



Dynamic processes of the curved subduction system in Southeast Asia: A review and future perspective

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ABSTRACT

Southeast Asia is located in an important regional geodynamic intersection zone surrounded by inward subduction systems on three sides, consisting the largest and most complicated convergent subduction system in the earth. The deep circulation and ultimate destination of the subducted material have always been an elusive scientific mystery, lacking both systematic scientific observation and accepted theoretical models. In this review we present geophysical, geochemical and geodynamical models in last decades regarding the seismic tomographic deep structure, material exchanges and evolution history of the Curved Subduction System (CSS) in SE Asia, and identify remained challenges in constructing the deep mantle structure and quantifying the feedback between the subducting slab and the interior recycling materials relevant to the dynamic processes within the theme of mass and energy transfer. We propose that increased understanding of seismic tomography within the CSS, combined with geochemical analysis and computational geodynamic modeling, will aid clearer portrayal of the dynamic mechanisms controlling the evolution of such ring-shape subduction systems on Earth.

1. Introduction

Plate tectonics is undoubtedly one of the most successful scientific theories in Earth Science, with subduction as a major process for accommodating plate convergence within a probably unique framework of planetary convection. Subduction plays an essential role in the dynamics of the Earth's mantle (e.g. [Dziewonski et al., 1977](#); [Hofmann, 1988](#); [Bercovici et al., 1989](#); [Richards and Engebretson, 1992](#); [Calvert et al., 1995](#); [van der Hilst et al., 1997](#)). The recycling of oceanic plates into the mantle at different speeds is perhaps the most important geological process on Earth, providing the gravitational energy change that drives tectonic motions, as well as controlling the mixing of surficial materials, including sediment, water, and carbon, with those deep in Earth interior (e.g. [Iwamori, 1998](#); [Sleep and Zahnle, 2001](#); [Bebout, 2007](#); [Chauvel et al., 2008](#); [Handley et al., 2011](#); [Ryan and Chauvel, 2014](#); [Hammouda et al., 2014](#); [Li et al., 2017](#); [Zhang et al., 2017](#)). By focusing

vast amounts of mechanical energy into narrow coastal belts, subduction zones are also responsible for the enormous risks associated with the array of geohazards in densely populated regions, including mega-earthquakes, tsunamis, volcanic eruptions, and landslides (e.g. [Chlieh et al., 2008](#); [Chester et al., 2013](#); [Ruprecht and Plank, 2013](#); [Bangs et al., 2015](#); [Dura et al., 2016](#); [LaHusen et al., 2016](#)).

SE Asia lies in the area between the Eurasia, Australia and the Pacific, and much of which can be considered part of the Eurasia Plate (e.g. [Hall and Spakman, 2015](#)). The SE Asia region is surrounded largely by subduction zones where major plates are converging from the west, south and east (India, Australia, Pacific and Philippine sea), forming the super-convergent subduction system composing of the Andaman-Sumatra-Java trench in the west and south, the Philippine trench in the east. Here we name it as the "Curved Subduction System" (here after called CSS) since the shape of all these inward subduction zones is roughly like a circle, with the interior is complicated by internal subduction, such as

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the North Sulawesi trench and the Manila Trench, and a cluster of marginal basins, including the South China Sea, Sulawesi sea, and Sulu sea et al. (Fig. 1). This CSS shows quite high gravity signals in the free-air gravity map with the region much larger than the Tibet (Fig. 2), indicating a large amount of high-density materials have been subducted and accumulated in the deep. Following the identification of current plate boundaries, such kind of curved subduction system has also been occurring in the South Sandwich trench of the Scotia Sea, the Lesser Antilles trench in the east of Caribbean Sea, and the Hellenic trench in the Mediterranean. Govers and Wortel (2005) refer such kinks as Subduction-Transform Edge Propagator, which may result in substantial deformation, rotation, topography and sedimentary basins with specific temporal variation. However, CSS is a rare but more remarkable super-convergent system both in scale and complexity. It is a combination of this kind of curved subduction system and related marginal basins, providing a uniquely natural laboratory to understand the interactions between the overriding plates, the subducting and mantle convection. The slab pull associated with subduction in this system not only produces the main driving force of the plate movement in the Cenozoic (e.g. Hamilton, 1979; Zhao and Ohtani, 2009; Hall and Spakman, 2015), and

forms the most complex archipelagic ocean with the assembly of fragmented continental blocks (e.g. McCourt et al., 1996; Hall, 2002; Gibbons et al., 2013; Zahirovic et al., 2014; Dong et al., 2015), but also controls the ocean circulation, general atmospheric circulation, and air-sea interaction related to the changes in surface topography, volcanic eruption, etc. (e.g. Hafkenscheid et al., 2006; Gaina and Müller, 2007; Seton et al., 2012). Furthermore, the subduction of the Australian, Indian, Pacific and Philippine plates beneath the SE Asia along the CSS has resulted in numerous active volcanoes around the margin of Sumatra and Philippine islands, as well as devastating earthquakes, including the December 26, 2004 Mw 9.1–9.3 M-earthquake (Stein and Okal, 2005), and supervolcanoes, such as the Toba supervolcano (Chesner et al., 1991). In this paper we present an overview of seismic tomographic imagings of deep structures, material exchanges and evolution history of the CSS, and provide a new perspective of the mantle dynamics inspired by ongoing geophysical observations and geodynamic modeling, as well as future international collaborations on observations to better constrain the evolution history of the region.

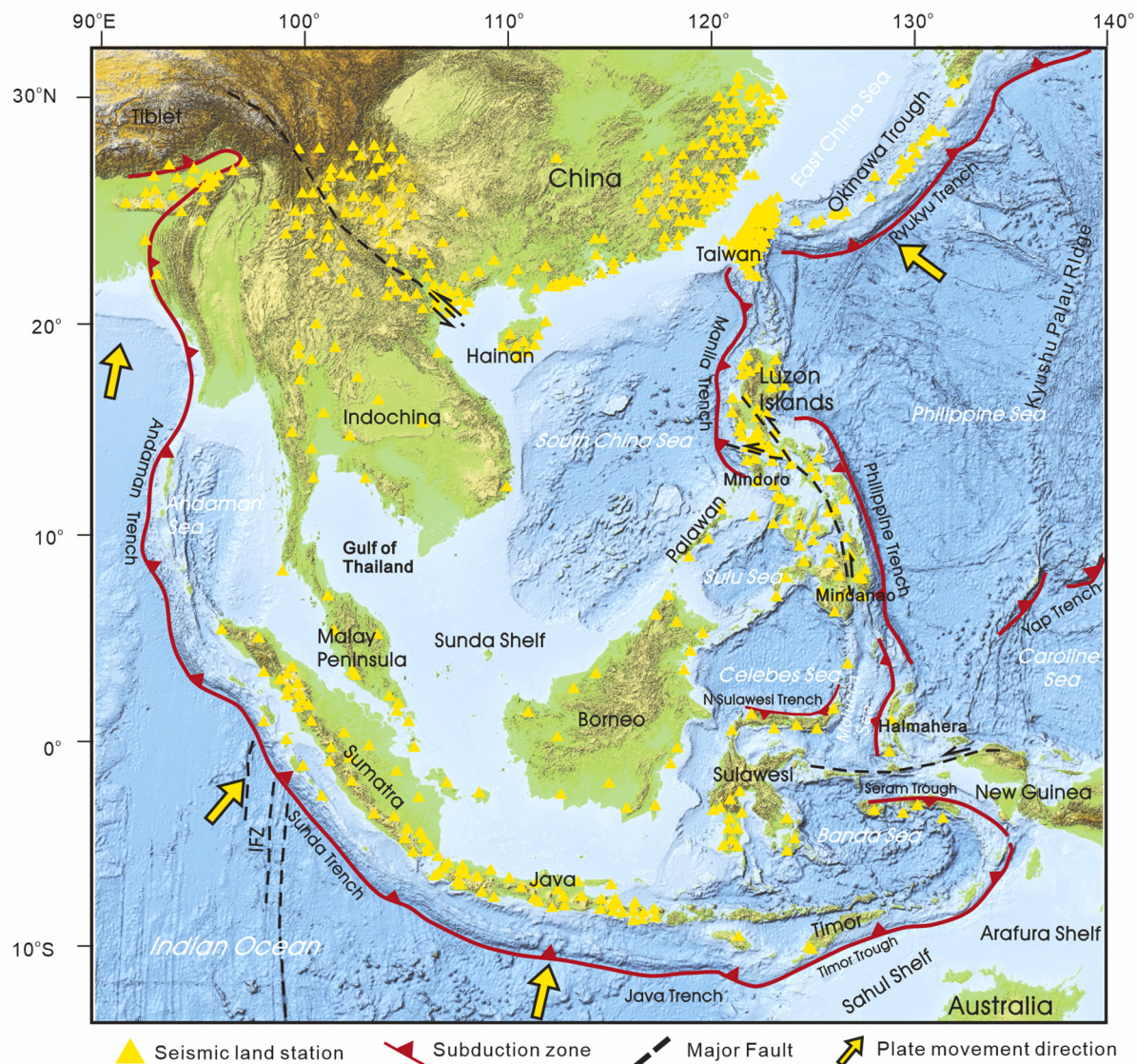


Fig. 1. Major morphological units and tectonic setting in Southeast Asia. Yellow triangles show the locations of land seismic stations. Red solid lines denote the subduction zone. Yellow arrows denote the absolute plate-motion directions of the surrounding plates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

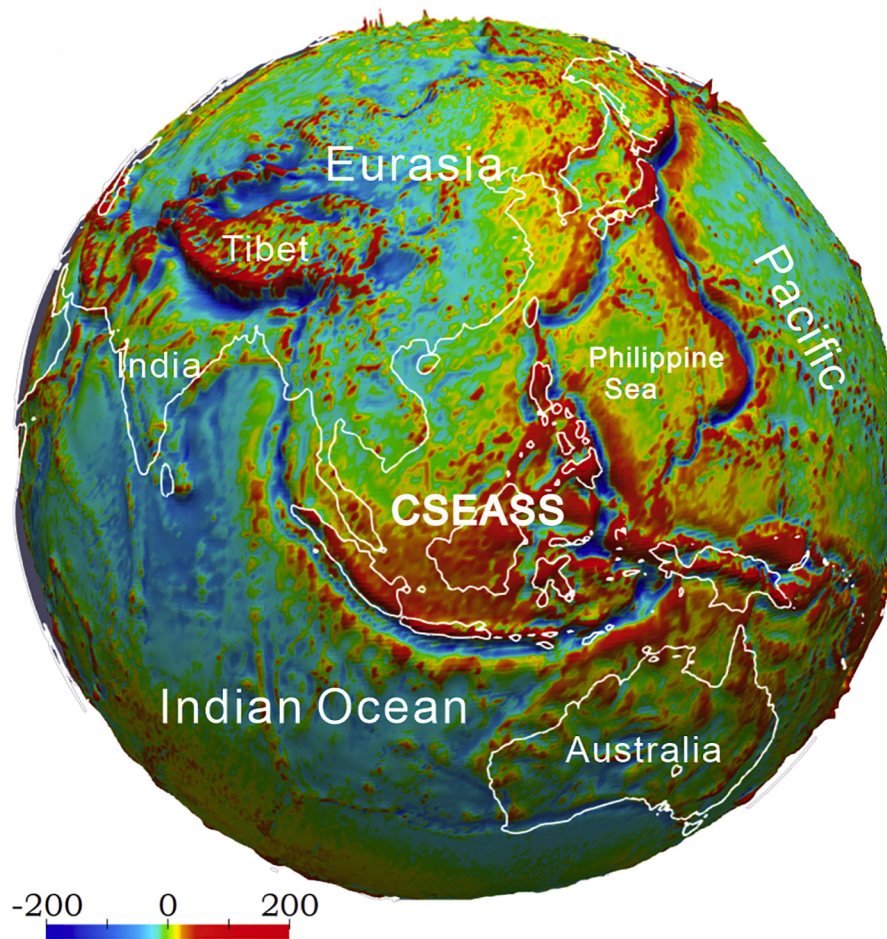


Fig. 2. Free-air gravity map shows quite gravity high signals within the CSS, with the region much larger than the Tibet.

2. How was the CSS created

2.1. Growth of the subduction system

Earth's history is dominated by Wilson cycle of unification-splitting-reunification controlled by seafloor spreading, subduction, and the collision of plates. SE Asia is a typical example which is largely composed of continental fragments rifted from Gondwana and added to Eurasia from the Triassic to the Cretaceous (e.g. Audley-Charles et al., 1988; Hall, 2002, 2012; Smyth et al., 2007; Metcalfe, 2011, 2013; Hall and Spakman, 2015). The main continental parts of the CSS include the South China Block in the north, the Indo-China Block in the west, and Sundaland in the south. It is boarded by two subduction systems, i.e. the Pacific-Eurasia convergent system in the east and the Indian-Australian-SE Asia subduction system in the west, which has experienced a long-term plate reorganization since Mesozoic (Fig. 3).

The continental margin of the South China Block, or the southeast Eurasia was an Andean Type margin dominated by the convergence between the Eurasia and Pacific, and its evolution history has undergone a complicated convergent process between the Eurasian and (paleo) Pacific plates, along with variations in convergence direction, rate, as well as the subducting angle of the slab (Li and Li, 2007; Suo et al., 2019; Li et al., 2019). Geochemical dating of the continental arc magmatism in the southeast South China Block indicated that the subduction of the paleo-Pacific, probably the Izanagi Plate, was initiated at mid-Permian (Li et al., 2006; Wu and Wu, 2019) and formed a NE-trending linear subduction belt. The Andean-type convergent plate margin is characterized by alternating sections of continental magmatic arc, and

magmatic gaps during Triassic (~260 Ma - ~190 Ma) due to a flat-slab subduction (Li et al., 2012; Müller et al., 2016; Cao et al., 2018). The subduction of Izanagi Plate continued to Eocene until the Izanagi-Pacific ridge-trench interaction at 56 Ma (Seton et al., 2012) (Fig. 3, 50 Ma), and possibly led to the 53–47 Ma Pacific plate reorganization (Wu and Wu, 2019). After that the present Pacific moved NWW and began its subduction (Hall, 2002; Sun et al., 2007; Wu et al., 2016).

To the west, the present Indochina and Sundaland were accreted together between the Permian and the Early Cretaceous through the closure of several Tethyans in between (Rangin et al., 1999; Metcalfe, 2011, 2013; Li et al., 2012; Hall, 2012; Hall and Spakman, 2015). With the opening of the Mesozoic Tethyan and the NE subduction of the Paleozoic Tethyan, continental fragments rifted from Gondwana moved northeastwards and added to Indochina and Sundaland at different times since the Mesozoic (Fig. 3). Some components of the Sundaland may come from the east-facing Pacific (Hall, 2002). The Mesozoic Tethyan began its subduction since the Late Triassic (Zahirovic et al., 2016), and the subduction continued at the Sumatra-Java margin throughout the Early Cenozoic (McCourt et al., 1996; Soeria-Atmadja and Noeradi, 2005). The separation between the Australia and Antarctica was very slow until about 45 Ma (Royer and Sandwell, 1989; White et al., 2013; Van den Ende et al., 2017). After that increased northward movement of the Australian Plate folded the Sundaland and made it rotate counter-clockwise (Rangin et al., 1999; Hall, 2012; Hall and Spakman, 2015). The present Indian-Australian Plate is composed of several segments with different ages, separated by a 2500 km long Investigator Fracture Zone (IFZ) (Lange et al., 2010; Koulakov et al., 2016) (Fig. 3, 10 Ma and 0 Ma). At the eastern end of Sundaland the

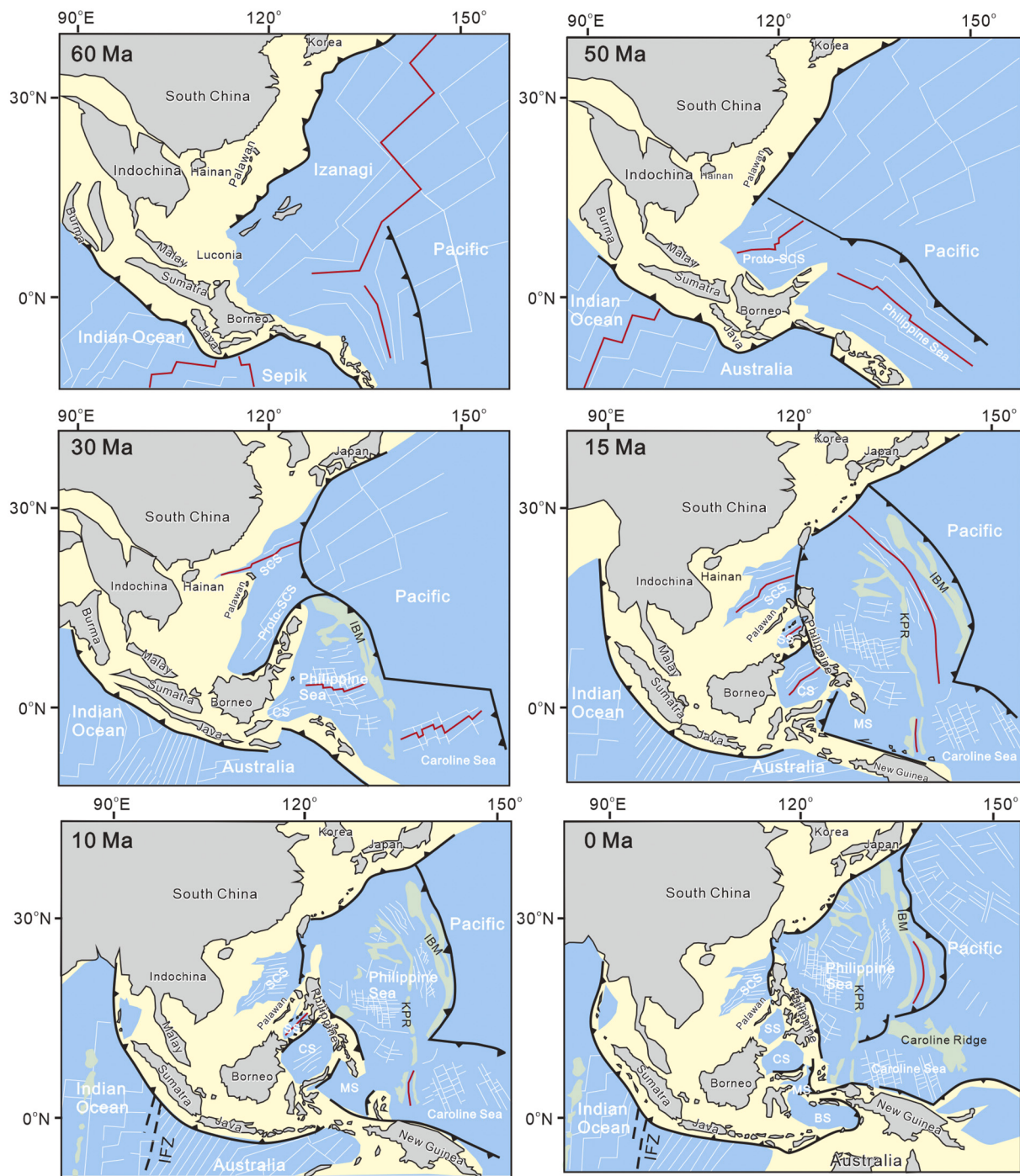


Fig. 3. Cenozoic plate reconstructions of the SE Asia and adjacent regions. Plate motion model before 30 Ma was referred from Zhang and Li et al. (2018); After 30 Ma was referred from Hall and Spakman (2015). The motions of some plates were referred from specific studies (Philippine Sea Plate from Wu et al., 2016, and Borneo from Advokaat et al., 2018).

convergent system changes from oceanic subduction to continent–island arc collision of the Scott Plateau, part of the Australian continent, colliding with the Banda island arc and Sumba Island in between (Honthaas et al., 1998; Schellart and Spakman, 2015; Wang and He, 2020) (Fig. 3, 10 Ma and 0 Ma).

The Philippine Sea Plate lying in the east is composed of several Cenozoic basins, including the West Philippine basin, the Shikoku and Parece Vela basins, and the Mariana Trough. It was originally a back-arc basin developed in the south of the equator, and the initial seafloor spreading of the West Philippine Sea occurred in the early Cenozoic with estimated ages of 58 Ma (Hilde and Lee, 1984), 55 Ma (Deschamps and

Lallemand, 2002; Hall, 2012), or 52–51 Ma (Ishizuka et al., 2018) (Fig. 3). Then it experienced NW-ward movement and anticlockwise rotation (Hall, 2002; Pubellier et al., 2003). Since ~50 Ma the paleo-Pacific began its subduction under the West Philippine Basin along a transform fault resulted from gravitational instability of oceanic lithosphere (Cosca et al., 1998; Ishizuka et al., 2011; Arculus et al., 2015; Stern and Gerya, 2018), or relic arcs (Leng and Gurnis, 2015) (Fig. 3). The Izu-Bonin-Mariana subduction system began its development with forearc spreading first (Stern, 2004; Stern and Gerya, 2018), the splitting of the IBM arc (Ishizuka et al., 2018), and the backarc spreading of the Shikoku and Parece Vela basins, and the Mariana Trough with

continuous eastward retreatment of the paleo-Pacific subduction (Watts and Weissel, 1975; Okino et al., 1994; Yamazaki et al., 2003; Sdrolias and Müller, 2006) (Fig. 3, 15 Ma, 10 Ma and 0 Ma). The N-S opening Caroline Sea impinged on the SE Philippine Sea around 34 to 30 Ma, and torqued the Philippine Sea plate with a westward movement and up to 60° clockwise rotation before finally subducted under the South China Sea-Eurasian margin and initiated Manila trench subduction by 15 to 20 Ma (Suppe et al., 1981; Clift et al., 2013; Wu et al., 2016; Cheng et al., 2019). A proto-Philippine Sea, or the East Asian Sea (Wu et al., 2016), existed between the Pacific and Indian Oceans before finally vanished by 15 Ma due to the convergence among the Pacific, the Philippine Sea, and the Australian plates. Since then, the initial curved subduction system came into being. From 15 to 2 Ma the Philippine Sea Plate moved NNW and the South China Sea and its margin were subducted at the Manila trench (Wolfe, 1988; Yumul et al., 2003; Huang et al., 2018) (Fig. 3, 15 Ma, 10 Ma and 0 Ma).

2.2. Opening of marginal basins

A unique feature of the CSS is the widely developed marginal basins within this super-convergent region, including the South China Sea, Sulu Sea, Celebes Sea and Banda Sea in the eastern part from north to south, and the Andaman Sea in the west (Fig. 1). The subduction/collision and rifting/spreading events both framed the Cenozoic tectonics of the SE Asia (Jolivet et al., 1989; Hall and Spakman, 2002, 2015; Hafkenscheid et al., 2006; Seton et al., 2012). All these marginal basins opened in Cenozoic with extremely complicated plate kinematics. Some marginal basins (e.g. Sulu Sea, Banda Sea) were dominated by back-arc or intra-arc extension (Rangin and Silver, 1991; Honthaas et al., 1998; Heine et al., 2012), while others were opened through transformation with pull-apart extension (Andaman Sea, Tapponnier et al., 1982; Hall and Spakman, 2015; Morley, 2017), or seafloor spreading (South China Sea) (e.g. Taylor and Hayes, 1983; Briais et al., 1993; Li et al., 2015; Sibuet et al., 2016; Sun et al., 2018; Ding et al., 2020).

As the largest marginal basin in SE Asia, the South China Sea was treated as a back-arc basin in early studies (Karig, 1973; Hilde et al., 1977). Further studies abandoned this opinion since no subduction system was related to the South China Sea. They suggested it was an “Atlantic-type” oceanic basin experienced continental rifting since the Late Cretaceous resulted from the rollback of paleo-Pacific subduction, and a seafloor spreading after the Early Oligocene (Taylor and Hayes, 1980, 1983). A proto-South China Sea was suggested to exist in the south of the present South China Sea, which might be a part of the paleo-Pacific (Hall, 2012), or a marginal basin connected with the East Asian Sea (Wu et al., 2016). It subducted under the Borneo since Eocene and triggered the NS opening of the present South China Sea (Hall, 2002). Recent studies indicated the opening mechanism of the South China Sea attributed to a sinistral strike-slip movement along the boundary between the Eurasian Plate and Huatung Plate on the east (Huang et al., 2019).

Based on the identification of magnetic anomalies, Briais et al. (1993) indicated that the seafloor spreading occurred between 32 and 16 Ma, and was complicated by a southward ridge jumps and a south-westward ridge propagation. This model has been generally accepted with more detailed analysis on the continental rifting pattern (e.g. Cullen, 2010; Franke et al., 2014), rift-to-drift transition (e.g. Larsen et al., 2018; Ding et al., 2020), magmatic activities (e.g. Fan et al., 2017; Zhao et al., 2020), episodic propagated rifting and spreading reorientation (e.g. Savva et al., 2014; Ding et al., 2018; Sun et al., 2019a, 2019b). Shipboard results of microfossil biostratigraphy and palaeomagnetic results from the International Oceanic Discovery Program (IODP) Expedition 349 (Li et al., 2015) and the IODP Expeditions 367&368 (Sun et al., 2018), combined with analysis on recently-acquired deep tow magnetic anomalies (Li et al., 2014), and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of basalts near the fossil spreading ridge (Koppers, 2014), have refined the seafloor spreading age between ~33 Ma and 16 Ma. The

cessation time coincides with the onset of collision between Palawan and Borneo and Mindoro-Central Philippines (Cullen, 2010), suggesting a causal relationship between the two events. New drilling results also indicated that the South China Sea is not a mini-Atlantic due to the absent of serpentinite, impulse *syn*-breakup magmatism and narrow continental-oceanic transition zone (Larsen et al., 2018; Ding et al., 2020). It is a “plate-edge” type rifting basin that was strongly affected by paleo-Pacific subduction (Wang et al., 2019; Sun et al., 2019a, 2019b).

The leading edge of the southward drifting continental terranes of the South China Sea, including the Dangerous Grounds, Reed Bank and Palawan, collided with the Late Cretaceous to Early Eocene subduction complex of the northernmost part of the proto-Sulu Sea, leading to the back-arc spreading of the Sulu Sea since the latest Oligocene (Schluter et al., 1996). The oceanic crust subducted toward the south since the early Middle Miocene due to the NNW movement of the Philippine plate, and finally ceased in the late Miocene (Hall, 2012).

The Celebes Sea is a fully closed marginal basin boarded by the Borneo, the Philippines, and the Sulawesi (Fig. 1). The Eocene age and origin caused by the spreading of basaltic crust was proposed by Weissel (1980), and the Celebes Sea was regarded as a back-arc basin, or a basin formed by rifting from a continental margin (Rangin and Silver, 1991; Hall, 1996). Oceanic Drilling Program (ODP) leg 124 in 1988/1989 drilled two holes in the oceanic basin and penetrated basaltic basement with a strong MORB affinity, indicating a late middle Eocene age (Silver et al., 1991), which is similar to the West Philippine Sea. Further studies on chemistry and nature of the overlying stratigraphic succession show consistence with the West Philippine Sea, suggesting these two basins are part of the same basin during middle Eocene time (50 Ma–37 Ma) (Nichols and Hall, 1999) (Fig. 3, 30 Ma, 15 Ma). They separated by the end of Oligocene firstly by strike-slip and later by convergent plate boundaries. The Philippine Sea Plate moved northwards as the plate began to rotate clockwise, while the Celebes Sea continued to stay its original position until subducted at the North Sulawesi trench at ~5 Ma (Nichols and Hall, 1999; Hall, 2012).

The Banda Sea lies in the southeast most of the CSS, and is surrounded by Sulawesi in the west, New Guinea in the east, and Timor in the south (Fig. 1). It contains two main basins: the North Banda Sea and the South Banda Sea opened as backarc or intra-arc basins relatively to the Banda subduction zone (Hinschberger et al., 2001, 2005; Shulgin et al., 2011). Geophysical and structural data, as well as geochemical features and ^{40}K – ^{40}Ar whole-rock ages of basalts from the deep North Banda basin, have confirmed the North Banda basin is a back-arc basin opened between 12.5 and 7 Ma in the south of the Banggai-Sula islands (Réhault et al., 1991; Hinschberger et al., 2001) (Fig. 3). The South Banda Sea located in a back-arc position with respect to the Banda volcanic arc, and was opened since 6 Ma due to the northward subduction of the Indian-Australian Plate. Back-arc spreading likely ceased at 3 Ma in relation with the collision of the Australian margin at the level of Timor (Honthaas et al., 1998; Hinschberger et al., 2005).

The Andaman Sea is proposed to have developed from a margin where Palaeogene back-arc collapse closed a mid-Cretaceous back-arc oceanic basin, and resulted in the collision between island arc crust to the west and the western margin of Sundaland (Morley and Alvey, 2015; Morley, 2017). As the Indian Plate subducted under the western Sundaland, the margin became dominated by dextral strike-slip and NWW-SSE extension between Late Eocene and Oligocene (Curry, 2005). This NWW-SSE pull-apart extension finally caused the initiation of active spreading of the Andaman Sea since the latest Miocene near the western part of the Mergui-Sumatra region, and propagated northward (Raju et al., 2004; Diehl et al., 2013; Morley and Alvey, 2015).

3. What's it like in the deep

Seismic tomography has been proved as one of the most powerful tools to study the heterogeneous structure of the Earth's interior. In recent years High-resolution (P-wave) seismic tomography images the

details of subducted slab morphology and structure, since the subducted lithosphere could produce strong negative temperature anomalies which are indicated as relatively high seismic velocities in tomographic images (e.g. Bercovici and Karato, 2003; Zhao, 2004; Huang and Zhao, 2006; Huang et al., 2015a, 2015b). It is helpful to understand the tectonic evolution of SE Asia. The morphology of subducted slabs in the mantle around Indonesia and the Philippines has been well imaged by many seismic tomography studies, as well as global models (Richard et al., 2013; Li et al., 2008; Hall and Spakman, 2015; Huang et al., 2015a, 2015b). With high-resolution tomographic imaging, Widiyantoro and van der Hilst (1997) illustrated the mantle structure of the Java trench, which is featured with a deep-to-lower mantle flattening subducted slab (Fig. 4). Further to the west, the morphology of the subducted Indian Plate below North Sumatra along the Sumatra Trench shows much steeper slab, and reached to the mantle transition zone, or much deeper into the lower mantle (Li et al., 2008; Huang et al., 2015a, 2015b) (Fig. 4). To the east the subducted slab folded the Banda arc and formed a spoon-shape due to the northward collision of Australia. The morphology of subducted Philippine Sea Plate in the eastmost is very similar to what happened in the west but with opposite subduction orientation (Li et al., 2008) (Fig. 4).

The Molucca Sea is widely known as a bipolar subduction with two slabs subducting to the west and east (hereafter called the Sangihe and

Halmahera slabs, respectively). The length and geometry of the two slabs are important in reconstructing the Philippine Sea Plate as there is a hypothesis that the Molucca Sea and Philippine Sea Plate once belonged to a single plate (e.g., Hall, 1987; Wu et al., 2016; Zahirovic et al., 2014). The Halmahera slab has reached a depth of 375 km (Wu et al., 2016), which is comparable to the results from the UU-P07 (Amaru, 2007; Hall and Spakman, 2015). The depth extent of the western Sangihe slab is controversial among the previous studies, with a depth up to 1200 km in Li et al. (2008) and Wu et al. (2016), and a depth less than 660 km in the UU-P07 which is consistent with the seismicity distribution. The different depths and dips of the two slabs result in different unfolded length of the Molucca Sea Plate, with a length of 850 km to the north and 1550 km to the south in Wu et al. (2016), and a total length of 1500 to 1600 km in the UU-P07, which are, however, all much shorter than that in Rangin et al. (1999).

The eastern boundary of the CSS is featured with opposite subduction of the SCS and the Philippine Sea. The SCS slab reaches a maximum depth of 450 km, while the Philippine slab at the southwest margin of the Philippine Sea extends to a depth of 350 km, which is consistent with previous tomography studies (Amaru, 2007; Hall and Spakman, 2015; Huang et al., 2015a, 2015b; Li et al., 2008; Wu et al., 2016). Controversies are present in terms of the interpretations of the fast velocity anomaly associated with the SCS subduction, and the underlying fast

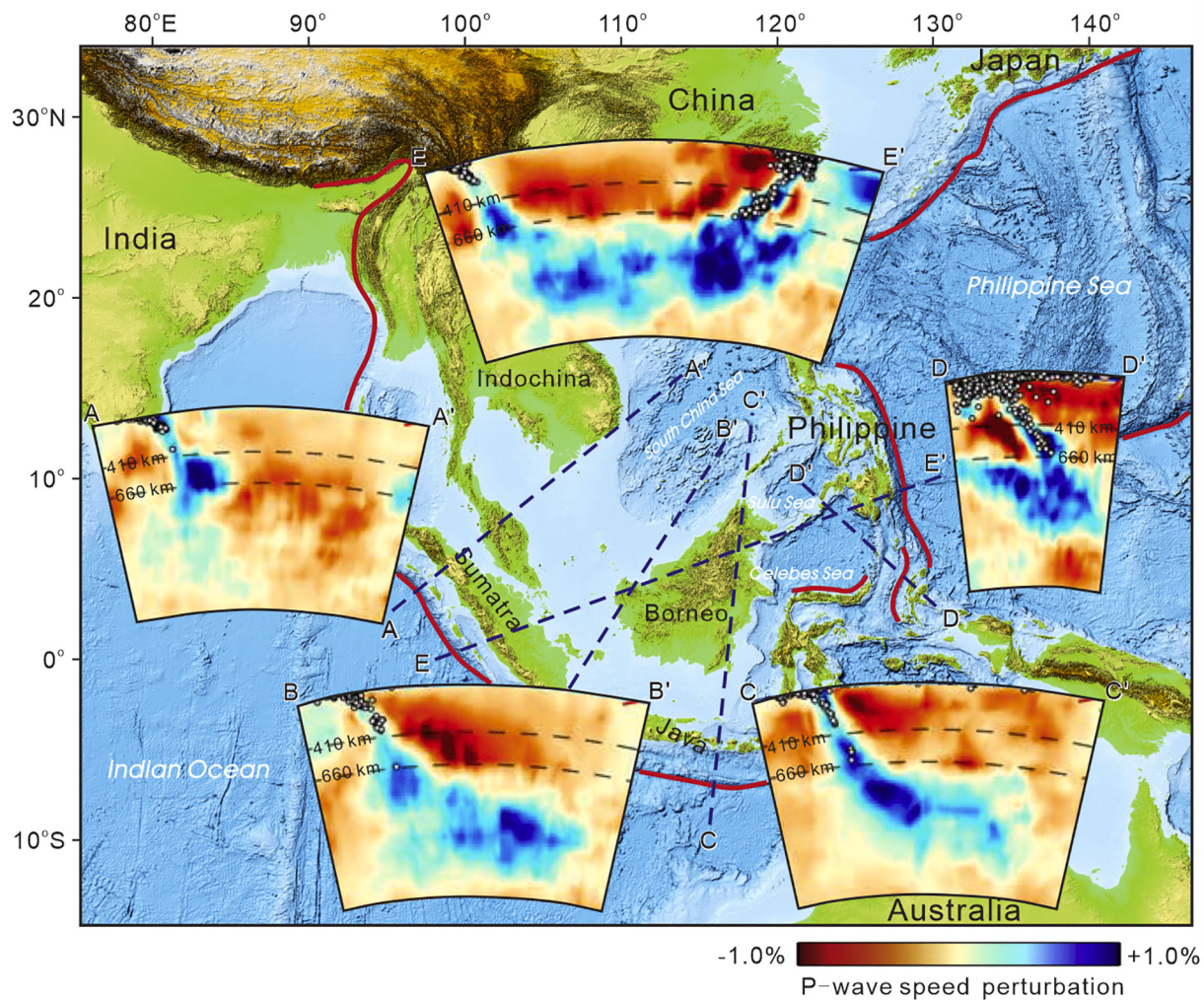


Fig. 4. Vertical cross sections of P wave velocity tomography along six profiles crossing the RRS of the SE Asia (Li et al., 2008). Red and blue colors denote low and high velocities, respectively. The white dots show earthquakes that occurred with 100 km from each other. The sources of the earthquake hypocentres are from the International Seismological Centre (ISC) and the U.S. Geological Survey's National Earthquake Information Center (NEIC). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

velocity anomaly in the mantle transition zone beneath the SCS which is regarded as the subducted Proto SCS (Wu et al., 2016), or an earlier subducted slab belonging to the Eurasian plate (e.g., Rangin et al., 1999), or related to a much earlier phase of subduction in Cenozoic (Hall and Spakman, 2015).

All these seismic tomography observations shape a structure composed of steeply subducted slabs in the east and west, but a flattening one in between. However, due to the limited amount of seismic data and relatively poor vertical resolution of the tomography results (Frederiksen et al., 1998; Martin-Short et al., 2016), the depth and extent of the subducting slab below 700 km are not well constrained and still in debates, especially for the subducted Australian Plate beneath the Sumatra. Significant discrepancies exist among previous studies regarding the depth extent, geometry and integrity of the subducted slab segments. Some previous studies suggest that the subducted slab segments are mainly concentrated above the bottom or top of the mantle transition zone (Gudmundsson and Sambridge, 1998; Amaru, 2007; Li et al., 2018), while others advocate that they have penetrated into the lower mantle (e.g. Li et al., 2008; Huang et al., 2015a, 2015b). Beneath the Java subduction zone and adjacent regions, Li et al. (2008) indicated that the slab has penetrated through the mantle transition zone and flattened at a depth between 1000 and 1200 km beneath Borneo.

A conspicuous kink structure has been suggested to be present below northern Sumatra (Pesicek, 2010) and the subducted slabs south and north of it are with different subducted depth and angle. The cause of this kink is currently under debate and has being a considerable interest for many years (Page et al., 1979; Richard et al., 2013; Pesicek, 2010; Hall and Spakman, 2015; Koulakov et al., 2016; Liu et al., 2018). Some studies reveal that this kink structure is actually a slab tear associated with the Investigator Fracture Zone (Page et al., 1979; Hall and Spakman, 2015; Liu et al., 2018), which is probably linked to the deep hot material supply of the Toba super-volcano (Koulakov et al., 2016; Kong et al., 2020a, 2020b). Recently conducting shear wave splitting (Kong et al., 2020a) and receiver function investigations (Kong et al., 2020b) suggest that advective thermal upwelling through a slab window is probably present beneath the Toba super-volcano, and the mantle flow escaped from the sub-slab and modulated by the slab window accounts for the dominantly trench-parallel mantle flow in the mantle wedge. Beneath southern Sumatra and adjacent areas, the 410 km and 660 km discontinuities are uplifted and depressed, respectively, which are probably caused by the cold temperature anomaly and slab dehydration associated with the subducted Australian Plate that has reached at least 660 km (Kong et al., 2020b).

The fate of a subducted plate can be roughly divided into two

scenarios: the slab sinks through the 660 km discontinuity and penetrates into the deep mantle, and stays in the Core-Mantle Boundary (CMB) like what happened beneath the Mariana trench (van der Hilst et al., 1997), or becomes stagnant in the mantle transition zone like the subducted Pacific slab under East China (Fukao et al., 1992; Huang and Zhao, 2006). The present seismic tomography shows that the subducted plate, especially the northward subducting Australian Plate has penetrated through the mantle transition zone, but flattened in the lower mantle instead of reaching to the CMB, which means the deep structure of the RRS does not belong to any scenarios, and challenges the classic mantle convection model (Fig. 5). The most fundamental question that needs to be answered is what factors controlled the angle, depth, and duration of plate subduction. Illuminating the structure beneath the mantle transition zone under the CSS is clearly critical to answering these questions.

4. Where did all the subducted materials go?

Formation of the CSS not only causes the coupling and decoupling of different platelets, splitting and assembling of continental blocks, and opening of marginal basins on various scales, but also leads to the exchange of materials from surface to deep, and to surface again. Based on the convergent rate derived from Global Positioning System measurement (Simons et al., 2007; DeMets et al., 2010), and with the nearly eight thousand kilometers of subducting plate boundaries (Bird, 2003), we estimated the annual amount of lithosphere subducted into CSS deep mantle by Sumatra-Java and Philippine subduction zones using

$$V = H_{\text{lithos}} * L * V_{\text{RPM}}$$

where H_{lithos} represents the thickness of lithosphere of the subducting plate, L denotes the length of the main boundary thrust, and V_{RPM} is the component of the relative plate motion (RPM) from MORVEL (DeMets et al., 2010) that is orthogonal to the main boundary thrust with the overriding plate as a reference. The estimation is based on several assumptions. First, the relative movement between the subducting plate and the overriding plate is entirely compensated by subduction. Second, the whole lithosphere is subducting beneath the overriving plate. Results show that there are 23.4 km³ materials entered into the deep CSS every year due to the NE-ward subduction of the Indian Plate and the northward subduction of the Australian Plate, and 5.8 km³ lithospheric materials per year with the westward subduction of the Philippine Sea Plate (Fig. 6). The total amount of subducted materials is near 29.2 km³/a in CSS. To the west, almost 10.8 km³ material is consumed every year

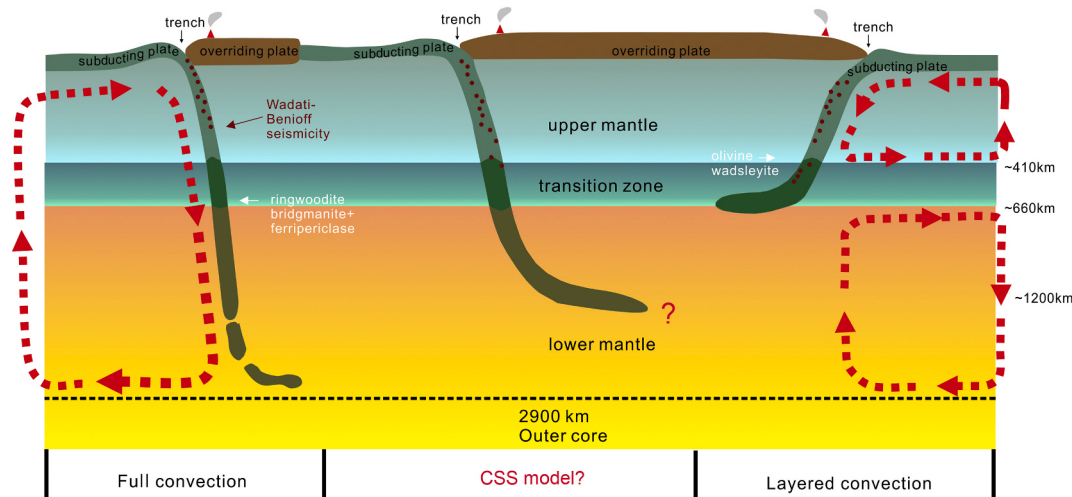


Fig. 5. Conceptual mantle convection models, not in scale. Left: Full mantle convection model (e.g. van der Hilst et al., 1997); Right: Layered convection model (e.g. Fukao et al., 1992; Huang and Zhao, 2006); Middle: CSS model.

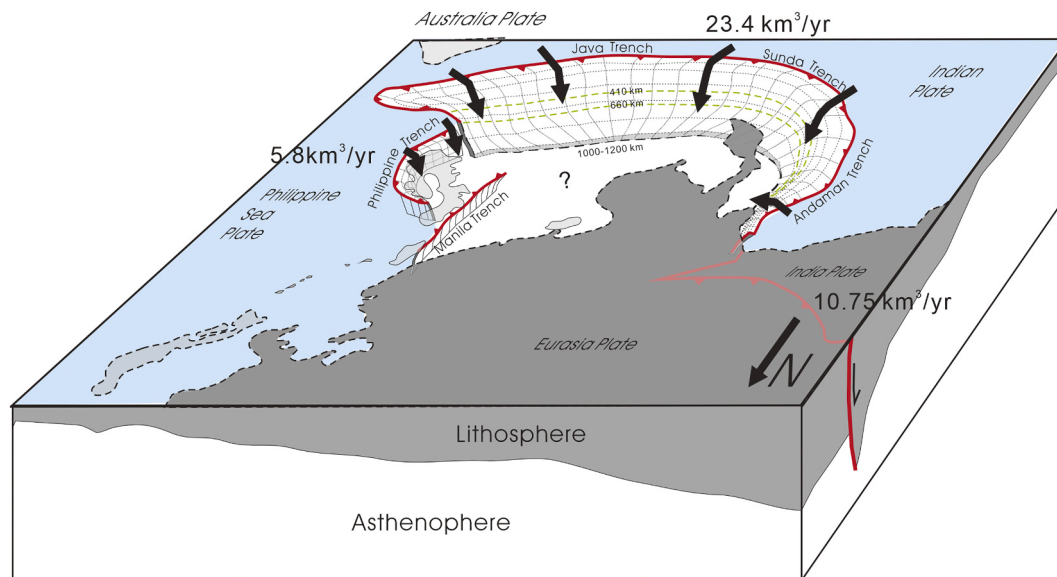


Fig. 6. Pseudo 3D structure of the CSS of SE Asia. Subducted angles and depths are based on seismic tomography results. Numbers denote the subducted lithospheric materials per year in different subduction zone. There are 23.4 km³ materials entered into the deep CSS every year due to the NE-ward subduction of the Indian plate and the N-ward subduction of the Australian plate, 5.8 km³ lithospheric materials per year with the W-ward subduction of the Philippine Sea plate, and 10.8 km³ material is consumed every year during the collision between the India and the Eurasia plate (Gan et al., 2007).

during the collision between the IndiaN and the Eurasian(Gan et al., 2007), which is only one third of that of the CSS. Such a volume of subducted hydrated and altered upper oceanic section and overlying sediments, also including water, carbon and other strong incompatible elements, preserve a geochemical record of low-temperature interactions with the ocean, the atmosphere, and the continents. Subduction-related recycling of these components into the mantle will produce large, locally variable, and ephemeral changes in the chemicals, mineral compositions, thermal structure and mantle rheology (e.g. Xu et al., 2012., Ryan and Chauvel, 2014; Li et al., 2017). Although we still have no idea about the destination of all these subducted material, or the detailed nature of slab-mantle mixing and melting processes, magmatic and hydrothermal outputs of the subduction process afford an incomplete return flux to the surface highlighted by the geophysical evidence for a broad region of low-seismic-velocity anomalies in the upper mantle beneath the CSS, especially in the South China Sea and adjacent regions, and great magma production in terms of volcanic lavas from across-arc transects and along arcs, interplate magmatism, and intraplate basaltic magmatism occurred extensively and voluminously in the northern continental margin of the South China Sea, the Indochina peninsula, and the South China Sea basin (Fig. 7).

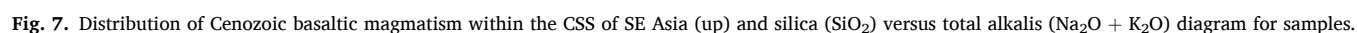
4.1. Island arc magmatism of the CSS

A series of island arc magmatism occurred along the CSS subduction zone, including the 1200 km long NS-trending Luzon island arc volcanic belt between the Taiwan Island and Mindoro resulted from the E-ward subduction of the South China Sea under the Luzon Islands, and the W-ward subduction of the Philippine Sea Plate beneath the Luzon Islands (Defant et al., 1989); the 5600 km Sunda-Banda island arc volcanic belt caused by the Indo-Australian Plate subduction beneath the Sundaland (Hamilton, 1979; Vroon, 1992; Honthas et al., 1998); and the Mindanao island arc volcanic belt due to the subduction of the Sulu Sea and Celebes Sea (Pubellier et al., 1991; Rangin and Silver, 1991).

Volcanic activity in the Sunda-Banda arc has continued from the Eocene to present and has undergone significant changes in composition. In Eocene it was mainly island arc tholeiite, and In Neogene it was mainly composed of andesite, with a small amount of dacite and basalt. It also had typical geochemical characteristics of island arc magma

(Hutchison, 1982). But in Pliocene-Quaternary period, the magma activity was mainly medium potassi-calc-alkaline, which showed the features of continental arc volcano (Soeria-Atmadja and Noeradi, 2005). Magmatic rocks in the arc volcanic region of Mindanao are also typical continental arc magmatic products, composed of a series of potassi-calc-alkaline volcanic rocks from basalt to rhyolite and adakite (Solidum et al., 2003; Rae et al., 2004; Macpherson et al., 2006). There have been a lot of studies on the magmatic rocks and their related sedimentary rocks in the Sunda-Banda island arc and Mindanao arc volcanic rocks, including mineralogy, petrology, whole-rock element geochemistry and Sr-Nd-Hf-Pb isotopes, involving their formation age, volcanic eruption mechanism, characteristics of source area and tectonic setting (e.g., Honthas et al., 1998; Handley et al., 2011; Harris et al., 2009; Métrich et al., 2017).

The subduction along the Manila trench in the South China Sea formed the Luzon island arc (Fig. 7). It comprises Oligocene to recent arc volcanism stretching roughly N-S from the Coastal Range of Taiwan (24°N) to Mindoro (13°N). There are still great disputes about the time of initial subduction, the material cycle of the subduction system and the mechanism of mid-oceanic ridge subduction. Based on regional geological observations, early studies proposed that the eastward subduction initiated in the later Oligocene (Bachman et al., 1983; Hayes and Lewis, 1984). Further works on the Sr-Nd isotope compositions indicated an early to middle Miocene timing for the subduction initiation (Polve et al., 2007), or even younger to 9 Ma (Liu et al., 2020), whereas the late Oligocene geologic records are related to the westward subduction of West Philippine Sea Plate along the Proto-East Luzon Through (Wolfe, 1988; Yumul et al., 2003; Hollings et al., 2011; Waters et al., 2011; Huang et al., 2018). Based on the analysis on the Sr, Nd, Pb isotopic composition of the Luzon island arc volcano, it was found that the isotope ratios change with the latitude, i.e. from 24°N (the Coast Range) to 16°N (north Luzon island arc) presenting a decreasing trend of Sr isotope ratio, but further south showing an increasing trend (Defant et al., 1990). This change is related to the different contributions of continental sediments from the north-south wings to mid-ocean ridge of the South China Sea. What's more, it should be noted that most of previous studies did not consider the contribution of the Proto-South China Sea to the magmatism and tectonics of the Luzon, which had been eliminated by subduction beneath northern Borneo-Cagayan-west



Luzon during the Cenozoic (Hall and Breitfeld, 2017), which adds further complexity of the Luzon island arc. Overall, the lack of robust geochemical constraints of oceanic crust in the South China Sea still leaves significant uncertainties on the magmatism of Luzon Islands and thus should be an important direction for future research.

In summary, the CSS not only develops island arcs by ocean-ocean plate subduction, but also continental arcs by ocean-continent subduction. The forming process and composition of continental arcs are controlled by the contribution of continental crust component, magmatic mixing, and fluid/melt from subducted oceanic crust, being more complicated than the island arc. The main feature of the CSS is that the subduction angle varies greatly, involving the Indian Ocean Plate, Philippine Plate and Pacific Plate. It is not clear how these boundary conditions affect the island arc magmatism. Answering this question requires a systematic investigation of the temporal and spatial variation of island arc magma in the CSS, including the age, composition and properties of subducted plates, and the relationship between the composition and properties of island arc magma source region and boundary conditions.

4.2. Intraplate magmatism and Hainan Plume

At present, the research on the intraplate magmatism of the marginal basins in the CSS is limited by the lack of samples (mainly relying on trawling and ocean drilling). The age of basalt-coarse andesite samples obtained by trawl in Sulu Sea basin is 9–7 Ma, featured with Nb–Ta negative anomaly (Honthaas et al., 1998). The trawl samples from the Banda Sea include back-arc basalt of ~10 Ma, calc-alkaline andesite of 8–7 Ma and oceanic island basalt and andesite of 7–3 Ma (Honthaas et al., 1998). In the South China Sea many geophysical studies have indicated the large volume of post-spreading magmatism in forms of seamounts, magma intrusion and underplating either in the continental margin (Xu et al., 2012; Fan et al., 2017) or the oceanic basin (Zhao et al., 2020). Limited seafloor drilling and rock dredging on seamounts indicate an age span of 17–23 Ma in the continental margin (Fan et al., 2017). Seamounts in the oceanic basins are much younger with an age span of 3–15 Ma (Yan et al., 2014). Zhao et al. (2020) calculated the volume of all the seamounts in the oceanic basin of the South China Sea, which is an essential indicator of the contribution from the mantle and deeper oceanic lithosphere, and got an integrated volume of ~32,676 km³, which is surprisingly large and is similar to the median value of the global large igneous provinces (LIPs) (Coffin and Eldholm, 1994). IODP Expedition 349 (2014) and 367&368 (2017) drilled into the basement near the fossil spreading ridge and the continent-ocean transition area of the South China Sea, and sampled MORB-type basalt representing the final and initial spreading stage, which provided a rare opportunity for geochemical research on intraplate magmatism (Li et al., 2015; Sun et al., 2018). Trace elements and Sr–Nd–Pb–Hf isotope analysis on the MORB-type basaltic samples from Southwest and East Sub-basin indicated that these two sub-basins have distinct mantle source (Zhang et al., 2018). Increasing geochemical evidences point to the importance of subduction-induced mantle upwelling beneath the SCS. Volcanic rock samples from the SCS seamounts are mostly oceanic island basalts of intermediate to mafic compositions (Wang et al., 2013; Yan et al., 2014). Tholeiitic and alkalic basalts of the SCS and surrounding regions reveal from recycled oceanic components (Wang et al., 2012; Zhang et al., 2018). However, the lack of robust age and geochemical constraints on magmatism still leaves significant uncertainties in the rates of post-spreading magmatism, and it is still not clear whether this spatial distribution of mantle source is directly related to the subduction system.

Large-scale intraplate basaltic magmatism also occurred simultaneously in the South China coast regions and Indochina Peninsula during the Cenozoic. Cenozoic basalts were widely developed in the eastern Vietnam-Cambodia region, mainly distributed in the Tay Nguyen Highlands and its eastern islands. These basalts are dominated by

tholeiite and contain a small amount of alkaline basalts with a formation age between 16.5–0.2 Ma (e.g. Fedorov and Koloskov, 2005; Tri and Khuc, 2009). Alkaline basalt, olivine tholeiite and quartz tholeiite are developed in the Bolavens Plateau in southern Laos, and the eruption time was 15.7–0.5 Ma (Sanematsu et al., 2011). Alkaline basalt is distributed in Khorat Plateau of Thailand, and the eruption time was 0.9 Ma (Zhou and Mukasa, 1997). In general, the alkalinity of Cenozoic basalts in Indochina peninsula gradually increased since 16 Ma, until the eruption of alkaline basalt in 6 Ma. The study of element and isotope geochemistry showed that the Cenozoic basalts in Indochina peninsula have the characteristics of OIB trace elements. However, the Sr–Nd–Pb isotope showed the mixed characteristics of Indian Ocean type depleted mantle and Enriched Mantle 2 (EM2) (e.g., An et al., 2017; Hoang et al., 2018). There are great differences in the origin of the EM2 components, being from the recycled oceanic crust (Wang et al., 2012; Liu et al., 2015; An et al., 2017; Hoang et al., 2018), subducted sediments (e.g., Mukasa et al., 1996), or continental lithospheric mantle (Flower et al., 1992; Hoang et al., 1996; Zhou and Mukasa, 1997). Differences in understanding of the origin of rocks have led researchers to propose radically different geodynamic mechanisms: (1) The asthenospheric and lithospheric mantle interaction during the mantle extrusion process caused by the India-Eurasia collision (e.g. Flower et al., 1992; Hoang et al., 1996; Zhou and Mukasa, 1997; Koszowska et al., 2007), or (2) Decompression melting of peridotite + eclogite/pyroxenite during mantle plume rise (e.g. An et al., 2017; Wang et al., 2012).

Mantle plume has long been considered as a bottom-up flux of energy and mass from the core-mantle boundary (CMB) to the Earth's surface, and was linked to the subduction of oceanic slabs (e.g. Hofmann, 1988; Campbell and Griffiths, 1990; Courtillot et al., 2003; Li and Zhong, 2009; Wang et al., 2012). A significant and continuous low-V anomalies in the upper mantle beneath the Leizhou Peninsula and Hainan Island has been confirmed by many global, regional and local seismic studies (e.g. Lei et al., 2009; Hall and Spakman, 2015; Huang, 2014; Huang et al., 2015a, 2015b; Xia et al., 2016; Mériaux et al., 2015; Yu et al., 2018). Although Li et al. (2006) argued that these low-V anomalies originated from the mantle transition zone (MTZ, < 660 km), further studies indicated that the MTZ beneath the Hainan Island is 40–50 km thinner than the global average, and has a positive temperature anomaly of ~270–380 °C (Huang et al., 2015a, 2015b), and this anomaly was named as Hainan Plume from the deep mantle (e.g. Lei et al., 2009; Wang et al., 2013). This Hainan Plume is also supported by petrologic and geochemical evidence from the late Cenozoic flood basalts, which is dominated by tholeiites and alkali basalts and displays light rare-earth-element enriched patterns and typical oceanic island basalt (OIB)-type incompatible element distributions (e.g. Xu et al., 2002, 2012; Yan et al., 2014).

Most of the mantle plumes, and large igneous provinces (LIPs) are developed with close relationship with the two Large Low Shear-wave Velocity Provinces (LLSVPs), i.e. the Tuzo under the Africa, and Jason under the Pacific (Becket and Boschi, 2002; Courtillot et al., 2003; Burke and Torsvik, 2004; Burke et al., 2008). But Hainan Plume is far away from both LLSVPs, and it is not a classical one of a fixed thermal plume rising vertically from bottom to surface, like the Hawaii Plume. Xia et al. (2016) determined a mushroom-like continuous low-velocity anomaly characterized by a columnar tail with a diameter of 200–300 km extending down to the lower mantle and a head spreading laterally in and around the mantle transition zone. Further upward, the plume head is decomposed into smaller patches. Furthermore, the intraplate Cenozoic volcanism is widespread not only beneath the Leizhou Peninsula-Hainan Island, but in the northern continental margin of SCS, and Indochina Region (e.g. Yan et al., 2014; Fan et al., 2017; Zhao et al., 2018). All these challenge the view of a “Hainan Plume” as a classical fixed narrow thermal plume. Wang et al. (2013) identified ancient mantle reservoir and young recycled materials in the source region of these synchronous basalts, and speculated a dynamic linkage between deep subduction and mantle plume generation. At present, direct

evidence for a narrow Hainan plume arising from the CMB is still lacking. The Hainan Plume, together with the broad zone of low seismic velocity, is hypothesized to reflect a broad zone of mantle upwelling possibly induced by surrounding subducting plates (Lin et al., 2019).

5. Ongoing works and perspectives

As a super-complex convergent system, a great deal of geophysical and geochemical research have been done on the magmatism within the CSS, which is essential indicator of the contribution from the mantle and deeper oceanic lithosphere, and thus effectively reflect the recycling of the subducted materials. However, large uncertainties and controversies remain in our understanding of CSS due to the remaining knowledge gaps in the deep structure, especially the deep mantle, since most of passive source seismic data used for determining the velocity anomalies in the upper mantle were recorded by land-based seismic stations. For the vast region of the CSS, especially beneath the ocean basins such as the SCS, direct constraints on the upper mantle seismic structure are still lacking. There are still great differences in the degree of research on various regions and various magmatic activities, as well as the lack of unified understanding of rock origin, magmatic source region, dynamic mechanism and tectonic setting. Little is known about whether the magma produced under this system has special characteristics and how the CSS influences the circulation law and process of deep materials, including: Whether the island arc or intraplate magma is the main magma response of subduction? How did different subducting angles and different subducting plates control the island arc and intraplate magma activity? Is the post-spreading magmatism in the marginal seas the result of mantle plume activity or subduction-induced mantle flows?

To answer the above questions, it is necessary not only to illuminate the deep structures beneath the CSS, especially in the oceanic basins with limited geophysical survey, with the support of high-resolution geophysical observations, but also to systematically deepen the understanding of the nature, origin characteristics and dynamic mechanism of the magmatic activities, and obtain the composition characteristics of the recirculated materials, which is also the key to reveal the circulation law and process of the deep material in the CSS. A tectonic reconstruction model is also necessary to predict where lithosphere has been subducted and how much has been consumed in plate convergence zones. These modeling results can be compared to the deep structure imaged by the seismic tomography. The seismic tomography could provide constraints for the tectonic reconstruction, and conversely the plate tectonic model may suggest not well-imaged mantle structure.

Recently, state-of-the-art geodynamic simulation platforms (e.g., ASPECT, CitcomS) have been developed to model mantle flow evolution at time scale of hundreds of million years in three-dimensional spherical Earth coordinates (e.g. Hu et al., 2018). Together with high-performance computing power of super-computer clusters, we are able to reproduce high-resolution time-dependent 3D mantle evolution with surface constraint of the latest global plate reconstruction (Liu and Stegman, 2011; Hu et al., 2018; Mao and Zhong, 2018). Preliminary results reveal that the overall geometry of CSS in the Southeast Asia has evolved gradually from an early “V” shape to the present-day “U” shape (Zhou and Lin, 2019). The upper mantle flow beneath the Southeast Asia is driven primarily by the surface plate motion, as well as subduction-induced mantle return flow. The Izanagi Plate, which has subducted beneath the Eurasia Plate, has a profound impact on the mantle evolution of the eastern China and the South China Sea. Moreover, new geodynamic models coupled with melting of hydrous mantle suggest that the CSS might bring massive water into the mantle beneath the South China, accelerating mantle melting and upwelling during rifting of the South China Sea continental margin. These ongoing geodynamic models will bring new understanding and provide insightful views on the evolution and tectonic implications of the CSS. Future modeling work will investigate CSS slab evolution and focus on its dynamic mechanism.

Arguably, many of the recent technological advances arose from increasing the resolution of observation and focusing community efforts on individual subduction zones of concern, such as the Manila Trench in the South China Sea, or Java Trench offshore Sumatra. In order to examine the entirety of CSS tectono-magmatic events and cycles from surface to deep, and to surface again, we need to construct coordinated observatories that make multiscale and multidisciplinary measurements in four dimensions. The potential technological capabilities for observing subduction systems is expanding in many ways, but new innovations remain necessary in order to implement on large scales. The CSS is up to thousands of kilometers long, and contains multiple subduction zones activated in different geological time, study what controls the subducting angle, stagnant depth, and how they interact each other in the deep mantle are still challenging. To address these challenges, we need to focus on specific regions that represent the highest likelihood of testing key hypothesis in subduction zone dynamics, especially on those are not densely instrumented, e.g., the South China Sea.

Declaration of Competing Interest

None.

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References

- Advokaat, E.L., Marshall, N.T., Li, S., Spakman, W., Krijgsman, W., van Hinsbergen, D.J. J., 2018. Cenozoic rotation history of Borneo and Sundaland, SE Asia revealed by paleomagnetism, seismic tomography, and kinematic reconstruction. *Tectonics* 37 (8), 2486–2512. <https://doi.org/10.1029/2018TC005010>.
- Amaru, M.L., 2007. Global travel time Tomography with 3-D Reference Models. Ph.D thesis. Utrecht University, the Netherlands.
- An, A.R., Choi, S.H., Yu, Y., Lee, D.C., 2017. Petrogenesis of late Cenozoic basaltic rocks from southern Vietnam. *Lithos* 272, 192–204.
- Arculus, R.J., Ishizuka, O., Bogus, K.A., Gurnis, M., Hickey-Vargas, R., Aljohdali, M.H., Bandini-Mader, A.N., Alexandre, N., Barth, A.P., Brandl, P.A., Drab, L., do Monte Guerra, R., Hamada, M., Jiang, F., Kanayama, K., Kender, S., Kusano, Y., Li, H., Loudin, L.C., Maffione, M., Marsaglia, K., McCarthy, A., Meffre, S., 2015. A record of spontaneous subduction initiation in the Izu-Bonin-Mariana arc. *Nat. Geosci.* 8 (9), 728–733. <https://doi.org/10.1038/ngeo2515>.
- Audley-Charles, M.G., Ballantyne, P.D., Hall, R., 1988. Mesozoic–Cenozoic rift-drift sequence of Asian fragments from Gondwanaland. *Tectonophysics* 155, 317–330.
- Bachman, R.R., Hamilton, E.L., Curran, J.R., 1983. Sediment sound velocities from Sonobuoys: Sunda Trench and forearc basins, Nicobar and Central Bengal Fans, and Andaman Sea Basins. *J. Geophys. Res.* 88 (B11), 9341–9346. <https://doi.org/10.1029/JB088iB11p09341>.
- Bangs, N.L., McIntosh, K.D., Silver, E.A., Kluesner, J.W., Ranero, C.R., 2015. Fluid accumulation along the Costa Rica subduction thrust and development of the seismogenic zone. *J. Geophys. Res.* 120 (1), 67–86. <https://doi.org/10.1002/2014JB011265>.
- Bebout, G.E., 2007. Metamorphic chemical geodynamics of subduction zones. *Earth Planet. Sci. Lett.* 260, 373–393. <https://doi.org/10.1016/j.epsl.2007.05.050>.
- Becket, T.W., Boschi, L., 2002. A comparison of tomographic and geodynamic mantle models. *Geochem. Geophys. Geosyst.* 3 (1), 2001GC000168.
- Bercovici, D., Karato, S., 2003. Whole-mantle convection and the transition-zone water filter. *Nature* 425, 39–44.
- Bercovici, D., Schubert, G., Glatzmaier, G., 1989. 3-dimensional spherical-models of convection in the Earth's mantle. *Science* 244, 950–955.
- Bird, P., 2003. An updated digital model of plate boundaries. *Geochem. Geophys. Geosyst.* 1027 <https://doi.org/10.1029/2001GC000252>.
- Briaies, 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.* 98 (B4), 6299–6328.
- Burke, K., Torsvik, T.H., 2004. Derivation of large igneous provinces of the past 200 million years from long-term heterogeneities in the deep mantle. *Earth Planet. Sci. Lett.* 205 (3–4), 295–308.
- Burke, K., Steinberger, B., Torsvik, T.H., 2008. Plume generation zones at the margins of large low shear velocity provinces on the core-mantle boundary. *Earth Planet. Sci. Lett.* 265 (1–2), 49–60.
- Calvert, A.J., Sawyer, E., Davis, W.J., Ludden, J., 1995. Archean subduction inferred from seismic images of a mantle suture in the Superior Province. *Nature* 375 (6533), 670–674. <https://doi.org/10.1038/37560a0>.

- Campbell, I.H., Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. *Earth Planet. Sci. Lett.* 99, 79–93.
- Cao, X.Z., Flament, N., Müller, D., Li, S.Z., 2018. The dynamic topography of eastern China since the latest Jurassic Period. *Tectonics* 37. <https://doi.org/10.1029/2017TC004830>.
- Chauvel, C., Lewin, E., Carpentier, M., Arndt, N.T., Marini, J.-C., 2008. Role of recycled oceanic basalt and sediment in generating the Hf–Nd mantle array. *Nat. Geosci.* 1, 64–67.
- Cheng, Z.H., Ding, W.W., Faccenda, M., Li, J.B., Lin, X.B., Ma, L.T., 2019. Geodynamic effects of subducted seamount at the Manila Trench: Insights from numerical modeling. *Tectonophysics* 764, 46–61.
- Chesner, C.A., Rose, W.I., Deino, A., Drake, R., Westgate, J.A., 1991. Eruptive history of Earth's largest Quaternary caldera (Toba, Indonesia) clarified. *Geology* 19, 200–203. <https://doi.org/10.1130/0091-7613>.
- Chester, F.M., Rowe, C., Ujiie, K., Kirkpatrick, J., Regalla, C., Remitti, F., Moore, J.C., Toy, V., Wolfson-Schwehr, M., Bose, S., et al., 2013. Structure and composition of the plate-boundary slip zone for the 2011 Tohoku-Oki earthquake. *Science* 342 (6163), 1208–1211. <https://doi.org/10.1126/science.1243719>.
- Chlieh, M., Avouac, J.P., Sieh, K., Natawidjaja, D.H., Galetzka, J., 2008. Heterogeneous coupling of the Sumatran megathrust constrained by geodetic and paleogeodetic measurements. *J. Geophys. Res.* 113, B05305 <https://doi.org/10.1029/2007JB004981>.
- Clift, P.D., Carter, A., Nicholson, U., Masago, H., 2013. Zircon and apatite thermochronology of the Nankai Trough accretionary prism and trench, Japan: Sediment transport in an active and collisional margin setting. *Tectonics* 32, 377–395. <https://doi.org/10.1002/tect.20033>.
- Coffin, M.F., Eldholm, O., 1994. Large igneous provinces: Crustal structure, dimensions, and external consequences. *Rev. Geophys.* 32 (1), 1–36.
- Cosca, M., Arculus, R., Pearce, J., Mitchell, J., 1998. ⁴⁰Ar/³⁹Ar and K–Ar geochronological age constraints for the inception and early evolution of the Izu–Bonin–Mariana arc system. *Island Arc* 7 (3), 579–595. <https://doi.org/10.1111/j.1440-1738.1998.00211.x>.
- Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hot spots in the Earth's mantle. *Earth Planet. Sci. Lett.* 205, 295–308.
- Cullen, A., 2010. Transverse segmentation of the Baram–Balabac Basin, NW Borneo: refining the model of Borneo's tectonic evolution. *Pet. Geosci.* 16, 3–29.
- Curry, J.R., 2005. Tectonics of the Andaman Sea region. *J. Asia Earth Sci.* 25, 187–232.
- Defant, M.J., Jacques, D., Maury, R.C., et al., 1989. Geochemistry and tectonic setting of the Luzon arc, Philippines. *Geol. Soc. Am. Bull.* 101, 663–672.
- Defant, M.J., Maury, R., Joron, J.-L., Feigenson, M.D., Leterrier, J., Bellon, H., Jacques, D., Richard, M., 1990. The geochemistry and tectonic setting of the northern section of the Luzon arc (the Philippines and Taiwan). *Tectonophysics* 183, 187–205.
- DeMets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. *Geophys. J. Int.* 181, 1–80. <https://doi.org/10.1111/j.1365-246X.2009.04491.x>.
- Deschamps, A., Lallemand, S., 2002. The West Philippine Basin: An Eocene to early Oligocene back arc basin opened between two opposed subduction zones. *J. Geophys. Res.* 107 (B12), 2322. <https://doi.org/10.1029/2001JB001706>.
- Diehl, T., Waldhauser, F., Cochran, J.R., Raju, K.A., Seeber, L., Schaff, D., Engdahl, E.R., 2013. Back-arc extension in the Andaman Sea: tectonic and magmatic processes imaged by high-precision teleseismic double-difference earthquake relocation. *J. Geophys. Res.* Solid Earth 118, 1–19. <https://doi.org/10.1002/jgrb.50192>.
- Ding, W.W., Sun, Z., Dadd, K., Fang, Y.X., Li, J.B., 2018. Structures within the oceanic crust of the central South China Sea basin and their implications for oceanic accretionary processes. *Earth Planet. Sci. Lett.* 488, 115–125.
- Ding, W.W., Sun, Z., Mohn, G., Nirengarten, M., Tugend, J., Manatschal, G., Li, J.B., 2020. Lateral evolution of the rift-to-drift transition in the South China Sea: evidence from multi-channel seismic data and IODP Expeditions 367&368 drilling results. *Earth Planet. Sci. Lett.* 531, 1–14. <https://doi.org/10.1016/j.epsl.2019.115932>.
- Dong, S.W., Zhang, Y.Q., Zhang, F.Q., Cui, J.J., Chen, X.H., Zhang, S.H., Miao, L.C., Li, J.H., Shi, W., Li, Z.H., Huang, S.Q., Li, H.L., 2015. Late Jurassic–early Cretaceous continental convergence and intracontinental orogenesis in East Asia: a synthesis of the Yanshan Revolution. *J. Asian Earth Sci.* 114 (4), 750–770.
- Dura, T., Hemphill-Haley, E., Sawai, Y., Horton, B.P., 2016. The application of diatoms to reconstruct the history of subduction zone earthquakes and tsunamis. *Earth Sci. Rev.* 152, 181–197. <https://doi.org/10.1016/j.earscirev.2015.11.017>.
- Dziewonski, A.M., Hager, B.H., O'Connell, R.J., 1977. Large-scale heterogeneities in the lower mantle. *J. Geophys. Res.* 82, 239–255.
- Fan, C., Xia, S., Zhao, F., Sun, J., Cao, J., Xu, H., Wan, K., 2017. New insights into the magmatism in the northern margin of the South China Sea: Spatial features and volume of intraplate seamounts. *Geochem. Geophys. Geosyst.* 1–26. <https://doi.org/10.1002/2016GC006792>.
- Fedorov, P.I., Koloskov, A.V., 2005. Cenozoic volcanism of Southeast Asia. *Petrology* 13, 352–380.
- Flower, M.F.J., Zhang, M., Chen, C.Y., Tu, K., Xie, G., 1992. Magmatism in the South China Basin: 2. Post-spreading Quaternary basalts from Hainan Island, South China. *Chem. Geol.* 97, 65–87.
- Franke, D., Savva, D., Pubellier, M., Steuer, S., Mouly, B., Auxietre, J.L., et al., 2014. The final rifting evolution in the South China Sea. *Mar. Pet. Geol.* 58 (B), 704–720. <https://doi.org/10.1016/j.marpetgeo.2013.11.020>.
- Frederiksen, A.W., Bostock, M.G., VanDecar, J.C., Cassidy, J.F., 1998. Seismic structure of the upper mantle beneath the northern Canadian Cordillera from teleseismic travel-time inversion. *Tectonophysics* 294, 43–55.
- Fukao, Y., Obayashi, M., Inoue, H., Nishii, M., 1992. Subducting slabs stagnant in the mantle transition zone. *J. Geophys. Res.* 97, 4809–4822. <https://doi.org/10.1029/91JB02749>.
- Gaina, C., Müller, D., 2007. Cenozoic tectonic and depth/age evolution of the Indonesian gateway and associated back-arc basins. *Earth Sci. Rev.* 83 (3–4), 177–203. <https://doi.org/10.1016/j.earscirev.2007.04.004>.
- Gan, W., Zhang, P., Shen, Z., Niu, Z., Wang, M., Wan, Y., Zhou, D., Cheng, J., 2007. Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements. *J. Geophys. Res.* 112, B08416 <https://doi.org/10.1029/2005JB004120>.
- Gibbons, A.D., Whittaker, J.M., Müller, R.D., 2013. The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model. *J. Geophys. Res.* Solid Earth 118, 808–822. <https://doi.org/10.1002/jgrb.50079>.
- Govers, R., Wortel, M.J.R., 2005. Lithosphere tearing at STEP faults: Response to edges of subduction zones. *Earth Planet. Sci. Lett.* 236, 505–523.
- Gudmundsson, O., Sambridge, M., 1998. A regionalized upper mantle (RUM) seismic model. *J. Geophys. Res.* 103, 7121–7136.
- Hafkenscheid, E., Wortel, M.J.R., Spakman, W., 2006. Subduction history of the Tethyan region derived from seismic tomography and tectonic reconstructions. *J. Geophys. Res.* 111, B08401 <https://doi.org/10.1029/2005JB003791>.
- Hall, R., 1987. Plate boundary evolution in the Halmahera Region, Indonesia. *Tectonophysics* 144, 337–352. [https://doi.org/10.1016/0040-1951\(87\)90301-5](https://doi.org/10.1016/0040-1951(87)90301-5).
- Hall, R., 1996. Reconstructing Cenozoic SE Asia. *Geol. Soc. Lond., Spec. Publ.* 106, 153–184.
- Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. *J. Asian Earth Sci.* 20, 353–431.
- Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics* 570–571, 1–41.
- Hall, R., Breitfeld, T., 2017. Nature and demise of the Proto-South China Sea. *Bull. Geol. Soc. Malaysia* 63, 61–76. <https://doi.org/10.7186/bgsm63201703>.
- Hall, R., Spakman, W., 2002. Subducted slabs beneath the eastern Indonesia–Tonga region: Insights from tomography. *Earth Planet. Sci. Lett.* 201 (2), 321–336. [https://doi.org/10.1016/S0012-821X\(02\)00705-7](https://doi.org/10.1016/S0012-821X(02)00705-7).
- Hall, R., Spakman, W., 2015. Mantle structure and tectonic history of SE Asia. *Tectonophysics* 658 (C), 14–45. <https://doi.org/10.1016/j.tecto.2015.07.003>.
- Hamilton, W., 1979. Tectonics of the Indonesian region. In: U.S. Geological Survey, Prof. Pap., 1078, p. 345.
- Hammouda, T., Chantel, J., Manthilake, G., Guignard, J., Crichton, W., 2014. Hot mantle geotherms stabilize calcic carbonatite magmas up to the surface. *Geology* 42, 911–914.
- Handley, H.K., Turner, S., Macpherson, C.G., Gertisser, R., Davidson, J.P., 2011. Hf–Nd isotope and trace element constraints on subduction inputs at island arcs: Limitations of Hf anomalies as sediment input indicators. *Earth Planet. Sci. Lett.* 304, 212–223.
- Harris, R., Vorkink, M.W., Prasetyadi, C., Zobell, E., Roosmawati, N., Apthorpe, M., 2009. Transition from subduction to arc-continent collision: Geologic and neotectonic evolution of Savu Island, Indonesia. *Geosphere* 5, 152–171. <https://doi.org/10.1130/GES00209.1>.
- Hayes, D.E., Lewis, S.D., 1984. A geophysical study of the Manila Trench, Luzon, Philippines: 1. Crustal structure, gravity, and regional tectonic evolution. *J. Geophys. Res.* 85 (NB11), 9171–9195. <https://doi.org/10.1029/JB089iB11p09171>.
- Heine, C., Quevedo, L., McKay, H., Muller, D., 2012. Plate tectonic consequences of competing models for the origin and history of the Banda Sea subducted oceanic lithosphere. In: Paper Presented at Eastern Australian Basin Symposium 4, Brisbane, Australia.
- Hilde, T.W.C., Lee, C.-S., 1984. Origin and evolution of the West Philippine Basin: a new interpretation. *Tectonophysics* 102 (1–4), 85–104. [https://doi.org/10.1016/0040-1951\(84\)90009-X](https://doi.org/10.1016/0040-1951(84)90009-X).
- Hilde, T.W.C., Uyeda, S., Kroenke, L., 1977. Evolution of the western Pacific and its margin. *Tectonophysics* 38 (1–2), 145–165.
- Hinschberger, F., Malod, J.A., Dymet, J., Honthaas, C., Rehault, J.P., Burhanuddin, 2001. Magnetic lineations constraints for the back-arc opening of the late Neogene South Banda Basin (eastern Indonesia). *Tectonophysics* 333 (1–2), 47–59.
- Hinschberger, F., Malod, J.A., Rehault, J.P., Villeneuve, M., Royer, J.Y., Burhanuddin, S., 2005. Late Cenozoic geodynamic evolution of eastern Indonesia. *Tectonophysics* 404 (1–2), 91–118.
- Hoang, N., Flower, M., Carlson, R.W., 1996. Major, trace element, and isotopic compositions of Vietnamese basalts: interaction of hydrous EMI-rich asthenosphere with thinned Eurasian lithosphere. *Geochim. Cosmochim. Acta* 60, 4329–4351.
- Hoang, T.H.A., Choi, S.H., Yu, Y.J., Pham, T.H., Nguyen, K.H., Ryu, J.S., 2018. Geochemical constraints on the spatial distribution of recycled oceanic crust in the mantle source of late Cenozoic basalts, Vietnam. *Lithos* 296–299, 382–395.
- Hofmann, A.W., 1988. Chemical differentiation of the earth: the relationship between mantle, continental crust and oceanic crust. *Earth Planet. Sci. Lett.* 90, 297–314.
- Hollings, P., Wolfe, R., Cooke, D.R., Waters, P.J., 2011. Geochemistry of tertiary igneous rocks of Northern Luzon, Philippines: evidence for a Back-Arc setting for alkalic porphyry copper-gold deposits and a case for slab roll-back? *Econ. Geol.* 106, 1257–1277.
- Honthaas, C., Rehault, J.P., Maury, R., et al., 1998. A Neogene back-arc origin for the Banda Sea Basins: geochemical and geochronological constraints from the Banda Ridges (East Indonesia). *Tectonophysics* 298, 297–317.
- Hu, J., Liu, L., Zhou, Q., 2018. Reproducing past subduction and mantle flow using high-resolution global convection models. *Earth and Planetary Physics* 2 (3), 189–207. <https://doi.org/10.26464/epp2018019>.

- Huang, J., 2014. P- and S-wave tomography of the Hainan and surrounding regions: Insight into the Hainan plume. *Tectonophysics* 633, 176–192.
- Huang, J., Zhao, D., 2006. High-resolution mantle tomography of China and surrounding regions. *J. Geophys. Res.* 111, B09305. <https://doi.org/10.1029/2005JB004066>.
- Huang, Z., Zhao, D., Wang, L., 2015a. P wave tomography and anisotropy beneath Southeast Asia: Insight into mantle dynamics. *J. Geophys. Res.* 120, 5154–5174. <https://doi.org/10.1002/2015JB012098>.
- Huang, Z., Zhao, D., Wang, L., 2015b. P-wave tomography and anisotropy beneath Southeast Asia: insight into mantle dynamics. *J. Geophys. Res.* 120, 5154–5174.
- Huang, C.Y., Chen, W.H., Wang, M.H., Lin, C.T., Yang, S., Li, X., Yu, M., Zhao, X.X., Yang, K.M., Liu, C.S., 2018. Juxtaposed sequence stratigraphy, temporal-spatial variations of sedimentation and development of modern-forming forearc Lichi Mélange in North Luzon Trough forearc basin onshore and offshore eastern Taiwan: an overview. *Earth Sci. Rev.* 182, 102–140.
- Huang, C.Y., Wang, P.X., Yu, M.M., You, C.F., Liu, C.S., Zhao, X.X., Shao, L., Zhong, G.F., Yumul, G.P., 2019. Potential role of strike-slip faults in opening up the South China Sea. *Natl. Sci. Rev.* 6 (5), 891–901. <https://doi.org/10.1093/nsr/nwz119>.
- Hutchison, S.C., 1982. Indonesia. In: Thorpe, R.S. (Ed.), *Andesites*. Wiley, New York, pp. 207–224.
- Ishizuka, O., Tani, K., Reagan, M.K., Kanayama, K., Umino, S., Harigane, Y., Sakamoto, I., Miyajima, Y., Yuasa, M., Dunkley, D.J., 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island arc. *Earth Planet. Sci. Lett.* 306 (3–4), 229–240. <https://doi.org/10.1016/j.epsl.2011.04.006>.
- Ishizuka, O., Hickey-Vargas, R., Arculus, R.J., et al., 2018. Age of Izu-Bonin-Mariana Arc Basement. *E.P.S.L.* 481, pp. 80–90.
- Iwamori, H., 1998. Transportation of H₂O and melting in subduction zones. *Earth Planet. Sci. Lett.* 160, 65–80.
- Jolivet, L., Huchon, P., Rangin, C., 1989. Tectonic setting of Western Pacific marginal basins. *Tectonophysics* 160 (1–4), 23–47. [https://doi.org/10.1016/0040-1951\(89\)90382-X](https://doi.org/10.1016/0040-1951(89)90382-X).
- Karig, D.E., 1973. Plate convergence between the Philippines and the Ryukyu islands. *Mar. Geol.* 14, 153–168.
- Kong, F.S., Gao, S.S., Liu, K.H., Zhang, J., Li, J.B., 2020a. Seismic anisotropy and mantle flow in the Sumatra subduction zone constrained by shear wave splitting and receiver function analyses. *Geochim. Geophys. Geosyst.* 21, e2019GC008766. <https://doi.org/10.1029/2019GC008766>.
- Kong, F.S., Gao, S.S., Liu, K.H., Ding, W.W., Li, J.B., 2020b. Slab dehydration and mantle upwelling in the vicinity of the Sumatra Subduction zone: Evidence from receiver function imaging of mantle transition zone discontinuities. *J. Geophys. Res. Solid Earth* 125, e2020JB019381. <https://doi.org/10.1029/2020JB019381>.
- Koppers, A., 2014. On the ³⁹Ar/⁴⁰Ar dating of low-potassium ocean crust basalt from IODP expedition 349, South China Sea. In: 2014, AGU Fall Meeting. T31E-03.
- Kozowska, E., Wolska, A., Złochiewicz, W., Cuong, N.Q., Pécskay, Z., 2007. Crustal contamination of late Neogene basalts in the Dien Bien Phu Basin, NW Vietnam: some insights from petrological and geochronological studies. *J. Asian Earth Sci.* 29, 1–17.
- Koulakov, I., Kasatkina, E., Shapiro, N.M., Jaupart, C., Vasilevsky, A., El Khrepy, S., Al-Arifi, N., Smirnov, S., 2016. The feeder system of the Toba supervolcano from the slab to the shallow reservoir. *Nat. Commun.* 7, 12228. <https://doi.org/10.1038/ncomms12228>.
- LaHusen, S.R., Duvall, A.R., Booth, A.M., Montgomery, D.R., 2016. Surface roughness dating of long-runout landslides near Oso, Washington (USA), reveals persistent postglacial hillslope instability. *Geology* 44 (2), 111–114. [10.1130/G37267.1](https://doi.org/10.1130/G37267.1).
- Lange, D., Tilmann, F., Rietbrock, A., Collings, R., Natawidjaja, D.H., Suwargadi, B.W., Barton, P., Henstock, T., Ryberg, T., 2010. The fine structure of the subducted Investigator Fracture Zone in western Sumatra as seen by local seismicity. *Earth Planet. Sci. Lett.* 298, 47–56. <https://doi.org/10.1016/j.epsl.2010.07.020>.
- Larsen, H.C., Mohn, G., Nirengarten, M., et al., 2018. Rapid transition from continental breakup to igneous oceanic crust in the South China Sea. *Nat. Geosci.* <https://doi.org/10.1038/s41561-018-0198-1>.
- Lei, J., Zhao, D., Steinberger, B., Wu, B., Shen, F., Li, Z., 2009. New seismic constraints on the upper mantle structure of the Hainan plume. *Phys. Earth Planet. Inter.* 173, 33–50.
- Leng, W., Gurnis, M., 2015. Subduction initiation at relic arcs. *Geophys. Res. Lett.* 42, 7014–7021.
- Li, Z.X., Li, X.H., 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: a flat-slab subduction model. *Geology* 35, 179–182.
- Li, Z.-X., Zhong, S., 2009. Supercontinent-superplumecoupling, truepolarwanderandplumemobility:platedominanceinwhole-mantletectonics. *Phys. Earth Planet. Inter.* 176, 143–156.
- Li, C., van der Hilst, R., Toksoz, M.N., 2006. Constraining P-wave velocity variations in the upper mantle beneath Southeast Asia. *Phys. Earth Planet. Inter.* 154, 180–195.
- Li, C., van der Hilst, R., Engdahl, E., Burdick, S., 2008. A new global model for P wave speed variations in Earth's mantle. *Geochim. Geophys. Geosyst.* 9, Q05018. <https://doi.org/10.1029/2007GC001806>.
- Li, Z.X., Li, X.H., Chung, S.L., Lo, C.H., Xu, X.S., Li, W.X., 2012. Magmatic switch-on and switch-off along the South China continental margin since the Permian: transition from an Andean-type to a Western Pacific-type plate boundary. *Tectonophysics* 532–535, 271–290.
- Li, C.F., Xu, X., Lin, J., Sun, Z., Zhu, J., Yao, Y.J., Zhao, X.X., Liu, Q.S., Kulhanek, D.K., Wang, J., Song, T.R., Zhao, J.F., Qiu, N., Guan, Y., Zhou, Z., Williams, T., Bao, R., Briaies, A., Brown, E., Chen, Y., Clift, P., Colwell, F., Dadd, K., Ding, W., Almeida, I., Huang, X., Hyun, S., Jiang, T., Koppers, A., Li, Q., Liu, C., Liu, Z., Nagai, R., Peleo-Alampay, A., Su, X., Tejada, M., Trinh, H., Yeh, Y., Zhang, C., Zhang, F., Zhang, G., 2014. Ages and magnetic structures of the South China Sea constrained by deep tow magnetic surveys and IODP Expedition349. *Geochim. Geophys. Geosyst.* 15 (12), 4958–4983. <https://doi.org/10.1002/2014gc005567>.
- Li, C.F., Lin, J., Kulhanek, D.K., the Expedition 349 Scientists, 2015. In: *Proceedings of the International Ocean Discovery Program*, vol.349. South China Sea Tectonics. International Ocean Discovery Program, College Station, TX.
- Li, S.G., Yang, W., Ke, S., Meng, X., Tian, H., Xu, L., He, Y., Huang, J., Wang, X.C., Xia, Q., Sun, W., Yang, X., Ren, Z.Y., Wei, H., Liu, Y., Meng, F., Yan, J., 2017. Deep carbon cycles constrained by a large-scale mantle Mg isotope anomaly in eastern China. *Natl. Sci. Rev.* 4, 111–120.
- Li, X., Hao, T., Li, Z., 2018. Upper mantle structure and geodynamics of the Sumatra subduction zone from 3-D teleseismic P-wave tomography. *J. Asian Earth Sci.* 161, 25–34. <https://doi.org/10.1016/j.jseaeas.2018.05.004>.
- Li, S.Z., Suo, Y.H., Li, X., Zhou, J., Santosh, M., Wang, P., Wang, G., Guo, L., Yu, S., Lan, H., Dai, L., Zhou, Z., Cao, X., Zhu, J., Liu, B., Jiang, S., Wang, G., Zhang, G., 2019. Mesozoic tectono-magmatic response in the East Asian ocean-continent connection zone to subduction of the Paleo-Pacific Plate. *Earth Sci. Rev.* 192, 91–137.
- Lin, J., Xu, Y.G., Sun, Z., Zhou, Z.Y., 2019. Mantle upwelling beneath the South China Sea and links to surrounding subduction systems. *Natl. Sci. Rev.* 6 (5), 877–881.
- Liu, J.Q., Ren, Z.Y., Nichols, A.R.L., Song, M.S., Qian, S.P., Zhang, Y., Zhao, P.P., 2015. Petrogenesis of late Cenozoic basalts from North Hainan Island: constrains from melt inclusions and their host olivines. *Geochim. Cosmochim. Acta* 152, 89–121.
- Liu, J.J., Stegman, D.R., 2011. Segmentation of the Farallon slab. *Earth Planet. Sci. Lett.* 311 (1–2), 1–10. <https://doi.org/10.1016/j.epsl.2011.09.027>.
- Liu, S., Suardi, I., Yang, D., Wei, S., Tong, P., 2018. Teleseismic traveltimes tomography of northern Sumatra. *Geophys. Res. Lett.* 45, 13,231–13,239. <https://doi.org/10.1029/2018GL07861>.
- Liu, H.Q., Yumul Jr., G.P., Dimalanta, C.B., Queaño, K., Xia, X.P., Peng, T.P., Lan, J., Xu, Y., Guotana, J.M.R., Olfindo, V.S., 2020. Western Northern Luzon isotopic evidence of transition from proto-South China Sea to South China Sea fossil ridge subduction. *Tectonics* 39, e2019TC005639. <https://doi.org/10.1029/2019TC005639>.
- Macpherson, C.G., Dreher, S.T., Thirlwall, M.F., 2006. Adakites without slab melting: High pressure differentiation of island arc magma, Mindanao, the Philippines. *Earth Planet. Sci. Lett.* 243, 581–593.
- Mao, W., Zhong, S., 2018. Slab stagnation due to a reduced viscosity layer beneath the mantle transition zone. *Nat. Geosci.* 11, 876–881.
- Martin-Short, R., Allen, R.M., Bastow, I.D., 2016. Subduction geometry beneath south Central Alaska and its relationship to volcanism. *Geophys. Res. Lett.* 43, 9509–9517.
- McCourt, W.J., Crow, M.J., Cobbing, E.J., Amin, T.C., 1996. Mesozoic and Cenozoic plutonic evolution of SE Asia: Evidence from Sumatra, Indonesia. *Geol. Soc. London Spec. Publ.* 106 (1), 321–335.
- Mériaux, C.A., Duarte, J.C., Schellart, W.P., Mériaux, A.S., 2015. A two-way interaction between the Hainan plume and the Manila subduction zone. *Geophys. Res. Lett.* 42, 5796–5802. <https://doi.org/10.1002/2015GL064313>.
- Metcalf, I., 2011. Tectonic framework and Phanerozoic evolution of Sundaland. *Gondwana Res.* 19, 3–21.
- Metcalf, I., 2013. Gondwana dispersion and Asian accretion: tectonic and palaeogeographic evolution of eastern Tethys. *J. Asian Earth Sci.* 66, 1–33.
- Métrich, N., Vidal, C.M., Komorowski, J.-C., 2017. New Insights into Magma Differentiation and Storage in Holocene Crustal Reservoirs of the Lesser Sunda Arc: the Rinjani-Samalas Volcanic complex (Lombok, Indonesia). *J. Petrol.* 58, 2257–2284.
- Morley, C.K., 2017. Chapter 4 Cenozoic rifting, passive margin development and strike-slip faulting in the Andaman Sea: a discussion of established v. new tectonic models. *Geol. Soc. Lond. Mem.* 47 (1), 27–50.
- Morley, C.K., Alvey, A., 2015. Is spreading prolonged, episodic or incipient in the Andaman Sea? Evidence from Deepwater sedimentation. *J. Asia Earth Sci.* 98, 446–456.
- Mukasa, S.B., Fischer, G.M., Barr, S.M., 1996. The character of the subcontinental mantle in Southeast Asia: Evidence from isotopic and elemental compositions of extension related Cenozoic basalts in Thailand. In: Basu, A., Hart, S. (Eds.), *Earth Processes: Reading the Isotopic Code*. American Geophysical Union, pp. 233–252.
- Müller, R.D., Seton, M., Zahirovic, S., Williams, S.E., Matthews, K.J., Wright, N.M., Shephard, G.E., Maloney, K.T., Barnett-Moore, N., Hosseinpour, M., Bower, D.J., Cannon, J., 2016. Ocean basin evolution and global-scale plate reorganization events since Pangea breakup. *Annu. Rev. Earth Planet. Sci.* 44, 107–138.
- Nichols, G., Hall, R., 1999. History of the Celebes Basin based on its stratigraphic and sedimentological record. *J. Asia Earth Sci.* 17 (1–2), 47–59.
- Okino, K., Shimakawa, Y., Nagaoka, S., 1994. Evolution of the Shikoku Basin. *J. Geomagn. Geoelectr.* 46 (6), 463–479. <https://doi.org/10.5636/jgg.46.463>.
- Page, B.G.N., Bennett, J.D., Cameron, N.R., Bridge, D.McC., Jeffery, D.H., Keats, W., Thaib, J., 1979. A review of the main structural and magmatic features of northern Sumatra. *J. Geol. Soc.* 136, 569–579. <https://doi.org/10.1144/gsjgs.136.5.0569>.
- Pesicek, J.D., 2010. Teleseismic double-difference relocation of earthquakes along the Sumatra-Andaman subduction zone using a 3-D model. *J. Geophys. Res.* 115, B10303. <https://doi.org/10.1029/2010JB007443>.
- Polve, M., Maury, R.C., Jego, S., Bellon, H., Margoum, A., Yumul, G.P., Payot, B.D., Tamayo, R.A., Cotten, J., 2007. Temporal geochemical evolution of neogene magmatism in the Baguio gold-copper mining district (Northern Luzon, Philippines). *Resour. Geol.* 57, 197–218.
- Pubellier, M., Quebral, R., Rangin, C., Deffontaines, B., Muller, C., Butterlin, J., Manzano, J., 1991. The Mindanao collision zone: a soft collision event within a continuous Neogene strike-slip setting. *J. SE Asian Earth Sci.* 6, 239–248.
- 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. Soc. Geol. Fr.* 174, 561–584. <https://doi.org/10.2113/174.6.561>.
- Rae, A.J., Cooke, D.R., Phillips, D., Zaide-Delfin, M., 2004. The nature of magmatism at Palapinon geothermal field, Negros Island, Philippines: implications for geothermal activity and regional tectonics. *J. Volcanol. Geotherm. Res.* 129, 321–342. [https://doi.org/10.1016/S0377-0273\(03\)00280-4](https://doi.org/10.1016/S0377-0273(03)00280-4).
- Raju, K.A.K., Ramprasad, T., Rao, B.R., Varghese, J., 2004. New insights into the tectonic evolution of the Andaman Basin, Northeast Indian Ocean. *Earth Planet. Sci. Lett.* 221, 145–162.
- Rangin, C., Silver, E.A., 1991. Neogene tectonic evolution of the Celebes–Sulu basins: New insights from Leg 124 drilling. In: Silver, E., Rangin, C. (Eds.), *Proceedings, OceanDrilling Program Scientific Results, vol. 124. Ocean Drilling Program, College Station, TX*, pp. 51–64.
- Rangin, C., Spakman, W., Pubellier, M., Bijwaard, H., 1999. Tomographic and geological constraints on subduction along the eastern Sundaland continental margin (South-East Asia). *Bull. Soc. Geol. Fr.* 170, 775–788.
- Réhault, J.P., Malod, J.A., Larue, M., Burhanuddin, S., Sarmili, L., 1991. A new sketch of the central North Banda Sea, eastern Indonesia. *J. Southeast Asian Earth Sci.* 6 (3–4), 329–334.
- Richard, S., Lister, G., Kennett, B., 2013. A slab in depth: three-dimensional geometry and evolution of the Indo-Australian plate. *Geochim. Geophys. Geosyst.* 8, Q12003 <https://doi.org/10.1029/2007GC001657>.
- Richards, M.A., Engebretson, D.C., 1992. Large-scale mantle convection and the history of subduction. *Nature* 355, 437–440. <https://doi.org/10.1038/355437a0>.
- Royer, J.Y., Sandwell, D.T., 1989. Evolution of the eastern Indian Ocean since the late cretaceous: constraints from Geosat altimetry. *J. Geophys. Res.* 94, 13755–13782.
- Ruprecht, P., Plank, T., 2013. Feeding andesitic eruptions with a high-speed connection from the mantle. *Nature* 500 (7460), 68–72. <https://doi.org/10.1038/nature12342>.
- Ryan, J.G., Chauvel, C., 2014. The subduction-zone filter and the impact of recycled materials on the evolution of the mantle. In: Holland, H.D., Turekian, K. (Eds.), *Treatise on Geochemistry (Second Edition)*. Elsevier, Ltd.
- Sanematsu, K., Moriyama, T., Sotouky, L., Watanabe, Y., 2011. Mobility of the rare earth elements in basalt-derived laterite at the Bolaven Plateau, Southern Laos. *Resour. Geol.* 61, 140–158.
- Savva, D., Publier, M., Franke, D., Chamot-Rooke, N., Meresse, F., Steuer, S., Auxietre, J. L., 2014. Different expressions of rifting on the South China Seamounts. *Mar. Pet. Geol.* 58 (B), 579–598. <https://doi.org/10.1016/j.marpetgeo.2014.05.023>.
- Schellart, W.P., Spakman, W., 2015. Australian plate motion and topography linked to fossil New Guinea slab below Lake Eyre. *Earth Planet. Sci. Lett.* 421, 107–116. <https://doi.org/10.1016/j.epsl.2015.03.036>.
- Schlueter, H.U., Hinz, K., Block, M., 1996. Tectono-stratigraphic terranes and detachment faulting of the South China Sea and Sulu Sea. *Mar. Geol.* 130, 39–78.
- Sdrolias, M., Müller, R.D., 2006. Controls on back-arc basin formation. *Geochim. Geophys. Geosyst.* 7, Q04016 <https://doi.org/10.1029/2005GC001090>.
- Seton, M., Müller, R.D., Zahirovic, S., Gai, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma. *Earth-Sci. Rev.* 113, 212–270.
- Shulgin, A., Kopp, H., Mueller, C., Planer, L., Lueschen, E., Flueh, E.R., Djajadihardja, Y., 2011. Structural architecture of oceanic plateau subduction offshore Eastern Java and the potential implications for geohazards. *Geophys. J. Int.* 184 (1), 12–28. <https://doi.org/10.1111/j.1365-246X.2010.04834.x>.
- Sibuet, J.C., Yeh, Y.C., Lee, C.S., 2016. Geodynamics of the South China Sea. *Tectonophysics* 692, 98–119. <https://doi.org/10.1016/j.tecto.2016.02.022>.
- Silver, E.A., Rangin, C., von Breyman, M.T., et al., 1991. *Proceeding of ODP Scientific Results, 124. Ocean Drilling Program, College Station, TX*.
- Simons, W.J.F., Socquet, A., Vigny, C., Ambrosius, B.A.C., Haji Abu, S., Promthong, Chaiwat, Subarya, C., Sarsito, D.A., Matheussen, S., Morgan, P., Spakman, W., 2007. A decade of GPS in Southeast Asia: resolving sundaland motion and boundaries. *J. Geophys. Res.* 112, B06420 <https://doi.org/10.1029/2005JB003868>.
- Sleep, N.H., Zahnle, K., 2001. Carbon dioxide cycling and implications for climate on ancient Earth. *J. Geophys. Res.* 106, 1373–1399.
- Smyth, H.R., Hamilton, P.J., Hall, R., Kinny, P.D., 2007. The deep crust beneath island arcs: Inherited zircons reveal a Gondwana continental fragment beneath East Java, Indonesia. *E.P.S.L.* 258, 268–282.
- Soeria-Atmadja, R., Noeradi, D., 2005. Distribution of early Tertiary volcanic rocks in South Sumatra and West Java. *Island Arc* 14, 679–686.
- Solidum, R.U., Castillo, P.R., Hawkins, J.W., 2003. Geochemistry of lavas from Negros Arc, west central Philippines: Insights into the contribution from the subducting slab. *Geochim. Geophys. Geosyst.* 4 n/a/n/a.
- Stein, S., Okal, E.A., 2005. Speed and size of the Sumatra earthquake. *Nature* 434, 581–582. <https://doi.org/10.1038/434581a>.
- Stern, R.J., 2004. Subduction Initiation: Spontaneous and Induced, 226. *E.P.S.L.*, pp. 275–292.
- Stern, R.J., Gerya, T., 2018. Subduction initiation in nature and models: a review. *Tectonophysics* 746, 173–198. <https://doi.org/10.1016/j.tecto.2017.10.014>.
- Sun, W.D., Ding, X., Hu, Y.H., Li, X.H., 2007. The golden transformation of the cretaceous plate subduction in the West Pacific. *Earth Planet. Sci. Lett.* 262, 533–542.
- Sun, Z., Jian, Z., Stock, J.M., Larsen, H.C., Klaus, A., AvRarez Zarikian, C.A., The Expedition 367/368 Scientists, 2018. In: *Proceedings of the International Ocean Discovery Program, vol. 367/368. South China Sea Rifted Margin. International Ocean Discovery Program, College Station, TX*.
- Sun, Z., Ding, W.W., Zhao, X.X., Qiu, N., Lin, J., Li, C.F., 2019a. The latest spreading periods of the South China Sea: New constraints from macrostructure analysis of IODP Expedition 349 cores and geophysical data. *J. Geophys. Res. Solid Earth.* <https://doi.org/10.1029/2019JB017584>.
- Sun, Z., Lin, J., Qiu, N., Jian, Z.M., Wang, P.X., Pang, X., Zheng, J., Zhu, B., 2019b. The role of magmatism in the thinning and breakup of the South China Sea continental margin: special topic: the South China Sea Ocean Drilling. *Nat. Sci. Rev.* 6 (5), 871–876. <https://doi.org/10.1093/nsr/nwz116>.
- Suo, Y.H., Li, S.Z., Jin, C., Zhang, Y., Zhou, J., Li, X., Wang, P., Liu, Z., Wang, X., Somerville, I., 2019. Eastward tectonic migration and transition of the Jurassic–Cretaceous Andean-type continental margin along Southeast China. *Earth Sci. Rev.* 196, 10284. <https://doi.org/10.1016/j.earscirev.2019.102884>.
- Suppe, J., Liou, J.G., Ernst, W.G., 1981. Paleogeographic origins of the Miocene East Taiwan Ophiolite. *Am. J. Sci.* 281 (3), 228–246. <https://doi.org/10.2475/ajs.281.3.228>.
- Tapponnier, P., Peltzer, G., Dain, A.Y.L., Armijo, R., Cobbold, P.R., 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology* 10, 611–616.
- Taylor, B., Hayes, D.E., 1980. The tectonic evolution of the South China Sea. In: Hayes, D.E. (Ed.), *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 1. Geophys. Monogr.* vol. 23. AGU, Washington, D.C., pp. 89–104.
- Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea basin. In: Hayes, D.E. (Ed.), *The Tectonic and Geologic Evolution of the Southeast Asian Seas and Islands: Part 2. In: Geophys. Monogr.* vol. 27. AGU, Washington, DC, pp. 23–56.
- Tri, T.V., Khuc, V., 2009. *Geology and Earth Resources of Vietnam. General Department of Geology and Minerals of Vietnam*, pp. 344–345.
- Van den Ende, C., White, L.T., van Welzen, P.C., 2017. The existence and break-up of the Antarctic land bridge as indicated by both amphipacific distributions and tectonics. *Gondwana Res.* 44, 219–227. <https://doi.org/10.1016/j.gr.2016.12.006>.
- van der Hilst, R.D., Widiyantoro, S., Engdahl, E.R., 1997. Evidence for deep mantle circulation from global tomography. *Nature* 386, 578–584. <https://doi.org/10.1038/386578a0>.
- Vroon, P.Z., 1992. Subduction of Continental Material in the Banda Arc, Eastern Indonesia: Sr–Nd–Pb Isotope and Trace Element Evidence from Volcanics and Sediments. Ph.D. Thesis. Utrecht University, p. 205.
- Wang, L., He, X., 2020. Seismic anisotropy in the Java-Banda and Philippine subduction zones and its implications for the mantle flow system beneath the Sunda Plate. *Geochim. Geophys. Geosyst.* 21, e2019GC008658 <https://doi.org/10.1029/2019GC008658>.
- Wang, X.C., Li, Z.X., Li, X.H., Li, J., Liu, Y., Long, W.G., Zhou, J.B., Wang, F., 2012. Temperature, pressure, and composition of the mantle source region of late Cenozoic basalts in Hainan Island, SE Asia: a consequence of a young thermal mantle plume close to subduction zones? *J. Petrol.* 53, 177–233.
- Wang, X., Li, Z., Li, X., Li, J., Xu, Y., Li, X., 2013. Identification of an ancient mantle reservoir and young recycled materials in the source region of a young mantle plume: implications for potential linkages between plume and plate tectonics. *Earth Planet. Sci. Lett.* 377–378, 248–259.
- Wang, P.X., Huang, C.Y., Lin, J., Jian, Z.M., Sun, Z., Zhao, M.H., 2019. The South China Sea is not a mini-Atlantic: plate edge rifting vs intra-plate rifting. *Nat. Sci. Rev.* 6 (5), 902–913. <https://doi.org/10.1093/nsr/nwz135>.
- Waters, P.J., Cooke, D.R., Gonzales, R.I., Phillips, D., 2011. Porphyry and Epithermal Deposits and Ar-40/Ar-39 Geochronology of the Baguio District, Philippines. *Econ. Geol.* 106, 1335–1363.
- Watts, A.B., Weissel, J.K., 1975. Tectonic history of the Shikoku marginal basin. *Earth Planet. Sci. Lett.* 25 (3), 239–250. [https://doi.org/10.1016/0012-821X\(75\)90238-1](https://doi.org/10.1016/0012-821X(75)90238-1).
- Weissel, J.K., 1980. Evidence for Eocene oceanic crust in the Celebes Basin. In: Hayes, D. E. (Ed.), *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, 23. Am. Geophys. Union, Geophys. Monogr. Ser.* pp. 37–47.
- White, L.T., Gibson, G., Lister, G.S., 2013. A reassessment of paleogeographic reconstructions of eastern Gondwana: Bringing geology back into the equation. *Gondwana Res.* 23, 984–998. <https://doi.org/10.1016/j.gr.2013.06.009>.
- Widiyantoro, S., van der Hilst, R., 1997. Mantle structure beneath Indonesia inferred from high-resolution tomographic imaging. *Geophys. J. Int.* 130 (1), 167–182. <https://doi.org/10.1111/j.1365-246X.1997.tb00996.x>.
- Wolfe, J.A., 1988. Arc magmatism and mineralization in North Luzon and its relationship to subduction at the East Luzon and North Manila Trenches. *J. SE Asian Earth Sci.* 2, 79–93.
- Wu, J.E., Wu, J., 2019. Izanagi-Pacific ridge subduction revealed by a 56 to 46 Ma magmatic gap along the northeast Asian margin. *Geology* 47 (10), 953–957.
- Wu, J., Suppe, J., Lu, R.Q., Kanda, R., 2016. Philippine Sea and East Asian plate tectonics since 52Ma constrained by new subducted slab reconstruction methods. *J. Geophys. Res. Solid Earth* 121, 4670–4741.
- Xia, S.H., Zhao, D.P., Sun, J., Huang, H., 2016. Teleseismic imaging of the mantle beneath southernmost China: New insights into the Hainan plume. *Gondwana Res.* 36, 33–43. <https://doi.org/10.1016/j.gr.2016.05.003>.
- Xu, Y.G., Sun, M., Yan, W., Liu, Y., Huang, X.L., Chen, X.M., 2002. Xenolith evidence for polybaric melting and stratification of the upper mantle beneath South China. *J. Asian Earth Sci.* 20, 937–954.
- Xu, Y.G., Zhang, H.H., Qiu, H.N., Ge, W.C., Wu, F.Y., 2012. Oceanic crust components in continental basalts from Shuangliao, Northeast China: Derived from the mantle transition zone? *Chem. Geol.* 328, 168–184.
- Yamazaki, T., Seama, N., Okino, K., Kitada, K., Joshima, M., Oda, H., Naka, J., 2003. Spreading process of the northern Mariana Trough: Rifting-spreading transition at 22°N. *Geochim. Geophys. Geosyst.* 4 (9), 1075. <https://doi.org/10.1029/2002GC000492>.
- Yan, Q., Shi, X., Castillo, P.R., 2014. The late Mesozoic–Cenozoic tectonic evolution of the South China Sea: A petrologic perspective. *J. Asian Earth Sci.* 85, 178–201.
- Yu, Y., Gao, S.S., Liu, K.H., Yang, T., Xue, M., Le, K.P., Gao, J., 2018. Characteristics of the mantle flow system beneath the Indochina Peninsula revealed by teleseismic

- shear wave splitting analysis. *Geochem. Geophys. Geosyst.* 19, 1519–1532. <https://doi.org/10.1029/2018GC007474>.
- Yumul, G.P., Dimalanta, C.B., Tamayo, R.A., Maury, R.C., 2003. Collision, subduction and accretion events in the Philippines: a synthesis. *Island Arc* 12, 77–91.
- Zahirovic, S., Seton, M., Müller, R.D., 2014. The Cretaceous and Cenozoic tectonic evolution of Southeast Asia. *Solid Earth* 5 (1), 227–273. <https://doi.org/10.5194/se-5-227-2014>.
- Zahirovic, S., Matthews, K.J., Flament, N., Müller, R.D., Hill, K.C., Seton, M., Gurnis, M., 2016. Tectonic evolution and deep mantle structure of the eastern Tethys since the latest Jurassic. *Earth-Sci. Rev.* 162, 293–337.
- Zhang, G.L., Chen, L.H., Jackson, M.G., Hofmann, A.W., 2017. Evolution of carbonated melt to alkali basalt in the South China Sea. *Nat. Geosci.* 10, 229–236. <https://doi.org/10.1038/NGEO2877>.
- Zhang, G.L., Luo, Q., Zhao, J., et al., 2018. Geochemical nature of sub-ridge mantle and opening dynamics of the South China Sea. *Earth Planet. Sci. Lett.* 489, 145–155.
- Zhao, D., 2004. Global tomographic images of mantle plumes and subducting slabs: insight into deep earth dynamics. *Phys. Earth Planet. Inter.* 146, 3–34.
- Zhao, D., Ohtani, E., 2009. Deep slab subduction and dehydration and their geodynamic consequences: Evidence from seismology and mineral physics. *Gondwana Res.* 16, 401–413. <https://doi.org/10.1016/j.gr.2009.01.005>.
- Zhao, M., He, E., Jean-Claude, S., et al., 2018. Post-seafloor spreading volcanism in the Central East South China Sea and its formation through an extremely thin oceanic CRUST. *Geochem. Geophys. Geosyst.* 19 <https://doi.org/10.1002/2017GC007034>.
- Zhao, Y.H., Ding, W.W., Yin, S.R., Li, J.B., Zhang, J., Ding, H., 2020. Asymmetric post-spreading magmatism in the South China Sea: based on the quantification of the volume and its spatiotemporal distribution of the seamounts. *Int. Geol. Rev.* 62 (7–8), 955–969. <https://doi.org/10.1080/00206814.2019.1577189>.
- Zhou, Z., Lin, J., 2019. 3D mantle upwelling beneath the South China Sea and Southeast Asia: Multiple modes driven by plate motion, subduction slabs, and buoyancy forces. AGU Fall Meeting, Washington, DC, USA.
- Zhou, P.B., Mukasa, S.B., 1997. Nd–Sr–Pb isotopic, and major and trace-element geochemistry of Cenozoic lavas from the Khorat Plateau, Thailand: source and petrogenesis. *Chem. Geol.* 137, 175–193.