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Review of Granite-Related Gold Mineralization in the Altai Region: Deposit Classification and Exploration Prediction

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Abstract

The Altai region of Xinjiang represents one of the most significant gold metallogenic belts in China. In recent years, an increasing number of gold deposits have been identified as intimately associated with intermediate-acidic intrusive rocks, particularly granites. The Altai region extensively exposes multi-episodic, multi-source granitic plutons exhibiting distinct spatiotemporal distribution characteristics, which are closely related to gold mineralization. Based on a systematic review of previous research findings, combined with the orogeny, magmatism, and tectonism of the Altai orogenic belt, this paper classifies four representative gold deposits that exhibit close spatiotemporal relationships with granites in the Altai region. The primary characteristics of orogenic-type, low-temperature epithermal-type, and subvolcanic-structural alteration rock-type gold deposits are summarized, aiming to provide theoretical references and practical guidance for exploration prediction of granite-related gold mineralization in Xinjiang.

Keywords

Altai orogenic belt, granite, gold mineralization.

1. Introduction

The Xinjiang Altai orogenic belt is situated along the southern margin of the Central Asian Orogenic Belt—the most typical accretionary orogenic belt characterized by continental crustal growth on a global scale—and constitutes an integral component of the Central Asian Orogenic Belt, as well as a significant polymetallic metallogenic belt in China [1-4]. Granites are extensively distributed throughout the Altai orogenic belt, occupying approximately 70% of the regional area. Their formation is intimately associated with persistent Paleozoic subduction, accretion, and collision-related tectono-magmatic events [5-7]. These granites not only hold significant research value for investigating regional magmatic and tectonic evolution, but also maintain close spatiogenetic relationships with gold mineralization within the Altai orogenic belt [8,9].

Since the 1990s, numerous domestic and international scholars have conducted extensive research on gold mineralization in the Altai region, achieving breakthrough advances in aspects including granite formation ages, petrogeochemical analysis, deposit geological characteristics, and metallogenic mechanisms. Liu Wei conducted detailed investigations on representative granitic plutons in the Altai region, summarizing their chronological and genetic type characteristics [10]; Rui Xingjian et al. were the first to systematically summarize the fundamental characteristics of primary gold deposits in the Altai, classifying five major gold deposit types [11]; Shao Huiwen et al. (2009) investigated the relationship between regional granitic magmatism and gold mineralization chronology, further summarizing the types and characteristics of gold deposits in the Altai region [12]; Yang et al. conducted detailed studies on high-sulfidation and low-sulfidation epithermal gold mineralization in northern Xinjiang, summarizing the spatiotemporal distribution characteristics, tectonic settings, and ore-forming fluid sources of Paleozoic epithermal gold mineralization in northern Xinjiang [13].

In recent years, with the continuous discovery and investigation of gold mineralization, the intimate relationship between regional gold mineralization and intermediate-acidic magmatic activity—particularly with granites of different episodes and types—has become increasingly evident. Based on this, the present paper reviews published domestic and international literature, integrates the regional geological background of the Altai orogenic belt, and focuses on summarizing gold deposit types exhibiting spatiogenetic relationships with granites, aiming to provide theoretical references and guidance for in-depth research and exploration prediction of granite-related gold mineralization in the Altai region.

2. Relationship Between Granites and Gold Mineralization in the Altai Region

As an integral component of the Central Asian Orogenic Belt, granites in the Altai orogenic belt are extensively emplaced within stratigraphic sequences, occurring at the surface predominantly as stocks, dikes, and batholiths. Previous researchers have conducted detailed investigations on the formation ages and types of granites in this region. Early to Middle Paleozoic granites are predominantly calc-alkaline I-type, whereas Carboniferous-Permian granites are mainly transitional I-A type and A-type granites; Early Mesozoic S-type granites are also developed [14]. It is thus evident that the generation of granites in the Altai region exhibits distinct temporal distribution characteristics and is intimately related to the orogenic processes of the Altai orogenic belt.

Gold mineralization in the Altai region is primarily concentrated in the Late Paleozoic to Early Mesozoic, coinciding with the main collisional orogenic period (460–400 Ma) when granitic magmatic activity was intense. Large volumes of magma, carrying metallogenic materials, ascended and were emplaced from the lower crust or upper mantle. Granitic magma could not only provide partial metallogenic materials for gold mineralization, but also supply heat sources and partial fluids. By the Late Paleozoic, the region entered a post-collisional extensional setting, providing favorable conditions for gold element activation and migration [15]. During this period, numerous granites formed in post-orogenic extensional environments. The Ertix (Irtysh) fault zone and its subsidiary faults of the same orientation served as migration pathways for magma and fluids, together with granitic intrusions constituting favorable metallogenic tectonic environments. Gold deposits are mostly distributed along contact zones between granitic plutons and surrounding rocks or within fault fracture zones, with some ore bodies occurring directly within granitic dikes [16-20].

3. Classification of Granite-Related Gold Mineralization Types

3.1. Orogenic Gold Deposits

Orogenic gold deposits represent one of the most important gold deposit types globally and currently constitute one of the most spatiotemporally widespread gold deposit categories. Domestic and international scholars have conducted extensive research and synthesis on the geological settings, ore-forming fluids, metallogenic material sources, and metallogenic mechanisms of orogenic gold deposits [21-27]. Orogenic gold deposits maintain close spatiotemporal associations with orogenic events: temporally, deposit formation spans from the Archean to the Phanerozoic; spatially, mineralization may occur at depths ranging from 0 to 20 km [21]. Orogenic gold deposits generally form within continental margin accretionary orogenic belts and continent-continent collisional orogenic belts, with formation ages generally synchronous with or postdating corresponding orogenic events. They develop under transpressional to transtensional settings, with ore-forming fluids characterized predominantly by low-temperature, low-salinity, CO_2-rich H_2O-CO_2-CH_4 systems [25-27].

3.1.1. Duolanasayi Gold Deposit

Previous researchers have conducted extensive investigations on the geological background, rock-forming and ore-forming chronology, tectonic setting, and ore-forming fluids of the Duolanasayi gold deposit. However, due to the complexity of metallogenic characteristics at Duolanasayi, different scholars have proposed varying classifications for this deposit. Rui Xingjian et al. considered Duolanasayi as a low-temperature epithermal deposit [11]; Li Zhichun classified it as a structural contact zone-type gold mineralization [28]; Xiao Huiliang proposed it as a new gold deposit type, designating it the "Duolanasayi-type" gold deposit [29]. Regardless of the classification adopted for the Duolanasayi mining district, the role of surrounding granitic plutons in the metallogenic process cannot be overlooked. Consequently, previous studies on the Duolanasayi gold deposit have all emphasized the contributions of granitic magmatism to mineralization. After reviewing previous literature [27,30,31], the author classifies the Duolanasayi gold deposit as an orogenic-type gold deposit.

The Duolanasayi gold deposit is located in the southwestern Altai orogenic belt. The mining district primarily exposes a suite of low-grade metamorphic terrigenous clastic rocks and shallow marine carbonate rocks belonging to the Middle-Lower Devonian Tuokesalei Formation. Three magmatic rock bodies are exposed in the surrounding area: the Sarewuzeng pluton in the northwest and the Kelibayi pluton in the northeast, both occurring as sub-elliptical stocks, and the Donggele pluton in the east, which occurs as an irregular batholith exposed at the surface. All three plutons are compositionally uniform granodiorites, inferred to be products of the same magmatic event. Within the mining district, albite granite dikes, albite porphyry dikes, quartz diorite dikes, and alkali-feldspar granite dikes are developed. The strike orientations of these dikes are mostly consistent with the foliation trends of wall rock schistosity and mylonitization, having experienced intense ductile-brittle shear deformation accompanied by sericitization, silicification, carbonatization, and other alterations. Granodiorite and albite granite dikes constitute the principal ore-hosting rocks and gold mineralized bodies in the mining district.

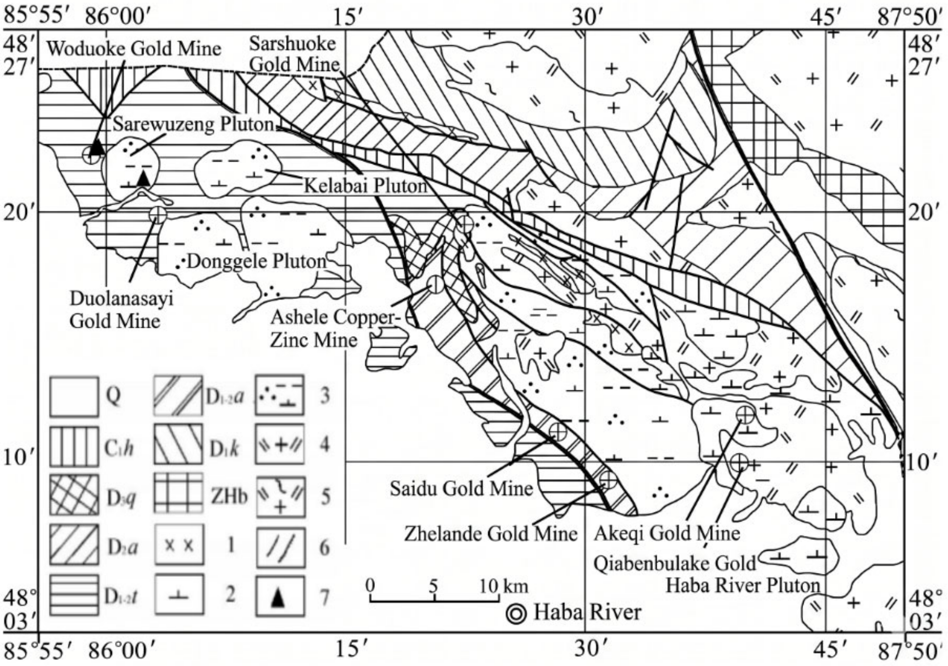

Figure 1. Geological sketch map of rock bodies and gold deposits in the Habahe region [32]

Q—Quaternary; C_1h—Lower Carboniferous Hongshanzhui Formation; D_3q—Upper Devonian Qiye Formation; D_2a—Middle Devonian Altai Formation; $D_{1-2}t$—Middle-Lower Devonian Tuokesalei Formation; $D_{1-2}a$—Middle-Lower Devonian Ashele Formation; D_1k—Lower Devonian Kangbutiebao Formation; ZHb—Sinian Habahe Group; 1—Gabbro; 2—Diorite; 3—Tonalite; 4—Monzogranite; 5—Gneissic monzogranite; 6—Fault; 7—Isotopic age sampling location

The main collisional orogenic period in the Altai region occurred during the Early-Middle Paleozoic (460–400 Ma); by the Late Paleozoic, the Altai region entered a post-collisional extensional setting [14]. Granitic plutons in the Duolanasayi gold deposit area formed during the Late Carboniferous (317 Ma), possibly representing products of late post-collisional magmatic activity [32]. The albite granite dikes and albite porphyry dikes constituting the gold ore bodies belong to magmatic I-type granites, with ages possibly of 352.5±40 Ma. Combined with previous research, the main metallogenic period of the Duolanasayi gold deposit likely occurred during 300–290 Ma. The ore-forming fluids belong to low-temperature, low-salinity H_2O-CO_2 systems, exhibiting multi-source mixing characteristics consistent with ore-forming fluids of orogenic gold deposits [27,31]. Temporally, Duolanasayi gold mineralization is intimately related to orogenic processes, with mineralization postdating the main collisional period and forming during the late orogenic to post-collisional stages. Spatially, gold mineralized bodies are controlled by both structural and lithological factors. Albite granite dikes represent the principal source of metallogenic materials. By the end of the Middle Devonian, the Siberian Plate compressed toward the southwest while oceanic crustal plates subducted northward, generating intense ductile shear deformation in the deep crust that caused temperature elevation, leading to remelting of subducted oceanic crust materials. Albite granitic magma ascended along ductile shear zones and strike-slip faults, crystallizing over time to form albite granite dikes. By the end of the Carboniferous, the Junggar oceanic basin closed and the Kazakhstan Plate amalgamated with the Siberian Plate, again promoting deep crustal-mantle heating and melting to form granitic magmas and hydrothermal intrusions, resulting in superimposed gold mineralization enrichment and eventual precipitation of ore [29].

3.1.2. Saidu Gold Deposit

The Saidu gold deposit is located in the western-southern part of the Chinese Altai orogenic belt, within the Keketuohai (Keketuohai) back-arc basin, situated at the junction between the Siberian Plate and the Kazakhstan-Junggar Plate. This area represents the core region of Paleozoic plate subduction-collision orogeny. The Ma'erkakuli fault serves as the ore-controlling structure for the Saidu gold deposit. Ore vein groups are strictly controlled by and occur within ductile shear zones, with veins generally parallel to the main shear deformation zone orientation and predominantly occurring within intensely deformed zones [33-35]. Stratigraphic units in the mining district are dominated by the Upper Subformation of the Middle Devonian Altai Formation and the Lower Subformation of the Tuokesalei Formation, accompanied by Quaternary sediments. Devonian magmatic activity in the district was intense, with large volumes of intermediate-acidic magmatic intrusions represented by lithologies including plagiogranite, diorite, granitic porphyry, and quartz porphyry. The largest and most representative pluton is the Habahe plagiogranite in the northern part of the mining district, covering an area of approximately 800 km^2, with whole-rock K-Ar ages of 284.4–277.3 Ma and Rb-Sr isochron ages of 297±11 Ma. Multiple diorite dikes are developed within the pluton, consistent in orientation with the regional ductile shear zone. The diorite dikes exhibit cross-cutting relationships with wall rock strata and the Habahe pluton [16,34,36,37].

The main metallogenic period of the Saidu gold deposit occurred around 300 Ma, consistent with the principal metallogenic period of the Duolanasayi gold deposit (300–290 Ma). From the early collisional orogenic compressional environment to the post-collisional extensional setting, the region experienced intense, multi-episodic ductile-brittle shear tectonic activity, with gold ore bodies strictly controlled by ductile-brittle shear zones. The hallmark of orogenic gold deposit ore-forming fluids is characterized by low-salinity, CO_2-rich H_2O-CO_2-CH_4 fluids [27,31]. The ore-forming fluids of the Saidu gold deposit were initially characterized by medium-high temperatures and enrichment in CO_2-N_2 volatiles, with inclusion homogenization temperatures of 252.0–408.0°C; the intermediate stage was dominated by CO_2-H_2O fluids, with inclusion homogenization temperatures of 203.0–325.8°C, reflecting medium-temperature hydrothermal characteristics; the middle-late stage evolved into medium-low temperature, medium-low salinity saline solution systems, with inclusion homogenization temperatures of 120.0–221.0°C. Sulfur and lead isotope results indicate that metallogenic materials were enriched from depth and were not of singular magmatic origin, but rather were extracted from deep rocks through hydrothermal leaching during post-collisional orogenic processes, consistent with the "multi-source, deep-source dominated" material source characteristics of orogenic gold deposits. The degree of hydrothermal alteration in the Saidu gold deposit is positively correlated with structural deformation. From the shear zone center outwardward, alteration types exhibit zonation from intense silicification-pyrite-sericitization to medium-low temperature sericitization, chloritization, and carbonatization. Gold mineralization is intimately associated with pyritization and silicification, representing the typical medium-low temperature hydrothermal alteration assemblage of orogenic gold deposits.

3.2. Low-Temperature Epithermal Gold Deposits

The concept of low-temperature epithermal gold deposits was originally proposed by Lindgren in 1922, who provided broad definitions regarding ore-forming fluid sources, mineralization depths, temperatures, and pressures, and proposed that deposit formation generally exhibits an inverse relationship with depth [38,39]. The current definition of low-temperature epithermal gold deposits is: hydrothermal gold deposits formed at shallow depths (generally <1.5 km), associated with volcanic-intrusive rock suites, under conditions of ore-forming temperatures of 200–300°C (occasionally <200°C or >350°C) and relatively low pressures (10–50 MPa). The characteristics of ore-forming fluids are dominated by magmatic hydrothermal fluids and meteoric water with relatively low salinity. Hydrothermal activity mainly occurs in the upper portions of volcanic-subvolcanic or porphyry systems. Gold mineralization is genetically related to volcanic activity, typically appearing during late stages of volcanic activity, with mineralization constrained within areas affected by volcanic geothermal systems [40,41].

3.2.1. Aketas Gold Deposit

Previous researchers have held different perspectives regarding the genesis of the Aketas deposit, including associations with intermediate-acidic subvolcanic dikes, magmatic hydrothermal type, and subvolcanic-structural alteration rock type [19,42-44]. Wei Xiaofeng et al. argued that previous research overemphasized the relationship between granitic magmatism and mineralization, whereas the biotite granite rock-forming age at Aketas differs from the metallogenic age by approximately 80 Ma, with both controlled by different dynamic mechanisms: the rock-forming process resulted from plate collision-induced passive magma emplacement, while the metallogenic event responded to strike-slip deformation induced by plate adjustment during the post-collisional orogenic stage. Their research indicated that the Aketas gold deposit exhibits characteristics of orogenic gold deposits [45]. After reviewing previous literature, the author classifies the Aketas gold deposit as a low-temperature epithermal gold deposit.

The Aketas gold deposit is located in the southern part of Fuyun County, Xinjiang, situated tectonically at the junction between the Kazakhstan Plate and the Siberian Plate, controlled by the NW-trending Sarebulake-Aketas major fault and the NNW-trending Kayiert-Ertai major fault [42,44]. Exposed strata in the mining district are predominantly the Middle Devonian Beitashan Formation, Yundukala Formation, Lower Carboniferous Jiangbasitao Formation, and

Quaternary. The regional stratigraphic sequence comprises a suite of marine-terrestrial transitional volcanic rocks and volcanic clastic rocks. Intrusive rocks in the district are predominantly subvolcanic to hypabyssal dikes, including plagiogranite, monzogranite, and diorite. Volcanic rocks are mainly andesite, andesitic porphyry, and tuff. In previous research, regional granites have been identified as intimately related to gold mineralization, with some ore bodies occurring directly within them [17,19,44].

The mineralization depth of the Aketas gold deposit is approximately 1–1.2 km, representing a subvolcanic environment. Quartz inclusion homogenization temperature measurements indicate: early pyrite-quartz stage homogenization temperatures of 334°C; intermediate native gold-pyrite-quartz stage temperatures of 260–270°C. The ore-forming fluids were predominantly magmatic water mixed with minor meteoric water, representing low-salinity, low-density solutions [42,43], consistent with the occurrence environment, temperatures, and fluid characteristics of epithermal deposits. The metallogenic systems of low-temperature epithermal gold deposits are considered to be primarily associated with volcanic-subvolcanic activity in magmatic arc regions and magmatic activity during the Late Paleozoic post-collisional orogenic period [39]. Zircon $^{206}Pb/^{238}U$ weighted average ages of 309.9±6.7 Ma from plagiogranite in the mining district represent the emplacement crystallization age of the plagiogranite, falling within the East Junggar post-collisional plutonic magmatic activity range of 330–265 Ma, indicating it as a product of post-collisional magmatic activity [17,43,46]. Moreover, the plagiogranite maintains close spatiotemporal relationships with gold mineralization, with gold mineralization occurring in the exocontact zone of the plagiogranite within wall rock sections exhibiting relatively developed pyritization and chalcopyritization. The plagiogranite not only serves as the principal ore-controlling host rock but also is temporally consistent with mineralization, both being products of the Carboniferous. Regarding metallogenic material sources, the plagiogranite in the district represents the parental rock for gold ore body occurrence and provided the principal material source for mineralization.

3.3. Subvolcanic-Structural Alteration Rock-Type Gold Deposits

The subvolcanic-structural alteration rock-type gold deposit was first proposed as a new gold deposit type by Wang Jingbin et al. in 1996. Its definition is: subvolcanic small intrusive bodies and structural alteration represent the principal ore-controlling factors; for the formation of industrial deposits of certain scale, the organic combination of both factors is essential and indispensable [18]. Subsequently, Liao Qilin et al. investigated the metallogenic background, typical deposits, and metallogenic characteristics of this deposit type along the northern margin of the Junggar Basin, discovering that such deposits primarily occur in Late Paleozoic island arc regions, with mineralization intimately associated with sodium-rich subvolcanic small intrusive bodies and structurally controlled fracture-alteration [47]. The author considers that this deposit type is essentially intermediate between low-temperature epithermal and structural alteration rock-type gold deposits, with ore bodies controlled by both structural and subvolcanic factors.

3.3.1. Buerkesidai Gold Deposit

Previous researchers have conducted extensive investigations on the regional geology, metallogenic chronology, metallogenic characteristics, and genetic classification of the Buerkesidai gold deposit, achieving certain consensus. However, divergent opinions persist regarding deposit genetic classification, including structural alteration rock-type, late volcanic hydrothermal, low-temperature epithermal, and subvolcanic-structural alteration rock-type gold deposits [18,20,48-53].

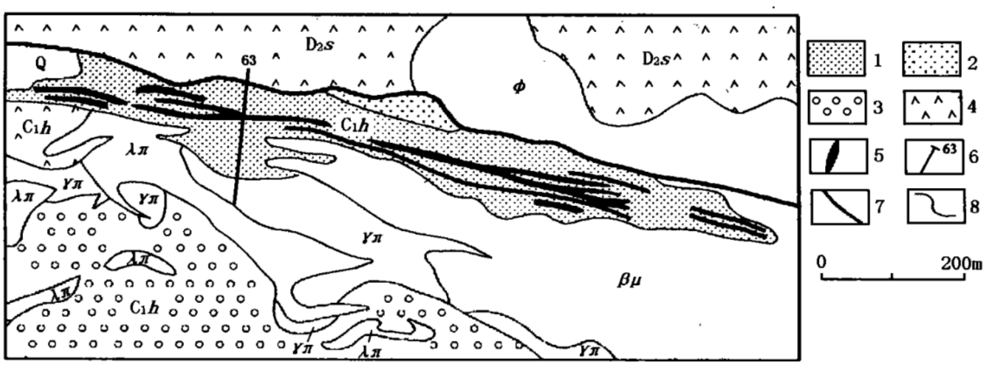

Figure 2. Simplified geological map of the Buerkesidai gold deposit [18]

1—Argillaceous carbonaceous siltstone; 2—Lithic sandstone; 3—Diamictite; 4—Andesitic volcanic rocks; 5—Gold ore body; 6—Exploration profile location; 7—Fault structure; 8—Geological boundary; Q—Quaternary; C_1h—Andesitic volcanic rocks; D_2s—Middle Devonian Sawurshan Formation; λπ—Quartz porphyry; γπ—Granitic porphyry; βμ—Diabase porphyrite; φ—Albite porphyry

The Buerkesidai gold deposit is located in the eastern section of the Sawur Mountains in northern Xinjiang, situated tectonically within the Late Paleozoic Sawur island arc zone along the northwestern margin of the Junggar Plate, administratively under the jurisdiction of Jeminay (Jimunai) County. Regionally exposed strata are predominantly the Middle Devonian Sawurshan Formation (D_2s), Upper Devonian Tarbagatai Formation (D_2t), and Lower Carboniferous Heishantou Formation (C_1h). The gold deposit wall rocks comprise a suite of basic-intermediate volcanic rocks and volcanic clastic rocks, representing calc-alkaline rocks formed in an island arc environment [51]. Structural activity is intense within the mining district, with approximately E-W trending folds and faults constituting the fundamental structural framework. The principal structure is the Buerkesidai fault, which serves as the ore-controlling and ore-hosting structure for the Buerkesidai gold deposit, with ore body attitudes clearly controlled by this fault and its subsidiary faults of the same orientation. In the research of multiple scholars, carbon content has been identified as significantly influencing gold mineralization enrichment and precipitation. Carbon-bearing structural fracture zones represent the most favorable ore-hosting locations; sections traversed by fracture zones exhibit significantly increased carbon content, while carbon-rich argillaceous wall rocks with developed porosity facilitate the infiltration, migration, and storage of gold-bearing fluids, and possess strong adsorption capacity for chalcophile elements and their compounds, further enhancing gold enrichment and mineralization [18,49,52]. Magmatic rocks in the mining district also constitute a principal ore-controlling factor. Regional acidic subvolcanic dikes are relatively developed, occurring predominantly as apophyses, stocks, and dikes. Subvolcanic dikes intimately related to gold mineralization are mainly granitic porphyry dikes and quartz porphyry dikes. Isotopic ages of intrusive rocks in the mining district range from 327–314 Ma, with a metallogenic age of 309 Ma; both ages belong to the same epoch, suggesting a certain genetic relationship. Subvolcanic intrusive magmatic activity most likely provided partial heat sources, fluids, and metallogenic materials for subsequent ore-bearing hydrothermal formation.

4. Conclusions

1. The Altai region extensively exposes multi-episodic, multi-source granites exhibiting spatiotemporal distribution characteristics, which maintain significant coupling relationships with regional gold mineralization.

2. This paper briefly summarizes the genetic relationships between the Duolanasayi, Saidu, Aketas, and Buerkesidai gold deposits and granites, and systematically synthesizes the primary characteristics of orogenic-type, low-temperature epithermal-type, and subvolcanic-structural alteration rock-type gold deposits.

3. Based on comprehensive regional metallogenic regularities, the following exploration directions are proposed: ① Gold ore bodies are likely to occur at intersections between deep major fault zones and their subsidiary faults with granitic plutons (or dikes) in the Altai region. ② In areas where regional granites are genetically classified as I-type, it is inferred that granitic magmas carried deep-seated Au elements upward during emplacement, providing material sources for mineralization. ③ In areas surrounding outcropping granitic plutons of small scale (stocks, apophyses, dikes) or with diorite dike intrusions, where wall rock alteration is dominated by silicification and pyritization, certain exploration efforts may be warranted to further enhance the precision of regional exploration prediction. ④ Within the Sawur island arc zone, targeting superimposed locations between high-carbon structural fracture zones and granitic dikes (or other subvolcanic dikes) will further improve research on subvolcanic-structural alteration rock-type gold deposits.

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