Mantle sources of Cenozoic volcanic activities around the South China Sea revealed by geochemical and isotopic data using the principal component analysis (PCA)

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1. Geological setting

Cenozoic basaltic rocks are widespread in the Southeast Asian region and occupy the SCS, Hainan Island, Fujian–Zhejiang, Taiwan, Vietnam, and Thailand (Fig. 1). These regions show evidence of a series of tectonic evolutionary processes, including rifting, subduction, terrane collision, and large-scale continental strike–slip faulting occurring via spatially and temporally complex relations (Cullen et al., 2010; Wang et al., 2012; Yan et al., 2018; Li et al., 2014a, 2014b). The SCS, one of the largest western Pacific marginal basins at the junction of the Eurasian, Indo-Australian, and Philippine–Pacific plates, is surrounded by the South China fold belt in the north, a subduction zone in the east, the Borneo Trough in the south, and the East Vietnam fault in the west (Fig. 1). Hainan Island and the adjacent Leizhou Peninsula are located at the northern edge of the SCS basin and the southeastern margin of the Eurasian plate (Fig. 1). Two volcanic eruptive styles, including massive eruptions from extensional fissures and sporadic eruptions from central volcanoes, led to the formation of massive Cenozoic basaltic flows in Hainan Island (Flower et al., 1992; Ho et al., 2000), which may be attributed to the influences of the Hainan mantle plume (Hoang and Flower, 1998; Wang et al., 2012, 2013; Yan et al., 2018) and the extension of the SCS basin (Cullen et al., 2010; Wang et al., 2012). The Zhejiang–Fujian region of SE China, which is located on the East Asiatic continental margin, shows a wide distribution of abundant Cenozoic basalts belonging to the circum–Pacific volcanic belt, including Xilong, Mingxi, and Nutoushan (Fig. 1; Ho et al., 2003; Chung et al., 1994; Smith, 1998). The Taiwan orogeny was formed by an arc–continent collision in which the buoyant passive margin of Asia underthrust the Manila Trench and collided with the Luzon Arc (Fig. 1; Lin et al., 2019), which mainly consists of five geomorphic units and three NS-trending structural belts from west to east (Tian et al., 2019). The volcanism in Vietnam mostly post-dates the mid-Miocene cessation of the SCS opening (Barr and MacDonald, 1981; Hoang et al., 1996, 2013; An et al., 2017). Large quantities of tholeiites and small amounts of alkaline basalts occupy Vietnam with an area of ca. 23,000 km^2 (Hoang and Flower, 1998; Hoang et al., 1996, 2013; An et al., 2017). Thailand and its surrounding region mainly consist of three tectonostratigraphic units, including a western Sibumasu block, a middle Sukhothai arc terrane, and an eastern Indochina block (Yan et al., 2018; Barr and Macdonald, 1987; Metcalfe, 2011, 2013). The pre-Cambrian basements beneath the Sibumasu and Indochina blocks were formerly part of the eastern Early Paleozoic Gondwanaland (Metcalfe, 2011, 2013; McCabe et al., 1988; Yan et al., 2017). Two major Cenozoic strike–slip faults, including the Mae Ping and Tree Pagodas faults, cut through the western part of Thailand (Fig. 1).

2. Discussion

2.1. Effects of the Hainan mantle plume on volcanic activities in different periods

The PC1 values of nine 0–12.6 Ma Hainan Island combined samples are consistently positive and range from 0.38 to 4.62; by contrast, the PC1 values of nineteen 4.6–33 Ma Hainan Island samples are negative (-2.66 – -0.44) (Appendix 6;

Wang et al., 2012; Liu et al., 2015). This result indicates than an enriched OIB-type mantle plume plays a more significant role in Hainan volcanic activities during the period 0–12.6 Ma than in those during the period 4.6–33 Ma. A similar phenomenon occurs in the seamounts of the SCS, the expansion center of the SCS, Zhejiang–Fujian, Thailand, and Vietnam (Appendix 6). In detail: (1) in the seamounts of the SCS, eight younger combined volcanic rocks (3–8 Ma) have high positive PC1 values in the range of 1.38–7.63, whereas, three older volcanic rocks (16.5 Ma) have relatively low positive PC1 values (0.75 –1.27) (Appendix 6; Yan et al., 2008, 2015). (2) In the expansion center of the SCS, the 3.8–12.8Ma combined volcanic samples are characterized with a high PC1 value (1.29–7.63), whereas the three older volcanic rocks (15–17 Ma) have relatively low negative PC1 values (-2.90 – -2.01) (Appendix 6; Zhang et al., 2017, 2018). (3) In the Zhejiang–Fujian region, younger 0–16.2 Ma volcanic rocks have significantly higher PC1 values (1.27–7.08) compared with three older volcanic rocks (>9 Ma), which have low positive or even negative values (-2.86 – -2.60) (Appendix 6; Huang et al., 2017). (4) In Thailand and its surrounding areas, older volcanic rocks (8.8–11 Ma) have negative PC1 values (-0.18), while younger volcanic rocks (0.6–3.3 Ma) have high positive PC1 values ranging from 0.44 to 4.62 (Appendix 6; Yan et al., 2018). (5) In Vietnam, some older volcanic rocks (7.0–16.5 Ma) have low PC1 values ranging from -1.81 to -0.51, whereas some younger volcanic rocks (0.2–9.6 Ma) have significantly higher positive PC1values (1.07–4.93) (Appendix 6; Hoang et al., 2018).

The above observations reveal that younger combined samples collected in the same area have higher PC1 values than older samples. Similar phenomena have been observed in the SCS and its surrounding areas (Appendix 6), thus indicating that the phenomenon is not accidental but, instead, quite common in our study area. We speculate that the influence of the Hainan mantle plume on the Cenozoic volcanic activity in this area gradually strengthened. Specifically, the influence of the Hainan mantle plume on nearby young volcanic activity during the period of <13 Ma is much stronger than that during the period of >13 Ma.

We used the PCA method to analyze Sr, Nd, and Pb isotopic ratios and present the PC values of volcanic rocks from the SCS and its surrounding areas (Appendix 7). (1) For the volcanic rocks from the expansion center of the SCS, 3.8–12.8 Ma SCS samples have higher PC1 compositions relative to those of 15–17 Ma SCS samples (Appendix 7; Yan et al., 2008; Zhang et al., 2017, 2018), thus suggesting that younger volcanic activities (3.8–12.8 Ma) are more affected by enriched OIB- and EM1-type mantle plumes than older volcanism (15–17 Ma). (2) The same pattern could be observed in Thailand, where relatively younger volcanic activity (0.6–3.3 Ma) is more influenced by OIB- and EM1-type mantle plumes compared with older volcanism (8.8–11 Ma; Appendix 7; Yan et al., 2018). (3) Although seamounts in the SCS and Hainan Island have positive PC1 values, they do not show obvious differences at different ages (Appendix 7; Tu et al., 1991; Li et al., 2013; Yan et al., 2008). This result may be attributed to the fact that the PC1 value calculated by isotopic ratios represents a variety of enriched isotope components (e.g., OIB- and EM1-type components); thus, distinguishing whether the volcanic activity of different ages is affected by the mantle plume is difficult. Even though relatively older volcanic rocks are not significantly affected by the Hainan mantle plume compared with younger rocks, they may still be affected by other enriched isotopic compositions.

The results of isotope PCA calculations indicate that volcanic rocks from Thailand and the expansion center of the SCS show significant age variation patterns. Relatively older volcanic rocks are subject to a smaller degree of PC1 composition (i.e., enriched OIB- and EM1-type mantle sources) compared with younger samples (Appendix 7). This conclusion is consistent with the results of trace element PCA calculations described earlier.

2.2. Spatial scope of the influence of the Hainan mantle plume on Southeast Asia

The latest geochemical studies show that the influence range of the Hainan mantle plume includes a wide region, such as Hainan Island, the SCS, Thailand, and Vietnam (Wang et al., 2012; Liu et al., 2015; Yan et al., 2008, 2015, 2018; Zhang et al., 2017, 2018; An et al., 2017; Hoang et al., 2018). This study collected trace element data of Cenozoic volcanic rocks from the above regions as well as Fujian, Zhejiang, and Taiwan. PCA and cluster analysis of the trace element data revealed that over 75% samples clustered into a sample that is highly similar to the OIB standard sample (Fig. 3). This cluster sample extends from Zhejiang–Fujian in the north to Vietnam–SCS in the south and from Thailand in the west to Southern Taiwan in the east (black cross in the Fig. S1D). The PC1 value of this cluster sample is much higher than its PC2 and PC3 values (Appendix 3). PC1 may reflect the origin of the OIB-type mantle plume as a result of the above analyses, thus, the Hainan mantle plume may be assumed to play a significant role in the volcanism of these areas and affect the geochemical characteristics of their volcanic rocks. Similar findings (black cross in the Fig. S2C) can be obtained from the PCA and cluster analysis of isotopic ratios (Figs. 4, 5).

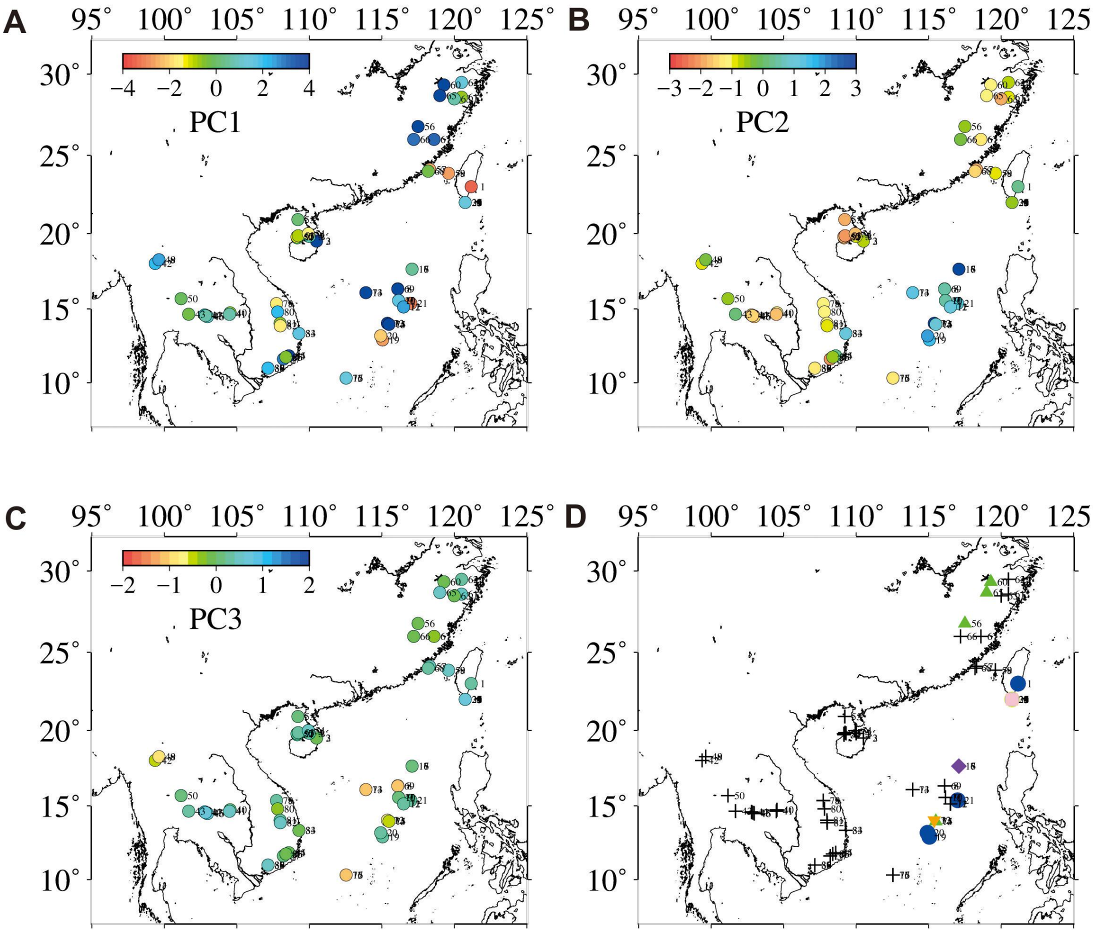

Fig. S1 The spatial distribution of <33Ma volcanic rocks from the Southeast Asian based on principal component values calculated by trace elements.

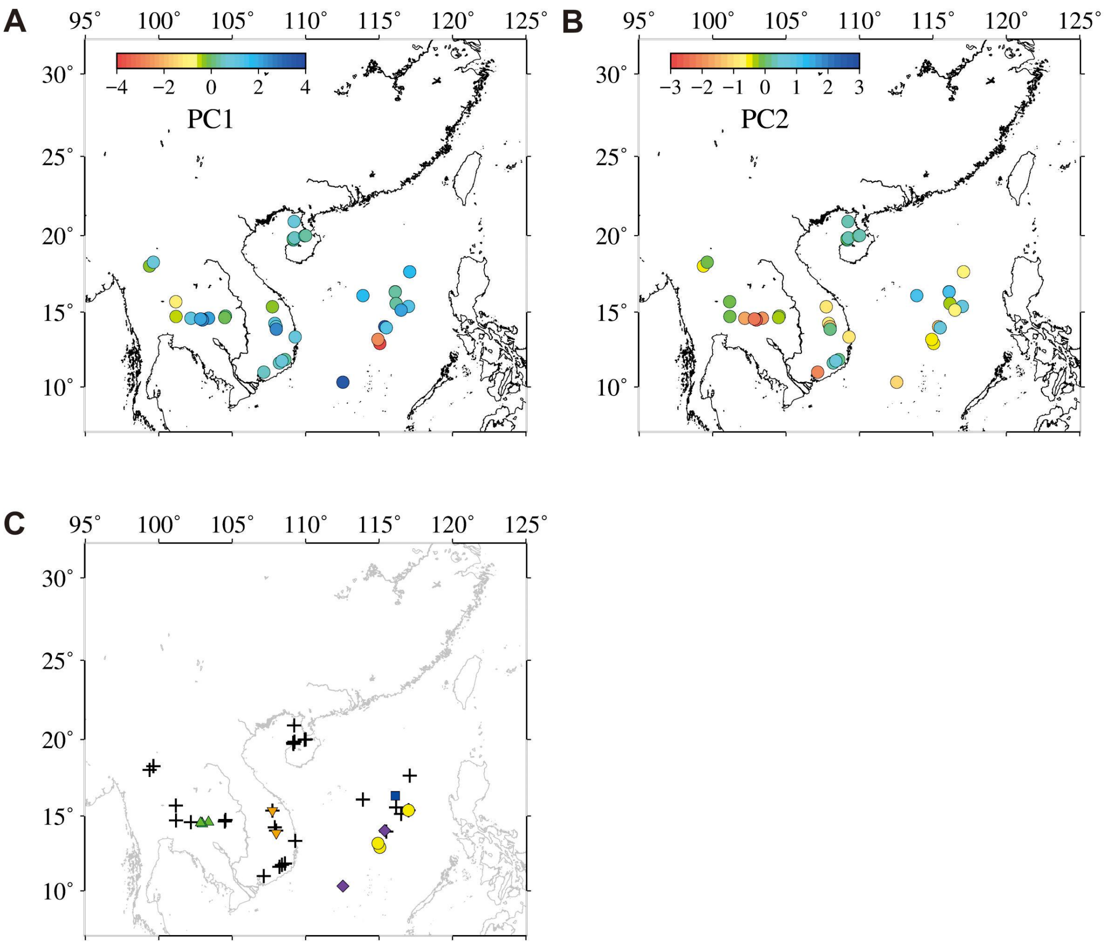

Fig. S2 The spatial distribution of <33Ma volcanic rocks from the Southeast Asian based on principal component values calculated by Sr, Nd, Pb isotopic ratios.

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