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REVIEW

Research on the Characteristics of Hydrothermal Alteration Minerals in the Qiucun Gold Deposit, SE China: Based on Hyperspectral Remote Sensing Technology

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ABSTRACT

This review summarizes studies of hydrothermal alteration minerals at the Qiucun gold deposit in southeastern China and focuses on characterization and mapping of the deposit using hyperspectral remote sensing. The deposit exhibits multistage fluid-rock interaction, as evidenced by systematic alteration assemblages, including silicification, sericitization by white micas, the development of argillaceous clays, variable chloritization, and locally significant carbonate alteration. We describe the genetic importance of such mineral groups and emphasize their diagnostic Visible and Near-Infrared to Short-Wave Infrared (VNIR–SWIR) spectral signatures, especially Al-OH, Mg-OH/Fe-OH, and CO_3 absorption bands, which make it possible to distinguish between minerals, not to mention the fact that, in some instances, compositional trends may be predicted. This review's methodological advances are discussed beginning with data collection at satellite, airborne, and ground levels, proceeding to processing procedures, such as atmospheric

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and topographic correction, and culminating in spectral analysis, including continuum removal, spectral matching, and unmixing/classification techniques. An integrated study of hyperspectral findings reveals that alteration minerals develop spatially coherent zones that are strongly controlled by fault/fracture structures and host-rock reactivity, producing proximal silicification/sericitization cores and larger silicified/larcenies of argillaceous rocks owing to diverse apex coverings of carbonate. This should be combined with petrography and geochemistry to address overprinting, mixed pixels, and surface weathering, and to couple mineral maps with ore-forming processes. The review finds that hyperspectral remote sensing offers a solid modeling platform for the deposit-scale alteration at Qiucun and other hydrothermal gold systems, and outlines the directions for future research to integrate quantitatively and more three-dimensional alteration characterization.

Keywords: Hyperspectral remote sensing, Hydrothermal alteration, Qiucun gold deposit, Alteration mineral mapping, VNIR–SWIR spectroscopy

1. Introduction

One of the most basic geological reactions to the interaction of the fluid and rock in mineralizing systems is hydrothermal alteration, which has important information on fluid composition, temperature, redox state, and fluid paths [1,2]. Systematic spatial and temporal assemblies of alteration minerals are typical of gold deposits (particularly deposits that are associated with structurally regulated hydrothermal systems) and closely follow the pathways used by ore-forming processes. Consequently, the characterization of the minerals that are altered by hydrothermal processes and their distribution has been traditionally viewed as an influential method of studying the genesis of ores and directing mineral exploration [3]. Nevertheless, alteration patterns are usually multifaceted, overprinted, and spatially discontinuous, so that when analyzed using only conventional field observation and point-based methods, they are difficult to map and interpret effectively.

The Qiucun gold deposit of southeastern China is an example of a typical hydrothermal gold system that is formed at a metallogenic province in a tectonically active sequence. Several periods have been known to have taken place in the region in terms of magmatism, deformation, and fluid activity that have led to structurally controlled gold mineralization with well-developed alteration halos. Past geologic geochemical research has established that the mineralization of gold at Qiucun has a close relationship with specific hydrothermal alteration assemblages, namely silicification, sericitization, argillic alteration, chloritization, and carbonate alteration. Such types of alterations are not only indicative of the physicochemical development of ore-forming fluids but also have a potent influence on the process of gold precipitation and enrichment. However, the available literature is mainly founded on small outcrops, drill core logging, and lab analysis, which in most cases do not adequately represent the complete spatial variation and zonation of alteration minerals at the deposit level [4,5].

The use of remote sensing methods in mineral exploration and alteration mapping has become more and more important due to the possibility of gathering spatially continuous information at a large scale, fast, non-invasively, and at low costs [6]. Initial uses were made mainly of multispectral satellite imagery, including Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which has been found useful in determining the general zones of alterations. The spectral bands of multispectral sensors are, however, limited, and the spectral resolution, in comparison to their spectral bands, is quite coarse, which limits their ability to distinguish mineral species that exhibit similar spectral responses. This is more severe with the hydrothermal modification minerals, including white micas, clay minerals, chlorite, and carbonates, whose diagnostic absorption characteristics are thin and delicate.

The type of technology that has made significant progress in that regard is hyperspectral remote sensing technology. Hyperspectral data available in hundreds of contiguous spectral bands permits direct identification of diagnostic-absorption bands associated with particular molecular bonds (e.g., Al-OH, Mg-OH, Fe-OH, CO_3). This has made the hydrothermal alteration minerals much easier to identify and map, as well as in some instances even to make inferences on how changes in mineral chemistry are potentially temperature or fluid-composition-dependent. As a result of this, hyperspectral remote sensing is currently a significantly relevant technology to alteration mineral mapping of a large variety of ore deposit types, such as porphyry, epithermal, and orogenic gold systems [7].

In spite of these developments, a full application of hyperspectral remote sensing in deposit-scale research has not been evenly employed, especially in geologically complicated regions like southeastern China. Numerous past hyperspectral studies have technologically three-dimensionally scouted regions or methodology, whereas fewer studies have syntactically incorporated hyperspectral findings with finer geological, mineralogical, and geochemical data to analyze ore-forming processes. In the case of the Qiucun gold deposit, in particular, there is no overall synthesis of hydrothermal alteration mineral characteristics based on the hyperspectral data. The space arrangement of alteration minerals, the extent to which spectral measurements may indicate mineral chemistry and hydrothermal environments, and the connection between hyperspectral-obtained alteration patterns and structural controls and gold mineralization remain in question [8].

The other issue is the interpretation of hyperspectral data in locations where the surface condition is complicated [9]. Spectral signatures can also be covered or altered by vegetation cover, weathering, soil development, and mixed pixels, which may result in misidentifying a mineral unless they are dealt with appropriately. Moreover, other alteration minerals can exist at sub-pixel scales or become fine-grained intergrowths, making spectral unmixing and classification difficult. These problems demonstrate the importance of strong methodological procedures, strong validation of field and laboratory data, and careful genetic interpretation of the application of the hyperspectral methods to hydrothermal systems.

In this respect, it is high time to give special attention to research on the nature of hydrothermal alteration minerals in the Qiucun gold deposit, which is conducted using the hyperspectral remote sensing technology. This kind of review can integrate the known geological and mineralogical data with the progress of hyperspectral data acquisition and analysis, which gives a better idea of the distribution of alteration mineral assemblages and what they tell us about ore-forming processes. Besides, this work could contribute to defining the best practices in hyperspectral research in the future in such gold deposits by a critical analysis of methodology and limitations [10,11].

This article has threefold objectives. To begin with, it will summarize the geological and metallogenic background of the Qiucun gold deposit with special reference to the development of hydrothermal alteration. Second, it describes the types of alteration minerals present in Qiucun and their diagnostic spectral characteristics, and their genetic implications in terms of gold mineralization. Third, it reviews hyperspectral remote sensing algorithms used in alteration mapping in Qiucun to synthesize the main results on mineral distribution, zonation, and exploration prospects, and determine the residual issues and future research [4,10,12].

Within a framework of the combination of the results of the hyperspectral remote sensing and the traditional geological and mineralogical views, this review attempts to offer a consistent paradigm to explain the phenomenon of hydrothermal alteration at the Qiucun gold deposit. On a larger scale, it seeks to show how hyperspectral technologies can be successfully utilized to describe alteration mineral systems in structurally regulated gold deposits in southeastern China and similar metallogenic provinces in the world.

2. Geological and Metallogenic Setting of the Qiucun Gold Deposit

2.1. Regional Tectonic Framework and Metallogenic Background

Qiucun Gold Deposit is located in the southeastern part of China, where tectonic evolution over a long period of time is complex, consisting of several phases of continental accretion, crustal reworking, and magmatism. This region is part of a large area of the Mesozoic metallogenic belt, which contains many gold, polymetallic, and rare-metal deposits. The fault systems are NE- to NNE-trending and are the prevailing structures of the regional tectonic architecture and have been reactivated many times in Mesozoic extensional and trans tensional regimes. These formations were important when it comes to regulating magma emplacement, movement of hydrothermal fluids, and the subsequent mineralization [4,5].

In the Late Jurassic-Early Cretaceous, there was extensive magmatic activity in southeastern China associated with thinning of the lithosphere and upwelling of the asthenosphere. The regional location of the Qiucun gold deposit and its tectonic framework within southeastern China are shown in **Figure 1**. The felsic intrusions and related volcanic rocks are common and are chronologically and spatially related to the gold mineralization in most of the districts. This tectono-magmatic imprint is recorded in the Qiucun region, where deformation of the local region offers good structural traps and openings to permeable pathways of the auriferous hydrothermal fluids. It is on this outline that the Qiucun gold deposit is a classic illustration of structurally regulated hydrothermal gold mineralization formed in an active continental margin to intracontinental extensional environment [13,14].

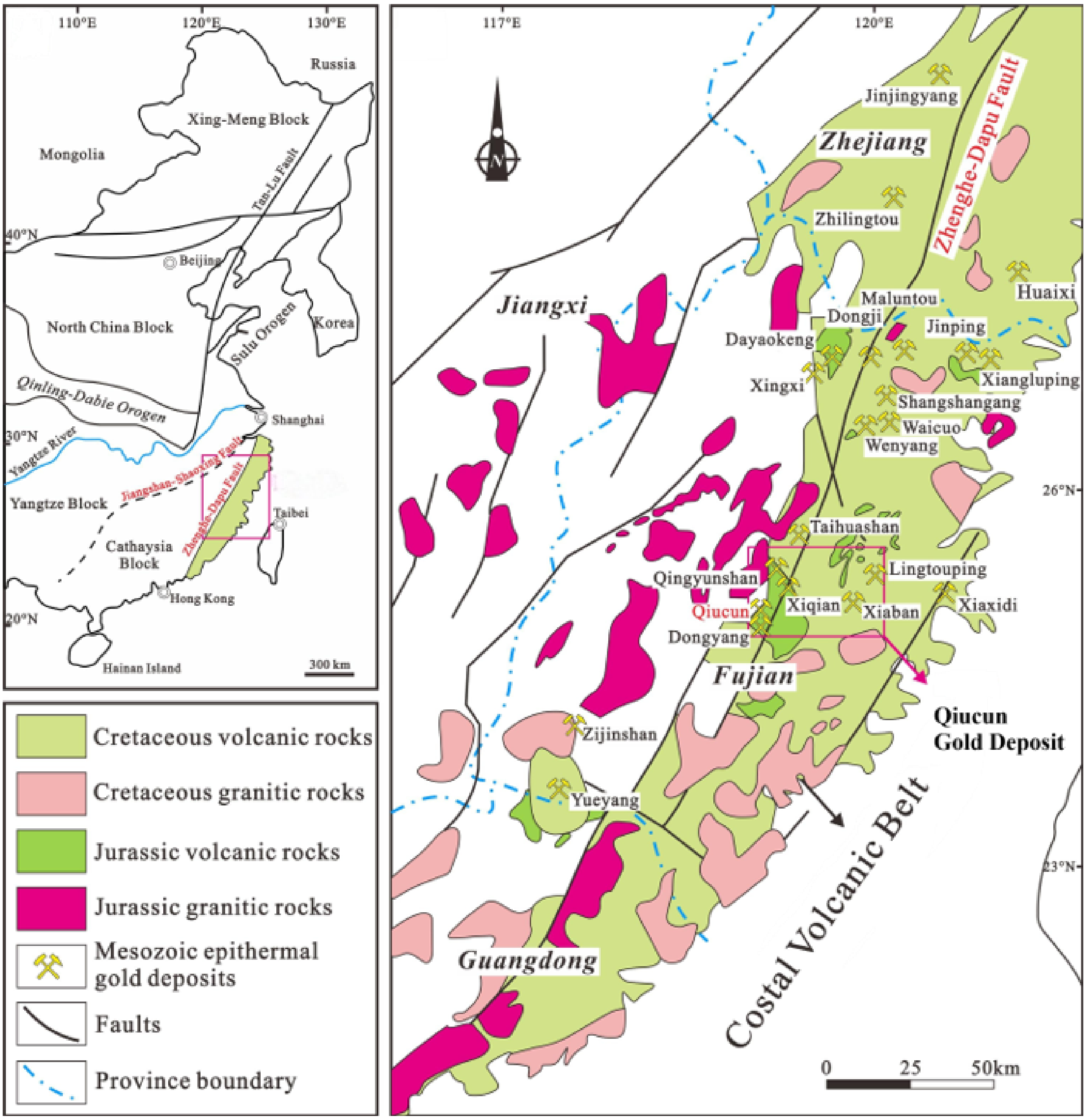

Figure 1. Regional location of the Qiucun gold deposit in southeastern China and simplified tectonic framework, showing major structural trends and metallogenic context relevant to hydrothermal gold mineralization.

Source: Modified from Ma et al. [5].

2.2. Stratigraphy and Lithological Characteristics

The stratigraphic sequence in the Qiucun deposit region consists mainly of Paleozoic and Mesozoic sequences, including both sedimentary and volcanic characteristics, which are occasionally intruded by Mesozoic granitoids and sub-volcanic bodies. Gold mineralization is predominantly in the variably metamorphosed sedimentary rocks such as sandstone, siltstone, shale, and carbonate-bearing rocks, where available, and in volcanic or volcaniclastic rocks. These lithologies have opposing physical and chemical characteristics, and they have a great impact on the style and strength of the hydrothermal alteration [15,16].

Siliceous and clastic rocks are more likely to react to the influx of hydrothermal fluids by becoming pervasively silicified and sericitized, whilst carbonate-rich units are more likely to be decarbonated, replaced, and altered to carbonates. Chloritization, epidotization and local argillaceous alteration are usually well developed in volcanic and subvolcanic rocks. Such a lithological variety at Qiucun also offers a good condition to form several alteration assemblages with various mineralogical and spectral properties [17,18].

2.3. Structural Controls on Mineralization and Alteration

At Qiucun, both gold mineralization and hydrothermal alteration are controlled by structural elements of the first order. The bodies of ore are mainly concentrated in major faults and fracture zones, which are channels of upward-flowing hydrothermal fluids. Such constructions are usually steeply dipping and have multistage evidence, such as brittle deformation, brecciation, and reopening. Branches of the primary fracture networks that run off the primary faults also increase fluid flow and the formation of alteration halos [19,20].

The intensity of hydrothermal alteration tends to be directed to these structurally constrained fluid conduits, creating distinct alteration zones that wrap mineralized veins or disseminated ore bodies. The structure-lithology interaction produces heterogeneous patterns of alteration spatially, with steep lateral and vertical gradients between the various types of alteration. The need to use the spatially continuous mapping tools, including hyperspectral remote sensing, to capture the structural alteration relationships at the deposit scale is revealed by such complexity [6,21].

2.4. Styles of Gold Mineralization and Ore Characteristics

The mineralization of gold in the Qiucun deposit is mainly hydrothermal and is distributed mostly in the vein and veinlet systems and local distributions in the altered host rocks [4]. The main gangue mineral is quartz, in most cases with the sulfides, which include pyrite, arsenopyrite, and minor base-metal sulfides. Gold is found as either native gold or electrum, but is usually found together with sulfide minerals or in the form of quartz-sulfide veins. A simplified geological map highlighting lithologies, principal structures, and the distribution of orebodies and ore-bearing veins is provided in **Figure 2**. Mineralization style is evidence of a close genetic relationship between gold deposition and hydrothermal alteration. Silicification is typically strongest in and around ore-bearing structures, and sericitization and anglicization represent much larger halos. Carbonates change, and chloritization are more flexibly evolved and can be either a form of distal change or an overprinting of subsequent hydrothermal processes. These geometries are significant hints to the understanding of the development of the hydrothermal system and to steering towards mineralized areas [5,22,23].

2.5. Hydrothermal Alteration Stages and Paragenesis

The petrographic and field data show that alteration by hydrothermal at Qiucun was formed in more than one stage, in line with the development of the hydrothermal system. Characteristic changes in host rocks, such as chloritization and early silicification, of a relatively high-temperature fluid-rock interaction are typical of an early stage. This phase is generally superimposed by a major ore stage characterized by severe silicification, sericitization, and deposition of sulfides, where the maximum gold precipitation took place [24].

Late hydrothermal modification is indicated by the existence of argillaceous alteration, carbonate veining, and local oxidation that can somewhat cover the previous alteration [25]. Alteration minerals are further modified by supergene processes, which alter the surface expression of minerals through weathering and oxidation. This aspect of Qiucun change leads to complicated mineral associations and overprinting correlation that should be unraveled carefully when using hyperspectral data to interpret the data.

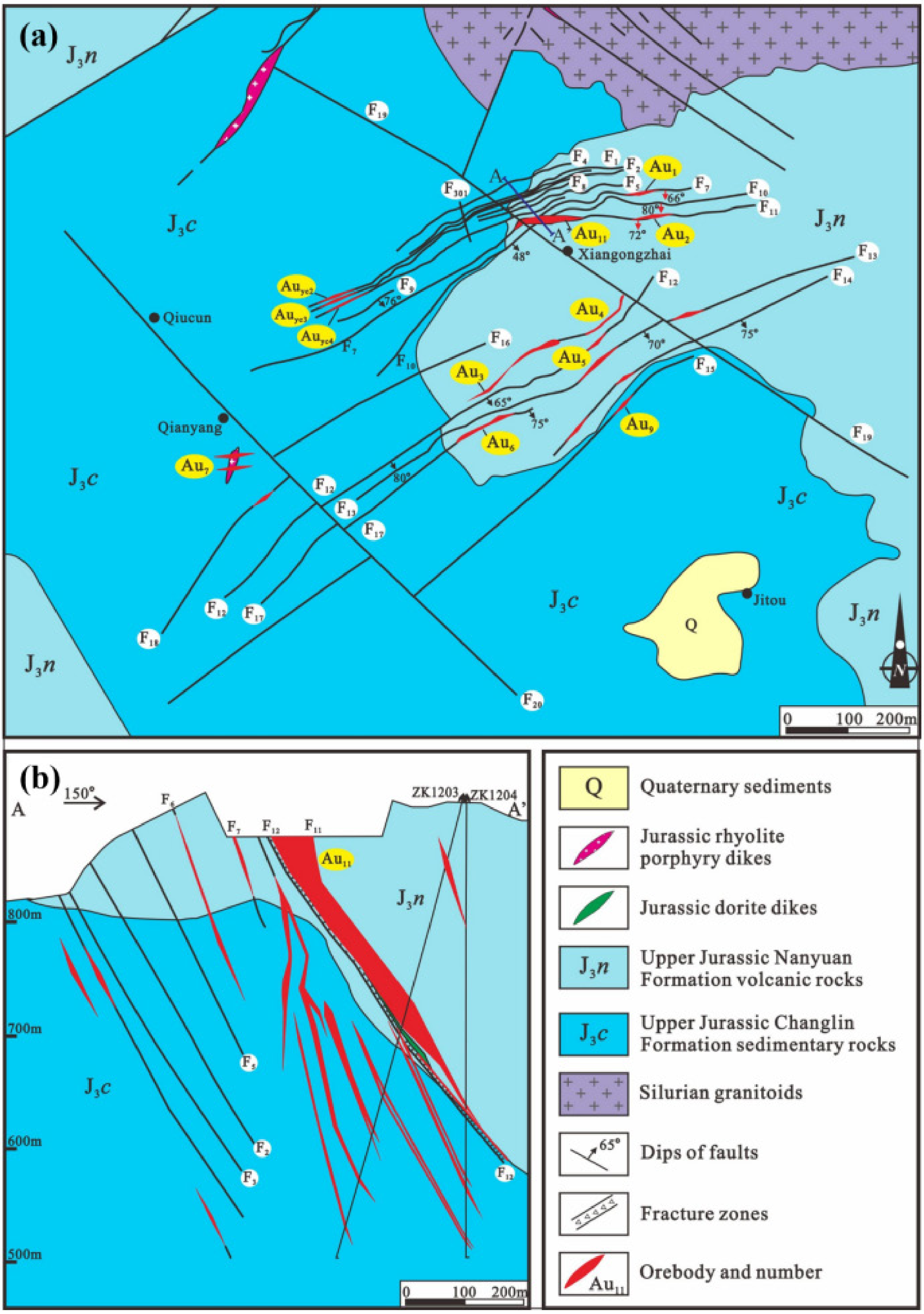

Figure 2. Simplified geological map: (**a**) orebody distribution of the Qiucun gold deposit; (**b**) its cross-section.

Source: Modified from Ma et al. [5].

2.6. Previous Studies and Remaining Knowledge Gaps

The other studies conducted on the Qiucun gold deposit have been centered on the geology of the region, the ore mineralogy, and their geochemical properties, and these studies give a simple outline of the life of the Qiucun gold deposit concerning its metallogenesis [5]. There has been a general description of alteration minerals, but a more spatially resolved characterization of alteration assemblages has not been performed in detail. Specifically, the patterns of distribution, zonation, and mineral-chemical variations of alteration minerals at the deposit scale are not completely constrained.

Such constraints emphasize why it is necessary to develop integrated research works that fuse the conventional geological studies with the advanced remote sensing systems. Hyperspectral remote sensing, a technique to identify and map alteration minerals using diagnostic spectral bands, is a potent technique in fighting these gaps. The geological and metallogenic context of the Qiucun gold deposit clearly presents the fundamental basis for understanding hyperspectral alteration maps as well as interpreting spectral observations in terms of hydrothermal activity and gold mineralization [10].

3. Hydrothermal Alteration Minerals: Types, Spectral Characteristics, and Genetic Significance

3.1. Conceptual Framework of Hydrothermal Alteration in the Qiucun System

Hydrothermal alteration minerals are minerals that document the mineralogical history of fluid-rock interaction and are a direct reaction to the fluctuation in temperature, pressure, fluid composition, and wall-rock chemistry [26]. Alteration minerals in structurally regulated gold systems, like the Qiucun Gold Deposit, develop along with and independently of gold deposition, in spatially organized assemblages that indicate the developmental history of the hydrothermal system. Knowing the kinds of these minerals and their properties is thus a prerequisite to both the reconstruction of the ore-forming processes as well as the recognition of mineralogical vectors leading to gold mineralization.

At Qiucun, hydrothermal change is not even throughout, nor is it single-origin. Rather, it is an indication of a multistage system where the initial fluid infiltrated and altered the physical and chemical characteristics of the host rocks, further increasing permeability and thereby providing good conditions to precipitate gold. The mineral assemblages that result are known to be sensitive to each successive phase of fluid activity and overprinting, thus being crucial in indicating hydrothermal evolution [3,27].

3.2. Major Alteration Types and Associated Mineral Assemblages

At Qiucun, several types of alteration are worked out, which can be described with different mineralogical associations. One of the most common alteration styles is silicification, which takes place in the form of huge quartz veins, veinlets, and replacement of host rocks. This change goes hand in hand with gold mineralization and indicates silica-filled hydrothermal fluid, which is usually related to a drop in the fluid solubility and gold deposition [28,29].

Sericitization is predominantly fine-grained white mica mineral, including muscovite, elite, and sericite, which is vastly developed around ore-bearing structures [30]. This kind of alteration generally overprints previous assemblages and develops very large halos, which are outside the actual mineralized areas. Surprisingly easy to identify is the argillaceous alteration that is typified by kaolinite and associated Al-rich phases and may indicate low-temperature, acidic fluid conditions or overprinting during the late stages of the hydrothermal system.

Alteration (chloritization and propylitic-style), which entails hardening and the use of chlorite, epidote, and even carbonate minerals, is variably developed and is mostly found within particular lithological units or in distal areas. Carbonate alteration, which is indicated by the replacement and veining of calcite, dolomite, or ankerite, represents interaction between hydrothermal fluids and carbonate-bearing host rocks or late-stage fluid development with CO_2-rich components. A combination of these types of alterations comprises a very complex yet genetically significant pattern of assemblage that would be utilized to explain the hydrothermal processes at Qiucun [31,32]. **Table 1** summarizes the main types of alterations, their mineral representatives, and their implications for the genetic system in the Qiucun system.

Table 1. Hydrothermal alteration types at the Qiucun gold deposit, representative mineral assemblages, typical expressions, and genetic significance for interpreting hydrothermal evolution and gold mineralization.

Alteration Type	Representative Minerals	Typical Field Expression	Genetic Significance in Hydrothermal System	Common Association with Au at Qiucun (Conceptual)
Silicification	Quartz, chalcedony (local)	Quartz veins/veinlets; pervasive replacement; hard, resistant outcrops	High silica activity; permeability focusing; common during main hydrothermal stages	Strongly proximal; commonly coincident with ore structures
Sericitization (phyllic)	Muscovite–illite–sericite (white mica) ± quartz	Bleached, fine-grained mica replacement; halo around veins	Fluid–rock reaction at moderate T; records K–Al metasomatism; useful vectoring halo	Typically proximal to intermediate; surrounds mineralized cores
Argillic alteration	Kaolinite ± illite/smectite (as applicable)	Soft, friable zones; clay-rich overprints	Lower T and/or more acidic fluids; commonly late-stage or shallow overprint	Variable; may overprint ore zones and mask earlier signals
Chloritization/propylitic	Chlorite ± epidote ± albite (context-dependent)	Greenish alteration; replacement of mafic phases	Distal and/or host-controlled; records wall-rock buffering and temperature gradients	Often distal or host-rock controlled; indirect vectoring value
Carbonate alteration	Calcite, dolomite, ankerite (if present)	Carbonate veining; replacement of reactive units	CO_2 activity, fluid mixing, and late-stage evolution; strong lithologic control	Local; can be proximal or late depending on paragenesis
Oxidation (supergene)	Goethite, hematite, jarosite (local)	Gossans, stains, limonitic crusts	Weathering modification of primary sulfides; affects spectral expression	Indirect; may mark sulfide-rich zones but not diagnostic alone

3.3. Diagnostic Spectral Features of Key Alteration Minerals

Hyperspectral remote sensing offers the potential of detecting the hydrothermal alteration minerals due to their diagnostic absorption characteristics in the visible, near infrared, and shortwave infrared [33,34]. White micas have a strong Al-OH absorption feature near 2.20, which shows slight wavelength variations, which can indicate a mineral chemistry change, such as changes in the Al content or octahedral substitutions. These spectrophotometric properties render white micas especially useful as detectors of the intensity of hydrothermal changes and fluid transformation.

Kaolinite and other related phases occur as clay minerals resulting from an argillaceous alteration and have distinct doublet absorption profiles at around 2.16–2.21 µm, which are quite easily identified in hyperspectral data. Chlorite displays Mg-OH and Fe-OH absorption peaks, which are normally located around 2.25–2.35 µm, enabling it to be differentiated against white micas and clays. Diagnostic CO_3 absorption characteristics near 2.33–2.35 µm are used to characterize carbonate minerals that may be difficult to detect through spectral mixing and weathering of the surface [35].

The iron oxides and hydroxides formed by oxidation of sulfide minerals exhibit characteristic characteristics in the visible region and near infrared region. Though quartz does not exhibit powerful diagnostic absorption characteristics in the VNIR 2.53–2.55 cm range, silicification may frequently be indirectly implied by the obscuration of other mineral signatures, or by textural relationships with spectrally identifiable alteration minerals. The spectral attributes of these phenomena are used to identify and map alteration minerals at Qiucun [36].

3.4. Mineral Chemistry Variations and Their Hydrothermal Implications

In addition to the aforementioned basic identification of minerals, the hyperspectral information is capable of giving insights into the chemical variations of minerals that are genetically meaningful [9]. In one example, the slight changes in the position of the Al-OH absorption by white micas have been associated with the variation in the Al content and metal substitution processes, and this can be correlated to an increase or decrease in temperature or fluid composition. In Qiucun, these spectral variations could document gradients between the areas of alteration, which were proximal and of high temperature, and those that were more distant or late-stage.

Likewise, compositional differences in chlorite that can be traced in differences in Mg-OH and Fe-OH absorption characterization can give details of the physicochemical circumstances of modification and the character of host-rock domination. Carbonate mineral assemblies and spectral expression could also indicate a process of fluid mixing or evolution of CO_2 activity, even in the evolution of hydrothermal systems. They are especially useful on systems where direct sampling is restricted, or systems whose alteration patterns are lateral in extent [37,38].

3.5. Spatial Zonation of Alteration Minerals and Relationship to Gold Mineralization

The systematic spatial distribution of alteration minerals at Qiucun is very much related to the distribution of gold minerals [39]. It has long been believed that the strong silicification and sericitization are found in the proximal ones, in those that are situated in proximity of major structures and ore bodies, and argillic and chloritic alteration is found in remote or peripheral areas. Reactive domains, Carbonate alteration can develop discrete domains that are dominated by lithology or late-stage fluid systems.

The progressive changes in fluid temperature, composition, and the interaction between fluids and rock walls can be seen in such zonation as the hydrothermal fluids emanated out of the conduits. These spatial structures are also important to map out the geometry of the hydrothermal system and to locate vectors to mineralized areas. Hyperspectral remote sensing, due to its ability to continuously provide spatial coverage of alteration minerals, provides an effective method of recording such zonation patterns at the deposit scale [6].

3.6. Challenges in Alteration Mineral Identification and Interpretation

Although the hyperspectral methods have a number of benefits, there are a few obstacles that make it difficult to identify and interpret the alteration minerals in Qiucun. Typical diagnostic spectral features can be lost by mixed pixels caused by the intergrowths of micro-mineral grains, weathering, and overall vegetation coverage. The mineral assemblage is further complicated by the overprinting of mineral assemblages by several hydrothermal stages, and it is hard to identify the different stages of mineral assemblage for a particular mineral [2].

Moreover, certain alteration minerals have spectral features that overlap, so it is necessary to pay great attention to the choice of spectral parameters, and high validity is necessitated by field data and laboratory data [40]. These difficulties demonstrate the necessity of combining hyperspectral with petrographic, mineralogical, and geochemical data, which should be integrated to guarantee the successful interpretation process. The ability to have a clear knowledge of alteration mineral properties and their genetic implications, thus gives the much-needed background in implementing hyperspectral remote sensing to unravel the hydrothermal history of the Qiucun gold deposit.

4. Hyperspectral Remote Sensing Technology and Methodological Framework

4.1. Principles of Hyperspectral Remote Sensing for Alteration Mapping

Hyperspectral remote sensing is premised upon acquisition of reflectance data in hundreds of contiguous, narrow spectral bands, usually spanning the visible, near-infrared, and shortwave infrared [41]. Hyperspectral sensors can resolve finer absorption characteristics relating to individual molecular bonds, unlike multispectral systems, e.g., Al-OH, Mg-OH, Fe-OH, and CO_3. The above properties are directly connected with the occurrence and the structure of the hydrothermal alteration minerals, so that the hyperspectral data is especially fitting to mineralogical research in the ore-forming systems. **Table 2** lists the diagnosis VNIR absorption features and typical interpretation caveats achieved with diagnostic VNIR-SWIR features of the key alteration minerals of Qiucun. In hydrothermal gold deposits, including the Qiucun Gold Deposit, this ability allows direct identification and location mapping of the alteration minerals that otherwise cannot be separated with the traditional remote sensing methods.

Table 2. Diagnostic VNIR-SWIR spectral features used to identify major hydrothermal alteration minerals at Qiucun and comparable hydrothermal gold systems, including characteristic absorption regions and key cautions for interpretation.

Mineral Group	Diagnostic Bond/Feature	Diagnostic Wavelength Region (Approx.)	Typical Spectral Expression in Hyperspectral Data	Common Confusions/Cautions
White mica (muscovite/illite/sericite)	Al-OH	~2.19–2.22 µm	Strong absorption near 2.20 µm; subtle shifts can indicate compositional variation	Can overlap with some clays; mixing with quartz reduces band depth
Kaolinite-group clays	Al-OH doublet	~2.16–2.21 µm	Characteristic paired absorptions; often sharp	Fine mixtures with illite/smectite blur doublet; surface moisture effects
Smectite/illite–smectite (if present)	OH/H_2O + Al-OH	~1.4 µm, ~1.9 µm, ~2.2 µm	Hydration bands plus 2.2 µm feature; typically broader	Strong sensitivity to atmospheric correction and moisture; mixed pixels common
Chlorite	Mg-OH/Fe-OH	~2.25–2.35 µm	Absorptions in 2.25–2.35 µm range; position/shape varies with Mg/Fe	Carbonates share 2.33–2.35 µm region; careful feature fitting needed
Carbonates (calcite/dolomite/ankerite)	CO_3	~2.30–2.35 µm	Distinct carbonate absorptions; may show multiple features depending on composition	Confusion with chlorite in mixed pixels; surface coatings can weaken features
Iron oxides/hydroxides	Electronic transitions	VNIR (broad)	Diagnostic slopes/absorption in visible–NIR; good for gossans	Not uniquely hydrothermal; can be purely supergene/soil-related
Quartz (silicification)	Lacks strong VNIR–SWIR bands	-	Often inferred indirectly (feature suppression, context, texture)	Quartz identification is indirect; requires geological cross-checking

The effectiveness of hyperspectral technology in geological applications depends not only on spectral resolution but also on signal-to-noise ratio, spatial resolution, and wavelength coverage. VNIR–SWIR hyperspectral data are especially valuable for hydrothermal alteration studies because most rock-forming and alteration minerals exhibit their most diagnostic absorption features in this spectral range. As a result, hyperspectral remote sensing has become a key tool for investigating alteration mineral assemblages and their spatial relationships to mineralization [7,33].

4.2. Hyperspectral Data Sources and Observational Scales

The hyperspectral data applied in alteration studies may be obtained in various scales of observations, including satellite-based sensors, airborne platforms, ground-based or field imaging spectrometers. The satellite hyperspectral data offer regional coverage and are especially applicable in reconnaissance-level identification of the area of alteration. Their spatial resolution can, however, not be very good, and they may fail to resolve finer patterns of alteration that may be due to individual ore bodies or structures [42,43].

The hyperspectral systems that are delivered airdronically provide the balance between the spatial detail and the coverage as well, so they are perfectly applicable to the investigation of a district-scale and a deposit-scale investigation [44]. They can be used to map alteration mineral distributions in more detail and are usually applied to define alteration halos and zonation patterns. On-ground hyperspectral observations and handheld spectrometers, as well as field imaging instruments, are the systems with the best spectral fidelity, needed to calibrate, validate, and fully characterize mineral assemblages. Such scale combinations of the hyperspectral data create a solid platform of observation in hydrothermal changes within Qiucun.

4.3. Data Preprocessing and Correction Procedures

Hyperspectral data must be preprocessed strictly to obtain a reliable interpretation of the data, which is necessary to eliminate non-geological effects and to achieve spectral consistency. Radiometric calibration is a method of converting digital numbers obtained directly to at-sensor radiance, and atmospheric correction eliminates atmospheric absorption and scattering due to atmospheric gases and aerosols. Precise atmospheric correction is of great essence in the SWIR, where absorption by water vapor can seriously misrepresent mineral absorption characteristics [45].

Geometric correction and co-registration make sure that the spatial alignment of hyperspectral data and other geological data, including maps, digital elevation models, and geophysical data, is maintained [46]. Topographic correction can commonly be performed in topographically rugged areas to factor in the difference in illumination based on slope and aspect. These steps of preprocessing are essential to eliminate the artifacts as well as to retain the fine spectral features needed to identify the alteration minerals.

4.4. Spectral Analysis and Mineral Identification Methods

Hyperspectral alteration mapping is based on spectral analysis. The continuum removal methods are normally used to improve diagnostic absorption characteristics, as well as to make comparisons of spectra. The parameters of the feature that are then used to differentiate between alteration minerals with similar overall reflectance characteristics include the absorption depth, wavelength position, and band shape [47].

The spectral matching and classification process is usually a way of identifying and mapping minerals [48]. Techniques like spectral angle mapping, spectral feature fitting, and matched filtering are measures that compare the image spectra with reference spectra of spectral libraries of field measurements. Linear spectral unmixing is usually used to solve mixed pixels by approximating the relative abundance of multiple endmember minerals in a single pixel. More recently, the data-driven method and machine learning have also been investigated in order to enhance the accuracy of classification in complex alteration systems. The methodology is to be chosen based on the quality of data, the complexity of geology, and the purposes of the study.

4.5. Integration with Geological and Geochemical Information

Independent geological and geochemical data sets are most suitable when combined with hyperspectral remote sensing. Geological maps give a prerequisite background to understand the alteration patterns vis-à-vis lithology and structure, whereas geochemical data limit the elemental relative to metallogenic importance of the mapped alteration minerals. The structural interpretations through remote sensing or field mapping can be used to correlate the distributions of alterations to the fluid pathways and ore controls [49].

This type of integration is especially critical at Qiucun, where both lithology and structure have a very strong effect on alteration mineral assemblages [4]. Hyperspectral maps have the potential to identify areas of great change or of compositional change, which can be assessed through petrographic observations, mineral chemistry, and geochemical anomalies. This combined method increases confidence in identifying minerals and genetic expositions about the hydrothermal system.

4.6. Validation, Uncertainty, and Methodological Limitations

Hyperspectral alteration studies cannot be done without validation because spectral interpretations should be supported by field studies and laboratory studies [50]. Field spectroscopy, petrography, X-ray diffraction, and electron microprobe data are all examples of ground truth data that are typically used to confirm the identifications of minerals and refine spectral endmembers. Classification reliability is an objective measure of mapping reliability given by a quantitative evaluation of the accuracy of classification, e.g., confusion matrices. In order to favor reproducible application and transparent reporting, a suggested end-to-end hyperspectral process of Qiucun-type alteration mapping is highlighted in **Table 3**.

Table 3. Recommended workflow for hyperspectral mapping of hydrothermal alteration minerals, from data acquisition and preprocessing to mineral mapping, validation, and uncertainty assessment, with practical considerations for Qiucun-like field conditions.

Workflow Stage	Purpose	Typical Inputs	Outputs	Practical Notes for Qiucun-Like Conditions
Data acquisition and selection	Match scale to target (regional vs deposit)	Satellite/airborne/field spectra; Digital Elevation Model (DEM); base maps	Selected dataset(s) with appropriate VNIR–SWIR coverage	Airborne/field data better for deposit-scale heterogeneity; satellite for regional context
Radiometric + atmospheric correction	Recover true surface reflectance	Raw radiance; atmospheric parameters	Surface reflectance cube	SWIR is sensitive to water vapor; Quality Control (QC) needed to avoid false absorption features
Geometric + topographic correction	Improve spatial alignment and reduce illumination effects	DEM, Ground Control Points (GCPs), orthophotos	Co-registered, terrain-corrected cube	Rugged terrain and shadows can bias classification; mask or normalize shadows
Noise reduction and dimensionality reduction	Improve Signal-to-Noise Ratio (SNR); reduce artifacts	Reflectance cube	Denoised cube; Minimum Noise Fraction (MNF)/Principal Component Analysis (PCA) products	Avoid over-smoothing narrow features; document parameters for reproducibility
Endmember selection/spectral library	Define reference mineral spectra	Field spectra, lab spectra, libraries	Endmember set	Prefer local field/lab spectra where possible; account for grain size and mixtures
Mineral mapping and unmixing	Identify and quantify mineral presence	Endmembers + corrected cube	Mineral distribution maps; fractional abundance (if unmixing)	Combine feature fitting with unmixing in mixed pixels; use consistent thresholds
Validation and uncertainty assessment	Confirm accuracy and map reliability	Field checks, X-ray Diffraction (XRD), thin section, Electron Probe Micro-Analyzer /Electron Probe Microanalysis (EPMA)	Accuracy metrics; refined maps	Report confusion matrix or equivalent; explicitly map "uncertain" classes

Hyperspectral remote sensing has its limitations, although it has its strengths. Mineral maps can be subject to uncertainty due to mixed pixels, surface weathering, vegetation cover, and similarity in spectra of some minerals. Also, hyperspectral data are mostly surface-based, and this might not be an accurate image of the patterns of subsurface alterations. To be responsible in their interpretation, it is important to identify and explicitly cope with these uncertainties. Hyperspectral remote sensing, in conjunction with proper validation and reporting of measurements, offers a potent and dependable platform for exploring the minerals of hydrothermal alteration in intricate gold formations like Qiucun [51].

5. Synthesis of Hyperspectral Results: Alteration Mineral Characteristics and Spatial Patterns at Qiucun

5.1. Overview of Hyperspectral-Derived Alteration Mineral Distribution

Hyperspectral remote sensing analysis of the Qiucun Gold Deposit has shown that the distribution of hydrothermal alteration minerals is very complex yet internally coherent, which indicates the structural and lithological structures of the deposit. The occurrence of alteration minerals detected in VNIR–SWIR hyperspectral data is not arbitrary, but it is rather continuous and discrete belts that are spatially correlated to known ore-controlling structures and host rock units. When compared to the conventional geology mapping, the hyperspectral results present a more continuous and objective visualization of alteration mineral variability of the area of the deposit, both of which identify the previously known alteration zones and less familiar features [6].

At the deposit scale, the hyperspectral mineral maps often represent the broad areas with white micas and quartz-rich alteration, and the more heterogeneous distributions of clay minerals, chlorites, carbonates, etc. [52]. These trends show a hydrothermal system that has steep spatial gradients in the composition and temperature of fluids and degrees of varying wall-rock interaction. Notably, the spatial continuity of hyperspectral data enables tracking of alteration trends in regions with limited exposure mode, improving general insights into alteration architecture at Qiucun.

5.2. Deposit-Scale Alteration Zonation and Its Geological Significance

Hyperspectral mapping at Qiucun has resulted in the identification of systematic alteration zonation around mineralized structures, which is one of the most significant. Through the abundant silicification and pervasive sericitization related to major fault systems and ore-bearing veins, proximal zones are defined as hyperspectral data have high white-mica signatures and a strong threshold of quashing other mineral absorptions. These areas tend to overlap with the expected gold sites and are the center of the hydrothermal system, in which fluid movement and reaction rate were the most intense [53].

Moving out of these central cells, the changeover to assemblages that are mainly found in argillic ores and analysis in view of decreasing temperatures and differing condition of fluids and rocks alike. Carbonate alteration results in belts or patches in certain regions, which are governed by good lithologies or subsequent fluid flow directions. This concentric asymmetric zonation pattern is in line with a structurally-oriented hydrothermal system and offers a strong mineralogical system to explain the processes of fluid evolution and gold deposition [21].

5.3. Spectral Indicators of Mineral Chemistry and Hydrothermal Gradients

In addition to locating mineral presence or absence, hyperspectral data of Qiucun also records changes in spectral parameters, which can be traced to mineral chemistry. Specifically, the systematic variations of the position of the Al-OH absorption of white micas indicate the change of composition, which can be associated with temperature or fluid composition gradients. These spectral differences are usually studied along structural pathways, and between proximal and distal zones of alterations, suggesting that the hyperspectral data can be used as a surrogate of physicochemical gradient in the hydrothermal system [54].

Otherwise, the difference between chlorite-related absorption characteristics is also an expression of the variation in Mg–Fe ratios, which are dependent upon host-rock composition and hydrothermal conditions. These spectral patterns give further understanding of the character of fluid-rock interaction and can be used to differentiate alteration regions that can otherwise be similar on hand specimen or thin section. These hyperspectral indicators can be used as an effective supplement to mineral-chemical data to characterize alteration at Qiucun when interpreted carefully.

5.4. Comparison with Petrographic and Geochemical Observations

Hyperspectral interpretations at Qiucun are enhanced by the comparison with the independent petrographic and geochemical observations, which increases their reliability. The occurrence and distribution of alteration minerals, as indicated by hyperspectral maps, are in most cases confirmed by field validation and laboratory analyses, especially those of white micas, clay minerals, chlorite, and carbonates. The relationship developed between the stages of alteration using spectral patterns is supported by petrographic evidence of overprinting relationships and textural associations [6].

Geochemical data also support the hyperspectral findings by showing elemental enrichments that are in line with the mapped alteration types, e.g., in sericitized parts, higher K and Al, or higher Mg and Fe in chlorite-bearing ones. These correlations suggest that hyperspectral mineral maps reveal any geologically significant signals, not just the surface artifacts. Mixed pixels, fine-grained intergrowths, or surface weathering effects can be one of the main causes of discrepancies between spectral and laboratory results, thus the importance of integrated interpretation [55,56].

5.5. Controls on Alteration Mineral Distribution and Spectral Expression

A combination of the structural, lithological, and post-hydrothermal factors governs the spatial expression of alteration minerals at Qiucun. The structures have the greatest control because the flow of fluids is localized and intense changes occur on the fault zones and fracture networks. Lithology also affects the nature and the extent of alteration, in that not all host rocks react the same way to the hydrothermal fluids and have differing spectral responses [4].

Spectral signatures are locally altered by surface mechanisms (i.e., weathering, oxidation, etc.) and may increase or conceal some mineral component (i.e., iron oxides, etc.) [33,57]. In certain regions, spectral interpretation is also complicated by vegetation cover and the development of soil. When analyzing hyperspectral data, these aspects have to be factored in because they cause variability that is not related to primary hydrothermal processes but, in any case, influences observed spectral patterns.

5.6. Implications for the Alteration Model of the Qiucun Gold Deposit

The development of hyperspectral mapping synthesis yields geological and geochemical data, which give rise to a fine-tuning alteration model of the Qiucun gold deposit. This model plays a key role in structurally governed fluid flow in the formation of focused areas of silicification and sericitization that are strongly linked to gold mineralization that are encircled by wider halos of argillaceous and chloritic alteration. This model can be improved even further by the identification of mineral-chemical gradients based on spectral parameters that can be used in the association of pattern variations with the changing physicochemical characteristics of the hydrothermal system [4]. A deposit-scale alteration zonation model distilled from hyperspectral mapping and supporting geology, together with exploration implications, is presented in **Table 4**.

Table 4. Conceptual alteration zonation model for the Qiucun gold deposit derived from hyperspectral mineral mapping and integrated geological interpretation, highlighting inferred hydrothermal conditions, controls, and exploration vectors.

Spatial Domain (Conceptual)	Dominant Alteration Minerals (Hyperspectral)	Interpreted Hydrothermal Condition	Likely Structural/Lithologic Control	Exploration Implication/Vector
Core zone (proximal to main structures)	Strong white mica signature ± quartz inference; local sulfide-associated oxidation signals	High fluid flux; main-stage alteration and mineralization	Major faults/fracture corridors; high permeability	Highest priority target area; follow continuity along structures
Inner halo	White mica with increasing clay contributions; local carbonate	Cooling and reaction with wall rock; evolving fluid composition	Secondary fractures; reactive units	Vector inward using increasing sericitization intensity and structural convergence
Outer halo (distal)	Chlorite ± epidote signals (where resolvable); weaker white mica	More buffered fluids; lower alteration intensity; host-controlled	Lithologic control (mafic/volcanic units)	Useful for district-scale targeting; identify gradients toward core
Late overprint/near-surface	Argillic clays ± iron oxides/hydroxides	Late, low-T and/or acidic overprint; weathering contribution	Shallow conditions; surface processes	Must be validated carefully; can mask ore-related signals
Carbonate-controlled domains	Carbonate absorptions (CO_3) ± mixed signatures	CO_2-rich fluids and/or mixing; strong host-rock dependence	Carbonate-bearing strata; late-stage pathways	Can mark fluid pathways; interpret with lithology and paragenesis constraints

Overall, hyperspectral remote sensing provides a powerful means of visualizing and interpreting alteration mineral systems at Qiucun. The resulting spatially continuous alteration framework not only improves understanding of deposit-scale hydrothermal processes but also offers practical guidance for exploration by highlighting mineralogical vectors toward gold mineralization [58].

6. Conclusions

This is a review of the existing literature on hydrothermal alteration minerals at the Qiucun gold deposit, and especially the information obtained through the use of the hyperspectral remote sensing technology. A combination of geological, mineralogical, and hyperspectral approaches shows that alteration mineral assemblages at Qiucun are systematic and have a genetically significant relationship, and are intimately connected to structurally regulated gold mineralization. The most common styles of core alteration that occur near ore-bearing structures are silicification and sericitization, and the more extensive and more heterogeneous halos are the styles of the argillic, chloritic, and carbonate alteration styles that reflect changing fluid conditions and interactions with walls.

Examples of these alteration minerals are effectively detectable and mapped using hyperspectral remote sensing because their diagnostic VNIR–SWIR absorption properties are diagnostic. In addition to mineral discrimination, differences in spectral parameters create useful proxies of mineral chemistry and hydrothermal gradients, which can give information on temperature change, fluid composition, and intensity of alteration that cannot be easily obtained with standard mapping methods. Hyperspectral-derived alteration maps provide geologically strong patterns, when rigorously validated by field observations, petrography, and geochemical analyses, and are very valuable in enhancing the knowledge of the Qiucun hydrothermal system.

At a deposit level, hyperspectral observations indicate definite alteration zonation and continuity over regions of restricted exposure, which results in the prevalence of faults and fracture networks in the concentration of fluid flow and gold deposition. These findings emphasize the significance of the combination of hyperspectral methods and structural analysis and lithological context in order to interpret patterns of alterations accurately. Simultaneously, this review highlights that surface impacts, mixed pixels, and multistage over printing is still one of the major issues that need to be carefully pre-processed, validated, and interpreted with caution during genetic applications.

All in all, studies conducted on the Qiucun Gold Deposit depict a vivid potential of hyperspectral remote sensing as an essential instrument in the study of hydrothermal modification of structurally controlled gold deposits. The strategies and interpretations that have been summarized here can not only be applied to Qiucun, but they can also be extended to other similar metallogenic environments in southeastern China and beyond. The combination of high-resolution hyperspectral observations, in vivo mineral chemistry, and geologic modeling should involve future work that will advance our understanding of alteration systems, as well as improve strategies of mineral exploration in complex hydrothermal systems.

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Data Availability Statement

All data supporting the findings of this study are included in the article. No new data were created or analyzed in this study.

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Conflicts of Interest

The authors declare no conflict of interest.

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