

Article

Geochronology and Geochemistry of the Galale Cu–Au Deposit in the Western Segment of the Bangong–Nujiang Suture Zone: Implications for Molybdenum Potential

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Abstract

The Galale Cu–Au deposit lies on the northern margin of the western Gangdese metallogenic belt, near the western edge of the Gangdese arc within the Bangong–Nujiang suture zone. Unlike the well-studied Miocene Cu belt in southern Gangdese, this region remains insufficiently investigated, particularly in terms of geochemical characterization, leading to an ambiguous metallogenic model and a debated tectonic setting—specifically, the unresolved issue of subduction polarity across the Bangong–Nujiang suture. This tectonic ambiguity has important implications for understanding magma sources, metal transport pathways, and, consequently, for guiding mineral exploration strategies in the area. To address this, we conducted zircon U–Pb dating on the ore-related quartz diorite and granodiorite, yielding crystallization ages of 84.05 ± 0.34 Ma and 77.20 ± 0.69 Ma, respectively. Integrated with previous data, these results constrain mineralization to 83–89 Ma, which includes both skarn-type Cu–polymetallic and porphyry-type Cu mineralization. Regional comparisons support a tectonic model involving slab rollback and southward subduction of the Bangong–Nujiang oceanic lithosphere. Geochemical analyses of quartz diorite, granodiorite, and monzonitic granite show high-K calc-alkaline, peraluminous I-type affinities, with enrichment in LREEs and LILEs, and depletion in HREEs and HFSEs. Notably, the monzonitic granite is marked by high SiO_2 , Sr/Y, and Rb/Sr ratios, low Zr/Hf, strong LREE enrichment, weak Eu anomalies, and pronounced Nb–Ta depletion, indicating high oxygen fugacity and favorable conditions for Mo mineralization. The deposit formed through tectono-magmatic processes related to the closure of the Bangong–Nujiang Neo-Tethys Ocean. Subduction and subsequent lithospheric delamination induced partial melting of mantle and crustal sources, generating quartz diorite and granodiorite intrusions. Magmatic fluids interacted with carbonate wall rocks to form skarn assemblages, concentrating ore metals along structures. The mineralization formed within the contact zones between intrusions and surrounding country rocks. Late-stage granite porphyry intrusions (~77 Ma), inferred from major, trace, and rare earth element compositions to have the highest Mo potential, may represent an extension of earlier skarn mineralization in the area (83–89 Ma). This study presents the first comprehensive geochemical dataset for the Galale deposit, refines its metallogenic model, and identifies key geochemical indicators (e.g., Sr, Y, Nb, Rb, Zr, Hf) for Mo exploration.



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Keywords: Galale Cu–Au deposit; molybdenum; geochemistry; genetic model; Bangong–Nujiang Suture Zone

1. Introduction

The Bangong–Nujiang Suture Zone delineates the boundary between the Gangdese and Qiangtang Blocks [1] and hosts a significant Cu–Au Metallogenic Belt. Despite a recent increase in identified resources within the Duolong ore concentration area [2] and evidence of active magmatism, the number of discovered ore deposits remains relatively limited. Consequently, it is critical to identify ore-forming intrusions and differentiate them from other intrusions. Furthermore, the metallogenic belt is far less studied compared to the Cu–polymetallic metallogenic belt of southern Gangdese, and its geotectonic framework remains debated. Two main points of contention persist: (1) timing of suture closure. One perspective suggests the suture zone closed during the Late Jurassic to Early Cretaceous [3], while another posits a later closure, occurring after the closure of the central-eastern segment [4,5], potentially extending into the early Late Cretaceous [6]. (2) Subduction polarity: Several models have been proposed, including unidirectional subduction, bidirectional subduction [7,8], and subduction polarity reversal [9]. These tectonic scenarios control the spatial distribution of magmatism, the nature of magma sources, and the pathways for ore-forming fluids, thereby exerting a primary control on mineralization patterns and exploration potential. Therefore, geochronological and geochemical studies of significant ore deposits are essential to resolve the subduction–closure history of the Bangong–Nujiang Suture Zone and to provide a more reliable framework for mineral exploration.

The Galale Cu–Au deposit, a skarn-type deposit located in the western segment of the Bangong–Nujiang metallogenic belt, contains over 1.5 Mt of copper resources [10]. Previous studies have linked its mineralization to granodiorite intrusions of Late Yanshanian age [11], with research focused on geochronology [12] and geochemistry [13]. Additionally, investigations into the metallogenic age [14] and alteration-mineralization characteristics have been progressively refined [15,16]. However, due to the number of intrusive units in the Galale deposit, the available geochemical studies on most of these intrusions remain insufficient to constrain relationships to mineralization. This study utilizes LA-ICP-MS zircon U–Pb dating and whole-rock analyses of major, trace, and rare earth elements to conduct geochronological and geochemical investigations. By integrating previous research, this study aims to refine the genetic model of the deposit and explore its magmatism-mineralization processes.

2. Geological Setting

The Galale Cu–Au deposit is located on the northern margin of the western segment of the Gangdese metallogenic belt (Figure 1a), at the western edge of the Gangdese arc in the Bangong–Nujiang suture zone and adjacent to the Shiquanhe ophiolite mélange belt to the north (Figure 1b). Intense tectonic activity has provided abundant sources of mineralizing materials, facilitated pathways for magmatic emplacement, and created space for the accumulation of ore bodies. Regionally, the identified intrusive rocks can be divided into two primary age groups: 75–90 Ma and 110–160 Ma [12,14,17]. Furthermore, the deposit is situated within a region extensively covered by Carboniferous to Cretaceous carbonate strata, which serve as host rocks for skarn-type mineralization. Within the mining district, skarn-type Cu–Au ore bodies have formed through contact metasomatism between Yanshanian intermediate-acid intrusions and Cretaceous carbonate formations, representing a key mineralization feature of the Galale deposit. Investigation of the Galale deposit has significant implications for regional mineral exploration [11].

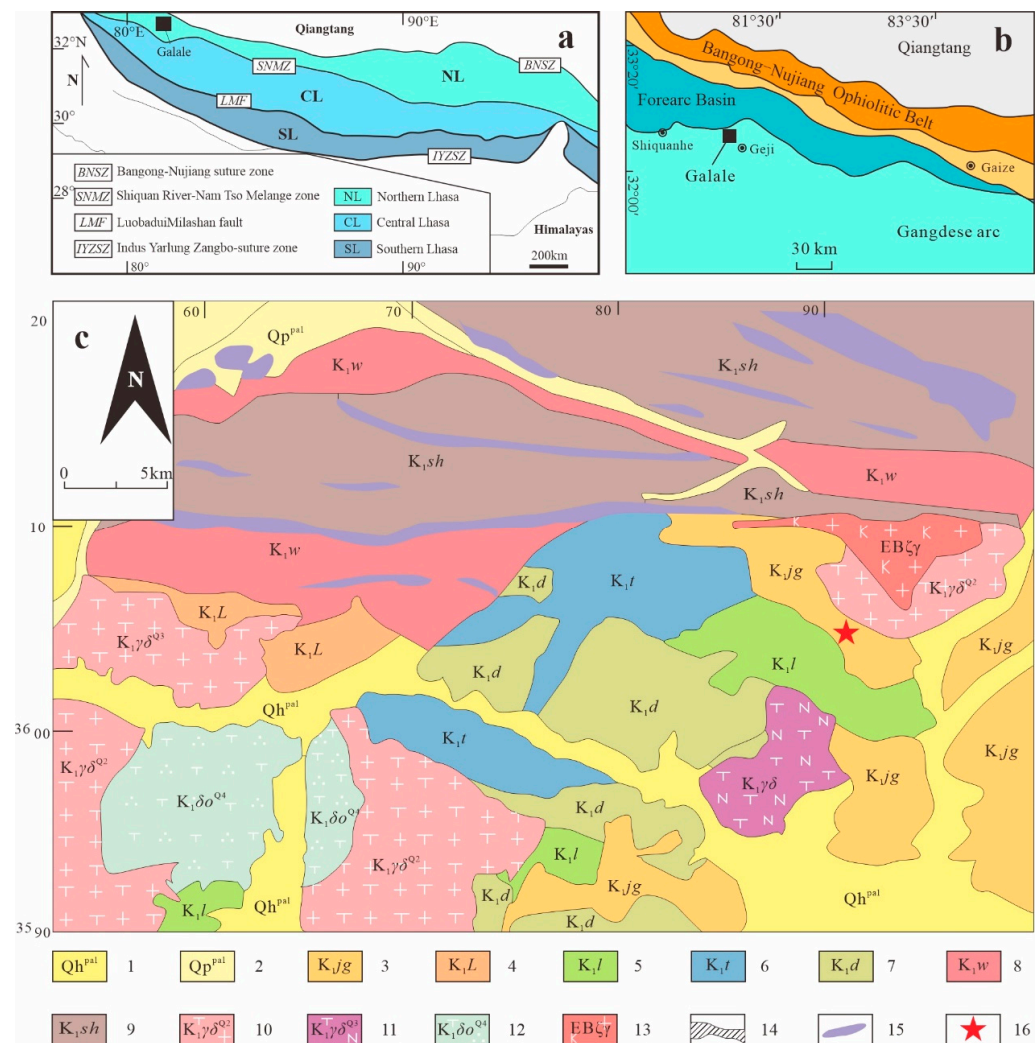


Figure 1. (a) Tectonic boundaries and major tectonostratigraphic units of the Tibetan Plateau [18], (b) location of the Galale study area and distribution of main continental volcanic rocks within the western Gangdese mineralization belt [12,19] and (c) simplified regional geology [20]. 1—Holocene Series Glutenite, 2—Pleistocene Series Alluvial Terrace, 3—Jiega Formation, 4—Langshan Formation, 5—Langjiu Formation, 6—Tuocheng Formation, 7—Duoai Formation, 8—Wangshi Formation, 9—Shiquanhe ophiolitic mélange, 10—Granodiorite, 11—Moyite, 12—Quartz diorite, 13—Granite, 14—Suture Zone, 15—Ophiolites, 16—Galale depos.

The Cretaceous strata represent the most extensively distributed stratigraphic unit in the region, covering approximately 80% of the total area. The primary formations include Shiquanhe Ophiolitic Mélange, the Jiega Formation, the Langshan Formation, the Wangshi Formation, and the Zenong Group, which comprises the Duoai Formation (K_1d), the Tuocheng Formation (K_1t), and the Langjiu Formation (K_1l). Furthermore, the Shiquanhe ophiolitic mélange (K_1sh), Wumolong Formation (K_1w), and Langshan Formation (K_1L) are present in the Galale deposit (Figure 1c). Among these, the Lower Cretaceous Langjiu Formation (K_1l) and Jiega Formation (K_{1jg}) constitute the most significant stratigraphic units in the study area [20].

3. Ore Deposit Geology

The Galale deposit comprises three principal stratigraphic units: the Langjiu Formation (K_1l), the Jiega Formation (K_1jg), and Quaternary (Q). The Langjiu Formation, primarily distributed in the eastern part of the Galale deposit (~20%). It is divided into three distinct

lithological members: the lower unit comprises interbedded sandstone, siltstone, and mudstone (180 m); the middle unit consists of feldspathic quartz sandstone interbedded with siltstone (100 m); and the upper unit is composed of volcaniclastic rocks and tuff lava flows (200–300 m). The Jiega Formation, the principal ore-bearing stratum (~30%), is in angular unconformity with the Langjiu Formation. It is subdivided into three units: the lower unit consists of limestone (80–100 m); the middle unit comprises dolomite interbedded with sandstone (100–200 m); and the upper unit consists of dolomite (150–200 m). The Quaternary (~20%) units mainly distributed on the eastern side of the area and consist of unconsolidated alluvial and diluvial gravelly silt.

The fault structures in the Galale deposit are primarily strike NE and NEE, with secondary NW and N-S minor faults. Among these, the F1, F2, and F4 faults are closely associated with mineralization. The F2 fault is a NEE-trending thrust fault (~2 km), accompanied by granodiorite intrusions and silicification. The F4 fault is a NE-trending structure (~4 km), with a breccia zone 20–30 m wide, characterized by pervasive silicification and hematitization. The primary ore-bearing structures consist of original faults and fractures along the contact zone between granodiorite and marble (Figure 2b).

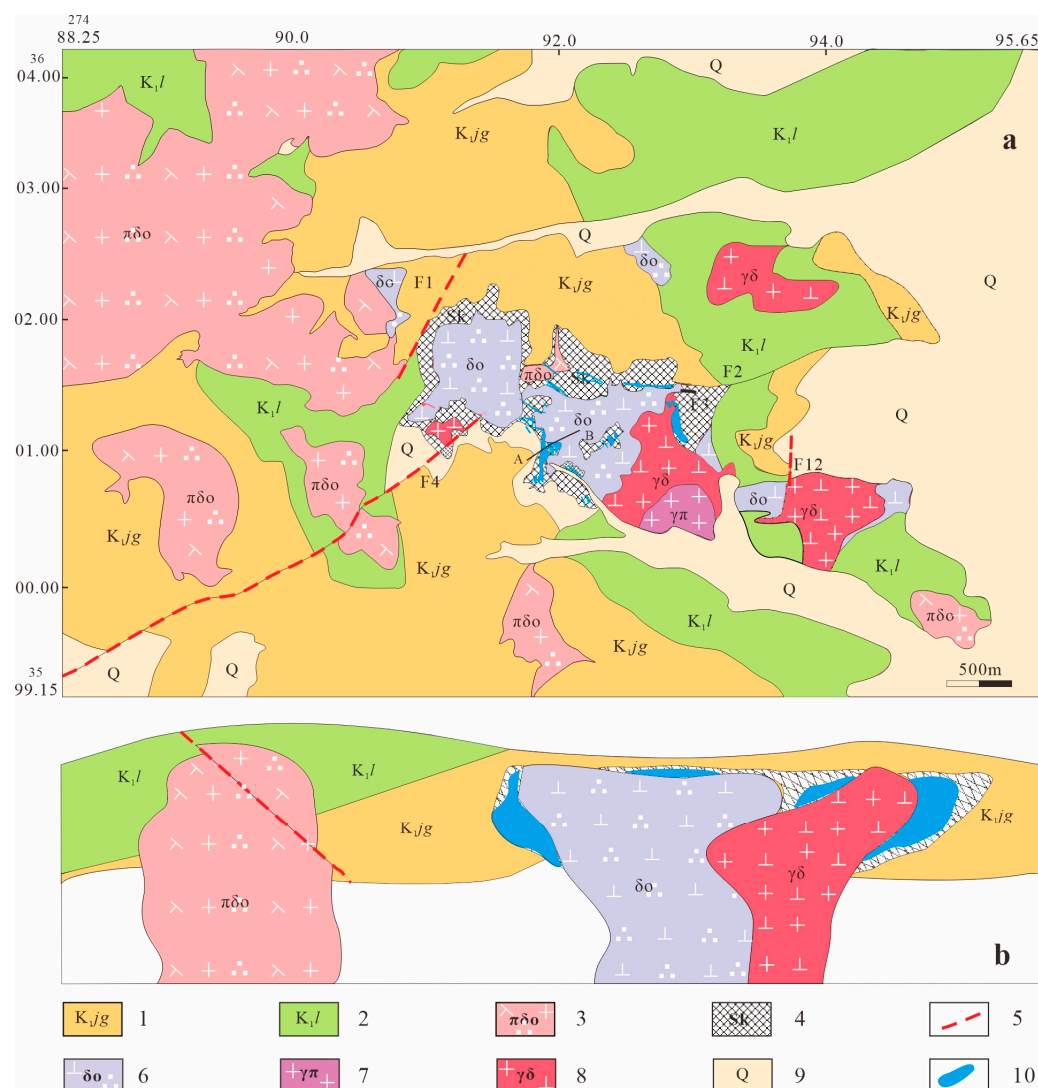


Figure 2. (a) Simplified geological map of the Galale deposit [10] and (b) cross-sections along A-B line. 1—Jiega Formation, 2—Langjiu Formation, 3—Porphyritic quartz diorite, 4—Skarn, 5—Fault, 6—Quartz diorite, 7—Monzonitic granite, 8—Granodiorite, 9—Quaternary, 10—Ore body.

The intrusive rocks comprise porphyritic quartz diorite, quartz diorite, granodiorite, and monzonitic granite (Figure 2a). Among these, quartz diorite and granodiorite are the ore-bearing intrusive rocks (Figure 2b). The quartz diorite ($\delta\sigma$) is extensively exposed in the central region of Galale deposit, where it intrudes the Jiege and Langjiu formations as stocks and dikes. The granodiorite ($\gamma\delta$) intrudes the Jiege and Langjiu formations as well as the quartz diorite, and further crosscuts quartz veins within the latter, thereby exhibiting a close spatial correlation with mineralization. The monzonitic granite ($\gamma\pi$) has a relatively limited outcrop area, occurring as small stocks, apophyses, and veins that intrude all geological units, including skarn zones and ore bodies.

The Galale deposit in Tibet is a representative skarn–porphyry copper–polymetallic system. Shallow skarn-type mineralization (Cu–Au) is developed along the contact between granodiorite and dolomite, whereas deeper porphyry-type mineralization (Cu–Mo) occurs within the intrusive body. Skarn mineralization was mainly controlled by carbonate metasomatism, while porphyry mineralization resulted from magmatic–hydrothermal differentiation [10,13]. The KT2 ore body (Au + Cu + Fe) is a stratiform–lenticular body developed along the granodiorite contact zone and is particularly enriched in magnetite. The KT8 ore body (Cu + Au) represents the largest deposit in the district. The occurrence of skarn-type molybdenite near Orebody No. 2 further suggests significant potential for skarn-type Cu–Mo mineralization in the Galale deposit (Figure 3g).

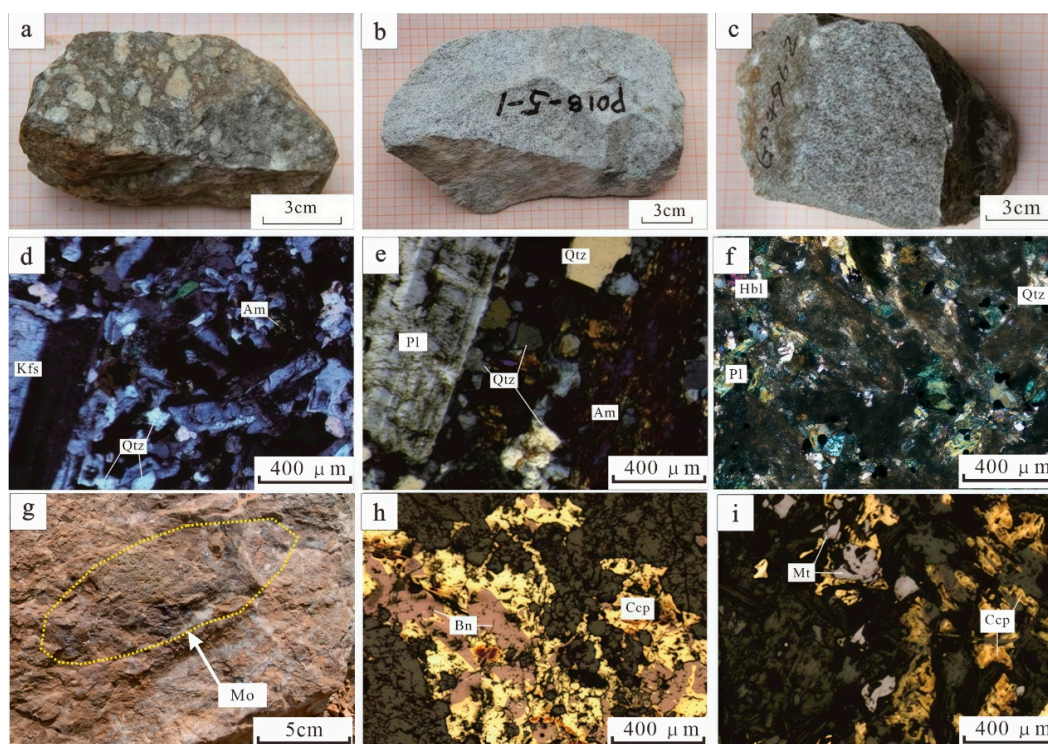


Figure 3. (a) Outcrop photograph of quartz diorite, (b) granodiorite and (c) monzonitic granite. (d) Photomicrograph of quartz diorite, (e) granodiorite and (f) monzonitic granite, (g) Outcrop photograph of skarn-type molybdenite (h,i) Photomicrograph of metallic minerals and skarn minerals in the Galale deposit. Qtz—Quartz, Kfs—K Feldspar, Am—Amphibole, Pl—Plagioclase, Hbl—Hornblende, Mo—Molybdenum, Mt—Magnetite, Ccp—Chalcopyrite, Cc—Chalcocite, Bn—Bornite.

4. Sampling and Analytical Methods

4.1. Sampling

Quartz diorite is gray to dark gray, exhibiting a fine-grained texture and a massive structure. Its mineral composition consists of approximately 55% plagioclase, 10% ortho-

clase, 15% quartz, 10% amphibole, and 10% biotite, with grain sizes ranging from 1 to 2 mm. Amphibole phenocrysts, constituting less than 5%, have a grain size of approximately 3 mm. The rock has undergone intense local alteration, primarily characterized by sericitization, kaolinization, chloritization, and epidotization (Figure 3a,d).

Granodiorite is light gray to grayish-red, with a medium- to fine-grained texture and a massive structure. It comprises approximately 40% plagioclase, 25% orthoclase, 25% quartz, and 10% biotite, along with minor amounts of amphibole, rutile, and magnetite. The grain size varies from 2 to 3 mm (Figure 3b,e).

Monzonitic granite is light gray to pale pink, displaying a porphyritic texture and a massive structure. Phenocrysts, accounting for 15%–20%, are primarily composed of orthoclase and quartz, with subordinate plagioclase and biotite, and grain sizes ranging from 1 to 2 mm. The cryptocrystalline to fine-grained matrix is composed chiefly of potassium feldspar and quartz in approximately equal proportions. The rock exhibits significant sericitization and carbonation (Figure 3c,f).

The Galale deposit is classified as a skarn-type deposit, with gold and chalcopyrite as the principal ore minerals. In this study, molybdenite was identified in skarn outcrops of Orebody No. 2 (Figure 3g), whereas chalcopyrite occurs predominantly in Orebodies No. 2 and No. 8 (Figure 3h,i).

4.2. Whole-Rock Geochemistry Methods

Whole-rock major, trace, and rare earth element (REE) analyses were conducted at the National Research Center for Geoanalysis, China. Samples were crushed and powdered to a grain size finer than 200 mesh prior to analysis. Major element concentrations were determined at the National Geological Testing Center of the Chinese Academy of Geological Sciences using an Axios wavelength-dispersive X-ray fluorescence (XRF) spectrometer (PANalytical B.V., Almelo, The Netherlands), in accordance with GB/T 14506.28–2010 standards (National Standard of the People's Republic of China) [21], with analytical accuracy better than 5%. Trace and REE concentrations were measured using a high-resolution inductively coupled plasma mass spectrometer (ICP-MS), following DZ/T 0223–2001 standards (Industry Standard of the People's Republic of China) [22], with analytical accuracy better than 10% [23].

4.3. LA-ICP-MS Zircon U–Pb Age Methods

LA-ICP-MS zircon U–Pb isotopic dating was performed at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, using a New Wave UP213 laser ablation system coupled with a Bruker M90 ICP-MS (Bruker, Billerica, MA, USA). During ablation, helium served as the carrier gas, while argon was used as the make-up gas to optimize sensitivity; the two gases were mixed via a Y-connector before introduction into the ICP. Each analysis comprised ~15–20 s of background signal acquisition followed by 45 s of sample signal collection. Offline data reduction—including signal selection, instrumental drift correction, elemental concentration and isotopic ratio calculations, and age determination—was conducted using ICPMS Data Cal [24,25]. For U–Pb dating, zircon standard GJ-1 (reported U/Pb age of 608.5 ± 0.4 Ma) [26] was employed as an external standard for mass bias correction, with two GJ-1 analyses conducted after every 5–10 sample measurements. Time-dependent U–Th–Pb ratio drift was corrected by linear interpolation based on GJ-1 variations [24]. Concordia diagrams and weighted mean ages were generated using Isoplot 4.15 [27].

5. Results

5.1. Zircon U–Pb Age Data

Quartz diorite: Zircon separated from sample GD049 are predominantly colorless and transparent, exhibiting prismatic morphologies. Their lengths range between 50 μm and 200 μm , with widths around 50 μm . The zircon crystals exhibit a high degree of automorphism, ranging from subhedral to euhedral, although some exhibit fracturing (Figure 4a). Cathodoluminescence (CL) imaging reveals these zircons are all classified as typical magmatic zircons [28], with heterogeneous Th and U distributions. The analyzed zircons exhibit high Th and U concentrations, with Th ranging from 360.81×10^{-6} to $13,737.12 \times 10^{-6}$ ppm and U ranging from 234.31×10^{-6} to 1198.56×10^{-6} ppm. The Th/U ratios range from 1.278 to 3.118 (Table 1). The LA-ICP-MS U–Pb dating results for the quartz diorite zircons are presented in Table 1. The U–Pb Concordia Age and Weighted Average Age are shown in Figure 4b, which demonstrates good concordance. The Concordia Age is 84.05 ± 0.34 Ma (MSWD = 1.3, $n = 24$), which reveals the crystallization age of the quartz diorite.

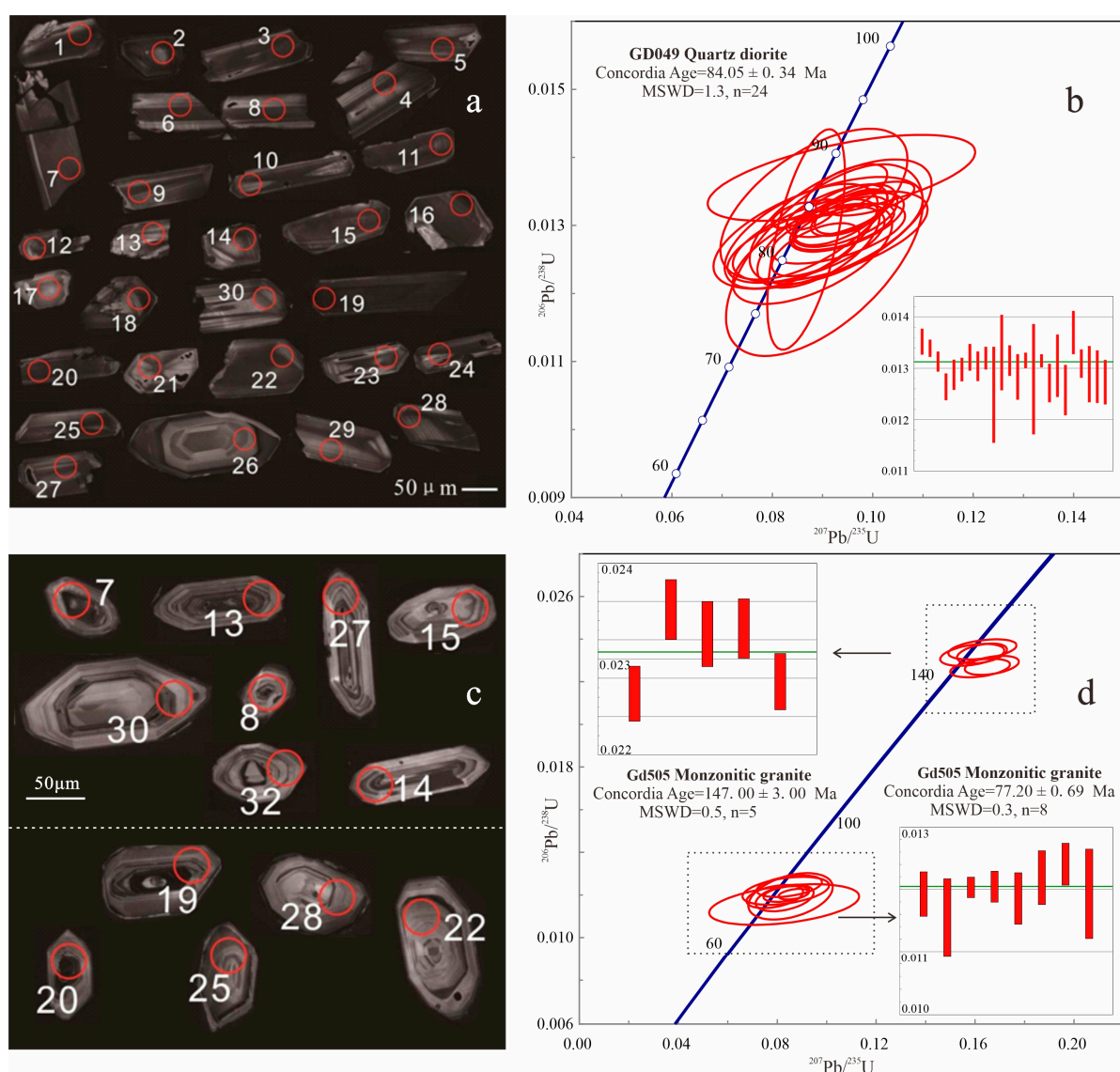


Figure 4. Cathodoluminescence (CL) images of (a) quartz diorite (GD049) and (c) monzonitic granite (GD505), LA-ICP-MS zircon U–Pb Concordia diagrams of (b) quartz diorite (GD049) and (d) Monzonitic granite (GD505). LA-ICP-MS, laser ablation-inductively coupled plasma–mass spectrometry. MSWD—Mean Square of Weighted Deviations.

Table 1. Zircon age data acquired by LA-ICP-MS methods for the quartz diorite and monzonitic granite from the Galale Cu-Au deposit.

Sample	Th/ 10^{-6}	U/ 10^{-6}	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{208}\text{Pb}/^{232}\text{Th}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$
Quartz diorite (GD049)												
GD049-1	1454.57	598.08	2.432	0.050998	0.002854	0.094648	0.005442	0.013522	0.000249	0.003942	0.000459	86.6 ± 1.6
GD049-2	997.63	461.95	2.160	0.054474	0.003088	0.099561	0.005767	0.013393	0.000164	0.003523	0.000106	85.8 ± 1.0
GD049-3	840.40	417.18	2.014	0.053276	0.002814	0.095293	0.005004	0.013135	0.000191	0.003464	0.000103	84.1 ± 1.2
GD049-4	1015.81	405.16	2.507	0.052827	0.004044	0.088620	0.005759	0.012644	0.000257	0.003289	0.000103	81.0 ± 1.6
GD049-5	763.83	342.27	2.232	0.056197	0.005930	0.093162	0.008784	0.012878	0.000290	0.003155	0.000103	82.5 ± 1.8
GD049-6	814.58	414.93	1.963	0.055083	0.004059	0.094188	0.006660	0.012979	0.000226	0.003206	0.000103	83.1 ± 1.4
GD049-7	633.28	315.99	2.004	0.051981	0.003826	0.093627	0.007165	0.013217	0.000256	0.003217	0.000121	84.6 ± 1.6
GD049-8	1058.88	430.48	2.460	0.054685	0.004601	0.094882	0.007499	0.013044	0.000285	0.003187	0.000109	83.5 ± 1.8
GD049-9	988.90	403.60	2.450	0.053464	0.002695	0.095741	0.004801	0.013202	0.000217	0.003060	0.000106	84.6 ± 1.4
GD049-10	546.68	427.61	1.278	0.055524	0.007982	0.090388	0.012928	0.012489	0.000930	0.003100	0.000262	80.0 ± 5.9
GD049-11	513.32	388.42	1.321	0.048458	0.007000	0.088290	0.012302	0.013311	0.000731	0.003319	0.000457	85.2 ± 4.6
GD049-12	1173.84	490.73	2.392	0.053809	0.003613	0.093538	0.006178	0.013154	0.000293	0.003081	0.000105	84.2 ± 1.9
GD049-13	916.45	446.68	2.052	0.052534	0.007545	0.091543	0.012796	0.012835	0.000439	0.002847	0.000136	82.2 ± 2.8
GD049-14	1660.95	855.97	1.940	0.049433	0.001875	0.087961	0.003300	0.013157	0.000147	0.003220	0.000105	84.3 ± 0.9
GD049-15	514.03	269.29	1.909	0.038910	0.003470	0.086742	0.005090	0.012792	0.001069	0.003538	0.000264	81.9 ± 6.8
GD049-16	3737.12	1198.56	3.118	0.047168	0.001665	0.084331	0.002912	0.013150	0.000123	0.003414	0.000105	84.2 ± 0.8
GD049-17	1420.14	613.99	2.313	0.052076	0.007083	0.086716	0.010333	0.012718	0.000371	0.003617	0.000168	81.5 ± 2.4
GD049-18	622.70	349.88	1.780	0.053612	0.006699	0.093607	0.011954	0.013054	0.000604	0.003843	0.000265	83.6 ± 3.8
GD049-19	753.47	409.73	1.839	0.051997	0.006781	0.087994	0.010483	0.012580	0.000486	0.003534	0.000198	80.6 ± 3.1
GD049-20	1195.49	550.54	2.171	0.046557	0.008036	0.093779	0.017583	0.013699	0.000417	0.003759	0.000206	87.7 ± 2.7
GD049-21	1194.01	533.57	2.238	0.053487	0.004054	0.094511	0.006897	0.013095	0.000272	0.003637	0.000137	83.9 ± 1.7
GD049-22	903.76	471.99	1.915	0.052348	0.008760	0.089138	0.013760	0.012890	0.000543	0.003373	0.000185	82.6 ± 3.5
GD049-23	791.52	348.16	2.273	0.049260	0.005546	0.085770	0.010069	0.012841	0.000508	0.003275	0.000269	82.3 ± 3.2
GD049-24	360.81	234.31	1.540	0.050200	0.004314	0.089221	0.008035	0.012734	0.000429	0.003225	0.000196	81.6 ± 2.7
Monzonitic granite (GD505)												
GD505-1	1875.14	728.22	2.575	0.048137	0.004737	0.079057	0.007557	0.011929	0.000356	0.002904	0.000391	76.4 ± 2.3
GD505-2	528.49	453.34	1.166	0.050566	0.011026	0.082843	0.020026	0.011545	0.000630	0.003080	0.000477	74.0 ± 4.0
GD505-3	652.73	646.93	1.009	0.052939	0.002623	0.086694	0.004074	0.012036	0.000164	0.002889	0.000444	77.1 ± 1.0
GD505-4	348.97	379.72	0.919	0.052733	0.004258	0.083742	0.006123	0.012047	0.000248	0.002886	0.000401	77.2 ± 1.6
GD505-5	206.65	250.92	0.823	0.051542	0.005143	0.083026	0.007740	0.011858	0.000412	0.002848	0.000360	76.0 ± 2.6
GD505-6	378.26	582.32	0.650	0.052293	0.002507	0.162089	0.007983	0.022641	0.000286	0.005695	0.000298	144.3 ± 1.8
GD505-7	616.16	421.42	1.462	0.051047	0.003019	0.163010	0.009120	0.023518	0.000311	0.005785	0.000253	149.9 ± 2.0
GD505-8	195.07	697.89	0.280	0.049025	0.002426	0.158863	0.008562	0.023262	0.000339	0.005685	0.000270	148.2 ± 2.1
GD505-9	264.64	343.50	0.770	0.051547	0.002162	0.162825	0.006683	0.023319	0.000309	0.006406	0.000179	148.6 ± 1.9
GD505-10	300.43	348.89	0.861	0.049058	0.006172	0.083488	0.011583	0.012192	0.000431	0.003712	0.000221	78.1 ± 2.7
GD505-11	200.25	219.61	0.912	0.053727	0.002317	0.166810	0.007208	0.022767	0.000293	0.006424	0.000196	145.1 ± 1.8
GD505-12	275.98	578.61	0.477	0.050825	0.005889	0.084918	0.008723	0.012409	0.000335	0.004612	0.000239	79.5 ± 2.1
GD505-13	260.38	316.68	0.822	0.055145	0.008185	0.085414	0.011258	0.011933	0.000717	0.003861	0.000382	76.5 ± 4.6

Monzonitic granite: The zircon separated from sample GD505 exhibit a high degree of automorphism, with aspect ratios ranging from 1 to 2. The oscillatory zoning is well-defined, and nearly half contain distinct cores. Dark zones are observed between the cores and the outer zoning, suggesting these are inherited zircons with secondary overgrowths and both cores and rims were analyzed (Figure 4c). The measured Th and U concentrations range from 195.07×10^{-6} to 1875.14×10^{-6} ppm for Th and from 219.64×10^{-6} to 728.22×10^{-6} ppm for U. The Th/U ratios predominantly fall between 0.280 and 2.575, consistent with typical magmatic zircons. The LA-ICP-MS U–Pb dating results for the monzonitic granite zircons are presented in Table 1. Two distinct age populations were identified: the weighted mean age of the inherited zircon cores is 147.00 ± 3.00 Ma (MSWD = 0.5, $n = 5$), representing older crustal components. The Weighted Average Age and Concordia Age of the primary magmatic zircon are shown in Figure 4d, with a crystallization age of 77.20 ± 0.69 Ma (MSWD = 0.3, $n = 8$).

5.2. Whole-Rock Geochemistry

Quartz diorite: The SiO_2 content ranges from 58.20% to 59.60% (average 59.10%). The total ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) content ranges from 6.46% to 7.27% (average 6.81%). The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio varies between 0.53 and 0.63 (average 0.59). The SiO_2 – K_2O diagram indicates that the

quartz diorite plots within the high-potassium calc-alkaline series (Table 2; Figure 5b). The Al_2O_3 content ranges from 16.66% to 17.06% (average 16.90%). The aluminum saturation index (A/CNK) [$\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$] range around 0.86, classifying peraluminous (Table 2; Figure 5c). The total REE content ranges from 182×10^{-6} to 208×10^{-6} (Table 2), with an average of 199×10^{-6} . The $(\text{La}/\text{Yb})_n$ ratio ranges from 21 to 25, indicate enrichment in light rare earth elements (LREE) and depletion in heavy rare earth elements (HREE). The Eu/Eu^* ratio ranges from 0.90 to 1.00 (average 0.95), showing no significant Eu anomaly (Figure 6a). In the primitive mantle-normalized trace element patterns diagram, quartz diorite is relatively enriched in large ion lithophile elements (LILEs) but shows relative depletion in high field strength elements (HFSEs) such as Nb, Ta, Ce, and Ti, while Th is relatively enriched (Figure 6b).

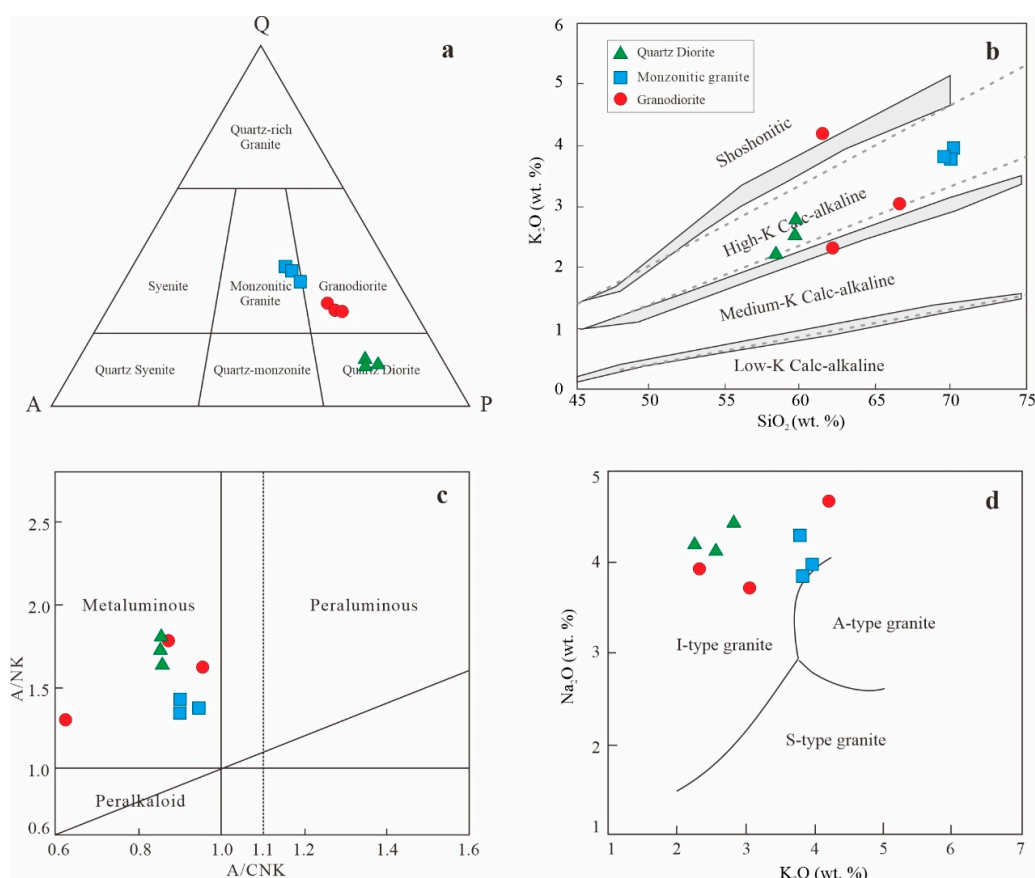


Figure 5. (a) The QAP classification diagram [29], (b) SiO_2 versus K_2O diagram [30], (c) A/NK – A/CNK diagram and (d) K_2O versus Na_2O diagram for the quartz diorite, granodiorite and monzonitic granite from the Galale Cu–Au deposit.

Granodiorite: The SiO_2 content ranges from 61.30% to 66.90% (average 65.00%). The total $(\text{K}_2\text{O} + \text{Na}_2\text{O})$ content ranges from 6.24% to 8.87% (average 6.95%). The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio varies between 0.59 and 0.90 (average 0.74). The SiO_2 – K_2O diagram suggests that the granodiorite primarily plots within the high-potassium calc-alkaline series (Table 2; Figure 5b). The Al_2O_3 content ranges from 14.83% to 15.99% (average 15.3%). The A/CNK ratio ranges from 0.62 to 0.97, classifying peraluminous (Table 2; Figure 5c). The total REE content ranges from 81×10^{-6} to 137×10^{-6} (average 113×10^{-6}) (Table 2). The $(\text{La}/\text{Yb})_n$ ratio ranges from 14 to 23, indicating LREE enrichment and HREE depletion. The Eu/Eu^* ratio ranges from 0.88 to 0.97 (average 0.93), showing no significant Eu anomaly (Figure 6a). In the primitive mantle-normalized trace element patterns diagram, the granodiorite is significantly enriched in LILEs, with Rb ranging from 82 to 128×10^{-6} (average 108×10^{-6}),

Ba ranging from 274 to 357×10^{-6} (average 328×10^{-6}), and Sr ranging from 397 to 904×10^{-6} (average 596×10^{-6}). The HFSEs, including Nb, Ta, Ce, and Ti, are relatively depleted, while Th is relatively enriched (Figure 6b).

Table 2. Whole-rock major (wt%) and trace elements (ppm) compositions of the quartz diorite and monzonitic granite from the Galale Cu-Au deposit.

Lithologic Map	Quartz Diorite			Granodiorite			Monzonitic Granite		
NO.	GD049-2	GD049-3	GD496-1	P01B-9-1	P01B-16-3	P01B-19-1	GD505-2	GD505-3	GD505-4
SiO ₂	59.50	58.22	59.56	61.34	62.02	66.50	69.93	70.13	69.47
TiO ₂	1.17	1.25	0.94	0.42	0.71	0.55	0.16	0.16	0.16
Al ₂ O ₃	16.66	16.99	17.06	15.89	15.99	15.22	14.91	14.79	14.87
Fe ₂ O ₃	2.81	3.13	3.07	0.48	2.47	1.50	0.24	0.37	0.32
FeO	3.24	3.44	2.63	1.90	2.62	1.89	0.37	0.27	0.23
MnO	0.10	0.12	0.10	0.07	0.09	0.05	0.01	0.01	0.01
MgO	3.02	3.17	2.83	2.48	3.09	1.85	0.24	0.50	0.24
CaO	5.42	5.75	5.21	7.29	5.16	3.59	2.96	2.64	3.30
Na ₂ O	4.15	4.22	4.46	4.68	3.93	3.72	4.30	3.98	3.85
K ₂ O	2.55	2.24	2.81	4.19	2.31	3.04	3.77	3.95	3.81
P ₂ O ₅	0.38	0.41	0.33	0.24	0.21	0.16	0.07	0.07	0.07
H ₂ O ⁺	0.58	0.68	0.62	0.40	1.12	1.34	1.36	1.14	1.70
CO ₂	0.16	0.17	0.16	0.16	0.10	0.50	1.78	2.05	2.07
LOI	0.56	0.59	0.51	0.43	1.10	1.47	2.70	3.00	3.23
A/CNK	0.86	0.86	0.86	0.62	0.87	0.95	0.90	0.95	0.90
A/NK	1.74	1.81	1.64	1.30	1.78	1.62	1.34	1.37	1.42
K ₂ O/Na ₂ O	0.61	0.53	0.63	0.90	0.59	0.82	0.88	0.99	0.99
Cs	4.19	4.71	3.21	1.57	5.60	7.08	7.37	13.0	10.6
Rb	61.5	54.2	66.3	116	82.1	128	96.8	112	103
Ba	316	298	380	357	274	352	337	390	335
Th	10.5	7.61	10.3	2.51	6.54	10.7	4.51	4.54	4.56
U	2.90	1.51	1.81	0.87	1.63	1.79	1.58	1.92	1.92
Nb	27.5	23.2	22.2	5.46	11.2	13.9	19.5	20.6	21.0
Ta	1.62	1.34	1.39	0.31	0.81	1.06	1.58	1.66	1.64
Sr	493	507	594	904	487	397	289	327	296
Zr	211	243	278	103	150	160	89.2	86.3	89.9
Hf	4.58	4.98	6.13	2.36	3.62	4.02	2.8	2.64	2.61
Y	20.0	17.9	16.9	8.53	14.9	13.1	5.94	5.96	5.84
Sr/Y	24.7	28.3	35.1	106.0	32.7	30.3	48.7	54.9	50.7
La	44.3	36.9	46.3	16	21.6	31.7	13.4	15.7	17.6
Ce	82.4	69.9	82.2	30.3	43.4	52.2	23.9	30.5	26.8
Pr	8.97	7.81	8.78	3.35	5.15	5.52	2.76	3.16	3.01
Nd	31.4	29.5	32	12.9	20.5	20.5	9.91	11.8	10.8
Sm	5.25	4.64	4.93	2.33	3.79	3.18	1.74	1.99	1.77
Eu	1.5	1.46	1.49	0.71	1.16	0.89	0.47	0.58	0.55
Gd	4.92	4.64	4.23	2.16	3.78	3.03	1.46	1.68	1.55
Tb	0.68	0.64	0.62	0.31	0.56	0.43	0.22	0.23	0.22
Dy	3.77	3.57	3.56	1.7	3.04	2.55	1.17	1.22	1.18
Ho	0.71	0.64	0.62	0.31	0.52	0.46	0.18	0.2	0.18
Er	2.01	1.94	1.83	0.84	1.57	1.3	0.49	0.49	0.53
Tm	0.28	0.28	0.28	0.12	0.23	0.21	0.07	0.07	0.07
Yb	1.94	1.77	1.82	0.81	1.51	1.36	0.43	0.44	0.44
Lu	0.3	0.25	0.29	0.13	0.24	0.22	0.07	0.07	0.06
ΣREE	188.43	163.94	188.95	71.97	107.05	123.55	56.27	68.13	64.76
(La/Yb) _N	15.40	14.06	17.15	13.32	9.64	15.71	21.01	24.06	26.97
δEu	0.89	0.95	0.97	0.95	0.93	0.86	0.88	0.95	0.99

Notes: H₂O⁺ (%) = $(W_{\text{before}} - W_{\text{after}})/W_{\text{initial}} \times 100$, representing structural water; CO₂ (%) = $(W_{\text{before}} - W_{\text{after}})/W_{\text{initial}} \times 100$, representing carbonate content (~950–1000 °C); LOI (%) = $(W_{\text{dry}} - W_{\text{ignited}})/W_{\text{dry}} \times 100$, total mass loss on heating, including H₂O⁺, CO₂, and other volatiles.

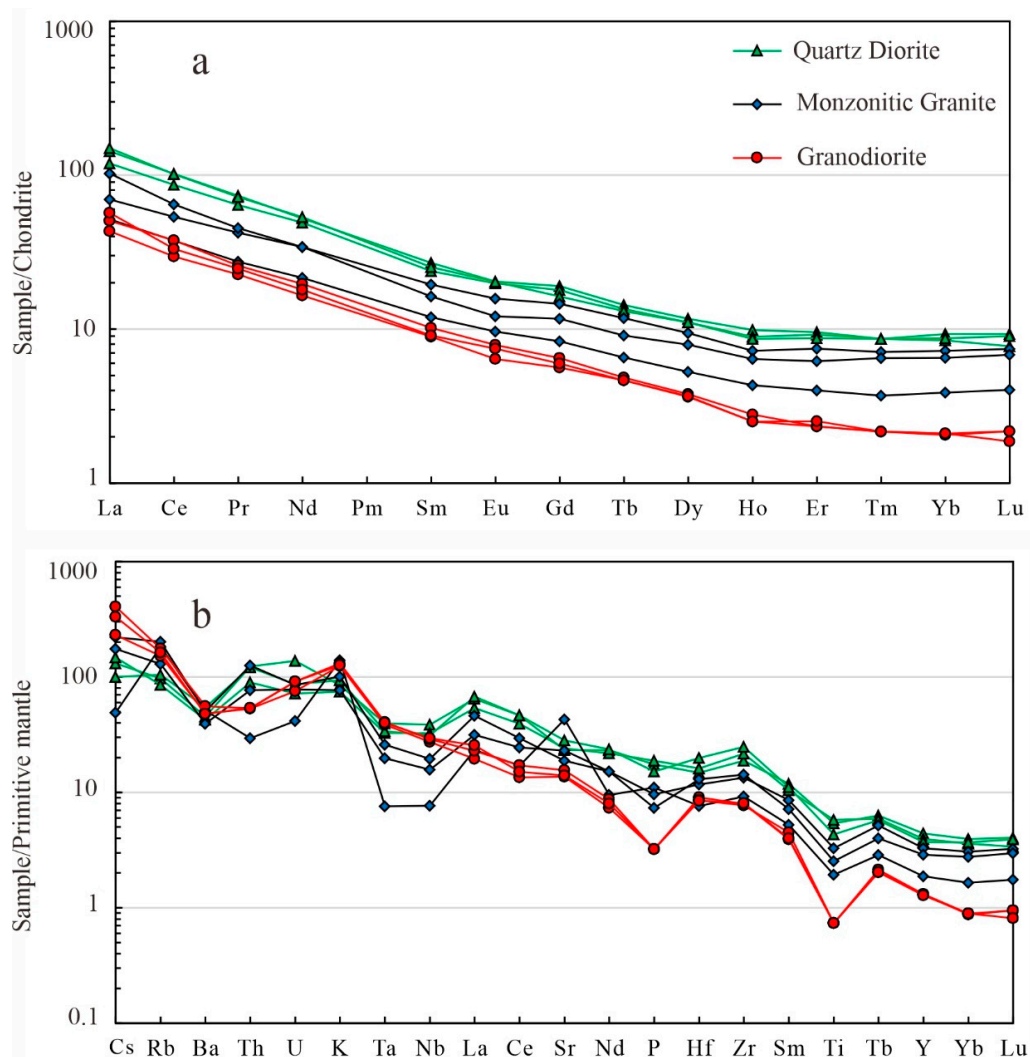


Figure 6. (a) Chondrite-normalized REE patterns and (b) primitive mantle-normalized trace element patterns for quartz diorite, granodiorite and monzonitic granite from the Galale Cu–Au deposit. Data for the chondrite and primitive mantle normalization are from Sun and McDonough, 1989 [31].

Monzonitic granite: The SiO_2 content ranges from 69.43% to 70.13% (average 69.84%). The total ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) content ranges from 7.66% to 8.07% (average 7.89%). The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio varies between 0.88 and 0.99 (average 0.95). The SiO_2 – K_2O diagram indicates that the monzonitic granite plots within the high-potassium calc-alkaline series (Table 2; Figure 4b). The Al_2O_3 content ranges from 14.79% to 14.91% (average 14.86%). The A/CNK ratio ranges from 0.90 to 0.95, classifying peraluminous (Table 2; Figure 5c). The total REE content ranges from 62×10^{-6} to 74×10^{-6} (average 68×10^{-6}) (Table 2). The $(\text{La}/\text{Yb})_n$ ratio ranges from 31 to 40, indicate LREE enrichment and HREE depletion. The Eu/Eu^* ratio ranges from 0.90 to 1.01 (average 0.96), indicating no significant Eu anomaly (Figure 6a). In the primitive mantle-normalized trace element patterns diagram, the monzonitic granite is relatively enriched in LILEs, including Rb, Ba, and K, while the HFSEs, such as Ce and Ti, are significantly depleted (Figure 6b).

6. Discussion

6.1. Age Supplement of the Galale Deposit

Magmatic and mineralization events in the Galale deposit define a coherent geochronological framework that constrains its tectonic setting (Figure 7). Two main magmatic phases can be distinguished. The Early Cretaceous stage is represented by porphyritic quartz

diorite (131.0 ± 1.7 Ma) and diorite (155.8 ± 2.3 Ma) [17]. The Late Cretaceous stage is more complex, encompassing syn-mineralization magmatic–hydrothermal activity and the post-mineralization emplacement of monzonitic granite (77.2 ± 0.7 Ma, this study). Mineralization ages of the Galale deposit have been constrained by multiple independent methods: (1) $^{40}\text{Ar}/^{39}\text{Ar}$ dating of phlogopite [14]; (2) Re–Os isochron ages of molybdenite [12]; (3) U–Pb zircon ages of quartz diorite (84.1 ± 0.3 Ma, this study); (4) U–Pb zircon ages of granodiorite; and (5) U–Pb zircon ages of diorite porphyry [17]. These chronometers consistently indicate that ore formation occurred during a single magmatic–hydrothermal episode at 83–89 Ma. The temporal coincidence of mineralization with Late Cretaceous hybrid magmatism and oxidized, metal-rich hydrothermal fluids suggests that the Galale deposit represents a post-collisional system genetically linked to lithospheric-scale geodynamics along the Bangong–Nujiang suture.

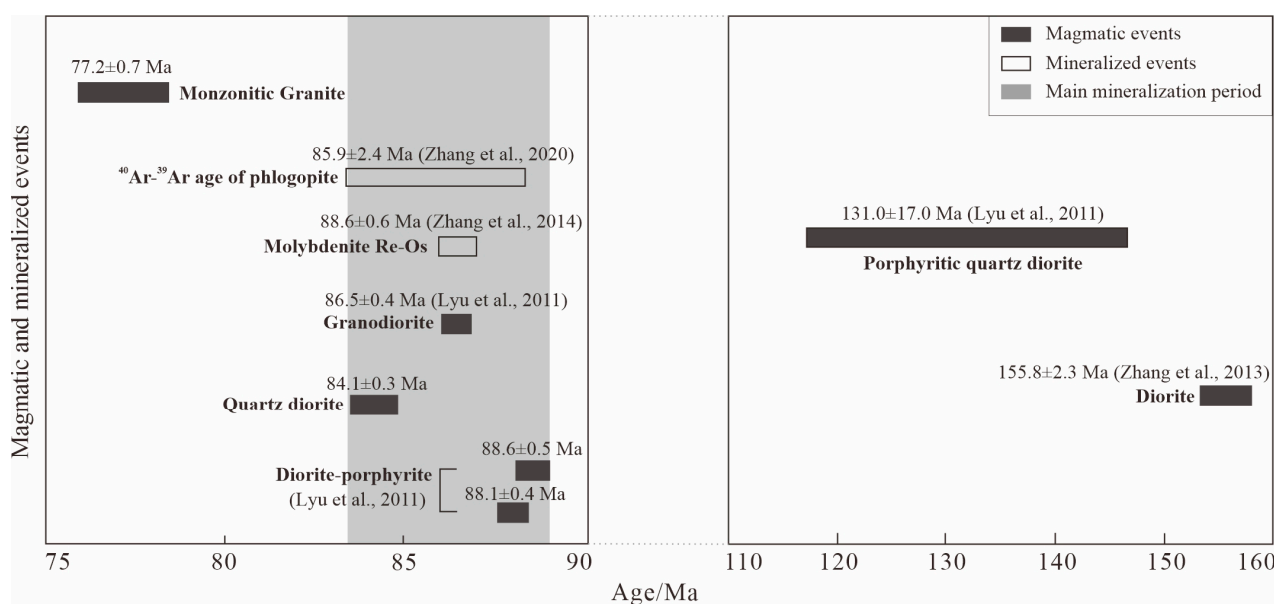


Figure 7. Chronology of magmatic and mineralization events in the Galale deposit [11–13,17].

The Bangong–Nujiang suture zone records a tectonic evolution from collision to diachronous closure and post-collisional extension. Bidirectional subduction was active during the Jurassic–Early Cretaceous. Southward subduction initiated at ~ 170 – 160 Ma, evidenced by the Shiquanhe–Jiali ophiolite belt with enriched MORB signatures reflecting slab-derived melts and back-arc extension [32]. Contemporaneously, northward subduction produced supra-subduction ophiolites and granitoids along the Qiangtang margin (~ 160 Ma), while adakitic and high-Mg andesitic magmatism (167 – 164 Ma) on the northern Lhasa margin indicates slab rollback [33]. By the Early Cretaceous, the eastern suture had closed (~ 115 Ma, pinpoint intrusions 116 – 112 Ma), whereas the western segment remained active until at least 100 Ma, marked by mafic dike swarms in the Bange region, turbidite deposition (127 – 126 Ma), and arc granitoids (~ 130 Ma) in the Shiquanhe–Namco belt [34]. Geophysical evidence of south-dipping conductors beneath the Lhasa block further confirms the persistence of southward subduction into the Early Cretaceous [35].

Within this geodynamic framework, the Galale deposit provides decisive Late Cretaceous evidence. Its mineralization age of 83 – 89 Ma, consistently constrained by multiple geochronological methods, falls within the post-collisional stage of the Bangong–Nujiang suture. These events clearly post-date the closure of the Bangong–Nujiang Ocean and are therefore linked to a post-collisional extensional regime [36–39]. The timing indicates that the deposit represents a deep hydrothermal response to the persistence of southward

subduction in the western segment into the Late Cretaceous. The synchronous occurrence of high-temperature, oxidized, metal-rich fluids together with hybrid magmatism bearing both crustal and mantle signatures [7,40,41] further supports a tectonic model involving slab rollback and southward subduction, which triggered asthenospheric upwelling, extensive crustal melting, and ultimately ore formation.

6.2. Evaluation of Mo Mineralization Potential

The Mo mineralization potential of the studied Late Cretaceous intrusive rocks from the Galale deposit, including quartz diorite, granodiorite, and monzonitic granite, can be assessed by integrating major, trace, and rare earth element geochemistry. These parameters reflect magma source characteristics, oxidation state, and fractionation processes, which are critical factors influencing Mo enrichment and transport.

1 Geochemical Characteristics Relevant to Mo Fertility

All three rock types exhibit SiO_2 contents between 58.22 and 70.13 wt.%, falling within the intermediate to felsic range. The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios vary between ~0.53 and ~0.99, with monzonitic granite showing relatively high K-enrichment, indicating evolved, crust-derived magmas [42]. A/CNK ratios mostly fall within 0.86–0.95 (Table 2, Figure 5), suggesting metaluminous compositions, consistent with I-type granitoids known for their Mo fertility [43,44].

Quartz diorite samples show lower SiO_2 and K_2O content and relatively higher Sr (Table 2), indicating less evolved magmas with limited Mo potential. Granodiorite displays moderate Rb/Sr ratios (Figure 8c), implying some degree of fractionation, yet the low Y and Nb values suggest a moderately oxidized magma, favoring Mo transport [45,46]. Monzonitic granite shows the highest Rb/Sr and K_2O values, and a strong depletion in Nb and Ta, indicating a highly evolved, oxidized, crustal-derived melt, comparable to magmas in Mo-productive porphyry systems [47,48].

The REE signatures further support this interpretation. Monzonitic granite shows strong LREE enrichment, weak HREE contents, and steep chondrite-normalized patterns. Combined with weak or absent Eu anomalies (Figure 6), these signatures indicate fractional crystallization under oxidizing conditions where plagioclase was suppressed—conditions favorable for Mo enrichment [49,50].

2. Magma Source Discrimination

Discrimination diagrams, such as R2 vs. R1 [51,52], indicate that the quartz diorite is associated with a post-collisional uplift setting, which is favorable for the formation of porphyry-type molybdenum deposits [53,54]. In contrast, the granodiorite and monzonitic granite are classified within a pre-collisional plate setting, which is predominantly characterized by Cu–Mo mineralization [55] (Figure 8a). Overall, the tectonic settings of all these rocks are favorable for molybdenum mineralization.

Furthermore, the monzonitic granite and granodiorite are characterized by high K_2O contents, higher Sr/Y (Figure 8b) and Rb/Sr ratios (Figure 8c), steep REE patterns, and depleted HFSEs (Nb, Ta), all of which indicate a highly fractionated and oxidized magmatic system with strong Mo fertility. By contrast, the quartz diorite shows lower SiO_2 , higher Zr/Hf ratios (Figure 8d), lower Rb/Sr ratios, and reduced K_2O contents, suggesting a less evolved magma with weaker Mo mineralization potential.

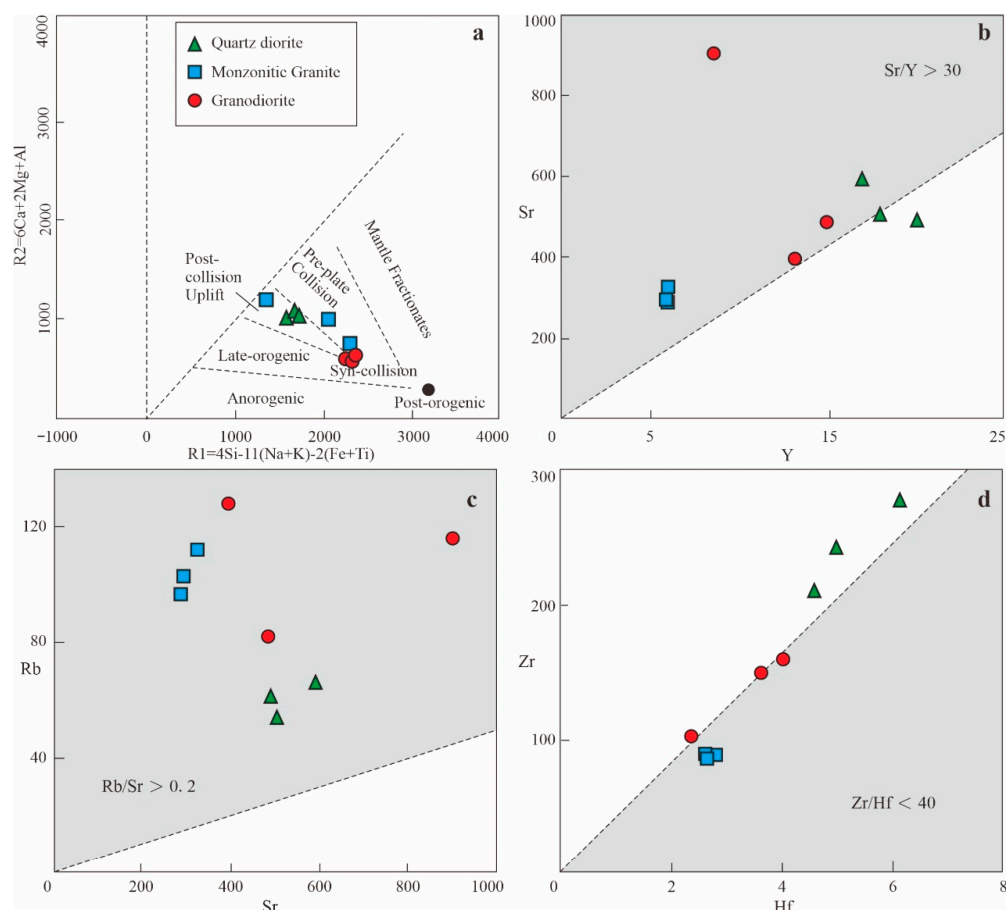


Figure 8. Geochemical discrimination and trace element diagrams for Galale deposit granitoids: (a) R2 vs. R1 [51,52], (b) Sr versus Y (c) Rb versus Sr and (d) Zr versus Hf.

6.3. Revised Metallogenic Model

Recent studies suggest that the opening of the Bangong Lake segment of the Neo-Tethys Ocean occurred no later than the Late Triassic [56,57], with subduction initiating in the late Middle Permian [5,33] and oceanic closure beginning in the Late Jurassic [4,58]. Subduction processes triggered asthenospheric upwelling (Figure 9a), which induced partial melting of both mantle and crustal sources, leading to the emplacement of diorite [13] and porphyritic quartz diorite [17]. The latter intruded into clastic sedimentary sequences, inducing contact metamorphism and producing hornfels, thereby enhancing the mechanical brittleness of host rocks [11]. Heat released during magma emplacement promoted recrystallization of the clastic material, forming dolomite and limestone units [59], which provided favorable lithological and structural conditions for subsequent mineralization.

Across the Albian-Cenomanian transition (106–99 Ma), the western segment of the Bangong Lake Neo-Tethys Ocean closed [60], marking the onset of the main collision between the Gangdese terrane and the Asian continental margin [58]. Continuous low-angle subduction of the Yarlung Zangbo oceanic crust from the south [61,62] caused sustained compression between the Gangdese terrane and the southern Qiangtang block. This continental collision-subduction process caused progressive crustal shortening and thickening, accompanied by deep crustal melting [63]. By the latest Cretaceous, lithospheric delamination induced asthenospheric upwelling, triggering partial melting of the lithospheric mantle and crust. The resulting mantle-derived magma, enriched in ore-forming elements (e.g., Cu, Fe, Au), interacted with crustal melts during ascent, forming crust–mantle hybrid magmas dominated by crustal components (Figure 9b). At this stage, the Galale ore district

experienced a post-collisional transition from a compressional to an extensional tectonic regime, with the principal stress orientation shifting from NW–SE to NE–SW. Magma underwent prolonged fractional crystallization within magma chambers and subsequently ascended along pre-existing NW- and NE-trending faults, leading to the emplacement of ore-related quartz diorite (84.07 ± 0.66 Ma) and granodiorite (86.52 ± 0.41 Ma) intrusions.

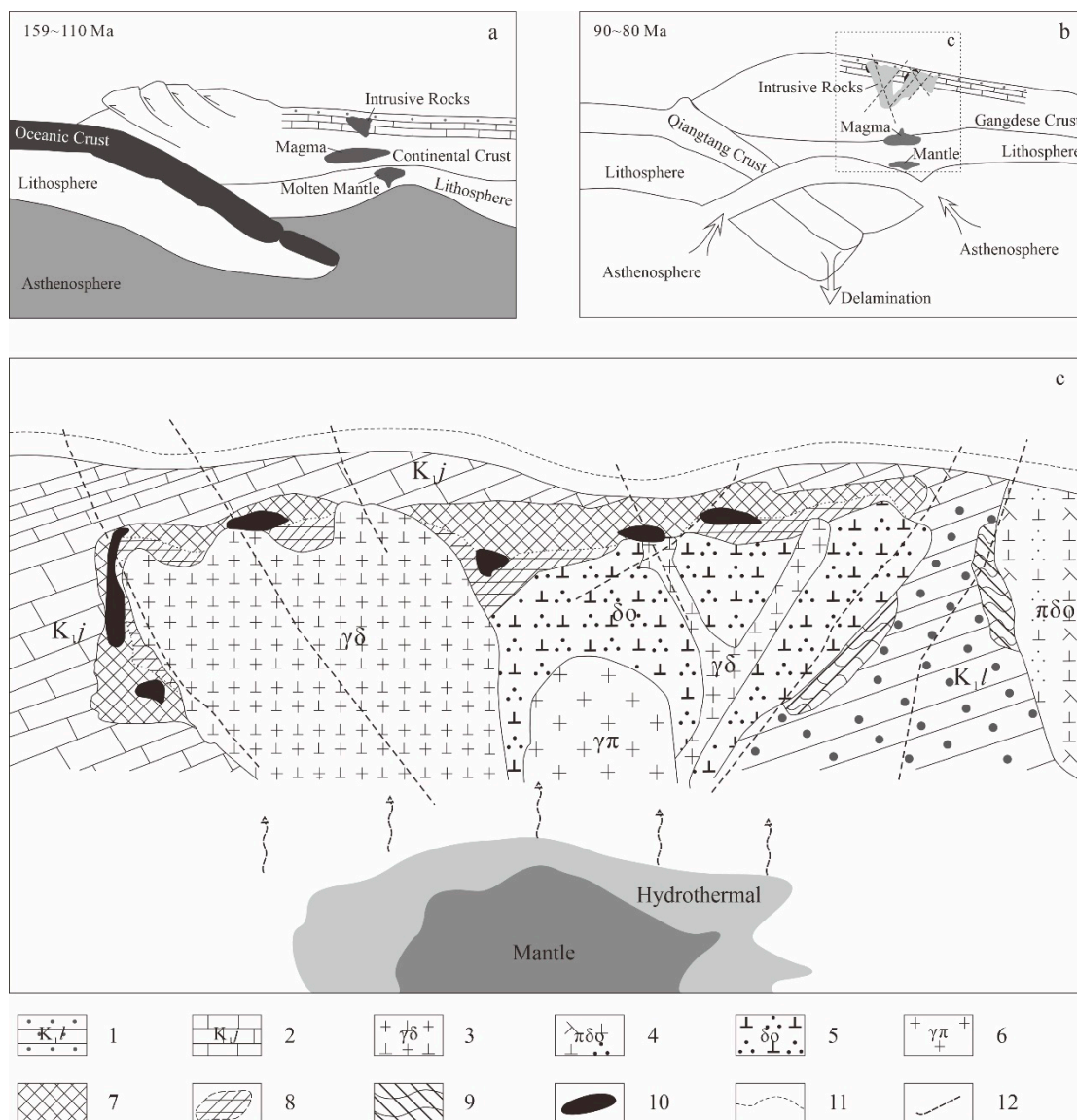


Figure 9. (a) Schematic model of oceanic slab subduction and associated magmatism (159–110 Ma), (b) Lithospheric delamination and intraplate magmatism (90–80 Ma), (c) Episodic Mineralization Model of the Galale Cu–Au Deposit: From Oceanic Subduction to Continental Delamination. 1—Langjiu Formation, 2—Jiege Formation, 3—Granodiorite, 4—Porphyritic Quartz diorite, 5—Quartz diorite, 6—Monzonitic granite, 7—Retrograde Skarn, 8—Prograde Skarn, 9—Hornfels, 10—Ore body, 11—Weathering Surface, 12—Fault.

During magma emplacement, large volumes of high-temperature, high-salinity, oxidized fluids rich in ore-forming elements exsolved from the evolving magmas. These metals were primarily transported as chloride complexes [64]. Upon interaction with the carbonate strata of the Jiege Formation, contact metasomatic reactions produced skarn assemblages dominated by olivine, diopside, and garnet [10]. As the fluids migrated outward from the intrusion, hydrothermal alteration led to the formation of retrograde skarn

zones characterized by serpentine, phlogopite, and epidote, due to water–rock interactions between acidic fluid components and host rock carbonates (e.g., CaCO_3 , MgCO_3). The influx of meteoric water, fluid boiling (which separated acidic volatiles), and decreases in temperature and salinity led to a drop in fluid pH and metal-carrying capacity [11]. Consequently, chloride complexes of Cu, Fe, and Au decomposed and precipitated along contacts between intrusions and host rocks, bedding planes in carbonates, and other favorable structural traps, forming significant ore bodies (Figure 9c). Extensive drill-core mapping indicates that the monzonitic granite (77.2 ± 1.3 Ma) intruded along pre-existing magma conduits, cross-cutting earlier quartz diorite bodies as stocks and dikes (Figure 9c). This late intrusive phase marks the termination of Late Cretaceous mineralization in the Galale district.

7. Conclusions

1. Magmatism and mineralization in the Galale area occurred in two principal stages: an early Cretaceous phase and a more complex late Cretaceous phase. U–Pb zircon ages of 84.1 ± 0.3 Ma (syn-mineralization quartz diorite) and 77.2 ± 0.7 Ma (post-mineralization monzonitic granite) tightly constrain Late Cretaceous magmatic activity. Combined with previous data, these results indicate that mineralization took place between 83 and 89 Ma during a single magmatic–hydrothermal episode. This event postdates the closure of the Bangong–Nujiang Ocean and is attributed to post-collisional extension, likely driven by slab rollback, southward subduction, asthenospheric upwelling, and extensive crustal melting.
2. The quartz diorite, granodiorite, and monzonitic granite are high-K calc-alkaline, peraluminous I-type granitoids. The quartz diorite formed in a post-collisional uplift setting and represents a relatively less evolved magma with limited Mo potential. In contrast, the granodiorite and monzonitic granite originated in a pre-collisional plate setting and exhibit highly fractionated, oxidized features, making them particularly favorable for porphyry-type molybdenum mineralization.
3. The Galale deposit formed through a series of tectono-magmatic processes associated with the closure of the Bangong–Nujiang Neo-Tethys Ocean. Late Triassic subduction and Late Cretaceous lithospheric delamination induced asthenospheric upwelling and partial melting of both mantle and crustal sources, generating quartz diorite and granodiorite intrusions. These magmas underwent prolonged fractional crystallization, with exsolution of high-temperature, high-salinity fluids that interacted with carbonate strata to form skarn assemblages and precipitate ore metals along structural conduits. Hydrothermal alteration, fluid boiling, and meteoric water influx further facilitated ore deposition. The emplacement of monzonitic granite at ~ 77 Ma may also have contributed to additional molybdenum mineralization.

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