

Article

Petrogenesis and Tectonic Setting of the Guantian and Shangbao Granodiorite, Southern Zhuguangshan Complex, China: Evidence from Zircon U-Pb-Hf Isotopes, and Whole-Rock Geochemistry and Sr-Nd Isotopes

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Abstract

The southern Zhuguangshan complex is one of the most important sources of granite-hosted uranium deposits in the Nanling region and consists predominantly of Caledonian (Cambrian–Silurian), Indosinian (Late Permian–Triassic), and Yanshanian (Jurassic–Cretaceous) granitoids. However, the Caledonian plutonic rocks have not yet been systematically investigated. In this study, we present new LA-ICP-MS zircon U–Pb ages and Hf isotopes, together with whole-rock elemental and Sr–Nd isotope data, for the Guantian and Shangbao granodiorites from the southern Zhuguangshan complex, in order to constrain their petrogenesis and tectonic setting. Zircon U–Pb dating yields emplacement ages of ca. 431.5 and 442.3 Ma for the Guantian and Shangbao plutons, respectively. Both plutons are characterized by high Al₂O₃ (14.35–14.77 wt.% and 13.55–14.38 wt.%) and total alkali (Na₂O + K₂O = 6.22–6.82 wt.% and 6.46–6.85 wt.%) contents, with A/CNK ratios <1.0, and are classified as metaluminous I-type granites. They show enrichment in light rare earth elements (LREE), K, Th, and U, coupled with marked depletion in Ba, Sr, Nb, Ta, P, and Ti, and exhibit pronounced negative Eu anomalies. These geochemical signatures indicate fractional crystallization of Ti-bearing minerals (e.g., rutile and ilmenite) and plagioclase. The granodiorites have initial ⁸⁷Sr/⁸⁶Sr ratios of 0.70595–0.71227, negative εNd(t) values (−7.8 to −4.1), and negative εHf(t) values (−8.7 to −0.4), pointing to a dominantly continental crustal source. Their average Nb/Ta (11.42) and Th/U (5.07) ratios are also consistent with typical continental crust. Based on the lithological assemblage and geochemical characteristics, we propose that the Guantian and Shangbao granodiorites were formed in a post-collisional extensional setting.

Keywords: Nanling polymetallic metallogenic belt; southern Zhuguangshan complex; granodiorite; Caledonian; post-collision



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1. Introduction

The Nanling polymetallic metallogenic belt (NMB) is one of the most important regions for rare and nonferrous metal mineralization in South China, hosting numerous granite-hosted magmatic and hydrothermal deposits of W, Sn, and Nb-Ta [1–5]. The NMB also hosts significant granite-hosted uranium deposits, mainly within the Guidong, Zhuguangshan, Taoshan, and Miaoershan complexes [6–10].

The Zhuguangshan complex is located in the southern segment of the NMB (Figure 1), and is mainly composed of Caledonian (Cambrian–Silurian), Indosinian (Late Permian–Triassic) and Yanshanian (Jurassic–Cretaceous) granitic rocks, hosting many significant uranium ore fields such as Changjiang, Lujing, and Lanhe (Figure 2B) [9,11]. Recent geochemical and geochronological studies of the Zhuguangshan complex reveal that uranium deposits are predominantly hosted by Indosinian and Yanshanian granites exhibiting metallogenic specialization [12–20]. However, our previous work identified abundant Silurian inherited zircons within zircons from Indosinian and Yanshanian granites, indicating that the Caledonian pluton was originally far more extensive than its present exposure. The Indosinian and Yanshanian granites may have been formed by source magma mixing with partial melting of the Caledonian pluton. Consequently, the Caledonian granodiorites may have contributed to uranium preconcentration that facilitated later mineralization. Nevertheless, no systematic investigation of the Caledonian pluton in the southern Zhuguangshan complex has yet been undertaken.

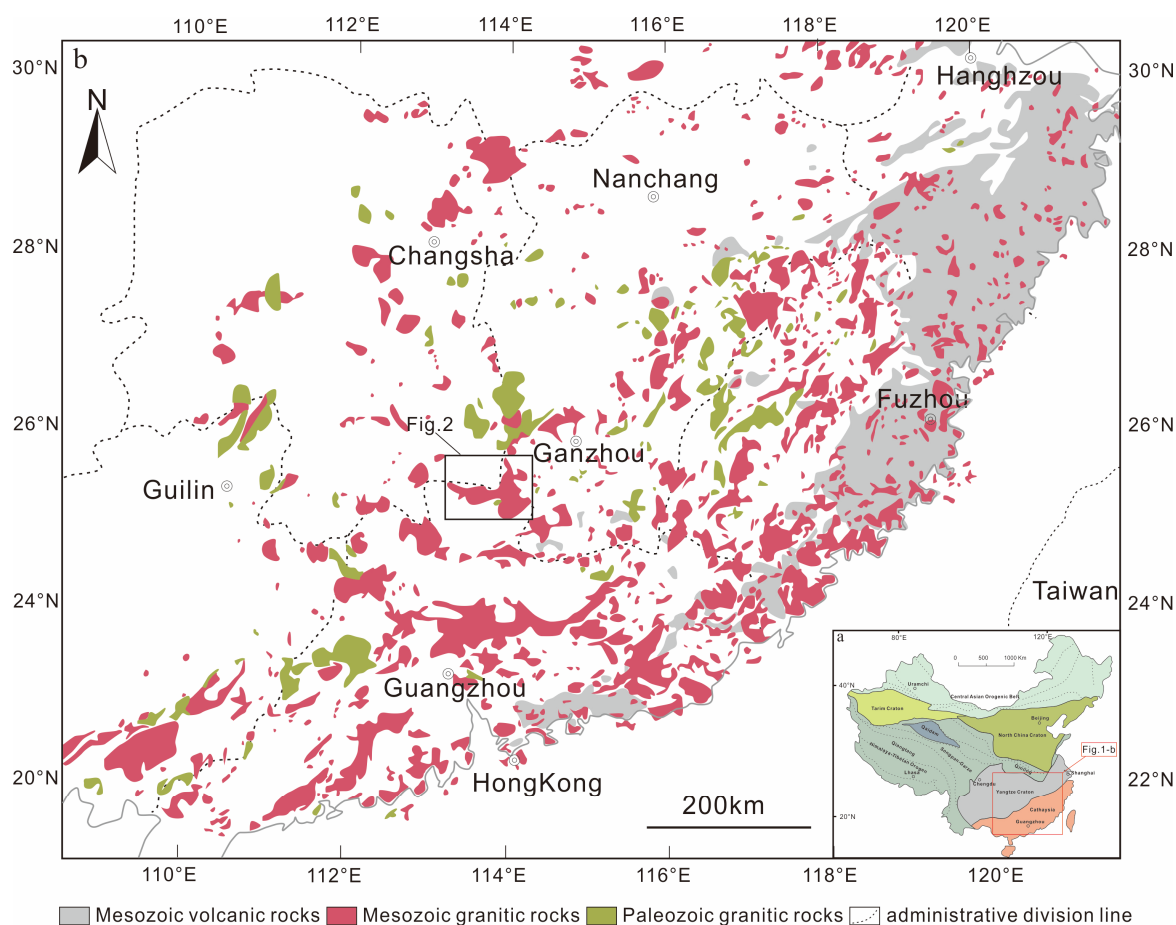


Figure 1. (a) Distribution of magmatic rocks in South China and the location of study area (modified after [21]). (b) Geological map of China showing the location of the study area.

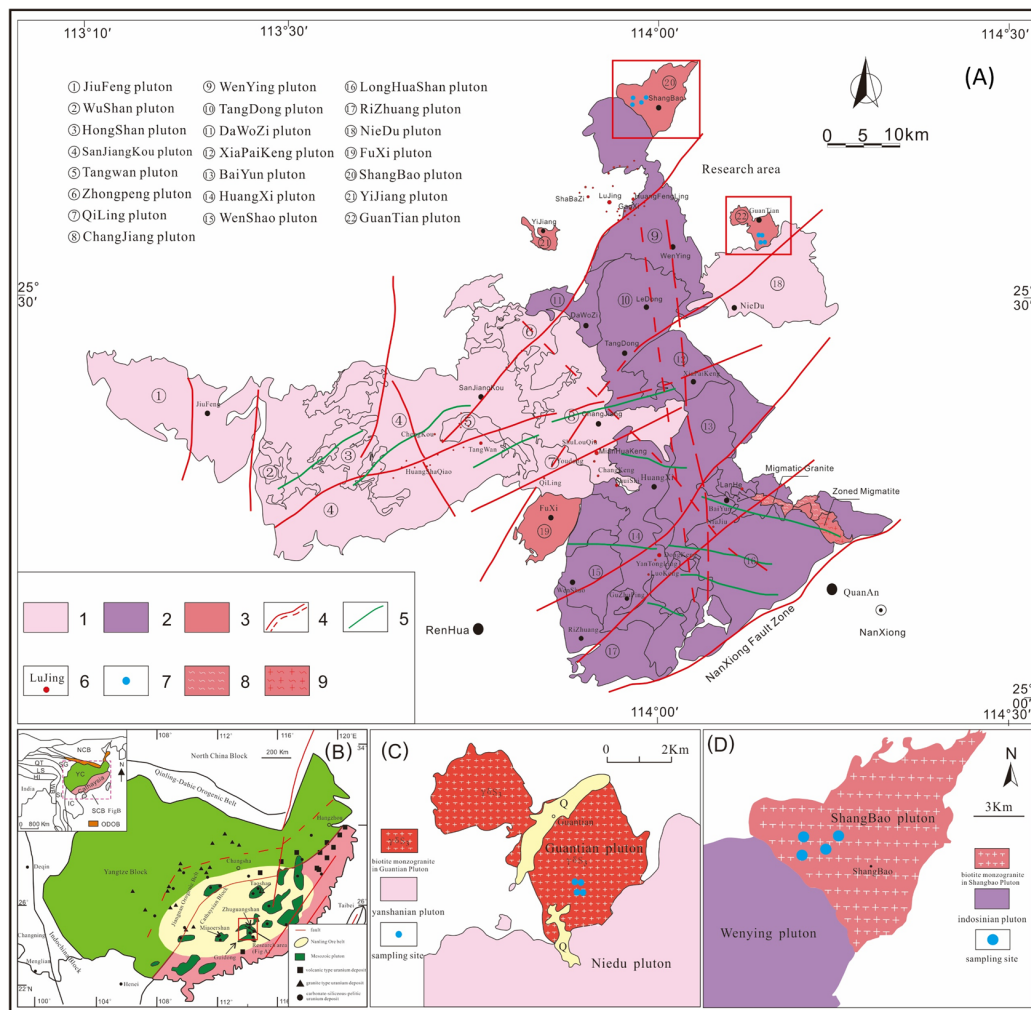


Figure 2. (A) Simplified geological map of Zhuguangshan complex (modified after [18,20]). Symbols: 1—Yanshanian pluton; 2—Indosinian pluton; 3—Caledonian pluton; 4—Faults; 5—Mafic dikes; 6—Uranium deposit; 7—sampling sites; 8—Migmatitic granite; 9—zoned migmatite. (B) Simplified geological map showing regional tectonic unit, deep-seated faults and distribution of uranium deposits (Modified after [22]). (C) Simplified geological map of Guantian pluton showing sampling sites. (D) Simplified geological map of Shangbao pluton showing sampling sites.

Although previous geochronological studies have confirmed the presence of Caledonian magmatism in the Zhuguangshan complex, the petrogenesis, magma sources, and tectonic implications of the individual plutons, particularly the Guantian and Shangbao intrusions, remain poorly constrained. Furthermore, their role in preconditioning the crust for subsequent U-REE mineralization has not been systematically evaluated. Here we report an integrated study of LA-ICP-MS zircon U-Pb geochronology, whole-rock geochemistry, and Sr-Nd-Hf isotopes for the Guantian and Shangbao granodiorites from the southern Zhuguangshan complex, aiming to constrain the petrogenesis and origin of these rocks. Combined with the published studies of the Caledonian plutons on the northern Zhuguangshan complex, we reconstruct the tectonic setting of the Zhuguangshan complex.

2. Geological Setting and Petrography

The southern Zhuguangshan complex is a composite granitic batholith covering ~2000 km² in Guangdong, Jiangxi, and Hunan Provinces. It is situated in the south-eastern Cathaysian Block, at the junction between the Cathaysian Caledonian fold belt and the Hunan–Guangxi–Guangdong Indosinian fold belt. The region is characterized

by numerous regional-scale structures (Figure 2B) [20,22]. The southern Zhuguangshan complex records a protracted history of tectonism and magmatism, generating granitoids of Caledonian, Indosinian, and Yanshanian period. The Yanshanian granites are mainly exposed in the western part of the complex, exhibit an E–W distribution, and include the Jiufeng, Wushan, Hongshan intrusions, etc. They yield emplacement ages of 150–170 Ma [10,11,22,23]. The Indosinian granites occur in the eastern part of the complex, trend N–S, and comprise the Wenying, Tangdong, Dawozi granites, etc. These were dominantly formed at 204–241 Ma [10,20]. The Caledonian granites include the Fuxi, Guantian, Yijiang, and Shangbao intrusions, which are sporadically distributed throughout the southern Zhuguangshan complex (Figure 2A). The stratigraphic sequences in the Zhuguangshan area consist of Sinian to Jurassic clastic and carbonate sedimentary rocks including sandstone, siltstone, mudstone, conglomeratic sandstone, limestone, metamorphic sandstone, shale and slate. The area is dominated by N–S, NE–SW, and NW–SE trending faults, with the NE–SW trending faults serving as the primary ore-controlling structures [24].

The Guantian and Shangbao plutons are composed of granodiorite, with outcropped areas of 20 km² and 80 km², respectively, and intruded into the Cambrian–Ordovician strata. The granodiorite is medium-grained with a massive structure (Figure 3a,b), and shows a mineral assemblage of plagioclase, quartz, K-feldspar, hornblende and biotite. The plagioclase, (55% and 45% in the Guantian and Shangbao plutons, respectively) is subhedral–euhedral thick tabular (1–3 mm) with polysynthetic twinning. Quartz (20% and 25%) is anhedral granular with undulatory extinction. K-feldspar (15% and 20%) is subhedral–anhedral granular with common Carlsbad twinning. Biotite (5% in both plutons) typically exhibits a brown, platy habit and is partially replaced by chlorite. Amphibole (5% in both plutons) is subhedral columnar, showing two prominent cleavage directions (Figure 3c,d). The granodiorite contains mafic microgranular enclaves (MME) of various size, which are characteristically oval, dark-colored, and sharply distinct from the host rock (Figure 3b).

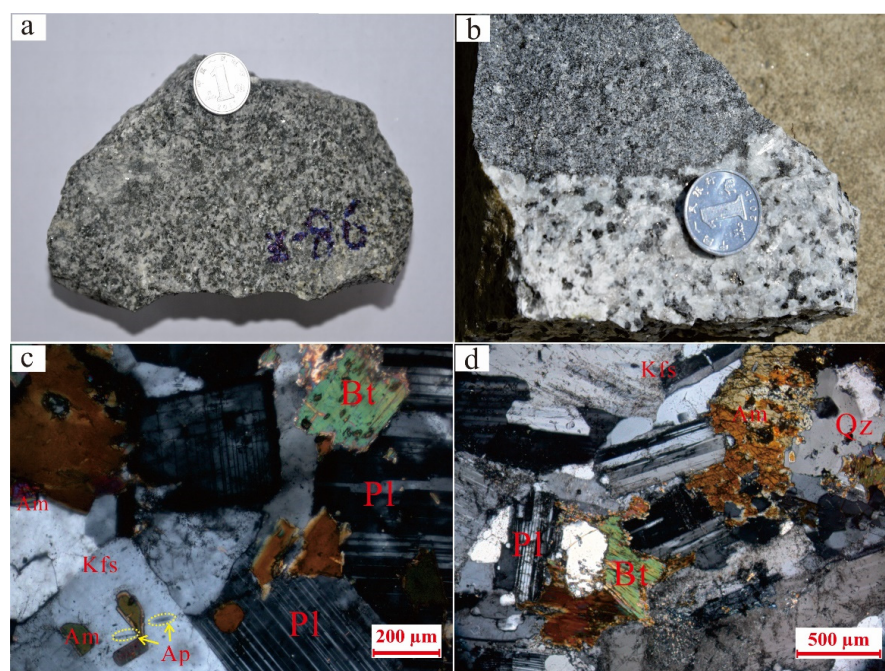


Figure 3. Photos/microphotographs of the Guantian and Shangbao granodiorites: (a) granodiorite hand specimen; (b) granodiorite hand specimen with mafic microgranular enclaves (MMEs); (c,d) thin-section photomicrographs of granodiorite. Abbreviation: Qz—Quartz; Kfs—K-feldspar; Pl—Plagioclase; Am—amphibole; Bt—biotite; Ap—apatite.

3. Sampling and Analytical Techniques

3.1. Sampling

Representative samples of the least-altered granodiorite were collected from outcrops in the Guantian and Shangbao plutons, with the sampling locations shown in Figure 2C,D.

For zircon U–Pb–Hf isotopic analyses, two representative granodiorite samples were selected; for major- and trace-element analyses, eight additional samples were analyzed, of which four were also analyzed for Sr–Nd isotopes.

3.2. Analytical Methods

3.2.1. LA-ICP-MS Zircon U–Pb Dating

Zircon grains were separated by conventional heavy liquid and magnetic separation techniques at LangFang ChenXin Geology Services Co., Ltd. (Lang Fang, China). Representative zircon grains were separated and set in epoxy resin, followed by polishing and carbon coating. To examine internal structures and select optimal analytical sites, transmitted-/reflected-light micrographs and cathodoluminescence (CL) images were obtained at the Key Laboratory of Crust–Mantle Materials and Environments, University of Science and Technology of China. For U–Pb dating, zircon grains with euhedral–subhedral morphology, well-developed oscillatory zonation, and no visible fractures or inclusions were preferentially chosen, using an Agilent 7700X LA-ICP-MS (Agilent Technologies, Santa Clara, CA, USA) equipped with a Geolas Pro 193nm laser ablation system (Coherent Inc. Santa Clara, CA, USA), following the method of [25]. A laser spot size of 32 μm was used, and external standard 91500 [26] ($^{206}\text{Pb}/^{238}\text{U} = 1065 \text{ Ma}$) was employed to correct for interelement fractionation. The data were processed with the LaDating@Zrn program, and Common Pb correction was subsequently applied following [27]. The age calculation and concordia plotting were generated using Isoplot v.4.5 [28]. All age uncertainties are reported at the 1 σ .

3.2.2. Whole-Rock Geochemistry and Sr–Nd Isotopes

Fresh rock samples were crushed and ground to ~200 mesh in an agate mill. For whole-rock geochemical analysis, approximately 50 mg of the resulting powder was weighed and digested in Teflon bomb with 1:1 mixture of HF and HNO₃ at 190 °C for over 24h. Major element oxides were determined using a Philips PW2404 X-ray fluorescence (XRF) spectrometer (PANalytical B.V., Almelo, The Netherlands) at the Geological Lab Center, Beijing Research Institute of Uranium Geology, following the standard GB/T14506.28-1993 [29]. Solution ICP–MS (Finnigan MAT) was used for trace-element and REE determination at the same lab, per the DZ/T 0223-2001 protocol [30]. Analytical errors were <5% for concentration > 10 ppm levels and <10% for lower-concentration samples.

Whole-rock Sr and Nd isotopic analyses were conducted using an ISOPROBE-T thermal ionization mass spectrometer (TIMS) (Isotopx, Middlewich, United Kingdom) at the Geological Lab Center, Beijing Research Institute of Uranium Geology. Approximately 100 mg of sample powder was dissolved in a mixture of HF, HNO₃, HClO₄ in Teflon bombs at 190 °C for over 24 h. Rb, Sr, Sm and Nd were separated using conventional cation-exchange resin technique. The measured Sr and Nd isotope ratios were corrected for instrumental mass fractionation by normalizing to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively.

3.2.3. LA-ICP-MS Zircon Hf Isotope Analysis

In situ zircon Hf isotope analyses were performed on the same grains that exhibited well-developed oscillatory zoning and were previously used for U–Pb dating. A Neptune Plus multi-collector ICP–MS (Agilent 7500a) (Agilent Technologies, Santa

display enrichment in light REEs (LREEs) relative to heavy REEs (HREEs) in the chondrite-normalized REE patterns (Figure 5a), with LREE/HREE ratios of 8.79–10.48 and 6.33–11.41, and $(\text{La}/\text{Yb})_N$ values of 10.70–14.13 and 6.48–14.98. The rocks exhibit negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.82\text{--}0.91$ and $0.44\text{--}0.61$), indicating plagioclase fractionation. In the primitive mantle-normalized trace-element diagram (Figure 5b), both plutons show marked negative anomalies in Sr, Ba, Zr, Nb, Ta, P, and Ti, coupled with enrichment in Th, U, Sm, and K. These characteristics are similar to those of the average middle–upper continental crust [43].

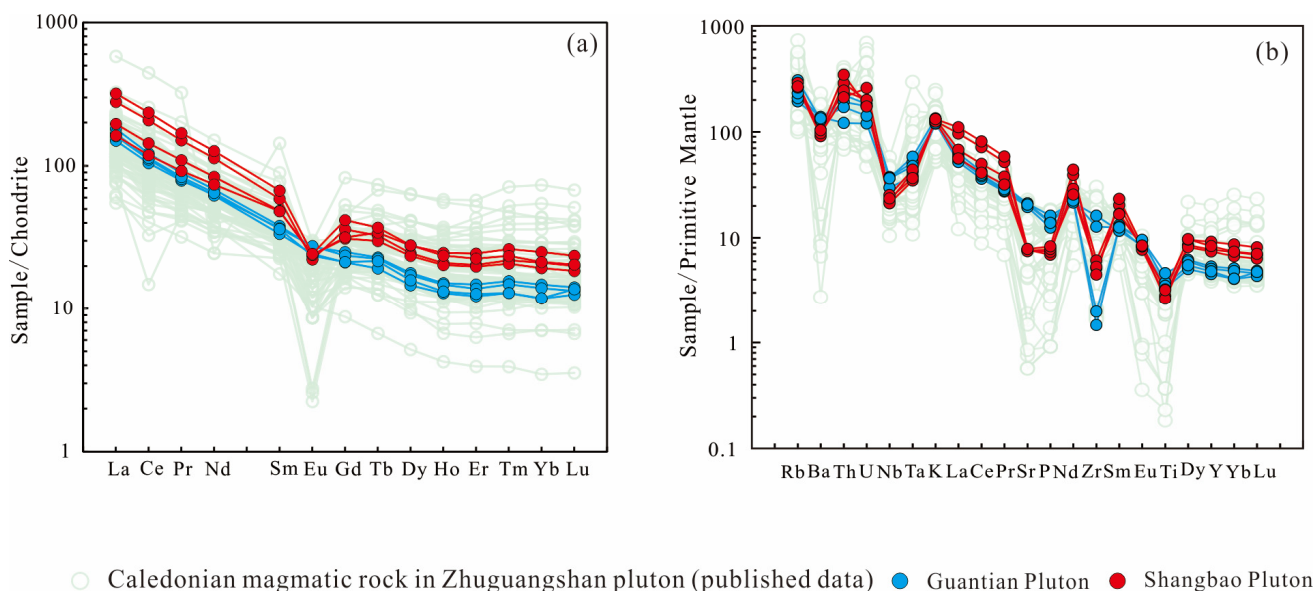


Figure 5. (a) Chondrite-normalized REE patterns; (b) primitive mantle-normalized trace element patterns for Guantian and Shangbao granodiorites (normalizing values after [44]). Data source [21,39–42].

4.2. Zircon U-Pb Age

Cathodoluminescence imaging reveals that most zircons from GT-01 and SB-02 possess clear core-rim structures and pronounced oscillatory growth bands, pointing to an igneous origin [45]. These grains are commonly grayish-black, subhedral to euhedral, and measure 50 to 250 μm in length, with aspect ratios ranging from 1:1 to 4:1.

Zircons from GT-01 have variable Th (66–666 ppm) and U (104–777 ppm) contents, with Th/U ratios of 0.41 to 1.49. These magmatic zircons yield concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 407 to 458 Ma and define a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 431.5 ± 5.9 Ma (MSWD = 0.87, $n = 29$) (Figure 6a,b). Zircons from SB-02 also show variable Th (106–592 ppm) and U (269–1456 ppm) contents and Th/U ratios of 0.18–0.63. They give concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 420–479 Ma, with a weighted mean of 442.3 ± 7.4 Ma (MSWD = 0.49, $n = 30$) (Figure 6c,d). The zircon U-Pb data from both samples indicate that the granodiorite was emplaced during the interval from the Early Ordovician to the Latest Silurian. The complete dataset of zircons U-Pb data is provided in Table S3 (Supplementary Materials).

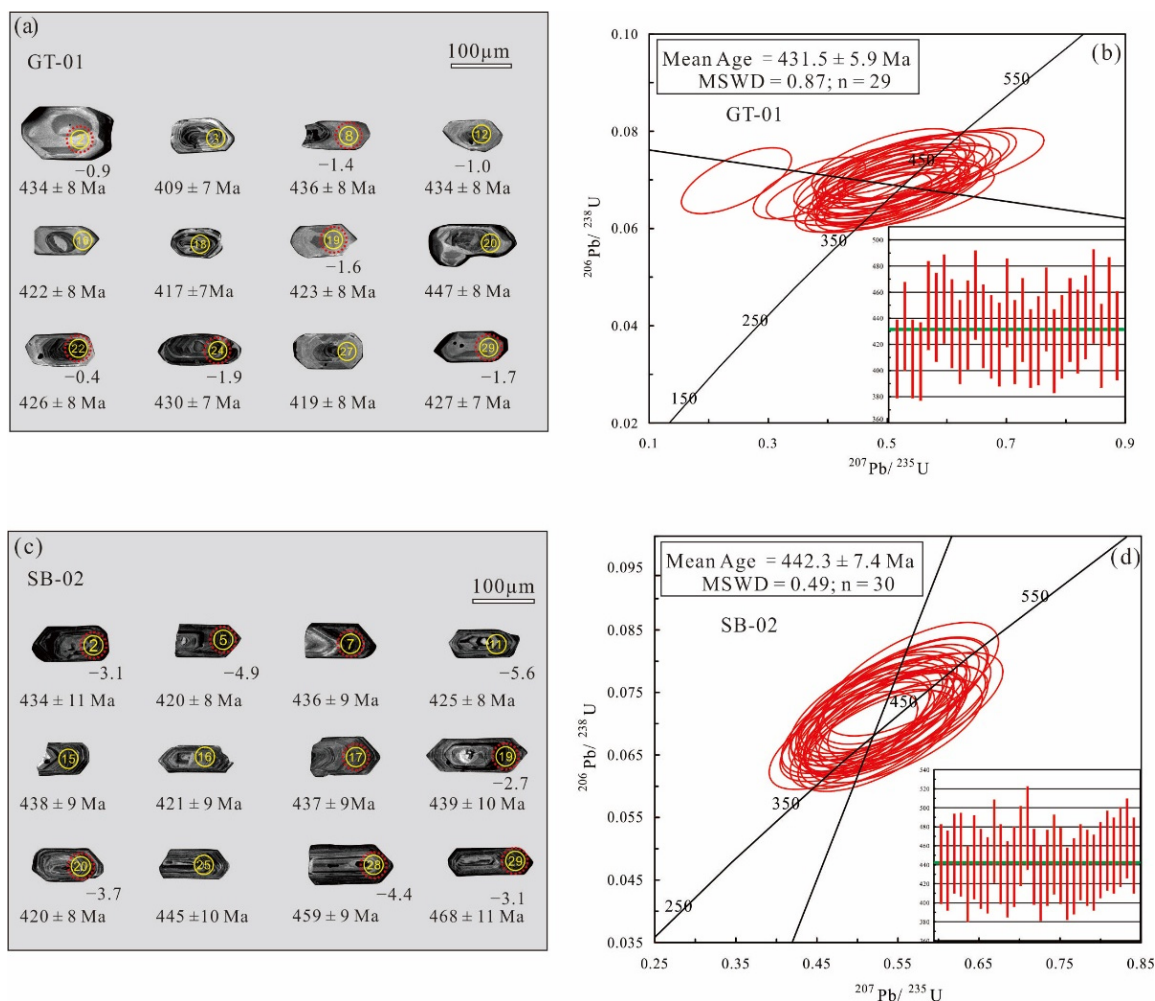


Figure 6. Cathodoluminescence images of representative zircon (a,c) and zircon U-Pb concordia plot (b,d) for the Guantian and Shangbao granodiorites.

4.3. Zircon Lu-Hf Isotopic Compositions

The zircon Hf isotope data are presented in Table S4 (Supplementary Materials). Zircon grains from sample GT-01 have relatively consistent $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282448 to 0.282505, corresponding to negative $\epsilon\text{Hf}(t)$ values of -0.40 to -2.2 ($n = 11$) at 431.5 Ma (Figure 7a). Their two-stage model ages ($T_{\text{DM}2}$) range from 1436 to 1562 Ma (Figure 7b). Zircon grains from sample SB-02 yield $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282256 to 0.282432, with negative $\epsilon\text{Hf}(t)$ values of -8.7 to -0.27 and $T_{\text{DM}2}$ ages of 1596–1980 Ma.

4.4. Whole-Rock Sr-Nd Isotope Compositions

Sr-Nd isotope data are presented in Table S5 (Supplementary Materials). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\epsilon\text{Nd}(t)$ values were calculated using zircon U-Pb ages of 431.5 and 442.3 Ma for the Guantian and Shangbao plutons, respectively. The Guantian samples have initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.71205 to 0.71227, which are significantly higher than the present-day primitive mantle value of 0.7045 [46]. Both plutons are characterized by elevated Rb (132–167 ppm) and Sr (161–444 ppm) contents. They yield negative $\epsilon\text{Nd}(t)$ values of -7.8 to -7.6 (Guantian) and -4.7 to -4.1 (Shangbao), with $T_{\text{DM}2}$ model ages of 1790 to 1802 Ma and 1513 to 1564, respectively.

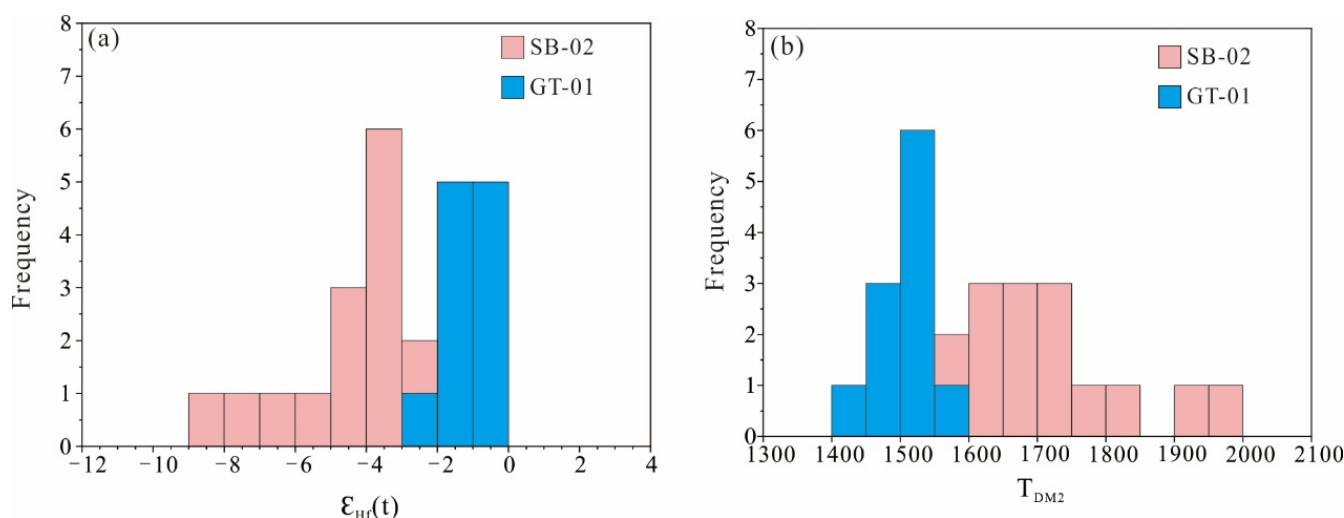


Figure 7. (a) Histograms of $\epsilon_{\text{Hf}}(t)$ and (b) two-stage Hf model age (T_{DM2}) of the Guantian and Shangbao granodiorites.

5. Discussion

5.1. Timing of Magmatism

We present a compilation of 15 published magmatic ages from the southern Zhuguangshan complex, which define three distinct age clusters at 154–160 Ma, 225–239 Ma, and 424–426 Ma, recording the multistage magmatic history of the complex (Table S1). Although previous studies have demonstrated that the granites in the southern Zhuguangshan complex were mainly emplaced during the Caledonian, Indosinian, and Yanshanian episodes [16–23], several intrusions, such as the Guantian and Shangbao plutons, have not yet been precisely dated.

LA-ICP-MS zircon U–Pb dating carried out in this study indicates that the Guantian and Shangbao plutons were emplaced at 431.5 ± 5.9 Ma and 442.3 ± 7.4 Ma, respectively. These ages are consistent, within analytical uncertainty, with previously reported ages for the Guantian (439 ± 5.9 Ma) and Shangbao (441 ± 3 Ma) intrusions [41]. Together with the Fuxi (426.7 ± 5.4 Ma) and Yijiang (424 ± 3 Ma) plutons, all of these ages fall within the Silurian, confirming that they are products of the Caledonian orogeny in South China.

5.2. Petrogenesis and Magma Source

5.2.1. Genetic Type

The granodiorite exhibits low Zr (16.4–180 ppm), Ce (63.9–144 ppm), $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ (130.2–294.5 ppm), and $\text{FeO}^{\text{T}}/\text{MgO}$ (1.6–2.7), which are distinct from those of typical A-type granites ($\text{Zr} > 250$ ppm, $\text{Ce} > 100$ ppm, $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y} > 350$ ppm, and $\text{FeO}^{\text{T}}/\text{MgO} > 16$) [47]. On the $10,000 \times \text{Ga}/\text{Al}$ diagram, all samples plot in the I- and S-type field with low Ga/Al ratios (Figure 8a,b) [47]. Furthermore, the estimated magma crystallization temperatures of the granodiorites, based on zircon saturation thermometry (T_{Zr} values are in the range of 573–740 °C) are significantly lower than those of typical A-type granites (>900 °C) [48].

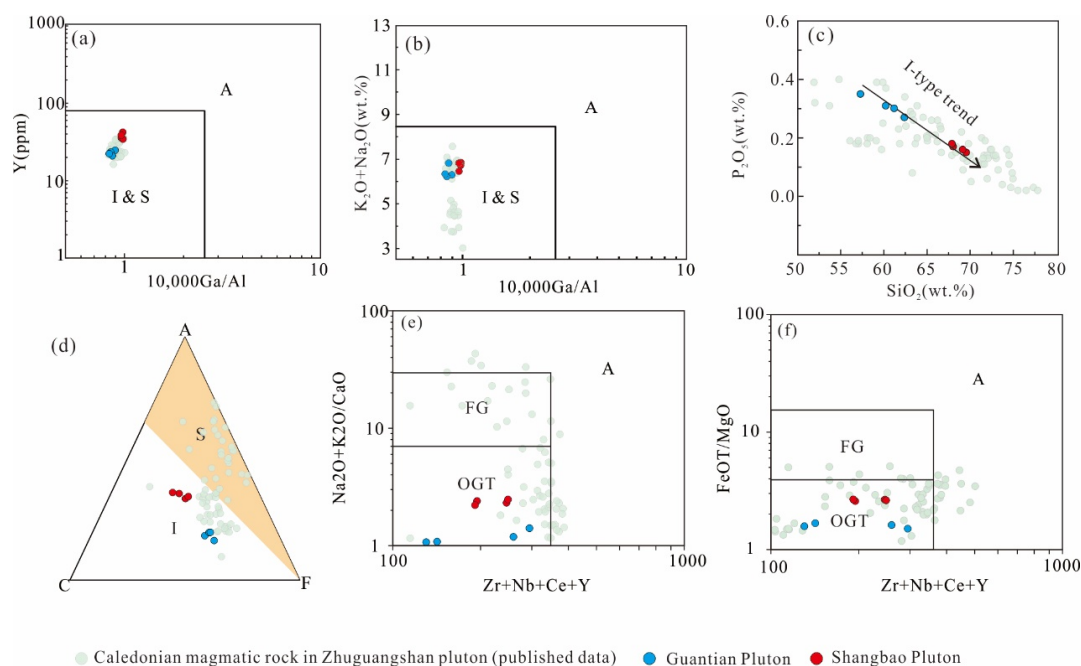


Figure 8. Petrogenetic discrimination plots for the Guantian and Shangbao granodiorites. (a,b) $10,000 \times \text{Ga}/\text{Al}$ vs. Y and $(\text{K}_2\text{O} + \text{Na}_2\text{O})$ [47]; (c) P_2O_5 vs. SiO_2 ; (d) $\text{A}(\text{Al}_2\text{O}_3\text{--Na}_2\text{O--K}_2\text{O})\text{--C}(\text{CaO})\text{--F}(\text{FeO}^{\text{T}} + \text{MgO})$ [49]. (e,f), $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ vs. $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ and $\text{FeO}^{\text{T}}/\text{MgO}$ [47]. Data source [21,39–42].

I-type granites are typically metaluminous ($\text{A}/\text{CNK} < 1$), having Ca, Na, and K in excess of Al, and commonly contain amphibole. In contrast, S-type granites are peraluminous and characteristically contain Al-rich minerals such as biotite, cordierite, and muscovite [50]. The Guantian and Shangbao plutons are metaluminous ($\text{A}/\text{CNK} = 0.72\text{--}1.02$), with moderate to high SiO_2 (57.30–69.54 wt.%) and relatively high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (1.27–1.48). They contain amphibole and minor biotite, features that collectively resemble I-type rather than S- or A-type granites [50].

Apatite solubility is low in metaluminous magmas, leading to a systematic decrease in P_2O_5 with increasing SiO_2 [51]. Hence, the $\text{P}_2\text{O}_5\text{--SiO}_2$ relationship serves as a useful indicator of magmatic affinity. The Guantian and Shangbao granodiorites display a negative correlation between P_2O_5 and SiO_2 , consistent with an I-type classification (Figure 8c). They also fall within the fields of unfractionated I- and S-type granites in the $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ vs. $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ and $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ vs. $\text{FeO}^{\text{T}}/\text{MgO}$ diagrams (Figure 8e,f). In the ACF discrimination diagram, all samples plot in the I-type field (Figure 8d), confirming that they are unfractionated I-type granites.

5.2.2. Magma Source

Several petrogenetic models have been proposed for calc-alkaline metaluminous I-type granites, including magma mixing between crustal and mantle melts [52,53], fractional crystallization of mantle-derived magmas [52], and partial melting of the lower crust with possible minor input of mantle-derived basic magmas [33,54]. Although the Guantian and Shangbao granodiorites are spatially associated, their detailed isotopic compositions and field occurrences dictate markedly distinct petrogenetic pathways, rather than a simple common origin as previously generalized.

The Guantian pluton, which lacks mafic microgranular enclaves (MMEs), exhibits relatively homogeneous and moderately negative $\epsilon_{\text{Hf}}(t)$ values (-0.40 to -2.2) and $\epsilon_{\text{Nd}}(t)$ values (-7.8 to -7.6). These coupled isotopic signatures, combined with the absence of MMEs, indicate that the Guantian magma was predominantly derived from the partial

melting of a relatively homogeneous ancient crustal source, with negligible involvement of mantle-derived components. In stark contrast, the Shangbao pluton displays significant isotopic heterogeneity and decoupling: its $\epsilon_{\text{Nd}}(t)$ values (-4.7 to -4.1) are notably higher than those of the Guantian pluton, suggesting a substantial contribution from depleted mantle-derived melts. However, its $\epsilon_{\text{Hf}}(t)$ values exhibit an extremely wide range (-8.7 to -0.27), which cannot be explained by simple two-endmember magma mixing alone. We propose that this Hf-Nd decoupling, together with the ubiquitous occurrence of MMEs in the Shangbao pluton, provides critical evidence for a complex magma mixing process with thermal and chemical disequilibrium. Although no geochemical analyses have been performed on the MMEs to directly constrain their source, their typical microtextural features (e.g., acicular apatite, chilled margins, and fine-grained textures) are widely regarded as indicators of thermal and compositional disequilibrium between two contrasting melt populations. While such textural evidence alone cannot uniquely fingerprint a mantle versus lower-crustal origin for the mafic endmember, the geochemical characteristics of the host Shangbao pluton provide critical constraints. As discussed above, the Shangbao pluton exhibits decoupled Hf-Nd isotopes, and this isotopic signature is best explained by the injection of hot, mantle-derived basaltic magmas into the felsic crustal chamber, which not only elevated the bulk Nd isotopic ratios but also created a non-equilibrium environment. This led to the incomplete dissolution of ancient zircon xenocrysts or kinetic fractionation of Hf isotopes, thereby preserving extremely variable Hf isotopic signatures while the whole-rock Nd system approached isotopic equilibrium with the mixed melts.

Ratios of certain incompatible element pairs, such as Nb/Ta and Th/U, have been shown to be useful tracers for constraining source regions [55]. The Guantian and Shangbao granodiorites have Nb/Ta ratios of 10.00–13.52 (average 11.42) and Th/U ratios of 3.30–8.08 (average 5.07), values that are close to the average crustal signatures (Nb/Ta = 11–12; Th/U = 3.8–6) but clearly distinct from typical mantle values (Nb/Ta $\approx$ 17.5; Th/U $\approx$ 4) [43,56]. This suggests that the crustal endmembers of both plutons were derived from ancient crustal materials, which is further supported by their negative $\epsilon_{\text{Hf}}(t)$ values and two-stage model ages (1436–1980 Ma) resembling an ancient crustal source (Figure 9a) [57], as well as low whole-rock $\epsilon_{\text{Nd}}(t)$ values and moderately radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70595–0.71227) plotting below the CHUR reference line (Figure 9b). The granitoids exhibit relatively low Mg# values ($\sim$ 50), which are significantly lower than those of primary mantle-derived melts (typically Mg# > 65–70), suggesting a dominant crustal source for the magma.

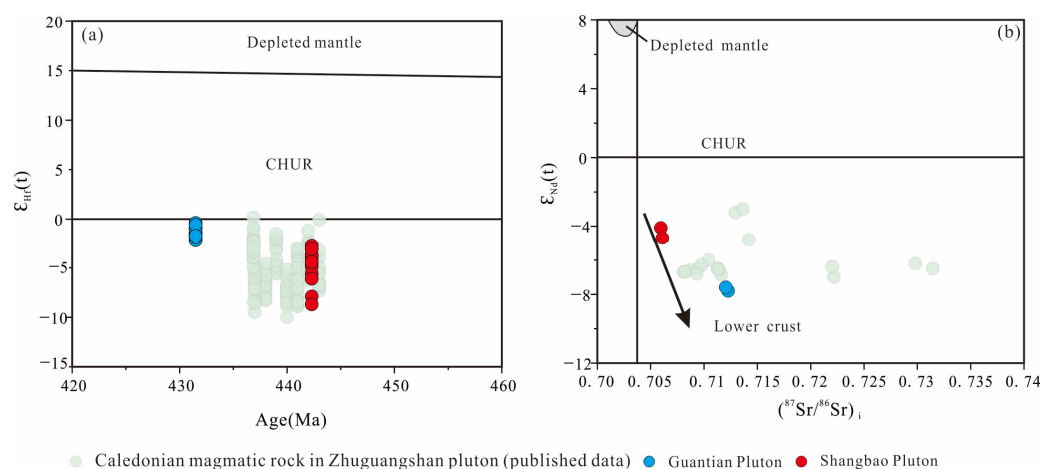


Figure 9. (a) Zircon U-Pb age vs. $\epsilon_{\text{Hf}}(t)$ and (b) $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs. $\epsilon_{\text{Nd}}(t)$ for the Guantian and Shangbao granodiorites. Data source: (a) [40,41]; (b) [40,41].

Integrating all lines of evidence, we propose a dual petrogenetic model: the Guantian pluton represents a relatively closed-system crustal anatexis with no significant mantle interaction. In contrast, the Shangbao pluton records an open-system hybrid origin, where mantle-derived magmas underplated and injected into the crustal magma chamber. The MMEs are the quenched relics of these mantle-derived basaltic melts. Thus, the petrological and geochemical evidence collectively suggests that while both plutons share a dominant crustal source component, the Shangbao pluton experienced a subordinate but critical mantle recharge event, which accounts for its isotopic decoupling and contrasting compositional heterogeneity compared to the Guantian pluton.

5.2.3. Magmatic Evolution

The petrogenetic evolution of the Guantian and Shangbao plutons cannot be reconciled by a single mechanism such as fractional crystallization (FC) alone, given their distinct isotopic compositions and emplacement ages. Instead, we propose a multi-stage model involving (1) crustal anatexis, (2) magma mixing (exclusively in the Shangbao pluton), (3) limited fractional crystallization within each magma batch, and (4) subsequent fluid-mediated alteration.

Stage 1—Crustal anatexis: both plutons share a common crustal source affinity, as indicated by their negative $\epsilon\text{Hf}(t)$ and $\epsilon\text{Nd}(t)$ values, Nb/Ta and Th/U ratios close to average crustal signatures, and Paleoproterozoic two-stage model ages. However, the source regions were not identical: the Guantian pluton exhibits relatively homogeneous and coupled Hf-Nd isotopes, suggesting melting of a relatively uniform ancient crustal protolith. In contrast, the Shangbao pluton shows isotopic heterogeneity and decoupling, implying a more complex source or subsequent modification.

Stage 2—Mantle-derived magma injection and mixing (Shangbao-specific): the Shangbao pluton contains abundant mafic microgranular enclaves (MMEs) with typical quench textures (acicular apatite, chilled margins), which, together with its elevated ϵNd values and extremely variable ϵHf values, provide compelling evidence for the injection of hot, mantle-derived basaltic magmas into the crustal magma chamber. This mixing event not only supplied the heat required for crustal melting but also introduced a depleted mantle component, accounting for the isotopic decoupling.

Stage 3—Limited fractional crystallization within individual magma batches: we acknowledge that FC cannot explain the compositional differences between the two plutons, given their different source compositions and emplacement ages (precluding a comagmatic relationship). However, within each pluton, subtle variations in SiO_2 and certain trace elements may reflect limited in situ FC of phases such as plagioclase, K-feldspar, and hornblende. The Harker diagrams (Figure 10) do not define continuous curved trends, which is consistent with the fact that FC was not the dominant process.

Stage 4—Sub-solidus fluid alteration: the scatter observed in sodium (Na_2O) and some other mobile elements does not follow magmatic differentiation trends, suggesting that post-crystallization fluid interaction may have disturbed the primary magmatic signatures. In the $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ vs. Al_2O_3 diagram (Figure 11c) reveals distinct trends, the Guantian data cluster follows a differentiation trend, whereas the Shangbao data deviates markedly, confirming the superimposed nature of these processes.

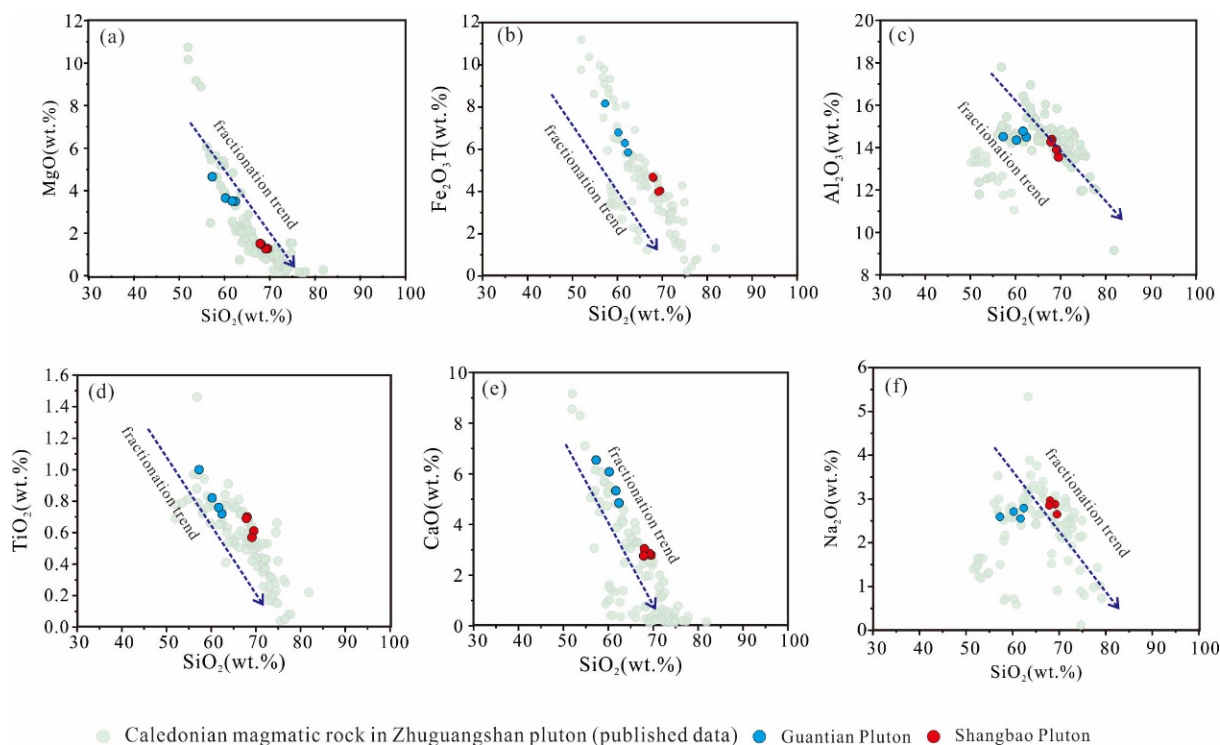


Figure 10. Hark diagrams for the Guantian and Shangbao granodiorites. (a) SiO_2 vs. MgO ; (b) SiO_2 vs. $\text{Fe}_2\text{O}_3\text{T}$; (c) SiO_2 vs. Al_2O_3 ; (d) SiO_2 vs. TiO_2 ; (e) SiO_2 vs. CaO ; (f) SiO_2 vs. Na_2O . Data source [21,39–42].

Integrated model: We conclude that the Guantian pluton records a relatively simple history of crustal anatexis followed by limited FC, whereas the Shangbao pluton experienced a more complex evolution involving crustal melting + mantle recharge (mixing) + limited FC + fluid alteration. This dual model reconciles all geochemical, isotopic, and field observations, and highlights the compositional heterogeneity of Mesozoic granitic magmatism in the region.

5.3. Tectonic Implications and Metallogeny

5.3.1. Tectonic Implications

Our study demonstrated that the I-type felsic rocks in Guantian and Shangbao plutons were formed by partial melting of ancient crustal material. Previous study has shown that I-type granites could be formed in subduction and syn-/post-collision setting [58–60]. As above-mentioned, the Caledonian orogeny in South China magmatic rocks were proposed to have formed under two contrasting models: (1) Intracontinental (intraplate) orogeny and post-orogenic extensional [61,62]; (2) Subduction–collision tectonic setting [63,64]. Some authors suggested that an Early Paleozoic active continental margin existed along the southern side of the Cathaysia Block, involving oceanic subduction, arc magmatism, and eventual continent–continent collision, as supported by the occurrence of sporadic reports of Early Paleozoic mafic–ultramafic rocks and geochronological constraints indicating a progression from subduction-related to syn-collisional magmatism (ca. 460–420 Ma). Some other authors, however, questioned the occurrence of Early Paleozoic ophiolites or arc magmatism and diagnostic high-pressure/low-temperature metamorphic rocks. Furthermore, they proposed that Caledonian event as a far-field intraplate response to remote plate-margin forces, without oceanic subduction [61,62].

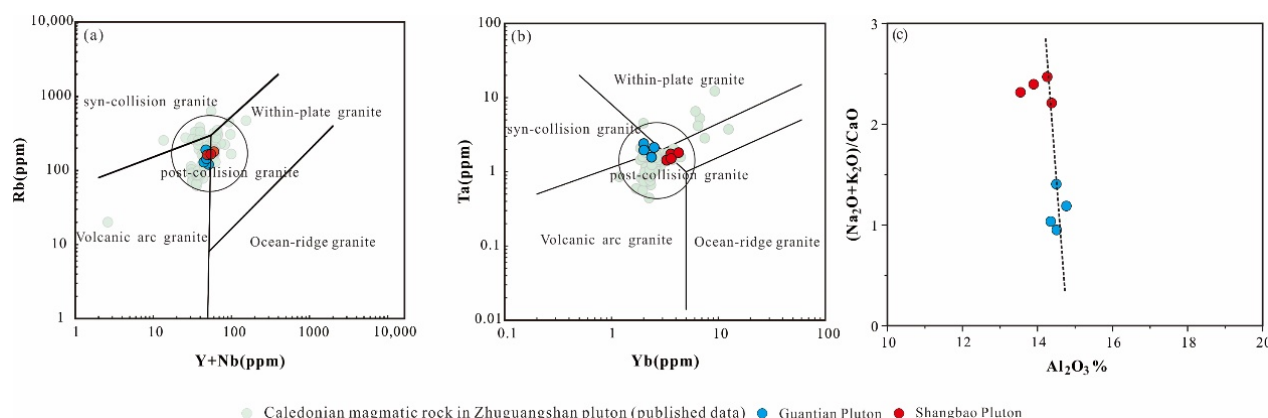


Figure 11. Tectonic discrimination plots for the Guantian and Shangbao granodiorites: (a) Y + Nb vs. Rb [65]; (b) Yb vs. Ta [66]; (c) Al₂O₃ vs. (Na₂O + K₂O)/CaO. Data source [21,39–41].

Our data compilation and comparison suggested that the magmatic rocks from Zhuguangshan complex have similar geochemical and Sr-Nd-Hf isotopic characteristics, and were likely formed in similar tectonic setting and magma source. The Guantian and Shangbao granodiorites are characterized by moderate LILE enrichments coupled with prominent Ba, Sr, and Eu depletions, and subdued Nb–Ta anomalies. Such a pattern contrasts sharply with subduction-related arc magmas, which typically exhibit strong LILE enrichment combined with pronounced HFSE troughs [65]. Instead, it points to an origin involving partial melting of ancient crustal sources in a post-orogenic or intraplate setting, with significant plagioclase fractionation. The Guantian and Shangbao granodiorites plot largely in the post-collisional field in the (Y + Nb) vs. Rb and Yb vs. Ta tectonic discrimination diagrams (Figure 11a,b). Consequently, we suggest that the Guantian and Shangbao granodiorites were formed in an intracontinental (intraplate) post-collision extensional setting.

In brief, we suggest that the Early Paleozoic intracontinental orogeny in South China resulted in crustal thickening and subsequent gravitational collapse, leading to an extensional tectonic environment. The thinning and decompression of the crust caused partial melting of the lower crustal volcanic. The Guantian and Shangbao granodiorites were formed by the partial melting of ancient crustal material in such extensional environment following the intracontinental orogeny, without the involvement of oceanic subduction or continental collision.

5.3.2. Metallogeny

The Zhuguangshan complex, a composite batholith formed during the Caledonian, Indosinian, and Yanshanian episodes, is one of the most important granite-hosted uranium and REE metallogenic districts in South China. The Caledonian orogeny in the Nanling region, associated with the Early Paleozoic Proto-Tethyan closure, triggered extensive crustal anatexis and established the fundamental NE-trending structural architecture that later controlled Mesozoic magmatic-hydrothermal activity [67].

The Caledonian granites in the Zhuguangshan complex, represented by the Wanyangshan–Zhuguangshan granites, are characterized by high degrees of magmatic differentiation and significant LREE enrichment. While these granites did not directly generate economic U mineralization, they played a critical preconditioning role for subsequent Indosinian and Yanshanian uranium mineralization by: (1) initiating the primary enrichment of U and REE in the crustal source through high-temperature differentiation; (2) elevating the background U content of the crust, making it a fertile protolith for later hydrothermal overprinting; and (3) establishing the regional structural framework that controlled later ore-fluid pathways.

In contrast, the Caledonian granites themselves host ion-adsorption type REE deposits, formed by prolonged subtropical weathering of the highly fractionated, LREE-enriched granites. The high total REE concentrations and significant LREE/HREE fractionation of these Caledonian granites make them favorable parent rocks for supergene REE mineralization. Thus, the Caledonian granites of the Zhuguangshan complex record a polyphase metallogenic history: they served as the metal-enriched basement for later U mineralization while directly hosting weathering-related REE mineralization, highlighting their dual role in the regional metallogenic system.

6. Conclusions

1. LA-ICP-MS zircon U-Pb dating of the Guantian and Shangbao granodiorites yields ages of 431.5 and 442.3 Ma, respectively. We suggest that the granodiorites were formed in an intracontinental (intraplate) post-collision extensional setting.
2. The Guantian and Shangbao granodiorites are characterized by being high-Al, alkali-rich, and moderate-Mg. The rocks are metaluminous I-type granites and display moderate LILE enrichments coupled with prominent Ba, Sr, Ti and Eu depletions. This suggests the fractionation of Ti-bearing minerals (e.g., rutile and ilmenite) and plagioclase.
3. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70595–0.71227), with negative $\epsilon\text{Nd}(t)$ values (−7.8 to −4.1) and $\epsilon\text{Hf}(t)$ values (−8.7 to −0.4), together with the average Nb/Ta (11.42) and Th/U (5.07), indicate that Guantian and Shangbao granodiorites were formed from partial melting of ancient crustal.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min16080813/s1>, Table S1: Summary of geochronological data of the Yanshanian, Indosinian and Caledonian pluton in the South of Zhuguangshan complex; Table S2: The result of major oxides (wt.%) and trace element ($\times 10^{-6}$) of Guantian and Shangbao Pluton; Table S3: Zircon U-Pb data of Guantian and Shangbao Pluton; Table S4: Zircon Lu-Hf isotope data of Guantian and Shangbao Pluton; Table S5: Whole-rock Sr-Nd isotope data of Guantian and Shangbao Pluton.

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