl River Mouth basin. Guangdong Geol 9(4):21–28

McIntosh K, van Avendonk H, Lavier L, Lester WR, Eakin D, Wu F, Liu CS, Lee CS (2013) Inversion of a hyper-extended rifted margin in the southern central range of Taiwan. Geology 41(8):871–874

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

Nissen SS, Hayes DE, Bochu Y, Zeng W, Chen Y, Nu X (1995) Gravity, heat flow, and seismic constraints on the processes of crustal extension: Northern margin of the South China Sea. J Geophys Res: Solid Earth 100(B11):22447–22483

Pichot T, Delescluse M, Chamot-Rooke N, Pubellier M, Qiu Y, Meresse F, Sun G, Savva D, Wong KP, Watremez L, Auxiètre JL (2014) Deep crustal structure of the conjugate margins of the SW South China Sea from wide-angle refraction seismic data. Mar Pet Geol 58:627–643

Pubellier M, Ego F, Chamot-Rooke N, Rangin C (2003) The building of pericratonic mountain ranges: structural and kinematic constraints applied to GIS-based reconstructions of SE Asia. Bull Société Géologique Fr 174(6):561–584

Qui XL, Zhao MH, Ao W, Lü CC, Hao TY, You QY, Ruan AG, Li JB (2011) OBS survey and crustal structure of the SW sub-basin and Nansha block, South China Sea. Chin J Geophys 54(6):1009–1021

Ru K, Pigott JD (1986) Episodic rifting and subsidence in the South China Sea. AAPG Bull 70(9):1136–1155

Sapin F, Pubellier M, Lahfid A, Janots D, Aubourg C, Ringenbach JC (2011) Onshore record of the subduction of a crustal salient: example of the NW Borneo Wedge. Terra Nova 23(4):232–240

Savva D, Pubellier M, Franke D, Chamot-Rooke N, Meresse F, Steuer S, Auxietre JL (2014) Different expressions of rifting on the South China Sea margins. Mar Pet Geol 58:579–598

Schlüter 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):39–78

Shen W (2008) Post-orogenic extension in the Pearl River Delta region (South China): an integrated morphological, structural, geophysical and thermochronological study. HKU theses Online (HKUTO)

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 W (2016) Initiation and evolution of the South China Sea: an overview. Acta Geochim 35(3):215–225

Sun Z, Jian Z, Stock JM, Larsen HC, Klaus A, Alvarez Zarikian CA, (2018) The Expedition 367/368 scientists. Proc Int Ocean Discov Program: IODP Publ 367/368

Sun Z, Zhong Z, Keep M, Zhou D, Cai D, Li X, Wu SH, Jiang J (2009) 3D analogue modeling of the South China Sea: a discussion on breakup pattern. J Asian Earth Sci 34(4):544–556

Sun Z, Zhou D, Zhong Z, Xia B, Qiu X, Zeng Z, Jiang J (2006) Research on the dynamics of the South China Sea opening: evidence from analogue modeling. Sci China Ser D: Earth Sci 49(10):1053

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

Tamaki K, Hoang N (1998) Mantle extrusion'A model for dispersed volcanism and DUPAL-like asthenosphere in East Asia and the Western Pacific. Mantle Dyn Plate Interact East Asia 27:67

Tapponnier P, Lacassin R, Leloup PH, Schärer U, Dalai Z, Haiwei W, Jiayou Z (1990) The Ailao-shan/Red river metamorphic belt: tertiary left-lateral shear between Indochina and South China. Nature 343(6257):431

Tapponnier P, Peltzer G, Armijo R (1986) On the mechanics of the collision between India and Asia. Geol Soc Lond Spec Publ 19(1):113–157

Taylor B, Hayes DE (1980) The tectonic evolution of the South China Basin. Tecton Geol Evol Southeast Asian Seas Isl 23:89–104

Taylor B, Hayes DE (1983) Origin and history of the South China Sea basin. Tecton Geol Evol Southeast Asian Seas Isl: Part 2(27):23–56

Taylor B, Goodliffe AM, Martinez F (1999) How continents break up: insights from Papua New Guinea. J Geophys Res: Solid Earth 104(B4):7497–7512

Wang P, Prell WL, Blum P (2000) Proceedings of the Ocean Drilling Program, initial reports, vol 184. http://www.ldeo.columbia.edu

Xu Y, Wei J, Qiu H, Zhang H, Huang X (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

Yan Q, Shi X, Wang K, Bu W, Xiao L (2008) Major element, trace element, and Sr, Nd and Pb isotope studies of cenozoic basalts from the South China Sea. Sci China, Ser D Earth Sci 51(4):550–566

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

Yeh YC, Sibuet JC, Hsu SK, Liu CS (2010) Tectonic evolution of the Northeastern South China Sea from seismic interpretation. J Geophys Res: Solid Earth 115(B6)

Yu X, Xue C, Shi H, Zhu W, Liu Y, Yin H (2017) Expansion of the South China Sea basin: constraints from magnetic anomaly stripes, sea floor topography, satellite gravity and submarine geothermics. Geosci Front 8(1):151–162

Zhao D (2007) Seismic images under 60 hotspots: search for mantle plumes. Gondwana Res 12(4):335–355

Zhou D, Yao B (2009) Tectonics and sedimentary basins of the South China Sea: Challenges and progresses. J Earth Sci 20(1):1–12

Zhou D, Chen HZ, Wu SM, Yu HS (2002) Opening of the South China Sea by dextral splitting of the East Asian continental margin. Acta Geol Sin 76(2):180–190

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

Ziying X, Jun W, Hongfang G, Guihua S, Meijing S, Xin N, Rongwei Z (2019) Research progress of the zhongnan-Lile Liyue fault zone in the South China Sea basin. J Trop Ocean 38(2):86–94

Zou H, Fan Q (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