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Key Structural Elements around the East Vietnam Sea (South China Sea) and implications on reconstructions: towards a clarification

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ABSTRACT

The East Vietnam Sea (EVS) or the South China Sea (SCS in this paper) is one of the best-studied basins in the world and one of the largest marginal basins. If the mechanisms of rifting and spreading are well documented and invoke many specific aspects of structure and evolution, it has nevertheless been highly controversial in terms of its relationships with the neighboring basins; some of which have partly or entirely disappeared. This paper recapitulates the critical structural elements, such as the localization of magmatic activity and rifted basins from the Cretaceous to the Present, to evaluate the arguments for the reconstructions. We begin with the location of the Cretaceous magmatic arc along the Vietnam and China margins to discuss the setting and timing of the subduction of an oceanic domain which is unlikely to be the Proto South China Sea (PSCS) itself. This evolution raises the question of the existence and modalities of docking of the Argo and Luconia blocks and requires an intensive stretching of this early docked continental basement before seafloor spreading in the PSCS and the Celebes Sea from the end of Cretaceous to the Oligocene. The SCS was the latest basin to open within the continental margin and is believed to have developed within the downgoing plate. The crustal blocks separated by rifting and sea-floor spreading were later shortened from the Early Miocene to the Present, leaving the appearance of a complex tectonic system. This exercise indicates simple solutions which had not been stated previously, such as the possible connection between the Tethys Ocean and an oceanic domain between the PSCS and the coastal regions of China and Vietnam. The PSCS developed later toward the South, probably in a back-arc position, and the EVS opened amid this system intrinsically linked to the subduction of the PSCS.

Keywords: East Vietnam Sea, reconstructions, rifted basins, Cretaceous, Tethys ocean.

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INTRODUCTION; THE MARGINAL BASINS OF SE ASIA

The East Vietnam Sea is one of the best-studied basins in the world due to its economic importance, especially in oil and gas. It now serves as a textbook example to illustrate the mechanisms of rifting and spreading of a marginal basin floored partly by oceanic crust. In addition to the *V* shape oceanic crust (Figure 1a), it is characterized by a wide magma-poor passive continental margin [1–3]. It is also characterized by limited ocean floor spreading, which allows relatively easy margin correlations over short distances [4–5]. The extension occurred principally during the Cenozoic, thus relatively recently in geological times, but may have begun earlier, by the Late Cretaceous [7–9]. The tectonic context in terms of slab configuration at depth [10, 11], the former margin morpho-structures [12], and the accurate dating of the surrounding rocks [13] need more studies. Also, despite extensive studies on SE Asia, the plate configuration is not fully resolved for the Late Cretaceous and Paleocene and better knowledge of the processes of rifting and ocean floor spreading.

The SCS is not a typical marginal basin as it did not develop in a back-arc position. It opened along the rim of a composite micro-continent surrounded by a Mesozoic volcanic arc [14, 15] (Figure 1), and its structural evolution is linked with that of the adjacent basins [16, 17]. The SCS offers the opportunity to observe the stretching and thinning of a continental margin occurring during the shortening of an older one, the Proto South China Sea (PSCS), which has nowadays been entirely consumed [18, 19]. This dual system is nowadays fossilized after the cessation of its spreading in the Mid-Miocene. The tectonic activity across the SCS margins continued in the Late Miocene, with the opening of the Sulu Sea situated next to it [20]. In that sense, the SCS developed on a downgoing plate which is being overthrust by relics of the PSCS along the NW Borneo/Palawan subduction zone.

The PSCS was a basin that developed amidst a Mesozoic magmatic Arc, found in South China, Vietnam, and extended to Southern Borneo. The former arc was active throughout the main stages of structuration of the Sunda Plate, in the Permian, Triassic to Jurassic, and finally, Cretaceous [21], which can be traced offshore [11, 22] (Figure 1). This arc eventually collapsed, triggering Southeast Asia's continental rifting [14].

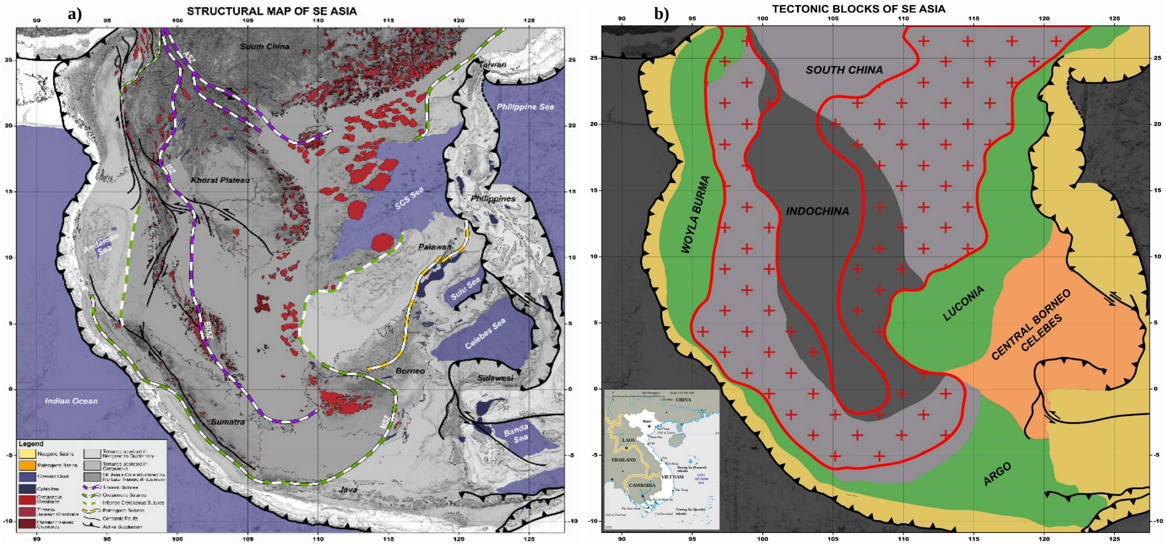

Figure 1. a) Right: Map of SE A formed by a backbone of accreted block in the Late Paleozoic and Mesozoic, and subsequently stretched by the opening of basins on its eastern part (modified from Sautter & Pubellier (2022) [15]); b) Left: Main blocks discussed in the text

These statements imply that the SCS is sitting both over a Mesozoic subduction zone, amid a Late Cretaceous orogen [8], and on the lower plate of an Eocene to Mid-Miocene subduction zone.

Nevertheless, many reconstructions have been attempted for the SE Asian region [23–28], or more locally, to explain the evolution of the SCS [1, 4, 6] and the links with the PSCS and the motion of Indochina [29, 30]. Some models do not invoke the existence of a PSCS [31, 32] but require a large free edge to the south. Several authors have already compared the different models [6, 33].

This review paper does not intend to pinpoint one specific reconstruction but explores the many options proposed for each of the complex steps of the evolution of the East Vietnam Sea (or the South China Sea). We used the step-by-step reconstructions of Pubellier et al., [34] until 20 Ma and extrapolated the block movements to 100 Ma, thus proposing a simple scenario of events and discussing several fundamental questions.

THE MESOZOIC SETTING

The early Mesozoic tectonics of South China and Vietnam directly results from the late Triassic Indosinian Orogeny [35]. The geometry of the margin is deduced mainly from the location of the Mesozoic arc (Figure 1b). From the Jurassic, the coastal strip of China, Vietnam, and their offshore basement was an active margin. The main issue concerning the Cretaceous setting is the location of the subducted crust, whose subduction generated the Mesozoic Yenshanian magmatic arc present along the margin of Vietnam and China's mainland [28, 36]. In front of Taiwan in the Fujian province of China, the granitic belt may be only a narrow strip along the coast that may extend into the Taiwan Strait. The granites lay in two chains parallel to the coast of China [37, 38] formed in the South China craton, with two major peaks of granite emplacement, the Early Yanshanian event (180–140 Ma) and the Late Yanshanian one (140–97 Ma) [21] or 136-118 [36]. The latest event of Cretaceous granite in Southern Vietnam ranges from 113 to 87 [39, 40], with a peak at 100 Ma according to Z/U-Pb geochronology. Recent geochronological data (Zircon U-Pb) also suggests the remobilization of Indosinian protoliths [40, 41].

Although the whole history of the magmatic arc, at least for the eastern Sundaland, may be explained by a single flat-subduction model since the Triassic [42, 43] tectonic event, most authors prefer to invoke a northward slab pull from north-dipping subduction of a Tethyan crust beneath Eurasia. Although the Jurassic and Cretaceous magmatism has been recently attributed to the Paleo-Pacific [41], the data only indicate a long-lasting west verging subduction beneath Eurasia notwithstanding, whether exotic blocks existed between the subduction zone and the Paleo Pacific Ocean. The simple geometry proposed hereafter is controlled by an ocean-floored basin situated east of the Cretaceous volcanic arc, which would correlate with the oceanic gap between the Argo Block and Sundaland Cretaceous (Figure 2).

Previous studies and reconstructions documented the accretion of several crustal blocks in the late Early Cretaceous and the Late Cretaceous. The main ones are the Argo block (or Sumba block, [26, 44, 45]) in East Java and Eastern Borneo (Mangkalihat Peninsula) and the composite Luconia block, which included the West Arm of Sulawesi and Palawan block. The two large blocks were offset by the Lupar Line of Central Borneo [14, 46–48].

The Argo block was probably narrow at its southwestern tip (Java), where the suture zone is mainly represented by the "melanges" of Karasambung (Indonesia) and broader in the Meratus Range of SE Kalimantan, where Jurassic ophiolite is known [49, 50]. To the north, the composite (Luconia-Palawan, Figure 2) terrane is nowadays disrupted by Late Cretaceous and Paleogene extension. It is believed to have comprised the western part of the Natuna platform, most of Palawan island and the Dangerous grounds, and the crustal strip carrying the Sulu arc, the Zamboanga Peninsula, and the Daguma Range in Mindanao [51]. It also had a possible narrow extension to the North

(MinTai block), which lay along the northern part of the coastal belt of China. This part is not documented enough since it is mainly offshore at Present and overlain by thick Tertiary shelf sediments. There is no apparent granitic intrusion in Taiwan, suggesting that the island is built on top of the accreted block's basement.

These blocks collided with the termination of the Tethyan subduction zone in the mid-Cretaceous and were subsequently accreted to the Sunda margin in the early Late Cretaceous [34, 35, 48, 52]. The simple scheme presented in Figure 1b also includes other blocks in Sumatra, Thailand, and Myanmar, although their shape is not well constrained. Remarkably, the timing of accretion of these isolated blocks is interestingly very similar. Thus, we may consider that the ocean which closed at this time was somehow connected with the Tethys. At the location of Southern China and Vietnam, we have indicated it in Figure 1b as T-SCS for "Tethyan South China Sea".

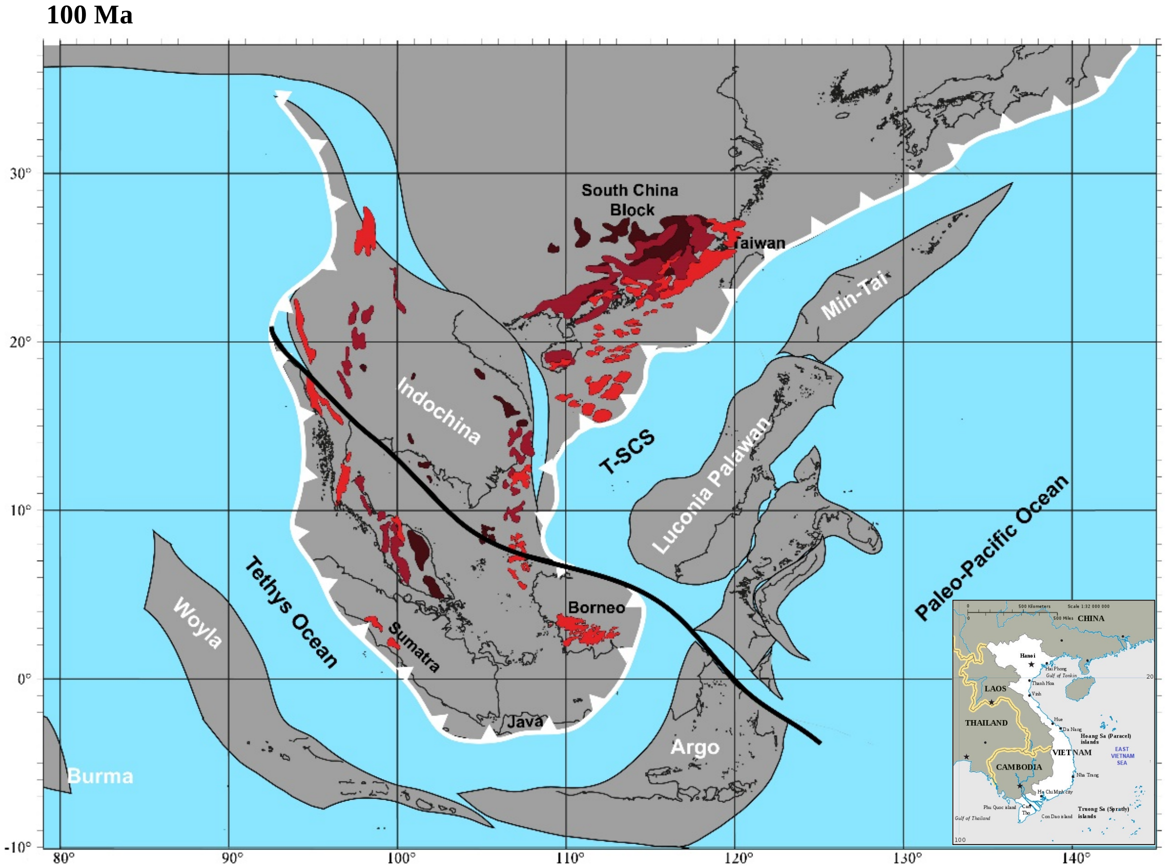

Figure 2. Main blocks reconstruction of SEA by the middle of Cretaceous; showing possible connection between the Tethys Ocean, an oceanic domain parallel to the margin (T-SCS for Tethysian SCS), and the Paleo-Pacific

Late Cretaceous-Paleocene compression

The accretion of crustal blocks during the Late Cretaceous postdates the granitic belt, whose ages are up to 100 Ma, but this deformation is difficult to pinpoint precisely. Published ages range mostly between 90 Ma and 80 Ma [8, 9]. Tang et al., [53] and Campbell and Sewell [54] have shown the existence of an important event from 100 Ma to 80 Ma based on ZFT, and 40Ar-39Ar dating [54] suggests a fully thermal reset between

80 Ma and 60 Ma. Data are available offshore with seismic images of Cretaceous folds sealed by Paleogene in the SCS [55] to the east of Sundaland and the Gulf of Thailand [34, 56] to the west (Figure 2). In Sumatra, the deformation of the Late Cretaceous age is attributed to the accretion of the Woyla Terrane, although it is still uncertain since the ophiolites are also attributed to a large seamount [57]. To the northwest, the accretion of the West Burma block is also unclear, although the deformation and the location of the Cretaceous arc are documented. Convergence was highly oblique, and a large component of horizontal shear was described [15, 34].

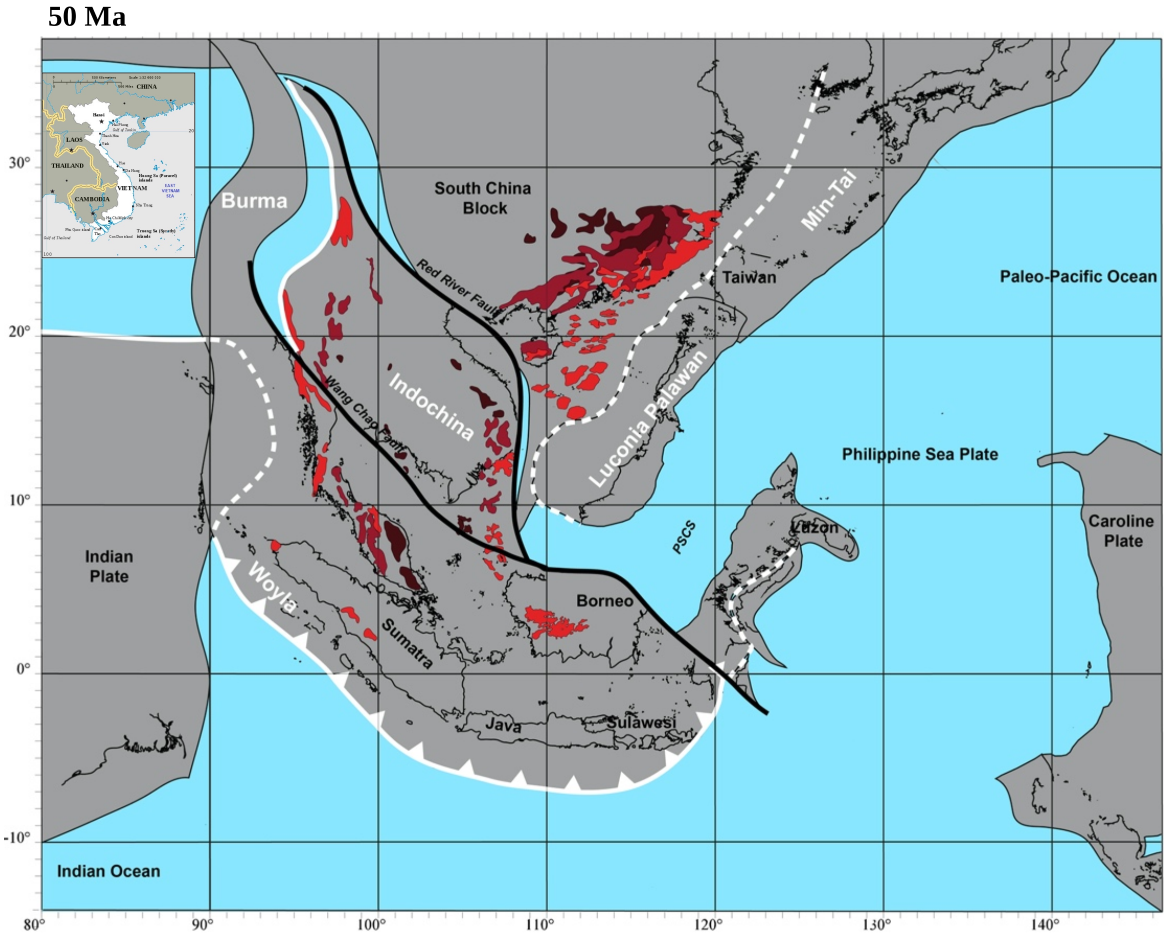

Figure 3. Main block reconstruction of SEA from Late Cretaceous to the Eocene; showing the suturing of the Tethys and T-SCS (black dash line), the last stages of opening (red lines) of the PSCS, and the early Celebes Sea (CS). The Paleo-Pacific and the Proto Philippine Sea Plate have not been differentiated

Relics of the Cretaceous oceanic crust between these blocks and the main continental margin are unknown because the ophiolitic rock of Northern Borneo (Telupid ophiolite) and Semporna-Dent peninsulas (Central and Eastern Sabah, respectively) are generally attributed to the Proto South China Sea. These are known to be Albian in age based on radiolarian biostratigraphy. If the PSCS developed to the SE of the accreted block from the Late Cretaceous, possibly to the Early Eocene (Sarawak orogeny in Borneo), the Middle Eocene to the latest Eocene Celebes Sea might have followed later in a regular trench advance system. However, some of the ODP Leg 124 results [17] pointed out the paucity of volcaniclastic sediments in the pre-Early Miocene sedimentary section of the Celebes Sea [17], and several reconstructions link the basin with the East Philippine Sea Basin [18, 26].

The PSCS developed just after the collision of the Argo-Luconia composite block (Figure 3). It is assumed to immediately follow the Yenshanian Orogeny subduction jump and thus could open in a back-arc setting. However, not many volcanic centers nor granitic complexes are associated with this Paleogene volcanic arc. It is also supposed that the oceanic accretion of the PSCS was still active in the Eocene, according to the sedimentary record of the NW Borneo wedge.

CENOZOIC SETTING

More is known but also debated on the complete subduction of the PSCS. Starting from the Middle Eocene, the rifting of the SCS margin accelerated until a breakup occurred at 33 Ma in front of the Pearl river and 23/24 Ma in front of Vietnam [3, 51, 58].

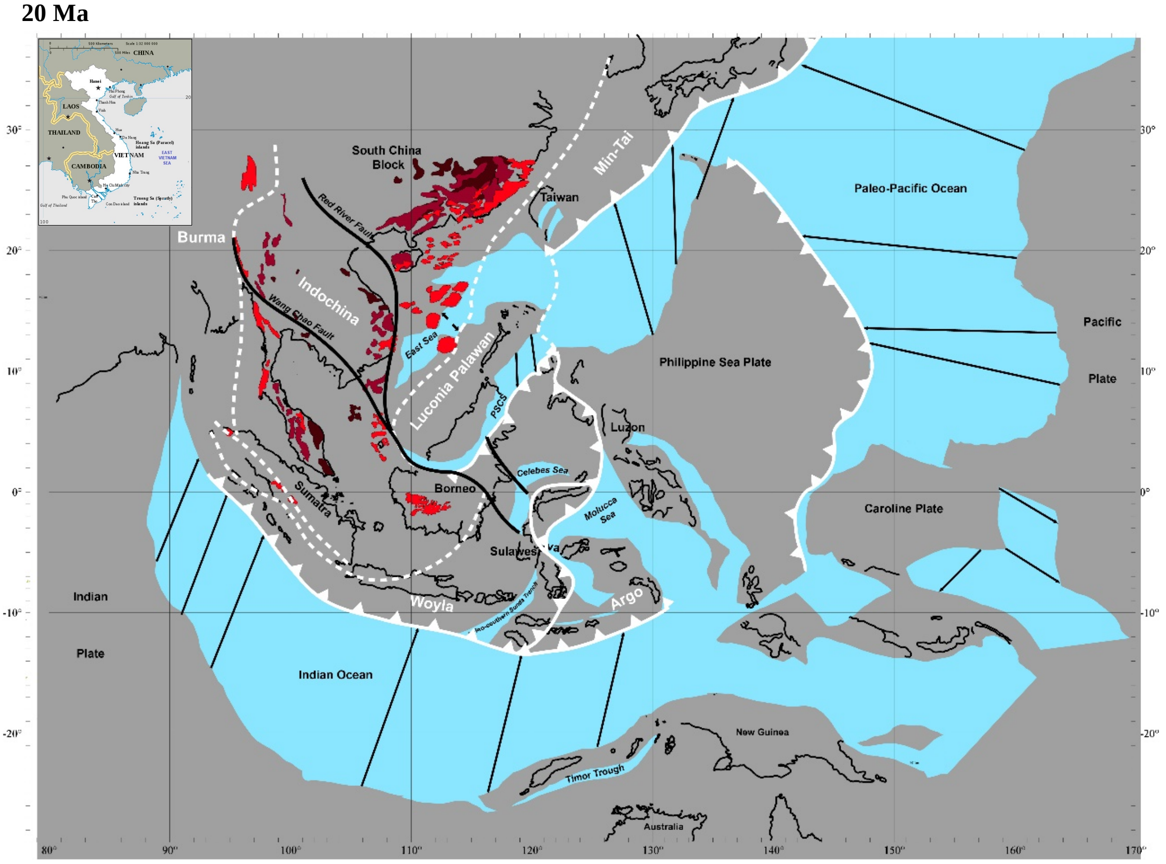

Figure 4. Main block reconstruction of SEA from Eocene to Early Miocene; showing the closure of the PSCS, the opening (red lines) of the SCS. Note the impact of the Philippine Sea Plate which encroached the marginal basins of SE Asia, and may have caused the beginning of the shortening of the PSCS

From the Oligocene collision of the first Australian fragment in Sulawesi, most of the basins which had opened during the Late Cretaceous and the Oligocene were inverted or started to subduct [35]. If many agree that the PSCS is a back-arc opening, the process and vergence of its subduction are debatable ([11] and references therein). Many studies have suggested that the opening of the SCS and the closure of the PSCS took place coevally in Cenozoic times [1, 3, 4, 13, 27, 59, 60]. Different geodynamics and boundary forces have been invoked and debated, such as the extrusion of the Indo-China Block [29, 31, 58], the opening of a supra-subduction basin [11, 59, 60], or basins opening on the downgoing plate [1, 5, 18, 28, 59]. It is, however, realistic if the models all contribute and interact (Figure 4); since the extrusion of Indochina is a fact, the subduction to the South of the PSCS is required from geological data, and the opening of the SCS within the down-going plate has no alternative so far. The presence of chunks of lithospheric slabs under the SCS may also result from westward subduction, sometimes during the shortening or a recumbent rolled-back slab.

Besides the PSCS closure, the SCS is also affected by the encroachment of the Philippine Sea Plate (PSP), starting from the Oligocene. The PSP was rotating clockwise from a position in front of Australia by the Eocene times [18, 26, 61]. We generally accept that it chopped pieces of the Australian margin and extruded some slivers toward the Banda Sea and Sulawesi [17, 60]. Starting from the Early Miocene, shortening along the Philippines is widely documented [20, 25].

DISCUSSION

The reconstructions must integrate the continental crustal blocks which have docked against Sundaland during the Mesozoic and the Cenozoic [15] and the subsequent extension of the Sunda margin [26, 28]. Along the Vietnam and China margins, the respective location of the Cretaceous magmatic arc, the Yenshanian deformation zone, the Proto South China Sea, and the Celebes Sea have often been treated separately and could be included in a simple scenario fitting the whole of SE Asia. The simple reconstruction presented above allows us to discuss the geodynamic options for an otherwise complex system.

The connection between Tethys and the “Yenshanian basin” (T-SCS)

The most critical and unresolved issue concerns the position of blocks and terranes and the geometries and dimensions of former oceanic basins in the middle of the Cretaceous to the Paleocene, particularly in front of Vietnam and southern China, and partly in the Western Philippines. Most of the region is covered by a widespread volcanic arc. There is no trace of a Mesozoic suture zone to the West of the arc, so the subducted crust would have headed westward from the East. The subducted crust was, therefore, older than the arc and is commonly referred to as the Paleo-pacific. However, at that time, the area was also located near or at the eastern termination of the Tethys. Therefore, the selected reconstruction of Figure 2 implies that a crustal block that presently underlies Palawan Island, the Luconia Platform in the South China Sea, also includes crustal fragments in Mindanao (Daguma Range and Zamboanga) [62].

This configuration is primarily based on the location and timing of the magmatic belt and the age of the former Yenshanian mountain range [7, 43, 56]. Unfortunately, from the Paleogene to Mid Miocene, the range has suffered a critical collapse and stretching, so its topography has been obliterated. However, the configuration is well documented in Indonesia, from Southern Kalimantan to Central Java [14, 15, 34, 52]. It suggests an early Late Cretaceous docking of a crustal block originated from the Australian margin [18, 47]. To the west of the Sunda margin, the suture zone may exist, but only patches of ophiolite are reported, such as in Nias island offshore Sumatra [63]. However, these relics of the ocean floor are always considered to represent the easternmost part of the Tethys. Therefore, the reconstruction of Figure 2 suggests a possible link between the Tethys and a disappeared basin located above the present-day SCS. We consider that the deformation zone which borders the granitic Schwanner

Mountains province was a trench-trench transfer zone during the Early Cretaceous, which became a transfer zone during the accretion of the Mesozoic blocks by the late Early Cretaceous. Remarkably, the timing of the closure of the oceanic domain, which could correspond to the Tethys, was coeval in eastern and western Sunda [28, 34, 50], although migration of ages possibly corresponding to a scissor-shape closure was proposed by Advokaat et al., (2018) [63]. Similarly, the timing of collision is around the early Late Cretaceous and was followed by an episode of subduction-related extension.

The Proto South China Sea and the Celebes Sea

The other debated issue is the presence, the location, and the closure of the PSCS. The oldest ages of the PSCS are Albian to Eocene and therefore post-date the Cretaceous magmatic arc. Indicators of the PSCS are documented in NW Borneo, where oceanic sediments of PSCS basin origin have been scrapped off. The PSCS was located south of the Yanshanian deformation zone and likely formed in a back-arc setting. After the Argo block collided with Sundaland, causing the Sunda subduction to jump to the South [64], the East of Sundaland became an active margin compatible with the development of back-arc basins such as PSCS and the Celebes Sea. However, some reconstructions [18] place the Celebes Sea in the western part of the Philippine Sea Plate (PSP). The seafloor age of these two basins is similar, but the Philippine Sea Plate was moving fast toward the North at that time, thus leaving little space for a connection between the PSP and Sundaland.

As for the PSCS, the difficulty is the scarcity of the occurrence of pieces of the ancient Sea floor. As mentioned before, the Cretaceous ages are known in NW Borneo and Palawan, but they may not be directly connected. In addition, some indicators of Cretaceous fragments may also exist in the Zambales massif of Western Luzon, although most of the ages are Eocene. This massif has also undergone a large displacement after the Eocene, raising doubt about its exact position in the Eocene. The presence of both Cretaceous, Late Eocene, and Early Oligocene ages in Palawan [65] also indicates that the structure of the PSCS may be more complex than previously thought. Seismic lines east of the coast of Palawan in the NW Sulu Sea suggest a continuation of the ophiolite of Palawan with part of the offshore NW Sulu basin.

The genetic correlation between the PSCS and the SCS

The idea that a correlation exists between the SCS opening and the PSCS closure is not new but lacks solid evidence. Several unconformities in the SCS [6, 13, 19] may be correlated with Borneo and Palawan changes in sedimentation styles. Recently, a detailed review of these events was presented [19], which concludes with the following evolution. The rifting of the SCS started early in the Latest Cretaceous and the Paleocene, and the PSCS was located south of the stretching area. During the Eocene and the Oligocene (45-23 Ma), the subduction initiated in Borneo and Palawan and is coeval with extension by low angle normal faults documented in the SCS. Although the PSCS subduction started in the Central part of Borneo, it accelerated in the North by the time of the SCS breakup (33 Ma). By the Early Miocene (23-16 Ma), a ridge jump to the South took place, allowing the expansion of the seafloor to propagate toward the SW until 16 Ma [58, 66]. At 16 Ma, the PSCS completely disappeared, and the collision peaked in NW Borneo. The slab pull of the subduction created the opening of the SE Sulu Sea basin. It was only after 16 Ma that intense adakitic magmatic activity started in Borneo and a little in N Palawan, probably related to a slab breakoff [10, 11, 66]. If the subduction of the PSCS is responsible for the opening of the SCS, it requires a rifting within the downgoing plate [1, 5, 18, 27]. This mechanism is not common and does not exist presently on Earth but is often invoked in older orogens, such as the closure of the Tethys in Eastern Europe [67].

CONCLUSION

The transition from opening to the closure of the SE Asian basins is driven by the combined northward motion of Gondwana-derived continental blocks ending with India, Australia, and the rapid rotation of the Philippine Sea Plate. The beginning of the closure may correspond to the "bacon-slicer mechanism" of the collision of Australian blocks [67]. The collision of India started both the extrusion of Indochina and South China bock [29, 30], but the long-lasting subduction of the Indian Ocean pulled the upper plate toward the Southeast [28]. The basins and ridges formed then were later shortened from the Early Miocene to the Present. This configuration leaves the appearance of a complex system, which can actually be unraveled in several key steps.

The simple reconstruction exercise presented in this paper suggests solutions that had not been stated previously, such as the possible connection between the Tethys Ocean and an oceanic domain between the PSCS and the coastal regions of China and Vietnam (T-SCS). The PSCS developed in the southern vicinity of this ancient margin, probably in a back-arc position, and the SCS opened partly as a result of the subduction of the PSCS.

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