Research Article

Multistage Fractional Crystallization in the Continental Arc Magmatic System: Constraints from the Appinites in Tengchong Block, Southeastern Extension of Tibet

Shao-Wei Zhao1,2, Chao Yang3, Shao-Cong Lai2, Xian-Zhi Pei1, Zuo-Chen Li1, and Ren-Zhi Zhu2

1Ministry of Education, Key Laboratory of Western China’s Mineral Resources and Geological Engineering, School of Earth Science & Resources, Chang’an University, Xi’an 710054, China
2State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi’an 710069, China
3China Geological Survey, Beijing 100037, China

Correspondence should be addressed to Shao-Wei Zhao; shwzhaoqx@163.com

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The petrogenesis and evolution process of continental arc magmatism provide insight into discovering the formation and differentiation of continental crust. Therefore, the geochemical, isotopic, and mineralogical analyses were conducted for coeval continental arc igneous rocks in the Tengchong Block to clarify their evolution process in the continental arc magmatic systems. The Middle Triassic appinites in the Tengchong Block, southeastern extension of Tibet, were generated at the subduction setting with zircon U-Pb age of ca. 243 Ma. The Nb/Yb, Zr/Yb, and Ta/Yb ratios along with depleted zircon Hf isotopic compositions indicate a source with an N-MORB affinity for the appinites. However, relatively enriched whole-rock Sr-Nd isotopic compositions with the characteristic of high Sr/Nd, Ba/Th, Th/La, and Th/Nd ratios suggest the source was metasomatized by ~2% subducted sediment-derived fluid. According to the REE ratios modeling, the primary magma of Nabang appinites was due to 5-10% partial melting of such metasomatized mantle source. The appinites are characterized by variable compositions, such as SiO2 contents of 47.82-61.74 wt.% and MgO of 10.61-2.61 wt.%, which resulted from the polybaric and multistage fractional crystallization of a slightly hydrous primary magma in a thick crust. At lower crustal pressures, clinopyroxene was the main fractionating phase, and at middle crustal pressures, amphibole+magnetite were the dominant fractionating phases; predominant plagioclase fractionation occurred at the magma emplacement level. This process could be an effective mechanism to induce the differentiation of continental crust. The fractionation of clinopyroxene and amphibole, accompanied by suppressing plagioclase at lower-middle crustal pressures, induces the high alumina in the evolved melt and forms high-alumina basaltic to andesitic magma.

1. Introduction

The subduction zone magmatism has long been considered an essential role in continental crustal formation and differentiation based on the trace element similarities [1]. However, there is a “crust paradox” that the bulk composition of arc magmatism is basalt, too basaltic relative to the “andesitic” bulk composition of continental crust [2]. Therefore, the evolution of magmatism in the arc crust is a key to understanding the formation and differentiation of continental crust. The fractionation of mantle-derived hydrous primary magma at different crustal levels within arc crust is proposed as an effective mechanism to explain this paradox [3–5]. The pyroxenite and hornblendite cumulates found in the arc magmatism expand the recognition of fractionation products [5–8]. In addition, the transcrustal magmatic system proposed by Cashman et al. [9] provided a new concept to understand the process of segregation, differentiation, ascend, and storage or final erupt through the deep to the shallow crust. Therefore, the coeval magmatic rocks in continental arc supply an
opportunity to further discover the evolution of magmatic system from depth to shallow.

Appinites are a group of coeval plutonic or hypabyssal rocks, ranging from ultramafic to felsic in compositions [10]. Generally, they occur as subordinate components associated with a large pluton complex in a region, such as a satellite around the pluton [11]. They are important water or fluid donor to induce migmatization and anatexis of crustal compositions [10, 12]. The common feature in appinites is that hornblende is the dominant mafic mineral, occurring both as a large phenocryst and fine-grained matrix, representing the high water content in mafic magma [10]. The primitive magma for appinites has been considered to be derived from a hydrated mantle previously metasomatized by fluid/melt released from subducted oceanic slab or/and sediment [10, 12]. Therefore, the appinites shed light on the early subduction setting was related to a branch of the Paleo-Tethys. This study is aimed at evaluating the petrogenesis and evolution of the appinites in the continental arc. The geochemical and mineralogical data indicate that the appinites were derived from N-MORB-type mantle metasomatized by subducted sediment-derived fluid and experienced the multistage fractionation in a thick crust.

2. Geological Setting and Petrography

The Tengchong Block is considered a continental arc related to Neo-Tethyan subduction and Indian-Asian continental collision during the Late Mesozoic to Cenozoic [14, 15]. It is bounded by the Gaoligong Belt from the Baoshan Block to the east and the Sagaing Fault and Mogok metamorphic belt bounded by the Gaoligong Belt from the Baoshan Block to the west (Figures 1(a) and 1(b)). The Tengchong Block is mainly composed of Paleo-Proterozoic basement, named Gaoligongshang Formation, Late-Proterozoic to Mesozoic sedimentary rocks and Early Paleozoic, Late Permian to Triassic, and Early Paleocene to Eocene intrusions with Late Miocene to Holocene volcanic rocks ([15] and references therein), which record the multistage oceanic subduction and microcontinental collision [17]. The Tengchong Block is considered to have an affinity with the Lhasa Block since Early Paleozoic [14, 18] and experienced similar tectonic evolution histories. The Lhasa Block is subdivided into northern, central, and southern subterrains by the Shiquan River-Nam Tso Melange zone, Luobadui-Milashan Fault [19]. The Permian-Triassic arc-type magmatism, eclogites, and Carboniferous-Triassic ophiolites were discovered in the Sundo area, suggesting the existence of a branch of Paleo-Tethyan Ocean within the Lhasa Block [20–24]. The arc-type, syn-collision, and within-plate magmatism from Late Permian to Early Jurassic were also reported in the Tengchong Block, southeastern extension of Lhasa Block [25]. Thus, a Permian to Triassic subduction setting was related to a branch of the Paleo-Tethyan Ocean within the Lhasa-Tengchong Block. The Middle Triassic appinites occurred in the Nabang area, Tengchong Block (Figure 1(c)), formed in a subduction setting consistent with the consensus of the tectonic setting for appinites [10].

The lithologies of appinites in the Nabang area are mainly composed of hornblende gabbros and diorites in the outcrop (Figures 2(a) and 2(b)). The hornblende gabbros and diorites are transitional contacts, and they have similar mineral assemblage but different volume contents, representing the different units in the same magmatic system. The hornblende gabbros selected in this study show porphyritic texture for whole rock and equigranular texture within the matrix, indicating the products of magmatic crystallization. The subedral to euhedral amphiboles are dominant mafic minerals in the hornblende gabbro (modal volume of 65-75%), and they are subdivided into two groups: the first group shows large and short columnar crystal with 1.5-3 mm in length (phenocryst), and another group is characterized by relatively small and granular crystal with <0.2 mm in diameter (matrix, Figures 2(c) and 2(d)). Parts of amphibole phenocrysts display apparent zoning texture (Figure 2(d)), enclose numerous minor plagioclase, quartz, and biotite, and show poikilitic texture (Figure 2(c)). Several amphibole phenocrysts contain the clinopyroxene, implying the replacement reaction between these minerals. The plagioclases are subordinate mineral phases in the hornblende gabbro with the modal volume of 20-25% and show prominent Carlsbad-albite compound twin with subhedral to anhedral crystal. A few opaque minerals and apatites are enclosed in plagioclase (Figures 2(e) and 2(f)). The biotite, quartz, and K-feldspar occur as interstitial phases, and they are 5-10% in modal volume (Figures 2(e) and 2(f)). The accessory minerals mainly include apatite, zircon, and opaque minerals, such as Fe-Ti oxide.

3. Analytic Methods

The zircon U-Pb and Lu-Hf isotopic compositions for Nabang appinites were analyzed at the State Key Laboratory of Continental Dynamics, Northwestern University in Xi’an, China. Zircon grains from three samples were separated by conventional heavy liquid and magnetic techniques and subsequently handpicked and mounted in epoxy resin disks, polished, and carbon-coated. The internal morphology and structure of representative zircons were examined by cathodoluminescence (CL). Laser ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) zircon U-Pb analyses were conducted on an Agilent 7500a ICP-MS equipped with a 193 nm laser, following the detailed methods of Yuan et al. [26]. The $^{206}\text{Pb}/^{235}\text{U}$ and $^{208}\text{Pb}/^{238}\text{U}$ ratios were calculated using the GLITTER program, and corrections were applied using Harvard zircon 91500 as an external calibration standard. The in situ zircon Lu-Hf isotopic compositions were analyzed using a Neptune MC–ICP-MS. The laser repetition rate was 6 Hz at 100 mJ, and the spot size was 30 μm. The analytical technique followed Yuan et al. [27]. During the analyses, the $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{187}\text{Lu}/^{177}\text{Hf}$ ratios of the standard zircon (91500) were 0.282294 ± 15 (2σ) and 0.00031, respectively.
Fresh whole-rock samples were chipped and powdered to 200 mesh using a tungsten carbide ball mill for the major and trace element analyses. Major and trace elements were analyzed by X-ray fluorescence (XRF; Rikagu RIX 2100) and ICP-MS (Agilent 7500a), respectively. Analyses of USGS and Chinese national rock standards (BCR-2, GSR-1, and GSR-3) indicated that the analytical precision and accuracy for major elements were generally better than 5%. Sample powders were digested using an HF + HNO3 mixture in high-pressure Teflon bombs at 190°C for 48 hours for the trace element analyses. For most trace elements, the analytical error was less than 2% and the precision better than 10% [28]. Whole-rock S–Nd isotopic data were conducted using a Nu Plasma HR multicollector mass spectrometer for four samples at State Key Laboratory of Continental Dynamics (SKLCD), Northwest University in Xi’an, China, and using a Neptune Plus MC-ICP-MS for another four samples at the Wuhan Sample Solution Analytical Technology Co.,

**Figure 1:** Simplified geological map of Himalaya-Tibet tectonic realm (a), Tengchong Block and adjacent area (b, modified after [15]), and Triassic appinites pluton and samples location in Nabang area (c).
Ltd. (WSSATL), Hubei, China. The Sr and Nd isotopic fractionations were corrected to $^{87}\text{Sr}/^{86}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. During the period of analysis, the NIST SRM 987 standard yielded a mean value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710250 \pm 12$ ($2\sigma$, $n = 15$) at SKLCD, and $0.710244 \pm 22$ ($2\sigma$, $n = 32$) at WSSATL, and the La Jolla standard gave a mean value of $^{146}\text{Nd}/^{144}\text{Nd} = 0.511859 \pm 6$ ($2\sigma$, $n = 20$) at SKLCD, and JNd1 standard gave a mean value of $0.512118 \pm 15$ ($2\sigma$, $n = 31$) at WSSATL.

Major-element compositions of the minerals were determined using an electron microprobe (JXA-8230) at the Ministry of Education, Key Laboratory of Western China's Mineral Resources and Geological Engineering, Chang'an University. The operating conditions included an acceleration voltage of 15 kV, a beam current of 10 nA, and a beam diameter of 1 μm. Natural and synthetic microprobe standards were supplied by SPI, including jadeite for Si, Al, and Na, diopside for Ca, olivine for Mg, sanidine for K, hematite for Fe, rhodonite for Mn, and rutile for Ti.

4. Results

4.1. Zircon U-Pb Ages. Three hornblende gabbro samples were collected for LA-ICP-MS zircon U-Pb isotopic analyses. The results are listed in Table S1 and Figure 3.

The representative zircons selected from hornblende gabros commonly show subhedral to euhedral, colorless, and transparent crystals, with widths of 50-120 μm, lengths of 50-200 μm, and aspect ratios from 1:1 to 1:4. The zircons show broad compositional zoning on the CL images, indicating that they are formed at high-temperature conditions [29]. Thirty-five spots have been analyzed for a sample of NB18-1 and yielded concordant $^{206}\text{Pb}/^{208}\text{U}$ ages ranging from 236 Ma to 245 Ma with a weighted mean age of $243 \pm 1$ Ma (MSWD = 0.6, $2\sigma$), U contents of 117-617 ppm and Th contents of 62-470 ppm with Th/U ratios of 0.53 to 1.20. Twenty-eight spots have been conducted for NB18-2 and given concordant $^{206}\text{Pb}/^{208}\text{U}$ ages from 237 Ma to 249 Ma with a weighted mean age of $243 \pm 2$ Ma (MSWD = 0.3, $2\sigma$), U contents of 102-
Figure 3: Zircon U-Pb Concordia diagrams, weighted mean age of $^{206}\text{Pb}/^{238}\text{U}$ and CL images of representative zircon grains for the Nabang appinites.
are similar to the adjacent diorites with $\epsilon_{Hf}(t)$ values of 7.8 to 14.9 (Figure 7(b); [30]). The isotopic compositions show obvious low radiogenic Nd and high radiogenic Hf indicating the Nd-Hf isotopic decoupling (Figure 7(c)).

4.4. Mineral Composition. The amphibole, clinopyroxene, and plagioclase were analyzed for the mineral compositions, and the results are listed in Table S5. The clinopyroxenes are enclosed in the amphibole phenocrysts as residual crystals. They belong to diopside in compositions according to the Wo-En-Fs diagram ([33]; Figure 8(a)) and are characterized by high CaO (23.68 to 25.22 wt.%), and MgO (13.16 to 15.55 wt.%) and low Al$_2$O$_3$ (0.92 to 1.58 wt.%), FeO (7.35-7.52 wt.%), and TiO$_2$ (0.05 to 0.13 wt.%) with high Ca/Al ratios of 15 to 26 and Mg# ratios of 80 to 84. According to the thermobarometers after Putirka [34], the clinopyroxene crystallizes at 7.1 kbar and 1037$^\circ$C, a minimum crystallization pressure and temperature. The plagioclases in the hornblende gabbros occur as subordinate mineral phases, and they have relatively consistent contents of An$_{44-50}$ belonging to labradorite (Figure 8(b)). The amphiboles in the hornblende gabbros are divided into phenocryst and matrix, showing different compositional variations. The compositions of amphibole in the matrix and unzoning phenocrysts are similar and characterized by relatively low SiO$_2$, MgO and high FeO, Al$_2$O$_3$, Na$_2$O, and K$_2$O with Mg# ratios of 64 to 70 (Figure 8(c)). The zoning amphibole phenocrysts show variable compositions from core to rim (Figures 8(c) and 9). The zoning amphibole cores are characterized by relatively high SiO$_2$, MgO and low FeO, Al$_2$O$_3$, Na$_2$O, and K$_2$O with Mg# ratios of 70 to 76. The zoning amphibole rims have variable compositions, such as SiO$_2$ contents of 45.29 to 49.58 wt.%, Al$_2$O$_3$ contents of 4.96 to 8.78 wt.%, and Mg# ratios of 64 to 72. The zoning amphiboles have an overall trend of decreasing SiO$_2$, MgO with increasing Al$_2$O$_3$, Na$_2$O, and K$_2$O from core to rim, and parts of them enclose the residual clinopyroxene (Figures 9(a)-9(d)). The amphiboles in the matrix could directly crystallize under the temperature of 771-819$^\circ$C [35] and pressure of 11-5.9 kbar [36] based on their compositions.

5. Discussion

5.1. Petrogenesis of Appinites. The appinites in Nabang area including hornblende gabbros and diorites exhibit variable compositions, e.g., SiO$_2$ contents of 47.82 to 61.74 wt.% and MgO of 10.61 to 2.61 wt.%, indicating the existence of potential magmatic evolution process, such as crustal contamination and fractional crystallization [37]. Therefore, the magmatic evolution should be evaluated when we further discuss and understand the petrogenesis of Nabang appinites.

5.1.1. Evaluation of Crustal Contamination. The mafic rocks derived from the mantle and intruding into the crust should estimate the influence of crustal contamination on their geochemical characteristics. Generally, the crustal contamination markedly modifies the elements and isotopic compositions of the primary magma [38], enriching Sr-Nd isotopes and increasing LILE. The appinites show Nb-Ta depleted,
and LILE enriched, but consistent Sr and Nd isotopes with a variation of MgO (Figure 10(a)), indicating negligible or limited crustal contamination. Therefore the compositional variations of the appinites are not mainly controlled by crustal contamination.

5.1.2. Fractional Crystallization and Evolution Process. The nonlinear trends between MgO and other oxides indicate a multistage process of fractional crystallization [31, 32]. According to the compositional variation of Nabang appinites, the processes of fractional crystallization are subdivided into three stages of paths at least (Figure 5).

The sharp decrease of MgO companied with Ca/Al ratios in the appinites indicates that clinopyroxene is the dominant phase in the earliest stage of crystallization and fractionation. Owing to high MgO and CaO content in the clinopyroxene, it raises the Al₂O₃, K₂O and Na₂O but decreases MgO contents and Ca/Al ratios in the residual melt during clinopyroxene fractionation (Figure 5). If the clinopyroxene differentiation predominates, the SiO₂ content of evolving melt could be depleted or constant [39]. This is observed in the variable trend between MgO and SiO₂, slightly decreasing SiO₂ with decreasing MgO within the first stage (Figure 5(a)).

Dy/Dy * is an important parameter to limit the curvature of the REE pattern [40]. During fractional crystallization, the amphibole and clinopyroxene are the major minerals capable of significantly decreasing Dy/Dy * [40]. Clinopyroxene may reduce or increase Dy/Yb with fractionation due to variable partition coefficient with D_{Dy}/D_{Yb} (cpx) ranging from 0.72 to 1.38 in peridotite to rhyolite, but amphibole fractionation generally reduces Dy/Yb because of D_{Dy}/D_{Yb} (amp) ranging from 1.32 to 2.35 in peridotite to rhyolite ([40]; GERM

Figure 4: Diagrams of SiO₂ versus alkali after Middlemonst [66] (a), SiO₂ versus K₂O after Peccerillo and Taylor [67] (b), SiO₂ versus FeOt/MgO after Miyashiro [68] (c), and FeOt-MgO-alkali after Irvine and Baragar [69] (d) for the Nabang appinites.
The clinopyroxene differentiation in the first stage increases Dy/Yb but decreases Dy/Dy* for the evolved melt (Figure 11(a)). Besides, the alkalis and Al₂O₃ contents increasing is against with the plagioclase crystallization and fractionation in the first stage. The suppression plagioclase crystallization occurs at a condition of high H₂O content or/and high pressure [41–45]. It is consistent with the consensus on the high H₂O content for the appinite magma [10] and the high pressure at 7.1 kbar, a calculation based on the clinopyroxene composition. The unchanged and consistent δEu values and gradually increasing Sr contents with decreasing MgO and SiO₂ also suggest that the plagioclase is not involved in the fractional process in the first stage (Figures 11(b) and 11(c)). Furthermore, the slight increase of Fe₂O₃T and minor change of TiO₂ with decreasing MgO in this stage argue against with the fractional crystallization of magnetite, which could be the late crystallization phase (Figure 5). Therefore, the clinopyroxene fractionation and suppression plagioclase crystallization are the mainly evolved processes in the first stage.

After the first stage of clinopyroxene crystallization and fractionation, an important feature is to strengthen H₂O content in the residual melt, which allows the reaction of early formed clinopyroxene with hydrous melt and forms the hydrous mineral, such as amphibole. This is marked in the second stage of evolution for the Nabang appinites. It is evidenced by residual clinopyroxene enclosed in amphibole (Figure 9) and further confirmed by the fact that the quartz crystals were enclosed in almost all of the amphibole phenocrysts or occurred as interstitial phases around amphibole.

**Figure 5:** Diagrams of MgO versus major elements for the Nabang appinites.
phenocrysts (Figure 2). Compared with clinopyroxene, the amphiboles have lower SiO$_2$ and CaO and higher FeO, Al$_2$O$_3$, and alkalis. Therefore, it would release exceeded silica and CaO and absorb FeO, Al$_2$O$_3$, and alkalis from the melt during the clinopyroxene reaction to amphibole, resulting in slightly increasing SiO$_2$ and CaO, decreasing or/and constant alkalis, and a relatively small slope of Ca/Al trend with decreasing MgO in the further evolved melt (Figure 5). Compositional variations of zoning amphiboles reflect these elemental exchanges, reaction-replacement amphibole core with more primitive elements than amphibole rim, such as higher SiO$_2$ and MgO core (Figures 9(a)–9(d)). Besides, the H$_2$O content in the second stage could be high to 5.6–6.1 wt.% during the crystallization of amphibole at the temperature of 771–819°C [35] and pressure of 1.1–5.9 kbar [36], based on the matrix amphibole composition. The high H$_2$O content is able to stabilize the amphibole and crystallize from silicate melt, represented by the amphibole in the matrix. The compositions of amphibole in matrix are similar to the unzoning phenocryst and rim in the zoning amphibole (Figures 8 and 9), indicating the complete replacement of clinopyroxene. Companied with the ongoing transition from clinopyroxene to amphibole, the dominant crystallizing and fractionating phase is amphibole, further confirmed by the increasing SiO$_2$, Al$_2$O$_3$, and alkali contents with decreasing MgO, and decreasing Dy/Dy$^*$ versus Dy/Yb (Figures 5 and 6).
The plagioclases in the second stage are likely to onset of crystallization, but a small amount of plagioclases is involved in the fractionation, because of the trend of decreasing $\delta$Eu with decreasing MgO and relatively slow increasing Sr with increasing SiO$_2$ comparing to the first stage of evolution (Figure 11). The accessory mineral, such as Ti-Fe oxide (magnetite) and apatite could be fractionated in the second stage because of the decreasing Fe$_2$O$_3$T, TiO$_2$ and P$_2$O$_5$ with decreasing MgO (Figure 5). Therefore, the amphiboles with accessory minerals fractionation, especially magnetite, are predominant in the second stage of the Nabang appinites evolution.

In the third stage of the fractional process, the major elements of Al$_2$O$_3$ and Na$_2$O and trace elements of Sr with $\delta$Eu are subsequent decrease in the evolved appinites, indicating the dominant plagioclase fractionation (Figures 5 and 11). The plagioclase fractionation results in the potassic enrichment in the intermediate composition (Figure 5). In addition, the successive decreasing MgO and Fe$_2$O$_3$T and Dy/Dy* and Dy/Yb indicate the amphibole is also involved in the fractional phase in the last stage (Figure 5).

The compositional variations of Nabang appinites were controlled by the multistage fractional process, which is sensitive to pressure and H$_2$O content in magma and changes the crystallization sequences. It is consistent with the experimental results [41, 44, 45].

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**Figure 8**: Mineral compositions and classification of clinopyroxene, plagioclase and amphiboles in the Nabang appinites after Morimoto [33], Parsons [73], and Leake et al. [74], respectively.
5.1.3. Magma Sources and Melting. The Nabang appinites are enriched in LILE and LREE and depleted in HFSE, similar to subduction-related mafic magmatism. The less-evolved appinites have high MgO contents of 9.62 to 10.61 wt.% with Mg# values of 66 to 70, similar to the primary composition in equilibrium with mantle peridotite [46]. Consequently, the compositions of less-evolved samples in the Nabang appinites are able to reveal the characteristics of their mantle.
source. The immobility of HFSE and HREE and their low concentrations in the slab or sediment-derived hydrous fluid/melt could be almost unaffected by subduction-related processes [47–49]. Thus, these trace elements were used to reveal the characteristics of mantle sources. On the diagrams of Zr/Yb versus Nb/Yb and Ta/Yb versus Nb/Yb, the less-evolved appinites fall close to the N-MORB, indicating mantle sources with an N-MORB affinity (Figures 10(b) and 10(c)). It is further confirmed by the depleted zircon Lu-Hf isotopic compositions with εHf(t) values of 6.0 to 16.4. However, their slightly enriched Sr and Nd isotopic compositions indicate that the mantle sources should be metasomatized by fluid/melt derived from subducted sediments or/and altered oceanic crust (AOC). The metasomatized mantle agent is generally estimated based on the variable mobility of incompatible trace elements in different subducted-related fluids/melts [50]. The LILEs are easily mobile in the hydrous fluid, and Th is mainly enriched in subducted sediments and participated into the melt [49]. The less-evolved appinites have markedly higher Sr/Nd (42-64) and Ba/Th (444-883) and slightly higher Th/La (0.05-0.10) and Th/Nd (0.04-0.08) ratios compared to N-MORB mantle (DMM: Sr/Nd = 13, Ba/Th = 71, Th/La = 0.04, Th/Nd = 0.01; [51]), suggesting the subducted sediments-derived fluid as the agent (Figure 12). The AOC shows lower radiogenic Sr and more depleted Nd composition than the subducted sediments (AOC: 87Sr/86Sr = 0.704858, 143Nd/144Nd = 0.513114; global subducted sediments (GLOSS): 87Sr/86Sr = 0.717300, 143Nd/144Nd = 0.51218; [49, 52]). Consequently, AOC has less effect on the Sr and Nd isotopic composition to the fluid/melts than subducted sediments. The Sr-Nd isotopic compositions and trace elemental ratios are widely utilized to quantify the subducted-related fluid/melt contribution. The parameters in the calculation are listed in Table S6. The results show that the sources for Nabang appinites were N-MORB-type mantle metasomatized by ~2% subducted sediment-derived fluid (Figure 12). In the process of metasomatism, the Nd-Hf isotope decoupling could achieve, due to the higher mobility of Nd with respect to Hf [47, 53], which is a common feature observed in Phanerozoic arc systems [54].

The REE concentrations and ratios are generally used to constrain the natures of source mineralogy and the degree of partial melting [55]. The HREEs more readily participate into the garnet, and MREE/HREE and LREE/MREE ratios are sensitive to the degrees of partial melting of garnet- or spinel-hydruletzolite sources. The melts produced by medium or small degree melting of garnet-hydruletzolite sources have high Sm/Yb and La/Sr, while the melts produced by spinel-hydruletzolite sources will have similar Sm/Yb but decreasing La/Sr with increasing melting degree [55]. We attempt to formulate the nature of sources and partial melting process for the Nabang appinites. The nonmodal batch melting model is used after Shaw [56]. The starting materials are based on the mentioned above, 98% DMM + 2% subducted sediments-derived fluids. On the La/Sr against Sm/Yb diagram (Figure 13), the Nabang appinites are close to the melting trajectories drawn for spinel-hydruletzolite source with ~5-10% melting degree.

5.2. Implications for High-Alumina Basalt and Continental Arc Magmatic System. In the Nabang appinites, it is noteworthy that Al2O3 contents (>16%) are high enough in the evolved members (MgO < 6%), which are similar to the compositions of low MgO high-alumina basalt and basaltic andesite (HAB) in the arc or midocean ridges [41, 44, 57].
Several models have been proposed for the origin of HAB magma: (1) directly derived from partial melting of subducted slab [58]; (2) evolved liquid that has experienced selected accumulation of plagioclase inducing the rise of aluminas [57]; and (3) the delayed plagioclase of hydrous mantle-derived basaltic magma at high-pressure condition [41, 44]. As mentioned above, the variable compositions of Nabang appinites are mainly controlled by the multistage fractional crystallization. According to the experimental results and natural sample researches, the water content and crystallization pressure of basaltic magma play important roles in the crystallization sequences and phases and influence on the chemical differentiation (e.g., [42–45, 59]). High H$_2$O (>3%) content has the following effects on the crystallization of basaltic magma: (1) suppressing the crystallization of plagioclase relative to mafic mineral; (2) suppressing the crystallization of silicate mineral relative to magnetite; and (3) stabilizing the hydrous mineral, such as amphibole [44, 45].

From Zimmer et al. [45], a new Tholeiitic Index (THI) was established to distinguish the tholeiitic and calc-alkaline magmatic trend and calculate magmatic water. Magma with THI > 1 indicates Fe enriched and are tholeiitic, while magma with THI < 1 shows Fe depleted and are calc-alkaline. The Nabang appinites have the THI value of 0.99, corresponding to primary magmatic water content of 2.3%, an effective break between tholeiitic and calc-alkaline trend, consistent with the plotting results in Figures 2(c) and 2(d).

H$_2$O content for the Nabang primary appinitic magma was too low to stabilize amphibole. Besides, the relatively low H$_2$O content, likely coupling with low oxygen fugacity, could not stabilize magnetite in the early crystallization. This is indicated that Fe-Ti oxide (magnetite) is not involved in the fractionation phase for the less-evolved Nabang appinites (Figure 5). The pressure is also an important factor in controlling the liquidus phase. At relative low pressure, the liquidus minerals of mantle-derived basaltic magma are olivine with magnetite, while the stability field (liquidus volumes) of clinopyroxene expands and crystallizes very early at the high-pressure condition, even with low magmatic water content [41, 44]. The increasing Fe$_2$O$_3$T and Al$_2$O$_3$ and decreasing CaO with decreasing MgO in the early evolution of the Nabang appinites indicate the Ca- and Mg-rich mineral differentiation and Al-rich mineral instability, such as fractionation of clinopyroxene and suppression of plagioclase, which requires a relatively high-pressure condition [41, 45]. However, the garnet could be a common phase during the crystallization of primary, hydrous arc magma at the high-pressure condition (generally more than 1-1.2 GPa; [5, 42]). In the Nabang appinites, the constant Gd/Yb and Dy/Yb ratios and slightly increasing Fe$_2$O$_3$T with decreasing MgO contents for the less-evolved appinites indicate the garnet is not involved in the fractionation phase [60]. However, it is noteworthy that the Gd/Yb and Dy/Yb show unobvious rise but display flatter pattern model of HREE for the high MgO garnet-poor pyroxene, because of small amounts of garnet, which is considered high-pressure cumulate and named arcolgite in Mesozoic Sierra Nevada from [5, 61]. Therefore, the fractionation of garnet for the less-evolved appinites cannot be completely ruled out. The early fractionation phase is dominated by clinopyroxene, and crystallization pressure is more than 7.1 kbar, corresponding to the lower crust, for the less-evolved appinites. This is further confirmed by a thick crust at 52-59 km for Tengchong Block during Middle Triassic, estimated according to the Sr/Y ratios after Chapman et al. [62]. The early fractionation products of could be similar to high-MgO garnet-poor pyroxene in the Sierra Nevada batholith [5, 6]. The suppression of plagioclase and magnetite along with fractionation of clinopyroxene for the slightly hydrous primary magma drives the depletion of Si, Mg, and Ca, as well as the enrichment of Al and slightly increasing Fe in the evolved melt at high-pressure condition. This fractional process also results in the rise of Fe/Mg values and drives the magma transition from calc-alkaline to tholeiitic. Subsequently, the water should increase during the evolution of slightly hydrous magma [63, 64] and induce the reaction between extant anhydrous minerals (clinopyroxene) and hydrous melt in the lower crustal mush zones, which ultimately forms hydrous minerals, such as amphibole [65]. This reaction is evidenced that the residual clinopyroxenes are enclosed into the amphiboles, and a partial of amphibole phenocrysts have more primitive compositions than the matrix amphiboles. Therefore, the partial of amphibole phenocrysts are the reaction-replacement origin, and the amphiboles in the matrix are the magmatic origin. Generally, the amphiboles crystallize from the basaltic magma requiring relatively high H$_2$O and Na$_2$O content (Grove, 2003). The H$_2$O contents increase to 5.6–6.1 wt.% during the amphibole crystallization for the evolved Nabang appinites. In addition,

![Figure 11: Dy/Yb versus Dy/Dy * after Davidson et al. [40] (a), MgO versus δEu (b), and SiO$_2$ versus Sr (c) for the Nabang appinites.](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2021/3367816/5330300/3367816.pdf)
the amphibole is considered an important and cryptic fractional mineral within the arc magmatic system [39, 40, 65]. The hornblendite cumulates are also found in the andesitic rocks in Central Andes [7], and the amphibole compositions generally record the fractionation process occurring at the mid-low crust in depth [7, 8]. The amphiboles in the matrix of Nabang appinites record their crystallization and fractionation pressure at 1.1-5.9 kbar, corresponding to the middle crust in depth. Therefore, the amphibole fractionation is identified posterior to the fractionation of clinopyroxene in the Nabang appinites. The fractionation products could be similar to the hornblende cumulates in Central Andes [7].

The magnetite and a small amount of plagioclase crystallize along with or posterior to the amphibole. The fractionation of amphibole and magnetite with a small amount of plagioclase further drive the residual melt to intermediate to acid composition with the depletion of Fe and enrichment of Si and Al. Furthermore, the Fe-rich mineral fractionations drive the melt from tholeiitic to calc-alkaline trend. Therefore, the high Al2O3 contents in the evolved member of Nabang appinites result from the fractionation of clinopyroxene and amphibole but the suppression of plagioclase within the lower to the middle crust. The extensive plagioclase fractionation mainly occurs at the last stage of magmatic evolution and finally leads to the Al2O3, Na2O, and Sr content decrease.

In summary, the broad spectrum of compositions in the Nabang appinites are the most accessible witness to the differentiation processes during the upward-moving of the depleted MORB mantle (DMM) composition from Workman and Hart [51], altered oceanic crust composition from Kelley et al. [75] and Hauff et al. [52]. Global subducted sediment composition from Plank and Langmuir [49]. The AOC and GLOSS fluid was calculated assuming the 2% Rayleigh distillation. The GLOSS melt was calculated assuming 20% modal batch melting. The subducted AOC compositions refer from Brenan et al. [76] with a modal compositions of 60% garnet (Grt) + 40% clinopyroxene (Cpx) and the partition coefficients for Grt and Cpx from Brenan et al. [76, 77]. The partition coefficients for calculation of GLOSS fluid and melts refer from Johnson and Plank [78]. The parameters are listed in Table S6.
slightly hydrous magmatic system in a thick crust. They have experienced the multistage fractional crystallization at a different depth, along with a pathway of clinopyroxene fractionation at the lower crustal pressure, amphibole + magnetite fractionation at the middle crust pressure, and plagioclase fractionation in the magma emplacement level (Figure 14). The Nabang appinites show a polybaric differentiation history in the transcrustral magmatic system, proposed by Cashman et al. [9], which is different from the traditional consensus of a melt-dominated magma chamber for the igneous processes. The multiple vertical fractional crystallization could form the corresponding igneous cumulates, such as pyroxenite and hornblendite [5, 7]. After the multistage fractionation, the mantle-derived hydrous melt are driven to variable compositions and finally generate the intermediate to acid magma. If the mafic-ultramafic pyroxenite cumulate delaminates into the mantle because of its high density [4, 6], compositions of the latter remaining could be consistent with the bulk compositions of continental crust.
6. Conclusion

Based on the geochronological, geochemical, isotopic, and mineralogical analyses of the Nabang appinites, it is concluded as the following: (1) The appinites in Tengchong Block are generated during the Middle Triassic with zircon U-Pb age of ca. 243 Ma. (2) The sources of appinites have an affinity with N-MORB but are metasomatized by 2% subducted sediments-derived fluid. The primary magma for the Nabang appinites was derived from about 5-10% melting of such mante sources. (3) The compositional ranges of the appinites indicate they underwent the multistage fractional crystallization within a thick crust, clinopyroxene fractionation at the lower crustal pressure, amphibole+magnetite fractionation at the middle crustal pressure, and plagioclase fractionation in the magma emplacement level. The high Al$_2$O$_3$ contents in the evolved appinites can be resulted from fractionation of clinopyroxene and amphibole but suppression of plagioclase at the lower-middle crustal depth.

Data Availability

The data are listed in the Supplementary Materials.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Diagrams of MgO versus Cr and Ni for the Nabang appinites. Table S1: zircon U-Pb isotopic data. Table S2: major and trace elements data. Table S3: whole-rock Sr-Nd isotopic compositions. Table S4: zircon Lu-Hf isotopic compositions. Table S5: mineral compositions. Table S6: input parameters. (Supplementary Materials)

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