**Petrogenesis and mineralization of REE-rich granites in Qingxi and
Guanxi, Nanling region, South China**

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Abstract

Mesozoic granites in the Nanling region, South China, are important primary rocks for ion-adsorption rare earth element (REE) deposits. Moreover, metallic deposits of W, Sn, Nb and Ta also develop in these granites, most of which formed in the Late Jurassic. The Qingxi and Guanxi granites in the Nanling region contain abundant REE minerals and have zircon U-Pb ages of 223.0 ± 0.7 Ma and 198.8 ± 1.4 Ma, respectively. They are of metaluminous to slightly peraluminous in character having a high K calc-alkaline composition, and have high K_2O+Na_2O and FeO_T+MgO contents and a Ga/Al ratio similar to A-type granites. These granites plot into the post-collision field, similar to the A2-type granites. The Qingxi and Guanxi granites indicate a crust-dominant origin by having high levels of Rb and Th relative to Nb and Ta normalized to ocean-ridge granites. They are characterized by LREE enrichment and the majority of REE accumulating in the primary REE minerals include REE-phosphates and fluorocarbonates. The Guanxi rocks have a stronger negative Eu anomaly, but lower REE composition than the Qingxi granites, implying that the basement may have played an important role in the REE mineralization rather than fractional crystallization. This further implies that the basement in South China may have been subjected to different evolutionary geodynamics, resulting in different multi-metallic mineralization of W-Sn-Nb-Ta-REE hosted by large scale Mesozoic granites.

Keywords: Granite; Petrogenesis; REE mineralization; Basement rocks;
South China

1. Introduction

Rare earth elements (REE) are important primary materials for the technological industry and belong to the so-called group of strategic elements. However, REE deposits are infrequent and exploited in only a few countries, including China, the United States, Russia, Australia, Brazil, India, Malaysia, South Africa and Thailand (USGS, 2016). Currently, China has more than 85% of the world's REE, and almost the entire heavy REE (HREE) production (USGS, 2016). Most light REE (LREE) resources in China are mined from the Bayan Obo (Yang et al., 2009) and the Panxi region (Hou et al., 2009), and HREE resources from ion-adsorption deposits in South China (Bao and Zhao, 2008).

The REE and Y ores from ion adsorption deposits have become an important REE resource, especially HREE in China since the early 1970's. The ion adsorption deposits were formed by the chemical weathering processes of REE-rich parent rocks, and REE occur as ions adsorbed on kaolinite, halloysite and other clay minerals, or on muscovite, biotite and magnetite in the weathered crust (Xu et al., 2015). These deposits mostly occur in the Nanling area of South China, and their parent rocks include granites (Huang et al., 1988; Wang et al., 2015), adamellites (Xu and Yuan, 1992),

granite-porphyrries and rhyolitic tuff lavas (Wang and Ruan, 1989). The ion-adsorption deposits in weathered profiles over granitoids have been found in Laos, southern Thailand, Malaysia and Indonesia (Sanematsu et al., 2009; Yusoff et al., 2013; Mauling et al., 2014); weathering environments play a role in the formation of this type of REE deposits. Annual precipitation in South China is high (up to 1600~2000 mm) and the annual average temperature ranges from 16°C to 25°C; environmental factors which result in strong chemical weathering (Wu et al., 1993). Low hills are the dominant topography in these areas which makes denudation rates relatively low and exposes well-preserved weathered crusts (Bao and Zhao, 2008).

Previous studies mostly focused on the mobility and concentration of REE during weathering (Maruejol et al., 1990; Aubert et al., 2001; Bao and Zhao, 2008; Murakami and Ishihara 2008). Little attention was paid to primary REE minerals in the fresh granites from South China (Wang et al., 2003; 2015). Although most granitoids in South China are of Mesozoic age, the geochemistry and REE mineralization characteristics of the Early Mesozoic granites are not clear. In this study, petrology, mineralogy and geochemistry of REE-rich Qingxi and Guanxi granites in South China are compared. The aim of this investigation is to study their origin and mineralization.

2. Geological Setting and Sampling

Mesozoic magmatic activities were widespread in South China, especially

in the Nanling region (E110°~117°, N23°20'~26°24'). Granites and rhyolites, together with some gabbros and basalts, occur in most parts of this region. The granite belts that occur in this area generally have an E-W trend from the coastal areas to the interior, with increasing ages from the Late to Early Mesozoic (Fig. 1a). Most Mesozoic granites in the Nanling region formed in the Yanshanian (Jurassic to Early cretaceous) with an outcropping area of 31546 km²; this is nearly ten times greater than that of the Indosinian (Permian to Triassic) granites (~3260 km²; Zhou, et al., 2006). These granites intrude into the Proterozoic and Paleozoic folded sedimentary rocks (Murakami and Ishihara, 2008).

REE mineralization in the Nanling region is dominated by ion-adsorbed type deposits related to weathering granites. These deposits were first explored in Zudong and Guanxi, Jiangxi Province. Their parent rocks include: 1) the Indosinian granites, represented by the biotite granites and porphyritic biotite adamellites in Dajishan, Jiangxi Province and Jiangmen, Guangdong Province; 2) the early-Middle Yanshanian granites, represented by the biotite moyites, muscovite granites and biotite granites in Zhaibei, Jiangxi Province, Qitianling, Hunan Province and Fogang, Guangdong Province; 3) the Late-Yanshanian granites, represented by the biotite adamellites and alkali-feldspar granites in Qingyuan, Guangdong Province.

Besides REE mineralization in the Nanling region, metallic deposits including W, Sn, Nb and Ta also occur associated with these granitoids as

pegmatite, greisen, vein and skarn types (Mao et al., 2008). Large scale poly-metallic mineralization took place in the Late Jurassic period (144-161 Ma), and most of the parent rocks formed between 148-167 Ma (Mao et al., 2008). These granites can be grouped into three major types: W-bearing muscovite and muscovite-biotite granites, mainly in the south of Jiangxi and Hunan Provinces; Sn-W-bearing biotite, muscovite and biotite-muscovite granites, mainly in Hunan and Guangdong Provinces; and Ta-Nb-bearing albite granites, mainly in Hunan and Guangxi Provinces (Chen et al., 2008).

The Qingxi granites are located in Ganzhou, Jiangxi Province, with an outcrop area of about 269 km² (Fig. 1b). The rocks intruded into the Sinian and Cambrian sediments and have intrusive contact with the Cambrian rocks in southern and western parts. Cretaceous sediments unconformably covered the eastern part of Qingxi granites. The rock is medium- to coarse-grained biotite granite and composed of alkaline feldspar (25-30%), plagioclase (27-32%), quartz (31-35%), biotite (3-10%) and muscovite (< 2%). The accessory mineral assemblages include zircon, apatite, magnetite, allanite and REE minerals (Fig. 2). Chloritization, kaolinization and potassic alteration are present at the margins of the granites.

The Guanxi granites intruded in the southern part of Late Caledonian uplifting zone in Ganzhou, Jiangxi Province, and are in fault contact with the Zudong granites (Fig. 1c). The latter, composed of REE-rich biotite moyites and muscovite alkaline-feldspar granites, underwent strong weathering to

produce a large ion-adsorption deposit (Huang et al., 1988). The Guanxi granites are relatively fresh and controlled by EW- and NNE-trending faults. They are associated with some Jurassic volcanic rocks, including tuffs, rhyolite and rhyodacite. The Guanxi rock has a medium to coarse-grained texture and is composed of alkaline feldspar (30-44%), plagioclase (18-33%), quartz (24-34%) and biotite (2-8%). The accessory mineral assemblages include zircon, apatite, titanite, allanite, rutile, magnetite, thorite and REE minerals (Fig. 2). Chloritization, kaolinization, albitization and potassic alteration are observed in the granites.

3. Analytical Methods

3.1. LA-ICP-MS U-Pb zircon dating

Zircon grains for U-Pb dating were selected using conventional magnetic and density techniques. Transmitted and reflected light photomicrographs and cathodoluminescence (CL) images were used to observe internal structures of the zircons. Age determination was undertaken using laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS). For LA-ICP-MS measurements, we used an Agilent 7500ce mass-spectrometer coupled to a 193-nm ArF excimer laser at the School of Earth and Space Sciences, Peking University. The laser beam was focused on the sample with a flux of 20 J/cm² and a spot of 32 μm in diameter at a repetition rate of 5 Hz for 40 seconds. Helium was used as the carrier gas to transport the ablated aerosol to the

mass-spectrometer. Zircon Nancy 91500 was used as an external calibration standard to correct for instrumental mass bias and elemental fractionation. Zircon standard PLE was used for quality control. The Pb content of zircon was externally calibrated against NIST 610 with Si as an internal standard; other trace elements were measured using Zr as the internal standard. Raw-data reduction was performed off-line using Glitter software.

3.2. Electron microprobe analyses

Representative mineral phases in the granites were analyzed on C-coated polished sections using an EPMA-JXA-8230 electron microprobe with wavelength-dispersive X-ray spectrometry (WDS) at the Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences. This measurement was performed with a 15 kV accelerating voltage, a 20 nA beam current and an electron beam of 1-5 μm . According to the components and sizes of separated minerals, the set of appropriate matrix-specific standards (including natural and synthetic ones) and corresponding instrumental conditions (including beam diameter, detector type and counting statistics) were selected. Specifically, the raw WDS data of REE bearing minerals were corrected on the basis of empirical interference values for REE (the well-characterized synthetic standards, REE glasses and orthophosphates) (Williams, 1996).

3.3. Major and trace element analyses

Major and trace element analyses were determined using wet chemical methods and ICP-MS, respectively, at the Institute of Geochemistry, Chinese Academy of Sciences. Specific measuring methods are given in Qi et al. (2000). Fifty milligrams of whole-rock powder were dissolved in a Teflon bomb using 1 ml HF (38%) and 0.5 ml HNO₃ (68%). The sealed bomb was placed in an electric oven and heated to 180 °C for 24 h. One milliliter of 1 µg/ml Rh was added to the cooled solution as the internal standard and the solution was then evaporated. One milliliter of HNO₃ (68%) was added, evaporated to dryness, and repeated. The final residue was re-dissolved in 8 ml HNO₃ (40%). The bomb was sealed and heated in an electric oven at 180 °C for 5 h. The final solution was diluted to 100 ml using distilled de-ionized water before ICP-MS analysis. The analytical precision for most elements was generally greater than 10%.

3.4. In-situ LA-ICP-MS analysis

In-situ LA-ICP-MS determination of trace element compositions of representative minerals from the granites was performed in polished sections at the School of Earth and Space Sciences, Peking University. The diameter of the ablation spot was 32 µm. NIST 610 glass was used as a calibration standard for all samples, with ²⁹Si and ⁴³Ca as internal standards for quantitative silicate mineral and apatite analysis, respectively. Analytical error

was $\leq 5\%$ at the ppm level. In-run signal intensity for indicative trace elements was monitored during analysis to ensure that the laser beam stayed within the phase selected and did not penetrate inclusions.

4. Results

The U-Pb geochronological data of zircon from the granites are summarized in Table 1. The electron microprobe and LA-ICP-MS analyses of representative minerals in the rocks are shown in Tables 2 and 3. Major and trace element data of the whole rocks are listed in Table 4.

4.1. Zircon U-Pb geochronology

Zircon crystals from the Qingxi and Guanxi granites range from 50 to 200 μm and 30 to 150 μm in length, respectively. Both granites show clear oscillatory zonings; few inherited cores were identified (Fig. 3). The Qingxi zircons show variable Th (102-411 ppm) and U (224-2008 ppm) contents with the Th/U ratio ranging from 0.13 to 1. Fifteen zircons give a concordia U-Pb age of 223.0 ± 0.7 Ma (Fig. 3a). The Guanxi zircons also have variable compositions of Th (58-2662 ppm) and U (144-4860 ppm). Their Th/U ratio ranges from 0.4 to 0.9 and fourteen zircons give a concordia U-Pb age of 198.8 ± 1.4 Ma (Fig. 3b).

4.2. Mineral chemistry

4.2.1. Feldspar

The feldspars selected from the Qingxi and Guanxi granites were examined by electron microprobe and LA-ICP-MS. The Qingxi samples are mainly plagioclases which belong to the oligoclase series with $Ab_{82}An_{17.1}Or_{0.9}$ to $Ab_{89}An_{10}Or_1$. They contain minor contents of P_2O_5 , MgO and FeO (up to 0.27 wt. %, 0.14 wt. % and 0.30 wt. %, respectively). High levels of Rb (385 - 1853 ppm), Sr (204 - 148 ppm) and Ba (585 - 182 ppm) were determined in the Qingxi plagioclase (Fig. 4a). Both K-feldspar and plagioclase occur in the Guanxi samples. The K-feldspars are represented by $Ab_{11.6}An_{1.4}Or_{87}$ and $Ab_{2.6}An_0Or_{97.4}$, and contain minor P_2O_5 (up to 0.19 wt. %) and FeO (up to 0.03 wt. %). Rb (730 ppm), Sr (98.6 ppm) and Ba (71.8 ppm) compositions were determined in one sample. The plagioclases contain variable levels of Rb (3.22 to 169 ppm), Sr (41.9 to 283 ppm) and Ba (8.54 to 160 ppm).

The total REE content of plagioclases and K-feldspars ranges from 16.8 to 69.8 ppm and 1.76 to 42.9 ppm for Qingxi and Guanxi, respectively. All the feldspars show strong LREE enrichment with an average $(La/Yb)_{cn}$ value of 121 at Qingxi and 37 at Guanxi (Fig. 5a). They have positive Eu anomalies ($\delta Eu = 4.8$ to 32) and negligible Ce anomalies ($\delta Ce = 0.8$ to 1.89). Compared with the feldspars (total REE ~ 58.8 and 19.2 ppm for plagioclases and K-feldspars, respectively) from nearby Zhaibei granites (average total REE of 216 ppm) (Wang et al., 2015), our samples contain less total REE contents and have similar REE distribution patterns.

4.2.2. Mica

Mica in this study can be classified into two main groups: biotite and muscovite. The Qingxi biotite plots in the ferri-biotite area on the $\text{Mg} - (\text{Al} + \text{Fe}^{3+} + \text{Ti}) \text{ VI} - (\text{Fe}^{2+} + \text{Mn})$ diagram with a $\text{Mg\#}$ value $[100 \times \text{molar Mg}/(\text{Mg} + \text{Fe})]$ ranging from 28 to 32; the Guanxi sample has slightly higher $\text{Mg\#}$ (36), and plots close to the magnesio - biotite area (Fig. 6). The biotite and muscovite from both locations occur as platy crystals up to 5 mm and < 1 mm across, respectively. Little F and TiO_2 were detected in the biotite (up to 0.92 wt. % and 3.52 wt. % for Qingxi; 1.35 wt. % and 2.30 wt. % for Guanxi). In contrast, the Qingxi biotite contains higher Al_2O_3 (~19 wt. % vs. 13.6 wt. %) and lower MgO (~6 wt. % vs. 8.6 wt. %) contents than that in the Guanxi samples.

LA-ICP-MS analysis results for biotite from Qingxi and Guanxi show positive Ba, Pb, Nb, Ta anomalies and negative Sr and Zr anomalies compared to primary mantle trace element compositions (Fig. 4a). Their total REE contents are low (0.06-11.4 ppm; 0.03-3.8 ppm for Qingxi and Guanxi, respectively). Biotite shows slight LREE enrichment with $(\text{La}/\text{Yb})_{\text{cn}}$ of 0.9-7.6 and 0.6-10 for Qingxi and Guanxi, respectively (Fig. 5a). Variable Eu anomalies were determined in the Qingxi and Guanxi biotites.

4.2.3. Apatite

Apatite from Qingxi has a stumpy or hexagonal prism shape up to 1 mm in

length, and mostly occurs as inclusions in the biotite; it rarely occurs in the plagioclase or quartz. The Guanxi apatite is minor and occurs as aggregate crystals up to 0.1 mm in length and was found as inclusions in the biotite, plagioclase and quartz. The Qingxi and Guanxi apatites have similar F contents (~3 wt. %) and are fluorapatite.

The apatite in Qingxi shows positive Th, Sr, Pb, U anomalies and negative Zr, Ta anomalies against the primary mantle normalized trace element compositions (Fig. 4a). It contains high REE, especially HREE (Y up to 4713 ppm). The Qingxi apatite shows a strong negative Eu anomaly ($\delta\text{Eu} = 0.05$ to 0.13) and a variable chondrite-normalized REE pattern from slight LREE enrichment to depletion [$(\text{La/Yb})_{\text{cn}} = 0.63$ to 1.20]. These results are similar to a “sea gull” pattern (Fig. 5a).

4.2.4. REE minerals

Because all of the LREE minerals identified in the granites contain Ce as the dominant lanthanide [i.e., allanite-(Ce), monazite-(Ce), etc.], we dropped the chemical modifier from all of the names for simplicity. The REE minerals in both the Qingxi and Guanxi granites mainly include monazite, allanite, bastnäsite and parisite. Minor xenotimes were found in the Guanxi samples (Fig. 2l).

Monazite from both locations occurs as ovoid grains within the biotite or sometimes muscovite. The Qingxi monazite contains minor Ca and Fe (up to

1.67 and 1.48 wt. % respective oxides). It shows a typical LREE-enriched pattern with a relatively constant $(\text{La}/\text{Nd})_{\text{cn}}$ ratio of 2.7 (Fig. 5b). The Guanxi sample also has similar LREE enrichment with an average $(\text{La}/\text{Nd})_{\text{cn}}$ ratio of 2.7, and contains minor Fe and high Ca and Th contents (up to 0.57, 2.85 and 8.67 wt.% respective oxides).

Allanite from the two locations contains small amounts of F, MnO and TiO_2 (up to 0.44, 0.46 and 1.85 wt. %, respectively). Chondrite-normalized REE patterns of the Qingxi and Guanxi allanites are characterized by LREE enrichment with an average $(\text{La}/\text{Nd})_{\text{cn}}$ ratio of 2.8 and 5.7, respectively (Fig. 5b).

Bastnäsite and parisite in Qingxi and Guanxi mainly occur as anhedral shapes within the biotite and in the interstitial positions between the biotite and feldspar or quartz. The bastnäsite in Qingxi samples contains a variable CaO content (3.64-7.91 wt. %) and shows strong LREE enrichment with an average $(\text{La}/\text{Y})_{\text{cn}}$ value of 23. The parisite from Qingxi and Guanxi has little FeO (up to 0.97 wt. %), and all the detected grains show LREE enrichment with $(\text{La}/\text{Y})_{\text{cn}}$ ranging from 29 to 199.

4.2.5. Other minor and accessory minerals

Zircons, analyzed by LA-ICP-MS, occur as euhedral grains with ovoid shapes. Results from the Qingxi and Guanxi samples show negative Sr and Ba anomalies and positive Nb, Pb, Hf and Ta anomalies on the primary mantle

normalized pattern (Fig. 4a). Their REE distribution patterns are strong HREE enrichment with $(La/Yb)_{cn} < 0.02$. Positive Ce ($\delta Ce = 1.8$ to 26) and negative Eu anomalies ($\delta Eu = 0.04$ to 0.1) were observed in zircons from both locations (Fig. 5a).

Titanite, rutile and thorite were observed in the Guanxi granites. Titanite occurs as euhedral to semi-euhedral crystals and contains small amounts of F, Al and Fe (up to 1.62, 3.13 and 1.82 wt. % respective oxides). On the primary mantle normalized pattern, titanite displays negative Sr, Ba anomalies (up to 7.1 and 1.7 ppm, respectively) and positive Zr, Nb, Pb, Ta anomalies (up to 696, 11966, 14.3 and 1104 ppm, respectively). This mineral contains high amounts of REE (up to 15934 ppm) and shows variable REE patterns of LREE depletion to slight LREE enrichment with $(La/Yb)_{cn}$ ranging from 0.05 to 1.14 (Fig. 5a). Negative Eu and positive Ce anomalies were also observed ($\delta Eu = 0.05$ to 0.23, $\delta Ce = 1.22$ to 1.43). Rutile has anhedral shapes and often occurs within or along the biotite grains. Minor concentrations of FeO, P_2O_5 and F were detected (up to 1.55, 0.03 and 0.08 wt. %, respectively). Rutile contains little REE, with Ce_2O_3 accounting for up to 0.05 wt. %. Thorite contains detectable levels of F, FeO and P_2O_5 (up to 0.51, 1.19 and 1.37 wt. %, respectively) and it has a minor REE content and LREE enrichment with $(La/Y)_{cn}$ of 5-17. Chlorite occurs as the secondary mineral in the Guanxi granites and was the product of alteration in biotite along the cleavage. Minor F, MnO and TiO_2 were determined in the chlorite.

4.3. Whole rock geochemistry

The granites record high SiO_2 contents ranging from 70.7 to 72.3 wt. % for Qingxi and 71.1 to 77.5 wt. % for Guanxi. All the samples plot in the high K calc-alkaline area (Fig. 7a). K_2O content is 4.8 to 5.17 wt. % for the Qingxi samples and 3.97 to 4.92 wt. % for the Guanxi samples. A plot of A/NK vs. A/CNK [A/CNK = molar ratios of $\text{Al}_2\text{O}_3/(\text{CaO}+\text{K}_2\text{O}+\text{Na}_2\text{O})$] (Maniar and Piccoli, 1989) shows a meta-aluminous to weakly peraluminous character (Fig. 7b). The CaO , P_2O_5 and TiO_2 contents of the samples decrease slightly with SiO_2 contents increasing in the Harker diagram (Fig. 8). The Qingxi granites have a slightly higher total FeO content than the Guanxi rocks (average 2.15 vs. 1.7 wt. %).

Both the Qingxi and Guanxi samples show enrichment in most trace elements, except Sr and Ti relative to the primary mantle (Fig. 4b). Strongly positive Rb, Th and U anomalies were observed in the samples. The Qingxi granites have higher Ba and Sr and less Nb contents than the Guanxi samples. Th/U and Rb/Sr ratios for Qingxi and Guanxi samples range from 1.4-4.4, 1.8-12.4, and 1.6-5.9, 1.2-99.5, respectively. They show LREE enrichment with a strongly negative Eu anomaly; one Guanxi sample has a negative Ce anomaly ($\delta\text{Ce} = 0.63$) (Fig. 5c). In contrast, the Qingxi granites have slightly higher total REE contents (average 201 ppm), a steeper REE pattern [$(\text{La/Yb})_{\text{cn}} = 12-18$] and a less negative Eu anomaly ($\delta\text{Eu} = 0.21-0.56$) than the

Guanxi samples [average total REE 175 ppm; $(La/Yb)_{cn} = 6-12$; $\delta Eu = 0.02-0.28$].

5. Discussion

5.1. Petrogenesis

The Qingxi and Guanxi granites have high K_2O contents and plot between the high K cal-alkaline and shoshonite field (Fig. 7a). Most Triassic granitoids formed in the Nanling area are characterized by a peraluminous character with high initial $^{87}Sr/^{86}Sr$ ratios (0.71049-0.74212) and low $\epsilon_{Nd(t)}$ ratios (-14.4 to -4.1) (Guo et al., 2012). Previous research has suggested an S-type origin (Wang et al., 2007; Mao et al., 2011; Gao et al., 2014). Similarly, the Yanshanian granites also show peraluminous character. Their petrogenesis is disputed, including S-type or differentiated I-type (Li et al., 2007), and A-type (Zhu et al., 2010; Wang, et al., 2015).

In this study, the Triassic Qingxi and Jurassic Guanxi granites are characterized by high Rb and low Sr and Ba compositions, and negative Eu anomalies (Fig. 4b, 5c), indicating a strong magmatic differentiation. Both granites show a meta-aluminous to slightly peraluminous character. However, the typical S-type mineral assemblages of cordierite and garnet are absent. The Qingxi and Guanxi granites have relatively higher K_2O/Na_2O ratios (1.2-1.4) than the typical I-type with a K_2O/Na_2O ratio less than 1.0 (Chappell, 1999; Chappell et al., 2012; Gao et al., 2014). In plots of FeO_T/MgO and

K₂O+Na₂O vs. Ga/Al, these rocks differ from M-, S-, and I-type granites, but similar to A-type granites (Fig. 9). The aluminous A-type granites were reported in Australia and China (King et al., 1997; Wang et al., 2015). Our samples show relatively small REE differentiation [(La/Yb)_{cn} <30] which is consistent with typical aluminous A-type granites, as summarized by Bonin (2007).

The petrogenesis of A-type granites remains controversial. Hypotheses include differentiation of mantle derived alkaline or tholeiite, or basaltic magmas (e.g., Eby, 1992; Frost and Frost, 1997), melting of lower crustal rocks affected by mantle materials (e.g., Collins et al., 1982; Whalen et al., 1987) and magma mixing of crustal and mantle sources (Yang et al., 2006). Many studies have suggested that A-type granites originated in post-orogenic or anorogenic settings (Whalen et al., 1987; Eby, 1990; Nédélec et al., 1995). Eby (1992) divided A-type granite into A1 and A2 groups. The A1 group has generated in a rift setting and is associated with hotspot or mantle plumes, and has similar Yb/Ta-Y/Nb ratios to oceanic-island basalts. This group represents magmas in continental rift or intraplate settings. The A2 group represents magmas derived from continental crust or underplated crust that has been through a cycle of continent–continent collision or island-arc magmatism, and has Yb/Ta-Y/Nb ratios between continental crusts and island-arc basalts. Based on the geochemical discrimination diagram of Eby (1992), most Qingxi and Guanxi granites fall into the A2 group; several Guanxi samples however

are affined to the A1 group. Note that the Middle Jurassic Zhaibei granites (172 Ma; Li et al., 2003), close to the Guanxi rocks (Fig. 1c), fall into the A1 group (Fig. 10).

In the Rb-(Y+Nb) diagram for discriminating the tectonic setting of granites, most samples plot into a post-COLG granite field (Fig. 11). In the ocean ridge granite-normalized diagram, these granites are characterized by strongly negative Ba anomalies and high levels of Rb and Th relative to Nb and Ta, suggesting a crust-dominated pattern (Pearce, 1984) (Fig. 4c). Models have been proposed to explain the tectonic setting of South China in the Mesozoic, including an active continental margin related to the subduction of the Paleo-Pacific plate (Zhou and Li, 2000), continental extension and rifting (Gilder et al., 1996; Li, 2000) and an Alpine-type continental collision (Hsü et al., 1988, 1990). The Late Triassic Qingxi and Early Jurassic Guanxi granites are characterized by A2-type, and the younger Zhaibei granites are characterized by A1-type, implying a transition environment from post-collision to within-plate. Paleomagnetic and petrological studies have suggested that the collision between the South and North China blocks began in the Late Permian and terminated in the Late Triassic (Zhao and Coe, 1987; Xu et al., 2014). Therefore, the Late Triassic-Early Jurassic granites in South China may have formed in a post-orogenic setting.

5.2. Metallogenic implications

By using the REE composition of different minerals (Table 5) we roughly estimate the REE contribution of the granites. Compared with the REE contents of whole rocks (201 ppm for Qingxi and 175 ppm for Guanxi), the major minerals, including apatite, contribute less than 30%. Most REE derive from the accessory REE minerals, especially LREE minerals of monazite and bastnäsite. The LREE minerals in the Qingxi and Guanxi granites mostly occur as inclusions in the biotite, showing primary characteristics (Fig. 2). This indicates that the granitic magmas in South China are enriched in REE which may derive from strong crystallization fractionation and/or REE-rich sources. Both the Qingxi and Gaunxi granites are characterized by strongly positive Pb, Th and U anomalies and negative Sr and Eu anomalies (Figs. 4b, 5c). Their apatites also show similar Sr and Eu geochemical features (Figs. 4a, 5a), indicating feldspar fractionation. Eu and Sr are compatible, whereas Pb, Th and U are incompatible with respect to feldspar in silicate melts, including andesitic to dacitic compositions (Bédard, 2006; Severs, et al., 2009). However, crystal fractionation may be not the key for REE enrichment in South China. The Guanxi granites show a more negative Eu anomaly than the Qingxi rocks (average $\delta\text{Eu} = 0.17$ vs. 0.38), suggesting a stronger fractionation. However, the former has a relatively lower total REE content (average $\Sigma\text{REE} = 174$ ppm vs. 218 ppm), therefore their source contribution cannot be neglected.

Investigations have demonstrated that peralkaline and alkaline granitic rocks are commonly associated with economic deposits of REE, such as

Strange Lake and Thor Lake alkaline complexes in Canada (Salvi and Williams-Jones, 1996; Gysi and Williams-Jones, 2013) and Khan Bogd and Khaldzan Buregte peralkaline granitoids in Mongolia (Kovalenko et al., 1995; Kynicky et al., 2011). The alkali-rich composition can enhance the solubility of volatiles in melt phases, which in turn increases the mobility of REE in the alkaline melt (Kogarko, 1990; Bartels et al., 2013). However, most granitoids in the Nanling region show a metaluminous to peraluminous character (Li et al., 2003, 2007; Wang et al., 2015, and this study). Both the Qingxi and Guanxi granites have a crust-dominant pattern (Fig. 4c). In the Nanling region, the basement is composed of biotite schist, biotite leptynite and biotite gneiss, which contains minor sillimanite and shows peraluminous composition (Luo et al., 2003). Although most Mesozoic granitoids in the Nanling region formed at the similar ages, they produced different multi-metallic mineralization of W-Sn-Nb-Ta-REE. This implies that their basement may have undergone different source evolution. Yu and Shen (2007), by comparing the petrology and geochemistry of the basements in South China, suggested that the basements in different areas have different source compositions, including Mesoproterozoic, Neoproterozoic and Early Paleozoic materials. Therefore, basement composition may play a role in REE enrichment.

6. Conclusions

Based on the petrological and geochemical analyses of the Qingxi and

Guanxi granites in the Nanling region, the following conclusions can be drawn:

1. LA-ICP-MS zircon U-Pb ages indicate that the Qingxi and Guanxi granites formed at 223.0 ± 0.7 Ma and 198.8 ± 1.4 Ma, respectively.
2. The Qingxi and Guanxi rocks are metaluminous to slightly peraluminous A-type granites. They may have formed in a post-collision environment.
3. Both the Qingxi and Guanxi granites contain abundant primary REE minerals which control the whole-rock REE content. Their magmas may have high REE composition due to sourced from REE-rich basements.

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Figure captions

Fig. 1. Simplified map showing the distribution of Mesozoic granites and volcanics in South China (a; modified after Zhou and Li, 2000), Qingxi (b) and Guanxi sampling sites (c; modified after Li et al., 2003 and Yu et al., 2012).

Fig. 2. Selected characteristic textures observed at the Qingxi (a-c, g-i) and Guanxi (d-f, j-l) granites under cross-polarized transmitted light (a–g) and back-scattered electron images (h–l). Pl, plagioclase; Kfs, K-feldspar; Q, quartz; Bt, biotite; Il, ilmenite; Spn, titanite; Chl, chlorite; Zrn, zircon; Rt, rutile; Mnz, monazite; Thr, thorite; Ap, apatite; Mag, magnetite; Xtm, xenotime.

Fig. 3. U-Pb concordia diagrams and CL images of representative zircons from the Qingxi (a) and Guanxi (b) samples.

Fig. 4. Primitive mantle (a, b) and ocean ridge granites (ORG) (c) normalized chemical compositions for the representative minerals and their whole rocks in Qingxi and Guanxi. The primitive mantle values are from Sun and McDonough (1989) and the ocean ridge granite values from Pearce et al. (1984).

Fig. 5. Chondrite normalized REE distribution patterns for apatites, titanites and zircons (a), REE minerals (b) and their whole rocks (c). Chondrite values are from Sun and McDonough (1989).

706 Fig. 6. Classification diagram for biotite (Foster, 1960). I- phlogopite; II-
707 iron-phlogopite; III – eastonite; IV – magnesio-biotite; V – ferri-biotite; VI –
708 annite (siderophyllite); VII – alumino-mica.

709 Fig. 7. K_2O vs. SiO_2 (a), and A/NK vs. A/CNK (b) diagrams for the Qingxi and
710 Guanxi granites. The compositional fields are from Rollinson (1993) and
711 Streckeisen and Le Maitre (1979).

712 Fig. 8. Harker diagrams for the Qingxi and Guanxi granites. Symbols are the
713 same as in Fig. 7.

714 Fig. 9. K_2O+Na_2O and FeO_T+MgO vs. $10,000Ga/Al$ discrimination diagrams of
715 Whalen et al. (1987). Symbols are the same as in Fig. 7.

716 Fig. 10. Plots of the Qingxi, Guanxi and Zhaibei granites in the Nb–Y–Ce
717 ternary diagram for a subdivision of the A1- and A2-type granites of Eby (1992).
718 The Zhaibei data are from Wang et al. (2015).

719 Fig. 11. Rb vs. (Y+Nb) discrimination diagram after Pearce et al. (1984). VAG,
720 volcanic arc granite; ORG, ocean ridge granite; WPG, within-plate granite;
721 syn-COLG, syn-collisional granite; post-COLG, post-collisional granite.
722 Symbols are the same as in Fig. 7.

Figures 1-11

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Table 1 LA-ICP-MS U-Pb analytical data of the zircons from Qingxi (A) and Guanxi (B) granites

Anal.	Pb	Th	U	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$	
	(ppm)	(ppm)	(ppm)		1s		1s		1s		Age (Ma)	1s	Age (Ma)	1s	Age (Ma)	1s
A-4-2	24	146	665	0.2201	0.05157	0.00122	0.24702	0.00564	0.03473	0.00040	266	32	224	5	220	2
A-4-4	16	279	367	0.7611	0.04884	0.00208	0.23765	0.00989	0.03528	0.00048	140	72	216	8	224	3
A-4-5	24	102	656	0.1550	0.05024	0.00121	0.24866	0.00576	0.03588	0.00041	206	33	225	5	227	3
A-4-7	19	215	478	0.4489	0.05077	0.00135	0.25206	0.00649	0.03599	0.00043	230	38	228	5	228	3
A-4-9	71	336	2008	0.1671	0.05149	0.00112	0.24717	0.00517	0.03480	0.00039	263	28	224	4	221	2
A-4-10	20	312	496	0.6301	0.05213	0.00144	0.24809	0.00662	0.03450	0.00042	291	39	225	5	219	3
A-4-11	31	118	873	0.1351	0.05149	0.00130	0.24653	0.00601	0.03472	0.00042	263	34	224	5	220	3
A-4-12	60	243	1670	0.1458	0.05144	0.00165	0.24780	0.00740	0.03494	0.00041	261	76	225	6	221	3
A-4-14	10	149	246	0.6049	0.05251	0.00195	0.25671	0.00928	0.03545	0.00048	308	58	232	7	225	3
A-4-19	18	411	408	1.0085	0.05148	0.00157	0.24894	0.00735	0.03506	0.00045	262	44	226	6	222	3
A-4-21	10	147	224	0.6564	0.05102	0.00197	0.25760	0.00969	0.03660	0.00051	242	61	233	8	232	3
A-4-22	19	383	419	0.9147	0.05206	0.00164	0.25226	0.00770	0.03513	0.00046	288	46	228	6	223	3
A-4-23	36	371	947	0.3918	0.05265	0.00136	0.24756	0.00619	0.03409	0.00042	314	35	225	5	216	3
A-4-26	20	300	467	0.6423	0.05151	0.00164	0.25374	0.00783	0.03572	0.00047	264	47	230	6	226	3
A-4-28	27	192	750	0.2564	0.05210	0.00147	0.24774	0.00675	0.03448	0.00044	290	39	225	5	219	3
B-2-3	28	466	778	0.5990	0.05153	0.00112	0.21682	0.00455	0.03051	0.00033	265	29	199	4	194	2
B-2-4	65	1031	1789	0.5762	0.05031	0.00090	0.21868	0.00375	0.03151	0.00033	209	21	201	3	200	2
B-2-5	158	1950	4556	0.4281	0.05034	0.00080	0.21814	0.00330	0.03142	0.00032	211	18	200	3	199	2
B-2-6	69	1179	1950	0.6047	0.05037	0.00089	0.21317	0.00359	0.03068	0.00032	212	21	196	3	195	2
B-2-7	50	723	1461	0.4950	0.05017	0.00091	0.21234	0.00370	0.03069	0.00032	203	22	196	3	195	2
B-2-8	69	1620	1776	0.9124	0.05263	0.00095	0.22186	0.00385	0.03057	0.00032	313	21	203	3	194	2
B-2-10	160	2662	4451	0.5979	0.05139	0.00087	0.21684	0.00349	0.03059	0.00032	258	19	199	3	194	2
B-2-11	14	174	387	0.4496	0.05220	0.00164	0.22693	0.00691	0.03152	0.00039	294	47	208	6	200	2
B-2-13	21	353	551	0.6413	0.05080	0.00139	0.22298	0.00588	0.03182	0.00038	232	39	204	5	202	2
B-2-18	137	1991	3783	0.5261	0.05079	0.00089	0.22218	0.00374	0.03172	0.00033	231	21	204	3	201	2
B-2-19	46	701	1254	0.5592	0.05082	0.00102	0.22152	0.00426	0.03160	0.00034	233	25	203	4	201	2
B-2-20	97	1298	2732	0.4749	0.05103	0.00091	0.22376	0.00380	0.03179	0.00033	242	21	205	3	202	2
B-2-26	5	58	144	0.4045	0.05236	0.00303	0.22405	0.01270	0.03103	0.00048	301	101	205	11	197	3
B-2-28	173	2492	4860	0.5127	0.05071	0.00091	0.21981	0.00379	0.03143	0.00033	228	21	202	3	199	2

Table 2 Electron microprobe analyses (wt. %) of representative minerals from the Qingxi and Guanxi granites

	Plagioclase		K-feldspar		Biotite		Muscovite		Rutile				
	Qingxi		Guanxi		Qingxi		Guanxi		Qingxi	Guanxi			
SiO ₂	63.99	60.45	64.24	65.05	63.93	35.27	33.20	34.32	33.38	36.00	45.17	0.19	0.10
TiO ₂	0.02	0.02	b.d.l	b.d.l	b.d.l	3.33	3.52	1.99	2.97	2.30	0.25	96.03	94.86
Al ₂ O ₃	23.05	23.55	21.82	19.04	18.52	17.99	19.14	18.85	19.71	13.57	30.21	0.10	0.01
FeO	b.d.l	0.30	0.03	0.03	b.d.l	23.70	23.12	22.05	23.30	27.80	2.49	0.30	1.55
MnO	0.04	0.00	b.d.l	0.04	b.d.l	0.31	0.36	0.58	0.64	0.31	0.07	b.d.l	b.d.l
MgO	0.01	0.09	0.14	b.d.l	b.d.l	6.37	5.64	5.77	5.02	8.63	2.10	b.d.l	0.01
CaO	3.64	2.04	2.06	0.27	b.d.l	0.01	b.d.l	0.01	b.d.l	0.01	0.00	0.05	0.00
Na ₂ O	9.67	7.16	10.58	1.27	0.28	0.04	0.17	0.11	0.16	0.10	0.15	0.00	b.d.l
K ₂ O	0.16	0.13	0.20	14.43	16.16	9.31	9.21	9.34	9.33	6.58	10.29	0.14	0.06
P ₂ O ₅	0.03	0.01	0.27	0.19	b.d.l	b.d.l	0.00	0.02	0.03	0.01	0.00	0.03	0.01
F	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.92	0.54	0.81	0.67	1.35	0.70	0.08	b.d.l
Cr ₂ O ₃	0.01	b.d.l	b.d.l	b.d.l	0.14	0.04	0.01	0.02	b.d.l	b.d.l	0.01	0.05	b.d.l
NiO	0.02	0.01	b.d.l	0.02	b.d.l	b.d.l	b.d.l	0.02	b.d.l	0.04	0.05	b.d.l	b.d.l
F=O						-0.39	-0.23	-0.34	-0.28	-0.57	-0.29	-0.03	
Total	100.61	93.76	99.32	100.33	99.03	96.90	94.67	93.55	94.92	96.13	91.21	96.93	96.59
	Allanite		Thorite		Monazite								
	Qingxi	Guanxi	Guanxi		Qingxi								
SiO ₂	25.67	32.32	32.28	18.23	21.30	1.09	0.25	2.41	0.77	1.00	0.47	0.92	1.38
TiO ₂	0.60	1.62	1.85	0.01	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Al ₂ O ₃	12.89	12.40	12.59	b.d.l	1.13	0.26	b.d.l	0.19	0.01	0.03	b.d.l	b.d.l	0.02
FeO	9.85	16.67	15.80	0.38	1.19	1.20	0.60	0.74	0.11	1.48	0.24	0.20	0.32
MnO	0.46	0.38	0.17	0.07	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
MgO	1.34	0.77	1.48	b.d.l	0.01	0.06	0.03	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.00
CaO	7.81	9.98	9.57	1.51	1.57	1.33	1.62	1.05	1.67	0.82	1.53	0.36	1.67
Na ₂ O	0.08	0.01	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
K ₂ O	0.12	0.01	b.d.l	b.d.l	b.d.l	0.11	0.05	0.01	0.01	b.d.l	b.d.l	0.00	0.03
P ₂ O ₅	0.63	0.03	b.d.l	1.37	0.15	30.08	30.05	27.38	29.77	29.34	29.31	29.66	29.73
F	0.38	0.27	0.44	0.31	0.51	0.80	0.79	0.93	0.73	0.51	0.55	0.63	0.83
Cr ₂ O ₃	b.d.l	b.d.l	b.d.l	b.d.l	0.01	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Nb ₂ O ₅	b.d.l	0.05	b.d.l	b.d.l	b.d.l	b.d.l	0.03	0.05	0.02	b.d.l	b.d.l	b.d.l	b.d.l
Ta ₂ O ₅	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.08	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
ThO ₂	-	0.41	0.48	53.37	41.25	-	-	-	-	-	-	-	-
ZrO ₂	0.20	0.01	0.04	b.d.l	0.00	b.d.l	0.04	0.13	0.06	0.08	0.08	0.05	0.07
La ₂ O ₃	4.80	8.64	8.47	0.82	0.44	11.87	12.46	12.75	13.58	12.79	11.92	14.10	11.93
Ce ₂ O ₃	10.11	11.55	12.50	1.97	1.33	28.40	27.99	29.80	30.74	30.93	28.63	33.20	24.27
Nd ₂ O ₃	3.35	2.74	3.18	1.33	0.84	9.43	9.96	10.46	9.86	11.30	11.03	11.76	11.37
Dy ₂ O ₃	0.20	0.31	0.51	b.d.l	0.01	0.30	0.62	0.14	0.47	0.38	0.24	0.34	0.13
Yb ₂ O ₃	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Lu ₂ O ₃	b.d.l	b.d.l	b.d.l	b.d.l	0.11	0.15	0.20	0.23	0.20	0.18	0.14	0.02	b.d.l
Y ₂ O ₃	0.33	0.05	0.22	0.35	0.61	2.76	1.67	0.36	1.37	0.88	1.90	0.43	0.77
F=O	-0.16	-0.11	-0.19	-0.13	-0.21	-0.34	-0.33	-0.39	-0.31	-0.21	-0.23	-0.27	-0.35
Total	78.65	98.10	99.38	79.59	70.24	87.55	86.01	86.24	89.04	89.51	85.80	91.41	82.16

Table2 (continued)

	Titanite		Apatite							Chlorite		
	Guanxi		Qingxi		Guanxi					Guanxi		
SiO ₂	29.93	29.88	0.14	0.36	0.02	0.05	1.15	0.55	0.05	29.21	27.98	27.56
TiO ₂	31.38	29.03	b.d.1	0.05	0.05	0.07	0.00	0.02	0.01	0.55	0.24	6.84
Al ₂ O ₃	2.92	3.13	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.03	b.d.1	16.46	17.04	15.24
FeO	1.73	1.82	0.15	0.53	0.24	0.51	0.10	0.26	0.25	28.79	32.21	27.93
MnO	0.09	0.16	0.54	0.97	0.79	1.10	b.d.1	0.03	0.81	0.28	0.35	0.29
MgO	0.14	0.17	0.05	0.07	0.03	0.06	0.01	b.d.1	0.05	12.82	11.49	6.98
CaO	26.17	25.80	53.43	54.13	52.92	51.85	52.16	54.45	52.73	0.05	0.03	5.83
Na ₂ O	0.01	0.01	0.13	0.13	0.15	0.16	0.01	b.d.1	0.21	0.11	0.01	0.02
K ₂ O	b.d.1	b.d.1	b.d.1	0.02	0.02	0.03	0.02	0.04	0.13	0.21	0.04	0.01
P ₂ O ₅	0.06	0.06	40.66	40.16	41.00	41.47	38.43	38.45	40.93	0.01	0.00	0.04
F	1.27	1.62	3.37	3.81	3.51	3.24	3.28	3.71	3.87	0.41	0.05	0.12
Cr ₂ O ₃	0.03	b.d.1	b.d.1	b.d.1	b.d.1	0.05	b.d.1	0.03	0.01	b.d.1	0.07	b.d.1
NiO	b.d.1	0.01	0.00	b.d.1	0.03	0.06	b.d.1	b.d.1	b.d.1	b.d.1	0.02	b.d.1
F=O	-0.53	-0.68	-1.42	-1.60	-1.48	-1.36	-1.38	-1.56	-1.63	-0.17	-0.02	-0.05
Total	93.18	91.02	97.05	98.64	97.29	97.28	93.78	96.01	97.42	88.72	89.52	90.81

	Monazite												
	Qingxi										Guanxi		
SiO ₂	0.83	0.60	0.79	0.44	0.66	0.60	0.71	0.51	0.74	0.55	0.67	0.57	0.37
TiO ₂	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Al ₂ O ₃	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
FeO	0.40	0.15	0.60	0.06	0.08	0.12	0.36	0.04	0.25	0.21	0.18	0.12	0.09
MnO	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
MgO	b.d.1	b.d.1	0.03	0.01	0.02	0.01	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
CaO	0.72	0.95	0.88	0.87	0.86	1.10	0.66	1.25	0.98	0.71	1.42	2.85	1.66
Na ₂ O	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
K ₂ O	0.02	0.02	0.05	0.04	b.d.1	0.00	0.01	b.d.1	0.03	0.01	b.d.1	b.d.1	b.d.1
P ₂ O ₅	29.38	29.80	29.96	30.14	29.93	30.37	29.87	30.28	30.11	28.86	30.38	28.95	30.29
F	0.54	0.65	0.54	0.89	0.39	0.85	0.76	0.60	0.73	0.57	0.69	0.76	0.70
Cr ₂ O ₃	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Nb ₂ O ₅	0.01	b.d.1	0.02	b.d.1	b.d.1	b.d.1	0.06	b.d.1	b.d.1	0.01	b.d.1	0.03	0.04
Ta ₂ O ₅	b.d.1	0.04	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.09	b.d.1	b.d.1	b.d.1	0.01
ThO ₂	-	-	-	-	-	-	-	-	-	-	-	-	-
ZrO ₂	0.09	0.13	0.01	0.08	0.07	0.06	0.09	0.01	0.03	0.10	0.11	0.01	0.06
La ₂ O ₃	15.47	14.88	15.16	15.54	13.85	13.59	15.24	13.99	15.63	15.00	12.88	10.68	11.97
Ce ₂ O ₃	32.48	30.42	32.25	30.94	30.73	32.13	31.41	30.15	31.91	32.79	28.37	28.32	26.70
Nd ₂ O ₃	9.45	10.32	10.08	9.71	10.45	9.95	9.29	9.61	9.78	9.12	9.65	9.96	9.95
Dy ₂ O ₃	0.08	0.03	0.12	0.12	0.05	b.d.1	b.d.1	0.21	0.63	0.40	0.64	b.d.1	0.60
Yb ₂ O ₃	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Y ₂ O ₃	0.73	1.21	1.24	0.74	1.58	1.50	0.95	2.50	0.96	1.13	1.95	2.02	2.26
F=O	-0.23	-0.27	-0.23	-0.37	-0.16	-0.36	-0.32	-0.25	-0.31	-0.24	-0.29	-0.32	-0.29
Total	89.98	88.92	91.49	89.19	88.49	89.92	89.10	88.88	91.54	89.21	86.67	83.95	84.39

Table2 (continued)

Monazite													
Guanxi													
SiO ₂	0.78	0.68	0.93	0.90	0.25	0.23	0.61	0.54	1.36	0.86	0.62	0.41	2.43
TiO ₂	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.00	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Al ₂ O ₃	b.d.l	0.02	b.d.l	b.d.l	0.01	0.03	0.10	0.12	b.d.l	b.d.l	b.d.l	b.d.l	0.06
FeO	0.22	0.57	0.02	0.11	0.11	0.02	0.07	0.11	b.d.l	0.03	0.02	0.02	0.01
MnO	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
MgO	b.d.l	0.00	b.d.l	b.d.l	b.d.l	0.01	0.03	0.09	0.01	b.d.l	b.d.l	b.d.l	0.03
CaO	0.43	0.91	1.03	0.76	1.28	1.27	0.81	1.02	0.97	1.20	1.94	2.34	2.14
Na ₂ O	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
K ₂ O	0.02	0.07	b.d.l	0.00	b.d.l	0.03	0.01	0.07	0.10	0.01	b.d.l	b.d.l	b.d.l
P ₂ O ₅	29.89	26.96	29.78	29.50	29.41	29.18	27.99	30.41	29.02	28.91	29.42	29.91	27.19
F	0.62	0.77	0.60	0.71	0.72	1.20	1.07	1.41	0.93	0.89	1.35	1.17	0.96
Cr ₂ O ₃	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Nb ₂ O ₅	b.d.l	0.11	b.d.l	b.d.l	0.01	0.04	b.d.l	0.02	b.d.l	b.d.l	0.00	0.05	0.02
Ta ₂ O ₅	b.d.l	b.d.l	b.d.l	b.d.l	0.12	b.d.l	0.04	0.06	0.01	b.d.l	b.d.l	b.d.l	b.d.l
ThO ₂	-	-	-	-	-	0.28	0.62	1.25	4.79	5.46	6.58	6.99	8.67
ZrO ₂	0.05	0.12	0.03	b.d.l	0.07	0.09	0.06	0.07	0.06	0.05	0.04	0.09	0.53
La ₂ O ₃	14.79	14.80	12.20	16.35	13.42	15.20	20.72	8.34	15.36	18.01	13.74	13.90	11.97
Ce ₂ O ₃	31.04	30.42	31.04	31.62	29.32	28.23	33.86	30.59	26.89	27.37	25.22	24.93	23.83
Nd ₂ O ₃	9.89	9.49	10.03	9.68	9.56	14.67	5.73	18.08	12.71	10.96	12.43	11.59	11.43
Dy ₂ O ₃	0.33	0.20	0.15	b.d.l	0.21	0.39	0.23	0.33	b.d.l	0.72	0.58	0.08	0.55
Yb ₂ O ₃	b.d.l	b.d.l	b.d.l	0.02	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Y ₂ O ₃	0.86	1.35	1.52	0.81	1.81	0.66	0.27	0.26	0.42	0.74	1.20	1.76	0.47
F=O	-0.26	-0.32	-0.25	-0.30	-0.30	-0.51	-0.45	-0.59	-0.39	-0.37	-0.57	-0.49	-0.40
Total	88.67	86.16	87.09	90.16	85.98	91.02	91.77	92.18	92.22	94.84	92.57	92.73	89.89
Bastnäsité													
Qingxi				Parisité		Guanxi							
SiO ₂	0.83	1.08	0.30	1.99	4.55	0.39	0.68	1.38	0.02	2.17	1.18	0.17	0.08
TiO ₂	b.d.l	0.15	0.10	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	8.95	b.d.l	b.d.l	b.d.l
Al ₂ O ₃	0.35	0.38	0.18	1.02	3.08	0.35	0.68	1.21	b.d.l	1.21	0.62	0.12	0.02
FeO	0.43	0.33	0.97	0.17	0.53	0.29	0.12	0.43	0.01	0.44	0.14	0.19	0.03
MnO	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
MgO	0.04	0.03	0.19	0.07	0.20	0.11	0.14	0.22	b.d.l	0.09	0.02	b.d.l	b.d.l
CaO	7.91	3.64	16.06	17.26	15.36	17.68	17.34	17.67	18.14	14.21	15.12	16.74	17.81
Na ₂ O	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
K ₂ O	0.05	0.04	0.02	0.19	0.41	0.02	0.21	0.32	0.01	0.33	0.21	0.12	0.11
P ₂ O ₅	b.d.l	0.04	0.14	0.02	0.03	0.03	0.12	0.08	0.02	b.d.l	b.d.l	0.02	0.04
F	7.18	7.41	5.16	5.80	5.25	5.96	5.49	6.80	5.37	6.76	6.78	6.49	5.28
Cr ₂ O ₃	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Nb ₂ O ₅	0.00	b.d.l	b.d.l	0.06	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.23	b.d.l	b.d.l	b.d.l
Ta ₂ O ₅	0.06	b.d.l	0.03	b.d.l	b.d.l	0.12	0.04	b.d.l	b.d.l	0.05	0.04	0.03	0.06
ThO ₂	-	-	-	0.08	0.20	0.02	0.08	0.10	0.19	0.60	0.88	0.02	0.05
ZrO ₂	b.d.l	b.d.l	0.05	b.d.l	b.d.l	b.d.l	0.05	0.03	0.01	0.00	b.d.l	0.02	b.d.l
La ₂ O ₃	12.07	14.93	9.24	13.78	14.32	13.59	12.87	13.74	18.73	9.94	9.43	15.07	13.65
Ce ₂ O ₃	30.78	33.01	22.29	22.97	22.42	25.09	23.50	22.63	25.35	18.85	22.30	24.29	22.65
Nd ₂ O ₃	10.53	12.08	7.99	10.20	10.68	9.60	11.44	10.82	4.60	10.46	15.28	11.36	11.62
Dy ₂ O ₃	0.97	0.60	0.71	0.34	0.34	b.d.l	0.33	0.01	0.80	0.05	b.d.l	0.43	0.23
Yb ₂ O ₃	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.06	b.d.l	b.d.l	b.d.l	b.d.l
Y ₂ O ₃	4.49	4.11	2.26	0.68	0.88	0.49	1.21	0.89	1.50	0.81	0.88	0.85	1.73
F=O	-3.02	-3.12	-2.17	-2.44	-2.21	-2.51	-2.31	-2.86	-2.26	-2.85	-2.85	-2.73	-2.22
Total	72.65	74.70	63.50	72.17	76.04	71.23	71.96	73.46	72.55	72.29	70.01	73.19	71.12

b.d.l, below the detection limits; - was not analyzed.

Table 3 LA-ICP-MS analyses (ppm) of feldspar, apatite, biotite, zircon and titanite crystals from Qingxi and Guanxi granites.

	Plagioclase									K-feldspar		Biotite					
	Qingxi		Guanxi							Guanxi		Qingxi					
Rb	1853	385	69.1	169	26.4	3.22	86.4	4.35	28.5	9.68	730	1468	1498	1729	1910	1533	1498
Sr	148	204	65.5	150	61.9	137	181	283	41.9	252	98.6	0.58	0.78	1.90	0.98	2.29	0.71
Y	1.65	1.00	0.24	0.09	0.09	b.d.1	0.04	0.23	2.44	0.12	b.d.1	0.17	0.07	0.32	0.10	1.22	0.07
Zr	0.67	0.06	0.04	0.03	0.05	0.27	0.36	b.d.1	37.4	0.16	b.d.1	0.07	0.11	0.70	0.17	0.34	0.16
Nb	0.31	b.d.1	0.08	0.05	0.06	b.d.1	b.d.1	b.d.1	2.17	0.12	0.09	108	120	128	117	108	99.4
Mo	0.19	0.09	0.08	b.d.1	0.10	b.d.1	0.29	b.d.1	0.68	0.67	b.d.1	0.44	0.43	0.42	0.44	0.47	0.43
Ba	182	585	20.9	24.4	8.54	24.0	46.0	160	70.1	87.1	71.8	874	841	808	393	274	256
La	32.6	4.30	1.32	1.52	0.64	1.23	1.03	17.0	4.59	12.6	0.46	0.04	b.d.1	0.94	0.67	0.65	0.02
Ce	29.9	7.22	1.67	1.91	0.66	1.08	0.89	18.1	15.1	14.1	0.66	0.11	0.02	1.73	0.52	1.16	0.02
Pr	1.87	1.14	0.13	0.14	0.04	0.14	0.04	1.17	0.84	0.71	b.d.1	b.d.1	b.d.1	0.22	0.06	0.10	b.d.1
Nd	3.99	2.23	0.37	0.34	0.19	0.11	0.33	3.60	3.34	2.19	b.d.1	b.d.1	b.d.1	0.73	0.35	0.56	0.06
Sm	0.39	0.60	b.d.1	0.06	b.d.1	b.d.1	b.d.1	0.30	0.60	0.26	0.29	b.d.1	b.d.1	b.d.1	b.d.1	0.17	b.d.1
Eu	0.40	0.51	0.31	0.12	0.18	0.17	b.d.1	2.27	b.d.1	1.64	0.31	b.d.1	0.02	b.d.1	b.d.1	b.d.1	b.d.1
Gd	b.d.1	0.18	b.d.1	b.d.1	b.d.1	b.d.1	0.10	0.15	0.95	0.18	b.d.1	b.d.1	b.d.1	0.08	b.d.1	0.23	0.08
Tb	0.04	0.03	b.d.1	b.d.1	0.01	0.02	b.d.1	0.04	0.07	b.d.1	b.d.1	0.02	0.02	b.d.1	0.02	b.d.1	b.d.1
Dy	0.18	0.32	b.d.1	b.d.1	0.04	0.07	b.d.1	0.06	0.32	0.04	0.32	0.06	b.d.1	0.05	b.d.1	0.12	b.d.1
Ho	0.08	0.04	0.03	b.d.1	b.d.1	b.d.1	b.d.1	0.04	0.07	0.04	b.d.1	b.d.1	b.d.1	0.02	b.d.1	0.03	b.d.1
Er	0.19	0.12	b.d.1	0.02	b.d.1	b.d.1	b.d.1	b.d.1	0.10	0.10	b.d.1	b.d.1	b.d.1	0.04	0.04	b.d.1	b.d.1
Tm	0.03	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.03	0.07	0.02	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Yb	0.11	0.13	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.14	b.d.1	0.16	0.24	b.d.1	b.d.1	0.09	b.d.1	0.14	b.d.1
Lu	0.06	b.d.1	0.02	0.01	b.d.1	0.03	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.01
Hf	b.d.1	b.d.1	b.d.1	b.d.1	0.05	b.d.1	b.d.1	b.d.1	0.93	0.09	b.d.1	0.08	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Ta	b.d.1	0.03	b.d.1	0.01	0.01	b.d.1	b.d.1	b.d.1	0.08	b.d.1	0.04	10.0	9.34	10.7	10.3	8.34	8.27
Pb	21.6	6.17	4.44	1.64	3.07	10.3	1.12	20.8	2.73	18.8	28.4	3.35	4.98	4.61	4.06	5.14	4.45
Th	0.48	0.03	0.03	0.02	0.03	0.06	0.06	0.04	1.78	b.d.1	0.02	b.d.1	b.d.1	0.13	0.04	1.63	b.d.1
U	0.08	b.d.1	0.03	b.d.1	0.02	0.09	0.12	b.d.1	1.83	b.d.1	0.06	b.d.1	b.d.1	0.09	b.d.1	1.45	b.d.1

Table 3 (continued)

	Biotite																
	Qingxi																
Rb	1457	2390	2148	1434	1351	868	911	1080	1717	1072	1925	1252	2146	660	1253	990	1166
Sr	0.83	0.82	1.99	0.67	0.40	0.43	0.34	0.40	1.25	0.71	0.53	0.58	2.05	5.87	0.55	0.36	1.42
Y	0.07	0.03	0.04	0.16	0.09	0.04	0.04	0.05	0.15	0.09	0.02	0.05	0.20	0.33	0.06	0.03	0.12
Zr	0.13	0.15	0.47	0.46	0.71	1.13	1.18	0.89	1.35	0.62	0.93	1.12	1.02	0.22	0.60	1.03	1.26
Nb	110	135	146	98.1	88.6	81.7	87.6	91.9	96.1	121	148	135	158	46.5	128	105	114
Mo	0.29	0.42	0.65	0.27	0.52	0.74	0.54	0.43	0.48	0.51	0.60	0.75	0.69	0.80	0.38	0.62	0.46
Ba	584	233	361	504	567	1015	1045	990	103	1202	52.6	1175	60.5	102	1991	848	345
La	0.01	0.01	0.04	0.05	b.d.1	b.d.1	b.d.1	0.01	0.09	0.01	b.d.1	b.d.1	0.06	0.11	b.d.1	0.01	0.05
Ce	0.01	b.d.1	0.05	0.13	0.11	b.d.1	0.04	b.d.1	0.40	0.03	b.d.1	b.d.1	0.22	0.55	b.d.1	0.01	0.24
Pr	b.d.1	b.d.1	b.d.1	0.01	b.d.1	b.d.1	0.01	b.d.1	0.05	0.03	b.d.1	b.d.1	0.02	0.07	0.02	0.01	0.03
Nd	b.d.1	b.d.1	b.d.1	0.10	b.d.1	b.d.1	b.d.1	0.04	0.23	0.09	b.d.1	b.d.1	0.16	0.15	b.d.1	b.d.1	0.06
Sm	0.09	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.05	0.06	b.d.1	b.d.1	b.d.1	b.d.1	0.08	b.d.1	b.d.1	b.d.1
Eu	0.02	b.d.1	b.d.1	0.03	0.03	0.05	b.d.1	0.03	0.02	b.d.1	b.d.1	0.03	b.d.1	b.d.1	0.04	0.05	b.d.1
Gd	b.d.1	b.d.1	0.07	0.05	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.05	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Tb	b.d.1	b.d.1	b.d.1	0.01	b.d.1	b.d.1	b.d.1	b.d.1	0.01	b.d.1	b.d.1	b.d.1	0.02	b.d.1	0.01	0.02	b.d.1
Dy	b.d.1	b.d.1	b.d.1	0.05	b.d.1	b.d.1	b.d.1	0.06	0.05	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.05
Ho	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.02	b.d.1	0.01	b.d.1
Er	b.d.1	b.d.1	b.d.1	0.02	0.03	b.d.1	b.d.1	b.d.1	0.03	0.02	b.d.1	0.02	0.04	0.05	b.d.1	b.d.1	b.d.1
Tm	b.d.1	0.01	b.d.1	0.01	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.01	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Yb	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.07	b.d.1	0.06	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1
Lu	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.01	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.02	b.d.1	b.d.1	b.d.1
Hf	0.10	b.d.1	0.05	0.11	0.08	0.15	0.13	0.07	0.06	0.09	0.12	0.21	0.16	0.05	0.11	0.14	0.15
Ta	7.94	11.6	12.6	10.9	6.28	4.27	5.56	6.63	15.3	14.8	22.1	12.2	23.6	5.74	15.4	7.07	12.0
Pb	6.07	4.22	7.06	4.54	3.92	3.66	3.19	4.07	3.87	4.01	5.97	5.11	10.2	2.52	5.30	4.32	4.31
Th	b.d.1	b.d.1	0.04	b.d.1	b.d.1	b.d.1	b.d.1	b.d.1	0.06	b.d.1	b.d.1	0.01	1.92	0.07	b.d.1	b.d.1	0.07
U	0.04	0.05	0.04	0.02	0.01	b.d.1	b.d.1	b.d.1	0.20	b.d.1	b.d.1	b.d.1	0.23	0.12	b.d.1	0.02	0.16

Table 3 (continued)

	Biotite						Guanxi						Apatite				
	Qingxi												Qingxi				
Rb	1380	1720	2055	2088	1541	1734	1325	1349	1344	1473	1764	1460	0.50	0.89	0.35	0.39	0.32
Sr	1.02	0.99	0.88	1.34	15.34	6.52	9.07	2.18	2.60	0.95	1.44	1.31	86.7	90.3	90.3	76.8	78.7
Y	0.09	0.13	0.14	0.08	0.72	1.38	0.04	0.02	1.07	0.05	b.d.l	0.02	3766	4701	3176	2982	2867
Zr	0.91	1.41	1.97	1.03	0.27	1.05	3.97	1.98	1.76	0.47	2.12	1.71	0.81	0.97	0.27	0.25	0.30
Nb	132	130	166	191	142	143	54	77.7	108	160	123	111	b.d.l	0.03	b.d.l	b.d.l	0.25
Mo	0.76	0.94	0.97	1.03	1.06	0.84	0.25	b.d.l	0.12	0.88	0.36	0.34	0.70	0.52	0.75	0.44	0.67
Ba	260	1592	1636	562	1252	1324	24.8	33.8	37.5	484	47.8	34.3	0.14	0.19	0.10	0.11	0.16
La	0.07	b.d.l	0.06	0.02	0.40	1.23	b.d.l	0.02	0.67	0.02	b.d.l	b.d.l	378	409	320	273	273
Ce	0.29	0.06	0.16	0.03	1.61	5.85	b.d.l	b.d.l	1.55	0.03	b.d.l	b.d.l	1218	1398	1018	917	899
Pr	0.05	0.01	b.d.l	b.d.l	0.23	0.69	0.01	b.d.l	0.16	b.d.l	b.d.l	b.d.l	201	238	168	156	152
Nd	0.17	b.d.l	0.10	b.d.l	0.62	2.49	b.d.l	0.06	0.50	b.d.l	b.d.l	b.d.l	1068	1280	894	856	838
Sm	b.d.l	b.d.l	b.d.l	0.10	b.d.l	0.25	b.d.l	0.10	0.11	b.d.l	b.d.l	b.d.l	445	548	370	353	345
Eu	b.d.l	0.07	0.05	b.d.l	0.05	b.d.l	0.02	b.d.l	b.d.l	b.d.l	b.d.l	0.04	17.9	25.3	16.2	16.9	16.4
Gd	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.31	b.d.l	b.d.l	0.16	0.04	0.07	b.d.l	528	653	437	430	415
Tb	b.d.l	b.d.l	b.d.l	b.d.l	0.03	0.05	b.d.l	0.02	0.03	0.02	b.d.l	b.d.l	107	133	88.6	85.7	83.0
Dy	b.d.l	b.d.l	0.05	b.d.l	b.d.l	0.11	b.d.l	b.d.l	0.22	b.d.l	b.d.l	b.d.l	697	865	573	554	528
Ho	0.01	b.d.l	b.d.l	0.01	b.d.l	0.05	b.d.l	0.02	0.07	b.d.l	b.d.l	b.d.l	140	171	112	110	106
Er	b.d.l	b.d.l	b.d.l	b.d.l	0.14	0.13	b.d.l	b.d.l	0.15	0.02	b.d.l	b.d.l	374	462	301	293	282
Tm	b.d.l	b.d.l	b.d.l	0.01	b.d.l	b.d.l	b.d.l	b.d.l	0.03	0.01	b.d.l	b.d.l	51.5	64.1	42.0	40.1	39.1
Yb	b.d.l	b.d.l	b.d.l	b.d.l	0.17	0.24	b.d.l	b.d.l	0.10	0.06	b.d.l	b.d.l	332	419	273	260	252
Lu	b.d.l	0.01	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.02	0.05	b.d.l	b.d.l	b.d.l	40.5	51.1	33.3	31.4	30.2
Hf	0.14	0.22	0.26	0.20	0.15	0.22	0.37	0.32	0.29	b.d.l	0.31	0.27	0.04	0.06	b.d.l	0.09	b.d.l
Ta	11.4	6.71	11.2	22.5	16.5	12.9	13.2	24.3	24.7	4.26	18.4	12.4	b.d.l	0.03	b.d.l	0.01	0.02
Pb	4.66	7.17	7.78	7.38	4.99	6.61	2.69	3.10	4.74	1.40	2.64	2.57	11.7	14.8	10.4	10.1	8.97
Th	0.07	b.d.l	b.d.l	b.d.l	0.09	0.34	0.35	0.04	1.39	b.d.l	b.d.l	b.d.l	21.3	36.9	7.79	9.29	10.0
U	0.06	b.d.l	0.03	0.09	0.16	0.61	0.35	0.07	0.40	0.04	b.d.l	0.03	97.0	198	76.6	94.5	53.8

Table 3 (continued)

	Apatite Qingxi																
Rb	0.48	0.72	0.49	0.48	0.31	4.16	0.42	0.35	0.32	0.87	0.40	0.53	0.53	0.41	0.11	0.37	0.29
Sr	73.8	70.8	92.2	76.9	83.2	91.0	89.6	91.0	74.4	97.4	84.3	96.7	101	96.6	84.7	43.0	49.9
Y	2683	4713	3771	3249	2252	3509	3213	3207	2723	3932	3065	3290	3404	3805	2663	3000	2977
Zr	0.23	1.67	0.68	0.44	0.10	7.40	0.34	0.34	0.32	0.61	0.25	0.24	0.72	0.73	0.14	0.25	0.12
Nb	1.14	0.10	0.01	0.02	0.04	0.16	0.02	b.d.1	b.d.1	b.d.1	0.01	b.d.1	0.12	b.d.1	b.d.1	b.d.1	0.01
Mo	0.88	0.47	0.82	0.51	0.62	0.90	0.67	0.80	0.75	0.89	0.84	0.42	0.51	0.56	0.49	1.00	1.12
Ba	b.d.1	b.d.1	b.d.1	0.11	0.12	14.8	0.09	0.13	b.d.1	0.20	b.d.1	0.20	0.35	0.16	b.d.1	0.21	0.18
La	272	381	431	331	227	352	353	359	284	429	318	348	383	411	281	344	456
Ce	869	1338	1337	1057	732	1138	1115	1123	890	1375	1012	1128	1287	1350	906	1103	1587
Pr	145	235	212	176	121	189	183	183	148	225	165	179	209	218	145	179	263
Nd	783	1293	1129	941	652	1018	980	979	799	1223	896	952	1131	1164	777	952	1434
Sm	319	551	445	386	265	416	391	388	330	475	365	381	440	461	312	366	446
Eu	14.1	24.5	16.7	17.2	11.0	15.7	13.4	13.0	14.9	15.4	15.0	13.6	12.7	14.5	12.9	7.72	9.92
Gd	384	676	523	462	320	497	457	454	389	557	432	450	501	531	368	434	451
Tb	75.7	137	105	92.6	63.6	99.2	90.2	89.0	79.0	110	86.7	89.2	95.3	105	74.3	86.9	82.3
Dy	489	887	677	599	404	639	578	577	503	705	557	570	595	666	467	559	527
Ho	98.4	179	138	119	81.5	128	118	116	99.8	144	110	116	120	136	93.4	111	108
Er	259	483	373	316	218	344	313	310	266	378	294	308	318	362	249	281	291
Tm	35.7	67.2	51.7	45.1	29.5	48.5	43.5	42.8	37.3	51.9	41.3	42.5	42.9	49.5	34.8	35.9	40.8
Yb	226	433	329	291	189	305	274	271	239	329	266	265	264	312	221	226	272
Lu	27.2	52.2	40.4	35.6	23.1	36.5	32.9	32.4	29.0	39.4	31.8	32.1	31.4	37.8	26.8	28.4	34.4
Hf	0.05	0.07	0.05	0.04	b.d.1	0.21	b.d.1	0.05	0.07	0.05	0.06	b.d.1	0.12	0.08	b.d.1	0.05	0.05
Ta	0.04	0.02	b.d.1	0.01	b.d.1	0.04	0.02	0.01	b.d.1	0.02	b.d.1	b.d.1	0.02	b.d.1	0.01	0.01	b.d.1
Pb	7.42	11.4	12.0	10.9	6.84	14.0	8.06	8.70	7.26	9.27	8.22	9.61	10.1	9.96	8.00	9.74	10.0
Th	6.87	61.2	24.2	12.3	4.31	20.3	12.6	12.4	14.5	21.2	8.05	9.90	14.8	19.6	4.59	9.24	4.81
U	32.6	196	75.7	98.6	35.6	114	35.3	30.1	68.4	95.4	77.2	61.8	33.5	33.2	48.9	53.8	48.2

Table 3 (continued)

	Apatite		Zircon		Titanite											
	Qingxi		Qingxi		Guanxi		Guanxi									
Rb	2.44	1.55	2.45	0.72	24.9	1.75	0.70	0.76	0.72	3.98	2.62	1.00	1.30	3.43	b.d.l	0.78
Sr	57.7	56.8	40.7	3.85	6.89	2.98	2.67	3.37	3.15	3.05	2.70	7.86	3.70	6.43	7.10	5.70
Y	3684	4517	3373	2830	3834	1478	5621	5635	6719	7523	4620	7397	9876	4979	6941	6447
Zr	0.72	1.16	0.58	470689	466980	474270	475	696	384	599	614	561	506	547	498	136
Nb	0.02	0.12	0.23	5.15	64.7	24.3	5411	11966	4147	8744	8806	10253	10210	4648	5475	5092
Mo	1.24	1.17	0.96	1.22	0.68	2.11	27.5	98.1	27.9	164	139	148	133	6.77	56.5	4.18
Ba	0.44	0.38	0.13	1.06	1.21	1.19	0.07	0.40	b.d.l	0.06	b.d.l	0.91	0.28	1.68	b.d.l	b.d.l
La	509	569	399	0.17	12.3	15.3	693	958	684	989	954	1280	882	91.5	1146	42.9
Ce	1689	1886	1281	19.6	81.0	58.9	3134	3438	3267	3921	3416	4626	3836	818	4616	507
Pr	275	307	200	0.20	6.57	3.91	534	489	590	579	468	681	615	234	730	176
Nd	1465	1638	1061	2.84	36.2	20.4	2612	2096	2982	2445	1882	3087	2808	1584	3531	1422
Sm	525	611	440	7.72	21.6	9.78	821	622	1013	704	492	940	960	700	1086	841
Eu	9.53	10.8	9.55	0.61	1.01	0.23	16.5	11.1	21.3	16.2	11.2	16.9	18.2	56.6	43.2	71.3
Gd	558	665	498	44.7	72.7	27.8	849	652	1065	733	492	985	1060	795	1151	1081
Tb	106	130	101	18.5	25.8	9.21	163	130	207	152	97.2	188	221	149	220	217
Dy	661	822	638	238	313	120	1044	873	1315	1060	660	1213	1511	934	1425	1430
Ho	129	162	122	96.7	124	47.6	210	190	259	243	147	255	327	186	291	285
Er	342	427	326	460	576	236	560	562	673	763	452	720	974	482	777	757
Tm	47.2	59.3	45.4	103	123	52.5	80.6	92.0	94.8	131	78.0	114	158	66.3	110	103
Yb	304	373	303	1009	1200	519	552	713	618	1042	641	883	1152	433	721	675
Lu	37.5	46.0	37.3	196	218	103	71.3	96.7	72.5	143	95.3	128	140	55.4	88.2	90.3
Hf	0.07	0.03	0.05	32235	10688	8512	65.0	128	44.8	113	113	110	91.6	49.5	60.6	22.8
Ta	b.d.l	0.01	0.05	3.58	16.0	7.16	160	1012	166	390	383	520	1104	232	655	200
Pb	10.4	11.2	8.99	75.9	333	60.9	5.58	13.5	3.19	8.72	9.09	14.3	9.37	2.00	4.86	1.60
Th	23.3	39.7	25.5	346	1737	758	152	155	151	165	150	206	184	53.8	231	49.5
U	62.3	51.4	28.9	1814	3816	1793	149	177	135	212	217	273	153	64.4	195	95.1

b.d.l, below the detection limits.

Table 4 Major (wt. %) and trace (ppm) element compositions of the Qingxi (QX) and Guanxi (GX) granites

Sample	QX-1	QX-2	QX-3	QX-4	QX-5	GX-1	GX-2	GX-3	GX-4	GX-5	GX-6	GX-7	GX-8
SiO ₂	71.00	72.31	70.68	72.07	72.31	71.43	77.50	74.62	73.33	77.46	76.54	71.06	74.21
Al ₂ O ₃	14.06	14.05	14.31	13.75	13.82	14.26	11.84	12.56	13.45	11.00	11.72	14.18	12.30
Fe ₂ O ₃	2.45	2.17	1.93	2.05	1.35	2.57	0.61	2.32	1.72	0.70	0.82	2.36	2.50
CaO	1.51	1.26	1.32	1.45	1.37	1.45	0.80	1.41	1.40	1.05	1.12	1.50	1.32
MgO	0.48	0.40	0.51	0.39	0.45	0.52	0.16	0.46	0.26	0.11	0.20	0.43	0.51
Na ₂ O	3.52	3.70	3.65	3.55	3.76	3.66	3.46	3.29	3.47	3.69	3.50	4.16	3.62
K ₂ O	4.86	5.00	4.80	4.87	5.10	4.74	4.50	4.20	4.86	4.61	4.92	5.00	4.36
TiO ₂	0.23	0.25	0.25	0.22	0.22	0.25	0.20	0.22	0.23	0.20	0.20	0.27	0.20
MnO	0.06	0.05	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.05	0.05	0.06	0.06
P ₂ O ₅	0.06	0.06	0.06	0.07	0.06	0.06	0.05	0.07	0.06	0.05	0.05	0.07	0.06
LOI	1.66	0.55	2.20	1.37	1.35	0.83	0.60	0.85	1.02	0.89	0.72	0.63	0.66
Total	99.89	99.80	99.77	99.85	99.84	99.83	99.78	100.1	99.86	99.82	99.84	99.72	99.79
Rb	283	286	600	268	288	505	298	311	355	348	292	198	594
Ba	377	675	276	438	735	197	73.1	186	269	92.7	126	304	28.6
Th	24.3	29.1	32.7	25.9	18.9	21.7	41.2	37.6	26.6	48.7	47.0	31.2	53.1
U	17.8	6.58	11.9	13.3	5.96	13.4	11.3	8.49	11.3	13.2	7.93	7.49	12.0
Nb	18.0	15.1	25.6	15.8	9.50	19.7	25.4	43.2	18.3	29.9	22.6	49.1	35.8
Ta	2.16	1.37	2.38	1.76	1.35	2.82	0.60	2.23	2.01	0.54	0.61	2.64	0.96
Pb	35.8	43.7	28.9	26.2	43.2	25.4	14.2	17.5	45.1	19.1	20.0	16.4	24.3
Sr	120	155	48.2	83.0	96.7	50.2	21.9	44.3	81.4	32.7	34.3	160	5.97
Zr	162	182	156	189	108	107	99.4	188	132	97.1	132	227	137
Hf	4.22	4.68	4.11	4.92	2.75	3.17	4.36	5.97	3.56	3.98	4.78	6.80	6.80
Y	38.1	28.7	35.7	41.2	24.0	19.2	29.1	53.6	20.4	39.7	44.3	71.3	73.7
La	51.4	53.0	42.9	59.7	34.7	29.9	28.7	40.5	37.1	35.2	53.6	36.6	34.9
Ce	95.2	99.5	85.0	107	63.8	58.6	34.4	73.4	73.1	65.3	97.8	71.2	67.2
Pr	11.8	12.6	10.7	13.4	8.11	7.39	6.25	9.06	9.12	7.25	11.5	10.1	9.39
Nd	41.5	45.3	38.2	47.2	28.6	24.9	20.6	30.7	31.4	23.9	38.8	39.5	32.8
Sm	7.70	8.74	8.08	8.93	5.49	5.18	4.35	6.46	6.28	4.96	7.77	9.39	8.45
Eu	0.83	1.02	0.50	1.00	0.90	0.41	0.12	0.40	0.51	0.20	0.30	0.90	0.06
Gd	6.31	6.69	6.74	7.18	4.49	4.32	3.74	6.49	5.23	5.56	7.97	10.5	9.40
Tb	0.96	0.89	1.04	1.02	0.67	0.62	0.68	1.21	0.73	1.02	1.22	1.78	1.63
Dy	5.58	4.82	5.90	6.18	3.67	3.41	4.37	7.09	3.55	6.63	7.09	11.0	10.0
Ho	1.07	0.81	0.97	1.17	0.65	0.53	0.87	1.46	0.53	1.34	1.30	2.11	2.00
Er	3.23	2.32	2.89	3.58	2.10	1.52	2.77	4.45	1.46	4.11	3.66	6.2	6.12
Tm	0.47	0.33	0.38	0.53	0.27	0.22	0.42	0.66	0.19	0.59	0.51	0.86	0.92
Yb	3.12	2.08	2.49	3.39	2.11	1.39	2.68	4.38	1.16	3.88	3.06	5.11	5.95
Lu	0.42	0.30	0.33	0.48	0.28	0.18	0.38	0.62	0.16	0.54	0.44	0.70	0.82

Table 5 Estimated REE composition of different minerals in Qingxi and Guanxi granites

Minerals	Average Mineral REE Contents (ppm)	Average Mineral Volume Percent	Offered Whole-rock REE Contents (ppm)
Qingxi			
Plagioclase	15.8	30%	4.74
K-feldspar	0.53	25%	0.13
Quartz	-	32%	-
Biotite	7.87	8%	0.63
Apatite	5228	<0.1%	<52
Total			<57.5
Guanxi			
Plagioclase	14.8	20%	2.96
K-feldspar	29.0	35%	10.2
Quartz	-	32%	-
Biotite	21.2	6	1.27
Total			14.5