

Article

Mineralogical and Geochemical Characteristics of Biotite in Granite from the Guanfang Tungsten Deposit, Bozhushan, Southeastern Yunnan, and Their Implications for Petrogenesis and Mineralization

Dai Zhang ^{1,2} , Liurunxuan Chen ^{3,*} , Xianchao Chen ³ , Xuelong Liu ³ , Jiehu Zhou ⁴, Bode Lu ³, Ruohan Zuo ³ and Shitao Zhang ³

¹ School of Geosciences, Yunnan University, Kunming 650500, China; dai_zhang@ynu.edu.cn

² Key Laboratory of Critical Minerals Metallogeny in Universities of Yunnan Province, School of Earth Sciences, Yunnan University, Kunming 650500, China

³ Faculty of Land Resources Engineering, Kunming University of Science and Technology, Kunming 650093, China; chenxianchao@163.com (X.C.)

⁴ Kunming Natural Resources Comprehensive Survey Center, China Geological Survey, Kunming 650000, China

* Correspondence: bigdi@foxmail.com

Abstract

The Guanfang tungsten deposit in the Bozhushan ore district, southeastern Yunnan, is genetically linked to Late Yanshanian granitic intrusions. To elucidate the petrogenesis and mineralization potential of the causative granite, this study presents a detailed mineral chemical analysis of biotite from the Guanfang pluton using electron probe microanalysis (EPMA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The biotite crystals exhibit relatively high euhedrality, show no obvious alteration features, and are chemically characterized by reduced Na and Ca contents. These features, along with petrographic observations, confirm its origin as primary magmatic biotite. Crystallization conditions, calculated from biotite chemistry, indicate temperatures of 700–720 °C and pressures of 1.22–1.73 kbar, corresponding to a mesozonal emplacement depth of 4.6–6.5 km. Oxygen fugacity estimates, plotting near the Ni–NiO buffer, reveal an oxidized magmatic environment. Geochemical discrimination diagrams suggest the Guanfang granite exhibits transitional features between S-type and I-type affinities and is classified as a syn-melting (high-temperature) type. The biotite contains relatively low F (0.71–0.97 wt%), but elevated Cl (0.13–0.20 wt%) and Sn (43–56 µg/g) contents. This specific geochemical signature—combined with the medium- to high-temperature crystallization setting—is highly favorable for W–Sn mineralization. Furthermore, the high-Ti, syn-melting character of the granite implies additional potential for Cu–Pb–Zn–Au–Ag polymetallic mineralization. This study employs biotite chemistry to assess the petrogenesis and metallogenic potential of the Guanfang granite. The subsequent discovery of industrial ore bodies corresponding to some of the elements identified as having metallogenic potential confirms the feasibility of this approach. Accordingly, this method provides a new tool for future exploration in the Bozhushan district.

Keywords: biotite; Guanfang tungsten deposit; granite; petrogenesis; Southeastern Yunnan



Academic Editors: Giovanni Grieco,
David Lentz and Jaroslav Dostal

Received: 13 January 2026

Revised: 7 March 2026

Accepted: 11 March 2026

Published: 16 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

A series of tungsten, tin, silver, copper, lead, zinc and other mineral deposits have been discovered around the Bozhushan composite granite body in southeastern Yunnan, establishing it as one of China's most important ore concentration areas. Consequently, both the granite body and the ore district have attracted considerable scholarly attention.

Research involving petrological, isotopic chronology, and geochemical studies indicate that the Bozhushan granite is a composite intrusion formed during the late Yanshanian period, consisting of multiple phases [1–5]. Zircon U-Pb dating of its various units yields ages ranging from 81.9 to 91.59 Ma [2,5–7].

Studies by multiple scholars collectively suggest that the composite granite body resulted from the superposition of multiple magmatic events, exhibiting characteristics of S-type granite. The magma was likely derived from Proterozoic metamorphic sedimentary rocks, with fractional crystallization becoming progressively more intense through successive phases of magmatic activity [1–6].

Furthermore, magmatic emplacement was closely related to regional tectonic activity. The intrusion's relatively shallow emplacement depth facilitated the activation, migration, and enrichment of ore-forming materials, providing a crucial hydrothermal source and dynamic setting for the formation of the surrounding mineral deposits [3,6].

The Guanfang tungsten deposit, situated in the western part of the Bozhushan composite granite body, is a large-scale, skarn-type deposit and represents one of the typical deposits in this ore concentration area. Scheelite is its primary ore mineral.

Previous research on the Guanfang deposit has focused on its ore-controlling structures, wall-rock alteration, mineralization, ore-forming material sources, and garnet U-Pb chronology. These studies indicate that mineralization is primarily controlled by the intrusive contact zone and the Xiachang Fault, which cuts across both the wall rocks and the granite body [8]. The main ore-bearing alteration zone is characterized by diopside-tremolite alteration [9].

Research suggests the ore-forming hydrothermal fluid of the Guanfang tungsten deposit was predominantly magmatic, with later-stage mixing of meteoric water. The ore-forming elements were primarily derived from the granite, with a secondary contribution from the wall rocks [8,9]. Garnet U-Pb dating from the ore-bearing skarn constrains the main metallogenic period to approximately 88 Ma [10].

Previous studies have primarily focused on the deposit's ore-controlling structures and ore bodies themselves. However, key aspects of the granites genetically linked to mineralization remain poorly understood and require in-depth investigation.

As one of the most common minerals in granite, unaltered magmatic biotite preserves a wealth of chemical information related to petrogenetic and metallogenic processes, offering a valuable window into deep geological environments. Tang Pan et al. [11] have systematically reviewed the use of magmatic biotite composition in constraining granite petrogenesis and guiding mineral exploration, establishing the feasibility of this approach. Accordingly, applying magmatic biotite chemistry to characterize granite petrogenetic environments and to support prospecting is both practical and methodologically sound.

This study presents major and trace element compositions of biotite from the Guanfang granite, obtained via EPMA and LA-ICP-MS analysis. These biotite compositions are used to constrain the magma source, physicochemical conditions of crystallization, and the evolution of the Guanfang tungsten deposit's ore-related granite. Furthermore, we discuss the genetic relationship between granite magmatism and tungsten mineralization. Our findings provide new theoretical constraints to guide future prospecting and research work in the region.

2. Geological Setting

2.1. Regional Geological Setting

The Guanfang Tungsten Deposit is situated in the southern limb of the Bozhushan Dome, within the Wenshan-Funing fold bundle of the Southeast Yunnan fold belt, South China fold system (Figure 1a). The exposed strata in the area range from Sinian to Quaternary age and include the Sinian, Cambrian, Ordovician, Devonian, Carboniferous, Permian, Triassic, and Quaternary systems. The oldest exposed unit is the Sinian Pingbian Group, a flysch formation. The Cambrian system conformably overlies the Pingbian Group. Its lower part consists of shallow-marine quartz sandstone interbedded with carbonate rocks, transitioning upward into shallow-marine to littoral carbonate rocks and sandy, silty, and argillaceous rocks that extend to the Ordovician, where halite pseudomorphs are observed. Lower Paleozoic strata exhibit low-grade (epizonal) metamorphism, with widespread slaty cleavage in sandy and argillaceous rocks and local marbleization of carbonates. Upper Paleozoic to Triassic strata comprise littoral argillaceous rocks and siltstones, and shallow marine reef limestones are developed [1,12].

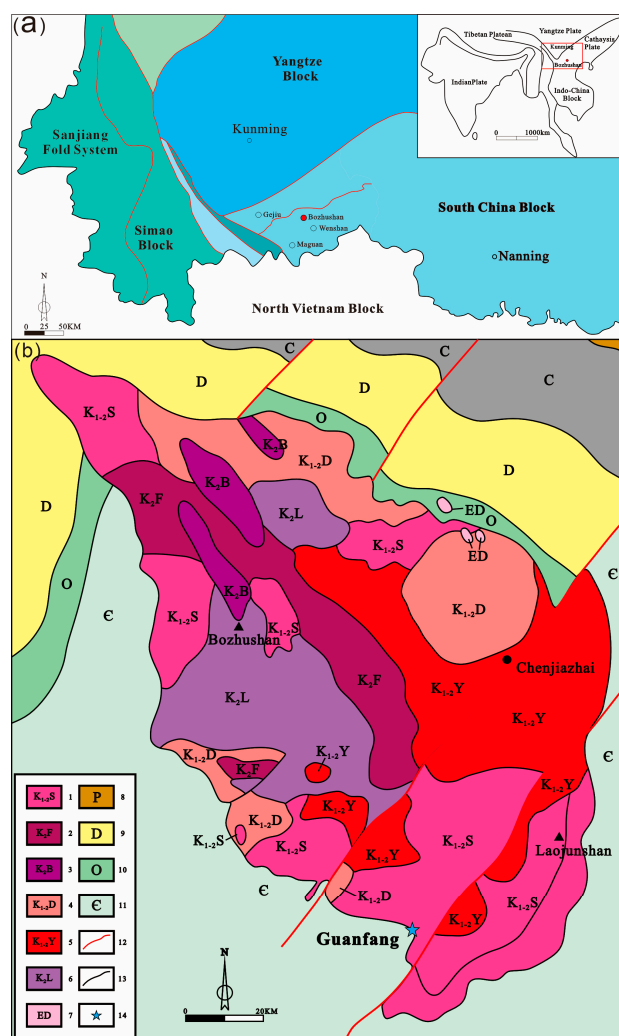


Figure 1. (a): Tectonic setting map of the study area; (b): geological map of Bozhushan ore concentration area. Note: Figure 1a. is modified from reference [12,13]; Figure 1b. is modified from reference [1]. Abbreviations: 1. Suozuodi Unit; 2. Fenshuiling Unit; 3. Bozhupo Unit; 4. Dashan Unit; 5. Yangyushi Unit; 6. Leidazhan Unit; 7. Dashanjiao Unit; 8. Permian; 9. Devonian; 10. Ordovician; 11. Cambrian; 12. Faults; 13. Geological Boundary; 14. Study Area.

The region has experienced relatively intense tectonic activity. Structures within the Bozhushan Dome area are dominated by arcuate features distributed concentrically around the North Vietnam Block, formed by tectonic deformation, and highly developed NE-trending faults. Magmatic rocks in the area are mainly Hercynian basic rocks and Yanshanian granites. The Hercynian basic rock suite is predominantly basalt, exposed in the northeast minor diabase and gabbro intrude Cambrian and Ordovician strata. Yanshanian granitic magmatism was intense, characterized by multi-stage activity and multi-phase evolution. Repeated intrusions formed the composite Bozhushan pluton [12,13].

Following the lithodemic unit classification of Zhang Shitao and Chen Guochang [1], the Bozhushan pluton is divided into the following two sequences: the Chenjiazhai Sequence and the Bozhushan Sequence, and one independent unit—the Dashanjiao Unit. The Chenjiazhai Sequence includes the Suozuodi, Yangyushu and Dashan Units, consisting predominantly of light pink, medium-to-fine grained, porphyroid biotite monzogranite. The Bozhushan Sequence comprises the Leidazhan, Fenshuiling, and Bozhupo Units, with lithologies ranging from fine-grained to medium-grained porphyroid and porphyritic biotite monzogranite. The Dashanjiao Unit is composed of grayish-white, fine-grained, tourmaline-bearing biotite monzogranite (Figure 1b) [1].

2.2. Deposit Geological Overview

The exposed strata in the Guanfang Tungsten Deposit mining area are limited, consisting primarily of the Lower Cambrian Chongzhuang Formation (C_{1ch}), Middle Cambrian Dayakou Formation (C_{2d}), Middle Cambrian Tianpeng Formation, along with Quaternary deposits. The argillaceous, silty, and sandy rocks of the Dayakou and Tianpeng Formations exhibit well-developed slaty cleavage. The carbonate rocks within these formations are strongly skarnized and constitute the principal ore-hosting horizons [9].

The exposed granite in the mining area belongs predominantly to the Suozuodi Unit of the Chenjiazhai Sequence of the Bozhushan composite pluton. This unit is composed of light pink porphyroid biotite monzogranite, with a medium-to-fine grained texture, and massive structure. The Suozuodi Unit granite is in intrusive contact with the surrounding strata. At its contact with carbonate rocks, hydrothermal metasomatism has produced skarn zones of variable width. The granite-proximal side of these skarns is concentrated primarily of tungsten mineralization within these zones [8].

3. Materials and Methods

3.1. Sample Materials

All samples were collected from the Guanfang Tungsten Deposit, comprising five granite outcrop samples from the surface mining area and five granite samples from stope tunnels. From these, six fresh, unweathered, and unaltered granite samples were selected for numbering, photographing, and hand specimen identification. Representative samples were then chosen to prepare petrographic thin sections.

A total of six thin sections were prepared as follows: three from surface outcrops (samples gf1, gf2, and gf3), and three from tunnel exposures (samples gf4, gf5, and gf6).

3.2. Methods

3.2.1. Petrographic Characteristics

Petrographic observations were conducted using a SOPTOP CX40P polarizing microscope (Ningbo, China) at the Faculty of Land and Resources Engineering, Kunming University of Science and Technology. Microscopy was employed for petrographic identification and imaging of granite samples. Based on this analysis, biotite grains that were

large, inclusion-free, and showed no evidence of weathering or alteration in thin sections were selected for further testing.

3.2.2. Electron Probe Microanalysis (EPMA)

Major element analysis of biotite was performed using a JEOL JXA-8230 electron probe microanalyzer (JEOL, Tokyo, Japan) at the Testing Center of Shandong Bureau, China Metallurgical Geology Bureau. Operating conditions were as follows: an accelerating voltage of 15 kV, a beam current of 20 nA, and an analytical beam spot diameter of 20 μm . The following natural mineral standards (SPI Supplies, West Chester, PA, USA) were used: jadeite (SiO_2 , Na_2O), rutile (TiO_2), yttrium aluminum garnet (Al_2O_3), olivine (FeO , MgO), rhodonite (MnO), diopside (CaO), sanidine (K_2O), apatite (P_2O_5 , F), and tugtupite (Cl). Data were corrected using the ZAF method.

For each sample, six representative biotite grains were analyzed. Multiple analysis points were measured per grain, distributed evenly while avoiding cracks and inclusions. Due to limited biotite availability in sample gf3, only four grains were analyzed from that sample.

3.2.3. Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)

Trace element analysis of biotite was conducted at the Testing Center of Shandong Bureau, China Metallurgical Geology Bureau. The analyses employed a GeoLasPro 193 nm ArF excimer ablation system (Coherent, New York, NY, USA), coupled to a Thermo Fisher ICAP Q inductively coupled plasma mass spectrometer (Thermo Scientific, Waltham, MA, USA).

Helium was used as the carrier gas during ablation. The resulting aerosol was mixed with argon (the plasma and makeup gas) via a T-shaped connector before introduction to the ICP. Helium and argon flow rates were optimized for maximum signal intensity using the NIST SRM 610 (a synthetic silicate glass reference material developed by the National Institute of Standards and Technology, Gaithersburg, MD, USA) as the tuning standard [14].

Laser operating conditions were set to a beam spot diameter of 40 μm , a repetition rate of 6 Hz, and an energy density of $\sim 10\text{--}12\text{ J/cm}^2$. The calibration was performed using the NIST SRM 610, NIST SRM 612, BCR-2G, and BIR-1G reference materials. Analyses of CGSG-1G and CGSG-2G were interspersed as unknown quality control monitors.

Data were acquired in time-resolved mode using a peak-hopping routine. Each analysis comprised a 25 s of a gas blank, 60 s sample ablation, and a 25 s washout period. A set of calibration standards (NIST 610 and NIST 612) was analyzed after every 10 unknown points. Raw data were processed offline using the ICPMSDATA CAL V9.5 software, with internal standardization based on calcium (Ca). Because some biotite grains were smaller than the laser spot size, three grains with diameters $>40\text{ }\mu\text{m}$ were selected from each thin section (gf1–gf6) for analysis.

4. Petrographic Characteristics

Observation under a polarizing microscope (Figure 2) reveals that the minerals of the granite from the Guanfang mining area are predominantly quartz, potassium feldspar, plagioclase, and biotite. Accessory minerals include zircon, tourmaline, apatite, magnetite, and monazite. Quartz occurs as irregular anhedral grains. Potassium feldspar forms columnar, tabular, and granular crystals; it commonly exhibits Carlsbad and perthitic twinning. Some crystals contain inclusions of euhedral, tabular plagioclase and granular and columnar zircon. Plagioclase is predominantly euhedral and tabular, displaying well-developed polysynthetic twins. Minor albite occurs as perthitic lamellae within potassium

feldspar or forms thin rims around it. Plagioclase crystals contain inclusions of euhedral, granular zircon.

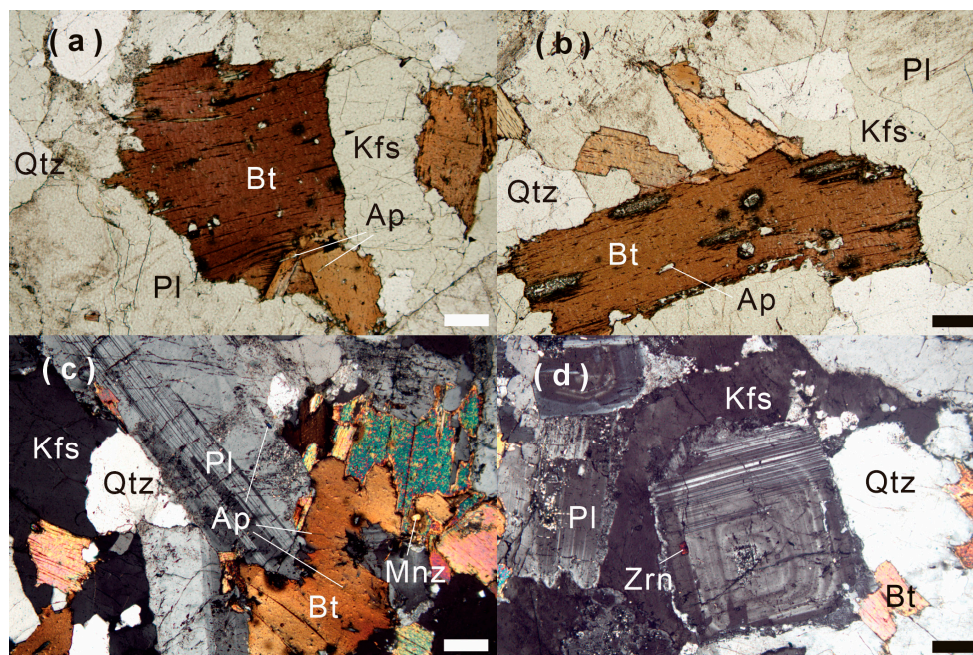


Figure 2. Photomicrographs of samples. (a): Plane-polarized light photomicrograph of sample; (b): Plane-polarized light photomicrograph of sample; (c): Crossed polars photomicrograph of sample; (d): Crossed polars photomicrograph of sample. Abbreviations: Qtz—quartz; Pl—plagioclase; Kfs—feldspar; Bt—biotite; Zrn—zircon; Ap: apatite; Mnz: monazite; Bar = 100 μm .

Biotite occurs as euhedral to subhedral flaky aggregates with distinct cleavage, exhibiting brownish-yellow to reddish-brown pleochroism, and locally contains inclusions of apatite. The biotite grains have smooth crystal margins and lack opacitization rims or lepidoblastic textures, characteristics indicating that the biotite in this study is magmatic primary biotite.

5. Compositional Characteristics

5.1. Major Element Compositions of Biotite

The major element compositions of biotite from the Guanfang granite, determined by electron probe microanalysis (EPMA), are provided in Appendix A (Table A1). Based on these compositions, the biotite is classified as aluminous biotite. Using the geochemical analysis software GeokitPro (build20250806), cationic contents were calculated on the basis of 22 oxygen atoms; results are presented in Appendix A (Table A2).

The combined data from Tables A1 and A2 reveal the following key characteristics of the Guanfang biotite:

(1) Major element composition

The biotite has the following oxide weight percentages (w): SiO_2 (34.87%–36.02%), Al_2O_3 (13.90%–14.97%), TiO_2 (3.49%–4.10%), K_2O (9.23%–9.86%), Na_2O (0.07%–0.36%), FeO^* (21.68%–23.39%), and MgO (8.28%–9.17%).

After hydrothermal alteration, biotite exhibits three principal alteration types, resulting in the formation of chlorite, sericite, and re-equilibrated biotite, respectively. Chloritization facilitates the mobilization of elements such as Ti and K into the hydrothermal fluid, whereas sericitization leads to the release of Fe, Mg, and Ti. In contrast, re-equilibrated biotite—formed through the interaction of magmatic biotite with K, Fe, and Mg-rich

hydrothermal fluids—is characterized by a pronounced decrease in TiO_2 and a significant increase in CaO content as a result of compositional re-equilibration [15].

The biotite grains in this study are enriched in Ti, K, Fe, and Mg, but depleted in Na and Ca (Ca was below detection in some analyses). This signature suggests crystallization in a relatively closed system without significant post-magmatic alteration. The dominance of Fe and Mg in octahedral sites further indicates a typical magmatic (primary) biotite origin [15].

(2) Petrogenetic implications

All analyzed samples are from the margin of the Suozuodi Unit within the Bozhushan pluton. The micas are exclusively ferruginous biotite; no muscovite was observed. The biotite's high Mg and low Na contents reflect a low degree of magmatic evolution. This is likely related to the geological setting at the pluton margin, characterized by weak thermal insulation, rapid cooling, and insufficient sustained magma supply. Rapid cooling inhibited extensive magmatic differentiation, preventing ferromagnesian minerals from evolving into more alkali-rich or Fe-Mg-poor mica species. Furthermore, strong heat exchange at the pluton-country rock contact likely promoted non-equilibrium crystallization, causing the biotite to retain more primitive magmatic compositions.

(3) Halogen contents and metallogenic significance

The analyzed biotite is compositionally homogeneous and exhibits relatively high F (0.71–0.91 wt%) and low Cl contents. This indicates an F-enriched character for the associated ore-forming fluids. The elevated F content likely enhanced the mobility of volatiles in the magma, promoted the transport and enrichment of metallic elements, and thus provided favorable conditions for subsequent W-Sn mineralization [16,17].

5.2. Trace Element Composition of Biotite

The trace element composition of biotite from the Guanfang granite, determined by LA-ICP-MS, is provided in Appendix B (Table A3). The results show an extremely low Ca content, which is consistent with a primary magmatic origin for the biotite [18].

Furthermore, the Sn content in biotite, a primary host for this element, is high (43 to 56 $\mu\text{g/g}$) and considerably exceeds typical granites values [18]. This indicates significant Sn metallogenic potential for the Guanfang granite. During subsequent hydrothermal alteration, the breakdown of primary biotite to form muscovite or chlorite can release substantial Sn, potentially leading to tin mineralization in associated alteration zones. Consequently, the Guanfang tungsten deposit is considered to possess clear potential for tin (Sn) mineralization.

6. Discussion

6.1. Genetic Type of Biotite in the Guanfang Granite

Petrographic observations indicate that biotite in the Guanfang granite occurs as euhedral to subhedral tabular or flaky crystals with well-developed cleavage. Crystal edges are distinct and smooth, lacking dark rims or significant embayment. The biotite contains inclusions of accessory minerals such as magnetite, apatite, and zircon. Its optical properties include a reddish-brown color with strong pleochroism (grayish-yellow to brownish-green), biaxial negative character, positive elongation, and parallel extinction. These features are inconsistent with hydrothermal biotite, which is typically fine-grained, scaly, and exhibits weak, pale green pleochroism. Instead, they align with primary magmatic biotite, characterized by high euhedrality, smooth edges, lack of dark rims or embayed edges, and strong reddish-brown, and exhibit strong pleochroism [11].

The magmatic origin is further supported by geochemical criteria. On the Foster mica classification diagram [15] (Figure 3), all analyzed biotite compositions plot within the field

of ferri-biotite, confirming a primary magmatic genesis and indicating crystallization from a reduced, acidic magma without subsequent hydrothermal overprinting.

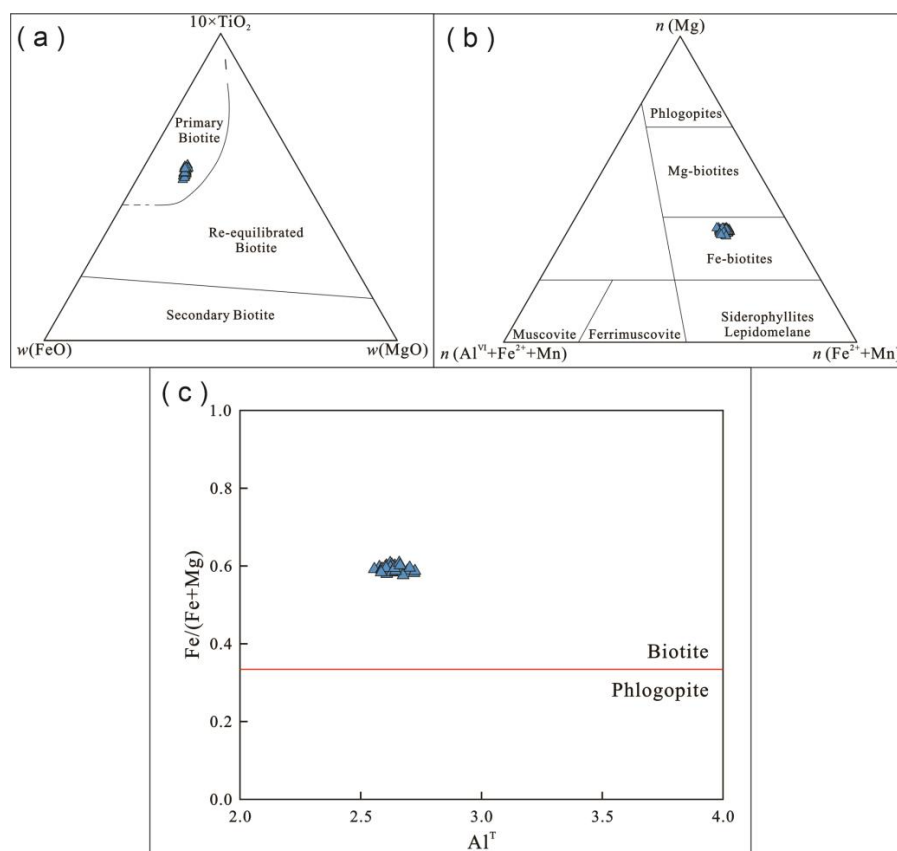


Figure 3. Diagrams for biotites from the Guanfang granite (a): diagram of $10w(\text{TiO}_2) - w(\text{FeO}^{\text{T}}) - w(\text{MgO})$; (b): diagram of $n(\text{Mg}) - n(\text{Al}^{\text{VI}} + \text{Fe}^{3+} + \text{Ti}) - n(\text{Fe}^{2+} + \text{Mn})$; (c): diagram of $\text{Fe}/(\text{Fe} + \text{Mg}) - \text{Al}^{\text{T}}$. The diagrams are modified according to [15]. Note: the meaning of “ w ” is “mass”. The meaning of “ n ” is the number of ions.

Furthermore, the calculated I_{Mg} values [$\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$] of the biotite range from 0.42 to 0.45, which falls within the 0.30–0.55 range typical of magmatic biotite as defined by Ma et al. [19]. The I_{Fe} values [$\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$] are tightly clustered between 0.55 and 0.58, indicating a homogeneous composition unaffected by post-magmatic fluid alteration.

6.2. Physicochemical Conditions of Biotite Crystallization in the Guanfang Granite

The physicochemical conditions such as crystallization temperature, pressure, and oxygen fugacity during the crystallization of primary magmatic biotite are key indicators for constraining the petrogenetic environment and magmatic evolution. As established, the biotite in the Guanfang granite is primary, making it a suitable mineral for reconstructing these parameters.

6.2.1. Crystallization Temperature, Pressure, and Intrusion Depth of Biotite

Previous studies have shown that the crystallization temperature of magma has a significant influence on the Ti content of biotite [20,21]. Crystallization temperatures were calculated using the formula:

$t/^{\circ}\text{C} = \{\ln n(\text{Ti}) - a - c(I_{\text{Mg}})^3/b\}^{0.333}$ (where $a = -2.359$, $b = 4.6482 \times 10^{-9}$, $c = -1.7283$) (the meaning of “ n ” is the number of ions).

The calculated temperatures range from 700 °C to 720 °C. Consistent results were obtained from the $n(\text{Ti}) - n(\text{Mg})/n(\text{Mg}+\text{Fe})$ diagram (Figure 4a) [20], indicating a medium–high temperature crystallization environment.

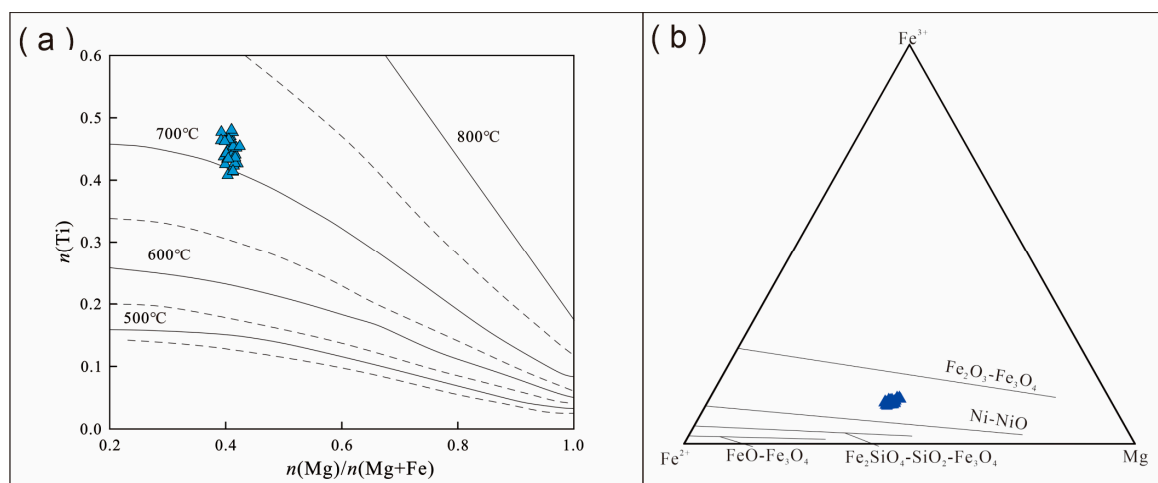


Figure 4. Diagrams for biotites from the Guanfang granite (a): diagram of $n(\text{Ti})/n(\text{Mg})/n(\text{Mg}+\text{Fe})$; (b): diagram of $n(\text{Fe}^{3+}) - n(\text{Fe}^{2+}) - n(\text{Mg})$. Note: the meaning of “ n ” is the number of ions.

Pressure during crystallization was estimated from the total Al content (Al^{T}) of biotite using the barometer of Uchida et al. [22]:

$$P \text{ (kbar)} = 3.03 \times n(\text{Al}^{\text{T}}) - 6.53 (\pm 0.33) \text{ (the meaning of “}n\text{” is the number of ions).}$$

This yields crystallization pressures of 1.2 to 1.7 kbar.

Assuming an average granite density (ρ) of 2700 kg/m³, the corresponding emplacement depth (h) is calculated as $h = P/(\rho g)$, where $g = 9.8 \text{ m/s}^2$. The resulting depth range of 4.6 to 6.5 km classifies the Guanfang granite as a mesozonal intrusion.

6.2.2. Oxygen Fugacity During Biotite Crystallization

For the equilibrium assemblage of biotite + K-feldspar + magnetite, oxygen fugacity ($f\text{O}_2$) can be estimated from the Fe^{3+} , Fe^{2+} , and Mg^{2+} contents of biotite [23].

On the corresponding $\log f\text{O}_2$ vs. temperature diagram (Figure 4b), all samples plot in a tight cluster between the Ni-NiO (NNO) and magnetite-hematite (MH) buffers, close to the NNO buffer line, indicating relatively high and consistent oxygen fugacity [24].

6.3. Petrogenesis and Tectonic Setting of the Guanfang Granite

The chemical composition of biotite can reflect key aspects of granite petrogenesis, including source rock characteristics and the magmatic environment. Key discriminant parameters are the oxidation coefficient $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ and magnesium ratio $\text{Mg}^{2+}/(\text{Mg}^{2+}+\text{Mn}+\text{Fe}^{2+})$, which are used to distinguish between I-type and S-type granites. I-type granites typically exhibit higher values for both ratios (oxidation coefficient $\sim 0.12\text{--}0.25$; magnesium ratio $\sim 0.384\text{--}0.626$), while S-type granites show lower values [25,26].

Furthermore, the I_{MF} values $n(\text{Mg})/n(\text{Fe}^{3+}+\text{Fe}^{2+}+\text{Mg}+\text{Mn})$ of biotite can differentiate between “transformation-type” (crustal anatexis) and “syntexis-type” (mantle-derived or hybrid) granites [26]. An I_{MF} value < 0.38 indicates a transformation-type origin, while $I_{\text{MF}} > 0.38$ suggests a syntexis-type. The Guanfang biotite I_{MF} values range from 0.39 to 0.42, classifying the granite as syntexis-type. This implies a magmatic source involving mantle-derived components or lower crustal melts that subsequently assimilated significant volumes of sialic crustal material during ascent.

6.4. Indicative Significance of Biotite Composition for Mineralization

Biotite composition provides key insights into the metallogenic potential of its host granite, particularly for Sn, W, Cu, Pb, and Zn.

6.4.1. Tin and Tungsten Potential

The crystallization of the Guanfang granite under oxidized conditions (the NNO and MH buffers) and medium–high temperatures (~ 700 °C) favors the partitioning of Sn into late magmatic fluids [27]. Furthermore, the biotite exhibits a high iron index ($I_{\text{Fe}} = 0.49\text{--}0.59$, avg. 0.53), a characteristic associated with Sn–W–Mo mineralized systems [26]. This indicates clear potential for tin and tungsten mineralization.

6.4.2. Role of Halogens (F, Cl)

The elevated total halogen contents in the magmatic biotite are critical for W–Sn metallogeny. These halogens lower magma solidus temperature and viscosity, prolonging crystallization and promoting the enrichment of incompatible elements (W, Sn) in the residual melt. They also facilitate the formation of soluble complexes, enabling efficient transport and subsequent deposition of ore metals during hydrothermal activity [28,29].

6.4.3. Petrogenetic and Tectonic Constraints

Biotite composition constrains the granite's origin and tectonic setting. On the $\text{Fe}/(\text{Fe}+\text{Mg})$ vs. F diagram [30], data plot in the fields for calc-alkaline and peraluminous granites typical of orogenic settings (Figure 5a). A low Rb/Ba ratio in biotite indicates a relatively low degree of magmatic differentiation (Figure 5b) [28,31].

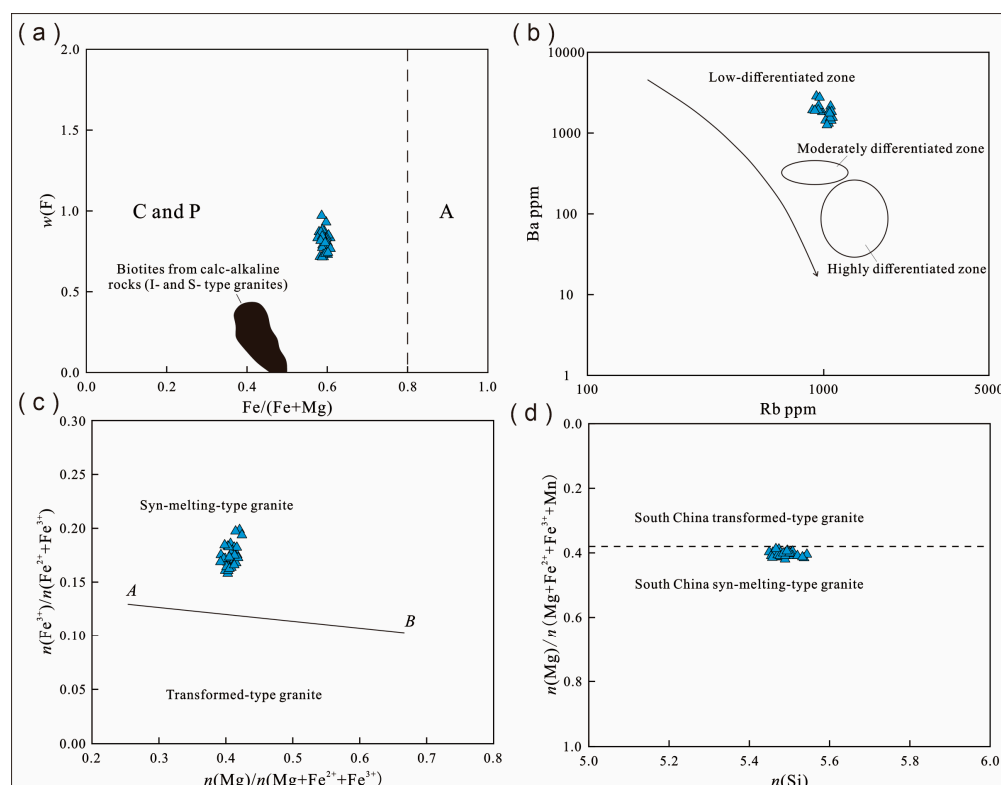


Figure 5. (a): compositions of biotite on $\text{Fe}/(\text{Fe}+\text{Mg})$ -F diagram; (b) compositions of biotite on Rb/Ba diagram; (c) compositions of biotite on $n(\text{Mg})/n(\text{Mg}+\text{Fe}^{2+}+\text{Fe}^{3+}) - n(\text{Fe}^{3+})/n(\text{Fe}^{2+}+\text{Fe}^{3+})$ diagram; (d): compositions of biotite on $n(\text{Mg})/n(\text{Mg}+\text{Fe}^{2+}+\text{Fe}^{3+}+\text{Mn}) - n(\text{Si})$ diagram. Note: the meaning of “w” is “mass”. The meaning of “n” is the number of ions.

6.4.4. Implications for Base Metal (Cu-Pb-Zn) Mineralization

Genetic discriminant diagrams classify the Guanfang granite as “Syn-melting-type” (or syntexis-type) rather than “Transformed-type” (Figure 5c) [14]. In South China, Syn-melting-type granites are principally associated with Cu-Pb-Zn-Au-Ag mineralization, whereas W-Sn-Nb-Ta deposits are typically linked to Transformed-type granites [32]. This association is supported by the biotite data, which plot within the Syn-melting-type field on the corresponding discriminant diagram (Figure 5d) [32].

7. Conclusions

(1) Biotites from the Guanfang granite exhibit high euhedrality, with smooth crystal margins and no development of opacitization rims or lepidoblastic textures. Chemically, they are characterized by reduced Na and Ca contents. These features indicate that all analyzed grains are primary, iron-rich biotite, with compositions consistent with a magmatic origin.

(2) Biotite geothermobarometry yields a crystallization temperature range of 700–720 °C, and a pressure range of 1.2–1.7 kbar. This corresponds to an emplacement depth of 4.6–6.5 km, classifying the Guanfang Granite as a mesozonal intrusion.

(3) The biotite composition indicates the host granite is an S-type granite with transitional I-type affinities. Discriminant diagrams further classify it as a South China syn-melting (syntexis) type, genetically related to hybrid magmas.

(4) The biotite crystallized from an oxidative, medium- to high-temperature magma with elevated total halogen (F+Cl), and Sn contents. These features indicate significant potential for W-Sn mineralization. The high TiO₂ content further suggests the granite belongs to the high-Ti syn-melting type, which is associated with polymetallic (Cu, Pb, Zn, Au, and Ag) mineralization in South China.

Consequently, future exploration in the Guanfang deposit should target not only tungsten but also tin, while further research is required to assess the prospectivity of other metals, including Cu, Pb, Zn, Au, and Ag.

Author Contributions: Conceptualization, L.C.; methodology, L.C., D.Z., R.Z., B.L. and J.Z.; investigation, X.C., R.Z., S.Z., X.L., J.Z., L.C., B.L. and D.Z.; formal analysis, J.Z. and B.L.; writing—original draft preparation, L.C., X.C. and D.Z.; writing—review and editing, L.C., D.Z., X.C. and S.Z.; visualization, L.C., X.C., B.L., J.Z., R.Z. and X.L.; supervision, S.Z., X.L. and D.Z.; project administration, S.Z. and X.L.; funding acquisition, S.Z., X.L. and D.Z.; resource, X.L. and D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the New round of mineral exploration operation of Yunnan (grant No. Y202407); Kunming University of Science and Technology “Double First Class” Science and Technology Special Project: Study on Late Yanshanian Magmatic-Metallogenic System and Metallogenic Regularity of the Bozhushan Area (No. 202202AG050006-2); National Natural Science Foundation of China (grant No. 42320104005).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. EPMA Analytical Results

Table A1. EPMA analytical results of biotites from Guanfang granite.

Points	wt/%														
	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cr ₂ O ₃	P ₂ O ₅	SO ₃	F	Cl	Total
gf1-1	35.139	3.785	14.292	22.321	0.347	8.434	0.019	0.168	9.629	0.017	Bdl	0.059	0.771	0.144	94.768
gf1-2	35.19	3.763	14.258	22.19	0.368	8.543	Bdl	0.128	9.473	Bdl	Bdl	0.044	0.873	0.165	94.59
gf1-3	35.143	3.972	14.001	22.68	0.361	8.584	0.015	0.174	9.327	0.01	Bdl	0.06	0.93	0.181	95.004
gf1-4	34.871	3.895	14.001	22.247	0.365	8.293	Bdl	0.21	9.498	Bdl	Bdl	0.063	0.803	0.146	94.021
gf1-5	35.012	4.056	14.231	22.825	0.385	8.275	Bdl	0.201	9.423	0.025	Bdl	0.073	0.833	0.195	95.139
gf1-6	35.031	3.709	14.22	22.697	0.395	8.379	Bdl	0.165	9.436	0.011	0.002	0.036	0.85	0.174	94.708
gf2-1	36.018	3.687	14.395	22.222	0.433	9.048	0.069	0.123	9.316	0.025	0.005	0.027	0.87	0.159	95.995
gf2-2	36.022	3.869	14.571	22.597	0.474	8.972	0.066	0.083	9.329	0.01	Bdl	0.064	0.848	0.163	96.674
gf2-3	35.144	4.008	13.92	22.782	0.383	8.818	0.011	0.255	9.382	0.016	0.008	0.048	0.853	0.166	95.398
gf2-4	35.153	3.704	13.909	21.994	0.393	8.537	0.05	0.358	9.232	0.035	0.009	0.091	0.715	0.199	94.033
gf2-5	35.584	3.859	14.215	22.929	0.448	8.843	0.007	0.134	9.401	0.019	Bdl	0.057	0.799	0.152	96.077
gf2-6	35.796	3.561	14.298	22.672	0.347	8.934	0.021	0.222	9.536	0.033	Bdl	0.08	0.881	0.181	96.15
gf3-1	35.145	3.713	14.526	23.138	0.372	8.741	0.024	0.125	9.301	0.037	Bdl	0.072	0.758	0.139	95.741
gf3-2	35.402	3.64	14.432	23.103	0.357	8.604	0.024	0.161	9.409	0.093	Bdl	0.048	0.729	0.129	95.795
gf3-3	35.065	3.803	14.128	22.935	0.397	8.679	0.003	0.144	9.463	0.04	0.013	0.051	0.775	0.16	95.294
gf3-4	35.254	3.949	14.262	22.941	0.329	9.006	0.028	0.112	9.35	0.01	Bdl	0.071	0.788	0.142	95.878
gf4-1	35.25	3.809	14.447	23.398	0.39	8.791	0.031	0.109	9.323	0.015	Bdl	0.031	0.833	0.154	96.195
gf4-2	35.46	3.807	14.273	22.735	0.349	8.948	0.016	0.096	9.523	0.002	Bdl	0.058	0.883	0.166	95.907
gf4-3	35.385	3.63	14.361	22.622	0.362	8.964	0.03	0.07	9.577	0.015	Bdl	0.055	0.971	0.164	95.76
gf4-4	35.504	3.796	14.54	22.465	0.333	9.011	0.014	0.135	9.542	0.022	0.002	0.057	0.865	0.138	96.029
gf4-5	35.371	3.491	14.333	23.051	0.418	8.747	0.047	0.11	9.501	0.006	Bdl	0.075	0.829	0.176	95.766
gf4-6	35.815	3.714	14.591	22.984	0.342	9.166	0.019	0.1	9.599	0.02	Bdl	0.036	0.869	0.135	96.994
gf5-1	34.939	3.938	14.141	22.665	0.334	8.666	0.108	0.228	9.397	0.021	0.006	0.069	0.818	0.177	95.123
gf5-2	35.298	4.101	14.786	22.147	0.304	8.721	0.025	0.179	9.561	0.025	Bdl	0.044	0.772	0.186	95.782
gf5-3	35.376	3.892	14.966	22.03	0.33	8.889	0.021	0.15	9.663	0.027	0.004	0.047	0.717	0.148	95.925
gf5-4	35.15	4.104	14.475	22.216	0.332	8.661	0.045	0.132	9.484	0.013	0.01	0.067	0.729	0.16	95.235
gf5-5	35.462	3.907	14.972	21.873	0.374	8.632	0.06	0.127	9.863	0.029	0.016	0.069	0.714	0.138	95.904
gf5-6	35.586	3.914	14.718	21.675	0.376	8.955	0.044	0.166	9.543	0.021	Bdl	0.072	0.833	0.159	95.675
gf6-1	35.632	3.576	14.562	22.717	0.349	8.95	0.03	0.095	9.689	0.005	Bdl	0.051	0.843	0.156	96.265
gf6-2	35.672	3.736	14.14	22.338	0.328	8.942	Bdl	0.135	9.457	0.023	0.005	0.068	0.816	0.176	95.452
gf6-3	35.347	3.986	14.436	22.407	0.393	8.564	0.026	0.143	9.696	0.006	Bdl	0.065	0.803	0.138	95.641
gf6-4	35.535	3.73	14.816	22.46	0.332	8.554	0.013	0.141	9.432	0.015	0.018	0.049	0.736	0.131	95.622
gf6-5	35.038	3.95	14.463	22.906	0.414	8.283	0.048	0.134	9.487	0.02	Bdl	0.064	0.766	0.153	95.368
gf6-6	35.303	3.948	14.523	22.638	0.342	8.405	Bdl	0.148	9.327	0.007	0.019	0.065	0.742	0.163	95.281

Abbreviations: Bdl: below detection limit.

Appendix A.2. Chemical Composition of Biotites (n_B) from Guanfang Granite**Table A2.** Chemical composition of biotites (n_B) from Guanfang granite.

Points	n_B (Number of Ions Calculated on the Basis of $n(O) = 22$)																	
	Si	Al ^{IV}	Al ^{VI}	Ti	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Na	K	I_{MF}	I_{Mg}	I_{Fe}	$n(TAl)$	$t/^{\circ}C$	P/kbar	h/km
gf1-1	5.50	2.50	0.14	0.45	0.49	2.43	0.05	1.97	0.00	0.05	1.92	0.40	0.45	0.55	2.64	711.36	1.47	5.54
gf1-2	5.51	2.49	0.14	0.44	0.54	2.37	0.05	1.99	0.00	0.04	1.89	0.40	0.46	0.54	2.63	711.91	1.44	5.44
gf1-3	5.49	2.51	0.07	0.47	0.54	2.42	0.05	2.00	0.00	0.05	1.86	0.40	0.45	0.55	2.58	718.31	1.28	4.84
gf1-4	5.51	2.49	0.11	0.46	0.50	2.43	0.05	1.95	0.00	0.06	1.91	0.40	0.45	0.55	2.61	716.12	1.37	5.17
gf1-5	5.47	2.53	0.10	0.48	0.52	2.46	0.05	1.93	0.00	0.06	1.88	0.39	0.44	0.56	2.62	719.44	1.42	5.35
gf1-6	5.49	2.51	0.12	0.44	0.51	2.47	0.05	1.96	0.00	0.05	1.89	0.39	0.44	0.56	2.63	708.04	1.44	5.42
gf2-1	5.54	2.46	0.14	0.43	0.57	2.29	0.06	2.07	0.01	0.04	1.83	0.42	0.48	0.52	2.61	709.35	1.37	5.19
gf2-2	5.51	2.49	0.13	0.45	0.57	2.32	0.06	2.05	0.01	0.02	1.82	0.41	0.47	0.53	2.63	714.22	1.43	5.39
gf2-3	5.48	2.52	0.03	0.47	0.49	2.48	0.05	2.05	0.00	0.08	1.87	0.40	0.45	0.55	2.56	719.15	1.22	4.60
gf2-4	5.54	2.46	0.13	0.44	0.50	2.40	0.05	2.01	0.01	0.11	1.86	0.40	0.46	0.54	2.59	710.39	1.30	4.92
gf2-5	5.50	2.50	0.09	0.45	0.51	2.45	0.06	2.04	0.00	0.04	1.85	0.40	0.45	0.55	2.59	713.06	1.31	4.97
gf2-6	5.52	2.48	0.12	0.41	0.50	2.42	0.05	2.05	0.00	0.07	1.88	0.41	0.46	0.54	2.60	702.24	1.34	5.08
gf3-1	5.46	2.54	0.12	0.43	0.49	2.52	0.05	2.02	0.00	0.04	1.84	0.40	0.45	0.55	2.66	707.19	1.53	5.77
gf3-2	5.50	2.50	0.14	0.43	0.48	2.52	0.05	1.99	0.00	0.05	1.86	0.40	0.44	0.56	2.64	703.80	1.47	5.56
gf3-3	5.48	2.52	0.08	0.45	0.47	2.52	0.05	2.02	0.00	0.04	1.89	0.40	0.44	0.56	2.60	711.26	1.35	5.11
gf3-4	5.46	2.54	0.06	0.46	0.49	2.48	0.04	2.08	0.00	0.03	1.85	0.41	0.46	0.54	2.60	716.95	1.36	5.14
gf4-1	5.45	2.55	0.08	0.44	0.50	2.53	0.05	2.03	0.01	0.03	1.84	0.40	0.44	0.56	2.63	710.03	1.45	5.46
gf4-2	5.48	2.52	0.09	0.44	0.51	2.43	0.05	2.06	0.00	0.03	1.88	0.41	0.46	0.54	2.60	712.13	1.35	5.11
gf4-3	5.48	2.52	0.10	0.42	0.51	2.41	0.05	2.07	0.00	0.02	1.89	0.41	0.46	0.54	2.62	705.97	1.41	5.33
gf4-4	5.48	2.52	0.12	0.44	0.51	2.39	0.04	2.07	0.00	0.04	1.88	0.41	0.46	0.54	2.64	712.13	1.48	5.59
gf4-5	5.49	2.51	0.12	0.41	0.48	2.51	0.05	2.02	0.01	0.03	1.88	0.40	0.45	0.55	2.62	698.51	1.42	5.36
gf4-6	5.47	2.53	0.10	0.43	0.49	2.45	0.04	2.09	0.00	0.03	1.87	0.41	0.46	0.54	2.63	707.28	1.44	5.42
gf5-1	5.46	2.54	0.07	0.46	0.48	2.48	0.04	2.02	0.02	0.07	1.87	0.40	0.45	0.55	2.61	716.71	1.36	5.16
gf5-2	5.45	2.55	0.15	0.48	0.52	2.34	0.04	2.01	0.00	0.05	1.88	0.41	0.46	0.54	2.69	722.57	1.63	6.16
gf5-3	5.46	2.54	0.18	0.45	0.49	2.35	0.04	2.04	0.00	0.04	1.90	0.41	0.47	0.53	2.72	715.71	1.71	6.48
gf5-4	5.47	2.53	0.13	0.48	0.52	2.37	0.04	2.01	0.01	0.04	1.88	0.41	0.46	0.54	2.66	723.12	1.52	5.73
gf5-5	5.48	2.52	0.20	0.45	0.49	2.33	0.05	1.99	0.01	0.04	1.94	0.41	0.46	0.54	2.72	715.63	1.73	6.52
gf5-6	5.49	2.51	0.16	0.45	0.54	2.25	0.05	2.06	0.01	0.05	1.88	0.42	0.48	0.52	2.68	718.40	1.58	5.96
gf6-1	5.49	2.51	0.13	0.41	0.49	2.44	0.05	2.06	0.00	0.03	1.90	0.41	0.46	0.54	2.64	702.48	1.48	5.60
gf6-2	5.53	2.47	0.12	0.44	0.53	2.37	0.04	2.07	0.00	0.04	1.87	0.41	0.47	0.53	2.58	710.94	1.30	4.92
gf6-3	5.48	2.52	0.12	0.47	0.50	2.40	0.05	1.98	0.00	0.04	1.92	0.40	0.45	0.55	2.64	717.78	1.47	5.55
gf6-4	5.50	2.50	0.20	0.43	0.53	2.38	0.04	1.97	0.00	0.04	1.86	0.40	0.45	0.55	2.70	708.57	1.66	6.27
gf6-5	5.47	2.53	0.13	0.46	0.50	2.48	0.05	1.93	0.01	0.04	1.89	0.39	0.44	0.56	2.66	715.19	1.53	5.77
gf6-6	5.49	2.51	0.16	0.46	0.54	2.40	0.05	1.95	0.00	0.04	1.85	0.39	0.45	0.55	2.66	716.33	1.54	5.82

Note: $I_{MF} = n(Mg)/n(Fe^{3+}+Fe^{2+}+Mg+Mn)$; $I_{Fe} = n(Fe^{2+})/n(Fe^{2+}+Mg)$; $I_{Mg} = n(Mg)/n(Fe^{2+}+Mg)$.

Appendix B

LA-ICP-MS Analytical Results of Biotites from Guanfang Granite

Table A3. LA-ICP-MS analytical results of biotites from Guanfang granite.

Points	µg/g																			
	Li	Na	Mg	Al	K	Ca	Ti	V	Cr	Mn	Fe	Zn	Rb	Zr	Nb	Sn	Sb	Cs	Ba	Hf
gf1-1	196.3	603.3	49,130	79,400	85,870	Bdl	22,150	422.2	104.4	3061	141,000	411.2	1069.0	0.470	141.4	44.94	0.063	36.61	2147	0.046
gf1-2	186.8	622.6	49,310	78,220	84,500	Bdl	21,220	382.9	97.0	3088	139,500	417.1	931.0	0.374	135.8	43.41	0.040	22.34	2858	0.043
gf1-3	191.7	628.4	50,420	77,710	85,230	Bdl	19,830	378.8	96.8	3088	140,700	432.7	944.0	0.608	128.0	44.07	Bdl	22.34	2104	0.068
gf2-1	237.5	642.0	51,080	78,390	85,620	Bdl	19,710	389.0	80.9	2795	138,000	395.9	986.7	0.406	154.1	44.64	Bdl	35.39	1826	0.068
gf2-2	217.3	567.1	52,630	78,350	85,920	Bdl	18,950	378.0	112.3	2707	137,900	396.5	1080.0	0.355	152.4	45.98	Bdl	51.63	1839	0.047
gf2-3	243.9	613.9	50,890	78,900	86,390	Bdl	20,130	414.2	112.6	2879	137,900	389.3	1052.7	0.354	155.3	45.38	Bdl	35.41	1839	0.053
gf3-1	226.8	950.0	53,000	81,500	86,600	650	20,420	386.0	94.4	3060	145,400	344.0	1048.0	0.420	133.7	53.70	Bdl	30.80	1315	0.031
gf3-2	244.5	860.0	51,800	83,900	84,200	400	20,760	395.0	75.0	2990	137,400	367.0	952.0	0.540	135.5	56.10	Bdl	26.80	2190	0.078
gf3-3	218.6	711.0	52,400	81,100	84,700	120	20,490	379.8	95.1	3037	143,000	432.8	896.0	0.321	152.0	44.00	0.050	23.19	1930	0.040
gf4-1	227.8	676.0	52,900	81,600	85,600	127	20,630	390.1	96.2	3064	145,000	440.0	1018.0	0.456	136.4	46.50	Bdl	35.10	1437	0.055
gf4-2	213.8	815.0	55,000	84,000	86,700	500	21,430	395.0	105.7	3151	144,200	429.0	948.0	0.485	141.5	46.50	Bdl	35.60	1925	0.103
gf4-3	223.8	683.0	54,200	82,000	85,900	128	20,520	381.4	94.5	2966	146,100	437.0	960.0	0.254	153.4	46.60	Bdl	31.39	2758	0.047
gf5-1	224.9	665.0	54,400	82,100	87,600	250	20,060	378.0	100.0	2859	141,500	393.0	1076.0	0.260	146.3	45.00	Bdl	50.80	1430	0.048
gf5-2	239.6	692.0	54,600	84,000	87,100	240	20,190	392.3	97.9	2823	141,800	407.0	1090.0	0.179	148.4	45.80	Bdl	53.30	1554	0.031
gf5-3	232.9	716.0	52,600	80,200	85,000	270	20,540	388.9	100.3	2233	137,300	270.0	917.0	0.493	132.8	45.90	0.062	27.83	1902	0.056
gf6-1	246.9	722.0	52,900	82,300	87,500	248	21,130	408.5	111.1	2088	141,000	240.7	1065.0	0.301	131.7	50.90	0.051	48.64	1536	0.075
gf6-2	246.3	603.0	57,600	88,500	86,100	274	19,820	415.0	106.7	2911	146,600	413.7	1032.0	0.890	157.9	46.20	Bdl	61.20	1260	0.112
gf6-3	212.4	617.0	51,450	80,400	85,100	87	20,540	382.8	93.3	2817	139,900	406.5	1059.0	0.344	152.6	46.20	Bdl	50.60	1764	0.062

Abbreviations: Bdl: below detection limit.

References

1. Zhang, S.T.; Chen, G.C. Geological characteristics and evolutionary patterns of the Bozhushan composite pluton in southeastern Yunnan. *Yunnan Geol.* **1997**, *16*, 222–232.
2. Li, K.; Geng, J.; Liu, H.; Zhang, Q.; Wang, D.; Cai, Y. Late Yanshanian Magmatism-Related Polymetallic Mineralization in Southeastern Yunnan. *Acta Mineral. Sin.* **2011**, *31*, 607–608. [\[CrossRef\]](#)
3. Xie, H.; Zhang, Q.; Zhu, Z.; Fan, L.; Wang, D. Petrology and Rare Earth-Trace Element Geochemistry of the Bozhushan Granite in Southeastern Yunnan. *Acta Mineral. Sin.* **2009**, *29*, 481–490. [\[CrossRef\]](#)
4. Jiao, S.-T.; Zhu, X.-Y.; Li, S.-T. Petrological and geochemical characteristics of the ore-forming geological bodies in southeastern Yunnan. *Miner. Depos.* **2014**, *33*, 407–408. [\[CrossRef\]](#)
5. Xu, S.-H.; Ren, T.; Lü, C.-L. Research progress on Cretaceous highly fractionated S-type granites in southeastern Yunnan. *Acta Mineral. Sin.* **2019**, *39*, 149–165. [\[CrossRef\]](#)
6. Cheng, Y.-B.; Mao, J.-W.; Chen, X.-L.; Yao, J.-M.; Zhao, H.-J. LA-ICP-MS zircon U-Pb dating and geological significance of the Bozhushan granite in southeastern Yunnan Province. *J. Jilin Univ. (Earth Sci. Ed.)* **2010**, *40*, 869–878. [\[CrossRef\]](#)
7. Mi, X.; Liu, X.; Zhang, S.; Chen, S.; Meng, G.; Zhang, H.; Cheng, J.; Zhou, J.; Lu, B.; Dao, J.; et al. Petrogenesis and Mineralization Implication of Monzogranites Granites from Bainiuchang in Silver Polymetallic Deposit, Southeast Yunnan: Constraints from Geochronology U-Pb, Geochemistry and Hf Isotope. *Geoscience* **2025**, *39*, 1016–1038. [\[CrossRef\]](#)
8. Zhang, Y.; Zhang, S.; Feng, M.; Liu, X.; Sun, Q.; Zhang, B. Regularity of Wall Rock Alteration and Mineralization in the Tuanshan Ore Section, Guanfang Scheelite Ore Deposit, Wenshan, Yunnan. *Geoscience* **2011**, *25*, 740–749.
9. Zhang, Y.; Zhang, S.; Fan, Y.; Ma, H.; Zhang, L.; Zhang, D. Geology and fluid inclusion study of the Guanfang skarn type W deposit, Wenshan County, Yunnan Province. *Acta Petrol. Sin.* **2014**, *30*, 877–888.
10. Liu, Y.; Kong, Z.; Chen, G.; Shao, F.; Tang, Y.; Sun, B.; Yang, G.; Cai, J. In-situ LA-SF-ICP-MS U-Pb dating of garnet from Guanfang tungsten deposit in southeastern Yunnan Province and its geological significance. *Acta Petrol. Sin.* **2021**, *37*, 847–864. [\[CrossRef\]](#)
11. Tang, P.; Tang, J.-X.; Zheng, W.-B.; Song, J.-L.; Lin, B.; Wang, X.; Yang, C.; Li, Z.-Y. Research progress on mineral chemistry of magmatic and hydrothermal biotites. *Miner. Depos.* **2017**, *36*, 935–950. [\[CrossRef\]](#)
12. Shi, L.; Chen, J.C.; Wu, S.L. *Special Geological Report of the Ministry of Geology and Mineral Resources of the People's Republic of China—IV—Ore Deposits and Minerals—No. 12—Metallogenic Regularity of Tin Ore Belt in Western Yunnan*; Ministry of Geology and Mineral Resources of the People's Republic of China: Beijing, China, 1989.
13. Cheng, Y.B. Spatial-Temporal Evolution of the Magmatism and Mineralization in the Gejiu Supergiant Sn Poly Metal Lie Distinct and Insights into Several Key Problems. Ph.D. Thesis, China University of Geosciences Beijing, Beijing, China, 2012.
14. Günther, D.; Hattendorf, B. Solid sample analysis using laser ablation inductively coupled plasma mass spectrometry. *TrAC Trends Anal. Chem.* **2005**, *24*, 255–265. [\[CrossRef\]](#)
15. Foster, M.D. *Interpretation of the Composition of Trioctahedral Micas*; US Government Printing Office: Washington, DC, USA, 1960; pp. 1–49.
16. Munoz, J.L. F-OH and Cl-OH exchange in micas with applications to hydrothermal ore deposits. *Rev. Mineral. Geochem.* **1984**, *13*, 469–493. Available online: <https://pubs.geoscienceworld.org/msa/rimg/article/13/1/469/87167/F-OH-and-Cl-OH-exchange-in-micas-with-applications> (accessed on 3 March 2017).
17. Candela, P.A. Toward a thermodynamic model for the halogens in magmatic systems: An application to melt-vapor-apatite equilibria. *Chem. Geol.* **1986**, *57*, 289–301. [\[CrossRef\]](#)
18. Rudnick, R.L.; Gao, S. Composition of the Continental Crust. In *Treatise on Geochemistry*, 2nd ed.; Holland, H.D., Turekian, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 1–51. [\[CrossRef\]](#)
19. Ma, C.-Q.; Yang, K.-G.; Tang, Z.-H. *Granitoids and Magma Dynamics: Theoretical Methods and Case Studies of Granitoids in Eastern Hubei*; China University of Geosciences Press: Wuhan, China, 1994.
20. Henry, D.J.; Guidotti, C.V.; Thomson, J.A. The Ti-saturation surface for low-to-medium pressure metapelites biotites: Implications for geothermometry and Ti-substitution mechanisms. *Am. Mineral.* **2005**, *90*, 316–328. [\[CrossRef\]](#)
21. Henry, D.J.; Guidotti, C.V. Titanium in biotite from metapelitic rocks: Temperature effects, crystal-chemical controls, and petrologic applications. *Am. Mineral.* **2002**, *87*, 375–382. [\[CrossRef\]](#)
22. Uchida, E.; Endo, S.; Makino, M. Relationship between solidification depth of granitic rocks and formation of hydrothermal ore deposits. *Resour. Geol.* **2007**, *57*, 47–56. [\[CrossRef\]](#)
23. Wones, D.R.; Eugster, H.P. Stability of biotite: Experiment, theory and application. *Am. Mineral.* **1965**, *50*, 1228–1272. Available online: <https://pubs.geoscienceworld.org/msa/ammin/article/50/9/1228/540155/Stability-of-biotite-experiment-theory-and> (accessed on 6 July 2018).
24. Linnen, R.L.; Pichavant, M.; Holtz, F. The combined effects of fO₂ and melt composition on SnO₂ solubility and tin diffusivity in haplogranitic melts. *Geochimica Cosmochim. Acta* **1996**, *60*, 4965–4976. [\[CrossRef\]](#)
25. Xu, K.; Tu, G. *Geology and Mineralization of Granitoids*; Jiangsu Science and Technology Press: Nanjing, China, 1986.

26. Zhou, Z.-X. Intrusive rocks mafic mica chemical composition characteristics and its geological significance. *Acta Petrol. Sin.* **1988**, *3*, 63–73.
27. Štemprok, M. Solubility of tin, tungsten and molybdenum oxides in felsic magmas. *Miner. Depos.* **1990**, *25*, 205–212. [[CrossRef](#)]
28. Nadia, M.; David, R.L.; Christopher, R.M.M.; Yang, X.Y. Biotite composition as a tool for exploration: An example from Sn-W-Mo-bearing Mount Douglas Granite, New Brunswick, Canada. *Lithos* **2021**, 382–383, 105926. [[CrossRef](#)]
29. Kirsten, L.R.; James, K.M. Magmatic petrogenesis and the evolution of (F:Cl:OH) fluid composition in barren and tungsten skarn-associated plutons using apatite and biotite compositions: Case studies from the northern Canadian Cordillera. *Ore Geol. Rev.* **2013**, *50*, 118–142. [[CrossRef](#)]
30. Dahlquist, J.A.; Alasino, P.H.; Eby, G.N.; Galindo, C.; Casquet, C. Fault controlled Carboniferous A-type magmatism in the proto-Andean foreland (Sierras Pampeanas, Argentina): Geochemical constraints and petrogenesis. *Lithos* **2010**, *115*, 65–81. [[CrossRef](#)]
31. Villaros, A.; Pichavant, M. Mica-liquid trace elements partitioning and the granite-pegmatite connection: The St-Sylvestre complex (Western French Massif Central). *Chem. Geol.* **2019**, *528*, 119265. [[CrossRef](#)]
32. Xu, K.Q.; Hu, S.X.; Sun, M.Z.; Ye, J. On The Two Genetic Series Of Granites In South China and Their Metallogenic Characteristics. *Miner. Depos.* **1982**, *2*, 1–14. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.