Late Triassic U-bearing and barren granites in the Miao'ershan batholith, South China: Petrogenetic discrimination and exploration significance

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Abstract

The Miao'ershan uranium ore district is one of the most important granite-hosted uranium producers in South China. There are several Triassic granite plutons in the Miao'ershan batholith, but uranium ore deposits mainly occur within the Douzhashan granitic body. Precise zircon U-Pb dating indicated that these Triassic granite plutons were emplaced during 204 to 215 Ma. The Douzhashan U-bearing granite lies in the central part of the Miao'ershan batholith, and has higher U contents (8.0 to 26.1 ppm, average 17.0 ppm) than the nearby Xiangcaoping granite (5.0 to 9.3 ppm, average 7.0 ppm) and the Yangqiaoling granite (6.4 to 18.3 ppm, average 11.5 ppm) in the south part of the batholith. The Douzhashan granite is composed of medium-grained two-mica granite, whereas the Xiangcaoping and Yangqiaoling granites are composed of porphyritic biotite granite. Both the Xiangcaoping and Douzhashan granites have high A/CNK ratios (>1.10), high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios (>0.720) and low $\epsilon_{\text{Nd}}(t)$ values (-11.3 to -10.4), suggesting that they belong to strongly peraluminous S-type granites. The Douzhashan granite has low CaO/Na₂O ratios, high Rb/Sr and Rb/Ba ratios, indicating a partial melting origin of clay-rich pelitic rocks. In contrast, the Xiangcaoping granite formed from clay-poor psammite-derived melt. The Yangqiaoling granite shows different geochemical characteristics with the Douzhashan and Xiangcaoping granites, indicating a different magma source. The Yangqiaoling granite has higher $\epsilon_{\text{Nd}}(t)$ of -9.4 to -8.3 and variable A/CNK values from 0.98 to 1.19, suggesting a mixture source of meta-sedimentary rocks and meta-igneous rocks. Crystallization fractionation is not the main mechanism for U enrichment in the Douzhashan granite. We suggest that U-rich pelitic rock sources may be the key factor to generate peraluminous U-bearing granites in South China. Searching for those granites which are reduced, strongly peraluminous and were derived from U-rich pelitic rocks, is the most effective way for exploring granite-hosted U deposits.

Keywords: U-bearing granite; Geochemistry; Douzhashan granite; Miao'ershan batholith; South China

1. Introduction

The Mesozoic geology of the South China Block (SCB) is characterized by the widespread occurrence of granitic rocks and economically important granite-related W-Sn-Ta-Nb-U-REE mineralization. These Mesozoic granitic rocks fall in three main age groups, the Triassic (commonly referred to as “Indosinian”), the Jurassic (“Early Yanshanian”) and the Cretaceous (“Late Yanshanian”) (Zhou et al., 2006). Previous studies have revealed that the Triassic granites mainly occur in the interior region of the SCB, far away from the continental margins (Fig. 1).

Granite-hosted uranium ore deposits are important commercial U-producers in South China (Hu et al., 2008). This type of deposits has contributed about 30% of the U production in China. Previous mineral explorations and scientific studies have revealed that such deposits are closely related to a few granitic bodies, known as U-bearing granites (Fig. 1) (Zhang and Zhang, 1991; Luo et al., 2015). Precise zircon U-Pb dating indicated that most of these U-bearing granites in South China were emplaced during the Indosinian era (e.g. Xie et al., 2008; Dong et al., 2010; Chen et al., 2012; Zhao et al., 2013b) with lesser amounts emplaced during the Early Yanshanian era (e.g. Zhao et al., 2011). These U-bearing granites are generally rich in U contents (>10 ppm) with leachable U sources, which have been regarded as the sources of uranium mineralization. Although these U-bearing granites were emplaced in the Triassic or the Jurassic, the uranium mineralization age peaks in the Cretaceous to Tertiary (Hu et al., 2008). The granite-hosted uranium deposits were suggested to have formed from the circulation of meteoric fluids which leached uranium from the U-bearing granites during the Cretaceous to Tertiary crustal extension in South China (e.g. Hu et al., 2008; Ling, 2011). Discrimination of U-bearing and U-barren granites is important not only for the targeting of more granite-hosted U deposits in South China, but also for a better understanding of the mechanism of U enrichment in granites in general (e.g. Cuney et al., 1990; Zhao et al., 2011, 2014a).

The Miao’ershan granitic batholith is a ca. 1,633 km² composite batholith and it contains an important granite-hosted uranium ore district (Fig. 2). The Miao’ershan batholith can be classified into Paleozoic granites and Triassic granites (e.g. Wu et al., 2012; Zhao et al., 2013c). The Triassic granites mainly intruded in the central part (Xiangcaoping and the Douzhashan granites) and the south part (Yangqiaoling granite) of the batholith. However, uranium deposits mainly occur inside the Douzhashan pluton with an outcrop area of only 32 km² (Fig. 2). The Douzhashan granite

pluton shows higher U contents than coeval granites and has been suggested as the main U source (Min et al., 2003). The geochronology, geochemistry and sources of these Indosinian U-bearing and U-barren granites are still poorly constrained (e.g. Min et al., 2003; Xie et al., 2008; Shi et al., 2010). Especially, comparative studies on geochemistry and petrogenesis for contemporaneous U-bearing and U-barren granites are lacking. In this paper, we present zircon U-Pb ages, major and trace element concentrations, and Sr-Nd-Hf isotopic data for these Indosinian U-bearing and barren granites in the Miao'ershan batholith. The aim of this work is to compare the differences of geochemistry and petrogenesis of U-bearing and barren granites. This approach enables us to evaluate the mechanism of U enrichment in those U-bearing granites in South China and to guide further mineral exploration.

2. Geological settings and petrography

The Miao'ershan granitic batholith extends from northern Guangxi Province to southern Hunan Province. During the Early-Middle Paleozoic orogeny which affected a vast region of South China (Li et al., 2010), the Miao'ershan granitic rocks intruded into the core of the Miao'ershan-Yuechengling anticlinorium, forming a huge granitic batholith (e.g. Zhao et al., 2013c). The core unit of the Miao'ershan-Yuechengling anticlinorium consists stratigraphically of Neoproterozoic-Silurian carbonaceous slates, pelitic schists, felsic volcanoclastics, metasandstones and dolostones.

The Miao'ershan batholith can be classified into several granite plutons according to their petrography and emplacement ages (Fig. 2):

- (1) The Paleozoic Miao'ershan coarse-grained, porphyritic biotite granite and medium-grained equigranular biotite granitic plutons intruded into Neoproterozoic-Cambrian metasedimentary rocks. They are composed of biotite (5 vol. %), plagioclase (30 vol. %), K-feldspar (30 vol. %) and quartz (35 vol. %). Detailed zircon U-Pb dating indicated that the Paleozoic granites were emplaced at about 415-381 Ma (Zhao et al., 2013c), which belong to fractional I-type possibly related to the late orogenic magmatism of the Early-Middle Paleozoic Wuyi-Yunkai orogeny in South China (Zhao et al., 2013c).
- (2) The Triassic Yangqiaoling coarse-grained, porphyritic biotite granitic pluton occurs in the south part of the Miao'ershan batholith and intruded into the Paleozoic granites (Fig. 2). The

granitic pluton has an outcrop area of about 200 km². The Yangqiaoling granite contains abundant K-feldspar and plagioclase megacrysts up to 5cm in length (Fig. 3a). The abundance of the megacrysts range from 10 to 40 vol. %. The groundmass is composed of biotite (3 vol. %), plagioclase (30 vol. %), K-feldspar (32 vol. %), and quartz (35 vol. %). Accessory minerals mainly include apatite, zircon and monazite.

- (3) The Triassic Xiangcaoping medium to coarse-grained, porphyritic biotite granitic pluton occurs in the central part of the Miao'ershan batholith and intruded into the Paleozoic granites. The pluton has an outcrop area of about 117 km² (Fig. 2). The Xiangcaoping granite contains K-feldspar megacrysts up to 3 cm in length (Fig. 3b). The abundance of K-feldspar megacrysts ranges from 10 to 25 vol. %. They set in a medium- to coarse-grained groundmass of biotite (10 vol. %), plagioclase (30 vol. %), K-feldspar (20 vol. %), and quartz (40 vol. %). Accessory minerals include apatite, zircon and monazite.
- (4) The Triassic Douzhashan medium-grained two-mica granitic pluton intruded in the central part of the Xiangcaoping granitic body with an outcrop area of about 32 km² (Fig. 2). The Douzhashan granite is characterized by the presence of abundant muscovite, which occur as large crystals (Fig. 3c-d). The Douzhashan granite is composed of muscovite (3 vol. %), biotite (2 vol. %), plagioclase (25 vol. %), K-feldspar (35 vol. %) and quartz (35 vol. %). Accessory minerals include apatite, zircon, monazite, uraninite, thorianite, and xenotime. Uraninite is generally regarded as a typical mineral for U-bearing granites (Cuney and Friedrich, 1987).

An important economic uranium ore district occurs in the central part of the Miao'ershan batholith. Several middle- and large-scale uranium ore deposits (e.g. Shazijiang, Shuanghuajiang, Baimaochong and Menggongjie) have been found inside the Douzhashan pluton (Fig. 2). The orebodies in these deposits occur as veins controlled by NNE-trending faults. The faults cut through the Xiangcaoping and the Douzhashan granites, but mineralization only occurs within the Douzhashan granite. These uranium ore deposits are hydrothermal vein-type according to the classification of Cuney (2009). Uranium mineralization is restricted to fractured, strongly altered zones within the Douzhashan granite. The hydrothermal alteration package associated with U-minerals consists of hematite, quartz, chlorite and fluorite. The ore is generally medium-grade (average 0.2 wt. % U). The mineralization age was estimated to be 136±17 Ma based on chemical

U-Th-Pb dating of hydrothermal apatites (Hu et al., 2013), which is far younger than the emplacement age of the Douzhashan granite. Previous studies have suggested that hydrothermal alteration of U-rich accessory minerals (uraninite, monazite, xenotime and thorianite) in the Douzhashan granite provided the uranium source for the mineralization (e.g. Hu et al., 2012).

3. Analytical methods

Fresh granite samples from the three Triassic granite bodies were collected from the outcrops and mine tunnels. Using the conventional heavy liquids, magnetic techniques and hand picking under binocular microscope, zircon grains are separated from the crushed granite sample powders. The zircon grains were mounted in epoxy resin and polished to approximately half their thickness. Examination of internal structures was performed using cathodoluminescence (CL) imaging techniques, the internal structures of zircon were examined with an Electron Microprobe at the Scanning Electron Microscope lab of Beijing SHRIMP Center, Chinese Academy of Geological Sciences. *In situ* zircon U-Pb isotopic analyses were undertaken using the SHRIMP II ion microprobe at the Beijing SHRIMP Center. More detailed mount-making and analytical procedures were described by Song et al. (2002). During the analysis a primary ion beam of 4.5 nA, 10 kV O⁻² and 25 or 30 µm spot diameter was used. Average value of data acquisition from five scan cycles was used for determination ages in each analysis. The common Pb components were estimated from ²⁰⁴Pb counts, assuming a typical terrestrial common Pb composition for the indicated age. The standard TEMORA zircon (ca. 417Ma) was used to correct for inter-element fractionation, and U, Th and Pb concentrations were determined based on the Sri Lankan gem zircon standard SL13 (age=572Ma, ²³⁸U=238 ppm). Data processing was carried out using the SQUID 1.03 and Isoplot/Ex2.49 programs of Ludwig (2001a, 2001b), and the ²⁰⁴Pb-based method of common Pb correction was applied. The error for the weighted mean ages is quoted at 95% confidence level.

Fresh granite samples were used for analysis of major and trace element concentrations and Sr-Nd isotopic compositions. Major elements of whole rocks were analyzed using an ICP-AES at State Key Laboratory for Mineral Deposits Research at Nanjing University after alkaline fusing with analytical uncertainties better than 0.5% for most elements. Trace element contents were determined by a Finnigan MAT Element II HR-ICPMS at Nanjing University, and the analytical

procedures are similar to those described by Gao et al. (2003). About 50 mg of the powdered sample was dissolved in a high-pressure Teflon bomb using a HF+HNO₃ mixture. Rh was used as an internal standard to monitor signal drift during ICP-MS counting. The USGS rock standard GSP-1 was chosen for calibrating element concentrations of measured samples. Analytical precisions for most elements were better than 5%.

Sr and Nd isotopic analyses of samples were carried out using the chemical separation and mass spectrometry method described by Pu et al. (2004, 2005). About 100 mg samples were dissolved in the same way as for trace element analyses. Complete separation of Sr was achieved by a combination of cation-exchange chromatography (BioRad 50WX8) in H⁺ form and pyridinium form with the DCTA complex. Nd was then separated from the REE fractions by the same cation-exchange resin using HIBA as eluent. The Sr and Nd isotopic compositions were determined by a Finnigan MAT Triton TI TIMS at State Key Laboratory for Mineral Deposits Research, Nanjing University. The NBS-987 Sr standard gave an average value of 0.710260 ± 0.000007 (n=108, 2 σ). The JNdi-1 Nd standard gave an average value of 0.512110 ± 0.000005 (n=65, 2 σ), which is similar to the referenced value of 0.512115 ± 0.000007 (Tanaka et al., 2000). The $\epsilon_{Nd}(t)$ values are calculated using a decay constant for ¹⁴⁷Sm of $6.54 \times 10^{-12} \text{ year}^{-1}$ (Lugmair and Marti, 1978) and chondritic values of ¹⁴³Nd/¹⁴⁴Nd (0.512638) and ¹⁴⁷Sm/¹⁴⁴Nd (0.1967) (Jacobsen and Wasserburg, 1980). Depleted mantle values of ¹⁴³Nd/¹⁴⁴Nd (0.513151), ¹⁴⁷Sm/¹⁴⁴Nd (0.2136) and a mean crustal value of ¹⁴⁷Sm/¹⁴⁴Nd (0.118) (Jahn and Condie, 1995) are used for calculating two-stage depleted mantle Nd model ages.

In-situ zircon Hf isotope analysis was carried out using a Geolas 193 nm Excimer laser ablation system attached to a Neptune multi-collector ICP-MS at Institute of Geology and Geophysics, Chinese Academy of Sciences. Instrumental conditions and data acquisition were comprehensively described by Wu et al. (2006). A stationary spot was used for the present analyses, with a beam diameter of either 40 μm or 55 μm depending on the size of ablated zircon domains. The Yb isotope ratios were normalized to ¹⁷²Yb/¹⁷³Yb of 1.35274 and Hf isotope ratios to ¹⁷⁹Hf/¹⁷⁷Hf of 0.7325 using an exponential law to correct the instrumental mass bias (Wu et al., 2006). The mean β_{Yb} value and β_{Hf} value of the individual analytical spot were applied for in-situ analysis correction. Helium was used as carrier gas to transport the ablated sample from the laser-ablation cell to the ICP-MS torch via a mixing chamber mixed with Argon. Standard zircon

91500 was used as the reference standard, with a weighted mean $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282315 ± 0.000010 ($n=20$, 2σ) in this study. To calculate model ages and $\varepsilon_{\text{Hf}}(t)$ values, a depleted-mantle model with $^{176}\text{Hf}/^{177}\text{Hf}=0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf}=0.0384$ (Nowell et al., 1998; Griffin et al., 2000) and a chondritic model with $^{176}\text{Hf}/^{177}\text{Hf}=0.282772$ and $^{176}\text{Lu}/^{177}\text{Hf}=0.0332$ (Blichert-Toft and Albarède, 1997) are adopted. The decay constant of ^{176}Lu is 1.865×10^{-11} (Scherer et al., 2001). The average crustal $^{176}\text{Lu}/^{177}\text{Hf}$ value of 0.015 is adopted to calculate the two-stage model ages (T_{DM}^{C}) (Griffin et al., 2002).

4. Results

4.1 Zircon U-Pb ages

Samples 06MES-10A (Location: N25°48'34.4", E110°27'25.9") and 06MES-14A (Location: N25°51'55.1", E110°24'43.7") collected from the Yangqiaoling granite are chosen for zircon U-Pb dating. Both of them are fresh porphyritic biotite granites (Fig. 3a).

Zircon grains from Sample 06MES-10A are euhedral, with lengths ranging from 100 to 400 μm , and length/width ratios of 1:1 to 3:1. Their CL images display euhedral concentric zoning, implying a magmatic origin (Hoskin and Schaltegger, 2003; Wu and Zheng, 2004). Nine spot analyses were carried out on zircon grains with oscillatory zoning and the results are listed in Table 1. U concentrations vary from 746 ppm to 3,216 ppm and Th concentrations vary from 361 ppm to 808 ppm. Th/U ratios vary from 0.22 to 0.50, indicating magmatic origins for these zircons (Belousova et al., 2002). $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 205 Ma to 225 Ma and give a weighted average age of 215 ± 5 Ma ($n=9$, MSWD=6.7) (Fig. 4a).

Zircon grains from Sample 06MES-14A are euhedral, with lengths ranging from 200 to 400 μm , and length/width ratios of 2:1 to 3:1. Their CL images display euhedral concentric zoning, implying a magmatic origin. A total of nine spot analyses were carried out on zircon grains, which show U concentrations of 121 to 1,745 ppm and Th concentrations of 90 to 590 ppm, with Th/U ratios of 0.35 to 0.78. The $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 212 Ma to 224 Ma and yield a weighted average age of 215 ± 2 Ma ($n=9$, MSWD=1.4) (Fig. 4b).

4.2 Geochemical and isotopic results

4.2.1 The Yangqiaoling granite

Major and trace element contents of granite samples are listed in Table 2. The Yangqiaoling granite has variable SiO₂ contents of 71.25% to 75.75% and Al₂O₃ contents of 12.34% to 14.59%, and relatively high MgO contents (0.56% to 1.35%) and CaO contents (1.35% to 2.09%). The samples show high CaO/Na₂O ratios of 0.54 to 0.70, variable A/CNK values (molar ratio of Al₂O₃/[CaO+Na₂O+K₂O]) of 0.98 to 1.19 (Fig. 5), and low TiO₂ contents (0.31% to 0.38%) and P₂O₅ contents (0.10% to 0.13%). In Harker diagram (Fig. 6), TiO₂, Al₂O₃, MgO and CaO contents decrease with the increasing of SiO₂ contents.

This granite has Rb contents of 305 to 395 ppm and Sr contents of 50.1 to 76.1 ppm, with Rb/Sr ratios of 1.50 to 7.88. Zr contents vary from 145 to 194 ppm, yielding zircon saturation temperatures of 773°C to 823°C based on the equation of Watson and Harrison (1983). U contents vary from 6.39 to 18.3 ppm with an average value of 11.5 ppm, and Th contents vary from 24.9 to 45.8 ppm with an average value of 37.2 ppm. Th/U ratios vary from 2.00 to 4.66 (Fig. 7) with an average ratio of 3.24, close to the average ratio of the upper continental crust (Rudnick and Gao, 2003).

In primitive mantle-normalized trace element spider diagram (Fig. 8a), the Yangqiaoling granite shows depletion of Ba, Sr, Eu and Ti. Total REE contents vary from 177 to 219 ppm. Chondrite-normalized REE patterns show enrichment of light rare earth elements (LREEs) with (La/Yb)_N ratios of 4.12 to 9.07, and negative Eu anomalies (Eu/Eu* = 0.22 to 0.35, Fig. 9a). Eu depletion requires fractional crystallization of plagioclase and/or K-feldspar (Fig. 10).

Sr-Nd isotopic compositions of the granite samples are listed in Table 3. The initial ⁸⁷Sr/⁸⁶Sr ratios and ε_{Nd}(t) values have been calculated at 215 Ma. The Yangqiaoling granite samples have high ⁸⁷Rb/⁸⁶Sr ratios (12.7 to 23.0) and ⁸⁷Sr/⁸⁶Sr ratios (0.761343 to 0.790218). Calculated (⁸⁷Sr/⁸⁶Sr)_i vary from 0.719977 to 0.723984. The samples have ¹⁴⁷Sm/¹⁴⁴Nd ratios of 0.1204 to 0.1343 and ¹⁴³Nd/¹⁴⁴Nd ratios of 0.512058 to 0.512105. The ε_{Nd}(t) values vary from -9.4 to -8.3, and two-stage model ages vary from 1.67 to 1.76 Ga. Sr-Nd isotopic compositions of the Yangqiaoling granite samples plot in the range of the Proterozoic basement of the Cathaysia Block (Fig. 11). Sr-Nd isotopic compositions also fall in the range of the Paleozoic I-type granite in the Miao'ershan batholith (Fig. 11) (Zhao et al., 2013c).

Twenty-one spots on zircon grains from Sample 06MES-10A and twenty-two spots from Sample 06MES-14A were analyzed for Lu-Hf isotopic compositions and the results are listed in

Table 4. The $\varepsilon_{\text{Hf}}(t)$ values vary from -8.4 to -4.2, with a peak value at -6.0 (Fig. 12a). The two-stage Hf isotopic model ages vary from 1.52 to 1.78 Ga, with a peak age of 1.63 Ga (Fig. 12b).

4.2.2 The Xiangcaoping granite

The Xiangcaoping granite samples have SiO_2 contents of 73.59% to 74.27% and Al_2O_3 contents of 13.31% to 14.35%. They have relatively lower TiO_2 (0.19% to 0.33%), MgO (0.42% to 0.59%) and CaO contents (0.61% to 1.2%) but slightly higher P_2O_5 contents (0.13% to 0.18%) than those of the Yangqiaoling granites. $\text{CaO}/\text{Na}_2\text{O}$ ratios vary from 0.27 to 0.49. The Xiangcaoping samples have A/CNK values of 1.09 to 1.37, suggesting they are strongly peraluminous granites (Fig. 5).

The Xiangcaoping granite has Rb contents of 338 to 374 ppm and Sr contents of 42.0 to 64.8 ppm. Rb/Sr ratios vary from 5.56 to 8.76. Zr contents vary from 145 to 194 ppm, yielding zircon saturation temperatures of 759°C to 809°C. U contents vary from 4.98 to 9.30 ppm with an average value of 6.97 ppm and Th contents vary from 26.9 to 35.4 ppm with an average value of 30.8 ppm. Th/U ratios vary from 2.89 to 8.27 (Fig. 7) with an average value of 4.42.

In primitive mantle-normalized trace element spider diagram (Fig. 8b), the Xiangcaoping granites show depletion of Ba, Sr, Eu and Ti. Total rare earth element contents vary from 137 to 169 ppm. Chondrite-normalized REE patterns show enrichment of light rare earth elements (LREEs) with $(\text{La}/\text{Yb})_{\text{N}}$ ratios of 9.82 to 16.1, and negative Eu anomalies with Eu/Eu^* values of 0.26 to 0.38 (Fig. 9b).

The Xiangcaoping samples have high $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (17.7 to 25.6) and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.779846 to 0.808714). Calculated $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vary from 0.726820 to 0.733565. The samples have $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of 0.1079-0.1198 and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.511955 to 0.511980. The $\varepsilon_{\text{Nd}}(t)$ values vary from -11.3 to -10.4, lower than those of the Yangqiaoling granite (Fig. 11). The two-stage Nd model ages vary from 1.84 to 1.90 Ga. Sr-Nd isotopic compositions of the Xiangcaoping granite also fall in the range of the Proterozoic basement of the Cathaysia Block (Fig. 11).

Twenty-two spots of zircon grains from Sample SZJ-06B were analyzed for Lu-Hf isotopic compositions (Table 4). The $\varepsilon_{\text{Hf}}(t)$ values vary from -9.4 to -2.8, and mostly fall in -7.1 to -5.6 (Fig.

12c). The two-stage Hf isotopic model ages vary from 1.42 to 1.83 Ga, and most fall in 1.60 to 1.69 Ga (Fig. 12d).

4.2.3 *The Douzhashan granite*

The Douzhashan granite samples have relatively higher SiO₂ contents (73.25% to 76.02%) and Al₂O₃ contents (13.10% to 15.02%), relatively lower MgO contents (0.18% to 0.46%), CaO contents (0.30% to 1.01%), and TiO₂ contents (0.09% to 0.24%), and P₂O₅ contents (0.09% to 0.17%) than the Yangqiaoling and Xiangcaoping granites. The Douzhashan granite has the lowest CaO/Na₂O ratios (0.11 to 0.37, except one sample) compared to other granites studied. The Douzhashan granite belongs to strongly peraluminous granites with high A/CNK values of 1.10 to 1.70 (Fig. 5).

The Douzhashan granite shows relatively higher Rb contents (423 to 688 ppm), lower Sr contents (10.3 to 63.3 ppm), and the highest Rb/Sr ratios (7.14 to 66.8). The Douzhashan granite has the lowest contents of high field strength element (HFSE). Zr contents vary from 28.7 to 120 ppm and calculated zircon saturation temperatures vary from 670°C to 788°C, lower than those of the Yangqiaoling and Xiangcaoping granites. The Douzhashan samples have relatively higher U contents from 7.98 to 26.1 ppm, with an average value of 17.0 ppm. Th contents vary from 7.23 to 41.7 ppm, with an average value of 28.6 ppm. Th/U ratios vary from 0.35 to 3.26, with an average ratio of 1.93, which are lower than those of the Yangqiaoling and Xiangcaoping granites (Fig. 7).

In primitive mantle-normalized trace element spider diagram (Fig. 8c), the Douzhashan granite shows depletion of Ba, Sr, Eu and Ti. Total rare earth element contents vary from 30.2 to 161 ppm, lower than those of the Yangqiaoling and Xiangcaoping granites. Chondrite-normalized REE patterns show enrichment of light rare earth elements (LREEs) with (La/Yb)_N ratios of 3.25 to 6.75, and negative Eu anomalies with Eu/Eu* values of 0.18 to 0.30 (Fig. 9c). The Douzhashan granite experienced strongly fractional crystallization of plagioclase and/or K-feldspar (Fig. 10).

The Douzhashan samples have the highest ⁸⁷Rb/⁸⁶Sr ratios (31.3 to 83.8) and ⁸⁷Sr/⁸⁶Sr ratios (0.824244 to 0.980501) among the three granites studied. Calculated (⁸⁷Sr/⁸⁶Sr)_i vary from 0.724148 to 0.737406. The samples have ¹⁴⁷Sm/¹⁴⁴Nd ratios of 0.1183 to 0.1435 and ¹⁴³Nd/¹⁴⁴Nd ratios of 0.511991 to 0.512033. The ε_{Nd}(t) values vary from -10.8 to -10.4, and the two-stage Nd model ages vary from 1.83 to 1.86 Ga. The ε_{Nd}(t) values of the Douzhashan granite are similar to

those of the Xiangcaoping granite, but lower than those of the Yangqiaoling granite (Fig. 11).

Seventeen spots of zircon grains from Sample DZS-01A were analyzed for Lu-Hf isotopic compositions (Table 4). The $\varepsilon_{\text{Hf}}(t)$ values vary from -12.8 to -7.3, and mostly fall in -9.8 to -8.0 (Fig. 12e). The two-stage Hf isotopic model ages vary from 1.70 to 2.04 Ga, and mostly fall in 1.74 to 1.86 Ga (Fig. 12f). The $\varepsilon_{\text{Hf}}(t)$ values of the Douzhashan granite are lower than those of the Yangqiaoling and Xiangcaoping granites.

5. Discussion

5.1 Petrogenetic type and magma sources

Granites have commonly been divided into three types (I-, S- and A-type) according to the nature of their protolith and their petrographical and geochemical features (Chappell and White, 1974; Loiselle and Wones, 1979). The A-type granites show special mineralogical and geochemical characteristics (e.g. Bonin, 2007; Whalen et al., 1987), such as very high HFSE contents ($\text{Zr} > 250$ ppm, $\text{Nb} > 20$ ppm, $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y} > 350$ ppm), and high $10000 \times \text{Ga}/\text{Al}$ ratios (> 2.6) (Whalen et al., 1987). The Yangqiaoling, Xiangcaoping and Douzhashan granites do not show such mineralogical and geochemical characteristics. They have low $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ contents (269 to 380 ppm for the Yangqiaoling granite, 195 to 266 ppm for the Xiangcaoping granite, 78 to 218 ppm for the Douzhashan granite), ruling out the possibility of A-type granites.

The S-type granites are mineralogically characteristics with abundant Al-rich minerals, such as muscovite, garnet, cordierite and tourmaline (Zen, 1988; Clemens, 2003), while I-type granites generally contain amphibole. Most S-type granites are strongly peraluminous with A/CNK values > 1.1 , while most I-type granites are metaluminous with A/CNK values < 1.0 (Chappell, 1999). The Douzhashan granite has high A/CNK values (1.10 to 1.70) and belongs to strongly peraluminous granites (Fig. 5). The Douzhashan granite also contains abundant muscovite, which occur as large crystals (Fig. 3d). Thus, the Douzhashan granite belongs to S-type granite. The Xiangcaoping granite also has high A/CNK values (1.09 to 1.37) and most belong to strongly peraluminous granites (Fig. 5). They have relatively higher P_2O_5 contents (0.13% to 0.18%) than Paleozoic I-type granites in the Miao'ershan batholith ($< 0.1\%$ when $\text{SiO}_2 > 73\%$, Fig. 6, Zhao et al., 2013c). In addition, the Xiangcaoping granite shows very high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (0.726820 to 0.733565) and low $\varepsilon_{\text{Nd}}(t)$ values (-11.3 to -10.4) (Fig. 11), indicating a sedimentary rock source

origin. Thus, we suggest that the Xiangcaoping granite also belongs to S-type granites.

The strongly peraluminous S-type granites are considered to be derived from partial melting of supra-crustal rocks that have undergone some extent of weathering (Chappell and White, 1974; Clemens, 2003). The high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios and low $\epsilon_{\text{Nd}}(t)$ values of the Douzhashan and Xiangcaoping granites support that the two granites were derived from partial melting of sedimentary protoliths (Fig. 11). The Douzhashan granite has relatively low CaO/Na₂O ratios (most <0.3), high Rb/Sr (7.14 to 66.8) and Rb/Ba ratios (1.75 to 36.9). As shown in Fig. 13, the Douzhashan granite should be derived from partial melting of clay-rich pelitic rocks. The Xiangcaoping granite has similar Sr-Nd isotopic compositions with the Douzhashan granite, but it has different zircon Hf isotopic compositions. This Nd-Hf isotope decoupling indicates that the Xiangcaoping granite should be derived from sediments possibly with different sources or amounts of detrital zircons from the Douzhashan granite. The Xiangcaoping granite has relatively higher CaO/Na₂O ratios (most >0.3), lower Rb/Sr (5.56 to 8.76) and Rb/Ba ratios (1.14 to 1.82), indicating a derivation from partial melting of clay-poor psammite-derived sources (Fig. 13).

The Yangqiaoling granite samples have variable A/CNK values of 0.98 to 1.19 and most are weakly peraluminous (Fig. 5). It is not easy to distinguish I-type or S-type for weakly peraluminous biotite granites (Chappell, 1999). As shown in Harker diagram (Fig. 6), the Yangqiaoling granite shows different crystallization differentiation evolution with the Douzhashan granites, indicating they may have formed from different sources. The Yangqiaoling granite has higher $\epsilon_{\text{Nd}}(t)$ values than the Douzhashan and Xiangcaoping granites (Fig. 11), also indicating that they may come from a different source. The $\epsilon_{\text{Nd}}(t)$ values of the Yangqiaoling granite are similar to those of Paleozoic I-type granites in the Miao'ershan batholith (Fig. 11) (e.g. Zhao et al., 2013c). The Yangqiaoling granite has highest CaO/Na₂O ratios (0.54 to 0.70) and zircon saturation temperatures (773°C to 823°C). Variable A/CNK ratios give a first-order constraint that their sources are most likely a mixture of meta-sedimentary rocks with meta-igneous rocks, and this characteristics may account for the Yangqiaoling granite sharing both I and S type granite features. All Sr-Nd isotopic compositions of the three studied granites plot in the range of Proterozoic basement crust, indicating they were derived from partial melting of the basement crust without involvement of mantle materials (Fig. 11).

5.2 Emplacement ages and possible tectonic implications

Triassic granites have a widespread occurrence in the SCB, but few coeval volcanic rocks and basaltic rocks are found in the region (Zhou et al., 2006; Wang et al., 2013). These Triassic granites are distributed sporadically within the central SCB, far away from the continental margins (Fig. 1). Most of them belong to strongly peraluminous S-type granites with A/CNK values larger than 1.1. These granites generally have high $(^{87}\text{Sr}/^{86}\text{Sr})_i$, low $\epsilon_{\text{Nd}}(t)$ values and low zircon $\epsilon_{\text{Hf}}(t)$ values. Strongly peraluminous S-type granites generally form from collision-related magmatism in various orogens (Sylvester, 1998). The SCB should be under a compressional tectonic environment during the Indosinian era concerning the tectonic evolution of the SCB and neighboring areas (Li et al., 1993; Shu et al., 1994; Lepvrier et al., 1997; Nam et al., 1998; Carter et al., 2001; Zhang and Zhu, 2003; Zheng et al., 2008; Zhang et al., 2009). Strong metamorphism up to granulite facies occurred in the interior of the SCB (Zhao et al., 2012). The Triassic granites in the SCB should form at the within-plate environment. Some reliable ages for the Triassic granites in the SCB have become available in recent years (e.g. Wang et al., 2013; Zhao et al., 2013a; and references therein). The zircon U-Pb ages for these granites vary from 202 to 248 Ma, and statistically fall into two episodes: the Early Indosinian (248 to 225 Ma) with a peak value at 239 Ma, and the Late Indosinian (225 to 202 Ma) with a peak value at 220 Ma (Yu et al., 2007; Wang et al., 2007; Chen et al., 2011; Wang et al., 2013). Thus, the Early Indosinian granites were suggested to be derived from dehydrate-melting of thickening crust at syn-collisional compressional environment, and the Late Indosinian granites may have formed at the post-collisional collapse and extension environment.

Although older Rb-Sr age of 260 ± 5 Ma and single-grain zircon U-Pb ages of about 296 ± 31 Ma have been reported by Min et al. (2003) for the Xiangcaoping granite, new SHRIMP U-Pb dating results indicated that this granite emplaced at 211 ± 3 Ma ($n=8$, MSWD=1.3) (Zhao et al., 2014b). Field observation indicated that the Douzhashan granite intruded the Xiangcaoping granite. Thus, the Douzhashan granite should intrude later than the Xiangcaoping granite. A Rb-Sr age of 214 ± 3 Ma for the Douzhashan granite was reported by Xu (1994). Recently, LA-ICP-MS U-Pb dating of monazite and xenotime in the Douzhashan granite yielded ages of 220 ± 6 Ma and 211 ± 7 Ma (Hu et al., 2013). Zircons from the Douzhashan granite have very high U concentrations (up to 3.0%). SHRIMP zircon U-Pb method did not yield reliable ages due to high

U matrix effect. However, LA-ICP-MS zircon U-Pb method yield a reliable age of 204 ± 4 Ma ($n=13$, MSWD=1.4), which is consistent with the ^{40}Ar - ^{39}Ar age of muscovite from the granite (207 ± 4 Ma) (Zhao et al., 2014b). Thus, 204 ± 4 Ma was suggested to be the best estimate of the emplacement age of the Douzhashan granite (Zhao et al., 2014b). The Yuntoujie granite, southwest to the Xiangcaoping granite, was dated at 217 ± 5 Ma ($n=8$, MSWD=1.44) by LA-ICP-MS zircon U-Pb method (Wu et al., 2012). In this study, the Yangqiaoling granite in the south part of the Miao'ershan batholith was dated at 215 ± 2 Ma. Thus, the Triassic granites in the Miao'ershan batholith were emplaced at the Late Indosinian era. From the 215 Ma Yangqiaoling granite to the 204 Ma Douzhashan granite, the magma temperatures gradually decrease and the magma sources change from meta-igneous rocks to pelitic rocks.

Recent precise zircon U-Pb data indicated that most U-bearing granites in South China formed during the Early Indosinian stage as syn-collisional granites (Fig. 1), including the Xiazhuang granite (234 Ma, Chen et al., 2012), the Fucheng granite (239 Ma, Yu et al., 2007), the Baimianshi granite (241 Ma, Dong et al., 2010), the Jintan granite (239 Ma, Zhao et al., 2013b), the Aigao granite (234 Ma, Deng et al., 2012) and the Zhuguang granite (239 Ma, Deng et al., 2012). All these granites might have generated from dehydrate-melting of thickening crust at syn-collisional compressional environment. They are similar to U-bearing S-type granites in other orogenic belts in the world. For example, at the French Massif Central representing the West European Variscan belt, the syn-collisional peraluminous granites are enriched in rare metals (in particular, uranium) and are sources for later mineralization (Marignac and Cuney, 1999). The Douzhashan U-bearing granite emplaced at the Late Indosinian stage and formed at the post-collisional setting. Thus, this study indicated that the U-bearing granite in South China might form at the post-collisional setting of the Indosinian orogeny. It is a useful indicator for the further exploration of granite-hosted uranium ore deposits in South China.

5.3 Mechanism of enrichment of U in granites and implication for exploration

Previous explorations and studies have indicated that granite-hosted uranium deposits in South China were closely related to the U-bearing granites (Zhang and Zhang, 1991). The U-bearing granites are rich in U and have been regarded as uranium sources for later hydrothermal mineralization. The Douzhashan granite has high U contents with an average value of 17.0 ppm,

which is five times higher than the average upper crust value (2.7 ppm, Rudnick and Gao, 2003).

Fractional crystallization plays important role in enrichment of U in peralkaline granites (Cuney, 2009). Generally, peralkaline magmas are highly depolymerized with high temperature, which result in very high solubility of accessory minerals. The high solubility of U, Th, Zr and REE in such melts leads to their continuous enrichment during magmatic fractionation, and finally to crystallization of complex minerals that incorporate uranium together with these elements. A good example is the Kvanefjeld deposit at Ilimaussaq, Greenland (Cuney, 2009). In this deposit U is mainly hosted by steenstrupine, a complex U-Th-REE silicophosphate, disseminated in peralkaline syenites. The Douzhashan U-bearing granite is a strongly peraluminous, not peralkaline granite (Fig. 5). Uranium mineralization in the Douzhashan granite belongs to post-magmatic hydrothermal vein-type, not granite-type (e.g. Cuney, 2009). As shown in the plots of U vs. Rb/Sr and U vs. TiO_2 (Fig. 14), fractional crystallization is not the main mechanism for enrichment of U in the Douzhashan granite.

Alternatively, we suggest that a U-riched source may be the key to generate U-rich peraluminous granite. As discussed above, the Douzhashan granite was likely derived from partial melting of clay-rich pelitic rocks. The Douzhashan granite shows similar mineralogical, geochemical and isotopic characteristics with other U-bearing granites in South China, such as the Daguzhai granite (Zhao et al., 2011), the Baimianshi granite (Dong et al., 2010), the Xiazhuang granite (Chen et al., 2012), the Jintan granite (Zhao et al., 2013b), and the Fucheng granite (Chen et al., 1997). Most of these U-bearing granites contain muscovite and belong to strongly peraluminous S-type granite. These granites are also highly reduced (Zhang et al., 2011), and may have derived from anatexis of clay-rich carbonaceous pelitic rocks (e.g. Zhao et al., 2011; Chen et al., 2012; Zhao et al., 2013b). Such source rocks are similar to black shales forming in shallow marine environments in Neoproterozoic-Cambrian era in South China. If forming under anoxic conditions, these shales generally contain high contents of U, which is syngenetically deposited, absorbed onto organic material and clay minerals. For example, U contents in the black shales from the Cambrian Hetang Formation in South China vary from 25.8 to 167 ppm (Zhou and Jiang, 2009). Partial melting of these shales will produce reduced, strongly peraluminous and U-rich granitic magma (Cuney et al., 1990). Early monazite and zircon fractionation, due to the low solubility of the two minerals in peraluminous low-temperature melts, leads to strong Zr, Th, and

REE depletion. On further fractionation, U continues to be enriched, until uraninite saturation is reached. Th-poor uraninite then crystallizes which represents the most easily leachable uranium sources (Cuney and Friedrich, 1987), which can be easily transferred by oxidized meteoric fluids (Hu et al., 2008; Ling et al., 2011; Hu et al., 2012) to form hydrothermal vein-type uranium ore deposits. Thus, searching for such granites, which are reduced, strongly peraluminous and are derived from U-rich pelitic rocks, might be helpful in the exploration for granite-hosted uranium deposits in South China.

Beside U contents, Sn (22.3 to 64.2 ppm, average 32.4 ppm) and W contents (4.9 to 15.7 ppm, average 9.7 ppm) of the Douzhashan granite are also far higher than the Clarke values (2.1 ppm for Sn and 1.9 ppm for W, Rudnick and Gao, 2003). The Sn contents of the Douzhashan granite are even higher than many stanniferous granites in South China (e.g. Mao et al., 1988; Jiang et al., 2008). As shown in Fig. 14, the Sn and W contents of the Douzhashan granite are controlled by fractional crystallization. It is similar to most Sn-W bearing granites in the world (Lehmann, 1982; 1987). Recently, mineral explorations in the Miao'ershan district have found some W-Sn mineralization in the contact zones of the Miao'ershan batholith and the sedimentary strata (Wu et al., 2012; Wang et al., 2013). Although further studies are needed in order to make clear of the relationship between the granites and mineralization, the W-Sn mineralization potential of the Douzhashan granite should gain attention in the further explorations.

6. Conclusions

The Triassic granites in the Miao'ershan batholith emplaced at the Late Triassic (204 to 215 Ma). The U-bearing Douzhashan granite (204 Ma) belongs to strongly peraluminous S-type granite and was derived from anatexis of clay-rich pelitic rocks. The Xiangcaoping granite (211 Ma) also belongs to strongly peraluminous S-type granite, but formed from psammite-derived melt. The Yangqiaoling granite (215 Ma) was derived from a mixture source of meta-sedimentary rocks and meta-igneous rocks. U-rich pelitic-rock sources (e.g. black shales) may be a key factor to generate U-rich peraluminous granites in South China. In addition, the Douzhashan granite also shows good W-Sn mineralization potential which may need further attention.

Acknowledgements

This work is supported by projects from Major State Basic Research Program of China (2012CB406706) and China National Science Foundation (No. 41273038, No.41422203). Kui-Dong Zhao is also grateful for the financial support from China Scholarship Council. Prof. Franco Pirajno and two reviewers are thanked for their constructive and valuable comments and suggestions on this paper.

Reference

- Belousova, E., Griffin, W., O'Reilly, S., Fisher, N., 2002. Igneous zircon: trace element composition as an indicator of source rock type. *Contributions to Mineralogy and Petrology* 143(5), 602-622.
- Blichert-Toft, J., Albarède, F., 1997. The Lu-Hf isotope geochemistry of chondrites and the evolution of the mantle-crust system. *Earth and Planetary Science Letters* 148(1-2), 243-258.
- Bonin, B., 2007. A-type granites and related rocks: Evolution of a concept, problems and prospects. *Lithos* 97(1-2), 1-29.
- Boynton, W.L., 1984. Geochemistry of the rare earth elements: meteorite studies. In: Henderson, P. (Ed.), *Rare Earth Element Geochemistry*. Elsevier, Amsterdam, pp. 63-114.
- Carter, A., Roques, D., Bristow, C., Kinny, P., 2001. Understanding Mesozoic accretion in Southeast Asia: Significance of Triassic thermotectonism (Indosinian orogeny) in Vietnam. *Geology* 29(3), 211-214.
- Chappell, B.W., 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* 46(3), 535-551.
- Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. *Pacific Geology* 8, 173-174.
- Chen, C.-H., Hsieh, P.-S., Lee, C.-Y., Zhou, H.-W., 2011. Two episodes of the Indosinian thermal event on the South China Block: Constraints from LA-ICP-MS U-Pb zircon and electron microprobe monazite ages of the Darongshan S-type granitic suite. *Gondwana Research* 19(4), 1008-1023.
- Chen, Y.W., Bi, X.W., Hu, R.Z., Dong, S.H., 2012. Element geochemistry, mineralogy, geochronology and zircon Hf isotope of the Luxi and Xiazhuang granites in Guangdong Province, China: Implications for U mineralization. *Lithos* 150, 119-134.
- Clemens, J.D., 2003. S-type granitic magmas-petrogenetic issues, models and evidence. *Earth-Science Reviews* 61(1-2), 1-18.

- Cuney, M., 2009. The extreme diversity of uranium deposits. *Mineralium Deposita* 44(1), 3-9.
- Cuney, M., Friedrich, M., 1987. Physicochemical and crystal-chemical controls on accessory mineral paragenesis in granitoids: Implications on uranium metallogenesis. *Bulletin of Mineralogy* 110, 235-247.
- Cuney, M., Friedrich, M., Blumenfeld, P., Bourguignon, A., Boiron, M.C., Vigneresse, J.L., Poty, B., 1990. Metallogenesis in the French part of the Variscan orogen. Part I: U preconcentraions in pre-Variscan and Variscan formations-a comparison with Sn, W and Au. *Tectonophysics* 177, 39-57.
- Deng, P., Ren, J.S., Ling, H.F., Shen, W.Z., Sun, L.Q., Zhu, B., Tan, Z.Z., 2012. SHRIMP zircon U-Pb ages and tectonic implications for Indosinian granitoids of southern Zhuguangshan granitic composite, South China. *Chinese Science Bulletin* 57(13), 1542-1552.
- Dong, C.Y., Zhao, K.D., Jiang, S.Y., Chen, W.F., Chen, P.R., Ling, H.F., Yang, S.Y., 2010. Zircon geochronology, geochemistry and petrogenesis of the Baimianshi granite in the Southern Jiangxi Province. *Geological Journal of China Universities* 16(2), 149-160 (in Chinese with English abstract).
- Gao, J.F., Lu, J.J., Lai, M.Y., Lin, Y.P., Pu, W., 2003. Analysis of trace elements in rock samples using HR-ICP-MS. *Journal of Nanjing University (Nature Sciences)* 39, 844-850 (in Chinese with English abstract).
- Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., van Achterbergh, E., O'Reilly, S.Y., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICP-MS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta* 64(1), 133-147.
- Griffin, W.L., Wang, X., Jackson, S.E., Pearson, N.J., O'Reilly, S.Y., Xu, X., Zhou, X., 2002. Zircon chemistry and magma mixing, SE China: In-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* 61(3-4), 237-269.
- Hoskin, P.W.O., Schaltegger, U., 2003. The compositions of zircon and igneous and metamorphic petrogenesis. *Reviews in Mineralogy and Geochemistry* 53, 27-55.
- Hu, H., Wang, R.C., Chen, W.F., Chen, P.R., Ling, H.F., Liu, G.N., 2013. Timing of hydrothermal activity associated with the Douzhashan uranium-bearing granite and its significance for uranium mineralization in northeastern Guangxi, China. *Chinese Science Bulletin* 58, 4319-4328.

- Hu, H., Wang, R.C., Chen, W.F., Ding, H.H., Chen, P.R., Ling, H.-F., 2012. Study on uranium resource minerals of Douzhashan uranium-bearing granite, northeastern Guangxi. *Geological Review* 58(6), 1056-1068 (in Chinese with English abstract).
- Hu, R.Z., Bi, X.W., Zhou, M.F., Peng, J.T., Su, W.C., Liu, S., Qi, H.W., 2008. Uranium metallogenesis in South China and its relationship to crustal extension during the Cretaceous to Tertiary. *Economic Geology* 103, 583-598.
- Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. *Earth and Planetary Science Letter* 50, 139-155.
- Jahn, B.M., Condie, K.C., 1995. Evolution of the Kaapvaal Craton as viewed from geochemical and Sm-Nd isotopic analyses of intracratonic pelites. *Geochimica et Cosmochimica Acta* 59(11), 2239-2258.
- Jahn, B.M., Wu, F.Y., Lo, C.H., Tasi, C.H., 1999. Crust–mantle interaction induced by deep subduction of the continental crust. *Chemical Geology* 157, 119-146.
- Lehmann, B., 1982. Metallogeny of tin: magmatic differentiation versus geochemical heritage. *Economic Geology* 77, 50-59.
- Lehmann, B., 1987. Tin granites, geochemical heritage, magmatic differentiation. *Geologische Rundschau* 76, 177-185.
- Lepvrier, C., Maluski, H., Van Vuong, N., Roques, D., Axente, V., Ranguin, C., 1997. Indosinian NW-trending shear zones within the Truong Son belt (Vietnam) ^{40}Ar - ^{39}Ar Triassic ages and Cretaceous to Cenozoic overprints. *Tectonophysics* 283(1-4), 105-127.
- Li, S., Xiao, Y., Liou, D., Chen, Y., Ge, N., Zhang, Z., Sun, S.S., Cong, B., Zhang, R., Hart, S.R., Wang, S., 1993. Collision of the North China and Yangtze Blocks and formation of coesite-bearing eclogites: Timing and processes. *Chemical Geology* 109(1-4), 89-111.
- Li, Z.X., Li, X.H., Wartho, J.A., Clark, C., Li, W.X., Zhang, C.L., Bao, C., 2010. Magmatic and metamorphic events during the early Paleozoic Wuyi-Yunkai orogeny, southeastern South China: New age constraints and pressure-temperature conditions. *Geological Society of America Bulletin* 122(5-6), 772-793.
- Ling, H.F., 2011. Origin of hydrothermal fluids of granite-type uranium deposits: Constraints from redox conditions. *Geological Review* 57(2), 193-206 (in Chinese with English abstract).
- Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. *Abstracts of*

- papers to be presented at the Annual Meetings of the Geological Society of America and Associated Societies, San Diego, California, November 5-8 11, p. 468.
- Luo, J., Hu R., Shi S., 2015. Timing of uranium mineralization and geological implications of Shazijiang granite-hosted uranium deposit in Guangxi, South China: New constraint from chemical U-Pb age. *Journal of Earth Science* 26(6): 911–919.
- Ludwig, K.R., 2001a. SQUID1.02. A User Manual. Berkeley Geochronological Center Special Publication, Berkeley, pp. 1-219.
- Ludwig, K.R., 2001b. Using Isoplot/EX, version 2.49. A Geochronological toolkit for Microsoft Excel. Berkeley Geochronological Center Special Publication, Berkeley, pp. 1-55.
- Lugmair, G.W., Marti, K., 1978. Lunar initial $^{143}\text{Nd}/^{144}\text{Nd}$: differential evolution of the lunar crust and mantle. *Earth and Planetary Science Letter* 39, 349-357.
- Marignac, C., Cuney, M., 1999. Ore deposits of the French Massif Central: insight into the metallogenesis of the Variscan collision belt. *Mineralium Deposita* 34(5-6), 472-504.
- Min, M.Z., Luo, X.Z., Li, X.G., Yang, Z., Zhai, L.Y., 2003. Geochemical constraints on the petrogenesis of the Middle Miaoershan granitoids, South China. *Geochemical Journal* 37, 603-625.
- Nam, T.N., Toriumi, M., Itaya, T., 1998. P-T-t paths and post-metamorphic exhumation of the Day Nui Con Voi shear zone in Vietnam. *Tectonophysics* 290(3-4), 299-318.
- Nowell, G.M., Kempton, P.D., Noble, S.R., Fitton, J.G., Saunders, A.D., Mahoney, J.J., Taylor, R.N., 1998. High precision Hf isotope measurements of MORB and OIB by thermal ionisation mass spectrometry: insights into the depleted mantle. *Chemical Geology* 149(3-4), 211-233.
- Pu, W., Gao, J.F., Zhao, K.D., Ling, H.F., Jiang, S.Y., 2005. Separation method of Rb-Sr, Sm-Nd using DCTA and HIBA. *Journal of Nanjing University (Nature Sciences)* 41, 445-450 (in Chinese with English abstract).
- Pu, W., Zhao, K.D., Ling, H.F., Jiang, S.Y., 2004. High precision Nd isotope measurement by Triton TI mass spectrometry. *Acta Geoscientica Sinica* 25, 271-274 (in Chinese with English abstract).
- Rudnick, R.L., Gao, S., 2003. Composition of the continental crust. *Treatise on Geochemistry* 3, 1-64.
- Scherer, E., Munker, C., Mezger, K., 2001. Calibration of the Lutetium-Hafnium clock. *Science* 293(5530), 683-687.
- Shen, W.Z., Zhu, J.C., Liu, C.S., Xu, S.J., Ling, H.F., 1993. Sm-Nd isotopic study of basement

- metamorphic rocks in South China and its constraint on material sources of granitoids. *Acta Petrologica Sinica* 9, 115-124 (in Chinese with English abstract).
- Shi, S.H., Hu, R.Z., Wen, H.J., Sun, R.L., Wang, J.S., Chen, H., 2010. Geochronology of the Shazijiang uranium ore deposit, northern Guangxi, China: U-Pb ages of pitchblende and their geological significance. *Acta Geologica Sinica* 84(8), 1175-1182 (in Chinese with English abstract).
- Shu, L., Guo, L., Shi, Y., Sun, Y., 1994. Kinematic study on the southern marginal fault zone of the Jiuling Mountains, Jiangxi Province. *Scientia Geologica Sinica* 29, 209-219 (in Chinese with English abstract).
- Song, B., Zhang, Y.H., Wan, Y.S., 2002. Mounting and analytical procedure of SHRIMP zircon dating. *Geological Review* 48, 26-40 (in Chinese with English abstract).
- Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalt: implications for mantle composition and processes. *Geological Society of London, Special Publication* 42, 528-548.
- Sylvester, P.J., 1998. Post-collisional strongly peraluminous granites. *Lithos* 45(1-4), 29-44.
- Tanaka, T., Togashi, S., Kamioka, H., Amakawa, H., Kagami, H., Hamamoto, T., Yuhara, M., Orihashi, Y., Yoneda, S., Shimizu, H., Kunimaru, T., Takahashi, K., Yanagi, T., Nakano, T., Fujimaki, H., Shinjo, R., Asahara, Y., Tanimizu, M., Dragusanu, C., 2000. JNdi-1: a neodymium isotopic reference in consistency with LaJolla neodymium. *Chemical Geology* 168(3-4), 279-281.
- Wang, Y., Fan, W., Sun, M., Liang, X., Zhang, Y., Peng, T., 2007. Geochronological, geochemical and geothermal constraints on petrogenesis of the Indosinian peraluminous granites in the South China Block: A case study in the Hunan Province. *Lithos* 96(3-4), 475-502.
- Wang, Y., Fan, W., Zhang, G., Zhang, Y., 2013. Phanerozoic tectonics of the South China Block: Key observations and controversies. *Gondwana Research* 23(4), 1273-1305.
- Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* 64, 295-304.
- Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* 95(4), 407-419.
- Wu, F.Y., Yang, Y.H., Xie, L.W., Yang, J.H., Xu, P., 2006. Hf isotopic compositions of the standard zircons and baddeleyites used in U-Pb geochronology. *Chemical Geology* 234(1-2), 105-126.
- Wu, J., Liang, H.Y., Huang, W.T., Wang, C.L., Sun, W.D., Sun, Y.L., Li, J., Mo, J.H., Wang, X.Z., 2012.

- Indosinian isotope ages of plutons and deposits in southwestern Miaoershan-Yuechengling, northeastern Guangxi and implications on Indosinian mineralization in South China. *Chinese Science Bulletin* 57, 1024-1035.
- Wu, Y.B., Zheng, Y.F., 2004. Genesis of zircon and its constraints on interpretation of U-Pb age. *Chinese Science Bulletin* 49(15), 1554-1569.
- Xie, X.H., Chen, W.F., Zhao, K.D., Sun, T., Chen, P.R., Jiang, S.Y., Zhu, K.R., Li, W.W., 2008. Geochemical characteristics and geochronology of the Douzhashan granite, northeastern Guangxi Province, China. *Acta Petrologica Sinica* 24(6), 1302-1312 (in Chinese with English abstract).
- Xu, W.C., 1994. Geochronological study on the Miaoershan composite granitic batholith. *Acta Petrologica Sinica* 10, 330-337 (in Chinese with English abstract).
- Yu, J.H., Wang, L.J., Wang, X.L., Qiu, J.S., Zhao, L., 2007. Geochemistry and geochronology of the Fucheng complex in the southeastern Jiangxi province, China. *Acta Petrologica Sinica* 23(6), 1441-1456 (in Chinese with English abstract).
- Zen, E.-A., 1988. Phase relationships of peraluminous granitic rocks and their petrogenetic implications. *Annual Review of Earth and Planetary Sciences* 16, 21-51.
- Zhang, J., Chen, W.F., Chen, P.R., 2011. Compositional differences of the biotites from the uranium-forming and non uranium-forming Indosinian granites in South China. *Geotectonica et Metallogenia* 35(2), 270-277 (in Chinese with English abstract).
- Zhang, K.J., Zhu, J.X., 2003. Intracontinental deformation of South China due to penetration of North China: fold and thrust structures and their ore-controlling in southern Anhui, South China. *Journal of Nanjing University (Nature Sciences)* 39, 746-753 (in Chinese with English abstract).
- Zhang, Y.Q., Xu, X.B., Jia, D., Shu, L.S., 2009. Deformation record of the change from Indosinian collision-related tectonic system to Yanshanian subduction-related tectonic system in South China during the Early Mesozoic. *Earth Science Frontier* 16, 234-247 (in Chinese with English abstract).
- Zhang, Z.H., Zhang, B.T., 1991. On the uranium-bearing granites and their related uranium deposits in South China. Atomic Energy Press, Beijing, pp. 1-258 (in Chinese with English abstract).
- Zhao, K.D., Jiang, S.Y., Chen, W.F., Chen, P.R., Ling, H.F., 2013a. Zircon U-Pb chronology and

- elemental and Sr–Nd–Hf isotope geochemistry of two Triassic A-type granites in South China: Implication for petrogenesis and Indosinian transtensional tectonism. *Lithos* 160-161, 292-306.
- Zhao, K.D., Jiang, S.Y., Chen, W.F., Chen, P.R., Ling, H.F., 2014a. Mineralogy, geochemistry and ore genesis of the Dawan uranium deposit in southern Hunan Province, South China. *Journal of Geochemical Exploration* 138, 59-71.
- Zhao, K.D., Jiang, S.Y., Dong, C.Y., Chen, W.F., Chen, P.R., Ling, H.F., Zhang, J., Wang, K.X., 2011. Uranium-bearing and barren granites from the Taoshan Complex, Jiangxi Province, South China: Geochemical and petrogenetic discrimination and exploration significance. *Journal of Geochemical Exploration* 110(2), 126-135.
- Zhao, K.D., Jiang, S.Y., Ling, H.F., Palmer, M.R., 2014b. Reliability of LA-ICP-MS U-Pb dating of zircons with high U concentrations: a case study from the U-bearing Douzhashan granite in South China. *Chemical Geology* 389, 110-121.
- Zhao, K.D., Li, J.R., Ling, H.F., Chen, P.R., Chen, W.F., Sun, T., 2013b. Geochronology, geochemistry and petrogenesis of two-stage Indosinian granites from the Xiajiang uranium ore deposit, Jiangxi Province: Implication for Indosinian tectonics and genesis of uranium-bearing granites in South China. *Acta Petrologica Sinica* 29(12), 4349-4361 (in Chinese with English abstract).
- Zhao, K.D., Jiang, S.Y., Sun, T., Chen, W.F., Ling, H.F., Chen, P.R., 2013c. Zircon U–Pb dating, trace element and Sr–Nd–Hf isotope geochemistry of Paleozoic granites in the Miao’ershan–Yuechengling batholith, South China: Implication for petrogenesis and tectonic–magmatic evolution. *Journal of Asian Earth Sciences* 74(0), 244-264.
- Zhao, L., Guo, F., Fan, W., Li, C., Qin, X., Li, H., 2012. Origin of the granulite enclaves in Indo-Sinian peraluminous granites, South China and its implication for crustal anatexis. *Lithos* 150, 209-226.
- Zheng, Y.F., 2008. A perspective view on ultrahigh-pressure metamorphism and continental collision in the Dabie-Sulu orogenic belt. *Chinese Science Bulletin* 53(20), 3081-3104.
- Zhou, C.M., Jiang, S.Y., 2009. Palaeoceanographic redox environments for the lower Cambrian Hetang Formation in South China: Evidence from pyrite framboids, redox sensitive trace elements, and sponge biota occurrence. *Palaeogeography, Palaeoclimatology, Palaeoecology* 271(3-4), 279-286.

Zhou, X.M., Sun, T., Shen, W.Z., Shu, L.S., Niu, Y.L., 2006. Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: A response to tectonic evolution. *Episodes* 29(1), 26-33.

Figure Captions

Figure 1 Distribution of Triassic granites and main granite-hosted U ore districts in South China.

Age data of U-bearing granite came from: Daguzhai granite (Zhao et al., 2011); Baimianshi granite (Dong et al., 2010); Fucheng granite (Yu et al., 2007); Xiazhuang granite (Chen et al., 2012); Zhuguang granite (Deng et al., 2012).

Figure 2 Simplified geological map of the Miao'ershan batholith (modified from Zhao et al., 2013c)

Figure 3 Photographs of represented samples from the Yangqiaoling (a), Xiangcaoping (b) and Douzhashan (c-d) granites. Bt-biotite, Mus-muscovite, Pl-plagioclase, Q-quartz.

Figure 4 U-Pb Concordia diagrams of zircons for Sample MES-10A and Sample MES-14A from the Yangqiaoling granite. Represented CL images of zircon grains are shown in this figure.

Figure 5 Plot of A/CNK vs. A/NK for the Yangqiaoling, Xiangcaoping and Douzhashan granites.

Figure 6 Plots of selected major oxides (wt. %) and trace element contents (ppm) vs. SiO₂ contents (wt. %) for the Yangqiaoling, Xiangcaoping and Douzhashan granites. Symbols are as in Fig. 5.

Figure 7 Plot of Th vs. U contents for the Yangqiaoling, Xiangcaoping and Douzhashan granites. Fractionation trends of peralkaline, metaluminous and peraluminous magma and fluid are shown in the figure. Symbols are as in Fig. 5.

Figure 8 Primitive mantle-normalized trace element spidergrams for the Yangqiaoling (a), Xiangcaoping (b) and Douzhashan (c) granites. The normalization values of primitive mantle are from Sun and McDonough (1989).

Figure 9 Chondrite-normalized REE diagrams for the Yangqiaoling (a), Xiangcaoping (b) and

Douzhashan (c) granites. The normalization values of Chondrite are from Boyton (1984).

Figure 10 Plots of Ba vs. Sr, Ba vs. Rb, Ba vs. Eu and $(La/Yb)_N$ vs. La for the Yangqiaoling, Xiangcaoping and Douzhashan granites. Fractional crystallization trends by different minerals are shown in this figure. Symbols are as in Fig. 5.

Figure 11 Plots of $\epsilon_{Nd}(t)$ vs. $(^{87}Sr/^{86}Sr)_i$ and $\epsilon_{Nd}(t)$ vs. t for the Yangqiaoling, Xiangcaoping and Douzhashan granites. The fields correspond to the Yangtze lower crust, North China lower and upper crust and upper continental crust (Jahn et al., 1999), Proterozoic basement of Cathaysia Block (Shen et al., 1993) and Paleozoic I-type granites in the Miao'ershan batholith (Zhao et al., 2013c). Symbols are as in Fig. 5.

Figure 12 Histograms of zircon $\epsilon_{Hf}(t)$ values and T_{DM}^C (Ga) of the Yangqiaoling, Xiangcaoping and Douzhashan granites.

Figure 13 Plot of Al_2O_3/TiO_2 vs. CaO/Na_2O for the Yangqiaoling, Xiangcaoping and Douzhashan granites (after Sylvester, 1989).

Figure 14 Plots of U, Sn, W vs. Rb/Sr and TiO_2 for the Yangqiaoling, Xiangcaoping and Douzhashan granites. Symbols are as in Fig. 5.

Table 1 SHRIMP zircon U-Pb data for the Yangqiaoling granite

Spots	U (ppm)	Th (ppm)	²³² Th / ²³⁸ U	²⁰⁷ Pb / ²³⁵ U	error (±%)	²⁰⁶ Pb / ²³⁸ U	error (±%)	²⁰⁶ Pb/ ²³⁸ U Age	1s error
Sample 06MES-10A									
MES-10A-1.1	746	361	0.50	0.2731	4.0	0.0339	1.5	214.9	3.2
MES-10A-2.1	2143	726	0.35	0.2533	2.5	0.0355	1.2	224.7	2.6
MES-10A-3.1	2645	801	0.31	0.2379	1.7	0.0337	1.1	213.9	2.4
MES-10A-4.1	3154	762	0.25	0.2629	2.7	0.0332	1.1	210.6	2.4
MES-10A-5.1	2185	467	0.22	0.2500	2.1	0.0347	1.2	219.9	2.5
MES-10A-6.1	3216	770	0.25	0.2512	2.2	0.0345	1.1	218.5	2.5
MES-10A-9.1	2739	664	0.25	0.2397	3.0	0.0324	1.2	205.4	2.3
MES-10A-10.1	2531	808	0.33	0.2635	2.4	0.0345	1.2	218.9	2.5
MES-10A-11.1	3002	633	0.22	0.3638	5.2	0.0327	1.1	207.6	2.3
Sample 06MES-14A									
MES-14A-1.1	914	358	0.41	0.2822	5.8	0.0339	1.3	214.6	2.6
MES-14A-2.2	618	350	0.59	0.3601	6.1	0.0350	1.6	221.5	3.5
MES-14A-4.1	237	150	0.65	0.3249	15.5	0.0334	1.8	212.0	3.6
MES-14A-9.1	1745	590	0.35	0.2395	3.6	0.0335	1.2	212.4	2.5
MES-14A-10.1	829	343	0.43	0.3295	4.0	0.0339	1.3	215.0	2.8
MES-14A-11.2	363	274	0.78	0.2936	11.6	0.0341	1.5	215.9	3.2
MES-14A-12.1	615	342	0.58	0.2816	2.6	0.0341	1.5	215.9	3.2
MES-14A-12.2	1158	398	0.35	0.2414	3.4	0.0333	1.2	211.5	2.5
MES-14A-13.2	121	90	0.77	0.4786	17.7	0.0354	2.0	224.0	4.4

Table 2 Major element (in %) and trace element (in ppm) compositions of the Yangqiaoling, Xiangcaoping and Douzhashan granites

Sample	Yangqiaoling granite								Xiangcaoping granite				
	06MES-10	06MES-10	06MES-11	06MES-13	06MES-13	06MES-14	06MES-14	06MES-14	06SZJ-06	06SZJ-06	06DZS-02	06DZS-02	SZJ-3
	A	B	A	A	B	A	B	C	A	B	A	B	4
SiO₂	71.5	71.86	71.25	74.23	72.78	73.08	75.75	72.65	74.06	74.11	73.89	73.59	74.27
TiO₂	0.38	0.37	0.36	0.34	0.31	0.35	0.34	0.35	0.24	0.23	0.19	0.33	0.23
Al₂O₃	13.94	13.98	14.59	12.81	14.11	13.35	12.34	14.2	14.25	14.16	13.66	14.35	13.31
Fe₂O₃	0.86	0.81	1.03	0.78	0.61	0.80	0.56	0.70	0.50	0.50	0.34	0.66	0.42
FeO	1.62	1.62	1.73	1.47	1.45	1.69	1.68	1.59	1.18	1.24	1.11	1.56	1.23
MnO	0.06	0.06	0.06	0.05	0.05	0.08	0.06	0.05	0.04	0.06	0.05	0.06	0.04
MgO	0.76	0.76	1.35	0.65	0.56	0.63	0.61	0.63	0.44	0.52	0.42	0.59	0.47
CaO	2.09	1.74	1.84	1.48	1.35	1.55	1.36	2.03	0.75	0.97	0.61	1.20	1.08
Na₂O	3.29	3.04	3.04	2.50	2.51	2.64	2.04	2.90	2.12	2.29	2.28	2.43	2.77
K₂O	4.65	5.19	3.62	4.95	5.51	5.07	4.57	4.40	5.14	4.92	6.24	4.19	5.19
P₂O₅	0.13	0.12	0.12	0.10	0.11	0.11	0.10	0.12	0.15	0.15	0.15	0.18	0.13
LOI	0.38	0.49	1.29	0.40	0.58	0.44	0.30	0.30	1.20	0.66	1.07	0.65	1.12
Total	99.69	100.04	100.28	99.76	99.93	99.79	100.07	99.92	100.07	99.81	100.01	99.79	100.26
CaO/Na₂O	0.64	0.57	0.61	0.59	0.54	0.59	0.57	0.70	0.35	0.42	0.27	0.49	0.39
A/CNK	0.98	1.01	1.19	1.05	1.12	1.05	1.08	1.07	1.37	1.30	1.17	1.34	1.09
Li	111	84.0	62.5	99.7	97.8	84.3	99.0	88.4	147	134	164	183	86.4
Be	5.44	5.11	7.46	4.92	5.29	5.21	5.63	7.04	4.80	5.54	2.86	3.78	7.80
Sc	7.77	7.35	7.73	7.02	6.30	7.00	6.81	6.70	4.45	4.29	4.15	6.83	3.95
Ti	2264	2091	2025	1961	1731	1992	2050	2138	1373	1405	1187	1873	1233
V	39.79	38.53	52.47	34.48	29.58	33.37	32.98	35.71	19.20	19.23	14.78	27.46	17.42

Cr	17.96	18.76	24.74	15.06	10.26	13.73	15.62	23.00	25.93	18.51	127.82	27.93	12.35
Mn	380	396	484	385	343	357	455	492	277	295	407	409	312
Co	6.99	6.97	8.38	6.02	5.04	6.04	5.87	6.27	3.37	3.10	4.06	4.38	3.41
Ni	8.42	8.87	18.01	6.35	4.74	5.38	6.72	10.61	13.63	10.02	71.28	12.98	3.58
Ga	19.04	18.42	16.84	16.53	17.18	16.53	16.73	18.31	19.12	18.79	18.01	21.29	17.30
Rb	340	343	220	371	391	349	395	305	338	354	368	374	360
Sr	76.08	73.05	141.89	67.54	59.69	58.33	50.11	69.84	51.4	58.3	42.0	53.0	64.75
Y	46.57	30.14	36.85	37.97	37.63	39.04	46.21	31.49	16.41	18.03	13.53	19.49	16.14
Zr	152	184	14.6	194	147	236	185	190	142	159	115	140	107
Nb	15.74	14.98	12.46	13.11	12.19	12.96	14.42	12.55	13.68	13.5	13.8	21.03	12.3
Mo	0.58	0.67	0.75	0.57	0.56	0.84	0.69	0.98	0.82	0.65	3.01	0.94	3.09
Sn	14.63	13.20	7.23	13.12	13.79	13.08	15.59	12.29	12.78	11.55	17.94	19.38	17.80
Cs	41.7	50.4	20.3	30.2	44.0	29.61	37.1	30.9	33.17	43.9	56.7	60.9	34.0
Ba	251	353	500	283	332	284	204	255	266	310	202	217	296
La	37.04	35.80	36.74	42.28	33.81	39.57	32.60	42.79	31.07	35.42	27.27	27.99	31.49
Ce	81.94	75.38	74.16	94.17	74.25	92.31	76.01	93.75	68.57	75.11	61.26	65.92	59.45
Pr	9.72	9.29	8.02	10.82	8.97	10.60	8.88	10.73	7.51	8.40	7.27	7.97	7.04
Nd	38.36	35.49	28.53	40.22	34.21	40.08	35.34	40.53	28.68	29.62	25.10	29.51	26.83
Sm	8.52	7.40	5.53	8.05	7.43	8.49	7.82	8.07	5.59	5.87	4.75	5.27	5.20
Eu	0.79	0.79	0.86	0.62	0.69	0.63	0.54	0.75	0.44	0.57	0.38	0.51	0.58
Gd	8.41	6.50	5.83	7.35	6.91	7.56	7.35	6.82	4.71	5.09	4.01	4.88	4.32
Tb	1.46	1.07	0.98	1.20	1.17	1.31	1.30	1.05	0.69	0.75	0.57	0.78	0.66
Dy	8.32	6.20	6.05	6.91	6.93	7.42	8.08	6.09	3.47	3.49	3.19	4.52	3.36
Ho	1.69	1.13	1.25	1.32	1.34	1.43	1.61	1.14	0.58	0.61	0.50	0.75	0.58
Er	4.91	3.26	3.81	3.93	4.06	4.34	5.02	3.36	1.55	1.67	1.43	2.19	1.56
Tm	0.71	0.48	0.59	0.58	0.62	0.64	0.83	0.51	0.23	0.23	0.22	0.32	0.21

Yb	4.56	3.15	3.75	3.63	4.00	4.21	5.34	3.18	1.53	1.49	1.23	1.92	1.37
Lu	0.64	0.46	0.56	0.54	0.57	0.61	0.79	0.47	0.18	0.20	0.20	0.27	0.20
Hf	5.11	6.11	4.66	6.38	5.04	8.48	6.85	6.15	4.21	4.94	3.91	4.93	3.53
Ta	2.55	2.37	1.89	2.06	2.29	2.19	3.42	2.00	2.69	2.46	3.16	4.09	2.67
W	1.16	2.27	3.13	0.86	0.69	0.86	0.92	0.97	4.39	2.60	4.97	10.71	4.50
Pb	53.43	52.86	55.84	49.06	53.53	52.58	48.59	47.13	39.96	37.94	33.20	36.72	46.04
Bi	1.13	1.30	1.06	3.38	2.96	4.56	1.38	1.32	1.50	3.42	2.26	6.21	1.48
Th	43.38	34.64	24.85	40.10	36.62	45.81	34.56	37.59	32.75	35.35	26.86	31.91	27.09
U	9.33	10.59	6.39	14.12	18.33	13.55	11.42	8.07	3.96	4.98	9.30	8.99	7.61
Zr+Nb+Ce+													
Y	295.9	304.2	269.0	339.5	271.5	379.9	321.5	327.6	241.1	265.9	203.1	246.1	194.6
Rb/Sr	4.47	4.69	1.55	5.49	6.55	5.98	7.88	4.37	6.58	6.07	8.76	7.06	5.56
Rb/Ba	1.35	0.97	0.44	1.31	1.18	1.23	1.93	1.20	1.27	1.14	1.82	1.73	1.22
Th/U	4.65	3.27	3.89	2.84	2.00	3.38	3.03	4.66	8.27	7.10	2.89	3.55	3.56
REE	207	186	177	222	185	219	191	219	155	169	137	153	143
T_{Zr} (°C)	773	794	789	807	787	823	808	804	803	809	771	799	759

Douzhashan granite															
Sample	06DZS-01	06DZS-01	SZJ-43	06SZJ-0	06SHJ-1	06DZS-06	06DZS-08C	06DZS-09A	06DZS-09B	06DZS-10B	SZJ-01	SZJ-07	SZJ-08	SZJ-21	SZJ-35
	A	B	a	3	2	H	*	*	*	*	*	*	*	*	*
SiO ₂	75.4	75.3	74.96	75.33	73.25	73.82	75.54	75.58	75.09	75.55	75.1	74.67	75.85	75.80	76.02
TiO ₂	0.14	0.14	0.09	0.15	0.24	0.12	0.10	0.12	0.12	0.11	0.15	0.14	0.14	0.15	0.09
Al ₂ O ₃	13.58	13.66	13.70	13.14	14.00	15.02	13.78	13.43	13.92	13.40	13.29	13.72	13.16	13.14	13.69
Fe ₂ O ₃	0.31	0.38	0.52	0.64	0.42	0.49	0.39	0.37	0.30	0.35	0.47	0.48	0.29	0.49	0.48
FeO	0.96	0.93	0.70	0.74	1.30	0.68	0.63	0.85	0.86	0.83	0.98	0.89	0.97	0.94	0.40
MnO	0.05	0.05	0.07	0.05	0.05	0.06	0.06	0.09	0.07	0.07	0.06	0.05	0.05	0.07	0.06
MgO	0.29	0.31	0.39	0.30	0.46	0.23	0.18	0.21	0.21	0.23	0.30	0.31	0.28	0.30	0.13
CaO	0.82	0.91	1.01	0.67	0.88	0.30	0.32	0.70	0.73	0.77	0.89	0.80	0.84	0.90	0.49
Na ₂ O	2.53	2.48	1.39	2.94	2.94	1.34	2.88	3.11	3.28	3.17	3.02	2.95	2.93	2.80	3.50
K ₂ O	5.02	5.07	4.52	5.15	5.31	5.59	4.88	4.77	4.91	4.71	5.00	5.00	4.75	4.96	4.25
P ₂ O ₅	0.11	0.11	0.16	0.10	0.16	0.12	0.10	0.14	0.13	0.13	0.11	0.09	0.10	0.09	0.17
LOI	0.71	0.72	2.60	0.93	1.30	2.19	0.89	0.65	0.66	0.87	0.8	1.02	0.64	0.71	0.87
Total	99.92	100.06	100.1	100.14	100.31	99.96	99.75	100.02	100.28	100.19	100.2	100.1	100	100.4	100.1
CaO/Na ₂ O	0.32	0.37	0.73	0.23	0.30	0.22	0.11	0.23	0.22	0.24	0.29	0.27	0.29	0.32	0.14
A/CNK	1.22	1.22	1.52	1.13	1.15	1.70	1.30	1.16	1.15	1.14	1.11	1.17	1.14	1.13	1.22
Li	163	166	116	120	75.9	232	274	207	198	203	156	144	167	167	139
Be	7.73	8.56	5.33	7.39	6.55	10.69	7.54	13.85	5.15	4.32	8.50	6.17	8.37	5.50	3.34

Sc	4.19	4.77	6.34	4.64	4.46	3.31	3.56	2.37	3.80	3.75	4.44	4.33	4.55	4.68	5.49
Ti	779	921	526	854	1315	737	605	632	610	710	904	796	776	860	515
V	8.26	9.23	5.58	9.41	18.76	7.32	5.69	6.63	6.86	7.50	8.97	8.13	8.36	9.10	3.69
Cr	19.33	23.03	8.35	17.60	10.33	26.18	13.79	16.89	20.40	9.12	17.12	11.94	7.54	14.16	11.40

Sample	06DZS-01A	06DZS-01B	SZJ-43a	06SZJ-03	06SHJ-12	06DZS-06H	06DZS-08C*	06DZS-09A*	06DZS-09B*	06DZS-10B*	SZJ-01*	SZJ-07*	SZJ-08*	SZJ-21*	SZJ-35*
Mn	376.7	416.8	488.3	377.3	312.3	451.9	430.9	434.0	492.4	498.9	366.6	414.6	384.0	441.5	422.0
Co	2.00	1.70	1.22	2.48	3.28	2.51	0.84	1.29	1.34	1.47	1.98	1.85	1.70	1.78	0.99
Ni	10.02	10.11	2.76	6.46	3.40	9.43	4.62	7.85	7.59	2.11	5.14	3.41	2.05	3.96	2.89
Ga	17.66	18.30	22.13	18.58	19.46	19.20	20.02	18.07	20.13	18.97	18.18	18.86	17.69	18.39	24.76
Rb	423.1	441.5	626.7	462.5	452.2	561.9	589.1	498.7	500.0	522.0	444.1	474.1	464.3	471.4	688.0
Sr	39.5	36.1	20.51	38.23	63.31	27.4	20.9	34.5	36.1	38.13	39.12	40.29	43.18	47.92	10.30
Y	28.39	28.76	16.39	27.26	14.89	24.08	16.70	22.53	24.38	26.70	30.28	26.35	26.86	30.01	9.47
Zr	82.2	101.6	57.0	84.8	119.6	100.0	66.7	65.9	72.2	94.4	115.5	90.8	92.3	99.7	28.7
Nb	18.42	19.46	26.30	18.94	16.12	19.75	23.21	20.34	21.72	25.99	20.30	18.95	18.44	19.95	29.12
Mo	0.98	1.11	0.81	0.84	0.80	0.60	0.43	0.62	0.89	0.60	0.51	0.52	0.48	0.81	16.88
Sn	23.72	25.66	52.59	25.62	22.25	27.04	44.34	32.54	32.09	42.95	26.73	25.51	25.28	27.03	64.17
Cs	58.12	71.91	78.87	69.90	36.16	74.18	89.33	72.38	74.29	75.43	63.69	56.38	61.15	68.70	103.33
Ba	142.0	147.4	60.5	157.8	257.9	148.9	76.2	86.2	100.4	102.4	145.7	138.7	144.7	150.7	18.7
La	23.95	28.20	13.31	25.98	27.75	23.82	14.14	18.88	19.10	19.43	25.92	27.43	27.69	29.00	5.48
Ce	58.21	68.03	27.41	64.78	62.85	55.24	30.59	40.02	44.57	41.56	50.45	53.74	47.91	52.89	11.14
Pr	6.74	8.11	3.16	6.79	7.33	6.17	3.57	4.45	5.16	5.08	6.56	6.37	5.95	6.41	1.24
Nd	25.53	28.76	11.37	25.45	28.06	21.38	13.45	17.14	18.66	19.84	23.65	23.24	21.85	25.01	4.95
Sm	5.00	5.83	2.65	5.67	5.65	4.63	2.71	3.63	4.06	4.71	5.05	4.80	4.73	5.46	1.32
Eu	0.32	0.35	0.17	0.32	0.49	0.32	0.16	0.21	0.25	0.27	0.31	0.29	0.29	0.32	0.06
Gd	5.13	5.52	2.56	5.18	4.46	4.41	2.76	3.69	3.97	4.07	5.05	4.73	4.70	5.08	1.34

Tb	0.91	1.04	0.52	0.89	0.63	0.74	0.48	0.68	0.72	0.75	0.90	0.80	0.82	0.87	0.29
Dy	5.40	6.28	3.14	5.19	3.25	4.22	2.99	3.86	4.40	4.67	5.43	5.02	4.83	5.51	1.75
Ho	0.96	1.14	0.55	1.01	0.54	0.83	0.56	0.71	0.76	0.87	1.08	0.97	0.93	1.05	0.30
Er	2.96	3.48	1.58	3.03	1.53	2.52	1.80	2.26	2.51	2.67	2.92	2.85	2.72	3.22	0.90
Tm	0.52	0.54	0.25	0.47	0.22	0.42	0.27	0.36	0.39	0.46	0.47	0.43	0.40	0.49	0.16
Yb	3.24	3.66	1.71	3.20	1.38	2.86	1.82	2.27	2.65	3.41	3.29	3.00	2.77	3.35	1.14
Lu	0.48	0.53	0.24	0.48	0.20	0.45	0.25	0.33	0.40	0.59	0.54	0.46	0.45	0.52	0.17
Hf	3.15	3.89	2.31	3.68	3.97	3.28	2.29	2.49	2.74	4.20	4.03	3.03	2.86	3.36	1.41
Ta	4.19	4.66	6.40	4.64	3.81	4.64	7.10	4.83	5.75	5.86	5.36	3.87	3.87	4.41	8.16
W	8.35	7.88	10.96	22.88	4.85	7.05	15.67	6.97	7.61	8.95	9.38	6.72	6.58	6.24	15.19
Pb	47.95	48.46	27.18	53.06	42.88	52.50	34.12	38.83	40.64	41.61	43.33	46.01	43.39	54.13	21.46
Bi	4.54	5.00	12.55	4.75	4.22	6.21	8.29	5.69	6.36	5.69	4.15	4.39	4.73	4.03	2.17
Th	36.14	41.69	15.61	35.21	29.06	35.89	23.48	26.12	32.00	29.13	29.04	31.64	25.39	30.71	7.23
U	20.86	21.58	19.24	26.09	10.67	11.00	10.57	7.98	9.88	12.13	15.56	12.27	20.93	23.93	20.75
Zr+Nb+Ce+Y	187.2	217.8	127.1	195.7	213.4	199.1	137.2	148.8	162.9	188.7	216.6	189.8	185.5	202.6	78.4
Rb/Sr	10.71	12.23	30.56	12.10	7.14	20.54	28.21	14.44	13.86	13.69	11.35	11.77	10.75	9.84	66.77
Rb/Ba	2.98	3.00	10.37	2.93	1.75	3.77	7.73	5.79	4.98	5.10	3.05	3.42	3.21	3.13	36.89
Th/U	1.73	1.93	0.81	1.35	2.72	3.26	2.22	3.27	3.24	2.40	1.87	2.58	1.21	1.28	0.35
REE	139	161	69	148	144	128	76	98	108	108	132	134	126	139	30.2
T_{Zr} (°C)	748	765	736	744	771	788	736	727	732	754	767	752	753	758	670

Sample	06SZJ-04*	06SZJ-05*
SiO ₂	75.06	75.26
TiO ₂	0.14	0.13
Al ₂ O ₃	13.27	13.10
Fe ₂ O ₃	0.35	0.05
FeO	0.93	1.12
MnO	0.06	0.05
MgO	0.33	0.32
CaO	0.89	0.86
Na ₂ O	2.75	2.67
K ₂ O	5.22	5.45
P ₂ O ₅	0.12	0.11
LOI	1.14	1.04
Total	100.26	100.16
CaO/Na ₂ O	0.32	0.32
A/CNK	1.12	1.10
Li	153.8	160.5
Be	7.82	12.01
Sc	4.24	4.15
Ti	785	759
V	9.32	8.57
Cr	12.24	9.14

Sample	06SZJ-04*	06SZJ-05*
Mn	394.7	450.7
Co	1.46	2.08
Ni	4.98	1.71
Ga	17.83	18.81
Rb	473.7	488.5
Sr	38.38	36.82
Y	28.47	24.75
Zr	90.9	72.2
Nb	19.27	19.02
Mo	1.01	0.61
Sn	24.92	27.81
Cs	61.95	71.61
Ba	146.9	147.9
La	23.38	20.42
Ce	60.78	52.38
Pr	6.19	5.57
Nd	23.00	20.83
Sm	5.43	4.83
Eu	0.30	0.28
Gd	4.90	4.63
Tb	0.87	0.80
Dy	5.22	4.70
Ho	1.02	0.91
Er	3.05	2.74

Tm	0.49	0.43
Yb	3.32	2.90
Lu	0.49	0.42
Hf	3.52	2.95
Ta	4.35	4.51
W	8.48	10.44
Pb	46.33	50.45
Bi	5.89	4.21
Th	29.78	27.96
U	21.53	23.15
Zr+Nb+Ce+Y	199.4	168.3
Rb/Sr	12.34	13.27
Rb/Ba	3.23	3.30
Th/U	1.38	1.21
REE	138	122
T_{Zr} (°C)	749	730

Table 3 Sr-Nd isotopic composition of the Yangqiaoling, Xiangcaoping and Douzhashan granites

Sample	age (Ma)	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	error	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	error	$\epsilon_{\text{Nd}}(t)$	T_{DM}^{C} (Ga)
Yangqiaoling granite														
06MES-10A	215	340	76.1	13.01	0.763755	0.000003	0.723984	8.52	38.36	0.1343	0.512079	0.000007	-9.2	1.74
06MES-10B	215	343	73.2	13.64	0.764965	0.000003	0.723267	7.40	35.49	0.1260	0.512058	0.000004	-9.4	1.76
06MES-13A	215	371	67.5	15.98	0.770338	0.000004	0.721472	8.05	40.22	0.1210	0.512105	0.000005	-8.3	1.67
06MES-13B	215	391	59.7	19.08	0.778775	0.000005	0.720422	7.43	34.21	0.1313	0.512074	0.000007	-9.2	1.74
06MES-14A	215	349	58.3	17.42	0.775380	0.000007	0.722114	8.49	40.08	0.1281	0.512065	0.000004	-9.3	1.75
06MES-14B	215	395	50.1	22.97	0.790218	0.000004	0.719977	7.82	35.34	0.1337	0.512080	0.000004	-9.2	1.74
06MES-14C	215	305	69.8	12.71	0.761343	0.000004	0.722494	8.07	40.53	0.1204	0.512074	0.000004	-8.9	1.72
Xiangcaoping granite														
06SZJ-06A	211	338	51.4	19.20	0.791175	0.000004	0.733565	5.59	28.68	0.1179	0.511971	0.000005	-10.9	1.88
06SZJ-06B	211	354	58.3	17.67	0.779846	0.000005	0.726820	5.87	29.62	0.1198	0.511955	0.000004	-11.3	1.90
06DZS-02A	211	368	42.0	25.59	0.808712	0.000004	0.731916	4.75	25.10	0.1145	0.511971	0.000003	-10.8	1.87
06DZS-02B	211	374	53.0	20.60	0.793436	0.000009	0.731609	5.27	29.51	0.1079	0.511980	0.000003	-10.4	1.84
Douzhashan granite														
06DZS-01A	204	423	39.5	31.34	0.824244	0.000003	0.733314	5.00	25.53	0.1183	0.512002	0.000003	-10.4	1.83
06DZS-08C	204	589	20.9	83.80	0.980501	0.000003	0.737406	2.71	13.45	0.1217	0.512005	0.000004	-10.4	1.83
06DZS-09A	204	499	34.5	42.34	0.846987	0.000003	0.724148	3.63	17.14	0.1279	0.511991	0.000006	-10.8	1.86
06DZS-10B	204	522	38.1	40.16	0.851375	0.000004	0.734868	4.71	19.84	0.1435	0.512033	0.000002	-10.4	1.83

Table 4 Lu-Hf isotopic compositions of zircons from the Yangqiaoling, Xiangcaoping and Douzhashan granites

Spots	$^{176}\text{Lu}/^{177}\text{Hf}$	error	$^{176}\text{Hf}/^{177}\text{Hf}$	error	Age(Ma)	$(^{176}\text{Hf}/^{177}\text{Hf})_i$	$\varepsilon_{\text{Hf}}(\text{t})$	T_{DM}^{C}
Yangqiaoling granite (Sample 06MES-10A)								
MES-10A-01	0.001120	0.000019	0.282453	0.000016	215	0.282449	-6.7	1.67
MES-10A-02	0.001143	0.000005	0.282459	0.000015	215	0.282455	-6.5	1.66
MES-10A-03	0.001451	0.000024	0.282406	0.000016	215	0.282400	-8.4	1.78
MES-10A-04	0.001626	0.000011	0.282465	0.000014	215	0.282458	-6.4	1.65
MES-10A-05	0.000957	0.000019	0.282500	0.000016	215	0.282496	-5.1	1.57
MES-10A-06	0.001261	0.000010	0.282489	0.000016	215	0.282484	-5.5	1.59
MES-10A-07	0.001476	0.000013	0.282458	0.000015	215	0.282452	-6.6	1.66
MES-10A-08	0.001403	0.000032	0.282503	0.000016	215	0.282498	-5.0	1.56
MES-10A-09	0.001196	0.000006	0.282445	0.000015	215	0.282440	-7.0	1.69
MES-10A-10	0.001531	0.000007	0.282442	0.000014	215	0.282435	-7.2	1.70
MES-10A-11	0.001510	0.000007	0.282492	0.000013	215	0.282485	-5.4	1.59
MES-10A-12	0.001465	0.000043	0.282468	0.000014	215	0.282462	-6.2	1.64
MES-10A-13	0.000904	0.000005	0.282505	0.000014	215	0.282501	-4.9	1.56
MES-10A-14	0.002811	0.000036	0.282476	0.000014	215	0.282464	-6.2	1.64
MES-10A-15	0.001068	0.000011	0.282487	0.000015	215	0.282483	-5.5	1.60
MES-10A-16	0.001890	0.000032	0.282461	0.000015	215	0.282454	-6.5	1.66
MES-10A-17	0.001358	0.000017	0.282421	0.000015	215	0.282416	-7.9	1.74
MES-10A-18	0.001705	0.000046	0.282483	0.000018	215	0.282477	-5.7	1.61
MES-10A-19	0.001373	0.000019	0.282457	0.000017	215	0.282452	-6.6	1.66
MES-10A-20	0.001587	0.000008	0.282463	0.000015	215	0.282456	-6.4	1.65
MES-10A-21	0.001567	0.000051	0.282390	0.000017	215	0.282383	-9.0	1.82
MES-10A-22	0.001323	0.000042	0.282438	0.000016	215	0.282432	-7.3	1.71

Yangqiaoling granite (Sample 06MES-14A)

MES-14A-01	0.000941	0.000012	0.282461	0.000021	215	0.282457	-6.4	1.65
MES-14A-03	0.003327	0.000029	0.282472	0.000015	215	0.282458	-6.4	1.65
MES-14A-04	0.000583	0.000004	0.282520	0.000016	215	0.282517	-4.3	1.52
MES-14A-05	0.001402	0.000031	0.282461	0.000017	215	0.282455	-6.5	1.66
MES-14A-06	0.001837	0.000028	0.282484	0.000013	215	0.282476	-5.7	1.61
MES-14A-07	0.002574	0.000033	0.282467	0.000014	215	0.282457	-6.4	1.65
MES-14A-08	0.002464	0.000096	0.282480	0.000016	215	0.282470	-6.0	1.62
MES-14A-09	0.002600	0.000024	0.282473	0.000016	215	0.282462	-6.2	1.64
MES-14A-10	0.004172	0.000130	0.282465	0.000016	215	0.282449	-6.7	1.67
MES-14A-11	0.002336	0.000059	0.282474	0.000015	215	0.282465	-6.2	1.64
MES-14A-12	0.003206	0.000017	0.282524	0.000018	215	0.282512	-4.5	1.53
MES-14A-13	0.001414	0.000010	0.282487	0.000015	215	0.282481	-5.6	1.60
MES-14A-14	0.000694	0.000004	0.282522	0.000017	215	0.282519	-4.2	1.52
MES-14A-15	0.001566	0.000129	0.282481	0.000017	215	0.282474	-5.8	1.61
MES-14A-16	0.000907	0.000001	0.282498	0.000017	215	0.282494	-5.1	1.57
MES-14A-17	0.001514	0.000101	0.282486	0.000015	215	0.282479	-5.6	1.60
MES-14A-18	0.001246	0.000046	0.282498	0.000016	215	0.282493	-5.1	1.57
MES-14A-19	0.002559	0.000107	0.282527	0.000016	215	0.282517	-4.3	1.52
MES-14A-20	0.002152	0.000024	0.282437	0.000014	215	0.282429	-7.4	1.72
MES-14A-21	0.001016	0.000002	0.282496	0.000015	215	0.282492	-5.2	1.58
MES-14A-22	0.002497	0.000090	0.282502	0.000021	215	0.282492	-5.2	1.58

Xiangcaoping granite (Sample 06SZJ-06B)

SZJ-06B-01	0.002482	0.000074	0.282478	0.000016	211	0.282468	-6.1	1.63
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SZJ-06B-02	0.003734	0.000070	0.282457	0.000019	211	0.282442	-7.0	1.69
SZJ-06B-03	0.000914	0.000015	0.282380	0.000013	211	0.282377	-9.4	1.83
SZJ-06B-04	0.001559	0.000047	0.282489	0.000015	211	0.282483	-5.6	1.60
SZJ-06B-05	0.001613	0.000017	0.282454	0.000015	211	0.282448	-6.8	1.68
SZJ-06B-06	0.001769	0.000020	0.282516	0.000016	211	0.282509	-4.7	1.54
SZJ-06B-07	0.001727	0.000037	0.282447	0.000014	211	0.282440	-7.1	1.69
SZJ-06B-08	0.001536	0.000025	0.282475	0.000014	211	0.282468	-6.1	1.63
SZJ-06B-09	0.003477	0.000030	0.282574	0.000021	211	0.282561	-2.8	1.42
SZJ-06B-10	0.001722	0.000059	0.282483	0.000014	211	0.282476	-5.8	1.61
SZJ-06B-11	0.002370	0.000020	0.282492	0.000018	211	0.282483	-5.6	1.60
SZJ-06B-12	0.003041	0.000091	0.282466	0.000013	211	0.282454	-6.6	1.66
SZJ-06B-13	0.001431	0.000009	0.282464	0.000019	211	0.282458	-6.5	1.65
SZJ-06B-14	0.001802	0.000021	0.282431	0.000014	211	0.282424	-7.7	1.73
SZJ-06B-15	0.001666	0.000026	0.282475	0.000014	211	0.282469	-6.1	1.63
SZJ-06B-16	0.001613	0.000014	0.282487	0.000015	211	0.282481	-5.7	1.60
SZJ-06B-17	0.002010	0.000054	0.282455	0.000012	211	0.282447	-6.8	1.68
SZJ-06B-18	0.002033	0.000022	0.282483	0.000012	211	0.282475	-5.9	1.62
SZJ-06B-19	0.001650	0.000005	0.282421	0.000011	211	0.282414	-8.0	1.75
SZJ-06B-20	0.002648	0.000031	0.282524	0.000020	211	0.282513	-4.5	1.53
SZJ-06B-21	0.001539	0.000014	0.282458	0.000014	211	0.282451	-6.7	1.67
SZJ-06B-22	0.002261	0.000013	0.282491	0.000018	211	0.282482	-5.6	1.60

Douzhashan granite (Sample 06DZS-01A)

DZS-01A-03	0.002562	0.000028	0.282378	0.000015	204	0.282368	-9.8	1.86
DZS-01A-04	0.006611	0.000060	0.282383	0.000016	204	0.282357	-10.2	1.88
DZS-01A-05	0.007435	0.000019	0.282333	0.000022	204	0.282303	-12.1	2.00

DZS-01A-06	0.001372	0.000014	0.282405	0.000024	204	0.282399	-8.7	1.79
DZS-01A-08	0.005700	0.000158	0.282333	0.000021	204	0.282310	-11.9	1.98
DZS-01A-09	0.001777	0.000217	0.282394	0.000024	204	0.282387	-9.1	1.82
DZS-01A-10	0.005707	0.000050	0.282306	0.000017	204	0.282283	-12.8	2.04
DZS-01A-11	0.002304	0.000071	0.282449	0.000016	204	0.282439	-7.3	1.70
DZS-01A-12	0.001249	0.000027	0.282425	0.000014	204	0.282420	-8.0	1.74
DZS-01A-13	0.006893	0.000013	0.282383	0.000017	204	0.282356	-10.2	1.88
DZS-01A-15	0.003577	0.000022	0.282422	0.000012	204	0.282408	-8.4	1.77
DZS-01A-16	0.006264	0.000016	0.282328	0.000013	204	0.282303	-12.1	2.00
DZS-01A-17	0.002372	0.000086	0.282421	0.000014	204	0.282412	-8.3	1.76
DZS-01A-18	0.003924	0.000063	0.282417	0.000015	204	0.282401	-8.6	1.78
DZS-01A-19	0.006419	0.000080	0.282439	0.000020	204	0.282414	-8.2	1.75
DZS-01A-20	0.007718	0.000036	0.282401	0.000023	204	0.282371	-9.7	1.85
DZS-01A-21	0.005450	0.000051	0.282399	0.000015	204	0.282377	-9.5	1.84

(a) Yangqiaoling granite

(b) Kangziaping granite

(c) Douzhashan granite

(d) Douzhashan granite