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Back-Arc Tectonics and Plate Reconstruction of the Philippine Sea-South China Sea Region Since the Eocene

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Key Points:

- A new plate reconstruction model of Philippine Sea-South China Sea (SCS) region since 55 Ma by integrating the latest geological geophysical data
- The western boundary of the Philippine Sea Plate was a constant sinistral strike-slip fault at 55–22 Ma
- The geodynamic model indicates the seismic high-velocity body under the SCS likely to be the leading edge of the Pacific Slab

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Insight into the evolution of Philippine Sea-South China Sea (SCS) plate motions helps reveal the driving mechanisms of the long-term tectonic complexity in Southeast Asia. Here, based on the integration of the most recent geological and seismic data, we present a new plate reconstruction model for this region characterized by back-arc extension and subduction since the Eocene. We suggest that the western boundary of the Philippine Sea Plate was a constant sinistral strike-slip fault at 55–22 Ma with a clockwise self-rotation. The connection between the SCS and Shikoku Ridges possibly initiates at 30 Ma, when their spreading times overlapped indicating an affinitive origin and magma source. Regional-scale geodynamic simulations interfaced with our reconstructed plate motion indicate that the seismic high-velocity body under the SCS is likely to be the leading edge of the Pacific Slab.

Plain Language Summary Since 55 million years ago, East Asia has been going through a complex plate recombination. Several quantitative plate motion models have been published, but there remain several irrationalities, for example, a footwall plate was moving away from the trench. We established a new model for the Philippine Sea-South China Sea (SCS) region as an improvement. Our model provides a smooth movement of the Philippine Sea Plate (PSP) from the equatorial zone to its present position, with a clockwise rotation. Based on it, we deduce: (a) the western boundary of the PSP was a sinistral strike-slip fault; (b) the spreading ridges in SCS and Shikoku Basin were connected at 30 Ma; (c) the stagnant slab under the SCS is a part of the subducting Pacific Slab.

1. Introduction

Southeast Asia is a region of intense tectonic convergence, which underwent complex evolution in the Cenozoic involving long-term plate subduction, birth and growth of microplates (S. Li et al., 2018), and intense plate deformation. Since the Philippine Sea (PS) and South China Sea (SCS) are closely connected with this region, elucidating the evolution of their plate motions can help us better understand the driving mechanisms of the long-term tectonic complexity and shed light on topographical changes and implications for ocean circulation and paleoclimate (e.g., Hall, 2002, 2009; J. C. Hu et al., 1996).

Several plate motion models (e.g., Hall, 2002; Ma et al., 2019; Müller et al., 2019; Wu et al., 2016; Zahirovic et al., 2016) have been conducted to explore the tectonic evolution of this region (Figure 1). Hall (2002) proposed a model for the back-arc opening with oceanic crust formation, which provides a framework for the East Asian plate reconstruction. To explain extensive magmatism and the absence of earlier subduction at the Izu-Bonin-Mariana margin, this study points out the Manus Hotspot/Plume was located under the eastern edge of the Philippine Sea Plate (PSP) at 52 Ma, when the seafloor spreading of the West Philippine Basin (WPB) initiated, then the rotation of PSP began at 25 Ma when the Halmahera Island collided with the New Guinea Island. As a response to continuous subduction of the Pacific Plate (PP) and island arc splitting, the Shikoku-Parece Vela Basin and the Mariana Trough opened at 30 and 5 Ma, respectively. This model also roughly shows that the opening event of the SCS opening occurs between 30 and 15 Ma with a ridge jump at ~25 Ma.

Contrary to Hall (2002), Wu et al. (2016) argued the Manus Plume was located under the central portion of the WPB and was related to the PSP origin based on their subducted slab reconstruction model. They used a

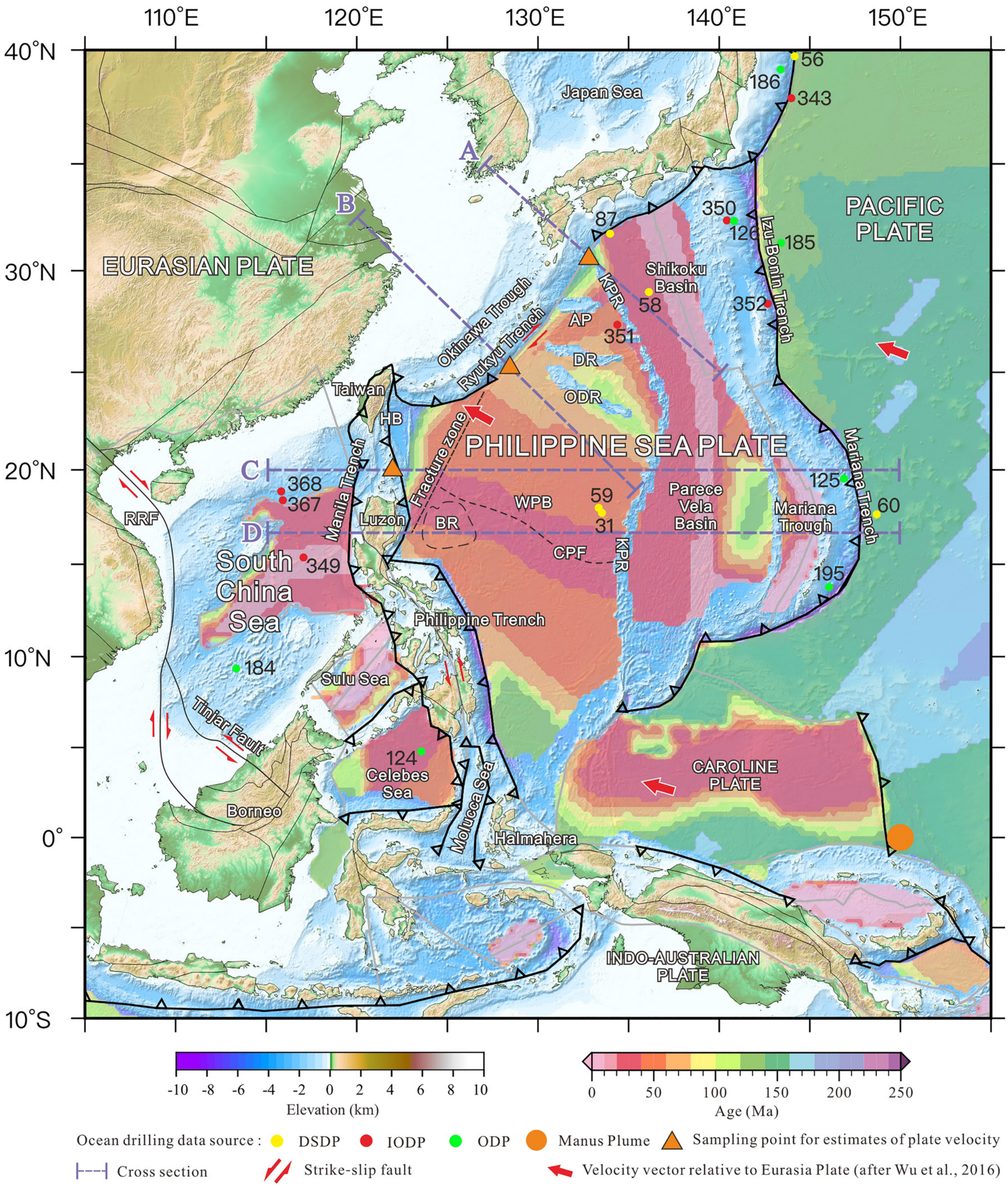

Figure 1. Tectonic map of the present-day Philippine Sea-South China Sea region. AP, Amami Plateau; BR, Benham Rise; CPF: Central Philippine Fault; DR, Daito Ridge; ODR, Oki-Daito Ridge; HB, Huatung Basin; KPR, Kyushu-Palau Ridge.

seismic tomographic model (MIT-P08) to identify the locations of past subduction zones in the Philippine Sea. Their model indicated the PSP rotated 80° clockwise while moving northwestward to its present-day location. Moreover, a N–S-directed bidirectional subduction model of the Proto-SCS was suggested to explain the stagnant slab (i.e., seismic high-velocity body) right under the present-day SCS (Wu et al., 2016; Wu & Suppe, 2018). The nature of this geological body is still unclear, which is worth discussing (Sun et al., 2019). It's notable that their model lacks complete plate boundaries (topological polygons) for kinematic analysis, which is one of our motivations to build a new model.

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Mesozoic–Cenozoic deforming global plate motion models (Müller et al., 2019; Zahirovic et al., 2016) show a divergence event at the Ryukyu Trench caused by the back-and-forth oscillation of the subducting PSP as it moves northward. The initial spreading of the Proto-SCS in the global models was set to 65 Ma based on the onset of a Late Cretaceous tectonic subsidence history of the Xihu Sag, East China Sea Shelf Basin on the East Asian continental margin (Yang et al., 2004) and the supra-subduction zone ophiolites on Mindoro (Yumul et al., 2009). However, regional stress field in Xihu Sag which reflects a possible extension event at ∼65 Ma unlikely represent that of the southern South China continental margin which is nearly 1,000 km away.

Due to the limited geological and geophysical data of the PS-SCS area, aforementioned plate reconstruction models may not accurately identify the timing and processes of the tectonic events in this region. For example, these models predict different trajectories of the PSP motion, where the plate has migrated from the equatorial region toward the north with a clockwise rotation since the early Cenozoic. They also make differing predictions on the original location of the Luzon-East Philippine Islands, which are a key part of the PSP. Besides, the reconstruction models of Müller et al. (2019) and Zahirovic et al. (2016) show that the PSP had a velocity opposite to the subduction direction during 20–15 Ma, which contradicts local geological records and/or tectonic rules.

To better understand the boundary evolution and back-arc spreading in the Philippine Sea-SCS region, at first, we update the existed digital plate motion model of Cao et al. (2020) and present a new evolution model for Southeast Asia since 55 Ma by integrating local geological and geophysical observations such as new ocean drilling data (Figure 1). We further present a 3-D regional data-assimilation geodynamic model with the input of reconstructed plate motion to test the rationality and credibility of the reconstruction model and explore a new possible origin of the stagnant slab under the SCS.

2. Methods

2.1. Plate Reconstruction Model

We used GPlates to construct the regional model based on the frame of earlier plate reconstruction models (Cao et al., 2020; S. Liu et al., 2017; Müller et al., 2019), but updating the motion and boundaries of the PSP, SCS, and surrounding micro-plates. Traditionally, plate reconstructions are mainly constrained by magnetic anomalies and hotspot tracks. In our study, we also incorporate seismic tomography (MIT-P08, C. Li et al., 2008) to determine the locations of paleo-trenches during 46–15 Ma (called "age-coding" by Zahirovic et al. (2016), see Figure S2 in Supporting Information S1), and Global Positioning System observations are used for the kinematic framework for the period since the Late Pliocene (Gripp & Gordon, 1990). We further used a high-resolution seismic profile and ocean drilling data (Ding et al., 2018; C. F. Li et al., 2014) to constrain the location of fossil mid-ocean ridges and the age of SCS oceanic crust. Please see Supporting Information S1 for details.

2.2. Data-Assimilation Geodynamic Model

We developed a 3D data-assimilation geodynamic model by using the spherical mantle code CitcomS (J. Hu et al., 2018; L. Liu & Stegman, 2011; Zhong et al., 2008) to evaluate the credence of our plate reconstruction model and figure out the origin of the seismic high-velocity body under the SCS. In particular, this regional model assimilated the data of plate motion, seafloor age, and topology of the subduction zone associated with our study region from our GPlates reconstruction model for every million year. More details about the model setup and results can be seen in Supporting Information S1.

3. Results

3.1. Plate Reconstruction Model

We divided the tectonic evolution of the PS-SCS region estimated from our new plate reconstruction since 55 Ma (Figure 2) into four chronostratigraphic stages: Eocene, Oligocene to Middle Miocene, Middle to Late Miocene, and Pliocene to present. This allows a better comparison with tectonic events.

3.1.1. Eocene (55–33 Ma)

The main tectonic event in this stage is the opening of the WPB. Linear magnetic anomaly and dating data (Hall, Ali, & Anderson, 1995, Hall, Ali, Anderson & Baker 1995; Hilde & Lee, 1984) suggest that back-arc spreading

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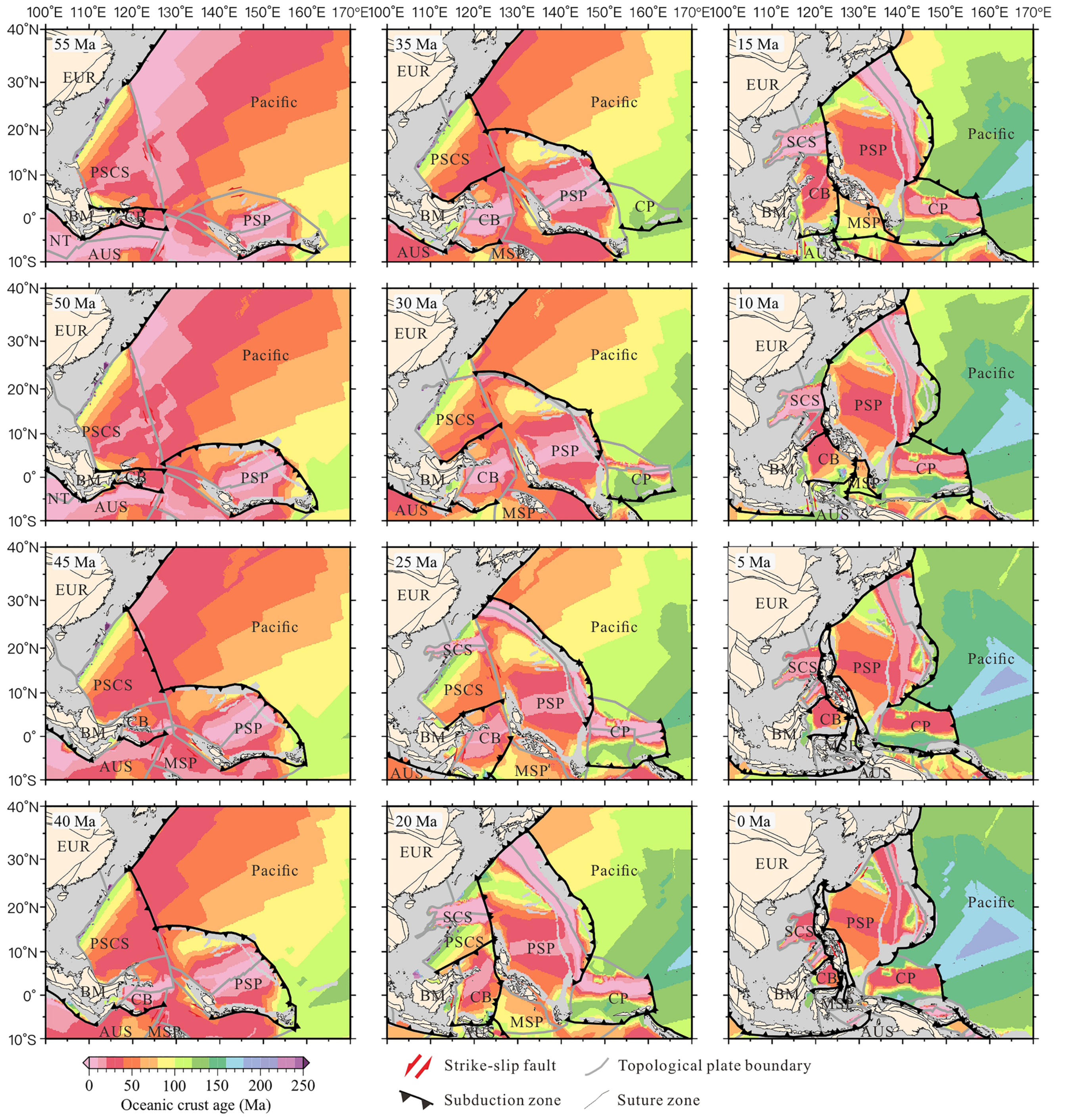

Figure 2. Plate reconstruction of the Philippine Sea-South China Sea region since 55 Ma. PSP, Philippine Sea Plate; SCS, South China Sea; PSCS, Proto-South China Sea; EUR, Eurasia; AUS, Australia; CP, Caroline Plate; CB, Celebes Basin; MSP, Molucca Sea Plate; BM, Borneo Micro-block; NT, New Tethys.

of the WPB started after ~70 Ma. Striped magnetic anomalies are symmetrically distributed on the north and south flanks of the Central Philippine Fault (in the center of WPB, see Figure 1), indicating that this fault is a fossil spreading center, which is consistent with high heat flow zones along it (Wu et al., 2016). In particular, the Amami Plateau and the Daito and Oki-Daito Ridges (DRs) in the northern basin show obvious negative linear magnetic anomalies and the ages of the oldest basalts are around 120 Ma (Wu et al., 2016). Therefore, the basement of the DR is likely the remnant of an ancient island arc. The ^{40}Ar-^{39}Ar age of oceanic island basalt

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on the DR is dated at 47–49 Ma, indicating that the DR sill was intruded by hotspot magmas (Hickey-Vargas et al., 2013). OIBs dated at 36 Ma was found at the Benham Rise (the westernmost WPB) by Deep Sea Drilling Program (DSDP) Leg 31 Site 292 (see Figure 1), and these rocks are likely influenced by mantle plumes (Wu et al., 2016). Thus, we link the birthplace of the WPB to the Manus Plume near the equator following previous studies (Hall, 2002; Wu et al., 2016).

Data from Ocean Drilling Program (ODP) confirmed that the basement age of the hanging wall of the Izu-Bonin-Mariana Trench was ~52–30 Ma when the west Pacific began to subduct to this trench, which is supported by paleomagnetic dating (Hickey-Vargas et al., 2013). $^{40}Ar/^{39}Ar$, K/Ar, and U-Pb isotopic dating indicates that the formation of the Luzon-East Philippine Islands basement is concentrated within two chronological periods: the Mesozoic constrained by Late Jurassic-Early Cretaceous complexes (Geary et al., 1988), and the Eocene (around 45 Ma) yielded by intrusive rocks, for example, granodiorite and tonalite (Encarnacion et al., 1993; Fuller et al., 1989). In addition, the Mid-Miocene mélange, ophiolitic complexes and radiolarians on the Luzon Island indicate a specific subduction event at ~14 Ma (Queaño et al., 2017; Suppe, 1981). Based on these data, we infer that the Luzon Island wasn't the hanging wall of a subduction system during the Mid-Eocene to the Early-Miocene, and the western margin of the Luzon Island was a sinistral transform fault. The East Philippine Islands were not connected to the Borneo Micro (BM)-block which was a subduction hanging wall in this period as shown in Hall (2002). On the contrary, the Oki-Daito Rise and the East Philippine Islands appeared on different sides of the spreading center of the WPB.

3.1.2. Oligocene to Middle Miocene (33–15 Ma)

3.1.2.1. Philippine Sea Plate

Seafloor spreading isochrons record the spreading history of the Shikoku-Parece Vela Basin. The spreading of the WPB stopped at ~30 Ma (Deschamps & Lallemand, 2002), and then the rifting center jumped to the island arc on the eastern margin of the basin (Okino et al., 1999; Sdrolias et al., 2004). The rifting produced a north-south-trending valley and split the island arc into the eastern Izu-Bonin Island Arc and the western relic Kyushu-Palau Island Arc. The spreading of the Parece Vela Basin started at approximately 30 Ma according to an incorporated analysis of magnetic, gravity, and bathymetric data (Ma et al., 2019) and ceased at 15 Ma (Yumul et al., 2003). The activity of the southern part of Shikoku-Parece Vela Ridge suddenly decreased at ~19 Ma, meanwhile its northern part became more active, gradually forming the main body of Shikoku Basin. ^{40}K–^{40}Ar isotopic radiometric and paleontological dating results showed that the type of plate boundary in the Manila Trench changed from strike-slip to convergent with the initiation of subduction at 22 Ma (Yumul et al., 2003). Kinematically, this transition may be related to the southward subduction of the Proto-SCS and anticlockwise rotation of the Celebes Sea. The collision between the PSP and the Shikoku Island initiated at 20 Ma based on fault kinematics and Raman spectra of Carbonaceous Material-rich metasediments, followed by the opening of the Okinawa Trough at 15 Ma (Raimbourg et al., 2017).

3.1.2.2. Proto-South China Sea

Recent studies showed that the main subduction time of the Proto-SCS was between the Eocene and Early Miocene (Sibuet et al., 2016). This coincides with the time of the SCS opening (Hall & Breitfeld, 2017). After the Sabah Orogeny event (a collision between the Nansha Block and the BM-block) in the Middle Miocene (15.5 Ma), the western Proto-SCS subduction in this area stopped, leading to the cessation the SCS spreading whereas the eastern Proto-SCS kept subducting until ~10 Ma (S. Zhao et al., 2019). During this period, the subduction direction was southeast-east, which is inconsistent with the spreading direction of the SCS, so the ridge spreading was terminated (S. Zhao et al., 2019). Seismic tomography revealed that fast anomalies beneath the Borneo at 800 km depth should be the subducted Proto-SCS slabs (Hall & Spakman, 2015). The Proto-SCS slabs were only found east of the West Baram Line (see Figure 1)—a dextral strike-slip fault zone as known as the Tinjar Fault that were active in the Late Eocene-Middle Miocene (F. Zhao et al., 2017). Accordingly, our reconstruction model also shows the western boundary of the subducted Proto-SCS along the Tinjar Fault.

3.1.2.3. South China Sea

The evolution of the SCS basin is already included in the model of Müller et al. (2019). Here, we adopt their model but update the timing of oceanic spreading initiation and cessation and a ridge jump event based on oceanic drilling data and seismic profile data (Ding et al., 2018; C. F. Li et al., 2014). The northwestern and

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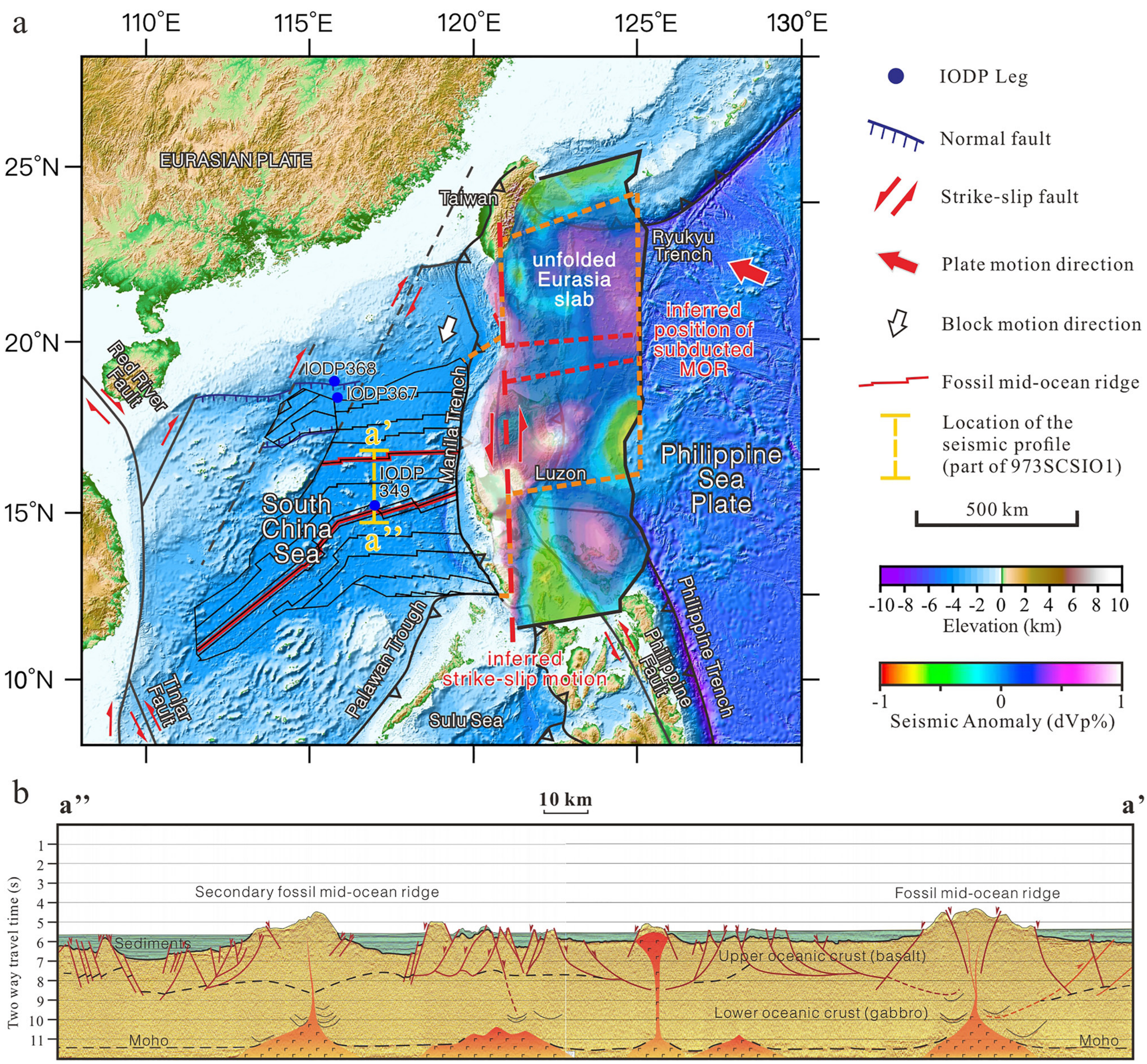

Figure 3. Tectonic map showing the two fossil mid-ocean ridges in the South China Sea Basin. The two fossil mid-ocean ridges are indicated in the cross section a′–a″. PSP, Philippine Sea Plate; HB, Huatung Basin.

eastern sub-basins of the SCS opened at 33 Ma (30 Ma in Müller et al. (2019)) based on the age of an unconformity at Integrated Ocean Drilling Program (IODP) Site U1435; after this, the southwest sub-basin opened at ~23 Ma (Li et al., 2014). The spreading of the southwest and the eastern sub-basins stopped at 16 and 15 Ma, respectively, according to IODP Leg 349 (Li et al., 2014).

There was a southward jump of the mid-ocean ridge in the eastern SCS sub-basin at ~23.6 Ma according to a study of lower crustal reflectors (C. F. Li et al., 2014). The ridge jump caused two regression events during the early spreading stage of the SCS basin observed in slope deposits sampled at IODP Leg 367 Site U1499 (Ding et al., 2018). Two fossil mid-ocean ridges were identified in the multi-channel seismic profile 973SCSIO1 (Figure 3) and we use this seismic profile to constrain the locations of the two ridges before and after the jump in our model. The width of the unfolded Eurasian slab described in Wu et al. (2016) was used to constrain the past position of the Manila Trench (Figures 3 and S1 in Supporting Information S1). Results of our plate reconstruction model shows that the western border of the Luzon Island still has a sinistral strike-slip character after 15 Ma under oblique subduction (Figure 3).

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3.1.3. Middle to Late Miocene (15–6 Ma)

During this period, the PSP was rotating clockwise and the northern section of the Ryukyu Trench has a sinistral strike-slip motion component. We revised the reconstruction of the PSP at 15 Ma through incorporating the latest information from seismic tomography in accordance with the position of the Izu-Bonin Trench (Figure S1a in Supporting Information S1).

The WPB subducted westward under the East Philippine Islands along the Philippine Trench since 8–9 Ma (Fan & Zhao, 2018). Seismic tomographic data show that the maximum depth of slabs is about 400 km (Wu et al., 2016), implying a relatively young age of the Philippine Trench.

At ~14 Ma the Proto-SCS was mostly subducted beneath the BM-block and the SCS began to subduct under the PSP. This formed the North Luzon Arc as shown by petrologic and paleontological evidence (Queaño et al., 2017; Suppe, 1981). The basement of the Taiwan Island is divided into two parts by the Hsingchuang Fault: the Coastal Plain in the west and the Western Foothills in the east (Huang et al., 2012). The west part belongs to the South China Plate (SCB) and the east part belongs to the North Luzon Arc. Petrological evidence indicates that the North Luzon Arc collided with the South China continental margin at ~6 Ma (Huang et al., 2012), causing the uplift of the Taiwan Island. The age of ophiolites in the Hengchun Peninsula, southernmost Taiwan, is ~14–7 Myr (S. Li et al., 2013).

3.1.4. Pliocene to Present (6–0 Ma)

This period is characterized by the NW-SE-directed compression and shortening of the Taiwan Orogen (Suppe, 1980) and the opening of the Mariana Trough (Fryer, 1996). The amount of shortening of the Taiwan Orogen since 3 Ma is 160–200 km (~70 mm/yr) based on retro-deformed cross section (Suppe, 1980). In our model, the predicted shortening is approximately 200 km for the last 3 Myr and 360–400 km for the last 6 Myr (measured by the GPlates built-in tool), which are in general agreement with Suppe (1980). The Mariana Trough resulted from a breakup of the Mariana Arc during 8–6 Ma (Fryer, 1996). According to DSDP Leg 60, the eastward migration of back-arc extension behind the Mariana subduction zone and the opening of the north-south-striking Mariana Trough began in the Early Pliocene (Hickey-Vargas, 1998). At the end of the Pliocene, the oceanic crust of the Mariana Trough was formed from the Mariana Ridge in the southern segment.

With the northwestward movement of the PSP, the mid-south segment of the Philippine Fault with sinistral strike-slip characteristics became active at ~4 Ma (Aurelio, 2000). Its slip velocity on the east side of Mindanao was 19–25 mm/yr (Aurelio, 2000), so the total fault displacement until present is about 100 km. After 2 Ma, the Taiwan Island has been constantly wedging into the SCB, resulting in a top-to-west thrust-nappe belt (S. Li et al., 2013). The eastward retreat of the Ryukyu subduction led to the formation of the Northeast Asian trench-arc-basin system (Hall, 2002).

3.2. Geodynamic Model

To test our reconstruction model and find insights for stagnant slabs, a regional mantle flow model from 55 Ma to the present was conducted using our plate reconstruction results as surface boundary conditions. We compared the geodynamic predictions with two seismic tomographic models of UU-P07 (Amaru, 2007) and MIT-P08 (C. Li et al., 2008). Results are shown in Figure 4. Our model is in general agreement with the tomographic models. The model shows that the wide horizontal slab under the PSP results from continuous subduction of the PP (Figures 4a–4c). The predicted slab along the Ryukyu Trench stagnated at the depth of 410–660 km, showing a good fit with seismic tomography as well. The subducted SCS crust along the Manila Trench shows a gentle dip angle and a shallower position compared with seismic results. Besides, the subducted WPB slab matches the seismic image well, but the position of the Molucca Sea slab shows westward deviation.

4. Discussion and Conclusions

4.1. Comparing With Previous Plate Reconstruction Models

Our new reconstruction model shows the detailed Cenozoic tectonic evolution of the Philippine Sea-SCS region. We modified problematic aspects of previous models, which were either in contradiction with the geological record and/or tectonic rules. For example, it was the Semitau, Kalimantan and South Palawan blocks, rather than

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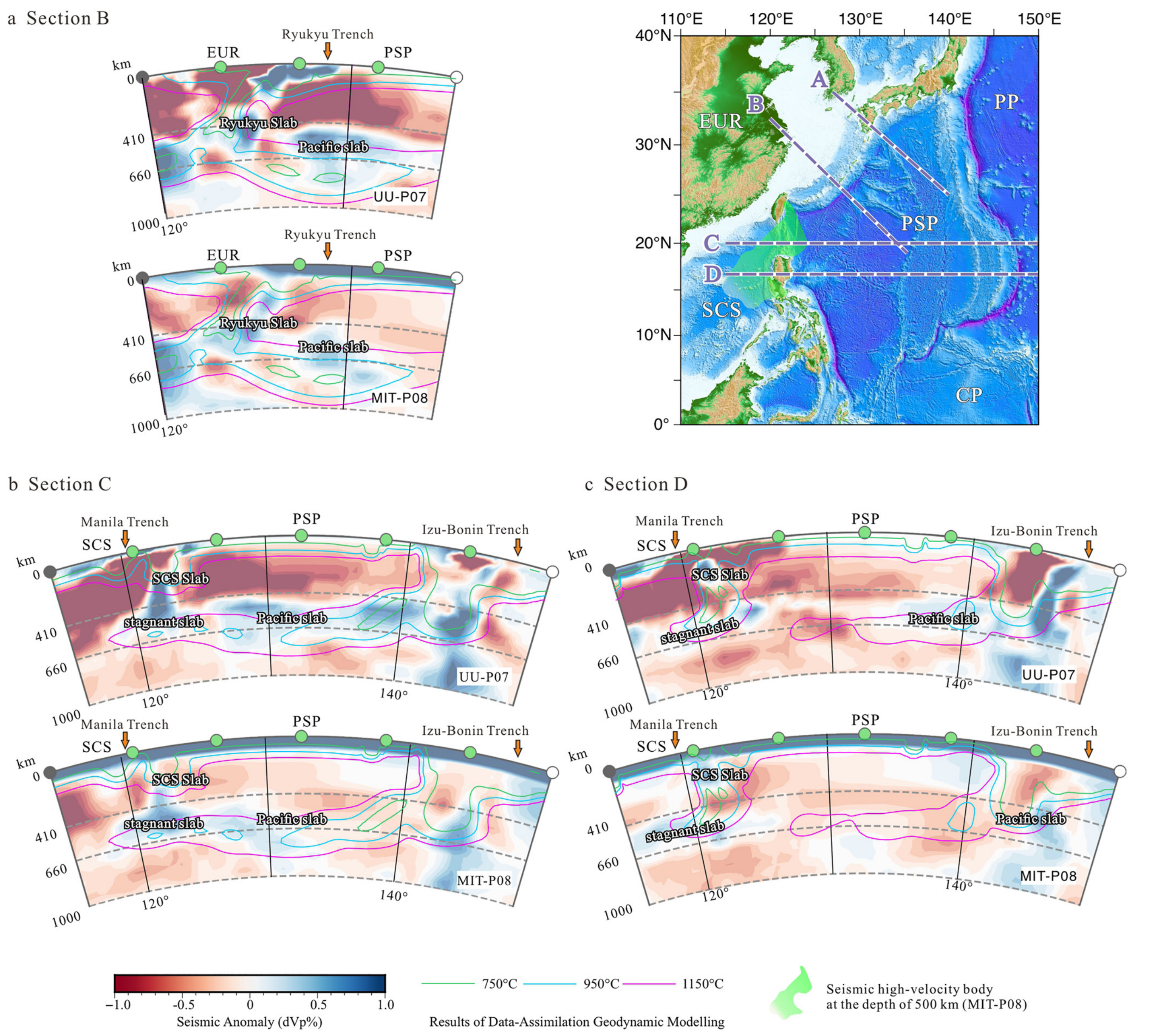

Figure 4. Comparison between the predicted slab structures and the global seismic tomographic models UU-P07 (Amaru, 2007) and MIT-P08 (C. Li et al., 2008) along cross sections B–E. The slabs from the numerical models are defined as regions 10% colder than the ambient mantle temperature which was set to ∼1250°C. Locations of cross sections are shown in Figure 1. CP, Caroline Plate; EUR, Eurasia Plate; PP, Pacific Plate; PSCS, Proto-South China Sea; PSP, Philippine Sea Plate; SCS, South China Sea.

the Mindoro Block as in Müller et al. (2019), that were located at the southernmost tip of the Proto-SCS and collided with the Borneo forming the Meratus Orogen (Hall, 2012). Additionally, the subduction rate appears to be negative (diverging) at 25–15 Ma (Figure S4 in Supporting Information S1) in the model of Müller et al. (2019). As mentioned above, the PSP oscillates back and forth to the north and south since the Cenozoic, which is shown in Figure S4 in Supporting Information S1. The modified plate motion direction and the subduction rate in our model are more tectonically reasonable (Figure S4 in Supporting Information S1).

With respect to the northern boundary of the PSP, structural analysis and paleo-geothermal evaluation show that the initial PSP subduction under the western Shikoku Island (southern Japan) took place at approximately 20 Ma (Raimbourg et al., 2017). The presented data from ocean drilling suggest that volcanic activity was absent in southern margin of the Japan Sea at 10–6 Ma (Tamaki et al., 1992). In response, the margin was initially

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uplifted and compressed during this period. Consequently, the northern PSP subduction was suspended and the retreat of the North Ryukyu Trench became slower (Ma et al., 2019). The agreement between the reconstructed subduction zones and the subducted slabs supports the occurrence of this event (Figures S1 and S3 in Supporting Information S1).

Based on the paleomagnetic data and detrital zircon constraints obtained from ODP Leg 190, a recent study (W. Liu et al., 2021) proposed that the SCS and the Shikoku Basin both have Indian-type mantle sources, and were sharing a common spreading center at ∼20 Ma. However, results of our model indicate that the two basins were once connected due to their similar formation ages and basement composition, but the connection initiated 10 Myrs earlier based on the plate motion trajectory (Figure 2). This is more consistent with the study illustrating the initial overlapping spreading time and the geographical affinity at ∼30 Ma of two basins (Queaño et al., 2020).

4.2. The Origin of the Stagnant Slab Under the South China Sea

Although seismic tomographic results show high-velocity bodies beneath the SCS at a depth of 410–660 km (Figure S1a in Supporting Information S1), its origin is not yet clear (Sun et al., 2019). A previous mantle convection model proposed a northwestward subduction mode under the SCS for the Proto-SCS at 30 Ma (Wu et al., 2016). It interpreted the slab as the north-diving part of the Proto-SCS based on the consistency of horizontal position on the premise of that the Eurasian Plate was stationary. However, the SCS was located 6° longitude west of its present-day position at 30 Ma, with no subducted slabs beneath it at that time (Müller et al., 2019). In contrast, our regional geodynamic model reproduces the discussed stagnant slab beneath the SCS (Figures 4b and 4c and Figure S5 in Supporting Information S1). This result provides a hypothesis that it is one part of the continuous westward subducting PP. As the consumption of the PP under the Proto-SCS initiated at 47 Ma, the stagnant slab can lead a westward-moving constant horizontal subduction and be torn slightly accompanied with SCS opening. Thus, there is no continuous subducted slab east of the fossil slab at 17°N but it was successive at 20°N (Figures 4b and 4c).

In summary, the PSP moved smoothly from the equatorial region in Cenozoic to its present position with an 80° self-rotation. Its western boundary was a sinistral strike-slip fault from 55 to 22 Ma. Based on this plate motion framework, we propose that the spreading ridges in the SCS and Shikoku Basin were connected as early as 30 Ma and the stagnant slab under the SCS could be a part of the subducting Pacific Slab.

Data Availability Statement

Our GPlates plate reconstruction model, CitComS simulation original results and supplementary movies can be found at https://doi.org/10.5281/zenodo.7630023. The seismic tomography data are available at http://submachine.earth.ox.ac.uk/. The authors declare that the seismic profile 973SCSIO1 used in this paper is from C. Li et al. (2015).

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