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Dynamic processes of the Southeast (SE) Asia convergent system and its impact on continental deformation and marginal basin formation: Preface

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ABSTRACT

Southeast (SE) Asia is situated at the convergent region between the Eurasian, Philippine Sea, and Indo-Australian plates. The dynamic interplay of these plates has shaped the geological landscape of the region, resulting in a diverse array of tectonic features, including subduction zones, volcanic arcs, marginal basins, and continental deformation. Its unique tectonic setting provides a rare opportunity to investigate the plate convergence processes and their impacts on the Earth's interior dynamics. Understanding the intricate relationships between these processes is crucial for unraveling the tectonic evolution of SE Asia and its role in the global geodynamic framework. This special issue presents a collection of original research papers covering a wide range of topics, including the lithospheric structure and strength of the SE Asia convergent system, magmatic processes and geochemical variations in subduction zones, the formation and evolution of the subduction-derived microplates, the deep genesis of heat flow anomalies, and the crustal structure and magmatism in the South China Sea. These advances have been made possible through multidisciplinary approaches, incorporating techniques such as seismic imaging, gravity analysis, numerical modeling, geochemistry, and geochronology. The findings presented in this special issue provide new insights into the complex tectonic history and geodynamic processes of the Southeast Asia and its surrounding regions.

1. Introduction

Subduction plays an essential role in the dynamics of the Earth's mantle, not only controlling the mixing of the surficial materials with those deep in Earth interior, but is also closely related to the enormous risks associated with geohazards in densely populated regions. Southeast (SE) Asia lies in the joint area of the Eurasia, Indian-Australia, and the Pacific plates, largely surrounded by subduction zones where these major plates converge from the west, south, and east, forming a curved-shaped subduction system in map view (Fig. 1). The interior of SE Asia is further complicated by internal subduction zones, such as the Molucca dual subduction zone and the Manila Trench, and a cluster of marginal basins, including the South China Sea, Sulawesi Sea et al. Simultaneously, this convergence process was accompanied by various geological responses such as crustal shortening and thickening, extensive magmatic activity, intraplate deformation, and crust-mantle interaction, which have had a profound impact on the regional geological pattern. This unique convergent environment makes the SE Asia a natural laboratory for understanding the interactions between the multiple overriding plates, the subducting slab and mantle convection (Li et al., 2021).

Decades of studies on SE Asia have greatly improved our understanding on the deep structure, deformation, material exchanges and evolution history of this convergent system. However, large uncertainties and controversies remain due to the knowledge gaps in the deep mantle structure, especially beneath the ocean basins lack of seismic experiments and petrology samples. There are also great differences in the degree of research on how the subducted materials influenced the island arc and intraplate magmatic activities. All in all, it is important yet remains unclear how the deep structure, material cycling, and thermal state inherited from the interactions between the Pacific, Indian-Australia, Eurasia Plates, or even the disappeared Neo-Tethys slabs, control the tectonics of the SE Asia.

As a growing body of dataset have been collected across the SE Asia, different fields such as geology, geochemistry, geophysics, and dynamic modeling, must be integrated for further understanding. In the current research context of SE Asian earth science, the time is ripe for summarizing the current state of knowledge in all relevant disciplines and regional fields in a special issue paper collection.

In this collection, scientists have made important progress in the dynamics of the SE Asia convergent system, the deep structure and dynamic process of the South China Sea, the Mesozoic magmatism in South China, and the destruction of the East Asian continental margin through joint efforts of multiple disciplines, including structural geology, basin research, onshore and offshore geophysics, thermochronology, numerical modeling, geochemistry, and classic field geology. In-depth and systematic research on these issues is of great scientific value for exploring the dynamic mechanisms of plate tectonics, revealing the driving processes of mantle circulation, and deepening the understanding of Earth system evolution.

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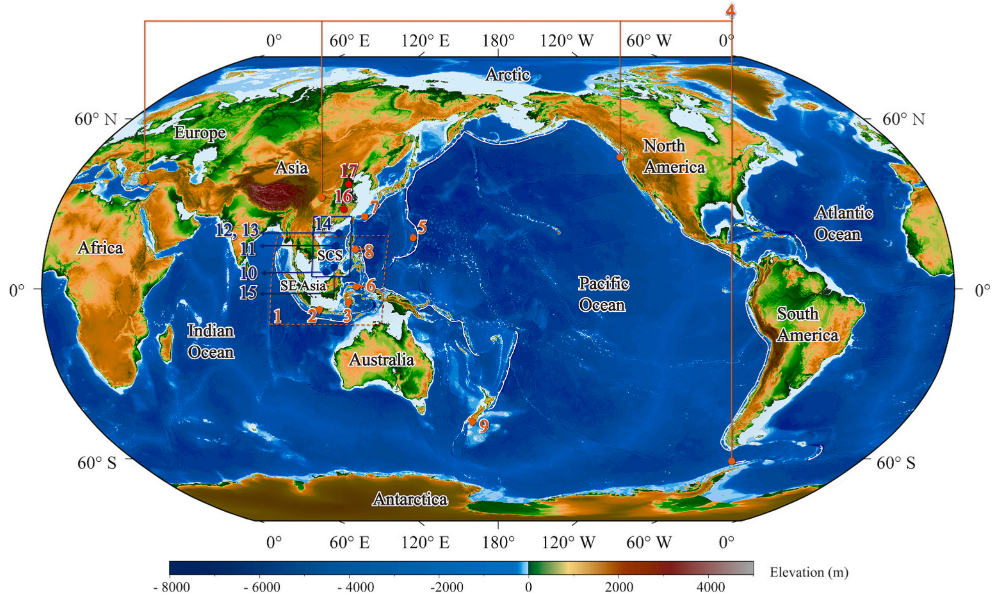

Fig. 1. Locations of all studies in this special issue.
Numbers and dots represent the following relevant papers and their research area; the orange ones indicate papers of the Southeast (SE) Asia convergent system, the orange dotted box shows the location of paper 1 below; blue ones represents the related papers of this special issue in the South China Sea, the solid blue box shows the region of paper 14; The red ones represents papers related to East Asia.
1. Liu et al., 2023a; 2. Handini et al., 2024; 3. Hsia et al., 2024; 4. Liu et al., 2023b; 5. Cheng et al., 2023a; 6. Dong et al., 2024; 7. Chen et al., 2023; 8. Austria et al., 2023; 9. Cao et al. 2023; 10. Guo et al., 2023; 11. He et al., 2023; 12. Zhang et al., 2023; 13. Yuan et al., 2023; 14. Cheng et al., 2023b; 15. Wei et al., 2024; 16. Yan et al., 2024; 17. Ma et al., 2024

2. Southeast Asia subduction system

On the lithosphere structure of the subduction zones in SE Asia, Lu et al. (2023) estimated the effective elastic thickness (Te) of the lithosphere over Southeast Asia convergent system using the free-air admittance function calculated from topography/ bathymetry and gravity data via continuous wavelet transform. They suggest that apart from temperature and composition, tectonic factors dynamically control lithospheric strength in this tectonically active region. The geothermal state seems to have limited influence on integrated strength.

Using major, trace, trace, and radiogenic isotope data, Handini et al. (2024) investigated variations in slab-derived components contributing to the magmas feeding the volcanoes arranged in a north-south transect across Central Java, Indonesia. They provide a conceptual model for differential material transfer from the subducting slab across the southeast Asian convergent margin, with implications for understanding geochemical cycling in the region.

Hsia et al. (2024) conducted a detailed petrographic, phase equilibrium modeling, and geochronological study on two garnet-epidote-glaucophane schist samples from the Bantimala Complex of Western Sulawesi, Indonesia. They interpreted the peak metamorphism occurred in the Early Cretaceous before 125 Ma by $40_{Ar}/39_{Ar}$ dating yielded, which is probably caused by the subduction and collision between the East-Java West-Sulawesi and Sundaland blocks.

Considering the characteristics and genetic models of subduction-derived microplates, which are remnants of larger plates formed in the footwall of subduction systems, Liu et al. (2023b) divided these microplates into Subduction-derived Oceanic Microplates (SOMs) and Subduction-derived Continental Microplates (SCMs). For the SOMs off North America, oceanic crust younger than 3–4 Myr can impede subduction, leading to ridge segmentation. The authors suggest subduction zones facilitate seafloor spreading near continental margins based on spatiotemporal variation of mid-ocean ridge activity.

Dong et al. (2024) investigated the absence of arc magmatism in the young North Sulawesi subduction zone (NSS) by comparing it with the middle section of the Philippine subduction zone (MPS). The authors propose that the lack of arc magma in the NSS is due to little water influx and shallow dehydration of the subducting slab. They suggest that a long arc magma history may not be observed in the early subduction stage when the angle between a young slab and the overriding plate is small.

By investigating the deep genesis of the high heat flow anomaly in the Okinawa Trough (OT), Chen et al. (2023) analyzed the heat flow data, calculated the residual and interlayer geoid anomalies using gravity data, and studied the earthquake hypocenter distributions. They propose a preliminary model in which deep mantle upwelling material enters the upper mantle and converges with molten mantle flow caused by slab dehydration, forming two branches that feed the southern OT and the Changbai Volcano.

Based on the gravity data, Austria et al. (2023) investigated the shallow and deep crustal structure of the Macolod Corridor in the Philippines. High-density bodies were identified in the shallow and deep crust, possibly reflecting magmatic bodies. They suggest the Macolod Corridor exhibits extensional features in the shallow crust but lacks a thinned crust at depth, reconciled by magma ponding in the lower crust driving passive rifting.

Liu et al. (2023b) investigated the post-rift magma plumbing system in the northern Great South Basin, New Zealand, using high-resolution 3D seismic reflection data. The study identified igneous intrusions, including sills and dykes, that developed between ~75 Ma and ~ 58 Ma, corresponding to the spreading of the Tasman Sea and the Southern Ocean. The study explored the possible origin of post-rift magmatism and provided a detailed understanding of the post-rift magma plumbing system.

Regarding the Western Pacific subduction zone, Cheng et al. (2023b) proposed a new subduction initiation model to explain the observed forearc spreading cessation and backarc basin evolution in the Izu-Bonin-Mariana (IBM) subduction system. They conducted 2D thermo-mechanical numerical simulations incorporating the plate motion history of the Pacific Plate. The model involves two stages: 1) spontaneous subduction initiation (SSI) without imposed convergence in the first 5 Myr, leading to forearc spreading; and 2) subduction with an imposed convergence rate after 5 Myr, resulting in the cessation of forearc spreading. As the subduction continues, slab rollback induces backarc spreading, arc splitting, and the formation of a remnant arc. The study highlights the importance of considering plate motion changes in understanding the tectonic evolution of the IBM subduction system.

3. South China sea deep structure

To understand the crustal structure of the South China Sea continental margin, Guo et al. (2023) obtained the S-wave velocity structure and *Vp/Vs* ratios beneath the Liyuexi Trough in the Nansha Block of the South China Sea by processing the horizontal component data of the wide-angle seismic line. A high-velocity lower crustal layer, possibly consisting of amphibolite and related to magmatic intrusions and underplating, was identified and linked to the Zhongnan-Liyue Fault. Comparisons of crustal lithology indicate the Liyue Block is more similar to the Zhongsha Block than the Dongsha Block.

He et al. (2023) investigated the crustal structures of the Zhenbei and Huangyan seamounts in the South China Sea using seismic refraction and wide-angle reflection data. They found that the original oceanic crust is characterized by a thin lower crust, thick upper crust, and low crustal velocity compared to typical Atlantic oceanic crust, reflecting reduced magma supply and intense tectonic fracturing during the late stages of seafloor spreading.

Zhang et al. (2023) present a new high-resolution wide-angle seismic velocity model across the northern continental margin of the South China Sea. A High-velocity lower crustal layer up to 10 km thick is found below the Yunli uplift and oceanward margin, indicating magmatic underplating. The authors favor a model where the lithospheric mantle broke up prior to the crust in the SCS, with mantle breakup occurring at ~43–38 Ma based on stratigraphic relationships and volcanic rock dating.

Based on a wide-angle reflection/refraction profile in the mid-northern South China Sea (SCS) margin, Yuan et al. (2023) use forward and inverse modeling to obtain the detailed crustal structure. A high-velocity layer is observed at the base of the crust, interpreted as *syn*-rift magmatic underplating. The COT zone is determined to be ~20 km wide based on crustal structure, sedimentary sequence, and gravity anomaly.

Cheng et al. (2023b) used ambient noise surface wave tomography to study the lithospheric velocity structure of the South China Sea (SCS) basin. The results indicate that the Zhongnan fault zone is a lithospheric-scale fault that played a role in regulating the expansion of the SCS basin from the East Subbasin to the Southwest Subbasin. Additionally, a low-velocity body extending from the post-spreading seamounts on the ocean crust to the uppermost mantle (about 10–30 km) was found in the north flank of the Southwest Subbasin, suggesting oblique magma migration during post-spreading volcanism.

Wei et al. (2024) present a seismic study of the deep crustal structure of the Nansha Trough (NT) in the South China Sea using wide-angle reflection and refraction data. A thinned continental crust in the east and a probable oceanic crust in the west of the Nansha Trough. Velocity models reveal crustal differences between the seamounts. The authors infer that the seamounts formed through multiple stages of magmatism following the spreading of the South China Sea, suggesting the Nansha Trough remains magmatically active.

4. East Asia Mesozoic tectonics

To investigate the Mesozoic tectonic evolution of East Asia, Yan et al. (2024) present new geochronological and geochemical data for the Danguanzhang granitic pluton in the South China. Compilation of published data reveals three distinct episodes of Mesozoic magmatism in the interior South China Block, which differ from the typical flat-slab subduction scenario. They propose that the interior South China Block underwent complex deep dynamic processes in the Mesozoic, involving prolonged flat-slab subduction and unique slab rollback caused by slab break-off and foundering in the central part of the subducted slab.

Ma et al. (2024) studied inherited zircons from Early Cretaceous dykes across the Jiaodong Peninsula in eastern China to explore the continental crustal evolution in this region. The ancient zircon records confirmed the Mesoarchean juvenile crust in the Jiaodong. Negative $\varepsilon_{Hf}(t)$ values confirmed few additions of subduction material to the Mesozoic crust. The authors suggest the continental crust in Jiaodong thickened rapidly as the Paleo-Pacific Plate subducted directly beneath the lithospheric mantle and had little contact with the lower crust in the Mesozoic.

5. Conclusion and perspective

As a highly complex and convergent geological system, extensive geophysical and geochemical research has been conducted on the deep dynamics of the SE Asia. We appreciate the contributions of all authors and the valuable comments from reviewers, which has greatly deepened our understanding of the material circulation, formation, and evolution processes. However, large uncertainties and controversies remain in our understanding of the SE Asia convergent system due to knowledge gaps in the deep structure, especially the deep mantle. This is because most of the passive source seismic data used to determine velocity anomalies in the upper mantle were recorded by land-based seismic stations, and direct constraints on the upper mantle seismic structure beneath vast ocean basins, such as the South China Sea, are still lacking. There are also significant differences in the degree of research on various regions and magmatic activities within the SE Asia, as well as a lack of unified understanding of rock origin, magmatic source regions, dynamic mechanisms, and tectonic settings. Important questions remain unanswered, such as whether island arc or intraplate magmatism is the primary response to subduction, how different subduction angles and subducting plates control island arc and intraplate magmatic activity, and whether post-spreading magmatism in marginal seas is the result of mantle plume activity or subduction-induced mantle flows.

Future research on the SE Asia convergent system should focus on its deep mantle structure, magmatic response mechanisms, material circulation flux, and mantle convection patterns. This will require multidisciplinary collaboration in geology, geophysics, and geochemistry on land, as well as deep-sea seismic observations and comprehensive studies of the basement and seamounts in the multi-island sea areas of SE Asia.

Declaration of competing interest

None

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