

Article

Prospecting Prediction of the Tieyaoshan Tin Deposit Based on Zircon U–Pb Geochronology, Geochemical Data and Tectonic Numerical Simulation

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Abstract

This study integrates zircon U–Pb geochronology, whole-rock geochemical analysis, and tectonic numerical simulation to determine the emplacement age, petrogenesis, and tectonic setting of ore-bearing granites in the Tieyaoshan tin deposit and further clarify the structural ore-controlling characteristics to provide effective geological evidence and favorable prospecting indicators for tin deposit prediction in the study area. The Tengchong block is located in the Sanjiang–Tethys tectonic domain. The Tieyaoshan deposit is situated at the southwestern end of the regional metallogenic belt and belongs to the Early Cretaceous Donghe granite belt, with ore-bearing lithology dominated by medium-fine grained biotite granite. Zircon U–Pb dating yielded a precise emplacement age of 123.45 ± 0.64 Ma for the ore-related granite. Geochemically, these granites are enriched with sodium and potassium. In comparison to the primitive mantle, the rock samples exhibit a marked enrichment in large-ion lithophile elements (LILEs). Additionally, there are distinct negative anomalies in typical high-field-strength elements (Nb, Ta, P, Ti). The analysis of major and trace element discrimination diagrams collectively suggests that the granites originated in a tectonic setting characterized by subduction-collision and subsequent post-collisional extension. The consistent geochronological and geochemical signatures between the ore district plutons and the igneous rocks from the central and eastern Lhasa block demonstrate that the Early Cretaceous Tengchong magmatic belt represents the southeastern extension of the central Lhasa magmatic belt, which was a magmatic response to the subduction and collision of the Meso-Tethyan oceanic crust beneath the Lhasa–Tengchong block along the Bangong Co–Nujiang suture zone. Tectonic stress field numerical simulation reveals that the study area is dominated by NW–SE compressive stress, and the central region exhibits obvious shear stress concentration, which accounts for widespread rock fragmentation and well-developed structures. During the mineralization period, shear stress was predominantly concentrated along the NE-trending fracture structures. Therefore, the NE-trending fracture zones formed during mineralization, together with the early-stage E–W-trending guiding and host structures, constitute favorable metallogenic spaces. This study provides important theoretical guidance for tin ore prospecting in the region.

Keywords: granite geochemistry; prospecting prediction; numerical simulation; Tieyaoshan tin deposit



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1. Introduction

Granites in western Yunnan have garnered significant attention due to their close association with mineralization [1–6]. Mineral resources such as tin, tungsten, antimony, and rare earth elements are crucial to the new-energy, new-materials, and new-technology industries, with their enrichment and mineralization closely linked granitic magmatism. Granitic magmas serve the primary source of ore-forming materials, and the volatiles and ore-bearing fluids exsolved during their evolution play a critical role in the mobilization, migration, enrichment, and ultimate emplacement of metallic elements. Taking southeastern Yunnan as an example, the large- to superlarge-scale tin polymetallic deposits in this region commonly exhibit a close coupling with specific generations of granitic plutons in terms of both spatiotemporal distribution and genetic evolution. Studies have shown that the mineralization of the Dulong superlarge Sn–Zn–In polymetallic deposit is closely related to Late Cretaceous granitic magmatism, and cassiterite U–Pb geochronology together with trace-element compositions reveals the intrinsic link between the ore-forming materials and granite evolution [1]. The concealed Late Yanshanian granite at depth, based on its geological and geochemical characteristics, further indicates a direct genetic connection with Sn–Zn polymetallic mineralization [2]. Geochronological and geochemical evidence indicates that the granites in this area formed during the Late Cretaceous, and their whole-rock geochemistry, mineral chemistry, and Nd–Hf isotopic compositions jointly record the evolutionary history of highly fractionated granitic magmas [3–5]; moreover, a clear genetic tie exists between this Late Cretaceous granitic magmatism and Sn mineralization [6]. In addition, multi-stage fluid-mixing events are considered one of the key mechanism responsible for the super-enrichment of Sn polymetallic mineralization at Dulong [7]. In addition to the the Yanshanian granites, Caledonian granites are also present in the Laojunshan area; their SHRIMP zircon U–Pb geochronology and lithogeochemical characteristics record the collision and amalgamation between the Yangtze and Cathaysia blocks [8], indicating that the western–southeastern Yunnan region experienced multistage, long-lived granitic magmatic evolution and superimposed mineralization.

As an important part of the Sanjiang Tethyan domain in Southwest China, the Tengchong block has experienced Meso–Neo-Tethyan tectonic evolution, developing and preserving tectonic traces, magmatic associations, and associated hydrothermal W, Fe, Sn, and rare-metal deposits during different periods of the Cretaceous–Paleogene. According to their formation ages, the regional intrusions can be divided into the Early Cretaceous Donghe granite belt, the Late Cretaceous Guyong granite belt, and the Paleogene Binalangjiang granite belt. Controlled by regional tectonic lineaments, these intrusions are distributed in parallel from northeast to southwest along a nearly north–south trend. Multiple tectonomagmatic events provided favorable conditions for hydrothermal mineralization, and numerous granite-related magmatic-hydrothermal deposits formed in the Tengchong–Lianghe area, such as the Sn polymetallic deposits at Xiaolonghe, Tiechang, Lailishan, Xinqi, Diantan, Tieyaoshan, and Jianguan [9–13]. Additionally various other polymetallic deposits are present in the area, such as the Datongchang Cu–Pb–Zn deposit, the Maliba Mo–Pb–Zn deposit, the Xiaochang Mo deposit, and the Baihuanao Rb–Cs–Y–Sc deposit [14–18].

The Tieyaoshan Sn–W–Fe polymetallic deposit is located at the southwestern end of this metallogenic belt and belongs to the Early Cretaceous Donghe granite belt sequence, with medium- to fine-grained biotite granite as the ore-bearing pluton. Compared with other deposits in the region, it remains relatively poorly studied, and its ore-forming genesis remains poorly constrained. In this study, zircon U–Pb dating of the deposit supplements the geochronological framework of tin-related granites in the Tengchong Block. On this basis, numerical tectonic simulation was integrated with geochemical data from the mining

area to (i) clarify the temporal and genetic link between local granitic magmatism and Sn–W–Fe mineralization of the Tiewaoshan deposit, (ii) identify the structural controls on ore-forming fluid migration and metal accumulation for this deposit, and (iii) delineate favorable prospecting targets within the district. This integrated approach not only aids in understanding the genesis of the Tiewaoshan Sn–W–Fe polymetallic deposit, but also enhances our comprehension of the tectonic-magmatic evolution and mineralization of the Sanjiang Tethys, providing valuable research insights and practical references for prospecting prediction in this region.

2. Regional Geological Characteristics

The study area is located in the Lushui–Tengchong fold belt of the Gangdise–Nyainqentanglha fold system. During the evolution of the Meso–Neo-Tethys Ocean, magmatic activity was widespread in the area, and the exposed area of magmatic rocks can reach 70%. Sedimentary strata and rock bodies undergo different degrees of metamorphism. Regional faults are relatively well developed, especially in the east, parallel to the folds and distributed in a north–south direction. It has obvious linear structural characteristics.

The Quaternary system is well-developed in the region and has a wide range of types. In addition to volcanic deposits, there are river terrace, lake deposits, proluvial and slope deposits. Frequent magmatic activity since the Cambrian has resulted in the extensive development of magmatic rocks in the Tengchong block, of which the Cambrian–Ordovician rocks are mainly distributed in the Longjiang and Luxi areas on the eastern margin of the block, and the Cretaceous to Paleogene magmatic rocks are exposed in an area of up to 50%, which is most closely related to mineralization. The Tengchong Massif is divided into three blocks from east to west by the Binlangjiang–Dayingjiang fault and the Guyong–Tengchong fault, the eastern part of which is dominated by Early Cretaceous granites (128–108 Ma) and the central part by Late Cretaceous–Paleogene granitic intrusions (76–55 Ma). The western part is composed of Paleogene (56–51 Ma) granite and gabbro intrusions. In recent years, evidence of Indosinian magmatism has been reported from several studies [19–22]. At present, Triassic rock bodies have been found in Lianghe, Nabang, Gudong, Mangshi and other areas, while Jurassic rock bodies are only distributed around Lianghe County (Figure 1).

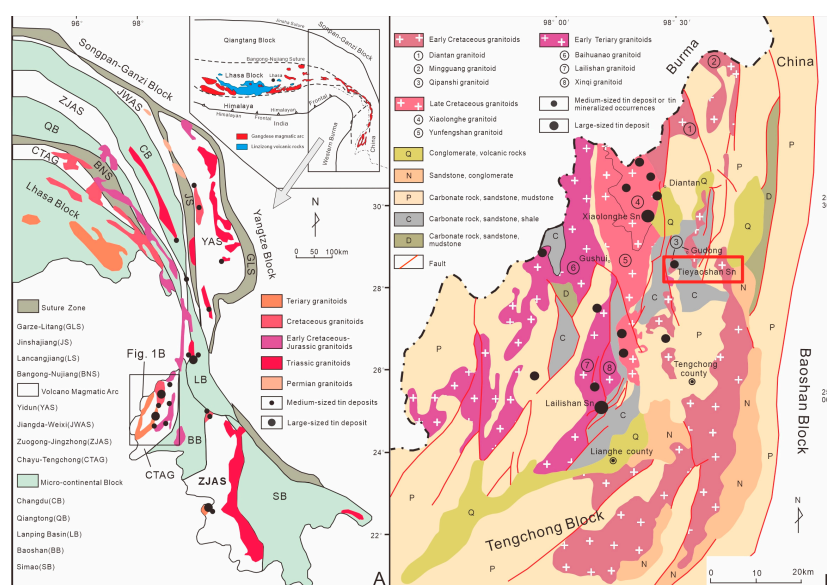


Figure 1. Sketch map showing (A) the tectonic framework of the Tibetan Plateau and (B) the distribution of magmatic rocks, as well as tin deposits in the Tengchong–Lianghe tin district. Modified after Liu [1].

3. Geologic Features of the Deposit

The Tieyaoshan mining area is located near the Tengchong–Qipanshi fault in the central and eastern part of the metallogenic belt. Several rock bodies of the Donghe rock group are exposed in the mining area, in which fine grained biotite granite and medium-fine grained biotite granite are closely related to mineralization. The area is mainly distributed with the Siguangping Formation of the Middle Carboniferous System of the Upper Paleozoic and the Kongshuhe Formation of the Upper Carboniferous System. In addition to the incomplete syncline of Daxishan in the central part of the mining area, there are 12 faults with different sizes in four groups, namely, nearly north–south, northwest, northeast and east–west. Among them, the nearly north–south fault is the regional ore-conducting structure, the northwest (north–northwest) fault is the ore-hosting structure in the mining area, and the northeast fault is the ore-breaking structure.

Sn–W–Fe ore bodies are found in the fault fracture zone. The geological exploration report shows that 16 ore bodies have been identified and mined in the mining area, and the ore bodies are strictly controlled by the NNW fault fracture zone. Most ore bodies occur as veins and lenses. The occurrence of the ore body is basically consistent with that of the fault fracture zone, with a strike of $310\text{--}350^\circ$ and a dip angle of $40\text{--}85^\circ$, and some are even vertical. The average grades of the ore bodies are Sn 0.12%–1.26%, WO_3 0.137%–0.389%, and TFe 33.74%–38.51%.

The types of Sn–W–Fe polymetallic ore in Tieyaoshan are relatively complex, mainly including brecciated quartz–limonite (pyrite) type tungsten–tin ore and quartz–magnetite type tin–tungsten ore, followed by skarn type tin–tungsten ore. The main metallic minerals are cassiterite, scheelite, limonite, pyrite and magnetite; the minor minerals are magnetite, hematite, pyrite, specularite, scheelite, cassiterite and molybdenite. Gangue minerals are mainly quartz, muscovite, garnet (andradite) and diopside, which are characteristic of skarn-type W–Sn mineralization (Figure 2).

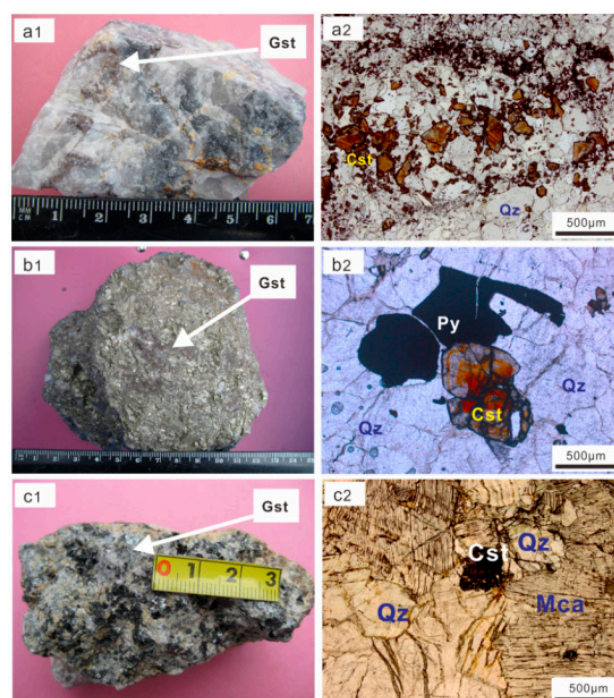


Figure 2. Photographs of the greisen-type ore from the Tieyaoshan tin deposit (a1,a2) Quartz vein type tin ore; (b1,b2) sulfide type tin ore; and (c1,c2) greisen type tin ore. Cst—cassiterite, Mca—muscovite, Qz—quartz, and Py—pyrite. Modified after Chen [2].

4. Sampling and Experimental Methods

In this study, samples were collected from ore-related granite. Before sampling, a geological hammer was used to remove the rock-indicative layers, and fresh samples were collected. Petrographic observation (Figure 3) and chemical analysis (Table 1, see below) showed that these samples were not subjected to hydrothermal alteration. Two representative granite samples were selected: medium-coarse-grained biotite granite and fine-grained biotite granite. Petrogeochemical analysis was performed.

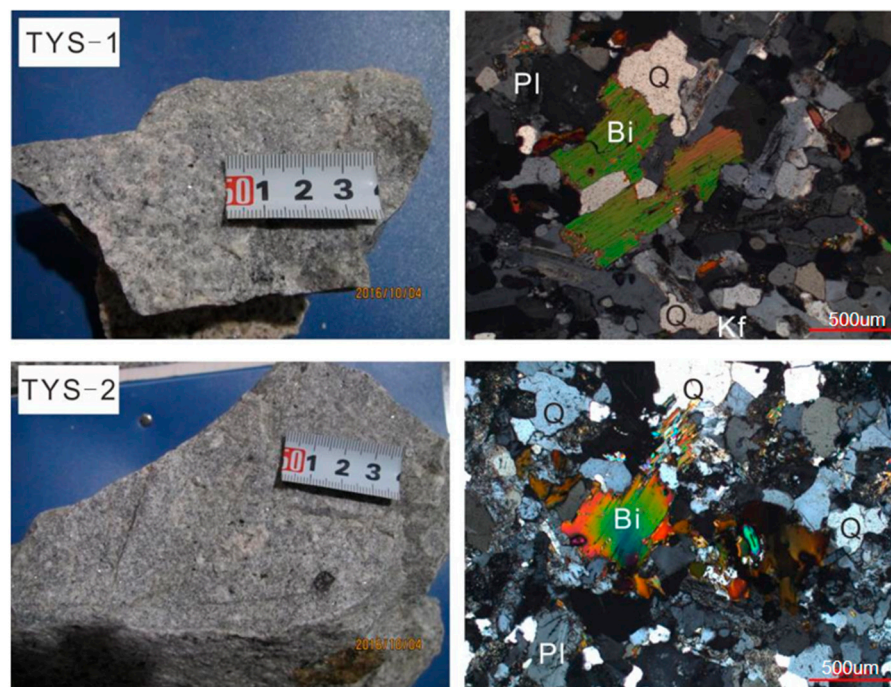


Figure 3. Hand-specimen photographs and cross-polarized light micrographs of granite samples (TYS-1 and TYS-2) from Tieyaoshan. Left column: Hand-specimen photos of samples TYS-1 and TYS-2; metric rulers are placed on a white background for clear scale reading. Right column: corresponding thin-section microphotographs under cross-polarized light. Q—quartz, Pl—plagioclase, Kf—K-feldspar, and Bi—Biotite. Scale bar for microphotographs = 500 μm .

Table 1. Major elements of monzogranite from the Tieyaoshan ore field, Yunan (wt%).

SAMPLE		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	Na ₂ O	TiO ₂	MnO	P ₂ O ₅	TFeO *	LOI	Total (wt%)
TYS1	Medium-grained porphyritic biotite granite	76.35	12.34	1.41	0.24	1.77	4.08	3.09	0.13	0.05	0.02	1.269	0.40	99.88
TYS3		74.03	13.04	2.11	0.39	1.38	5.19	2.77	0.22	0.05	0.04	1.899	0.66	99.88
TYS5		76.13	12.43	1.49	0.28	1.56	3.74	3.26	0.13	0.05	0.03	1.341	0.49	99.59
TYS7		76.65	12.50	1.30	0.21	1.38	4.51	2.94	0.12	0.05	0.02	1.17	0.58	100.26
TYS2	Fine-grained biotite granite	74.23	13.03	1.85	0.37	1.70	4.66	3.1	0.19	0.06	0.04	1.665	0.52	99.75
TYS4		74.56	12.85	2.11	0.37	1.78	4.11	3.18	0.17	0.06	0.03	1.899	0.60	99.82
TYS6		76.78	12.66	1.47	0.26	1.75	3.49	3.38	0.13	0.04	0.03	1.323	0.61	100.6
TYS8		77.04	12.00	1.31	0.17	1.00	3.73	2.98	0.10	0.04	0.01	1.179	0.75	99.13

* TFeO (total iron as FeO) was calculated from the measured Fe₂O₃ using $\text{TFeO} = \text{Fe}_2\text{O}_3 \times 0.8998$.

The major element analysis was conducted by an X-ray fluorescence method in the State Key Laboratory of Mineral Deposit Geochemistry, the Institute of Geochemistry, the Chinese Academy of Sciences. The test instrument was an X-ray fluorescence spectrometer (model: PANalytical AXIOS), and the analysis error was less than 5% [23–26]. The detailed experimental process is as follows: (1) Calculate the loss on ignition: weigh the crucible (W1) and add 1 G of sample; then place the crucible with the sample into a muffle furnace, burn it for 3 h at 900 °C, cool it down, cover it, place it into a dryer, and weigh it after 30 min; finally, calculate the loss on ignition (LOI) of the sample. (2) Preparation of the sample to be tested: A total of 0.7 G of the sample and 7 G of the flux (Li₂B₄O₇) were placed

into a crucible, uniformly stirred with a glass rod, poured into a platinum crucible, adding a proper amount of LiBr, and the platinum crucible was melted at 1150 deg C. The sample melt was poured into a platinum mold, and cooled to obtain a flat glass sheet for testing. Standard sample GSR3 was used to correct for the matrix effect and the standard curve method was used to correct the data.

Trace element analysis was carried out in the State Key Laboratory of Mineral Deposit Geochemistry, the Institute of Geochemistry, the Chinese Academy of Sciences, using a Perkin Elmer Sciex ELAN DRC e inductively coupled plasma mass spectrometer (ICP-MS). The experimental procedure was as follows: A total of 50 mg of sample was weighed and placed into Teflon and 1 mL of HF was added and evaporated to dryness on an electric hot plate. Next 1 mL of HF and 0.5 mL HNO₃ were added and the sample was placed in an oven, after capping and tightening, and decomposed at 200 °C for 48 h. The samples were removed, cooled, evaporated on an electric hot plate at a low temperature, 1 mL of HNO₃ was added and evaporated again, repeating the above cycle. Finally, 2 mL of HNO₃ and 5 mL of distilled water were added. After re-capping, the residue was dissolved at 130 °C for 3 h. After cooling, 1 mL of 1 µg mL⁻¹ Rh solution was added and transferred to a 50 mL centrifuge tube for testing. Standard samples OU-6, AMH-1 and GBPG-1 were used for quality control, and Rh was used as an internal standard to detect instrument drift, which was corrected using the standard curve method [27–32].

Zircon U–Pb dating was performed at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan, China). The laser-ablation system was a GeoLas 2005 coupled to an Agilent 7500a ICP-MS for isotopic and trace element analysis. The laser operated at a wavelength of 193 nm, with a spot size of 32 µm, laser fluence of -8 J/cm^2 , and a repetition rate of 8 Hz. Helium was used as the carrier gas, and argon served as the make-up gas for sensitivity adjustment; the two gases were mixed via a T-junction prior to introduction into the ICP. Each time-resolved analysis comprised approximately 20–30 s of background acquisition followed by 50 s of sample ablation signal [33–36].

The standardized analysis process of the ANSYS software (Version 2023 R2; ANSYS, Inc., Canonsburg, PA, USA) is the same as that of all finite element software. It is divided into three processes: model pretreatment, solution operation and model post-processing. The pre-processing of the model is completed in the pre-processing module, the solving operation is completed in the analysis and calculation module, and the post-processing of the model is completed in the post-processing module [2,37,38].

5. Results of Geochemical Data

5.1. Geochemistry

5.1.1. Major Elements

The major element analytical results are listed in Table 1. The major element compositions were determined using X-ray fluorescence spectrometry (XRF). The SiO₂ content of the Tieyaoshan granite varies from 74.03 wt% to 77.04 wt%. The content of CaO in the sample changes greatly, from 1.00 to 1.78 wt%, the content of K₂O changes slightly and is relatively stable, from 3.49 to 5.19 wt%, and the content of TFe in the sample is generally high, from 1.17 to 1.899 wt%.

5.1.2. Trace Elements

Trace-element analyses for granite samples from the Tieyaoshan ore-field were carried out using inductively coupled plasma-mass spectrometry (ICP-MS). Noticeable geochemical variations in Ba are identified among medium-grained porphyritic biotite granite and fine-grained biotite granite, whereas the majority of other trace-element components exhibit

restricted compositional variations (Table 2). Collectively, these granites are marked by strong Rb enrichment. The large-amplitude variation of Ba is likely linked to magmatic fractional crystallization and possible fluid exsolution during magma emplacement. Notably, Sn abundances are generally high within the whole sample suite, varying from 3 to 6 ppm, which is more than twice the regional crustal background value. Such geochemical features further indicate that the granites in this area possess favorable material conditions for tin mineralization.

Table 2. Trace elements of granite from the Tieyaoshan ore field (ppm).

SAMPLE		Rb	Sr	Y	Zr	Nb	Sn	Cs	Ba
TYS1	Medium-grained porphyritic biotite granite	197	91.9	39.9	95	19.5	6	1.87	191
TYS3		347	71.7	38	152	19.1	3	5.32	407
TYS5		253	74.8	38.4	108	17.6	6	3.03	185.5
TYS7		262	74.9	51.1	101	22.9	6	2.24	168.5
TYS2	Fine-grained biotite granite	259	86.4	31.1	95	15.7	4	2.05	280
TYS4		231	78.2	30	107	14	4	2.05	232
TYS6		258	76.2	39.2	94	16.5	5	2.78	172.5
TYS8		247	66.3	22.4	84	10.3	4	2.85	161

5.1.3. REE

Rare-earth element concentrations were measured by ICP-MS, and the corresponding data are listed in Table 3; statistical parameters for REEs are summarized in Table 4. The composition of rare earth elements in Tieyaoshan granite is characterized by enrichment of total rare-earth elements, with $\Sigma\text{REE} = 377.01\text{--}752.73$ ppm; $\Sigma\text{LREE}/\Sigma\text{HREE} = 0.90\text{--}2.28$; $\text{Y}/\text{Nb} = 0.52\text{--}0.73$; and $\text{Nd}/\text{Ta} = 6.39\text{--}11.17$.

Table 3. Rare-earth element concentrations in granite from the Tieyaoshan ore field (ppm).

SAMPLE	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
TYS1	62.25	81.01	42.74	31.48	22.03	3.97	16.20	16.04	14.21	13.60	14.20	14.90	14.76	15.35	14.27
TYS2	66.99	82.28	48.53	38.54	35.10	4.83	30.02	33.16	34.09	33.39	36.74	35.29	35.82	35.43	32.55
TYS3	69.93	88.19	50.42	38.33	29.93	5.69	24.09	23.53	23.58	22.97	25.62	25.88	27.47	27.17	24.46
TYS4	70.42	88.61	51.47	37.04	30.98	5.52	23.02	24.60	23.74	24.56	27.49	27.06	28.53	29.13	24.97
TYS5	78.1	106.33	53.79	40.26	31.18	5.34	24.04	25.13	24.49	24.03	25.56	26.67	27.47	27.17	25.41
TYS6	88.07	112.66	61.68	44.33	31.37	8.62	21.61	19.25	19.02	18.37	18.85	19.22	20.29	21.65	19.11
TYS7	91.18	115.19	62.84	47.11	30.78	8.28	22.38	21.12	20.28	19.26	20.24	20.39	20.47	21.65	19.81
TYS8	135.95	170.46	93.47	69.38	44.44	9.66	28.61	26.20	25.39	23.67	25.50	24.71	24.71	26.38	24.20

Table 4. Rare-earth element characteristics in granite from the Tieyaoshan ore field.

SAMPLE		ΣREE	ΣLREE	ΣHREE	$\Sigma\text{LREE}/\Sigma\text{HREE}$	Y/Nb	Rb/Nb	Nd/Ta	3Ga	Y + Nb	Y + Ta
TYS1	Medium-grained porphyritic biotite granite	377.01	243.48	133.53	1.82	0.62	0.009678	8.17	45	59.4	42.2
TYS3		507.26	282.49	224.77	1.26	0.73	0.011771	11.17	45.3	57.1	40.9
TYS5		544.97	315	229.97	1.37	0.6	0.009654	6.39	43.8	56	41.2
TYS7		540.98	355.38	185.6	1.91	0.52	0.006223	7.83	43.2	74	53.4
TYS2	Fine-grained biotite granite	582.76	276.27	306.49	0.9	0.7	0.013759	13.75	44.7	46.8	32.7
TYS4		517.14	284.04	233.1	1.22	0.7	0.014352	11.5	45.6	44	31.8
TYS6		524.1	346.73	177.37	1.95	0.59	0.009373	6.41	44.7	55.7	41.9
TYS8		752.73	523.36	229.37	2.28	0.69	0.018897	9.19	41.1	32.7	24

5.2. Zircon U–Pb Geochronology

The test results of the samples in this study indicate that the zircon samples are of magmatic origin. The tests revealed that the weighted average $^{206}\text{Pb}/^{238}\text{U}$ age was 123.45 ± 0.64 Ma, and MSWD = 0.68 (31 test sites), as shown in Figures 4 and 5.

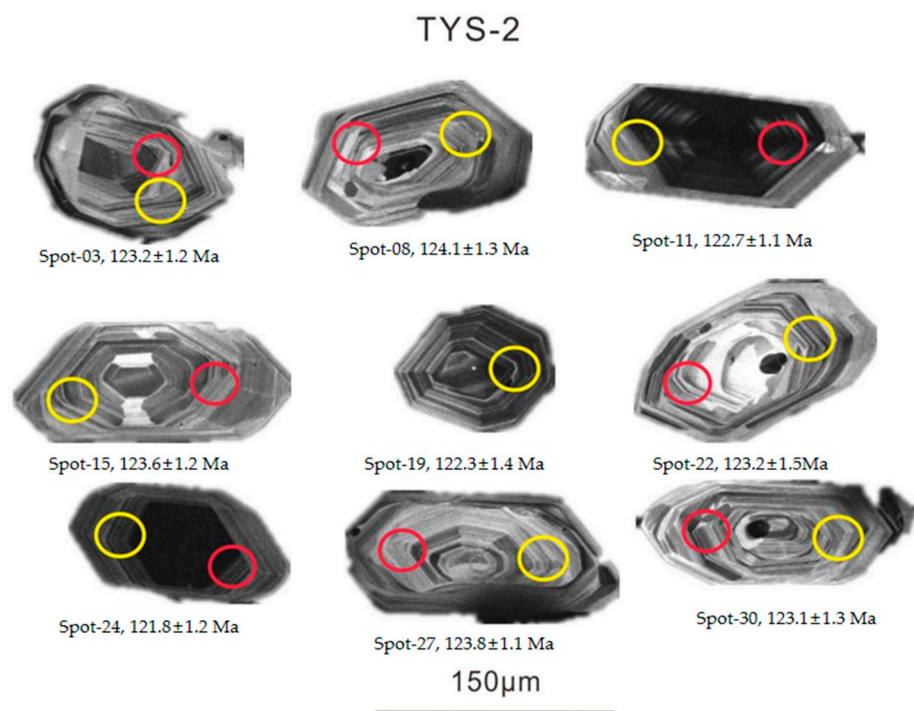


Figure 4. CL images of selected dated zircons from TYS-2. The red and yellow circles indicate the spot location.

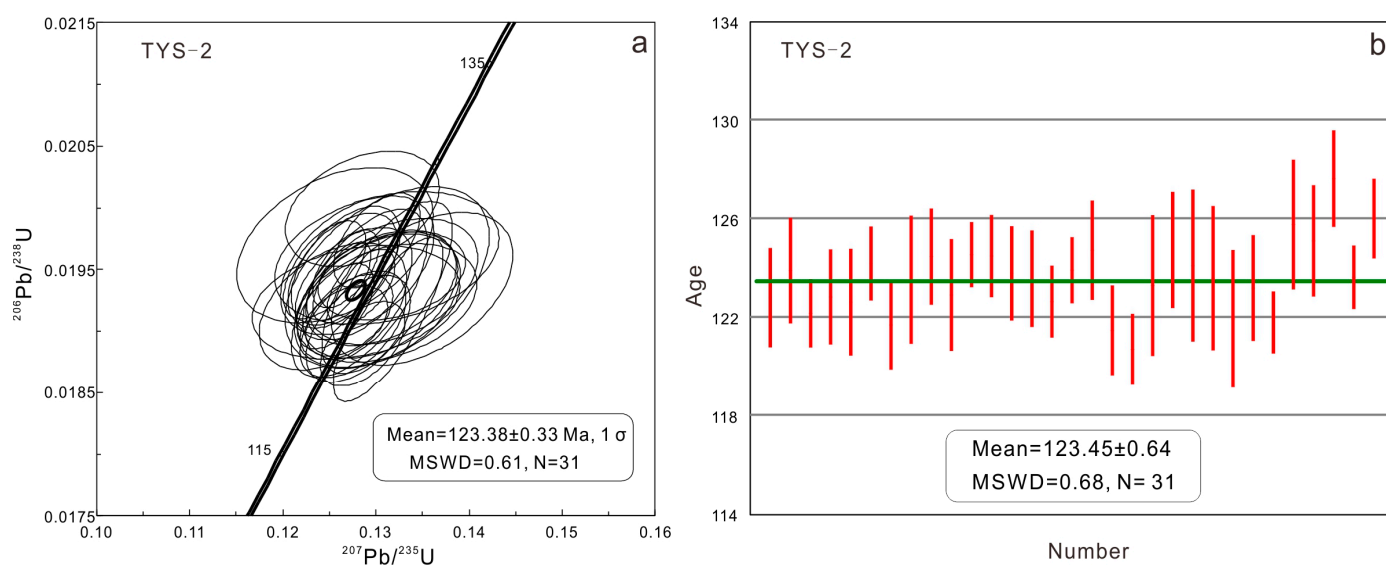


Figure 5. Zircon LA-ICP-MS U-Pb concordia diagrams for the samples TYS-2. (a) Concordia diagram for zircon U-Pb isotopic analyses; (b) Weighted-age plot of zircon $^{206}\text{Pb}/^{238}\text{U}$ ages.

5.3. Analysis

There are three stages of tin mineralization in the Tengchong–Lianghe area: the Early Cretaceous Tieyaoshan tin deposit was formed at 119–122 Ma; the Late Cretaceous Xiaolonghe tin deposit was formed at 71–74 Ma; and the Paleogene Lailishan tin deposit was formed at 47–52 Ma. The three stages of tin mineralization are genetically associated with the Qipanshi granite body (120–126 Ma), Xiaolonghe granite body (73 Ma) and Lailishan granite body (53 Ma) in their respective mining areas. The formation of the three granites and related tin mineralization is closely related to the Tethyan evolution. During the Jurassic period (200 Ma), seafloor spreading occurred along the Myitkyina line, forming the Middle Tethys Ocean Basin. During the Middle and Late Jurassic, the Middle Tethys Ocean subducted eastward, and the Middle Tethys Ocean closed [39–41]. The opening and

closing times of the Bangong Lake–Nujiang Ocean (Central Tethys Ocean) have always been controversial. However, the latest research shows that the Bangong Lake–Nujiang Ocean (Middle Tethys Ocean) was opened before the Early Cretaceous, and its subduction and subduction began in the Early Cretaceous and lasted until the end of the Late Early Cretaceous, with the ocean crust breaking off at 113 ± 5 Ma.

The Yarlung Zangbo Ocean opened during the Late Triassic, and the oceanic crust began to subduct during the Early Cretaceous. Currently, there is no reliable evidence to show that there are suture zones of the Middle Tethys and the New Tethys in the Tengchong and Baoshan blocks. The Sagaing suture zone and Naga maneper suture zone in Myanmar correspond to the Bangong–Nujiang Suture Zone and the Yarlung Zangbo River suture zone (New Tethys Ocean suture zone), respectively [42–44]. This indicates that the Middle Tethys Ocean subducted eastward on the west side of the Tengchong Block during the Jurassic and Early Cretaceous. A large number of Early Cretaceous granites (130–110 Ma) are distributed in the Tengchong block, Gaoligong Mountain and Bomi–Chayu areas. These granites exhibit geochemical characteristics similar to those of arc magma, indicating that their formation is related to subduction. The Tengchong block is closer to the Middle Tethys suture in tectonic position, and the subduction of the New Tethys oceanic crust had just begun in the Early Cretaceous. Therefore, the formation of the Early Cretaceous granite in the Tengchong block may be mainly related to the subduction of the Middle Tethys oceanic crust (Figures 6 and 7). Due to the influence of plate subduction orogeny, granite and related tin deposits of approximately 120 Ma were formed [45–47].

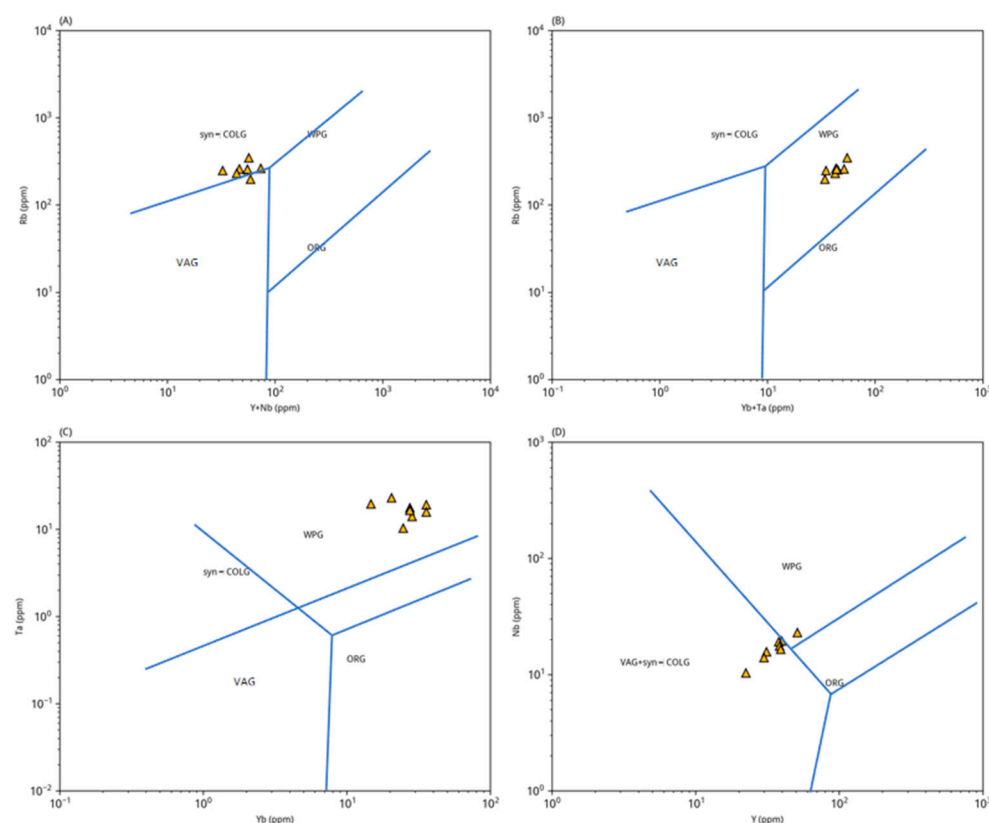


Figure 6. (A) Rb – (Y + Nb), (B) Rb – (Yb + Ta), (C) Ta – Yband and (D) Nb – Y discrimination diagrams of granites (Pearce J A, [47]). VAG—volcanic arc granite; syn-COLG—syn collisional granite; WPG—within plate granite; and ORG—ocean ridge granite.

To further constrain the petrogenesis and tectonic setting of the Tiewaoshan biotite granites, Whalen-type granite discrimination and Pearce tectonic discrimination diagrams were employed in this study. The Whalen diagrams show that all samples plot in the transi-

tion field between fractionated felsic granites (FG) and unfractionated M–I–S-type granites (OGT), with no data falling into the typical A-type granite domain. Although the granites exhibit relatively high $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ ratios, their total $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ contents and $10,000 \times \text{Ga}/\text{Al}$ values are generally low, lacking the characteristic high-field-strength-element enrichment of typical A-type granites. This suggests that the apparent high alkali-calcium ratios are not inherited from anorogenic A-type magmatism, but result from extensive fractional crystallization of minerals such as plagioclase, which leads to CaO depletion during magmatic evolution. Accordingly, the Tieyaoshan granites are dominantly highly fractionated I-type granites, rather than typical A-type granites. Compared with medium-grained porphyritic biotite granite, fine-grained biotite granite yields higher $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ values, implying more intense fractional-crystallization, and it is more closely associated with tin mineralization in this area [48].

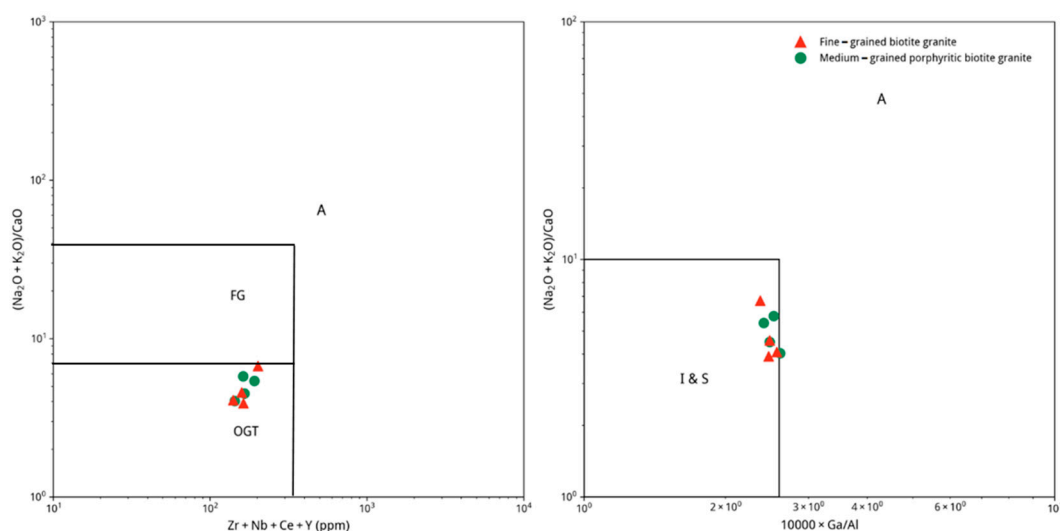


Figure 7. Plots of $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ versus $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ and $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ versus $10,000 \text{ Ga}/\text{Al}$ of the Tieyaoshan granite. The areas indicated in the above diagrams are from J.B. Whalen [49].

In the Pearce tectonic discrimination diagrams, the samples are mainly distributed in the transition zone between syn-collisional granites (syn-COLG) and within-plate granites (WPG), far from the ocean-ridge granite (ORG) field. It should be noted that the Pearce diagrams are established based on unfractionated granites; intense fractional crystallization can modify trace-element compositions. Therefore, the offset of samples toward the WPG field cannot be simply interpreted as an intraplate rift setting, and instead reflects the post-collisional intra-continental extensional regime. Collectively, regional orogeny triggered partial melting of crustal materials to generate crust-derived granitic magmas, which subsequently underwent intensive fractional crystallization under intra-continental extension. Such highly fractionated granites formed in a post-collisional extensional setting provided essential ore-forming materials and heat sources for the Tieyaoshan tin deposit.

6. Numerical Simulation of Elastoplastic Model

The geological model is converted into a mechanical model, and the elements of the mechanical model include the stress mode, the boundary properties, the mechanical parameters of the medium, and the deformation process. The orientation of the metallogenic principal stress is determined by using conjugate shear joints, magnetic fabrics and microstructures. The differential stress value of the metallogenic epoch is estimated by using the density of free dislocations of quartz crystals, the size of the conjugate shear angle and the size of dynamic recrystallization grain of quartz, and the spatial variation law of

differential stress value and magnetic fabric elements in shear zones is discussed [50–52]. Thirdly, the mechanical boundary conditions of the model and the physical properties of the medium were determined. Finally, the deformation process was simplified to an elastic process.

6.1. Model Establishment

6.1.1. Static Analysis and Transient Analysis

For an elastic model, if the load and boundary conditions are constant; it is a static (steady-state) analysis. If the stress field changes with the load, a transient analysis should be performed. The principle is briefly described as follows [53,54].

The overall equilibrium equation for Linear Stress Static Analysis is:

$$\{K\}\{u\} = \{F\} \text{ or } \{K\}\{u\} = \{F_a\} + \{F_r\} \quad (1)$$

where $\{K\}$ is the total rigidity matrix; $\{u\}$ is the node displacement vector; N is the number of elements; $\{F_r\}$ is the reaction load vector; and $\{F_a\}$ is the total applied load vector, defined as:

$$\{F^a\} = \{F^{nd}\} + \{F^{ac}\} + \sum_{m=1}^N \left(\{F_e^{th}\} + \{F_e^{Pr}\} \right) \quad (2)$$

where $\{F^{nd}\}$ is the load vector of the application node; $\{F^{ac}\} = -[M]\{a\}$ acceleration load vector; $[Me]$ is the element mass matrix; $\{a\}$ is the total acceleration vector; $\{F_e^{th}\}$ is the element heat load vector; and $\{F_e^{Pr}\}$ is the element pressure load vector.

The dynamic equilibrium equation of linear stress Transient Analysis is:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F_a\} \quad (3)$$

where $[M]$ is the structural mass matrix; $[C]$ is the structural inhibition matrix; $[K]$ is the structural sensibility matrix; $\{\ddot{u}\}$ is the nodal acceleration vector; $\{\dot{u}\}$ is the nodal velocity vector; $\{u\}$ is the nodal displacement vector; and $\{F_a\}$ is the applied load vector.

There are two program modules in ANSYS that can deal with Equation (3): the forward difference time integration method and the Newmark time integration method (including the modified HHT algorithm). The Newmark method for implicit transient analysis is mainly introduced here.

The Newmark method uses a finite difference extension of the time interval Δt :

$$\{\dot{u}_{n+1}\} = \{\dot{u}_n\} + [(1-\delta)\{\ddot{u}_n\} + \delta\{\ddot{u}_{n+1}\}]\Delta t \quad (4)$$

$$\{u_{n+1}\} = \{u_n\} + \{\dot{u}_n\}\Delta t + [(1/2-\alpha)\{\ddot{u}_n\} + \alpha\{\ddot{u}_{n+1}\}]\Delta t^2 \quad (5)$$

where, α and δ are Newmark integral parameters; $\Delta t = t_{n+1} - t_n$; $\{u_n\}$, $\{\dot{u}_n\}$, $\{\ddot{u}_n\}$ and $\{u_{n+1}\}$, $\{\dot{u}_{n+1}\}$, $\{\ddot{u}_{n+1}\}$ are the nodal displacement vector, nodal velocity vector and nodal acceleration vector at T_n and T_{n+1} , respectively.

Since the displacement $\{u_{n+1}\}$ is calculated initially, the governing Equation (3) at time t_{n+1} can be written as:

$$\{\ddot{u}_{n+1}\} + \{\dot{u}_{n+1}\} + [K]\{u_{n+1}\} = \{F_a\} \quad (6)$$

From (4) and (5),

$$\{\ddot{u}_{n+1}\} = a_0 \{\{u_{n+1}\} - \{u_n\}\} - a_2\{\dot{u}_n\} - a_3\{\ddot{u}_n\} \quad (7)$$

$$\{\dot{u}_{n+1}\} = \{\dot{u}_n\} + a_6 \{\ddot{u}_n\} + a_7 \{\ddot{u}_{n+1}\} \quad (8)$$

6.1.2. Thermal Stress Analysis

Owing to the mismatch of the coefficients of thermal expansion between different structures in contact with each other or different portions of the same structure, the degree of expansion or contraction of each other upon heating or cooling is inconsistent, resulting in the generation of thermal stress. The thermal stress is due to the temperature gradient and is set at each time interval ΔT_N ($n = 1, 2, \dots, N$), the increment of temperature is ΔT , the increment of displacement $\{\delta\}_n$, and the finite element equation of thermal stress is

$$[D]\{\Delta\delta\}_n = [F]\{\Delta T\}_n + \{G\} \quad (9)$$

where $\{\Delta T\}_n = \{T\}_n - \{T\}_{n-1}$, $[D] = \sum N_i = 1 [d]$, $[F] = \sum N_i = 1 [f]$, and $\{G\} = \sum N_i = 1 \{g\}$.

In this thermal-stress simulation under dual boundary conditions, thermal loads are applied based on tectonic-stress field simulation results. To account for the latent heat effect of magma, three widely used latent-heat treatment approaches in geomechanics are available: the temperature-recovery method, the equivalent heat-capacity method, and the enthalpy method. Although the temperature-recovery method demands substantial memory allocation during programming and generates numerous temporary files for breakpoint-restart functions, limiting its practical applicability, the enthalpy method introduces additional physical variables and increases computational complexity. Beyond computational efficiency considerations, the equivalent heat-capacity method is adopted herein primarily because it can realistically reproduce latent-heat release during magmatic cooling within the geological framework of this model.

6.2. Parameter Selection

The elastic modulus and Poisson's ratio, which characterize the elastic deformation of the simulated materials, are intrinsically controlled by the rock intrinsic physical properties of the rock. This numerical study focused on the stress-field evolution within limestone and fault zones prior to mineralization. Limestone in the study area exhibits weak fabric anisotropy, and the highly fractured fault zone is treated as a homogenized medium; accordingly, both are approximated as isotropic media. Rock fragmentation varies distinctly at different mineralization stages, leading to divergent rock-mechanical parameters. Based on the published rock-mechanical datasets, the physical parameters adopted in this calculation are listed in Table 5.

Table 5. Main rock mechanics parameters.

Lithology	Density (g/cm ³)	Modulus of Elasticity ($\times 10^4$ MPa)	Poisson's Ratio	Thermal Conductivity {W/(M·°C)}	Coefficient of Thermal Expansion (°C ^{−1})	Specific Heat Capacity (J/°C)
Large fracture broken rock	2.7	17,000	0.3	2.75	1.00×10^{-5}	1057
Small Fault Gouge	2.67	25,000	0.26	2.5	9.50×10^{-6}	1057
Limestone in the mining area	2.7	37,000	0.232	2.17	7.00×10^{-6}	1000

Setting real or near-real boundaries is the key to realizing the simulation of the stress field. In order to make the simulation of boundary conditions with the time of mineralization (Figure 8).

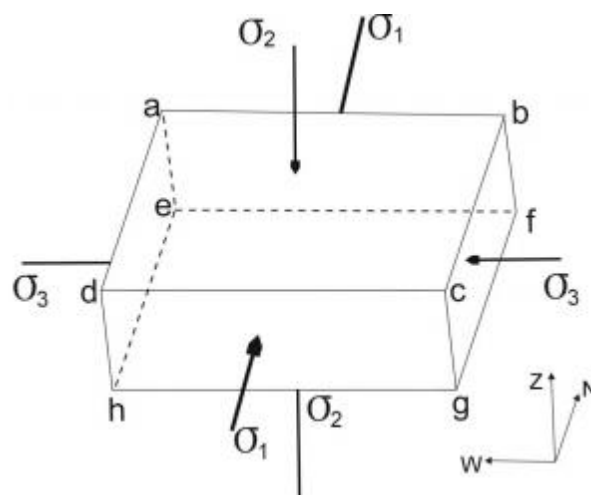


Figure 8. Mineralization period, north–south compression.

Consistent with the actual situation, the determination of the stress and boundary conditions of the model mainly considers the following:

1. Based on the field structural analysis and the regional tectonic evolution background, it is inferred that the principal stress orientation in the early stage of mineralization was east–west, while the main ore-forming period was dominated by north–south compression, which then turned to east–west compression in the later stage of mineralization.
2. According to the differential stress estimated by a quartz-free dislocation-density piezometer and previous regional data, the differential stress was relatively high during pre-mineralization. In this simulation, the pre-mineralization differential stress was assigned to 180 MPa, which decreased to 80 MPa in the main mineralization period.
3. For profile stress-field simulation, the burial thickness of the overlying strata during mineralization must be assumed. An overlying-strata thickness of 1.5 km was adopted in this simulation.
4. Except for the stressed boundary, the other boundaries were fixed.
5. In the thermal stress analysis, the temperature load in the thermal boundary condition was applied to the nodes. It is assumed that the limestone temperature is about 50 °C, and the temperature of 600 °C is loaded on all nodes of the fault unit during the mineralization period.

The process of unit division follows the following principles:

1. In the areas where it is estimated in advance that the stress may be concentrated or the stress changes greatly, such as the vicinity of the structural fracture development zone and the lithological contact zone, the unit division should be as fine and dense as possible.
2. In the key evaluation area, the grid units are added.
3. Equilateral triangles or quadrilaterals should be used instead of obtuse triangles and quadrilaterals to avoid large calculation errors. Triangles and quadrilaterals should be evenly distributed as far as possible.
4. Try to put the nodes and edges of the unit on the geological boundary.

6.3. Result Analysis

On the basis of a series of simulations, a comprehensive comparative analysis of the simulation results is carried out, including analyzing the abnormal parts in each simulation, especially the abnormal parts of special structures. According to the mechanics of materials,

the functional relationship between strain energy and stress of an object under stress can be expressed as follows:

$$U = 1/2 (\sigma_x \epsilon_x + \sigma_y \epsilon_y + \sigma_z \epsilon_z + \tau_{xy} \gamma_{xy} + \tau_{yz} \gamma_{yz} + \tau_{xz} \gamma_{xz}) \quad (U \text{ is the strain energy}) \quad (10)$$

According to the generalized Hooke's law of stress and strain of an elastic body, the Formula (11) can be transformed into:

$$U = 1/2E \times [(\sigma_1 + \sigma_2 + \sigma_3) - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)] \quad (11)$$

where E is the modulus of elasticity and μ is the Poisson's ratio.

Physically, the strain energy can be decomposed into the strain energy of shape change U_d and the strain energy of volume change U_Δ , and the change of strain energy U_d directly controls the movement of metallogenic substances.

$$U_d = U - U_\Delta \quad (12)$$

where $U_\Delta = (1 - 2\mu)/6E \times (\sigma_1 + \sigma_2 + \sigma_3)^2$.

E is the elastic modulus, μ is the Poisson's ratio, and σ_1 , σ_2 , and σ_3 are the maximum, intermediate, and minimum principal stresses, respectively.

It can be observed that U_d is closely related to the average stress $[\sigma_0 = (\sigma_1 + \sigma_2 + \sigma_3)/3]$. The smaller σ_0 is, the smaller U_d is, and conversely, the larger U_d is. The high gradient area of the strain energy is the favorable structural position for mineralization. Therefore, an area with a low average stress value is a favorable metallogenic position.

Mineral fluid migrates under the action of the tectonic stress field, and the migration of fluid is expressed as the migration potential. The mathematical analytical formula for the fluid migration potential can be simply expressed as:

$$\Phi_0 = gz + p/\rho_0 \quad (13)$$

where Φ_0 is the fluid potential, G is the acceleration of gravity, Z is the altitude, p is the fluid pressure (the difference between the total stress and the effective pore pressure), and ρ is the fluid density. When a porous medium containing fluid is subjected to an external force, the total stress in the rock mass is formed by the skeleton and pore fluid. Two cases were considered. In the case of drainage, the medium is squeezed by tectonic forces, the framework is deformed, the porosity is changed, and the pore fluid is squeezed out relative to the framework. It flows to areas with low tectonic pressure and good permeability conditions, where the skeleton bears relatively more force. In the case of no drainage, the pore fluid is sealed in the rock mass, so that the hydraulic pressure increases, and the tectonic stress will be mainly borne by the pore fluid. Since the liquid cannot bear the shear stress, the average stress in solid mechanics can be used to evaluate the pore fluid pressure caused by tectonic activity. For a saturated medium, the average stress is approximately equal to that of the fluid pressure. When the average stress is higher, the fluid potential is also higher. The migration law of ore fluid shows that it flows from the high value area of migration potential to the low value area, so the low value area of average stress is generally the center of fluid accumulation.

Fluid potential is correlated with the rate-of-change of tectonic stress; rapid variations in tectonic stress favor fluid migration, and zones of sharp tectonic-stress fluctuation constitute favorable metallogenic sites. Therefore, the spatial distribution of the mean stress and zones of abrupt stress variation are key targets for analysis. Comparing the simulation results derived from different boundary conditions and geological models helps constrain how the regional background controls the tectonic stress field patterns. Cross-

sections along multiple orientations were extracted to characterize the internal architecture of the three-dimensional model, cross-sections along multiple orientations were extracted. We compare model anomalies obtained under purely mechanical boundary conditions versus coupled stress-thermal boundary conditions, and we further examine stress-field architectures corresponding to varied principal-stress orientations. Based on the above analyses, the dominant controls on the stress-field configuration and their metallogenic contributions are summarized.

6.3.1. Simulation 1: EW 200 MPa, NS 20 MPa, Up and Down 30 MPa

The boundary conditions adopted in this simulation are as follows: an east–west principal compressive stress of 200 MPa, a north–south compressive stress of 20 MPa, and 30 MPa stress applied to the top and bottom model boundaries.

Simulation results indicate that, under east–west principal compression during the early mineralization stage, the fracture-fault zone corresponds to a compressive fracture surface characterized by low-stress and high-strain anomalies. The fault zone represents a low-value domain of maximum principal stress, whereas a strip-shaped high-maximum-principal-stress zone parallel to the fault develops on its western side. Results for intermediate principal stress, minimum principal stress and their corresponding principal-strain fields reveal prominent stress anomalies around the deep segments of the fault zone (Figure 9).

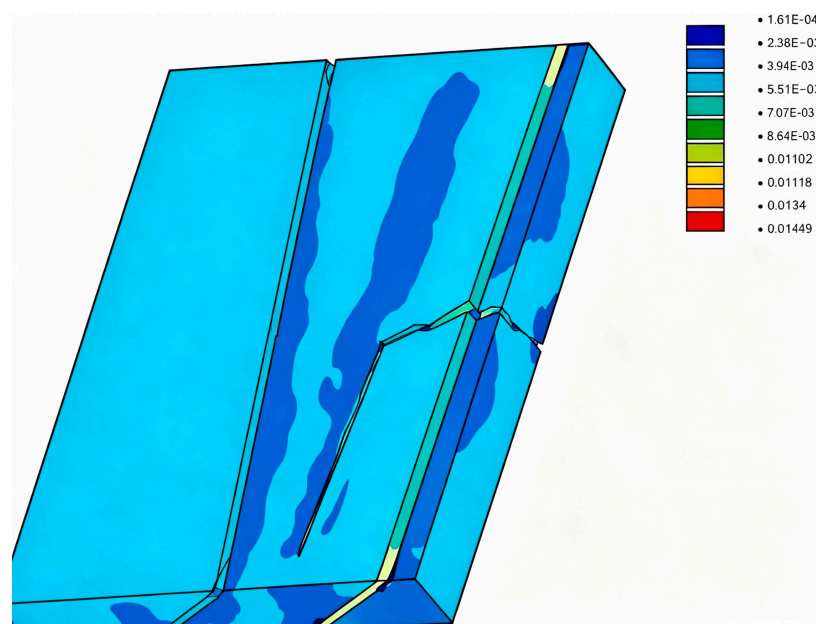


Figure 9. Tectonic stress field simulation: intermediate principal stress.

6.3.2. Simulation 2: Principal Stress in NS Direction: 100 MPa, in EW Direction: 20 MPa, Up and Down: 30 MPa

Simulation results indicate that the fracture zone corresponds to a region of low maximum principal stress and high maximum principal strain under the north–south principal compressive stress during the mineralization period. Additionally, the profile reveals that the area near the fault zone exhibits a high stress anomaly with maximum principal stress increasing from top to bottom. In contrast to the east–west principal compressive stress, under north–south principal compressive stress, the stress anomaly area near the latter fault is significantly larger than that near the former, regardless of whether it is at the top or bottom. The average principal stress diagram shows that the fracture and its vicinity constitute a low stress area, with the stress value at the bottom

fracture being considerably higher than that at the shallow part. Based on the fluid potential formula, it can be inferred that under north–south compression, the nearly N–S-trending fault zone constitutes an extensional domain (Figure 10). According to metallogenic theory, when ore-forming fluids are available, the fault and its adjacent zones represent favorable metallogenic sites. Fluids migrate upwards from deeper levels, and low-stress domains along faults and their surroundings act as favorable sites for fluid convergence.

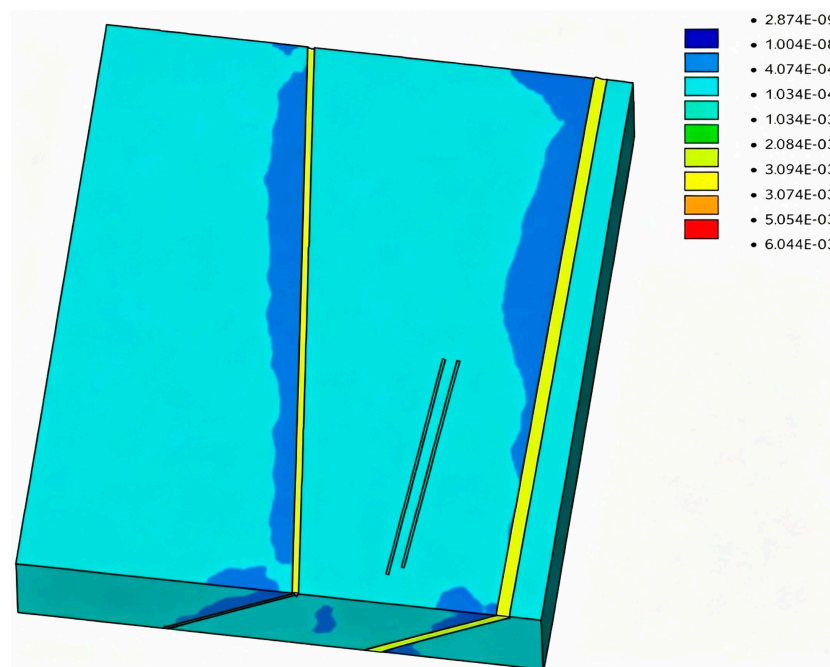


Figure 10. Intermediate principal strain.

7. Numerical Simulation of Tectonic Stress Field in Tieyaoshan Mining Area

7.1. Model Building

Different rock units within the tectonic-stress field exhibit distinct mechanical parameters, hence the geological-body model in this study adopts the elastic material assumption. Rock elements obey the Mohr–Coulomb failure criterion, faults are set as plane contact zones, and rock masses are treated as homogeneous elastic materials. A reasonable parameter selection directly controls the simulation reliability. In this work, triaxial and uniaxial compression laboratory tests were performed on field-collected outcrop rock samples of major lithological units from the mining area. For some special lithological units (altered mineralized rocks, fault zones and local interbeds) where high-quality intact core samples are difficult to obtain, mechanical parameters are comprehensively determined by combining test results with published geological and exploration data of the mining area. The final physical and mechanical parameters for each rock unit are listed in Table 6. It should be noted that Table 6 covers all lithological units used in the numerical model, including local intercalated lithologies, intrusive rocks and alteration-mineralization lithofacies besides the Middle Carboniferous Siguangping Formation and Upper Carboniferous Kongshuhe Formation described in Section 3.

Table 6. Mechanical parameter table of rock static uniaxial compression.

Rock Character	Compressive Strength (Mpa)	Elastic Modulus (Gpa)
Slate	28.21	11.57
Sandstone	62.54	22.75
Biotite granite	95.17	38.65
Granite	123.03	64.52
Skarn	193.17	25.23
Dolomite	82.69	63.13
Mineralized marble	173.85	52.96
Diabase	171.69	87.42
Sandstone	165.84	24.16
Mudstone	33.44	18.12
Sulfide ore	126.51	73.92
Dolomite limestone	55.61	32.26
Fault	/	14.74

In the plane discretization of two-dimensional geological body, the combination of triangular and quadrilateral elements is usually used to make the internal angle of the element less than 120° obtuse angle and reduce the calculation error. In areas where the estimated strain and stress change greatly or need to be refined, the design method of tight mesh is adopted, while the division of secondary elements is relatively sparse. Since the rock strength of the fault is lower than that of the surrounding rock, the fault should be given special rock physical parameters and represented by narrow strips. The Tieyaoshan field in the study area is affected by the tectonic activities of different periods and different intensities, and the structural form is relatively complex, so it is relatively difficult to automatically grid the model. With the powerful drawing function of ANSYS finite element software, the study area is automatically meshed by computer, and some manual control methods are used to reduce human error and refine the stress state of key areas. In this simulation, the geological model was meshed by combining computer and artificial methods. In this study, the tectonic differential stress value in the study area is calculated based on the measured conjugate plane angle of the conjugate fracture and the initial shear strength and compressive strength of the rock. The formula for calculating the limit stress before formation using the rock physical property constant and the angle between the X-shaped conjugate surface is as follows:

$$\begin{aligned}
 \sigma_1 &= \frac{\sigma_c(\sigma_c - 4k)}{4(\sigma_c - 2k)} + \frac{\sigma_c - 2k}{2} \left(\frac{1}{\cos \theta} - \frac{1}{2\cos^2 \theta} \right) \\
 \sigma_3 &= \frac{\sigma_c(\sigma_c - 4k)}{4(\sigma_c - 2k)} - \frac{\sigma_c - 2k}{2} \left(\frac{1}{\cos \theta} + \frac{1}{2\cos^2 \theta} \right) \\
 \tau_m &= \frac{1}{2}(\sigma_1 - \sigma_3)
 \end{aligned} \tag{14}$$

σ_1 is the maximum principal compressive stress,

σ_3 is the minimum principal compressive stress,

σ_c is the compressive strength limit of rock,

K is the initial shear strength of rock,

θ is the included angle of the type conjugate surface.

τ_m is rock shear strength.

7.2. Analysis and Discussion of Simulation Results

According to geological data from the mining area, the compressive strength limit of dolomite in this region is approximately 100 MPa, and the initial shear strength of intact rock is 32 MPa. The stress values for each evolutionary stage were calculated using the above-mentioned failure criterion. At approximately 120 m depth, the magnitude of differential stress reaches its maximum value (–100 MPa), with the principal stress oriented nearly north–south, which is broadly consistent with regional structural–geochemical observations. Under intense compressive stress, rock failure generates faults, joints and other fracture structures. During mineralization, compressive and shear stresses tend to concentrate along both sides of the northeast-trending fault zones. Tectonic domains are partitioned by low-stress zones, and the overall stress distribution exhibits a striped pattern that matches the spatial distribution of major tectonic units within the study area. This pattern is consistent with surface geological evidence showing fractured strata adjacent to faults and local compressional-tensional deformation characteristics. The maximum principal stress was preferentially concentrated on both sides of the Lutangba fault. Differences in stress magnitude produce heterogeneous stratigraphic deformation, where high-stress domains correspond to relatively intense rock deformation.

From the perspective of regional metallogenic setting, the nearly north–south oriented compressive stress field may drive large-scale fluid migration from deep levels toward shallow crustal levels. In the early mineralization stage, deep-sourced fluids can provide material and heat for shallow fluid systems. Within fault damage zones, interactions between ore-forming fluids and wall rocks trigger complex metasomatic reactions, facilitating the precipitation of metals and forming polymetallic mineralization. According to our numerical simulation results, the maximum principal stress concentrated along both sides of the major faults. Under regional tectonic stress, fractures preferentially re-activate within pre-existing fault zones; rock strength in these reactivated fault domains is markedly lower than that of surrounding intact rock, forming favourable low-pressure pathways for fluid flow. With increasing depth within a certain interval, both the temperature and pressure rise accordingly. Consequently, deep strata are more susceptible to fracturing, and deep-sourced fluids preferentially migrate in an upward direction. Under ongoing tectonic loading, fractures propagate toward shallower depths. However, stress conditions at shallow depths are insufficient to produce widespread new fracturing. Once deep high-pressure fluids migrate along fault zones, the enhanced fluid pressure further increases the fracture permeability. Fluids migrate along major fault zones and branch into secondary faults, where metals precipitate and accumulate to form orebodies.

Taken together, comparative analysis between simulated stress-field patterns and the distribution of known orebodies indicates that ore-body distribution is closely controlled by regional tectonism. Mineralization preferentially occurs within domains characterized by high maximum principal-stress magnitudes. This finding provides useful guidance for further mineral-prospecting work in this region.

7.3. Tectonic–Magmatic–Metallogenic Mechanism Constrained by Numerical Simulation

Tectonic stress-field switching, superimposition, and reactivation of pre-existing structures, along with hydrothermal fluid migration, are the primary tectonic controls on hydrothermal mineralization. The transformation of regional tectonic systems and crust–mantle superimposed metallogenic effects form the fundamental geodynamic background for Yanshanian mineralization. Generally, ore-forming fluids can maintain relatively stable physicochemical properties during regional migration; however, abrupt tectonic-stress

fluctuations may induce rock dilation, fluid immiscibility, decompression boiling, fluid mixing, and water-rock metasomatism. These rapid physicochemical changes in fluids directly trigger large-scale metal precipitation and enrichment. Unlike the Himalayan tectonic overprinting prevalent in western Yunnan, magmatic-hydrothermal mineralization in the study area occurred in the Early Cretaceous (approximately 120 Ma), influenced by the geodynamic background of Tethys oceanic subduction and intracontinental tectonic transition. During the Early Cretaceous, the study area experienced nearly north–south compression, which established the regional east–west-trending structural framework and controlled early magmatic emplacement and preliminary accumulation of ore-forming materials. Driven by subduction-related plate motion, the regional stress field gradually evolved toward NW–SE compression, forming the dominant NE-trending tectonic belt closely associated with the main mineralization episode. Multi-phase stress-field transitions from E–W to N–S compression facilitated the reactivation of deep basement faults, crustal heat-flow anomalies, and intensive magmatic ascent. The ascending acidic magmatic–hydrothermal fluids provided essential material and heat sources for tin-polymetallic mineralization. Stress-field transformation further altered the mechanical state of regional structural systems. Ductile shear zones were converted into brittle–ductile transition zones, and fault mechanical behavior shifted from compression–shear to tension–shear dominance. Transient dilational spaces generated by stress relaxation create a vacuum-suction effect, promoting the large-scale infiltration and migration of ore-bearing hydrothermal fluids. Intensive water–rock interactions led to the differentiation of tin, copper, lead, zinc, and silver, as well as local supergene enrichment, ultimately forming major ore-concentrated zones. Multidirectional superimposed tectonic stress results in heterogeneous stress distribution within fault belts. Pre-existing faults correspond to mechanically weak zones of rock masses, where deformation and fluid activity are most intense. Competent strata bear the principal tectonic stress, whereas weak interlayers experience concentrated shear deformation and provide favorable spaces for fluid migration and metal precipitation.

Our numerical simulation results substantiate the tectonically controlled metallogenic mechanisms. In the study area, widespread faults, interlayer fractures, and joint systems serve as primary conduits for the migration of hydrothermal fluids and as spaces for ore hosting. Multistage tectonic superimposition leads to significant rock fragmentation at fault intersections, which are optimal sites for large-scale orebody formation. Extensive wall rock alterations, such as limonitization and hematitization, occur along zones dense with fractures, and vein-type orebodies are strictly constrained by fault structures. In the western mining area, concentrated shear stress facilitates the formation of high-permeability dilational pore-fracture networks. When shear stress surpasses the rock's shear strength, fractured dilational zones are continuously formed, providing favorable pathways for the migration of ore-bearing fluids. Late-stage fluid accumulation and volume expansion further increase fracture apertures, transitioning the fluid system from a migration-dominated to a static precipitation-dominated regime, resulting in the formation of concealed tin-polymetallic orebodies. Consequently, shear-stress-concentrated fracture zones with high porosity and permeability are prioritized as metallogenic prospective targets for prospecting prediction.

8. Conclusions

1. Zircon U–Pb geochronology and whole-rock geochemical results indicate that the ore-bearing biotite granite in the Tieyaoshan tin-polymetallic deposit formed at ~120 Ma during the Early Cretaceous. The granitoids exhibit high silica and alkali-rich signatures, with typical enrichment of large-ion lithophile elements and depletion of

- high-field-strength elements, recording the regional magmatic response to Middle Tethys oceanic subduction within the Tengchong block.
2. The Early Cretaceous tectonic stress field underwent a critical transformation from near north–south compression to NW–SE compression. Such multi-stage stress switching controlled the formation of E–W-trending basement frameworks and NE-trending ore-controlling structures. Stress-induced basement fault reactivation and acidic magmatic ascent provide essential dynamic and material conditions for large-scale tin-polymetallic mineralization.
 3. Tectonic stress numerical simulations demonstrate that shear stress concentration zones and low-stress anomalous domains constitute the predominant metallogenic favorable spaces. Fault fractured zones and structural intersections produce dilational and high-permeability pore-fracture systems, which dominate hydrothermal fluid migration, metal precipitation and vein-type/concealed orebody localization.
 4. Integrating field geological observations, geochemical constraints and stress-field simulation results, the NE-trending fault belts and western shear stress concentration areas are the optimal prospecting targets. This study clarifies the Early Cretaceous tectonic–magmatic–hydrothermal coupling metallogenic mechanism in the Tengchong area, providing reliable theoretical guidance for future deep and peripheral ore prospecting in the Tieyaoshan mining district.

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

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