Geochemical characteristics of Cretaceous granitoids and their implication for tectonics in Vietnam

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Abstract. Vietnam is located between the Pacific subduction zone and Tethys orogenic belt. There are numerous Cretaceous granitoids in Vietnam, belonging quartz-diorite–granosyenite–granite–leucogranite magmatic series. According to geochemical data, granitoids are sub-alkaline. Samples in SV are calc-alkalic, with lower A/CNK and (Zr+Nb+Ce+Y) values, which belong to I-type granite. And those in NV are allali-calcic, with higher A/CNK values but lower (Zr+Nb+Ce+Y) values, which belong to S-type granite. Granitoids exhibit fractionated REE patterns with negative Eu anomalies, and show enrichment in LILEs and depletion in HFSEs. Because of the absence of alkaline dark-colored minerals, abundant intermediate igneous rocks and assemblage of I- and S-type granite with orogen-related geochemical characteristics, it is believed that there was compressive structure in Vietnam in Cretaceous due to Meso-Tethyan subduction.

1. Introduction
Vietnam lies in the east of Indo-China Peninsula and to the west of South China Sea, which is between the Tethyan Orogenic belt and Pacific subduction zone. There are plenty of Cretaceous magmatic records, especially in Vietnam, which are considered as a part of South China-Vietnam-South Borneo volcanic arc under the Paleo-Pacific plate’s subduction [1–2]. On the other hand, there are different views pointing out that there was a Cretaceous subduction zone extending from east to west in the northern part of the South China Sea, which may be caused by the subduction and closure of the Meso-Tethys [3–7]. In this study, geochemical data are collected to analyze the characteristics of granitoids in Vietnam and discuss their tectonic implication for Vietnam in Cretaceous.

2. Geological background and petrography
The geotectonic location of Vietnam belongs to the southern margin of Eurasia plate, between the Pacific subduction zone and Tethyan orogenic belt. There are abundant strata outcrops in Vietnam from Archean to Cenozoic. Generally by the division of the northwest-trending Song Ma zone, the North of Vietnam belong to South China block and the south to Indochina block [8]. Because of the Paleo-Tethys’s closure, the collision between Indochina Block and North Vietnam–South China Block took place during Permo-Triassic. Then in Paleogene, Indochina extruded along the Red River fault as a result of India–Asia collision [9].

In Cretaceous, a large volcanoplutonic belt was formed in South Vietnam (Da Lat plateau, SV), and minor granites in North Vietnam (NV). During the Cretaceous period, the volcanoplutonic belt was characterized by andesite–basalt–trachyandesite–basalt–rhyolite and quartz-diorite–granosyenite–
granite–leucogranite magmatic series showing signs of crustal-mantle origin. The granitoids’ ages are from 111.6–88.0 Ma. Major rock-forming mineral assemblage of granitoids in Da Lat is plagioclase, K-feldspar, quartz, hornblende biotite, and muscovite, with accessory minerals of zircon, apatite, titanite, tourmaline, and cassiterite. Mafic minerals are hornblende and biotite [10]. In North Vietnam, the stanniferous granite–leucogranites are presented by stock and fracture intrusions (S = 50–100 km²) centered in the northeastern part of the Bacbao zone. Among them, the Pia Oac massif is best known due to the presence of primary and placer stannic deposits [11–12]. The granites’ ages are 82.5–82.0 Ma. Petrographical study shows that the granites contain plagioclase, alkali feldspar, quartz, biotite, muscovite, with porphyritic texture [13].

3. Geochemical characteristics

The samples from Da Lat in SV with broader silica contents, are in the range from diorite to granite, contrasting to only granite of samples in Pia Oac in NV (figure 1a). With rising silica contents, granitoids mainly remain sub-alkalic (figure 1a), which are calc-alkalic mainly in SV and allali-calcic mainly in NV (figure 1b). In addition, samples become magnesian to ferroan with the increasing silica contents (figure 1c). As to A/CNK values, graitoids in SV are smaller than 1.1, belonging to metalumilous–weakly peraluminous range, whereas those in NV have bigger values larger than 1.1 and belong to peraluminous (figure 1d).

The ∑REE of the Da Lat granitoids are larger than Pia Oac’s as chondrite-normalized REE patterns in figure 2a. Obviously, the LREE and HREE of granitoids in SV are much higher than samples from Pia Oac in NV. The samples in Dal Lat in SV exhibit moderately fractionated REE patterns, slight fractionated HREE patterns and various negative Eu anomalies. On the other hand, samples from Pia Oac have strongly fractionated REE patterns and HREE patterns with large negative Eu anomalies.

In the primitive-mantle-normalized spidergram (figure 2b), samples in SV show enrichment in LILEs (such as Cs, Rb, Th and U) while depletion or negative anomaly in HFSEs (such as Nb, Ta, Sr and Ti). The phenomenon of the “TNT (ie. Ti-Nb-Ta) anomaly” was most characteristic of volcanic arcs in general [14]. In addition, granites from Pia Oac show no obvious anomaly of Nb and Ta, containing higher contents of Cs and Ta, and lower Y.

4. Discussion

Granitoids are usually divided into four main genetic types: M-type, I-type, S-type and A-type. There is few discoveries of alkaline dark-colored minerals in Cretaceous granitoids in Vietnam, and (Zr+Nb+Ce+Y) values are low, which indicate that those granitoids don’t belong to A-type granite (figure 3a). In addition, the granitoids with low A/CNK values are classified to I-type granite in Da Lat in SV, and those in Pia Oac in NV are classified to S-type granite with high A/CNK values conversely. The assemblage of I- and S-type granitoids mainly occur in the convergent environment [15]. In the Rb versus (Yb+Ta) discriminant diagrams (figure 3b), most Cretaceous samples in Vietnam are plotted in the volcanic arc granites and syn-collisional granites, which indicates that the formation of Cretaceous granites is closely related to the subduction.

There are some study of Cretaceous granitoids in Vietnam suggesting that those igneous rocks are similar to magmatism in southeastern China at the same time, as the result of the northwest subduction of paleo-Pacific [13,16–19]. In fact, granitoids association of I- & A-type and “bimodal igneous rock assemblages” are believed as the signals of extensive tectonics in South China [20–23]. However, as mentioned earlier, Cretaceous granitoids can be divided into I- and S-type in Vietnam, and there are a lot of intermediate igneous rocks during this period, such as andesite and diorite. According to zircon solubility simulation formula at 700–1300 °C [24], the diagenetic temperature of Vietnam granitoids
Figure 1. Chemical classification of the Vietnam Cretaceous granitoids in Vietnam. (a) Total alkalis (ie. Na$_2$O+K$_2$O, wt.%) versus SiO$_2$ (wt.%) [25]. The dividing line between alkalic and sub-alkalic magma series is from Miyashiro (1978) [26]. (b) modified alkali-lime (ie. Na$_2$O+K$_2$O-CaO) index versus SiO$_2$ (wt.%). (c) Fe* (FeO/(FeO+MgO)) versus SiO$_2$ (wt.%)) [27]; (d) A/NK (ie. molar Al$_2$O$_3/(K_2O+Na_2O)$) versus A/CNK (ie. molar Al$_2$O$_3/(CaO+K_2O+Na_2O)$) diagram [28].

Figure 2. (a) Chondrite normalized rare-earth element plots and (b) primitive mantle normalized incompatible element plots of Cretaceous granitoids in Vietnam. Element order and normalizing values are from Sun and McDonough (1989) [29].
Figure 3. (a) Tectonic discrimination of the Cretaceous granitoids from Vietnam using the diagrams [30]; (b) chemical compositions of the Cretaceous granitoids from Vietnam in the Rb versus (Y+Nb) and Rb versus (Yb+Ta) discrimination diagrams [31]. Abbreviations: VAG, granitoids in volcanic-arc; syn-COLG, syn-collisional granitoids; WPG, granitoids in intraplate; ORG, granitoids in ocean-ridge.

are 717-814 °C, which is much lower than A-type granites’ in eastern South China block (813-974 °C) [32–34]. So the Cretaceous magmatism in Vietnam would be the production of Tethyan subduction rather than paleo-Pacific’s. Together with E-W trend metamorphic belt in northern continental margin of South China Sea, intermediate-acid intrusions should form under the subduction of Meso-Tethys with a tectonic setting of compression from Pearl River Mouth Basin to Vietnam in Cretaceous.

5. Conclusion
The Cretaceous granitoids are sub-alkaline. Samples in SV are calc-alkalic, with lower A/CNK and (Zr+Nb+Ce+Y) values, which belong to I-type granite. However, those in NV are allali-calcic, with higher A/CNK values but lower (Zr+Nb+Ce+Y) values, which belong to S-type granite. Granitoids exhibit fractionated REE patterns with differently negative Eu anomalies, and show LILEs enrichment and HFSEs depletion. It is indicated that there was compressive structure in Vietnam in Cretaceous by the absence of alkaline dark-colored minerals, abundant intermediate igneous rocks and assemblage of I- and S-type granite with orogen-related geochemical characteristics. The magmatism can be thought the product of meso-Tethyan subduction.

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