MIOCENE – PLEISTOCENE BASALTIC VOLCANISM IN THE EAST VIETNAM SEA AND NEIGHBORING AREAS: AGE, SOURCE GEOCHEMISTRY AND MANTLE DYNAMICS

Nguyen Hoang

Institute of Geological Sciences, Vietnam Academy of Science and Technology, Hanoi, Vietnam
Graduate University of Science and Technology, Hanoi, Vietnam
E-mail: hoang_geol@hotmail.com

ABSTRACT

Post- East Vietnam Sea (EVS) opening Miocene - Pleistocene basalts were collected in the coastal areas, SE continental shelf of East Vietnam Sea (EVS), elsewhere in the south-Central Highlands, as well as in the Bolaven plateau (Laos) and Buri Ram (Thailand) for study. Samples were analyzed for ages, geochemical and Sr- Nd- Pb isotopic data. The data were compared with data for syn- and post- EVS opening basalts in the EVS basin and Hainan area. Syn-EVS opening basalts (33-16 Ma) are N-MORB- like geochemically depleted Pl ±Cpx- phyric tholeiites, in contrast, post- opening basalts (ca. 15 Ma to present) are relatively enriched to highly enriched Ol- phyric tholeiites or alkaline basalts. In difference from Hainan tholeiitic, sub-alkaline to alkaline basalts that form a geochemically linear correlation, other post- opening samples from different locations in Vietnam, Laos and Thailand plot in different fields, trending between depleted and enriched mantle endmembers. Computed melting pressures based on experimental results show post-opening tholeiites were formed by melting of spinel peridotite at 1.6 – 2.5 GPa, while alkaline basalts were produced by melting of garnet peridotite sources 2.5 - 3.4 GPa. Except for Hainan samples there are no intermediate rock types observed between the post- opening tholeiitic and alkaline basalts, suggesting (1) their mantle parental sources are different, (2) post- EVS opening basalts are spatially and temporally heterogeneous.

Key words: East Vietnam Sea, collision-induced volcanism, mantle dynamics

I. INTRODUCTION

Late Cenozoic intraplate volcanism is widespread in southeast Asia, forming basalt plateaus associated with pull-apart, extensional faults. The activity shares common source isotopic and lithosphere structural character with intraplate and back-arc volcanism in the western Pacific and has been referred to as a `diffuse' igneous province. The volcanism post-dates extrusion of Indochina block (Vietnam, Laos and Kampuchea) along regional strike-slip faults following the early Tertiary India-Asia collision with concomitant opening of the East Vietnam Sea (EVS). Similar with other `diffuse' provinces, the southeast Asian volcanic activity reflects contemporaneous, rapid appearance of dispersed basalt centers, an extensional setting, and proximity to major continent-continent plate collisions. The causes of dispersed, relatively sudden mantle melting events have not been extensively discussed in the literature. Hoang and Flower [1] proposed that `diffuse' volcanic provinces may reflect

the combined effects of lithosphere transtension and asthenosphere decompression concomitant with collision-induced extrusion of thermally anomalous mantle. Initial seafloor spreading started about 33 Ma in the NE East Vietnam Sea. A southward ridge-jump of about 20 km occurred about 23.6 Ma in the East sub-basin, was coeval to the onset of seafloor spreading in the SW sub-basin (Li et al., 2014). The seafloor spreading was ceased around 15 Ma in the East sub-basin and about 16 Ma in the SW deep sea sub- basin [2, 3, 4]. Ocean drilling records show that Cenozoic volcanism in the EVS occurred in three major periods: 1) pre-opening (Oligocene – Early Miocene), 2) syn-opening (Early – Middle Miocene) and 3) post-opening (Middle Miocene – present). In the SW sub-basin discovered were basaltic layers up to 180 m thick underlain by 9 to 7 Ma sediments, and numerous submarine volcanoes as young as 3.8 Ma [2, 3].

Post-opening Middle Miocene - Present basalts were collected from the coastal areas and SE continental shelf of EVS, including the Hon Tro (Ile des Cendres) submarine volcanic area. Samples were also collected at Kham Duc, Kong Plong, Song Cau- Tuy An- Van Hoa, K' Bang – Vinh Son and other locations from Dak Nong, Dzi Linh, Duc Trong, Xuan Loc, and elsewhere in Ba Ria – Vung Tau province. Samples were as well collected at the Bolaven plateau (Laos) and in the Den Chai and Buri Ram area of Thailand. The samples were analyzed for age data, major and trace element, and Sr-Nd-Pb-Hf isotopic compositions. The data were interpreted along with syn- and post-EVS opening (IODP 349, 367/368) and Hainan post-opening basalts [5, 6, 7] in terms of mantle melting mechanism and source characteristics.

II. DATA INTERPRETATION

Syn-opening basalts are similar to mid- ocean ridge (N-MORB) tholeiitic basalts. Post-opening basalts (15 – 0 Ma), both in the EVS basin and on-land occurrences, are tholeiitic or alkaline basalts with higher $Na_2O + K_2O$ (>4 wt%, up to 7 wt%), TiO_2 (>1.6 wt% up to 3.2 wt%) as compared to the syn-opening basalts. Almost post- opening older than 6 Ma are olivine- phyric sub-alkaline basalts or tholeiites, whereas those younger than 6 Ma are mostly subalkaline or alkaline basalts. Samples from Bolaven and Thailand are tholeiitic, subalkaline or alkaline basalts, distributed in separate fields, whereas Hainan basalts, in contrast, form a successively compositional range. Likewise, rare earth element chondrite normalization patterns show gradually increasing in LREE from Hainan three basaltic rock types, while those from Thailand, Bolaven and Vietnam show no transitional rock types between the alkaline and tholeiitic basalts. Isotopically basalts from different locations and having different eruption ages plot into different fields. Compared with contemporaneous basalts from the Central Highlands (Vietnam), Laos, Thailand and the deep-sea basin of EVS, almost the Vietnam coastal and continental shelf post- opening samples are more Sr, Nd and Pb isotopically enriched. All together the syn- and post- opening basalt samples trend between

depleted mantle (DM) and enriched mantle- type 2 (EM2) and/or continental crust (CC) domains with/or without involvement of enriched mantle type 1 (EM1) (Fig. 1)

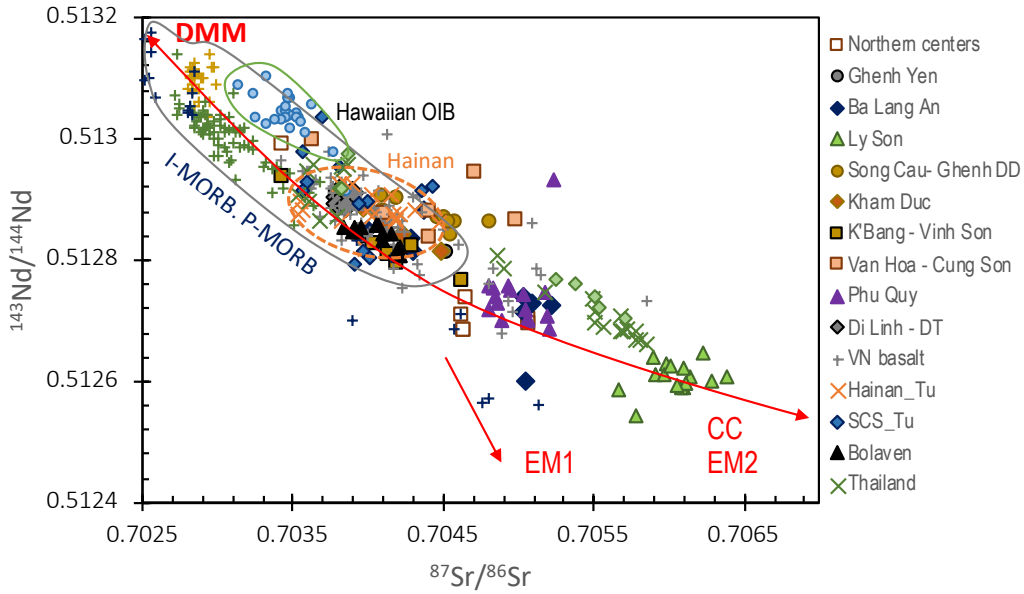

Figure 1. Correlation between $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios for post- East Vietnam sea opening basaltic magmas. Shown are data for Hainan island area [6], EVS basin [7], Bolaven and Thailand (Nguyen Hoang, unpublished) for comparison. Data for Indian and Pacific Ocean, Hawaiian oceanic island basalts are shown for reference. Domains for major isotopic endmembers are from the literature. Post-opening basalts are trending between depleted mantle to enriched continental crust and/or enriched mantle type 2 (EM2) and partially to EM1, reflecting possible binary mixing.

III. DISCUSSION

The basalt centers occupy short 'pull-apart' rift segments bounded by right lateral strike-slip faults within a broadly transtensional stress field [8]. Geochemical characteristics of post-opening Middle Miocene – Present basalts in the EVS basin and neighboring areas reveal two major eruptive episodes that reflect two major distinct mantle source domains. The earlier episode, aged between 15 and about 7-6 Ma and occurred as fissure eruption, is more voluminous forming the shield-like basement. The early phase is comprised by mostly tholeiitic and subalkaline basalt having high SiO_2, low TiO_2 and K_2O, and lower trace element concentrations. In contrast, the later volcanic episode occurred as monogenetic volcanoes showing less voluminous, is consisted mainly of subalkaline and alkaline basalt. They have lower SiO_2, higher TiO_2, and K_2O, and much higher trace element concentrations, as compared to those of the earlier episode. Isotopically, the early episode basalt shows high $^{87}Sr/^{86}Sr$: 0.7042 – 0.7055, low $^{143}Nd/^{144}Nd$: 0.51275 – 0.5126 and high $^{206}Pb/^{204}Pb$: 18.4 – 18.8 as compared to later basalt, respectively, at 0.7035 – 0.7045, 0.5129 – 0.51275, 18.1 – 18.4. Isotopic mixing modelling suggests the early volcanic rock inclines more toward lithosphere-rich source (EM2-like), whereas the later tends more to asthenosphere-rich source (EM1-like). Calculation of melting pressure based on petrologic experimental results suggested post- opening tholeiitic basalts were formed in the pressure range from 1.6 to 2.5

GPa, and alkaline basalts were produced between 2.5 and 3.4 GPa. The isotopic and geochemical compositions were interpreted to reflect interaction between depleted and refractory upper mantle-derived melts with heterogenous shallow lithospheric mantle and/or crustal material of the early episode, and the contribution of deeper, enriched (EM1-like) and fertile asthenospheric source of the later eruptive episode [9].

IV. SUMMARY

The formation of post-opening basaltic magmas in the EVS basin and neighboring areas may be explained as follows. After India- Eurasian collision-caused lithosphere extrusion and mantle uprising, the lithosphere was thinned during heating and transtension. Continuation of mantle uprising increased the temperature of overlying thinned lithosphere mantle, decreased its elasticity and gradually converted the conductive, mechanical layer into convective, thermal layer. Changes in physical and mechanical properties could create a column producing high-Si low- Mg melt at lower temperature and pressure replaced by low-Si high-Mg melt at higher temperature and pressure as hot mantle flows continued to rise with time.

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