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RESEARCH LETTER

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Slab Pull Driven South China Sea Opening Implies a Mesozoic Proto South China Sea

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Key Points:

- The slab pull such as the one of the Proto South China Sea (PSCS) may drive spreading within the continental margin of the lower plate
- Simulations show that the PSCS domain must be stronger than the China continental margin in order to localize the breakup on the continent
- A minimum Cretaceous age is required for at least part of the PSCS oceanic lithosphere

Supporting Information:

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

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Abstract Most paleo-reconstruction models agree that the South China Sea (SCS) opens within a continental domain located at the trailing edge of the subducting plate of a vanished ocean named Proto South China Sea (PSCS). Existing models do not agree on the age, size, and location of the putative oceanic domain, thus hindering the reconstruction of the plate circuit in the distant past. In this study, we test the relevance and implication of the opening of the SCS in the downgoing plate with a series of thermomechanical simulations which appear to impact the possible age of the PSCS. Our findings suggest that the oceanic domain must be stronger than the continental margin for the slab pull force to be transmitted to the continental margin, resulting in continental breakup. Our simulations support a Cretaceous age, rather than an Eocene, for at least part of the PSCS sea-floor spreading.

Plain Language Summary Most scientists agree that the South China Sea formed within the China margin through the subduction of an ancient oceanic plate, known as the Proto South China Sea (PSCS), beneath Borneo. Today, this oceanic plate has nearly vanished from the Earth's surface. Only a few scattered fragments found on the islands of Borneo and Palawan confirm its existence. The history of an ocean that no longer exist can be approach by physically driven models. In this study, we use numerical simulations of subduction zones to evaluate the mechanical conditions required for the PSCS subduction to be responsible of the South China Sea formation. We find that the subduction of old oceanic plate are more likely to generate new basin opening within continental margin. Combining our results with the limited age derived from the remaining fragments of the PSCS seafloor, we propose that this oceanic plate formed at least 65 million years ago, probably around 100 million years.

1. Introduction

The South China Sea is a well-documented marginal basin that formed during the mid-Oligocene to Early Miocene period within the Sundaland, a continental promontory of the Eurasian plate in Southeast Asia (Hall & Morley, 2004). Thanks to the amount of geophysical and geological data collected in the SCS area since the 1980s, its opening has been accurately reconstructed, starting from the Eocene continental rifting period to the Present. Seafloor spreading began in the eastern sub-basin at 33 Ma (Briaies et al., 1993; C.-F. Li et al., 2014), with a north-south opening direction. From 23.6 to 21.5 Ma, the breakup propagated toward the southwest sub-basin (C.-F. Li et al., 2014), with the opening direction changing by 15° (Sibuet et al., 2016). Finally, from 23.5 to 16 Ma (Briaies et al., 1993), the southwest sub-basin opened with a spreading rate of 4 cm/yr (C.-F. Li et al., 2014), until the southern margin of the SCS collided with Borneo.

Although a previous modeling study (F. Li et al., 2020) assumed that the SCS is formed in back-arc basin position based on tomography (Wu & Suppe, 2018) and found that is it possible to break a small block of the active margin if the subduction is kinematically forced to retreat, the southward vergence of the thrusts observed within the NW Borneo accretionary wedge (Figure 1) strongly suggest that the opening of the South China Sea occurred within the downgoing plate (Aurelio et al., 2014). This prism comprises Cretaceous to Early Miocene sediments (Rajang and Crocker formations) that were accreted during Oligocene to Mid-Miocene times supporting the existence of a southward dipping slab below Borneo from the Mid-Eocene (45 Ma) (Hall et al., 2008) to the Mid-Miocene (16 Ma) (Chang & Pubellier, 2023). This slab is attributed to a pre-existing oceanic domain known as the Proto South China Sea (PSCS), which occupied the position of the present-day South China Sea during the initial half of the Cenozoic.

However, uncertainties remain regarding the plate configuration of the region prior to the Middle Eocene, particularly concerning the spreading stage of the PSCS. This putative oceanic domain is first mention in

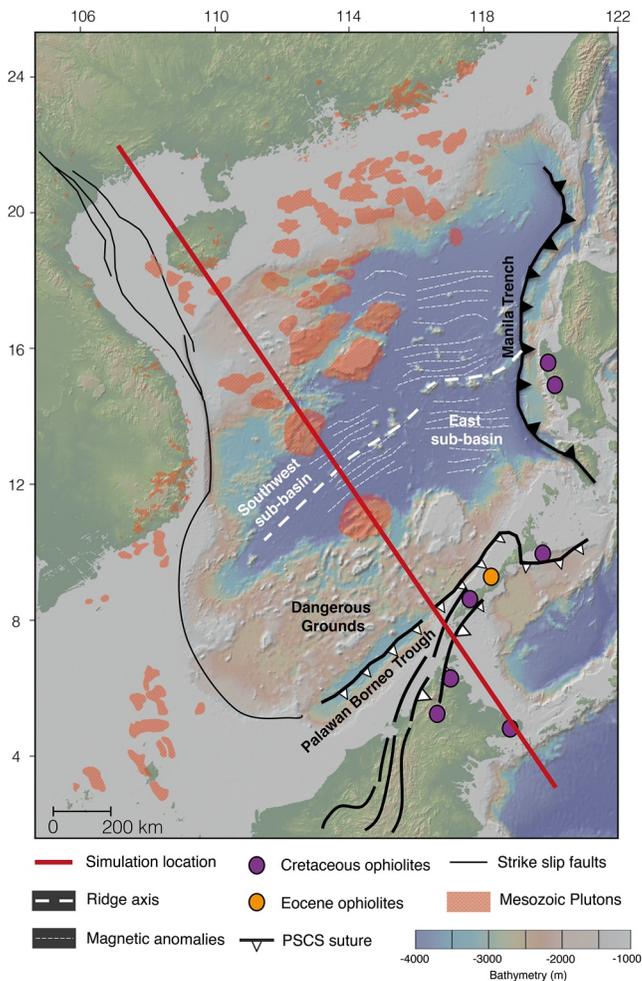


Figure 1. Map of the SCS. Magnetic anomalies reveal a SCS diachronous opening within the China margin. In the southwest sub-basin seafloor spreading started at 24 Ma and stopped at 16 Ma. The basin opened while the PSCS was subducting, as recorded by the West Borneo accretionary wedge and related ophiolite fragments. The dominant south-dipping thrusts within the prism suggest that the PSCS subduction is directed toward the south, beneath Borneo island. Bathymetry data from Ryan et al. (2009), magnetic anomalies from Briais et al. (1993) and mesozoic plutons from Pubellier et al. (2018).

the 90s (Hall & Breitfeld, 2017; Hinz et al., 1991) as a Mesozoic oceanic domain (Rangin et al., 1990). Since then, geochronological analyses were conducted in the region to estimate the age of formation of rocks within the ophiolitic complex. These confirm the presence of late Upper Cretaceous oceanic crust fragments in the north of Borneo and the south of Palawan (Dycoco et al., 2021), but also reveal much younger Eocene fragments in the central part of Palawan (Dycoco et al., 2021; Keenan et al., 2016) (Figure 1). Based on this discrepancy, recent studies proposed a two-step opening of the PSCS, with a first late Upper Cretaceous rifting stage and a second Eocene spreading phase in a back-arc context of Indo-Australian plate north-dipping subduction (Dycoco et al., 2021). In global paleo-reconstruction models (Matthews et al., 2016; Müller et al., 2019; Torsvik & Cocks, 2016), the opening of the PSCS is estimated to have occurred around 65 Ma, which is younger than Cretaceous ages given by the radiolarites and magmatic rock attributed to the PSCS from Palawan and NW Borneo.

This study aims to enhance our understanding of the spreading history of the PSCS. Assuming and as supported by the structural evidence that the South China Sea opened within the downgoing plate, we employ 2D thermo-mechanical simulations to assess the force balance in the Sundaland region during the Oligocene period. Our objective is to estimate the range of age of the PSCS required for the slab pull force to be transmitted to the continental margin and contribute to the opening of the South China Sea.

2. Methods

The simulations are using the open-source pTatin2d code, which solves non-linear viscosity Stokes flow coupled with energy conservation (May et al. (2015); See Supporting Information S1 for equation details), erosion-sedimentation processes (Jourdon et al., 2018), and thermodynamics-based density prediction. The details of thermodynamic calculations, including thermodynamic database list of solid solution models and bulk rock compositions, can be found in Supporting Information of Larvet et al. (2022). The simulation domain corresponds to the vertical N150 cross-section outlined in Figure 1, spanning 2,700 km in the horizontal direction and 900 km in depth with a grid discretized into 480 by 96 elements (Figure S1 in Supporting Information S1).

Assuming that the SCS opening occurred within the lower plate, the PSCS mid-oceanic ridge is deemed extinct when the southward subduction of the PSCS begins. To initiate this subduction, a convergence rate needs to be

applied to the system. From a previous study, we know that basal shear between the lower plate continental lithosphere and the underlying asthenosphere prevents the localization of the deformation within the lower plate (Larvet et al., 2022) which means that the velocity gradient between both should be zero. In the present study, we have chosen to work in stable China reference frame and therefore to apply the convergence to the upper plate to reduce the size of the model domain. We provide a simulation in the reference frame of Borneo with a fixed upper plate in Supporting Information S1 data to show it yields identical outcome but a larger model domain is needed to capture the dynamic of the subducting slab.

We systematically vary the age of the PSCS oceanic lithosphere (from 5 to 60 Ma Figure S2 in Supporting Information S1), the surface heat flux of the China continental margin (60–85 mW/m², Figure S2 in Supporting Information S1), and the convergence rate imposed on the southern part of Borneo (from 1 to 3 cm/yr) to assess the influence of each of these factors on the force balance. The velocity applied to the boundaries of the tectonic plates does not reflect the subduction velocity as the slab sinking rate is mostly governed by the slab pull force. It only represents the convergence rate between the two continent and is keeping slow as showed by the paleorecon-

struction models. In total, the results of 26 simulations are presented. The name of each simulation reflects these key parameters: (a) the surface continental heat flow, (b) the age of the oceanic domain, and (c) the velocity of the upper plate (Table S1 in Supporting Information S1).

The best constrained event in the history of the SCS is the continental break-up, which occurred at 24 Ma in the southwest sub-basin at the central location of the cross-section (Figure 1). We use this age as a reference to establish the temporal correspondence between the simulation time and geological time. We utilize the predicted age of the PSCS subduction initiation and the spreading rate of the SCS to determine which set of parameters best matches the geological record. We halt the interpretation of the simulations at the onset of continental collision between Dangerous Grounds and Borneo because the compressive forces recorded in the upper plate of the subduction simulation are artificial and reflect the use of kinematic boundary conditions to impose convergence (Figure S4 in Supporting Information S1).

3. Results

3.1. Continental Versus Oceanic Breakup

The occurrence of lower plate breakup is a recurring observation in all of the simulations. In most cases, the event is instigated by a density jump that emerges as the subducting slab tip reaches a depth of 410 km, which is associated with the wadsleyite to olivine mantle phase transition ($\Delta\rho = +100 \text{ kg/m}^3$). However, in simulations where the lower plate continent has relatively weaker mechanical properties (i.e., initial heat flux $\geq 75 \text{ mW/m}^2$), the increase in density resulting from the eclogitization of the oceanic crust can trigger the continental rifting at

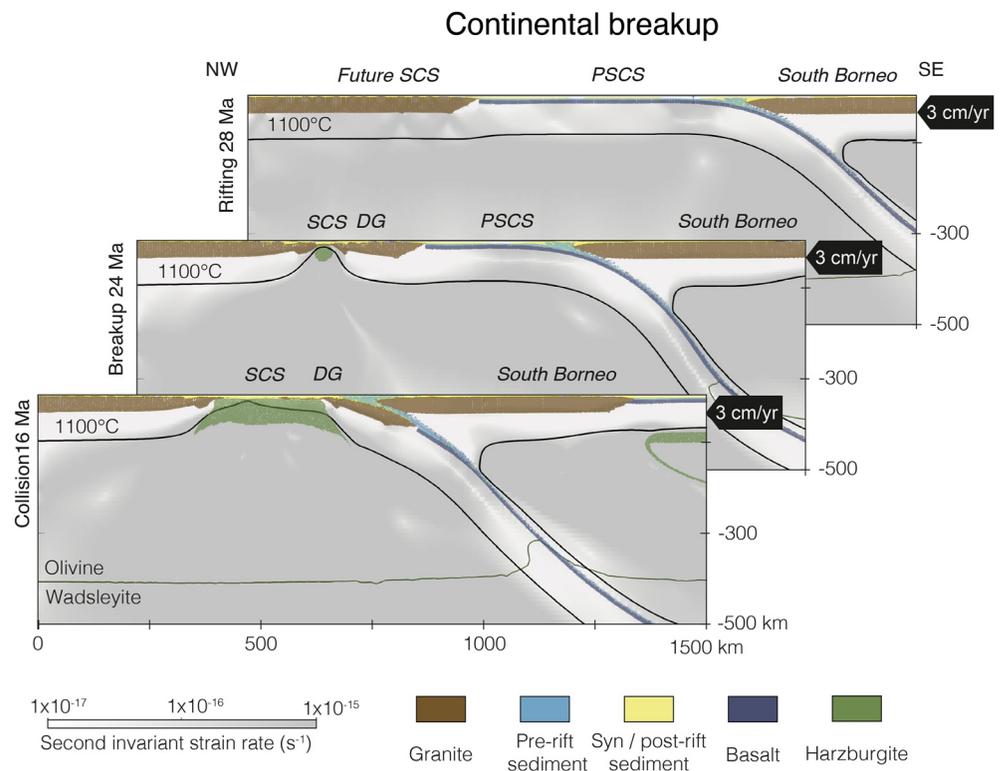
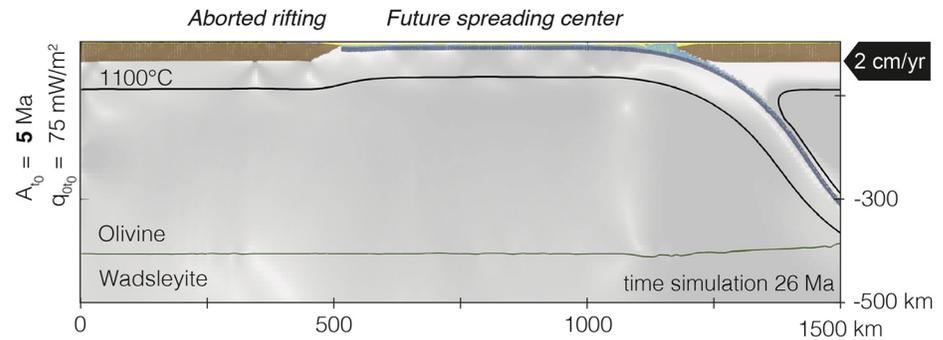


Figure 2. Series of screenshot zooms showing the evolution of the deformation in a simulation with continental breakup (70a30v3). The velocity imposed on the upper plate is represented by the black arrow on the right side. Rifting onset is shown by the large necking zones (gray area) which develops within the continental margin of the lower plate when the slab tip reaches the mantle phase transition. The rift zone rapidly evolves toward an active spreading center, as attested by the formation of depleted mantle rocks (green area), and the formation of a micro-continent that drift toward the subduction zone until it collides with the upper plate. For reasons of visibility, the figure shows an enlarged view of the fracture zone. The entire simulation can be seen in the films supplied with the article.

A. Aborted rift



B. Oceanic breakup

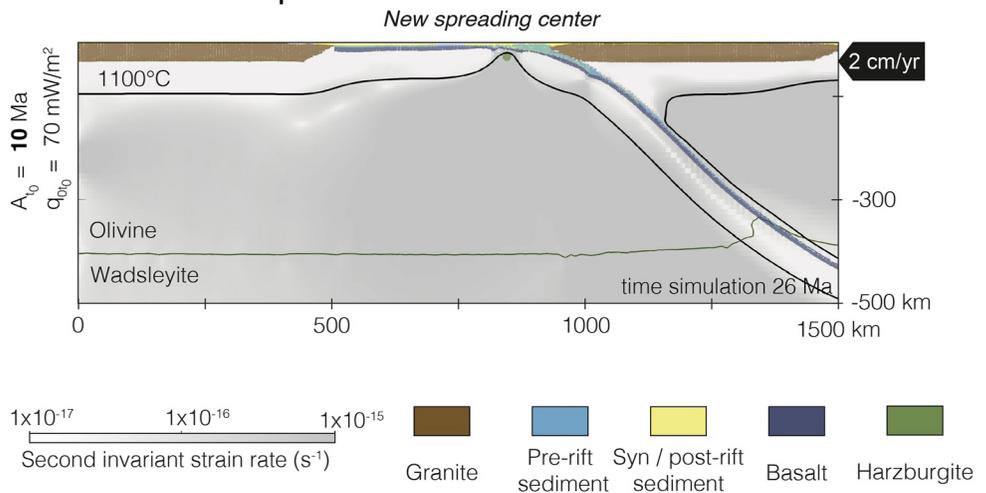


Figure 3. Screenshot zoom of a simulation with an aborted continental rift followed by an oceanic breakup (75a5v2) and oceanic breakup (70a10v3). Deformation is shown in gray. The velocity imposed on the upper plate is represented by the black arrow on the right side.

an earlier stage. More details about the respective role of eclogitization and mantle phase transitions is given in Figures S6 and S7 in Supporting Information S1.

The nature of the deformation observed depends on the relative strength of the continental and oceanic domains when the slab pull force exceeds the lower plate strength. Three distinct patterns of deformation can be identified:

1. In the scenario where the continental plate is weaker than the oceanic domain, a rift zone forms within the continental margin, which is then followed by a breakup phase. Subsequently, a microcontinent detaches and migrates toward the trench until it ultimately collides with the continent of the upper plate (Figure 2). The size of the micro-continent varies depending on the length of the China margin. If the China margin is less than 500 km long, the micro-continent's size is around 250–300 km. If the China margin is longer, the size is around 500–600 km (See Figure S5 in Supporting Information S1).
2. If the oceanic and continental domains exhibit comparable strength, both domains undergo deformation. An aborted rift zone typically develops in the continental margin, before the deformation eventually localizes in the oceanic domain and creates a new spreading center (Figure 3a).
3. When the continental domain is stronger than the oceanic domain, the breakup typically occurs in the oceanic domain, near the trench. In this case, a new spreading center emerges before it is eventually subducted beneath the upper plate (Figure 3b). Consequently, the continental margin does not undergo deformation.

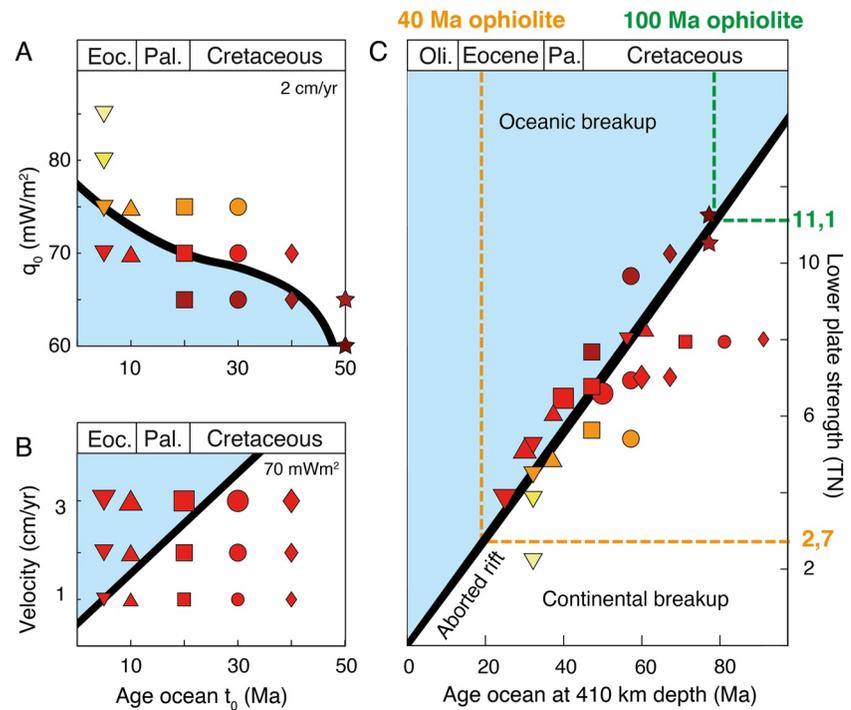


Figure 4. Synthesis of the 26 simulations that indicates the location of the breakup in the lower plate, based on the input parameters (a) and (b) and the predicted lower plate strength when the slab pull reaches the lower plate yield strength (c). See the methods online for details on how the strength is calculated. Color coded as a function of the continental initial heat flow (a). Symbol coded as a function of the oceanic lithosphere initial age (a) and (b). Size coded as a function of the velocity imposed on the upper plate (b).

3.2. What Factors Control the Force Balance Prior to Breakup?

In the simulations, for a constant rate of convergence, the strength of the continental and oceanic domains of the lower plate during the breakup process depends primarily on two factors: the initial surface heat flow of the continental domain and the initial age of its oceanic domain (Figure 4a). However, Figure 4b highlights that lower convergence rates more likely cause continental breakup than oceanic breakup. Lower convergence rates increase the duration of the subduction initiation leaving more time for the lower plate to age thermally, that is, to cool down and thicken. Mechanical decoupling (Burov & Diament, 1995) together with radiogenic heat production render the strength of the continental domain less dependent on aging than the strength of the oceanic domain which increases faster with time. If we account for the effective strength of the lower plate and the effective age of the oceanic domain when the slab tip reaches the mantle phase transition at 410 km depth to project all the simulations as in Figure 4c, the limit between the oceanic breakup and continental breakup becomes a simple linear relationship.

Once the lower plate is broken, the slab is free to sink under its own weight. However, this period of slab-pull-driven subduction is short-lived. As soon as the slab begins to interact with the lower mantle transition zone at a depth of 670 km, it stagnates due to the increase in viscosity of the surrounding mantle and the endothermic ringwoodite to bridgmanite transition. As a result, the slab-pull force becomes less efficient than the convergence rate at driving the subduction and extension in the lower plate decelerates.

4. Discussion

4.1. Convergence and Plate Strength Influence on the PSCS Subduction Timing

The timing of events related to subduction initiation and final closure of the PSCS varies significantly with the convergence rate imposed on the upper plate (Figure 4a) and, to a lesser extent, with the lower plate strength

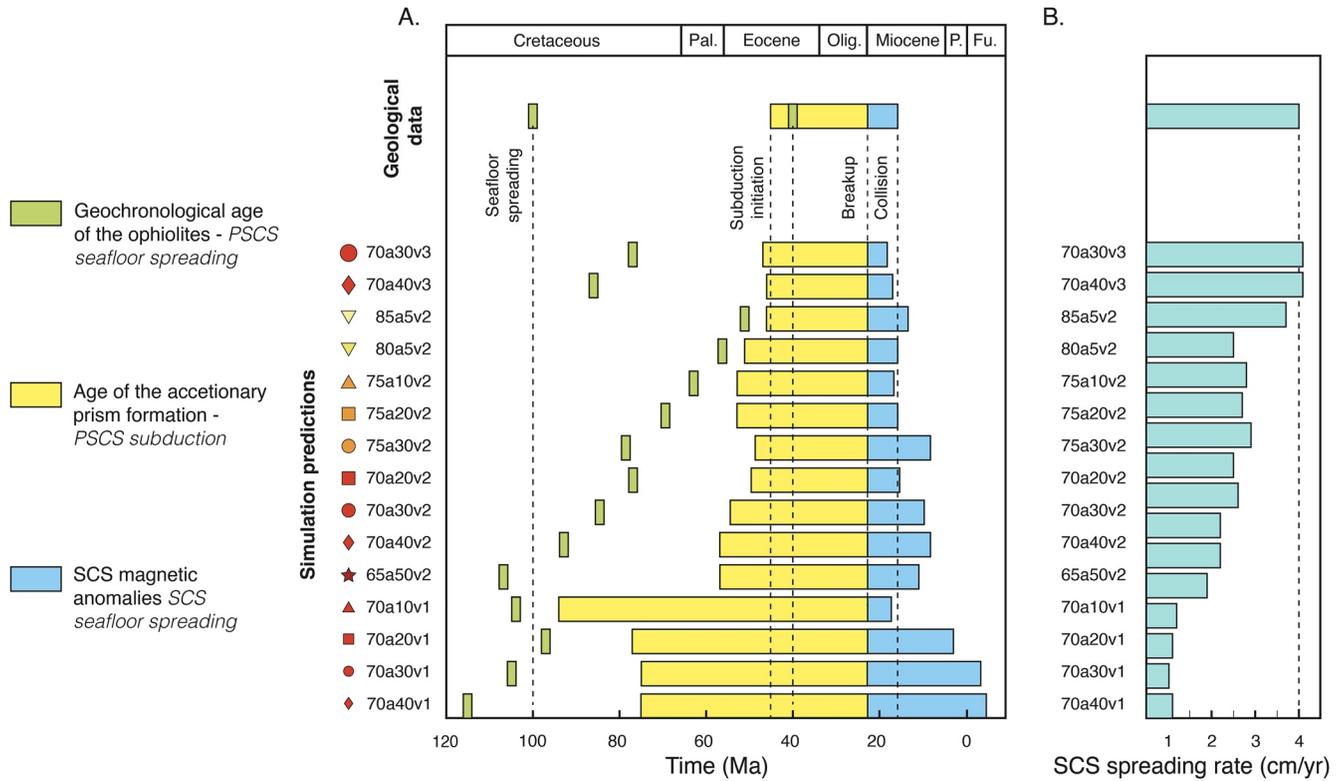


Figure 5. Comparison between geological data at the top and predictions of numerical simulations. The duration between the PSCS subduction onset and the complete closure of the ocean (collision) is mainly controlled by the velocity of the upper plate. Best match is obtained with 3 cm/yr (a). The age of the PSCS has a minor influence on the timing of the SCS opening, mainly by affecting the SCS spreading rate at the onset of opening (b).

and age of the subducting plate (Figure 4b). Moreover, these secondary effects can be easily taken into account to delimitate the outcome of simulations with a linear relationship between plate strength and the age of the subducting oceanic plate (Figure 4c and extended data). Simulations with a convergence rate of 1 cm/yr predict an ongoing period of subduction starting in the Cretaceous period, while simulations with a 2 cm/yr convergence rate are closer to the data (Figure 5a), but the rate of opening of the SCS is lower than suggested by magnetic anomalies (Briais et al., 1993). Furthermore, PSCS subduction starts slightly earlier, around 50 Ma instead of 45 Ma (Hall et al., 2008). Simulations with a 3 cm/yr convergence rate best fit the geological record and show the initiation of the PSCS subduction below Borneo around 47–46 Ma, followed by a rifting stage within the continental China margin, continental breakup, and detachment of the Dangerous Grounds continental micro-block, which then drifted southward until collision with Borneo around 17–18 Ma (Figure 2 and Table S1 in Supporting Information S1).

4.2. Implications for the SE Asia Configuration Prior Mid-Eocene

The mechanism of slab pull-related continental breakup depends on both the age of the subducting oceanic lithosphere and the strength of the continental margin. However, determining the exact strength of the margin at the time of SCS opening is challenging. Nevertheless, our study can help resolve the debate regarding whether the PSCS opened during the Cretaceous, Cenozoic, or in two stages. We demonstrate that a Cretaceous PSCS can easily breakup a continental margin with a strength of up to 11.1 TN (Figure 4c). In contrast, an active spreading center within the PSCS that is parallel to the trench during the Eocene would only lead to the formation of the SCS if the strength of the China margin before the breakup is lower than 2.7 TN.

Although the presence of Mesozoic magmatic arc relics and ophiolite fragments in the region (Wang et al., 2022; Zhou & Li, 2000) (Figure 1) suggests a relatively warm inherited thermal structure of the China margin when the PSCS began to subduct, 2.7 TN is an extremely low value for the strength of a continental tectonic plate. Therefore, the scenario of an Eocene PSCS transmitting the slab pull force to the continental margin is highly unlikely.

Regarding the two-stage opening scenario, which is the only one that can explain the age of the ophiolite fragments outcropping in Palawan and Borneo, an Eocene spreading center within the PSCS cannot be excluded, but its direction must not be parallel to the trench to allow the transfer of the PSCS slab pull force to the continental margin and generate the SCS opening within the continental margin of the downgoing plate.

Our 2D study focuses on the Southwest Sub-basin, where the opening event is cylindrical and monophasic. While the findings of this study about the PSCS age can be extrapolated to the eastern part of the South China Sea, this region has a more complex geological history: A first basin opening in the north part at 33 Ma followed by a ridge jump associated with a change of opening direction since 24 Ma (C.-F. Li et al., 2014). This phenomena has been attributed to either the rotation of Borneo (Chang & Pubellier, 2023) or the presence of compressive forces along the west boundary (Jourdon et al., 2020; Le Pourhiet et al., 2018) and require 3D modeling. Nonetheless, we can comment on the lateral variation in the dimensions of the Dangerous Grounds. We show that the distance between the continental breakup and the Continent Ocean Boundaries (COB) of the lower plate in our simulation is controlled by the length of the Chinese margin prior the breakup. If the margin measures 500 km in length, the resulting continental breakup forms a micro-continent spanning 250–300 km in length. Conversely, when the margin extends to a length of 1,000–1,500 km, the resulting micro-continent measures 500–600 km in length (see Figure S5 in Supporting Information S1). Present-day global strength maps (Tesauro et al., 2013) reveal a significant contrast between the southwest and east portions of the Chinese lithosphere, with the southwest exhibiting lower strength. This strength variation can be traced back to the influence of India's indentation into Eurasia, which is prior and during the onset of rifting in the South China Sea, impacts the western region of China (Tapponnier et al., 1982) and can explained why the Dangerous grounds is larger in the west (Figure S5 in Supporting Information S1) compared to the east (Figure S5 in Supporting Information S1).

5. Conclusion

We present a 2D numerical model of the South China Sea formation and confirm that the slab pull of the Proto-South China Sea subduction can trigger the opening of the South China Sea within the lower plate providing that the PSCS domain is stronger than the China margin during the breakup time. Knowing that both Cretaceous and Eocene ages exist for the PSCS ophiolites, this result suggests that the spreading starting at least during the Mesozoic. Our research further highlights the powerful capabilities of numerical modeling in establishing temporal constraints, particularly in situations where geological records are limited or absent.

Data Availability Statement

The version of pTatin2d and the input files used in this contribution are archived following the findability, accessibility, interoperability, and reuse principle (May & Le Pourhiet, 2023).

References

- Aurelio, M. A., Forbes, M. T., Taguibaio, K. J. L., Savella, R. B., Bacud, J. A., Franke, D., et al. (2014). Middle to Late Cenozoic tectonic events in south and central Palawan (Philippines) and their implications to the evolution of the south-eastern margin of South China Sea: Evidence from onshore structural and offshore seismic data. *Marine and Petroleum Geology*, 58, 658–673. <https://doi.org/10.1016/j.marpetgeo.2013.12.002>
- Briais, A., Patriat, P., & Tapponnier, P. (1993). Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of Southeast Asia. *Journal of Geophysical Research*, 98(B4), 6299–6328. <https://doi.org/10.1029/92jb02280>
- Burov, E. B., & Diament, M. (1995). The effective elastic thickness (T_e) of continental lithosphere: What does it really mean? *Journal of Geophysical Research*, 100(B3), 3905–3927. <https://doi.org/10.1029/94jb02770>
- Chang, S.-P., & Pubellier, M. (2023). Rifting and seafloor spreading in the South China Sea: A subduction-related extension on the down-going plate? Under review in *comptes rendus geoscience*.
- Dycoco, J. M. A., Payot, B. D., Valera, G. T. V., Labis, F. A. C., Pasco, J. A., Perez, A. D., & Tani, K. (2021). Juxtaposition of Cenozoic and Mesozoic ophiolites in Palawan Island, Philippines: New insights on the evolution of the Proto-South China Sea. *Tectonophysics*, 819, 229085. <https://doi.org/10.1016/j.tecto.2021.229085>
- Hall, R., & Breitfeld, H. T. (2017). Nature and demise of the proto-South China Sea. *Geological Society of Malaysia (GSM)*, 63, 61–76. <https://doi.org/10.7186/bgsm63201703>
- Hall, R., & Morley, C. K. (2004). Sundaland basins. Continent-ocean interactions within East Asian marginal seas (pp. 55–85).
- Hall, R., van Hattum, M. W., & Spakman, W. (2008). Impact of India–Asia collision on SE Asia: The record in Borneo. *Tectonophysics*, 451(1–4), 366–389. <https://doi.org/10.1016/j.tecto.2007.11.058>
- Hinz, K., Block, M., Kudrass, H. R., & Meyer, H. (1991). Structural elements of the Sulu Sea, Philippines. *Geologisches Jahrbuch. Reihe A, Allgemeine und regionale Geologie BR Deutschland und Nachbargebiete, Tektonik, Stratigraphie, Paläontologie*, 127, 483–506.

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- Jourdon, A., Le Pourhiet, L., Mouthereau, F., & May, D. (2020). Modes of propagation of continental break-up and associated oblique rift structures. *Journal of Geophysical Research: Solid Earth*, *125*(9), e2020JB019906. <https://doi.org/10.1029/2020jb019906>
- Jourdon, A., Le Pourhiet, L., Petit, C., & Rolland, Y. (2018). Impact of range-parallel sediment transport on 2d thermo-mechanical models of mountain belts: Application to the Kyrgyz Tien Shan. *Terra Nova*, *30*(4), 279–288. <https://doi.org/10.1111/ter.12337>
- Keenan, T. E., Encarnación, J., Buchwaldt, R., Fernandez, D., Mattinson, J., Rasoazanamparany, C., & Luetkemeyer, P. B. (2016). Rapid conversion of an oceanic spreading center to a subduction zone inferred from high-precision geochronology. *Proceedings of the National Academy of Sciences*, *113*(47), E7359–E7366. <https://doi.org/10.1073/pnas.1609999113>
- Larvet, T., Le Pourhiet, L., & Agard, P. (2022). Cimmerian block detachment from Gondwana: A slab pull origin? *Earth and Planetary Science Letters*, *596*, 117790. <https://doi.org/10.1016/j.epsl.2022.117790>
- Le Pourhiet, L., Chamot-Rooke, N., Delescluse, M., May, D. A., Watremez, L., & Pubellier, M. (2018). Continental break-up of the South China Sea stalled by far-field compression. *Nature Geoscience*, *11*(8), 605–609. <https://doi.org/10.1038/s41561-018-0178-5>
- Li, C.-F., Xu, X., Lin, J., Sun, Z., Zhu, J., Yao, Y., et al. (2014). Ages and magnetic structures of the South China Sea constrained by deep tow magnetic surveys and IODP Expedition 349. *Geochemistry, Geophysics, Geosystems*, *15*(12), 4958–4983. <https://doi.org/10.1002/2014gc005567>
- Li, F., Sun, Z., Yang, H., Lin, J., Stock, J. M., Zhao, Z., et al. (2020). Continental interior and edge breakup at convergent margins induced by subduction direction reversal: A numerical modeling study applied to the South China Sea margin. *Tectonics*, *39*(11), e2020TC006409. <https://doi.org/10.1029/2020tc006409>
- Matthews, K. J., Maloney, K. T., Zahirovic, S., Williams, S. E., Seton, M., & Mueller, R. D. (2016). Global plate boundary evolution and kinematics since the late Paleozoic. *Global and Planetary Change*, *146*, 226–250. <https://doi.org/10.1016/j.gloplacha.2016.10.002>
- May, D. A., Brown, J., & Le Pourhiet, L. (2015). A scalable, matrix-free multigrid preconditioner for finite element discretizations of heterogeneous Stokes flow. *Computer Methods in Applied Mechanics and Engineering*, *290*, 496–523. <https://doi.org/10.1016/j.cma.2015.03.014>
- May, D. A., & Le Pourhiet, L. (2023). Ptain2D [Software]. Zenodo. <https://doi.org/10.5281/zenodo.7997853>
- Müller, R. D., Zahirovic, S., Williams, S. E., Cannon, J., Seton, M., Bower, D. J., et al. (2019). A global plate model including lithospheric deformation along major rifts and orogens since the Triassic. *Tectonics*, *38*(6), 1884–1907. <https://doi.org/10.1029/2018tc005462>
- Pubellier, M., Aurelio, M., & Sautter, B. (2018). The life of a marginal basin depicted in a structural map of the South China Sea. *Episodes Journal of International Geoscience*, *41*(3), 139–142. <https://doi.org/10.18814/epiiugs/2018/018014>
- Rangin, C., Bellon, H., Benard, F., Letouzey, J., Muller, C., & Sanudin, T. (1990). Neogene arc-continent collision in Sabah, northern Borneo (Malaysia). *Tectonophysics*, *183*(1–4), 305–319. [https://doi.org/10.1016/0040-1951\(90\)90423-6](https://doi.org/10.1016/0040-1951(90)90423-6)
- Ryan, W. B., Carbotte, S. M., Coplan, J. O., O'Hara, S., Melkonian, A., Arko, R., et al. (2009). Global multi-resolution topography synthesis. *Geochemistry, Geophysics, Geosystems*, *10*(3), Q03014. <https://doi.org/10.1029/2008gc002332>
- 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>
- Tapponnier, P., Peltzer, G., Le Dain, A., Armijo, R., & Cobbold, P. (1982). Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology*, *10*(12), 611–616. [https://doi.org/10.1130/0091-7613\(1982\)10<611:petian>2.0.co;2](https://doi.org/10.1130/0091-7613(1982)10<611:petian>2.0.co;2)
- Tesauro, M., Kaban, M. K., & Cloetingh, S. A. (2013). Global model for the lithospheric strength and effective elastic thickness. *Tectonophysics*, *602*, 78–86. <https://doi.org/10.1016/j.tecto.2013.01.006>
- Torsvik, T. H., & Cocks, L. R. M. (2016). *Earth history and palaeogeography*. Cambridge University Press.
- Wang, Y., Liu, Z., Murtagh, S., Cawood, P. A., Qian, X., Ghani, A., et al. (2022). Jurassic subduction of the Paleo-Pacific plate in Southeast Asia: New insights from the igneous and sedimentary rocks in West Borneo. *Journal of Asian Earth Sciences*, *232*, 105111. <https://doi.org/10.1016/j.jseas.2022.105111>
- Wu, J., & Suppe, J. (2018). Proto-South China Sea plate tectonics using subducted slab constraints from tomography. *Journal of Earth Sciences*, *29*(6), 1304–1318. <https://doi.org/10.1007/s12583-017-0813-x>
- Zhou, X., & Li, W. (2000). Origin of late mesozoic igneous rocks in Southeastern China: Implications for lithosphere subduction and underplating of mafic magmas. *Tectonophysics*, *326*(3–4), 269–287. [https://doi.org/10.1016/s0040-1951\(00\)00120-7](https://doi.org/10.1016/s0040-1951(00)00120-7)

References From the Supporting Information

- Bouilhol, P., Magni, V., van Hunen, J., & Kaislaniemi, L. (2015). A numerical approach to melting in warm subduction zones. *Earth and Planetary Science Letters*, *411*, 37–44. <https://doi.org/10.1016/j.epsl.2014.11.043>
- Burov, E. B., & Guillou-Frottier, L. (1999). Thermomechanical behavior of large ash flow calderas. *Journal of Geophysical Research*, *104*(B10), 23081–23109. <https://doi.org/10.1029/1999jb900227>
- Connolly, J., & Petrin, K. (2002). An automated strategy for calculation of phase diagram sections and retrieval of rock properties as a function of physical conditions. *Journal of Metamorphic Geology*, *20*(7), 697–708. <https://doi.org/10.1046/j.1525-1314.2002.00398.x>
- Gleason, G. C., & Tullis, J. (1995). A flow law for dislocation creep of quartz aggregates determined with the molten salt cell. *Tectonophysics*, *247*(1–4), 1–23. [https://doi.org/10.1016/0040-1951\(95\)00011-b](https://doi.org/10.1016/0040-1951(95)00011-b)
- Magni, V., Bouilhol, P., & Van Hunen, J. (2014). Deep water recycling through time. *Geochemistry, Geophysics, Geosystems*, *15*(11), 4203–4216. <https://doi.org/10.1002/2014gc005525>
- Ranalli, G., & Murphy, D. C. (1987). Rheological stratification of the lithosphere. *Tectonophysics*, *132*(4), 281–295. [https://doi.org/10.1016/0040-1951\(87\)90348-9](https://doi.org/10.1016/0040-1951(87)90348-9)
- Rummel, L., Kaus, B. J. P., Baumann, T. S., White, R. W., & Riel, N. (2020). Insights into the compositional evolution of crustal magmatic systems from coupled petrological-geodynamical models. *Journal of Petrology*, *61*(2). <https://doi.org/10.1093/petrology/egaa029>
- Turcotte, D. L., & Schubert, G. (2014). *Geodynamics*. Cambridge university press.
- van Hunen, J., van den Berg, A. P., & Vlaar, N. J. (2000). A thermo-mechanical model of horizontal subduction below an overriding plate. *Earth and Planetary Science Letters*, *182*(2), 157–169. [https://doi.org/10.1016/s0012-821x\(00\)00240-5](https://doi.org/10.1016/s0012-821x(00)00240-5)