

Article

Identifying New Copper Mineralization via Multispectral Remote Sensing (MSRS) and Short-Wave Infrared (SWIR) Spectral Analysis in Dingyang, Western Gangdese Belt, Xizang

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Abstract

The Gangdese metallogenic belt (GMB), spanning nearly 2000 km across central Tibet, represents the primary copper–polymetallic metallogenic belt in Tibet and a world-class porphyry copper province. However, extreme high-altitude conditions, ecological fragility, and limited accessibility in western GMB have significantly constrained the efficacy of conventional exploration methods. Identifying effective mineralogical indicators and rapidly delineating mineralization–hydrothermal centers within this metallogenic system remain critical challenges for exploration geologists. This study integrates multispectral remote sensing (MSRS; Sentinel-2) with short-wave infrared (SWIR) spectral analysis to establish mineral spectroscopic exploration indicators for the periphery of the Zhunuo porphyry copper ore-concentrated area. Principal Component Analysis (PCA) and band ratio techniques were employed to delineate remote sensing alteration anomalies, followed by SWIR spectral features to identify mineralization–hydrothermal centers. Hydrothermal alteration in the study area is dominated by sericite, chlorite, and epidote, with subordinate carbonate and sulfate minerals. Multispectral anomalies (AI-OH, ferric contamination, and carbonate alterations) in the Dingyang area exhibit intensity and compositional patterns comparable to those of the Cimabanshuo, Beimulang, and Zhigunong deposits, indicating high mineralization potential. SWIR analysis identified sericite-based exploration indicators ($\text{Pos2200} < 2203 \text{ nm}$, $\text{Dep2200} > 0.3$, $\text{SWIR-IC} > 1.6$). A Spectral Feature-Based Geological Content Method (SFGCM) model was developed to delineate mineralization–hydrothermal centers, revealing new malachite and azurite mineralization in the Dingyang area. The MSRS-SWIR provides a novel perspective for applying spectroscopy to rapidly identify porphyry copper mineralized hydrothermal centers in high-altitude, ecologically fragile areas.

Keywords: porphyry copper deposit; multispectral remote sensing; short-wave infrared spectroscopy; Dingyang; western Gangdese belt



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1. Introduction

The Gangdese copper–polymetallic belt exhibits a distinctive metallogenic setting where multistage magmatism linked to continental collision orogenesis facilitates enrichment of metals such as copper, molybdenum, and gold [1]. Significant exploration breakthroughs have been achieved in the east (e.g., Qulong, Jiama, Tinggong, Gangjiang, Jiru

and Xiongcu); however, effective exploration methods in the west remain constrained by marked metallogenic disparities and high-altitude topography coupled with harsh environmental conditions [2,3]. Although the giant Zhunuo porphyry deposit has been identified in the western Gangdese belt, the exploration potential of surrounding and adjacent areas remains uncertain [3–6]. Therefore, developing novel, eco-friendly, and efficient integrated exploration approaches is urgently required.

Remote sensing technology has become an indispensable tool in mineral exploration for acquiring geological information and enabling regional-scale targeting, owing to its extensive spatial coverage and operational efficiency [7–12]. Multispectral remote sensing (MSRS) acquires surface reflectance data across the visible to short-wave infrared spectral range. It is widely applied in regional geological mapping, alteration anomaly extraction, and prospective mineralization targeting [13]. In multispectral remote sensing data sources, Sentinel 2 has unique advantages over other remote sensing data. Because it has key bands dedicated to iron staining and hydroxyl/carbonate mineral identification in the range of visible light to short-wave infrared, as well as having unique advantages of a 20 m spatial resolution, 5-day revisit period and free range across the world, it is an ideal data source for efficient alteration information extraction. While its spatial resolution (10 m, 20 m, and 60 m) limits pixel-level accuracy for fine-scale mineral mapping, the combination of visible, near-infrared (NIR), and SWIR bands supports detection of hydrothermal alteration zones through spectral pattern analysis [14]. Principal Component Analysis (PCA), a widely used remote sensing technique for alteration extraction, finds extensive application in mineral exploration [15,16]. In recent years, short-wave infrared (SWIR) spectroscopy has become the core means of mineral exploration. This technology achieves rapid and accurate identification and quantitative analysis of minerals by capturing the characteristic absorption bands of hydrothermal altered minerals in the range of 1300–2500 nm, which significantly improves the sensitivity of mineral identification and hydrothermal alteration evaluation. Combined with the spatial distribution of ore bodies and the alteration zoning model, the researchers constructed an alteration mineral assemblage exploration index system based on SWIR spectroscopy, which effectively improved the efficiency and accuracy of mineral exploration in deep and covered areas [17,18]. For example, Pos2200 and SWIR-IC indicators successfully delineated a high-grade gold mineralization zone [19]; Pos2250 can accurately indicate an ore body boundary [20]; and the combination of Pos2200, Dep2200 and SWIR-IC was established as a near-ore indicator [21]. Consequently, the MSRS-SWIR technological integration not only enhances prospecting efficiency for porphyry mineralization systems but also improves the identification accuracy of mineralization–hydrothermal centers in the western Gangdese belt.

To assess porphyry copper mineralization potential in the western Gangdese belt, we employ MSRS to delineate regional alteration anomalies, followed by SWIR spectroscopy to precisely identify altered mineral species. A Spectral Feature-Based Geological Connotation Method is established to construct spectral exploration indicators for porphyry copper deposits, enabling delineation of mineralization–hydrothermal centers.

2. Study Area

The study area is located in the western part of the Gangdise metallogenic belt in Tibet. The Gangdise metallogenic belt is located in the southern Lhasa terrane, with an east–west extension length of more than 1500 Km. The Gangdese belt on the southern margin of the Lhasa terrane experienced the subduction of the Neo-Tethys oceanic crust and triggered extensive magmatic activity. The Miocene is the main copper and molybdenum mineralization period. Many deposits have been formed in the Gangdese belt of the southern Lhasa terrane, including several world-class deposits, such as the three super-large

deposits of Qulong, Jiama and Zhunuo–Beimulang, and several large and medium-sized copper deposits, such as Jiru, Xiongkun, Tinggong, Gangjiang, and Demingding [22–31] (Figure 1).

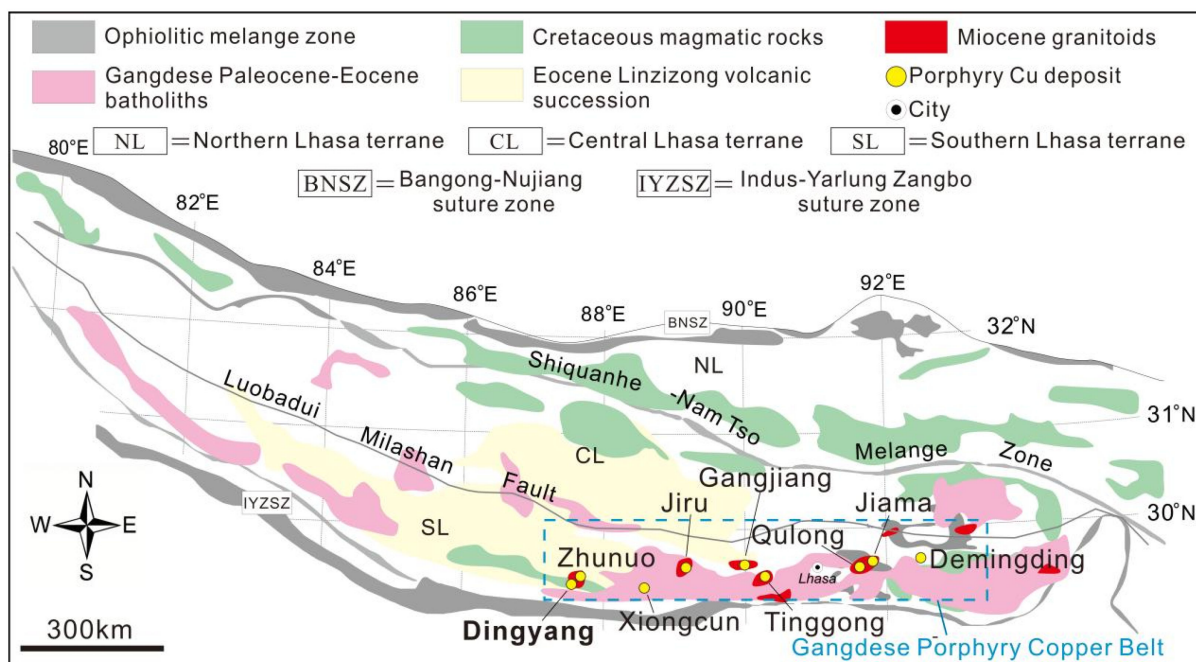


Figure 1. Distribution of porphyry Cu deposits in the Gangdese metallogenic belt and location of the study area (modified from [32–34]).

The study area (Dingyang) is located in the Zhunuo ore concentration area. The exposed strata are mainly volcanic rocks of the Linzizong Group, which are mainly exposed in the central and western parts of the study area. They are in intrusive contact with Eocene magmatic rocks in the southeast. Quaternary sediments only appear along valleys and ravines. The strata are generally inclined to the southwest, and the tectonic development is limited. The magmatic rock in the southeastern part is part of the Beimulang composite rock mass, which is biotite monzonitic granite porphyry.

3. Datasets and Methods

3.1. Data Acquisition and Preprocessing

3.1.1. Sentinel 2 Remote Sensing Image

The Sentinel-2 imagery utilized in this study was sourced from the European Space Agency (ESA) Copernicus Data Hub. The specific scene was acquired on 5 February 2025, with <2% cloud cover ensuring optimal feature discriminability and stable spectral response, thereby providing a high-quality dataset for hydrothermal alteration mapping.

The acquired Level-1C product had undergone orthorectification and subpixel-level geometric correction, representing top-of-atmosphere reflectance imagery. To obtain surface reflectance suitable for quantitative analysis, Level-1C data were batch-processed via the Sen2Cor plugin command line to generate atmospherically corrected Level-2A products, eliminating aerosol and water vapor effects. Subsequently, Level-2A imagery was spatially resampled to a uniform 10 m resolution using SNAP software (Version 10.0) and converted to ENVI (Version 5.6) format to facilitate subsequent mineralization alteration information extraction.

3.1.2. SWIR Spectrum

This study integrates detailed field geological surveys with SWIR spectral alteration mapping, including 11 spectral sampling lines. In key target areas, traverses were spaced at 250 m intervals with sampling points every 50 m, yielding 736 samples. Following the principles of typicality and systematic sampling design, comprehensive field investigations were conducted wherein alteration and mineralization characteristics were meticulously recorded at each sampling site, accompanied by the collection of one to three representative rock samples; all site-specific data—including sample ID, type, geographic coordinates, lithological descriptions, alteration assemblages, and mineralization features—were systematically documented using standardized sampling forms, ultimately achieving a high-resolution control point density of 82 points/km² across the entire study area.

Hyperspectral reflectance data of rock samples were collected using a TerraSpec Halo field-portable hyperspectral spectrometer (ASD Inc., Falls Church, VA, USA), covering the 350–2500 nm spectral range (VNIR: 350–1300 nm; SWIR: 1300–2500 nm) (Table 1). Prior to analysis, samples were surface-cleaned with a brush and air-dried under direct sunlight to eliminate surface moisture. For each sample, three replicate measurements (1 min each) were acquired at spatially distinct, flat surfaces devoid of non-hydroxyl minerals (e.g., quartz) to ensure data accuracy [35]. Measurements were taken under identical illumination conditions, resulting in a total of 2210 high-quality spectral datasets across all samples.

Table 1. Sentinel-2 satellite remote sensing data and hyperspectral data introduction.

Data Source	Subsystem	Band Number	Spectral Range (nm)	Spatial Resolution (m)	Spectral Resolution (nm)
Sentinel-2	VNIR	1	433–453	60 m	
		2	458–523	10 m	
		3	543–578	10 m	
		4	650–680	10 m	
		5	698–713	20 m	
		6	733–748	20 m	
		7	773–793	20 m	
		8	785–900	10 m	
		8 A	855–875	20 m	
		9	935–955	60 m	
	SWIR	10	1360–1390	60 m	
		11	1565–1655	20 m	
		12	2100–2280	20 m	
ASD TerraSpec Halo	VNIR		350–1300		3
	SWIR		1300–2500		8.1

3.2. Methods of Analysis

3.2.1. Multispectral Alteration Anomaly Extraction

In this study, the band ratio method combined with PCA was used to extract alteration information. Firstly, according to the spectral configuration of Sentinel-2 data, the key bands sensitive to altered minerals are selected. Based on the difference in the characteristic absorption and reflection of altered minerals in visible and short-wave infrared bands, Principal Component Analyses and band ratios of various alteration types were constructed, such as the following:

Al-OH alteration was analyzed by PCA using Band2, Band8, Band11 (1610 nm, high reflection region on the left side of Al-OH absorption peak) and Band12 (2190 nm, strong

absorption valley covering Al-OH). The band combinations of Band3, Band4, Band8A (865 nm, located at the high reflection peak of Mg-OH) and Band12 (2190 nm, located in the sensitive band range of the absorption valley near 2300 nm of Mg-OH minerals, and reflecting the mixed characteristics of Mg-OH and Al-OH) were used to extract the change in Mg-OH. Given the limited surface vegetation coverage in the study area, vegetation interference is negligible. Consequently, Band3 (green) was selected over Band4 (red) for carbonate alteration analysis. Band12 (2190 nm) is pivotal, as it aligns with the strong absorption valley (~2300 nm) of carbonate minerals, enabling the identification of carbonates through low reflectance values. Band11 (1610 nm), situated near the reflection peak (~1600 nm) of carbonate minerals, forms a pronounced spectral contrast when combined with Band12. Principal Component Analysis (PCA) effectively amplifies this absorption–reflection contrast. Therefore, Bands 3, 8, 11, and 12 were utilized for PCA to enhance carbonate alteration detection. In the ferric contamination anomaly, since Band4 (665 nm) corresponds to the strong absorption valley of Fe^{3+} and Band2 (492 nm) is at the reflection peak, the Band4/Band2 ratio method is employed to enhance and extract anomaly information, thereby improving the recognition accuracy of ferric contamination anomaly minerals.

Secondly, the constructed ratio image is combined with key bands to implement PCA. Through the feature vector load analysis, the bands or ratios that contribute the most to the alteration information in different principal components are identified, so as to realize the separation of background noise and alteration anomalies.

Finally, by comprehensively discriminating and comparing PCA results with ratio images, we adopted a threshold criterion of ' $\mu + 1.5\sigma$ ' (where μ denotes the mean value of the relevant principal component image and σ represents the standard deviation). Pixels meeting this criterion were identified as true anomalies containing alteration information. Subsequently, various types of alteration anomaly information were extracted, and the alteration anomaly zones were delineated through spatial superposition analysis.

3.2.2. SWIR Spectral Analysis

The SWIR spectral data were processed using the Spectral Geologist Version 8 (TSG 8) software. The software uses the spectral band position matching algorithm to identify altered minerals and quantifies their relative abundance and other spectral indicators by cross-correlation with the internally verified mineral spectral library. Thus, it can robustly describe the spatial variation of altered mineral assemblages and derive vector indicators for mineral exploration. In this paper, the maps of spectral parameters were made by the ArcGIS10.8 software. The spectral three-dimensional map is based on the Kriging interpolation method and superimposed ASTER GDEM 30M resolution digital elevation data.

4. Result

4.1. Alteration Anomaly Extraction

In the extraction of alteration information, the principal component results of Al-OH alteration information show that the band11 load in PC1 is positive and the band12 is negative. The alteration information is concentrated in PCA1 (Table 2), and the threshold 2697 is set to divide its alteration anomaly (Figure 2a). When extracting the Mg-OH alteration information, the band8 A load in PC4 is positive, band12 is negative, the alteration information is concentrated in PCA4 (Table 3), and threshold 123 is set to divide the anomaly (Figure 2b). When extracting carbonate minerals, the band11 load in PC4 is positive and the band12 load is negative, the alteration information is concentrated in PCA4 (Table 4), and the threshold value 210 is set to divide its distribution area (Figure 2c). The results of

extracting the band ratio of ferric contamination anomalies were compared and verified by multiple sets of experiments. The threshold was determined to be 1.85, and the pixel ratio reached or exceeded the value, which was determined as the real anomaly information (Figure 2d).

Table 2. Principal Component Analysis (PCA) of Sentinel-2 bands for Al-OH mineral mapping: Band2, Band8, Band11, and Band12.

Principal Component	Band2	Band8	Band11	Band12
PC1	0.20	0.50	0.66	−0.52
PC2	0.80	0.41	−0.37	−0.24
PC3	0.49	−0.68	−0.05	0.54
PC4	−0.29	0.33	−0.66	0.61

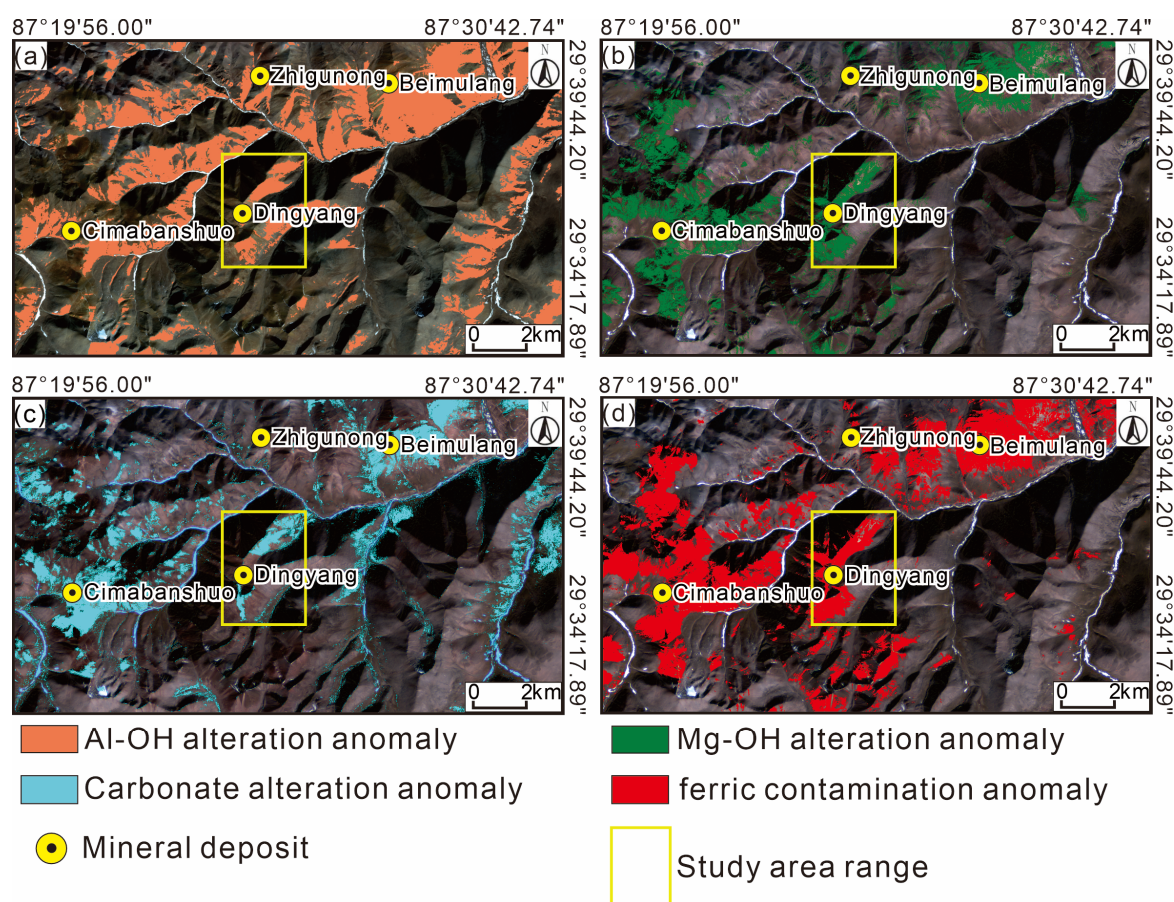


Figure 2. (a) Al-OH alteration anomaly; (b) Mg-OH alteration anomaly; (c) carbonatization anomaly; (d) ferric contamination anomaly.

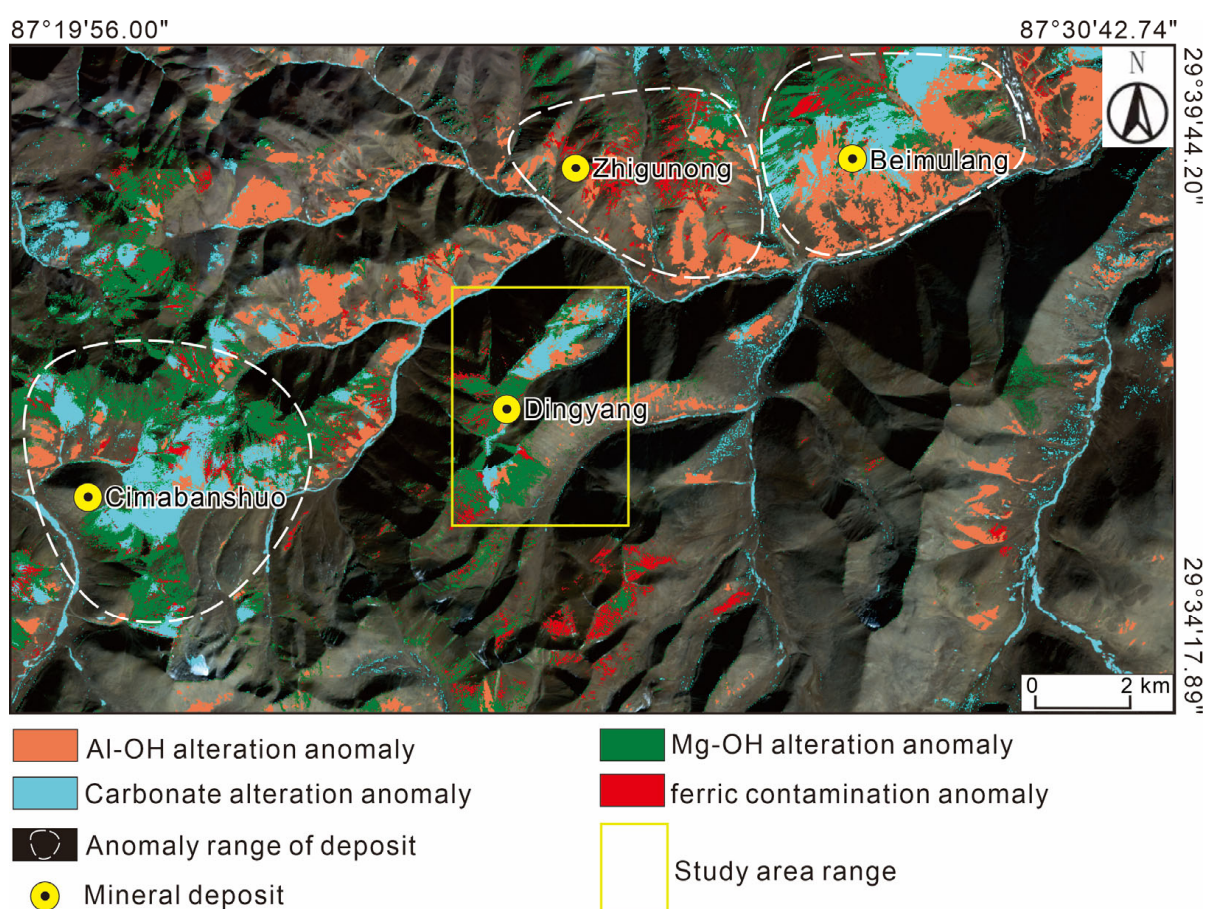
Table 3. Principal Component Analysis (PCA) of Sentinel-2 bands for Mg-OH mineral mapping: Band3, Band4, Band8A, and Band12.

Principal Component	Band3	Band4	Band8A	Band12
PC1	0.38	0.49	0.55	0.56
PC2	0.58	0.45	−0.10	−0.68
PC3	0.46	−0.06	−0.75	0.47
PC4	0.56	−0.75	0.36	−0.07

Table 4. Principal Component Analysis (PCA) of Sentinel-2 bands for carbonate mineral mapping: Band3, Band8, Band11, and Band12.

Principal Component	Band3	Band8	Band11	Band12
PC1	0.29	0.50	0.64	0.50
PC2	0.77	0.38	−0.41	−0.29
PC3	0.29	−0.43	−0.39	0.76
PC4	0.49	−0.65	0.51	−0.28

By integrating anomalies of key alteration types—including Al–OH minerals, Mg–OH minerals, carbonate alterations, and ferric contamination anomalies—this study demonstrates that, in addition to well-defined alteration associated with known deposits such as Beimulang, Zhigunong, and Cimabanshuo, the Dingyang area also exhibits significant surface alteration (Figure 3).

**Figure 3.** Superimposition of remote sensing alteration anomalies.

4.2. Identification and Distribution of Altered Minerals

A handheld SWIR spectrometer was employed in the Dingyang area to map hydrothermal alteration minerals. A large number of field samples were systematically collected and analyzed through laboratory spectral measurements. The acquired SWIR data were processed using TSG software, resulting in the identification of nineteen alteration minerals, including illite, kaolinite, sericite, paragonite, phengite, montmorillonite, gibbsite, chlorite-group minerals, biotite, phlogopite, amphibole, epidote, tourmaline, ankerite, siderite, magnesite, and jarosite. Relative mineral abundances were estimated based on the absorption depth spectral absorption features. Spatial distribution patterns and alteration intensity variations of key minerals were subsequently delineated across the study area.

The integration of SWIR spectral data and alteration characteristics facilitated the analysis of relative mineral abundances, allowing for the delineation of distinct hydrothermal alteration zones (Figure 4a).

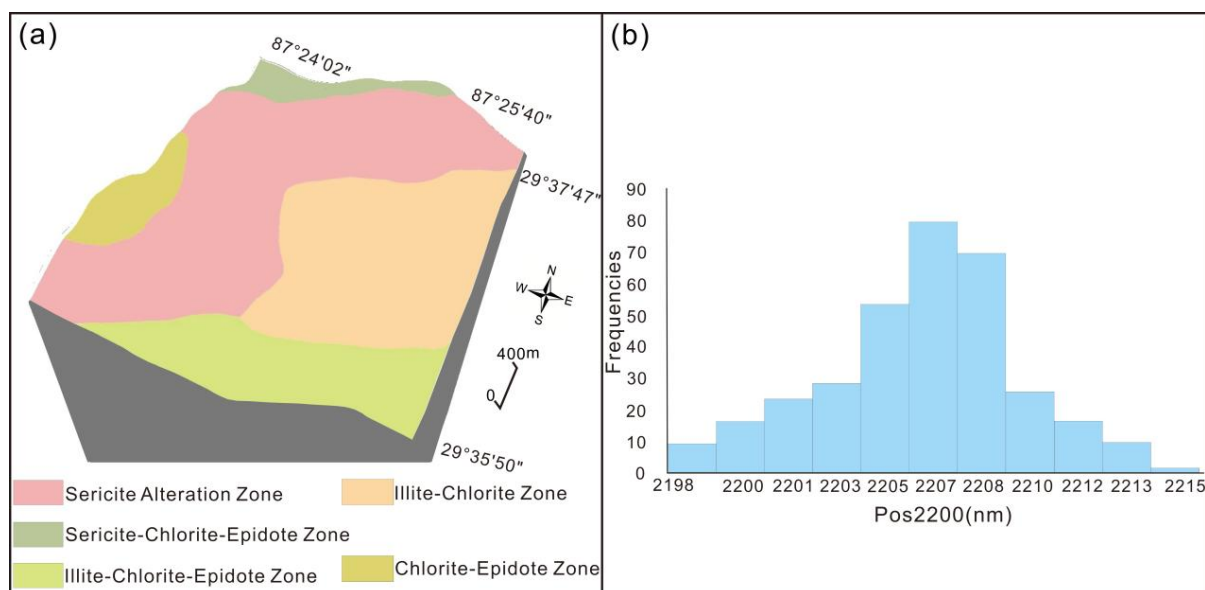


Figure 4. (a) Alteration zoning in the Dingyang study area; (b) histogram of sericite Al-OH absorption peak wavelength position (Pos2200).

Sericite Alteration Zone: Centrally located and trending NE–SW, this zone is spatially extensive and exhibits the highest abundance of sericite (Figure 5a). Sericite-group minerals here display crystallinity values generally exceeding 2 (Figure 5c), indicative of proximity to the hydrothermal fluid source. This zone exhibits the strongest spatial and spectral correlation with mineralization.

Sericite–Chlorite–Epidote Zone: This zone occurs north of the Sericite Zone, trending approximately east–west. Chlorite and epidote show elevated abundances (Figure 5d,e), while sericite content is notably reduced. Sericite crystallinity (SWIR-IC) decreases significantly ($\text{SWIR-IC} < 2$), suggesting a more distal position relative to the hydrothermal center. Chlorite is predominantly of the short-wavelength type, with an Fe–OH absorption peak wavelength position (Pos2250) typically < 2250 nm (Figure 5f).

Illite–Chlorite Zone: Located in the central–eastern portion of the study area and surrounding medium- to coarse-grained monzogranite, this semi-elliptical zone is extensive. Sericite is scarce, whereas chlorite is relatively abundant. Illite crystallinity ranges between 0 and 2, and chlorite is mainly of the short-wavelength type, with $\text{Pos2250} < 2250$ nm. This zone likely represents the outer boundary of hydrothermal influence.

Illite–Chlorite–Epidote Zone: This zone occupies a small area in the southeastern corner of the study region. Alteration is characterized by illite and chlorite with minor development of epidote, suggesting weak hydrothermal overprint.

Chlorite–Epidote Zone: Situated on the southwestern margin of the study area, this narrow, N–S-trending zone shows strong development of chlorite and epidote, with negligible sericite presence. Chlorite here is predominantly of the long-wavelength type, with $\text{Pos2250} > 2250$ nm, reflecting its distal nature relative to hydrothermal upflow zones.

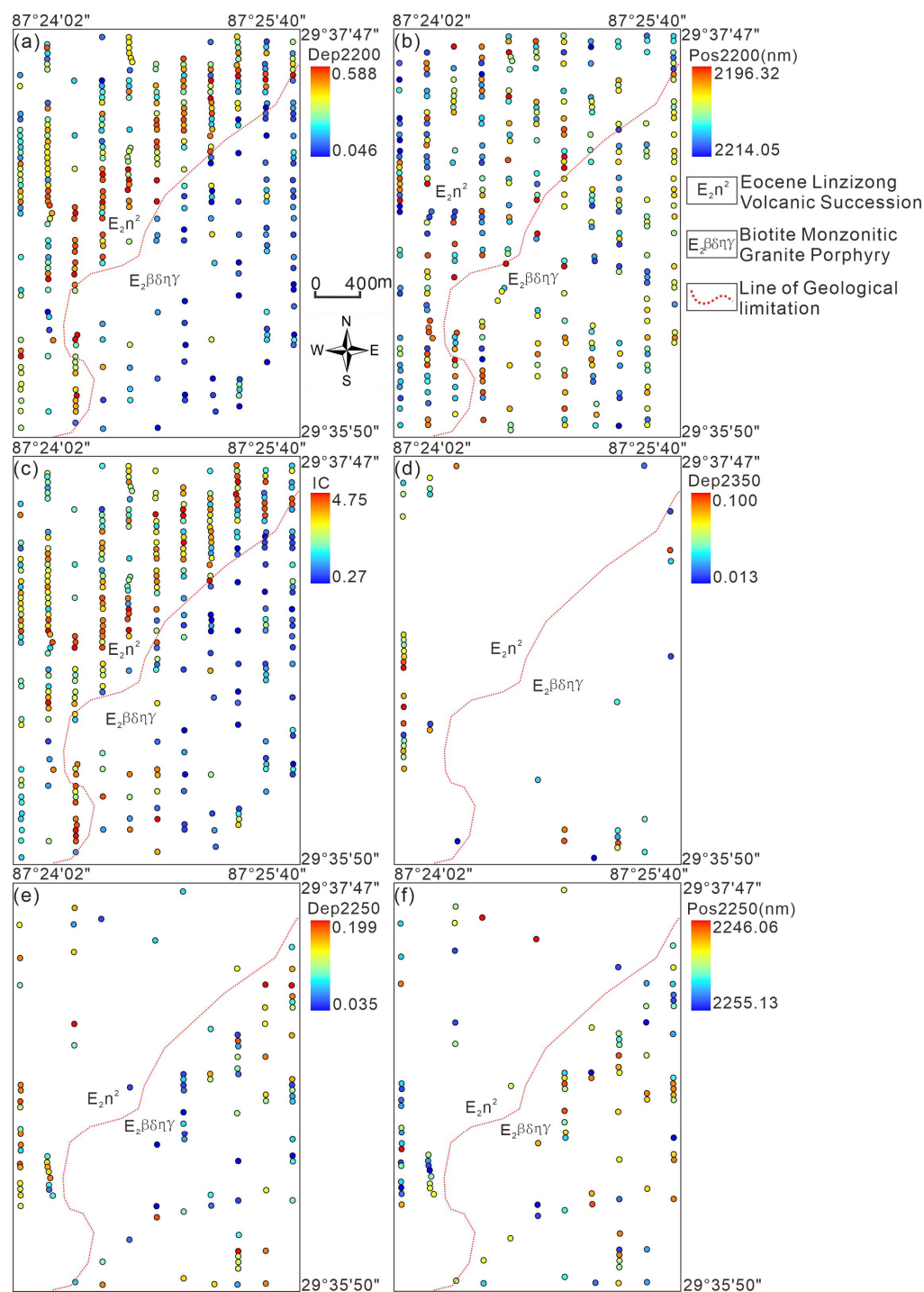


Figure 5. (a) Spatial distribution of sericite Dep2200 values; (b) spatial distribution of sericite Pos2200 values; (c) spatial distribution of sericite SWIR-IC values; (d) spatial distribution of epidote absorption depth (Dep2350) values; (e) spatial distribution of chlorite absorption depth (Dep2250) values; (f) spatial distribution of chlorite absorption position (Pos2250) values.

4.3. SWIR Spectral Features of Sericite

Sericite-group minerals are common hydrothermal alteration indicators widely distributed in magmatic–hydrothermal systems. Their composition and structure record changes in physicochemical conditions (P–T–X). Consequently, they provide critical constraints on ore-forming fluid migration pathways and hydrothermal evolution [36–38]. Sericite stands out as a predominant and pervasive alteration mineral across the entire Dingyang area, playing a pivotal role in the hydrothermal alteration system.

Integration of TSG software and manual spectral analyses identified all sericite-bearing spectra. The quantification of sericite abundance via Al-OH absorption peak depth (Dep2200) reveals that higher Al-OH absorption peak depth (Dep2200 > 0.3) is present in the NE, central, and SW sectors, predominantly within the Linzizong Group volcanic rocks (Figure 6b). Lower absorption depths occur in the SE sector, primarily within biotite monzonitic granite porphyry (Figure 5b). Sericite at the Dingyang surface exhibits Pos2200 ranging from 2198 nm to 2215 nm (Figure 4b), with most being phengitic [Si, Mg, Fe] and characterized by Pos2200 > 2210 nm. Two short-wavelength anomaly centers located in the northern and SW sectors show a systematic outward increase in Pos2200, reflecting crystal–chemical variation (Figure 6a). Furthermore, areas predominantly distributed in the northeastern, northern, and southwestern sectors of the study area are characterized by higher sericite crystallinity values, displaying prominent SWIR-IC anomalies (SWIR-IC > 2) with values decreasing systematically outward (Figure 6c). This diagnostic pattern of high-temperature hydrothermal environments, characterized by the described zoning, delineates core loci of deep hydrothermal activity and guides mineral exploration targeting.

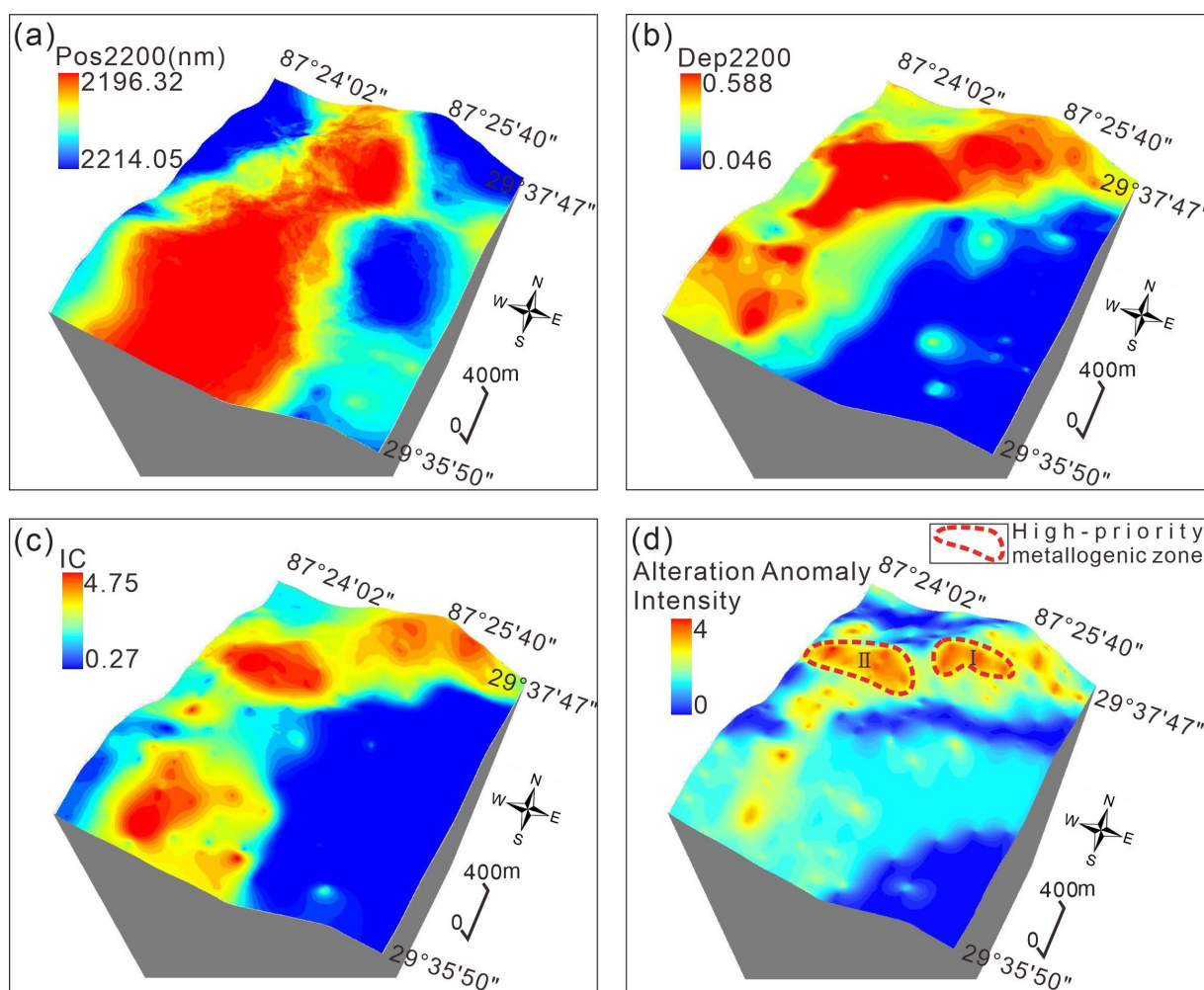


Figure 6. (a) A 3D distribution model of sericite Pos2200 values; (b) a 3D distribution model of sericite Dep2200 values; (c) a 3D distribution model of sericite SWIR-IC values; (d) a map of hydrothermal alteration anomaly intensity at the Dingyang surface.

5. Discussion

5.1. Sericite SWIR Spectral Indicators for Mineral Exploration

An SWIR-based exploration framework centered on sericite-group minerals has been developed. This approach has significant diagnostic value and field applicability for mineral targeting [39–42]. At the Zhule mineralization occurrence in Tibet, a diagnostic exploration indicator utilizing sericite crystallinity ($\text{SWIR-IC} > 2.4$) has been defined for delineating the hydrothermal center [43]. Research at the Demingding Cu-Mo deposit demonstrates that under acidic hydrothermal conditions, a combination of key spectral parameters—namely, the shorter wavelength of sericite ($\text{Pos2200} < 2201 \text{ nm}$), the higher crystallinity ($\text{SWIR-IC} > 1.2$), and the deeper absorption depth ($\text{Dep2200} > 0.4$)—effectively characterizes the hydrothermal center [41]. Sericite's Pos2000 is controlled by octahedral Al^{VI} content. Higher temperatures promote Al^{VI} substitution, systematically decreasing Pos2200 values [44–47]. Pos2200 values systematically increase outward from anomaly centers. This zoning records waning hydrothermal intensity from core to periphery, supporting a deep magmatic heat source. Hydrothermal fluid pH also controls Pos2200: during ascent in porphyry systems, cooling and SO_2 disproportionation generate acidic fluids that stabilize Al-rich sericite [48]. Al-rich sericite typically occurs along shallow-level fluid pathways and displays characteristically lower Pos2200 values [49].

SWIR-IC values in sericite track hydrothermal fluid temperatures [50]. At elevated temperatures, sericite approaches ideal stoichiometry with minimal interlayer water. During cooling, interlayer water adsorption generates a characteristic $\sim 1900 \text{ nm}$ absorption feature, depressing SWIR-IC values [51]. Higher SWIR-IC values, which indicate elevated temperatures [52,53], render SWIR-IC a key proxy for reconstructing hydrothermal temperature gradients. Three prominent sericite SWIR-IC anomalies in the study area, where values decrease systematically outward from each center, delineate high-temperature hydrothermal cores and zones of focused fluid upflow above deep heat sources.

Spatial patterns of sericite spectral parameters, showing markedly elevated fluid temperatures and pressures in the NE, N, and SW sectors relative to peripheral zones and signifying intense magmatic–hydrothermal activity, imply a concealed magmatic–hydrothermal center at depth. Based on the SWIR spectral indicators from the Zhunuo deposit, where sericite with a shorter wavelength ($\text{Pos2200} < 2203 \text{ nm}$), deeper absorption depth ($\text{Dep2200} > 0.2$), and higher crystallinity ($\text{SWIR-IC} > 2.0$) correlates with proximity to ore bodies and enhanced mineralization, combined with the Al-OH alteration information extracted by remote sensing, the parameter threshold is optimized and exploration criteria for sericite in the Dingyang district can be established, with the sericite there having a shorter wavelength ($\text{Pos2200} < 2203 \text{ nm}$), deeper absorption depth ($\text{Dep2200} > 0.3$), and higher crystallinity ($\text{SWIR-IC} > 1.6$), indicating proximity to hydrothermal/mineralization centers. This provides a critical geological foundation for subsequent mineral exploration targeting.

5.2. Spectral Feature-Based Geological Connotation Method (SFGCM)

Contemporary geochemical exploration methodologies integrate statistical modeling (mean-standard deviation, Q-Q plots, PCA), fractal theory (S-A, C-A), spatial scanning (Yang-Chizhong scan statistics), machine learning (autoencoders, Transformer, GAUGE graph networks), geostatistics (kriging), and modern analytical techniques (ICP-MS, isotope tracing), significantly enhancing anomaly detection and resource assessment capabilities [54–57]. Consequently, achieving quantitative and accurate assessment of anomalies within field geological contexts remains a critical challenge in geochemical data processing.

The Geological Connotation Method (GCM) is a geochemical data processing approach rooted in regional metallogenic patterns and geological settings. Its core objective involves quantifying correlations between ore-controlling geological factors and geochemical re-

sponses to identify mineralization-related anomalies [58,59]. The GCM excels in scenarios requiring robust geological constraints, weak-signal enhancement, resolution of episodic mineralization events, and cost-effective exploration. Its core capability lies in constraining solution-space ambiguity through metallogenic principles, achieving synergistic integration of data-driven and geology-driven approaches.

The GCM calculates an ore-concentration coefficient (C_a) for each element a by normalizing its concentration (x_a) against the subregional threshold (T_a):

$$C_a = \frac{x_a}{T_a} \quad (1)$$

The metallogenic anomaly value (A_t) for deposit type t is then

$$A_t = \sum_i C_i \quad (2)$$

where $i \in \{1, \dots, n\}$ denotes the indicator elements diagnostic for deposit type t .

This study integrates remote sensing alteration anomalies with SWIR spectral exploration indicators, introducing the Spectral Feature-Based Geological Connotation Method (SFGCM). The alteration anomaly intensity index is computed by integrating SWIR spectral parameters with remote sensing alteration data through the following workflow: First, spectral parameter quantification is applied to exploration indicator mineral samples: a value of 1 is assigned where $\text{Pos2200} < 2203 \text{ nm}$, $\text{Dep2200} > 0.3$, and $\text{SWIR-IC} > 1.6$; otherwise, 0 is assigned. Second, samples within multispectral remote sensing alteration anomalies receive a value of 1; otherwise, 0 is assigned. Third, per-point summation of both assigned values generates a spatial dataset quantifying alteration intensity. Finally, kriging interpolation produces alteration intensity contour maps (Figure 6d), with thresholds delineating hydrothermal architecture (e.g., >3 = strong anomaly; $0-1$ = weak anomaly).

$$I_a = \sum_{i=1}^n (V_{\text{SWIR}} + V_{\text{RS}}) \quad (3)$$

where I_a denotes the alteration anomaly intensity index, with V_{SWIR} and V_{RS} representing the quantified spectral and remote sensing scores, respectively.

Alteration anomaly intensity peaks in zones I and II, with strong anomalies both localized along regional fault intersections and superimposed on dacitic crystal tuff units. The high-degree spatial correlation between peak alteration intensity and predicted mineralization centers demonstrates dominant control by hydrothermal foci on significant ore–metal enrichment. Kriging interpolation reveals northeast–southwest (NE–SW) trending anomaly axes concordant with subsurface magmatic–hydrothermal conduits, corroborating the porphyry mineralization model in the Zhunuo ore concentration area.

5.3. Discovery of New Mineralisation

This study integrates remote sensing alteration anomalies with SWIR spectral data, utilizing Sentinel-2 data to extract hydroxyl and iron-oxide anomalies and combining them with the SWIR analysis results of 736 field samples, aiming to overcome traditional exploration limitations in complex terrains. SFGCM delineated alteration intensity zones in the Dingyang area, defining two high-priority exploration targets with mineralization potential (Figure 6d). Sentinel-2 multispectral bands effectively map regional hydroxyl-mineral distributions, enabling efficient large-scale reconnaissance. In the Dingyang surface area, Al-OH-bearing alteration minerals (e.g., sericite) dominate, with minor Mg-OH-bearing phases (e.g., chlorite, epidote) identified through SWIR spectrometer analysis. The spectral data confirm sericite as the primary alteration mineral, aligning with remote sensing

interpretations. However, field observations reveal discrepancies: chlorite and epidote occurrences are limited, yet their proportions in remote sensing extractions are overestimated, likely due to band selection constraints in capturing specific mineral signatures.

The presence of carbonate minerals was confirmed by field sampling of malachite, while ferric contamination anomalies reflect hematite-limonite enrichment, indicating a widespread red-brown iron oxidation zone. The observed surface limonite mineralization further validates the remote sensing interpretation of these iron-stained anomalies.

Where remote sensing alone struggles to distinguish mineral species, SWIR spectral analysis plays a critical role. Diagnostic Pos2200 absorption features confirm sericitization as the dominant process underlying target-zone hydroxyl anomalies, thereby reducing non-mineralizing alteration “noise” and refining exploration targets to high-probability mineralization zones.

Mineralization potential in new targets is confirmed via integrated remote sensing and diagnostic sericite SWIR criteria, as these signatures correlate with intense hydrothermal activity and coincide with hematite-limonite reflectance anomalies. The targets form an NE-SW linear cluster adjacent to the Zhunuo–Beimulang deposit, consistent with regional metallogenic models. During the field survey in the high-probability metallogenic zone I (Figure 7), new mineralization has been discovered, where disseminated malachite and azurite overprint hypogene bornite on monzogranite. The discovery of two new mineralization sites has expanded the known mineralization range of the Zhunuo ore concentration area (Figure 8).

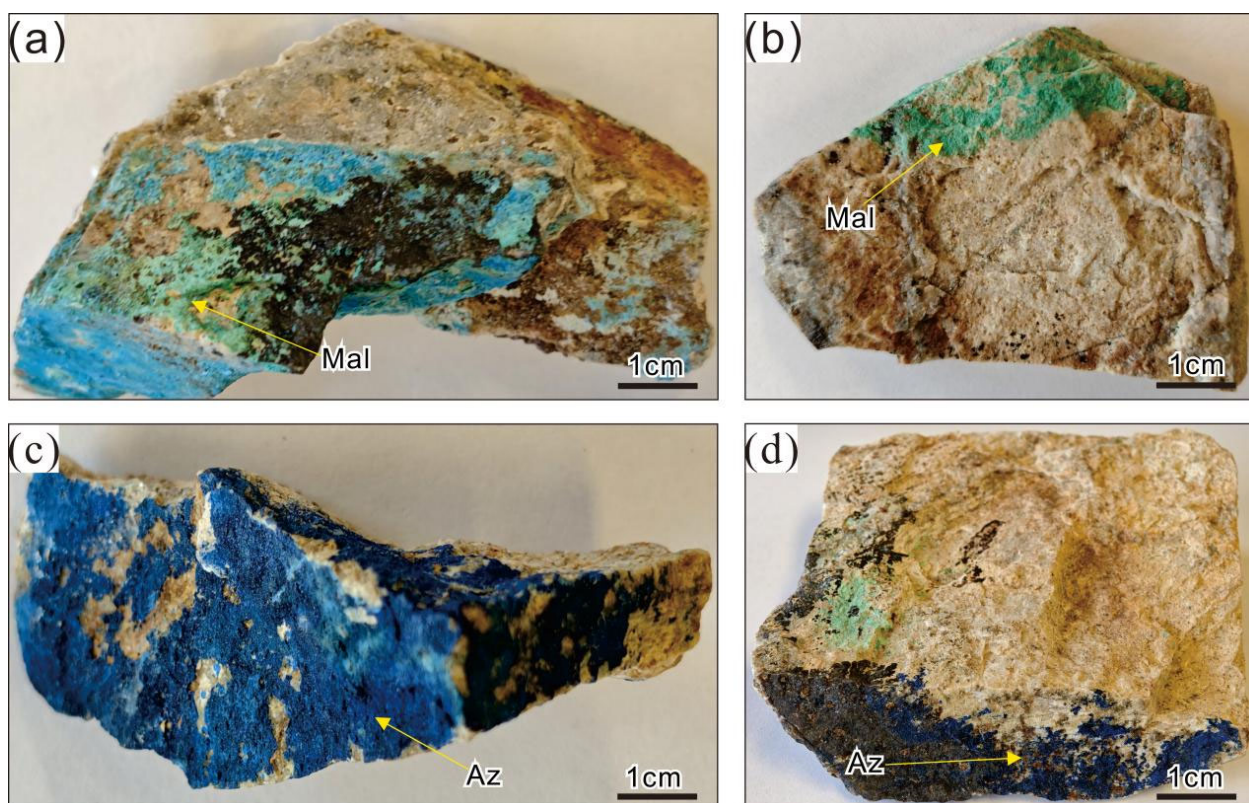


Figure 7. Mineralization within the target areas of the high-probability metallogenic zone I. (a–d) Copper mineralization. Abbreviations: Mal = malachite, Az = azurite.

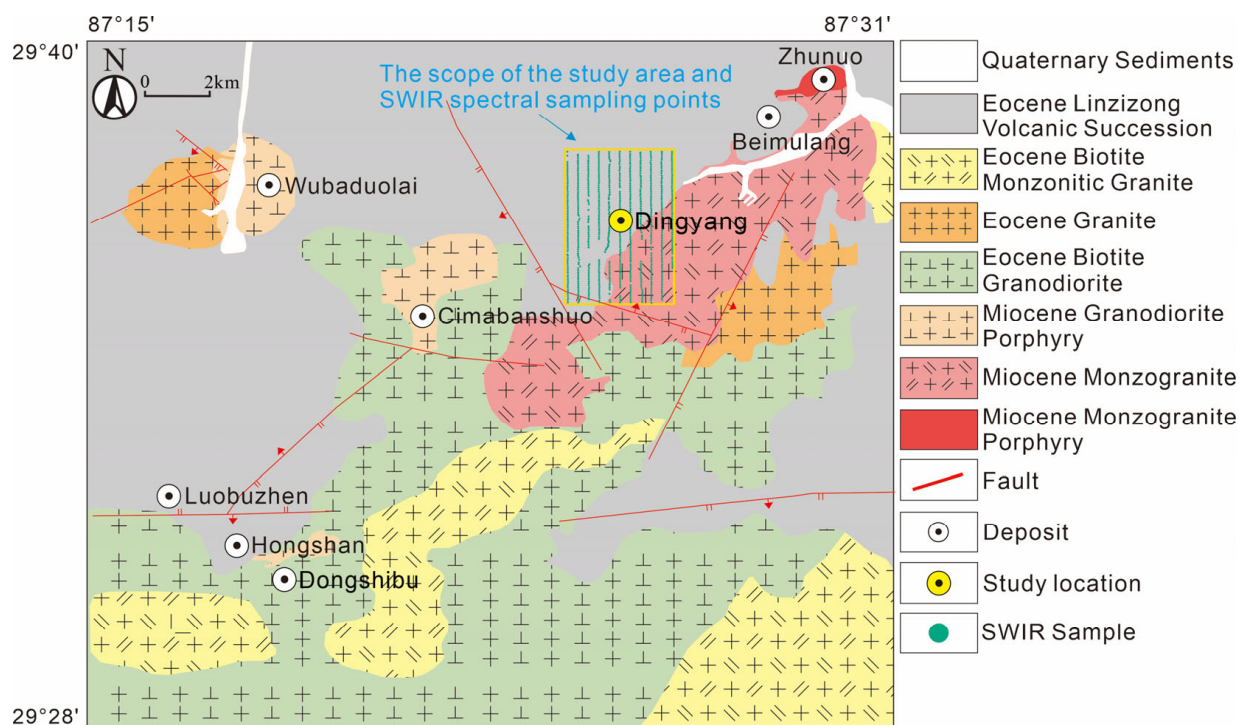


Figure 8. Distribution of porphyry deposits (points) in the Zhunuo ore concentration area.

6. Conclusions

- (1) Sentinel-2 data identified Al-OH, Mg-OH, carbonate alterations, and ferric contamination anomalies. Diagnostic exploration criteria were defined based on the SWIR spectral characteristics of targets: $\text{Pos2200} < 2203 \text{ nm}$, $\text{Dep2200} > 0.3$, $\text{SWIR} - \text{IC} > 1.6$.
- (2) The Spectral Feature-Based Geological Connotation Method (SFGCM) integrates remote sensing anomalies with SWIR spectral parameters to quantify alteration intensity and delineate ore-related anomalies.
- (3) SFGCM refines alteration anomalies, delineates mineralization centers, and discovers new prospects, providing a validated approach for targeting ore-forming cores in spectral-based exploration.
- (4) This study discovers new mineralized areas, expands the mineral resource potential of the Zhunuo ore concentration area, and demonstrates a replicable workflow for regional resource exploration.

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