Hainan mantle plume produced late Cenozoic basaltic rocks in Thailand, Southeast Asia

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Intraplate volcanism initiated shortly after the cessation of Cenozoic seafloor spreading in the South China Sea (SCS) region, but the full extent of its influence on the Indochina block has not been well constrained. Here we present major and trace element data and Sr-Nd-Pb-Hf isotope ratios of late Cenozoic basaltic lavas from the Khorat plateau and some volcanic centers in the Paleozoic Sukhothai arc terrane in Thailand. These volcanic rocks are mainly trachybasalts and basaltic trachyandesites. Trace element patterns and Sr-Nd-Pb-Hf isotopic compositions show that these alkaline volcanic lavas exhibit oceanic island basalt (OIB)-like characteristics with enrichments in both large-ion lithophile elements (LILE) and high field strength elements (HFSEs). Their mantle source is a mixture between a depleted Indian MORB-type mantle and an enriched mantle type 2 (EMII). We suggest that the post-spreading intraplate volcanism in the SCS region was induced by a Hainan mantle plume which spread westwards to the Paleozoic Sukhothai arc terrane.

After the cessation of Cenozoic seafloor spreading (32–16 Ma)1–4 of the South China Sea, intraplate volcanism almost simultaneously affected large areas in the South China Sea region, e.g., the Pearl River Mouth Basin (PRMB)5, Leiqiong Peninsula6–11 and the Beibu Gulf12–14 in the northern margin of the SCS, the Indochina Block15–25, the Reed Bank and Dangerous Grounds26,27, and the SCS basin itself28–30 (Fig. 1). The OIB-like geochemical characteristics of the volcanic rocks are distinct from those associated with Late Cenozoic subduction related lavas from the Luzon arc east of the Manila trench31,32 and northeast Borneo (southeast of the Nansha trough/NW Palawan trough)29,33 (Fig. 1). Thus, the Manila trench and Nansha trough can be considered as eastern and southern boundaries, respectively, of the region affected by the intraplate volcanism34. However, the western extent of the intraplate magmatism is uncertain, as Tengchong35, Myanmar36 and possibly the western part of Thailand have been continuously affected by the subduction of the Indian plate beneath the Eurasian plate during the Cenozoic Era. Therefore, the geodynamic settings of several late Cenozoic volcanic centers in western Thailand need to be better constrained.

The geodynamic setting of the intraplate volcanism in the SCS region is still debated. Far field effects of the India-Asia collision may not only play a significant role on the Cenozoic tectonic evolution of the SCS region (e.g., the opening of the SCS)23,37, but also facilitate the upwelling of a Hainan mantle plume38,34. Moreover, the Hainan mantle plume has been invoked to account for the intraplate volcanism along the northern margin of the SCS9,10,12–14, in southern Vietnam25 and in the SCS basin28–30. Similar to other localities in the SCS region, the late Cenozoic intraplate volcanism of the Indochina block has also been suggested to have formed in an extensional tectonic setting15–25. Previous studies of Indochina Block Cenozoic volcanism indicate that the mantle source can be largely explained by a two mantle end-members mixing model, involving depleted Indian MORB-type mantle and enriched mantle type II (EMII)9,10,23,25. For the origin of EMII, early studies proposed an origin from the sub-continental lithospheric mantle (SCLM)20,23, but recently several studies on late Cenozoic volcanism in the SCS region related the enriched component to a mantle plume8,11,25,28,30,38. In order to clarify the geodynamic setting of Indochina block Cenozoic volcanism, we obtained new Hafnium isotope data as well as major- and

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trace element and Sr-Nd-Pb isotope ratios of late Cenozoic volcanic lavas from Thailand (Indochina block). These data are combined with other published data for the Indochina block and the whole SCS region and are used to constrain the petrogenesis and mantle source nature of late Cenozoic volcanic lavas from Thailand and their deep mantle geodynamic process.
Geological setting and sampling details

Thailand and the surrounding region can be divided into three tectonostratigraphic units: a western Sibumasu block (Sino-Burma-Malaya-Sumatra, a middle Sukhothai arc terrane and an eastern Indochina block hosting the Khorat Plateau. These three terranes are separated by two Paleo-Tethys sutures. The western suture is the Chiangmai-Chanthaburi suture and includes Middle Devonian to Middle Triassic radiolarian cherts and deep oceanic sediments. The other suture is the back-arc Nan-Uttaradit Sra Kaeo suture which is composed of disaggregated Paleozoic ophiolites and melanges. Both the Sibumasu block and the Indochina block have Precambrian basalts, and were part of the India–Australia margin of eastern Gondwanaland in the Early Paleozoic. These two blocks, together with the SCS region, have been affected by the Tethys tectonic regime during the late Paleozoic to early Mesozoic period, and subsequently by the Pacific ocean tectonic regime during the late Mesozoic. In addition, two major Cenozoic strike-slip faults (Mae Ping fault and Three Pagodas fault) cut through the western part of Thailand.

The seventeen volcanic rock samples of this study were collected from 11 basaltic flows close to the Chiangmai-Chanthaburi suture and within and around the Khorat Plateau and Changthaburi suture (Fig. 2). From two basaltic flows close to the Chiangmai-Chanthaburi suture, we collected two basaltic rock samples (with phenocrysts of olivine (Fo = 82.9–84.5, clinopyroxene (Wo = 48.7, En = 40.0, Fs = 11.2) and plagioclase (An = 58.8–60.6)) from small outcrops in the Sop Prap basaltic flow (2.3–2.4 Ma) that covers an area of 70 km², and two basaltic samples (with phenocrysts of olivine (Fo = 83.3–90.7) and plagioclase (58.2–66.4)) from small outcrops in the Mae Tha basaltic flow (0.6–0.8 Ma) that extends over 120 km² (Supplementary Dataset Table 1). From the western margin of the Khorat Plateau, we collected three basalt samples (with olivine (Fo = 76.2–81.8) and plagioclase phenocrysts (An = 56.1–60.6) and microphenocrysts) from the Wichian Buri basaltic flow (8.8–11.0 Ma) that covers an area of 200 km² (Supplementary Dataset Table 1). Twelve basalt samples were collected from small outcrops of eight dispersed basaltic flows within the Khorat Plateau including Na Khon Ratchasima (1400 km², 0.9 Ma), Khao Kradong (120 km², 0.9 Ma), Surin (55 km², 0.9 Ma), Phu Naoan (23 km², 3.3 Ma), Si Sa Ket (74 km², 3.3 Ma), Khao Pha Nom Rong (20 km², 0.9 Ma), Prai Bat (6 km², 0.9 Ma), and Phu Phra (90 km², 0.9 Ma) (Supplementary Dataset Table 1). The rocks collected from the plateau show porphyritic textures and contain sparse phenocrysts of olivine (Fo = 60.1–84.6), clinopyroxene (Wo = 39.7–45.7, En = 41.9–45.6, Fs = 9.0–13.9) and plagioclase (An = 46.5–63.8), and some microphenocrysts in the groundmass. The ages of the volcanic rocks range from 0.4 to 11 Ma, and these samples can be distinguished into two groups by their ages, one is relatively older basalts with ages of 8.8–11.0 Ma, the other is younger ones with ages younger than 3.3 Ma (Supplementary Dataset Table 1).

Analytical methods

For our study, a volume of 10–25 cm³ of basaltic samples was trimmed of vein fillings and alteration rinds in order to obtain the freshest material. The samples were leached in 4 N nitric acid for 3 hours to remove surface contamination, and crushed into 0.5–1 cm³ chips in a stainless steel mortar and pestle, rinsed in distilled water and dried twice. Several of the freshest chips from the interior of each sample were separated for Pb isotopic analysis. The remaining samples were powdered in an alumina ceramic shatterbox.

Major and trace element analytical methods. Major elements for all samples were determined by X-ray fluorescence (XRF) spectroscopy at the Testing Center of Shandong Bureau, China Metallurgical Geology Bureau (TC-SB-CMGB). Samples powders were fused with lithium metaborate-lithium tetraborate, which includes an oxidizing agent (lithium nitrate), and then poured into a platinum mould. The resultant disk was analyzed by the XRF spectroscopy. Loss on ignition (LOI) of samples was measured at 1050°C, and after drying at 100°C. Trace element compositions were measured using an inductively coupled plasma-mass spectrometer (ICP-MS), also at the TC-SB-CMGB. The precision of the XRF is ±1 wt% (SiO₂, Al₂O₃, and CaO) and about ±2% for major elements present in concentrations >1 wt% (SiO₂, Al₂O₃, TiO₂, and P₂O₅). The precision of the ICP-MS for trace elements is better than 10%, and these samples can be distinguished into two groups by their ages, one is relatively older basalts with ages of 8.8–11.0 Ma, the other is younger ones with ages younger than 3.3 Ma (Supplementary Dataset Table 1).

Sr-Nd-Pb-Hf analytical methods. Sr-Nd-Hf isotopic ratios were measured using Neptune Plus multi-collector ICP-MS (MC-ICP-MS) at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The procedure for Sr-Nd-Hf isotopic analytical methods is the same as those described by Wei et al., Liang et al., and He et al. Normalizing factors used to correct the mass fractionation of Sr and Nd during the measurements are ⁸⁶Sr/⁸⁸Sr = 0.1194 and ¹⁴⁴Nd/¹⁴⁴Nd = 0.7219, respectively. The measured ¹⁷⁶Hf/¹⁷⁷Hf ratios were normalized to ¹⁷⁶Hf/¹⁷⁷Hf = 0.7235, and are reported adjusted relative to the standard JMC-475 with a ¹⁷⁶Hf/¹⁷⁷Hf = 0.282160. Reference standards were analyzed along with samples and give ⁸⁶Sr/⁸⁸Sr = 0.710266 ± 7 (2σ) for NBS987, ¹⁴⁴Nd/¹⁴⁴Nd = 0.512105 ± 6 (2σ) for JNd1-18, and ¹⁷⁶Hf/¹⁷⁷Hf = 0.282186 ± 4 (2σ) for JMC475.

Pb isotopic ratios were measured using a high resolution (Nu Instruments Ltd, Wrexham, North Wales, UK) multi-collector inductively coupled plasma- mass spectrometer at the Key lab of Marine Sedimentary and Environmental Geology, State Oceanic Administration, China. Details of the Pb separation procedure are presented by Janney and Castillo. The Pb standard NBS 981 was used to correct the measured isotopic ratios of samples for isotopic fractionation and the average correction was 0.1% per atomic mass unit. Procedural blanks were <0.5 ng for Pb. During the analysis, NBS981 standard yielded an average value of ²⁰⁶Pb/²⁰⁴Pb = 16.9382, ²⁰⁶Pb/²⁰⁴Pb = 15.4935, and ²⁰⁸Pb/²⁰⁶Pb = 36.7255.
Analytical Results

Major and trace element compositions. Bulk rock major and trace element compositions are reported in Supplementary Dataset Table 1. Loss on ignition (LOI) values of the samples range from 0.16 to 2.71 wt. %, which are due to variable amounts of secondary hydrous/altered minerals. After major oxides analyses recalculated to 100% on an H₂O and CO₂⁻ free (basically represented by LOI in this study) basis, all samples were plotted on a plot of total alkalis (Na₂O + K₂O) versus silica (SiO₂) (Fig. 3). In Fig. 3, samples plot into the fields of trachybasalt, basaltic trachyandesite, basalt (CHC-2 from the Na Khon Ratthasima basaltic flow the Mae Tha basaltic flow) and basanite, and all other samples belong to the alkaline lava series (Fig. 3).

The samples have a wide range in MgO (4.09–9.38 wt. %), with Mg# values of 43.9–67.7, and abundances of compatible trace elements (Ni = 58–240 ppm, Co = 26–50 ppm, Cr = 97–346 ppm) (Supplementary Dataset Table 1), that are too lower than those for partial melts from peridotite mantle (Mg# > 70, Ni > 400–500 ppm, Cr > 1000 ppm; see literature). Relative to those younger samples, the older ones from Wichian Buri basaltic flow have highest MgO and Mg#. In the correlation diagrams of Mg# versus other oxides, CaO/Al₂O₃ and trace elements (Sc, Cr) decrease with decreasing Mg# to 43.9, and increasing SiO₂ (Fig. 4a), FeO t (Fig. 4b), Al₂O₃ (Fig. 4c), TiO₂ (Fig. 4d), and a decreasing trend in CaO/Al₂O₃ (Fig. 4h), Sc (Fig. 4i) and Cr (Fig. 4j). There is no co-variation between Mg# and CaO, Na₂O and K₂O (Fig. 4e,g).

Several samples from the Paleozoic Sukhothai arc terrane exhibit light rare earth element (LREE) enrichment ([La/Yb]N = 12.2–13.2) with no Eu anomaly (Fig. 5a) and similar to those from the Kohrat plateau ([La/Yb]N = 6.7–24.0) (Fig. 5b) on the plots of chondrite-normalized REE patterns. In primitive mantle-normalized trace element diagrams, samples from both the Paleozoic Sukhothai arc terrane and the Kohrat plateau are generally enriched in large ion lithophile elements (LILEs) and high field strength elements (HFSEs, e.g., positive Nb-Ta anomaly), although samples from the Sukhothai arc terrane have slightly higher concentrations of LILEs than those from the Kohrat plateau (Fig. 5c,d). In general, these alkaline lavas from Thailand are similar to those reported from previous studies on late Cenozoic volcanic rocks from Thailand and Vietnam and are typical oceanic island basalts (OIBs) with (La/Yb)N = 12.35.

Sr-Nd-Hf-Pb isotopic compositions. The Sr, Nd, Hf, and Pb isotopic compositions for the Thailand basalitic rocks are listed in Supplementary Dataset Table 2 and shown on several isotopic correlation diagrams (Figs 6 and 7). Age correction was not applied because the samples are relatively young (majority of them < 3.3 Ma, Supplementary Dataset Table 1), and measured isotopic ratios can be regarded as their initial ratios (i.e., no effect from radiogenic ingrowth). The Sr, Nd, Hf and Pb isotopic ratios for these samples are as follows, ⁸⁶Sr/⁸⁸Sr = 0.70356–0.70588, ¹⁴₃Nd/¹⁴₄Nd = 0.51267–0.51297 (Nd = +1.7 to 5.7), ¹⁷⁶Hf/¹⁷⁷Hf = 0.28294–0.28312 (CHF = +4.0 to 10.9), ²⁰⁶Pb/²³⁸U = 18.204–18.587, ²⁰⁷Pb/²³⁸U = 15.540–15.613, and ²⁰⁸Pb/²³⁸U = 38.193–38.646 (Supplementary Dataset Table 2). In the ¹⁴₃Nd/¹⁴⁴Nd versus ⁸⁶Sr/⁸⁸Sr correlation plot (Fig. 6a), all alkali samples from Thailand have consistent plots with data from previous studies on late Cenozoic basaltic rocks from the Indochina block and of OIB. Moreover, the samples have slightly more variable Sr and Nd isotope ratios than samples from the northern margin of the SCS, and of OIB. In the ¹⁷⁶Hf/¹⁷⁷Hf versus ¹⁴₃Nd/¹⁴⁴Nd diagram (Fig. 6b), all samples in this study plot in the field of OIB and cover a range that is slightly larger than that of Vietnamese basalts. There is a positive correlation between Hf and Nd isotopes, suggesting that these two isotopic systems are coupled. In the Sr–Pb, Pb–Pb diagrams, all alkali samples from Thailand also plot within the Indochina block and OIB fields (Fig. 7) as well as within or close to the field of the SCS itself and the northern margin of the SCS.
Discussion

Petrogenesis of late Cenozoic basaltic rocks from Thailand. Possible continental crustal contamination?

Because the primary mantle magmas of Thailand volcanic rocks must pass through the continental crust before erupting on the surface, crustal contamination may play a significant role in their petrogenesis. Intraplate volcanic centers are widely dispersed within the Indochina block (Fig. 2), and we have collated the most recent data for these intraplate volcanic rocks from the literature. In Figs 8 and 9, our data overlap with previously published data. There is no positive correlation between Mg# and 87Sr/86Sr or negative correlation between Mg# and 143Nd/144Nd or 176Hf/177Hf, which suggests a minimal role of continental contamination. Furthermore, the trace element ratios of these samples do not reflect any effects of continental contamination (Fig. 10). For example, Nb/...
Ta ratios (5.3–18.8, with average value of 14.9) and Zr/Hf ratios (37.8–45.8, with average value of 41.3) are close to primitive mantle (Nb/Ta = 17.5 ± 0.5 and Zr/Hf = 36.27) and obviously higher than those of continental crust (7.6–18.5, with an average value of 12.2), and Nb/U ratios (33.8–52.6, with average value of 44.5) are mostly higher than those of primitive mantle (Ce/Pb ≈ 9 and Nb/U ≈ 30) and close to those of oceanic basalts. In Fig. 10, our new data plot outside the field of continental crust but within the field of basalts from the Indochina block and northern margin of the South China Sea, that are bracketed by primitive mantle and oceanic island basalt compositions. Finally, our new data, together with other published data, plot within the field defined by oceanic island basalts (OIBs) in Sr-Nd-Hf-Pb isotope diagrams (Figs 6 and 7). These characteristics suggest that continental crustal contamination has been minimal during the genesis of intraplate volcanism in the wider South China Sea region, as previously suggested for the more restricted SCS basin, Hainan Island, and the Indochina block. Some authors have however argued for a significant role of crustal contamination for Vietnamese basalts.

**Fractional crystallization.** Compared to peridotite mantle, low content of some compatible elements (Supplementary Dataset Table 1) and plots of Mg# versus other oxides, CaO/Al2O3 and trace elements (Sc, Cr) (Fig. 4), all show that the parent magma (derived from a mantle source) for late Cenozoic basaltic lavas in Thailand may have undergone fractional crystallization of mafic minerals (e.g., olivine and clinopyroxene) on route to the surface. For the younger group, with decreasing Mg#, SiO2, FeOt, Al2O3 and TiO2 decrease, CaO/Al2O3, Sc and Cr increase, and no systematic variations occur in CaO, Na2O and K2O (Fig. 4). These trends are consistent with a significant role of olivine + clinopyroxene crystallization in the magma evolution. Note that differences among samples from the same basaltic flow (e.g., Na Khon Ratchasima) may result from the variability of the parental magmas (Fig. 4). In addition, due to their highest content of MgO (and Mg# value), the older group (Wichian Buri basalts) with the oldest ages in this study can be regarded as relatively primitive magmas close to primary melts.

**Mantle end-members.** As shown in Fig. 6a, Sr and Nd isotopic compositions for late Cenozoic volcanic rocks from the Indochina peninsula show a larger variation than those from the SCS basin and the northern margin of the SCS, indicating that the mantle source beneath the former is more heterogeneous than those beneath the latter two. In Figs 6 and 7, Thailand basaltic rocks define a mixing trend between a depleted mantle end-member and a Samoa-like enriched mantle component (EMII), which is consistent with late Cenozoic volcanic rocks from the SCS basin and the northern margin of the SCS (Figs 6 and 7). In detail, except for these two younger samples (MATA-1 and CHC-1) that tap a local origin, the older samples with ages >2.3 Ma generally show more radiogenic Hf and Nd and less radiogenic Sr isotopic compositions than the younger samples (0.6–0.9 Ma) (Supplementary Dataset Table 2), which indicates that the mantle origin of basaltic rocks in Thailand may have evolved with time. As modelled in Fig. 7a, the older group have more depleted mantle end member compositions than that of the younger group, which suggests that the mantle beneath Thailand became more and more enriched with time. In general, the above characteristics show that the mantle source for the late Cenozoic
volcanic rocks from the SCS region can be explained by a simple binary mixing model. However, what are the depleted and enriched mantle end-members for the late Cenozoic volcanic rocks of Thailand?

For the depleted mantle end-member of the late Cenozoic volcanic rocks from Thailand, many scientists have proposed that it should be an Indian Ocean-type mantle, as shown on Figs. 6 and 7, because the Indian ocean-type mantle is prevalent in late Cenozoic intraplate volcanism in the southeast Asian region and the SCS region, and even widely distributed beneath the whole west Pacific region. For the enriched mantle end-member, it may be EMII (enriched mantle type II), although some scientists have proposed that EM1 showing a DUPAL Pb anomaly may be involved in the origin of a small amount of late Cenozoic volcanic rocks in southern Vietnam. Many scientists have proposed the involvement of EMII to explain the origin of post-spreading volcanic rocks from the SCS basin, the northern margin of the SCS, and southern Vietnam but the origin of EMII remains unclear.

Some scientists have proposed that the origin of EMII for late Cenozoic volcanic rocks of the Indochina block may be sub-continental lithospheric mantle (SCLM). However, SCLM, as the origin of EMII in this study, can be ruled out. Firstly, a significant Nd–Hf isotopic decoupling (resulting from fluid-driven metasomatism) can be observed for samples from the lithospheric mantle, and yet late Cenozoic volcanic rocks from Thailand lie along the Terrestrial array (Fig. 6b). Secondly, the SCLM generally shows different Hf-Nd isotopic compositions from oceanic basalts and MORB; and late Cenozoic volcanic rocks from Thailand plot within the field of the latter (Fig. 6b). Thirdly, late Cenozoic volcanic rocks from Thailand show a positive Nb-Ta anomaly (Fig. 5), and yet basaltic rocks derived from SCLM generally exhibited negative anomalies in Nb and Ta (e.g., An et al.). Thus, EMII did not originated from sub-continental lithospheric mantle (SCLM), but possibly from the Hainan mantle plume (see discussion below).
Mantle lithology and partial melting. It is important to consider lithological variations in the mantle source when trying to understand major- minor-, trace-element and isotopic compositions of basaltic rocks with no continental crustal contamination\(^6\--^7\). Partial melting experiments have shown that compositions equivalent to alkali basaltic magmas can be produced by melting garnet pyroxenite\(^6\--^8\), carbonated peridotite\(^7\), eclogite\(^7\) + CO\(_2\), and a mixture of these materials\(^7\). We have modeled the mantle lithology of late Cenozoic alkali volcanic rocks from Thailand, which are shown in Fig. 10. In addition, a batch partial melting model of garnet pyroxenite (50:45:5 garnet:clinopyroxene:orthopyroxene) alone can explain the genesis of late Cenozoic alkali volcanic rocks from Thailand (Fig. 10a,b). Relative to heavy rare earth elements (HREEs) only susceptible to melting garnet mineral in mantle source rock, light rare earth elements (LREEs) more likely reflect the extent of low degree partial melting. Additionally, we can conclude that late alkali Cenozoic volcanic rocks from Thailand can be produced by less than 15% partial melting as shown in Fig. 10a,. This result, combined with experimental petrologic data, imply that the mantle lithology of late Cenozoic alkali volcanic rocks in Thailand may be garnet pyroxenite\(^6\) already metasomatized by carbonaceous fluids (released from ancient recycled oceanic crust).

In addition, low contents of some compatible elements (Supplementary Dataset Table 1) and plots of Mg\# versus other oxides, CaO/Al\(_2\)O\(_3\) and trace elements (Sc, Cr) (Fig. 4), all show that parent magma derived from mantle source may undergo fractional crystallization of mafic minerals (e.g., olivine and clinopyroxene, etc) en route to the surface.

Tectonic significance. Tectonic setting of late Cenozoic volcanic rocks from Thailand. Except for those samples within or around the Khorat plateau that belong to intraplate basalts\(^2\) (Fig. 2), those samples from the Paleozone Sukhothai arc terrane between CCS (Chiangmai-Changthaburi paleo-Tethys suture) and NUSKS, Nan-Uttaradit Sra Kao paleo-Tethys suture\(^3\), are close to the subduction zone formed by underthrusting of the Indian plate beneath the Eurasian plate\(^4\). Thus, the tectonic setting for those samples (Mae Tha and Sop Prop) needs to be further
constrained. In the plot of Th/Yb versus Ta/Yb for discriminating tectonic setting of basaltic rocks, all samples plot in the array of basalts from non-subduction settings (e.g., MORB, and within plate basalts) and lies close to enriched mantle source (OIB-intra-plate basalts) (Fig. 11), which is consistent with previous studies for basalts from the Indochina block and northern margin of the SCS, and post-spreading, intra-plate seamounts in the SCS. The above characteristics, combined with major- and trace element and isotopic characteristics (Figs 3, 5 and 6), imply that most of samples are related to intraplate magmatism (mantle plume? See discussions below).

**Implications for deep mantle geodynamics process: Hainan plume.** The South China Sea (SCS) region located in the convergence zone between the Eurasian plate, Indo- Australian plate and Philippine Sea plate (Pacific plate). The integrated effects from the India-Asian collision, eastward rollback of the Pacific subduction zone and northern migration of the Philippine Sea Plate affect Cenozoic geological evolution of the SCS region and Southeast

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**Figure 8.** Mg# vs. $^{87}\text{Sr}/^{86}\text{Sr}$ (a), $^{143}\text{Nd}/^{144}\text{Nd}$ (b), and $^{176}\text{Hf}/^{177}\text{Hf}$ (c) isotopic ratios for late Cenozoic volcanic rocks from Thailand. Abbreviations: AFC = assimilation and fractional crystallization, and the possible contaminants is continental crust; FC = fractional crystallization. Symbols and data sources for Indochina block are the same as those in Fig. 6.
Asia, e.g., the closure of the Proto-SCS and the opening of SCS in the period 32–16 Ma. After cessation of SCS spreading, large-scale volcanism occurred in the SCS. The question then arises, what was the deep geodynamic process for the volcanism, plate tectonics or mantle plume?

Recent geophysical studies have shown that a mantle plume existed beneath Hainan Island. Seismic tomographic data indicate that a sub-vertical low-velocity column is imaged beneath Hainan Island and the South China Sea and extends from shallow depths down to the 660-km discontinuity, and even down to a depth of 1300 km, based on global tomographic modeling, further suggested a broad low-velocity anomaly can extend down to 1900 km depth. In addition, several geophysical studies have suggested that the Hainan mantle may have originated from the core–mantle boundary.

The existence of a Hainan plume has recently received support from increasing petrological and geochemical evidence. Based on calculation results for mantle potential temperatures beneath the SCS and geochemical studies...
on intraplate seamount basalts from the SCS, Yan and Shi\textsuperscript{26} and Yan et al.\textsuperscript{27} for the first time provided direct geological evidence for the presence of a Hainan plume as revealed by geophysical data.\textsuperscript{230}Th excesses in Hainan lavas imply a slowly (< 1 cm/year) rising mantle plume\textsuperscript{9}, as Montelli et al.\textsuperscript{81} suggested that it is a dying plume. Wang et al.\textsuperscript{10,11} also suggested that mantle potential temperatures beneath Hainan Island could be related to a Hainan plume. Yan et al.\textsuperscript{29} compiled petrological and geochemical data from the northern margin of the SCS, the SCS itself, and the Indochina block, and proposed that most late Cenozoic basaltic rocks from the region need an enriched end-member in the mantle source, implying the existence of a mantle plume (i.e., Hainan plume) in the SCS region. Yan et al.\textsuperscript{29} also further suggested that the plume may play a significant role on the overall Cenozoic tectonic evolution of the SCS, e.g., earlier rifted stage, subsequent seafloor spreading and later post-spreading volcanism. Details for the plume (including its duration, rifts (ridge) –plume interaction mechanism, etc) still need to be further clarified.

In particular, the question arises as to what is the western extent of the influence of the Hainan mantle plume? Considering the extensive occurrence of basaltic lava flows in SE Vietnam, Maruyama\textsuperscript{86} first proposed the idea that a Vietnamese mantle plume existed beneath Southeast Asia, and that it appeared to be verified by geological and geophysical data\textsuperscript{87}. However, many geophysicists recently challenged the above assertion and pointed out that the low velocity anomaly from the Hainan mantle may extend to southern Vietnam\textsuperscript{81,82,85}. Geochemically, Yan et al.\textsuperscript{29} suggested that late Cenozoic volcanic rocks in the Indochina block are genetically linked to the Hainan mantle plume, which is supported by recent studies of Vietnamese basalts\textsuperscript{25}. Major-, and trace element compositions, and Sr-Nd-Pb-Hf isotopic ratios for Thailand basalts in this study indicate that they may have originated from the Hainan mantle plume. In addition, the western extent of the influence of the Hainan mantle plume may reach close to part of the Chiangmai-Changthaburi paleo-Tethys suture (North of the Cenozoic Mae Ping fault) in the Paleozoic Sukhothai arc terrane (Fig. 1). We envisage a tectonic scenario for the Hainan mantle plume as similar to the model depicted by Kincaid et al.\textsuperscript{88}, i.e., a plume that ascends to the bottom of the lithosphere and then migrates along sloping rheologic boundary layers to lithospheric faults under extensional settings (e.g., reactivated paleo-sutures, spreading centers), eroding the lithosphere on its way upward (i.e., lithosphere/plume interaction) followed by eruptions at the surface\textsuperscript{25,29,30}.

**Conclusions**

In this study, we present new Hf isotope ratios, and major- and trace element concentrations, and Sr-Nd-Pb-Hf isotopic compositions of late Cenozoic basaltic lavas from Thailand. We suggested that,

1. Cenozoic basaltic lavas in Thailand are alkaline basaltic rocks and belong to a wider region of post-spreading intraplate magmatism in the SCS region.
2. Geochemically the alkaline basalts are oceanic island basalt (OIB)-like (e.g., enriched in mostly large-ion lithophile elements-LILEs and high field strength elements-HFSEs).
3. Sr-Nd-Pb isotopic compositions lay between DMM (depleted mid-ocean ridge basalt mantle) or Indian ocean-type mantle and EMII (enriched mantle type II) and imply that basalt origin can be explained by a simple binary mixture of these two mantle end-members.
4. The, EMII may have originated from the Hainan mantle plume.
5. Trace element partial melting modeling indicates that the alkaline basalts could have been produced by partial melting of garnet pyroxenite.
6. Post-spreading intraplate volcanism (induced by the Hainan mantle plume) in the SCS region extended westwards to affect the Paleozoic Sukhothai arc terrane between the Chiangmai-Changthaburi Paleo-Tethys suture and the Nan-Uttaradit Sra Kao suture.
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**Acknowledgements**

We thank Susanne Straub for her reviewing the original manuscript. Reviews by two anonymous referees are appreciated, along with editorial handling by Dan Zhu. This work was supported by the Scientific and Technological Innovation Project Financially Supported by Qingdao National Laboratory for Marine Science and Technology (no. 2016ASKJ05), the National Natural Science Foundations of China (grants no. 41776070, 4166401, 41230960, 41322036), the National Programme on Global Change and Air-Sea Interaction (nos. GASI-GEOGE-02 and GASI-01-02-01-04), Aoshan Talents Program Supported by Qingdao National Laboratory for Marine Science and Technology, Young scholar of “Shuxingbei” fund of FIO (2016501) and Taishan Scholarship from Shandong Province. IM acknowledges support from the Australian Research Council.

**Author Contributions**

Q.Y., X.S., S.L., T.X., N.K., T.S., and L.Y. conceived the experiments; Q.Y., X.S., T.X., N.K., T.S., L.Y., Y.Z., and H.Z. conducted experiments; Q.Y., and X.S., wrote the manuscript. All authors analyzed data, contributed to interpretive aspects and reviewed the manuscript.

**Additional Information**

**Supplementary information** accompanies this paper at https://doi.org/10.1038/s41598-018-20712-7.

**Competing Interests:** The authors declare no competing interests.

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