

## Research Article

# The Establishment of Ore-Controlling Fracture System of Baoginshan Gold Mine Based on Fracture-Tectonic Analysis

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The Baoginshan quartz vein type gold mine in the Baimashan-Longshan-Ziyunshan gold belt is the object of study, and the nature of the fracture structure and its ore-controlling effect are studied through surface and pit investigation, and the nature of the ore-controlling structure system and combination pattern of the Baoginshan gold mine is established. The F7 and F9 fractures in the near-east-west (EW) direction are the main fractures, which tend to the north and control the spreading of the ore zone; the northwest (NW) direction secondary tension fracture, with a dominant yield of  $221^{\circ}\angle 63^{\circ}$ , is a T-type fracture in the Riedel shear mode and is the ore-holding structure of the vein-like ore body; the northeast-east (NEE) direction secondary shear fracture, with a dominant yield of  $343^{\circ}\angle 53^{\circ}$ , is a P-type fracture and the combination of the two controls the specific positioning of the ore body. The characteristics and nature of the fracture structures in the whole ore zone, as well as their combination patterns, indicate that the overall ore-controlling fracture system of Baoginshan is a right-going tensional shear fracture zone composed of NW-oriented (T-type) and NEE-oriented (P-type) secondary fractures with F7 and F9 fractures as boundary fractures. The directions of the principal stresses are  $\sigma_1\approx 158^{\circ}\angle 40^{\circ}$ ,  $\sigma_2\approx 288^{\circ}\angle 38^{\circ}$ , and  $\sigma_3\approx 42^{\circ}\angle 28^{\circ}$ , respectively. In the next step of the prospecting process, based on increasing the spacing of prospecting pits (to 40m), in-pit drilling is deployed in the upper and lower discs of the NEE secondary fracture along with the tendency and strike for literacy, which can significantly improve the efficiency and effectiveness of prospecting and greatly reduce the cost of prospecting.

## 1. Introduction

The Baoginshan gold mine is located in the eastern section of the Baimashan-Longshan-Ziyunshan metallogenic belt in central Hunan, and the northern side of the Ziyunshan rock body. Previous studies on the Baimashan-Longshan-Ziyunshan metallogenic belt mainly focused on the Baimashan-Longshan area, where quartz vein-type gold deposits in Gutai Mountain [1], fractured-altered rock-type gold-antimony deposits in Longshan [2], microleaching-type gold deposits in Gaojiagao [3, 4], and quartz vein-type gold deposits in fractured-altered rock in Daxin [5] were found, and the mineral control laws and the prospect of ore search in this metallogenic belt were analyzed [6, 7]. In contrast, relatively little geological work has been invested in the Ziyunshan area, mainly to briefly describe and summarize the geological features, fluid characteristics, and

genesis of the gold deposit in Baoginshan, which is considered to be controlled by the combination of fractures and stratigraphy, and dominated by quartz vein type, and its genesis is closely related to the Ziyunshan granite body [8–15], but the research on the key ore-controlling factors in this area-ore-controlling structures is still obviously insufficient, mostly from local lots. However, the research on the key ore-controlling factor—ore-controlling tectonics—in this area is insufficient, most of them are from the local area, and they do not reveal the nature of ore-controlling fractures and spatial combination law. Because of the existence of a large number of blind ore bodies in the mine, the mine used to adopt encrypted prospecting works to solve the production prospecting problem, such as the vertical spacing of prospecting pits, has been shortened to 20 m. This prospecting scheme not only has low prospecting efficiency but also significantly increases the cost of prospecting, and the

overall prospecting effect is not satisfactory. Therefore, a comprehensive summary of the mine area tectonic control and the law of ore body output optimizes the prospecting method, reduces the cost of prospecting, improves the efficiency and effectiveness of prospecting, and is the urgent need to solve the mine based on the comprehensive analysis of existing data and field investigation; this paper focuses on summarizing the characteristics of the ore-controlling structure and analyzing the ore-controlling fracture system in this area in a more systematic way through the analysis of fracture packages and the study of the ore-controlling effect of fractures and concludes that the overall ore-controlling fractures of the Baoginshan gold mine belong to the right-going tension-shear fracture system. This study is expected to provide a theoretical basis for the prospecting work in this area and then promote the mineral search work in this area.

## 2. Regional Geological Background

The Ziyunshan area where the Baojinshan gold mine is located at the eastern edge of the Xiangzhong Basin and belongs to the secondary uplift area of the Xiangzhong Dome Basin Tectonics. In terms of geotectonic position, the area is in the middle part of the combination zone between the Yangzi and Huaxia massifs and has long experienced complex tectonic magmatic activities, accompanied by large-scale metal mineralization activities.

The shallow metamorphic rock systems of the Neopaleogene Panxi Group and Lengjiayi Group are distributed in a ring along with the core of the Ziyunshan uplift and in the wings of the uplift zone. There are strata of the Aurignan, Cambrian, Ordovician, Devonian, and Carboniferous systems, which are unconformably overlaid on the Panxi Group. The northeast and northwest basement fractures form a lattice-like pattern in the region, and the near east-west spreading Baimasan-Longshan-Ziyunshan pearl-like uplift constitutes the basic tectonic framework of the region (Figure 1). The magmatic activity in the region is multiphase, forming the Baimashan miscellaneous rock body of the Garridon-Yanshan period and the granite bodies of Tianlongshan and Ziyunshan of the Indo-Chinese period, among which the Indo-Chinese magmatic activity has a close spatial and temporal relationship and genesis with the gold, antimony, and tungsten mineralization in the region [16]. Regional geological map of the central Hunan Province is shown in Figure 1.

## 3. Geological Characteristics of the Mine Site

The mine site is in the northern flank of the Ziyunshan Dome, and the stratigraphy exposed in the area is mainly the second section of the Madyi Formation of the Neoproterozoic Banxi Group, which is a set of complex marble-built shallow metamorphic clastic rocks with a northern orientation. The ore-bearing strata are mainly calcareous slate interspersed with calcareous agglomerate striped slate and chert lenticular body. The zone is characterized by a monoclinic structure with a northward trend. The fractured structure mainly consists of four groups of near east-west,

northeast, northwest, and near north-south fractures, among which the near east-west fractures are most closely related to mineralization, mainly consisting of F9 and F7 fractures, which tend to the north and dip from  $46^\circ$  to  $77^\circ$ , all showing the characteristics of tension-torsion. The former is a south-trending tensional fracture, which is the main ore-bearing structure; the latter is a north-trending shear fracture, which is tightly closed and locally ore-bearing (Figure 2). The northeast, northwest, and gold-north-south fractures are all postmining fractures. The magmatic rocks in the mining area are late Indo-Chinese granodiorite porphyry veins with northwest direction and cut wrong ore body.

The gold ore in this area is mainly of quartz vein type, and there are mainly two types of ore bodies: vein and barrel. Among them, the vein-like ore body is mostly arranged in a group of veins in the shape of geese, towards NW, tendency SW, and dip angle  $45^\circ$ – $67^\circ$ . This type of ore body has a short strike extension, generally around 20m, and a relatively long tendency extension, and the thickness of the ore body is 0.2–2.0 m (Figures 2 and 3). The orientation and tendency of the barrel-shaped ore bodies are like those of the vein-shaped ore bodies, but the scale is relatively large, with thicknesses of several meters to more than ten meters and tendency extensions of up to 100 meters [17]. The gold mineralization is mainly located in the contact area between the quartz veins and the surrounding rocks, and bright gold is common in the quartz veins near the surrounding rocks, and the gold grade is highly variable [18].

The sericitization (mineral alteration caused by hydrothermal fluids invading permeable country rocks), silicification (process of replacing an original mineral of a rock by silicate), magnetic pyrite mineralization (decomposition of chemicals in organic matter into easily available form), and gold mineralization are most closely related to the alteration of the surrounding rocks. The geological plan of the mining level (+10) of the Baojinshan gold deposit is shown in Figure 4.

The rest of the journal is organized according to the following pattern. Ore-controlling fracture system is discussed in Section 3. Discussion is provided in Section 4, and the study is concluded in Section 5.

## 4. Establishment of the Mineral Control Fracture System

**4.1. Main Fracture Structure.** The F9 fault is the southern boundary fault of the Baoginshan gold belt, with a general orientation of nearly EW, inclined to N, dip angle  $46^\circ$ – $77^\circ$ , width 0.2–5.0 m, and strike length longer than 3 km (Figures 2 and 4). The fault breccia is developed, lenticular and subangular, and silicification, fading, sericite, chlorite, pyrite, and magnetic pyrite are seen in the upper and lower plates of the fault. Obvious abrasion marks are seen in the trench (Figure 3(a)), and the dip of the abrasion marks is about  $285^\circ$  with a dip angle of  $40^\circ$ , and the lateral dip is about  $270^\circ$  with a lateral dip angle of about  $25^\circ$ . Based on the analysis of the abrasion marks and step characteristics, it has obvious features of rightward shearing. No.42 geological

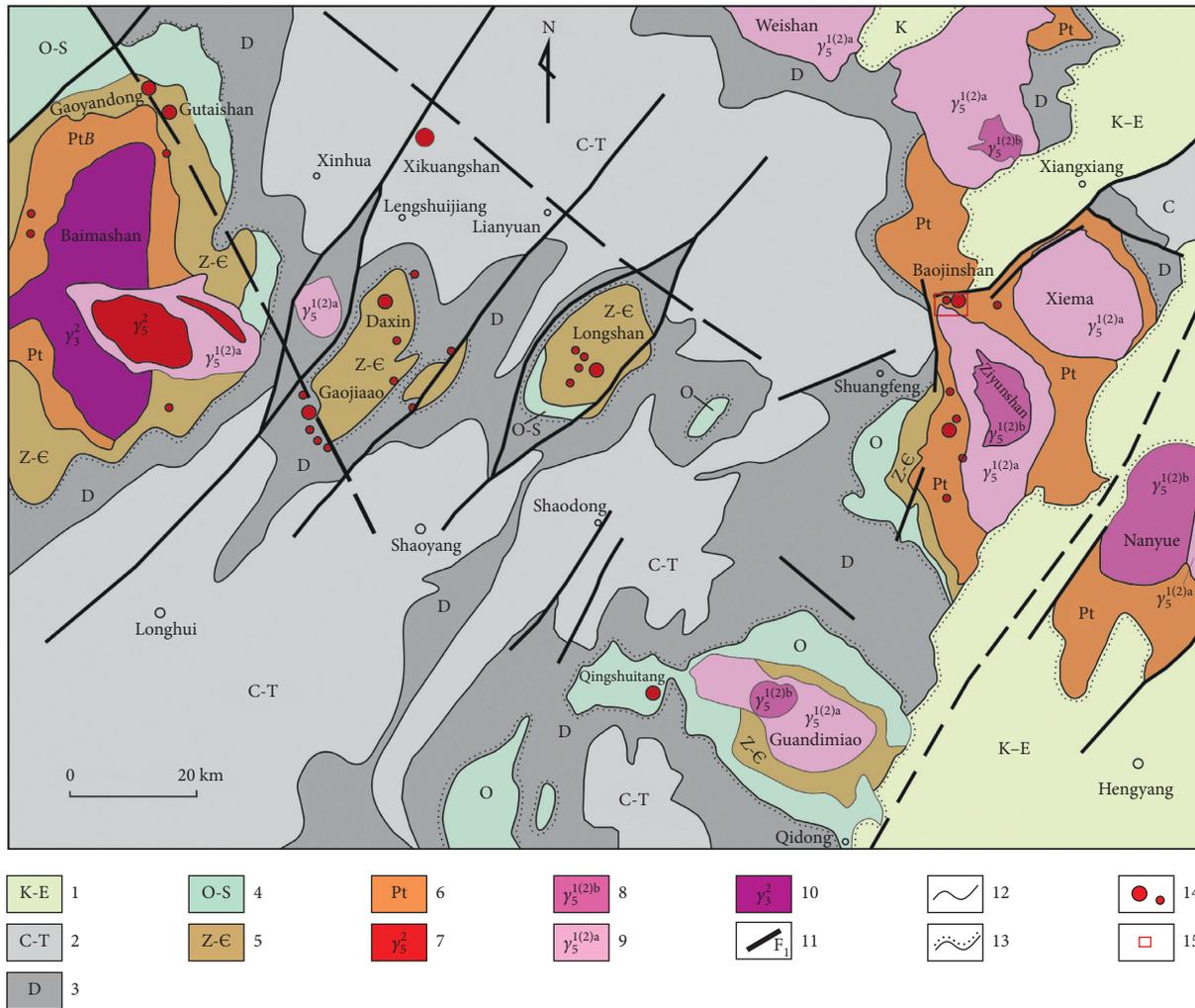


FIGURE 1: Regional geological map of the central Hunan Province. (1) Cretaceous-Paleogene. (2) Carboniferous-Triassic. (3) Devonian. (4) Ordovician-Silurian. (5) Sinian-Cambrian. (6) Neoproterozoic. (7) Yanshanian granite. (8) Late Indosinian biotite (two-mica) granite. (9) Late Indosinian porphyroid monzonitic granite. (10) Caledonian granite. (11) Major deep fracture. (12) Geological boundary. (13) Unconformable boundary line. (14) Ore deposit (ore spot). (15) Study area.

section map of the Baojinshan gold deposit is shown in Figure 2.

F7 fracture and F9 fracture are spreading in parallel, generally, 40–60m apart and are the northern boundary fractures of the Baoginshan gold belt (Figures 2 and 4). It is near the EW direction, inclined to N, dip angle 50°–70°, width 0.5–1.2 m, strike length longer than 1 km. Obvious fault mud is seen in the fault, mostly filled with milky white quartz veins, and local wolframite mineralization is seen (Figures 3(c) and 3(d)). The upper and lower plate surrounding rocks are strongly silicified.

**4.2. Secondary Fracture Structure.** The secondary fractures are mainly in two groups, NW and NEE, which are mainly distributed between the main fractures. The NW secondary fractures are the main ore-holding structure, with a strike of 290°–320°, a southwest orientation, and a dip angle of 45°–77°, with a small strike extension, generally within 30m, and a relatively large tendency to extend deeper, with a goose

shape arrangement, showing the characteristics of tensor fractures, all filled with gold-bearing quartz veins (Figures 3(b), 3(e), and 3(f)).

NEE secondary fracture, 70°–80° in the strike, north-northwest inclination, 45°–65° in dip, with large strike extension, tightly closed structure, smooth and straight tectonic surface, showing the characteristics of shear fracture (Figures 5(e) and 5(f)), locally filled with gold-bearing quartz veins.

**4.3. Combination Type of the Ore-Control Fracture System and Its Ore-Control Effect.** The entire mineral control fracture system extends far, but the secondary fracture zone is limited by the boundary trunk fracture and generally does not extend far. NW-oriented secondary tensional fracture intersects the main fracture at a large angle (Figure 4), and its tendency is opposite to that of the main fracture in the profile (Figure 2); NEE-oriented secondary shear fracture intersects the main fracture at a small angle (Figure 4), and

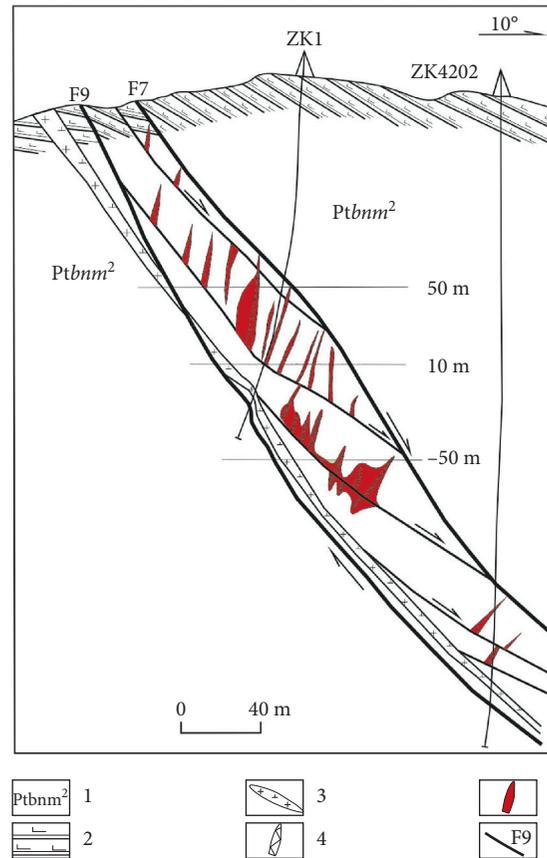


FIGURE 2: No. 42 geological section map of the Baojinshan gold deposit. (1) Second member of Madiyi formation, Banxi group. (2) Calc slate. (3) Granodiorite-porphphyry. (4) Quartz vein. (5) Gold vein. (6) Faults and number.

its tendency is the same as that of the main fracture in the profile, but the dip angle is slightly smaller (Figure 2). The NW-oriented secondary fracture intersects the NEE-oriented secondary fracture at a large angle and is staggered by the latter (Figures 3(a), 3(b)). Judging from the characteristics and nature of the primary and secondary fracture structures, as well as their combination patterns, the mineral control fractures in this area are brittle right-going shear fracture zones. Among them, the F9 and F7 fractures belong to the trunk fracture a principal displacement zone (PDZ) of the Riedel shear fracture system which is a common fault pattern within shear zones, while the NW and NEE secondary fractures belong to the T-type tensional fracture (in which crust undergoes extension) and P-type shear fracture (along which the relative movement is parallel to the fracture) of the Riedel shear fracture system, respectively. Therefore, the Baojinshan ore-control fracture system is a brittle right-lateral shear zone with a strike near EW and a width of 40–60m. Trunk fractures F9 and F7, both of which tend not to be ore-bearing per se but control the spreading of the ore zone (Figures 4 and 2). NW-oriented secondary tensor fractures are the main ore-bearing structures for veinlets, and at the intersection with NEE-oriented secondary shear fractures, the veinlets have the artifact of being truncated by the latter (Figure 3(e)).

Characteristics of subordinated faults in the Baojinshan deposit: an F9 fault scratch is shown in Figure 3.

However, through detailed observation, it was found that the gold-bearing quartz veins filled within the NW-oriented secondary fractures in some sections were not misplaced, but continuously filled along with the NEE-oriented secondary fractures, and the gold-bearing quartz veins were a whole (Figure 3(f)), indicating that both are pre-ore-forming fractures. It may be due to the tight fracture structure in the NEE direction, which acts as a shield to the ore filling and gives the illusion of local breakage. When the NW-trending fractures are denser, and the NEE-trending fractures are wider, the intersection of the two often forms a barrel-shaped ore body, which is more obviously controlled by the combination of the two, making it lateral to the NWW direction ( $290^\circ$ ) with a lateral angle of  $40^\circ$  to  $50^\circ$ . Therefore, the NW and NEE secondary fractures jointly control the specific positioning of the ore body.

## 5. Discussion

*5.1. Tectonic Stress Analysis of the Mineral-Controlling Fracture System.* Based on the comprehensive information on the ore-controlling fracture system and mineralization of Baoginshan, the NW and NEE directional secondary fracture properties were systematically investigated and counted, and Figure 6 shows the statistical results. The production characteristics of the two sets of secondary fractures can be recognized, in which the strike of NW secondary fractures is

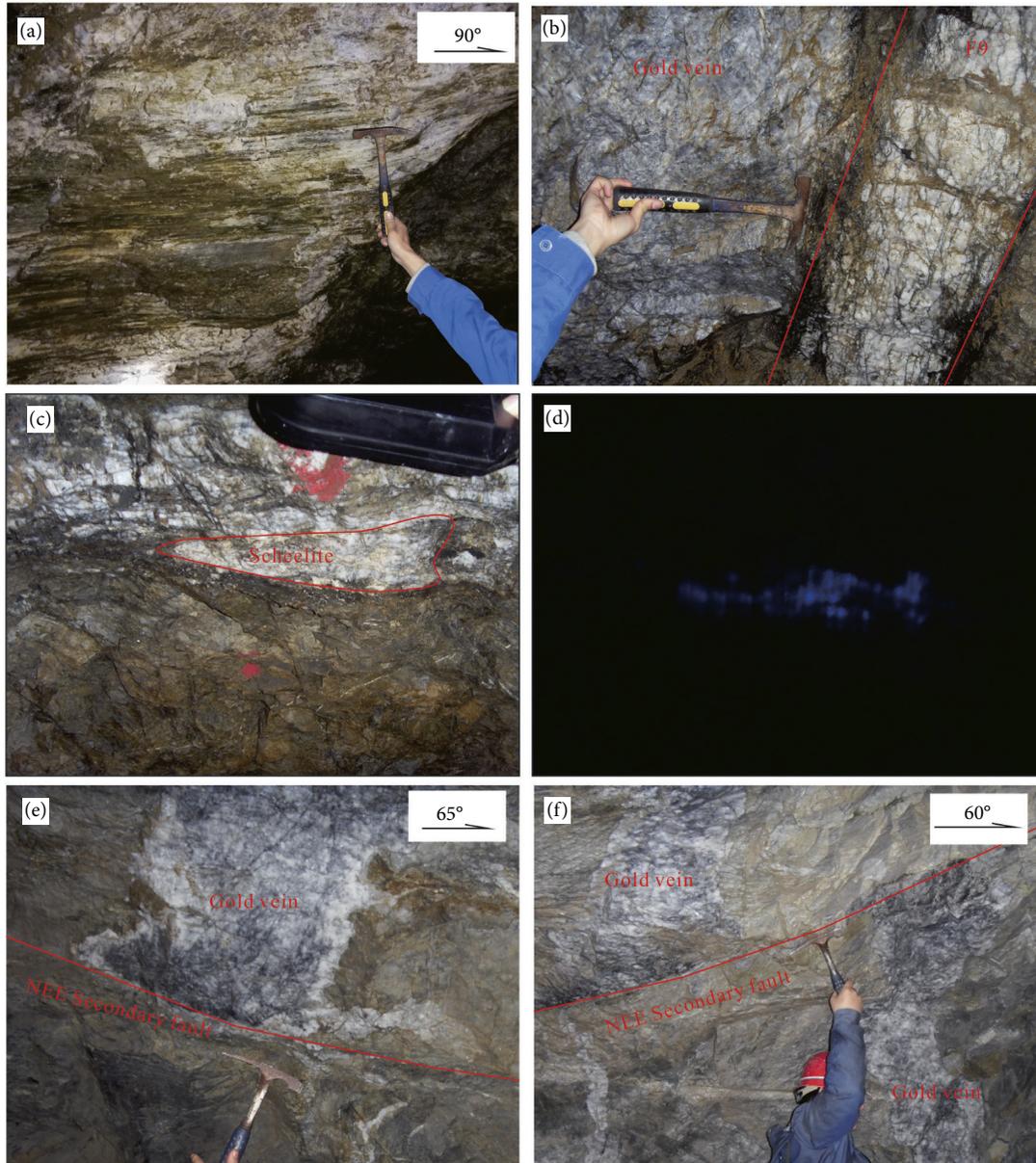


FIGURE 3: Characteristics of subordinated faults in the Baojinshan deposit. (a) F9 fault scratch. (b) NW secondary fault intersects with F9 fault at a large angle. ((c), (d)) Scheelite in F7 fault. (e) The NEE-trending secondary faults are dislocated by the NW trending secondary faults. (f) NEE trending secondary faults are staggered by NW trending secondary faults, but the quartz veins in them are continuously filled.

mainly  $311^{\circ}\text{--}131^{\circ}$  (Figure 5(a)), and the dominant production is  $221^{\circ}\text{--}63^{\circ}$  (Figure 5(b)); the strike of NEE secondary fractures is mainly  $253^{\circ}\text{--}73^{\circ}$  (Figure 5(c)), and the dominant production is  $343^{\circ}\text{--}53^{\circ}$  (Figure 5(d)).

Using the dominant yield of NW and NEE toward the secondary fracture, the direction of the principal stress is calculated by the equatorial projection. The intersection line of the two in the WU is the orientation of the intermediate stress  $\sigma_2$ , which has a dip direction of  $288^{\circ}$  and a dip angle of  $38^{\circ}$  (Figure 5(e)); in addition, combined with the feature that the direction of the principal compressive stress in the strain ellipsoid is parallel to the tensile rupture plane [19], the dip direction of the maximum principal stress  $\sigma_1$  can be determined as  $158^{\circ}$  and a dip angle of  $40^{\circ}$ ; the dip direction of

the minimum principal stress  $\sigma_3$  is  $42^{\circ}$ , and a dip angle of  $28^{\circ}$  (Fig. The dip angles of both  $\sigma_1$  and  $\sigma_3$  are less than  $45^{\circ}$ , indicating that the Baoginshan ore-control fracture system is formed in a horizontal-oriented northwest southeast (NW-SE) stress field (distribution of internal forces that balance a set of external forces). Rose diagrams and stress analysis diagrams of ore-controlling fractures system of the Baojinshan gold deposit is shown in Figure 5.

*5.2. Mechanism of Formation of Mineral-Controlling Fracture Systems.* Shear tectonics often forms a large number of derived structures that constitute a complex fracture system [20, 21]. The ideal shear rupture pattern, i.e., the Riedel shear

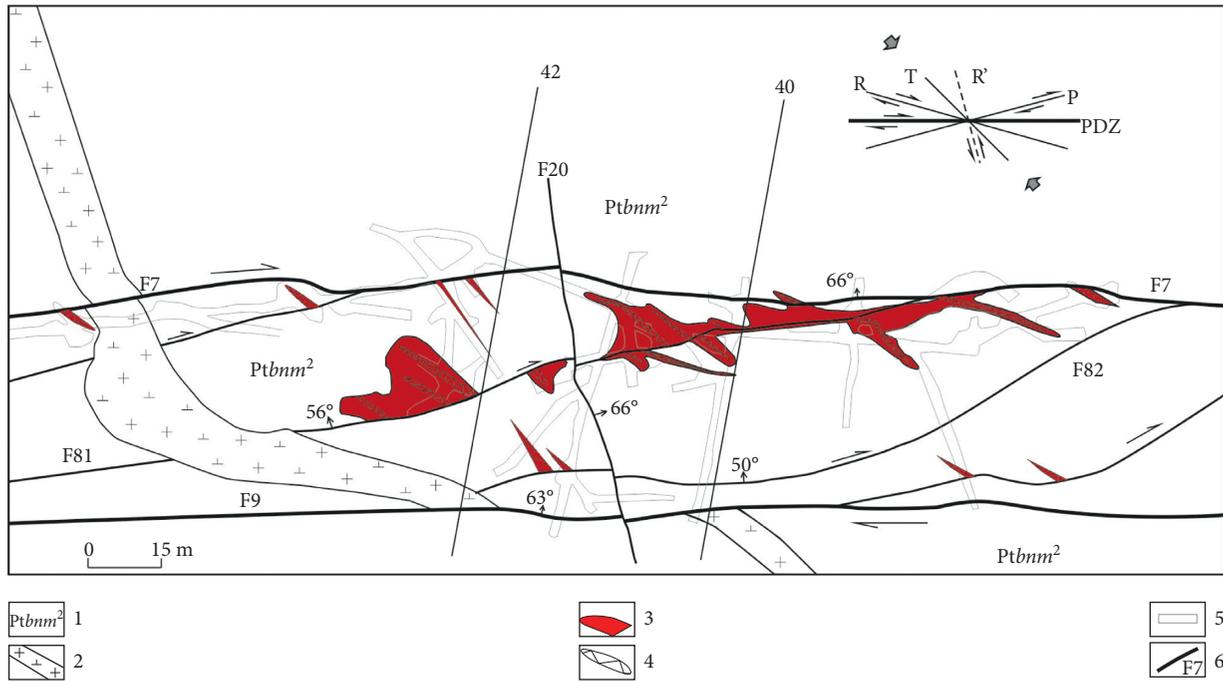


FIGURE 4: Geological plan of the mining level (+10) of Baojinshan gold deposit. (1) Third member of Madiyi formation of the Banxi group. (2) Granodiorite-porphry. (3) gold vein. (4) Quartz vein. (5) Gallery. (6) Faults and number.

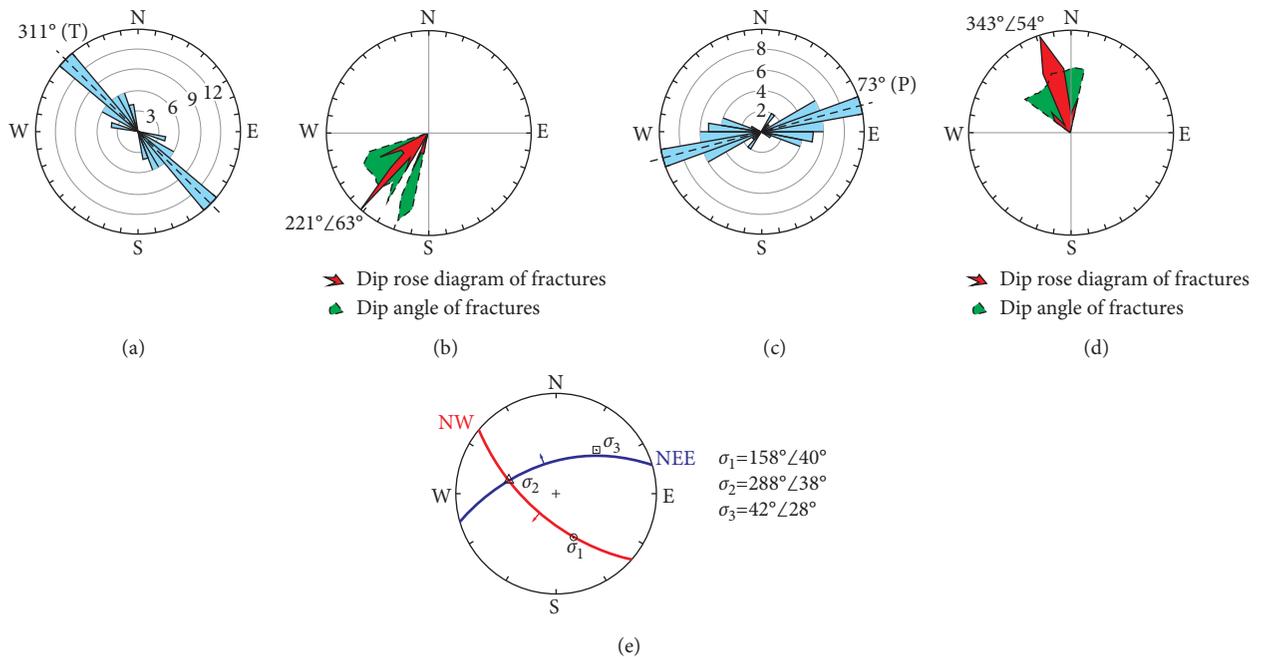


FIGURE 5: Rose diagrams and stress analysis diagram of ore-controlling fractures system of the Baojinshan gold deposit. (a) Dip rose diagram of NW fractures. (b) Angle of NW fractures. (c) Dip rose diagram of NEE fractures. (d) Angle of NEE fractures. (e) Stress analysis diagram.

pattern [19] develops two sets of conjugate shear rupture surfaces (R and R') in the early stage and forms T-type tensor fractures in the direction of the acute bisector of both; a set of P-type shear fractures symmetrical to the R-type fractures develops in the middle stage; the R and P-type fractures

gradually subsume the trunk fracture (PDZ) in the late stage and then forms large shear fault zone (Figure 6(a)). However, the influence of many factors in the crust, such as temperature, surrounding pressure, stratigraphic production, and stress action mode, leads to the phenomenon that

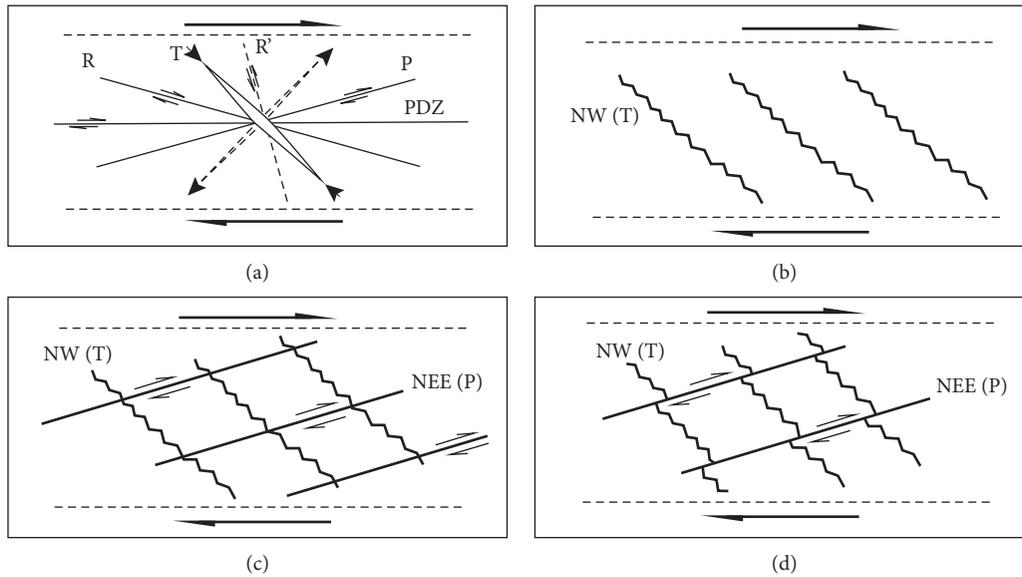


FIGURE 6: Formation mode of ore-controlling fractures system of the Baojinshan gold deposit. (a) Riedel cut pattern diagram. (b) Early deformation characteristics. (c) Middle deformation characteristics. (d) Late deformation characteristics.

not all types of rupture surfaces occur in the shear zone but often the rupture surface in one direction is dominant, and the rupture in other directions is relatively undeveloped [22, 23].

The Baojinshan ore-control fracture system is part of the Ziyunshan dome ring fault, and its maximum principal stress direction ( $158^{\circ}\angle 40^{\circ}$ ) is consistent with the intrusion direction of the Ziyunshan rock mass, implying that the (NW) intrusion of the Ziyunshan rock mass induced the formation of the Baojinshan right-going shear fracture system. At the early stage, NW-oriented secondary tensor fractures (i.e., *T* fractures) mainly appear (Figure 6(b)), and the *R* and *R'* fractures may not develop due to the stratigraphic production and mechanical inhomogeneity of the rocks [23]; at the middle stage, NEE-oriented secondary shear fractures (i.e., *P* fractures) appear (Figure 6(c)) with the tectonic evolution. NW-oriented and NEE-oriented fractures develop into tensor fractures and shear fractures, respectively, which in turn form the right-going shear fracture system in this area (Figure 6(d)). The formation mode of the ore-controlling fractures system of the Baojinshan gold deposit is shown in Figure 6.

**5.3. Ore-Forming Era.** The gold-bearing quartz vein is cut by the porphyry vein as shown in (Figure 7(a) and 7(b)). In addition, the granodiorite porphyry in the mine area has strong alteration, and the quartz dissolution is rounded (Figures 8(c), 8(d)), indicating that the Baujinshan mineralization and granodiorite porphyry were formed basically at the same time [8, 9]. Recent studies show that both the Ziyunshan granite and the Baujinshan granodiorite porphyry are products of the late Indo-Chinese period, and the ages of the Ziyunshan rock masses,  $227.0 \pm 2.2$ – $225.2 \pm 1.7$  Ma, can be taken as the lower limit of the main mineralization period of Baujinshan [24]; the

granodiorite porphyry veins interspersed with gold veins in the Baujinshan mine, and the intrusion time of the granodiorite porphyry,  $225.1 \pm 1.5$  Ma– $223.3 \pm 1.4$  Ma, can be taken as the lower limit of the main mineralization period of the mine [24]. 1.4 Ma can be taken as the upper limit of the main mineralization period of the mine [25]. Thus, it is assumed that the ore-controlling fracture system and mineralization of the Baojinshan gold mine were formed in the late Indo-Chinese period (227–223 Ma). Intersecting relationship between auriferous quartz vein and granodiorite porphyry vein in the Baojinshan mining area is shown in Figure 7. Microscopic characteristics of granodiorite porphyry dikes in the Baojinshan mining area: (Ser: sericite) is shown in Figure 8.

**5.4. Implications for Prospecting Work.** The most important feature of the shear structure is that the extension along the strike and tendency is large, and the tectonic zone is stable, so there is more room for finding ore in the deep part of the deposit. In recent years, 14 industrial ore bodies and 2 mineralized bodies have been seen in the 17 surface vertical drills, and the depth of prospecting has reached 500m, confirming the existence of ore-controlling structures and mineralization, which indicates that there is a large potential for finding ore in the deep part of the deposit. However, because the tendency of single ore bodies in this area is opposite to the tendency of the tectonic zone, and the scale is small and the dip angle is steep, resulting in the surface (in-pit) vertical drilling cannot be effectively controlled, mostly for a single project to see ore, and many blind ore bodies exist between drill holes. To expose these short-vein ore bodies, the mine has adopted the traditional scheme, i.e., encrypting the network of prospecting works to improve the degree of control over the ore bodies, such as reducing the height of the middle section (20m) and encrypting the

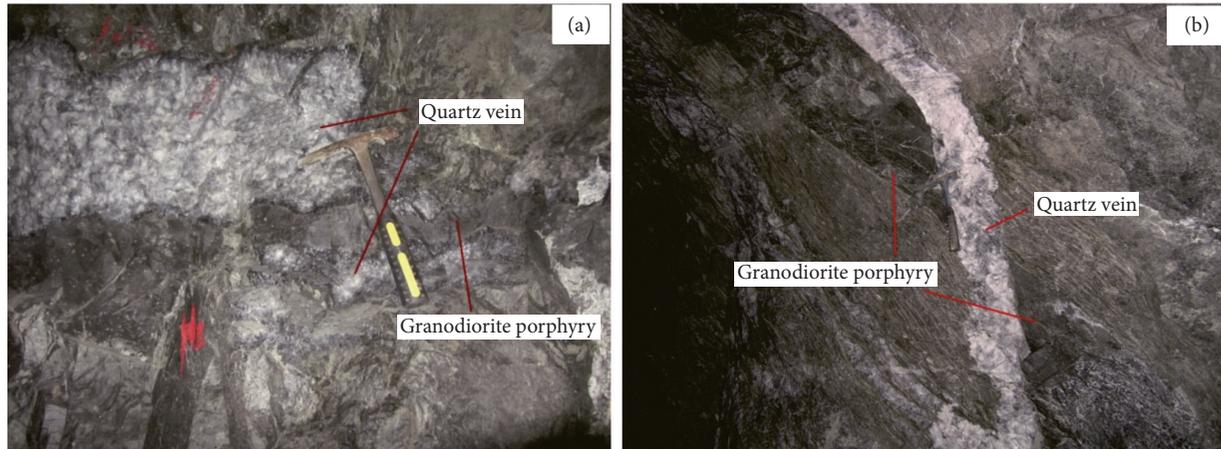


FIGURE 7: Intersecting relationship between auriferous quartz vein and granodiorite porphyry vein in the Baojinshan mining area. (a) The granodiorite porphyry dike breaks the quartz vein. (b) Quartz veins break the granodiorite porphyry dikes.

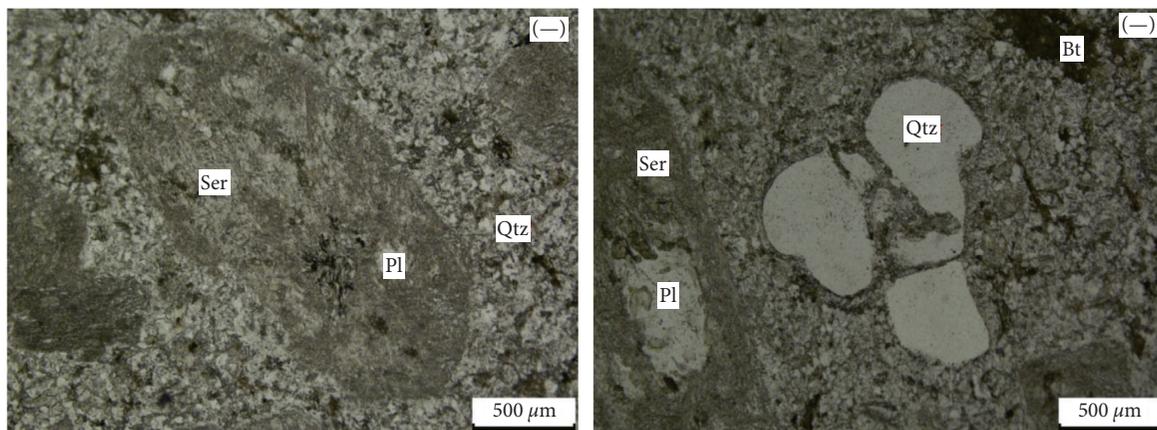


FIGURE 8: Microscopic characteristics of granodiorite porphyry dikes in the Baojinshan mining area. (Ser: sericite; Pl: plagioclase; Qtz: quartz; Bt: biotite).

density of the natural drill holes. However, the prospecting effect is general, and the cost of prospecting is high.

According to this understanding of the characteristics of the ore-control structure system and the law of ore control, the author believes that the mine can optimize the prospecting program from the following aspects to improve the efficiency and effect of prospecting. (1) Thinning control of the ore zone by surface (in-pit) vertical drilling to expose the tectonics and mineralization in the deep part of the main fracture and provide a basis for the engineering design of the pit exploration. (2) Increasing the spacing of the middle section of the pit exploration (which can be increased to 40m) to save the cost of prospecting. (3) Using in-pit drilling for literacy, mainly in the upper and lower discs of the NEE fracture along its strike or inclination to design in-pit drilling, which can effectively expose northwest (south-dipping) blind ore bodies within and between the middle sections.

## 6. Conclusion

- (1) The ore-controlling fractures in Baoginshan are near east-west trending, with a width of 40–60 m. The F7 and F9 fractures are the backbone fractures, controlling the spreading of the Baoginshan ore zone; the NW and NEE secondary fractures are T- and P-type fractures, respectively, and they jointly control the specific positioning of the ore body.
- (2) The right-lateral shear-controlling fracture system at Baoginshan is formed by the NW-SE oriented stress field, where  $\sigma_1$  is  $158^\circ \angle 40^\circ$ ,  $\sigma_2$  is  $288^\circ \angle 38^\circ$ , and  $\sigma_3$  is  $42^\circ \angle 28^\circ$ .
- (3) Based on improving the pit spacing, the mine can effectively control the blind ore bodies within and between the middle sections by placing in-pit drilling along with the tendency and strike in the upper and lower plates of the NEE secondary fractures, which not

only improves the efficiency and effectiveness of prospecting but also significantly reduces the cost of prospecting.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflicts of interest.

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