Original Article

Mathematical, Physical, and Chemical Interpretations of Structural Control and Contributions to Mineralization-Taking Global Gold Deposits as an Example

Jian Zhao Yin[1Ⓛ] , Kuinuan Li[2], Hongyun Shi[3], Haoyu Yin[4], and Yuhong Chao[5]

Abstract

Using the gold provinces in the North China Platform and western Canadian orogenic belt as examples, this article concludes that gold metallogenic series often correspond to the structures in that area. Structures at different hierarchical levels within the same system play distinct roles in deposit formation: the first-level deep-large structures are often channels for the rise of rock-forming materials and their carriers, and control countless gold belts on the earth's surface. The secondary structures control gold fields and/or deposits of different sizes. The third-level structures control the ore bodies of a specific deposit. The mechanical properties of structures, their activity periods, and development of structural rocks influence timing and stages of mineralization, as well as intensity and structure/texture of the deposits. The deep-seated mechanisms underlying structural control of mineralization align with principles of mathematics, physics, and chemistry. The localized dissipative structures resulting from tectonic activity drive the final stages of mineralization. The essence of mineralization is the result of steady-state instability developing into a non-equilibrium dissipative structure. The structures facilitate the conduction, extraction, further enrichment, and upward intrusion of deep ore-bearing fluids through physical effects like seismic pumping, expansion, and re-fracture of mineralized zones. Deep and large faults also contribute to certain mutations in the ore-forming fluid entering the nonlinear low-pressure expansion zone, which causes hydrothermal boiling and a rapid nonlinear decrease in the solubility of the ore fluid. Chemically, the low-pressure expansion spaces formed by these structures act as vast reactors, in which mineralizing materials from different sources undergo violent physichemical reactions. This melting reactor both changes the temperature and pressure of the fluid and leads to drastic changes in chemical conditions such as oxygen fugacity, pH, and electrolyte balance, thus creating conditions for the formation of deposits. Some structures such as epigenetic faults intersect and divide each other to create differences in the bottom topography, hydrodynamics, hydrogeochemistry, and physichemistry in the basin. These variations create favorable space for the accumulation of large quantities of minerals, contributing to the formation of large and/or super-large deposits.

Keywords: tectonic and/or structural hierarchy system; gold metallogenic series; localized dissipative structure; nonlinear coherence effects; physical effects; physicochemical differences

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1. Introduction

The formation of gold deposits is subject to multivariate ore-controlling factors, including complex structural systems with different levels, various igneous rocks with multi-period and multi-cycle origins, and a vast stratigraphic space with different physical and chemical properties following long periods of sedimentation. These ore-controlling factors can either provide migration channels for ore-forming materials and their carriers, are themselves the sources of ore-forming materials, provide the necessary physical and chemical conditions for the enrichment of ore-forming materials, or ultimately provide storage space for the precipitation and placement of ore-forming materials.

Among the three major metallogenic geological conditions mentioned above, structure, especially faults, is undoubtedly the most eye-catching, and to some extent, the most important. With various levels and different mechanical properties of faults, rock-forming and mineralizing materials such as igneous rocks occur, differentiate, and evolve, form ore-bearing fluids, and enrich to eventually form mineral deposits (Yin and Shi, 1995; Yin, 2019a; Wang et al., 2022; Yin and Shi, 2026 a & 2026b).

Therefore, summarizing and discussing the temporal and spatial distribution patterns and genetic relationships between structure and gold mineralization, especially the deep-seated mutual achievement mechanism between the two, has very important significance to both theoretical and practical mining. After all, the formation of a considerable proportion of hard rock gold, especially endogenous gold deposits, is closely related to structure. The survey, exploration, and development of gold deposits are also inseparable from the in-depth study and understanding of structure.

The authors' research, exploration, and development experience in the early Precambrian blocks and volcanic basins of the major gold provinces in the North China Platform, including Hebei, Liaoning, Henan and Shandong, in addition to gold deposits in the Mesozoic orogenic belt of western Canada, is combined with relevant research results of other scholars. This paper summarizes the close temporal, spatial, and causal connection between gold mineralization and structure, and explores the deep-seated intrinsic relationship between the two from the perspectives of mathematics, physics, and chemistry.

2. Examples of the relationship between structure and gold Mineralization

Although no two hard rock gold deposits in the world are exactly the same, almost all endogenous gold deposits around the world still have many commonalities. For example, the formation of these gold deposits is inseparable from the control and/or contribution of various geological structures. Below, we will take some typical gold provinces in China and Canada, thousands of miles apart, as examples to explain the close temporal and spatial relationship between structure and gold mineralization, so as to provide geological facts for the discussion of the internal mechanism of structure control and contribution to gold mineralization later in this article.

2.1. The gold province in the northern margin of North China Platform

In the thousands of years of Chinese civilization, Hebei Province, where the North China Platform is located, and its surrounding provinces of Liaoning, Inner Mongolia, Shanxi, Henan and Shandong, has been important gold-producing areas for successive Chinese dynasties. Historically the focus was mainly the development and utilization of extremely high-grade placer gold deposits. Among them, Hebei Province is a typical representative. Take as an example Zhangjiakou gold province in Hebei Province, which is located on the northern edge of the North China Platform. This area still has a large number of gold deposits of different sizes, and gold mining sites are scattered and numerous (Figure 1).

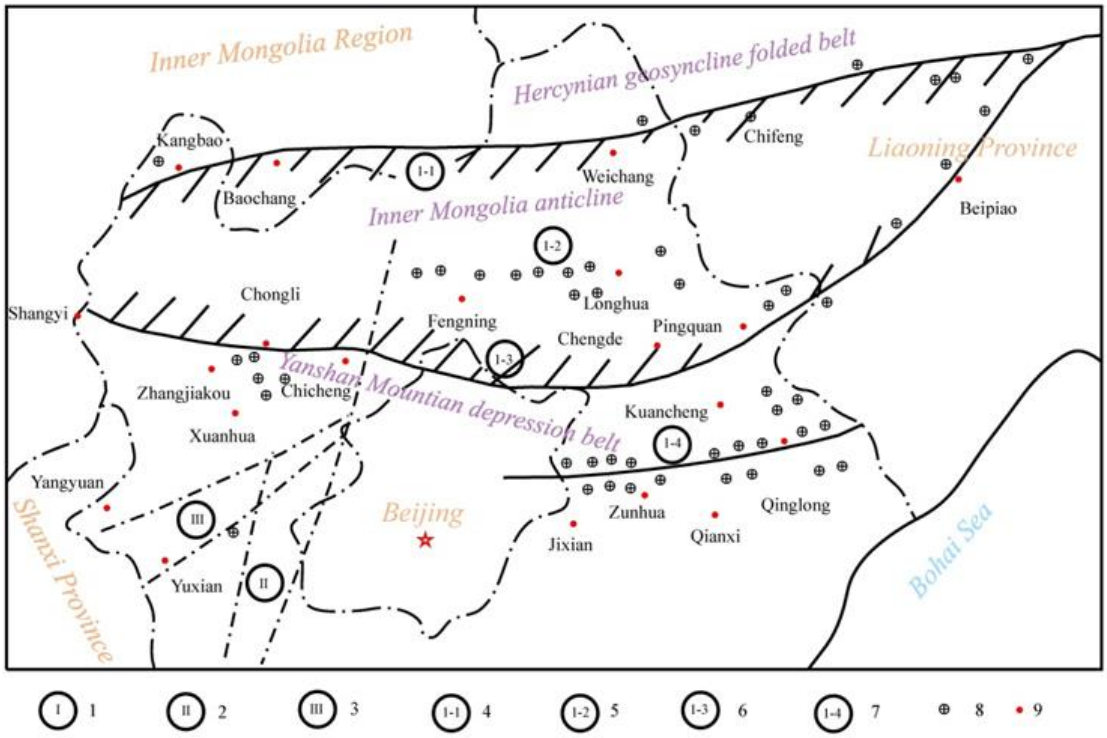


Figure 1. Spatial relationship between faults and gold deposits in the Zhangjiakou gold province of the North China Platform

1. East-West fault zone; 2. North-Northeast fault zone; 3. Northeast fault zone; 4. Kangbao-Weichang-Chifeng fault zone; 5. Fengning-Longhua fault zone; 6. Chongli-Chicheng-Pingquan-Beipiao fault zone; 7. Zunhua-Qinglong fault zone; 8. Gold deposits; 9. Settlements

Zhangjiakou gold province is located in the convergent part between the Inner Mongolian axis (anticline) and the Yanshan geosyncline folded belt of the North China Platform. Most of the over 100 lode gold deposits in the region are located within a 1,500 square kilometer triangular area among the towns of Xuanhua, Chicheng, and Chongli, and are thus called a gold triangle (Figures 2-3) (Song et al., 1994; Yin and Shi, 1995; Xu et al., 2014; Yin et al., 2021; Yin et al., 2023). The emergence of these gold deposits is closely related to the extremely developed faults and folds of different levels in the local area. Together with many gold deposits in eastern Hebei, Inner Mongolia, and western Liaoning, they are confined between and on both sides of two giant east-west fault tectonic zones on the

northern edge of the North China Platform (Figures 1-3). Among the numerous gold deposits in the area, the largest and most representative are the Xiaoyingpan, Dongping, and Zhangquanzhuang gold deposits (Wang, 1986; Dong, 1989; Hu et al., 1990; Zhang, 1990; Xu et al., 2014; Yin et al., 2021; Yin et al., 2023), followed by the Hougou, Shuijingtun, and Hanjiagou gold deposits (Figure 2) (Li, 1992; Li and Peng, 1994; Wang et al., 2021; Zhen et al., 2021). The Xiaoyingpan, Dongping and Zhangquanzhuang gold deposits also represent three different types of gold mineralization (Yin et al., 2021; Yin et al., 2023).

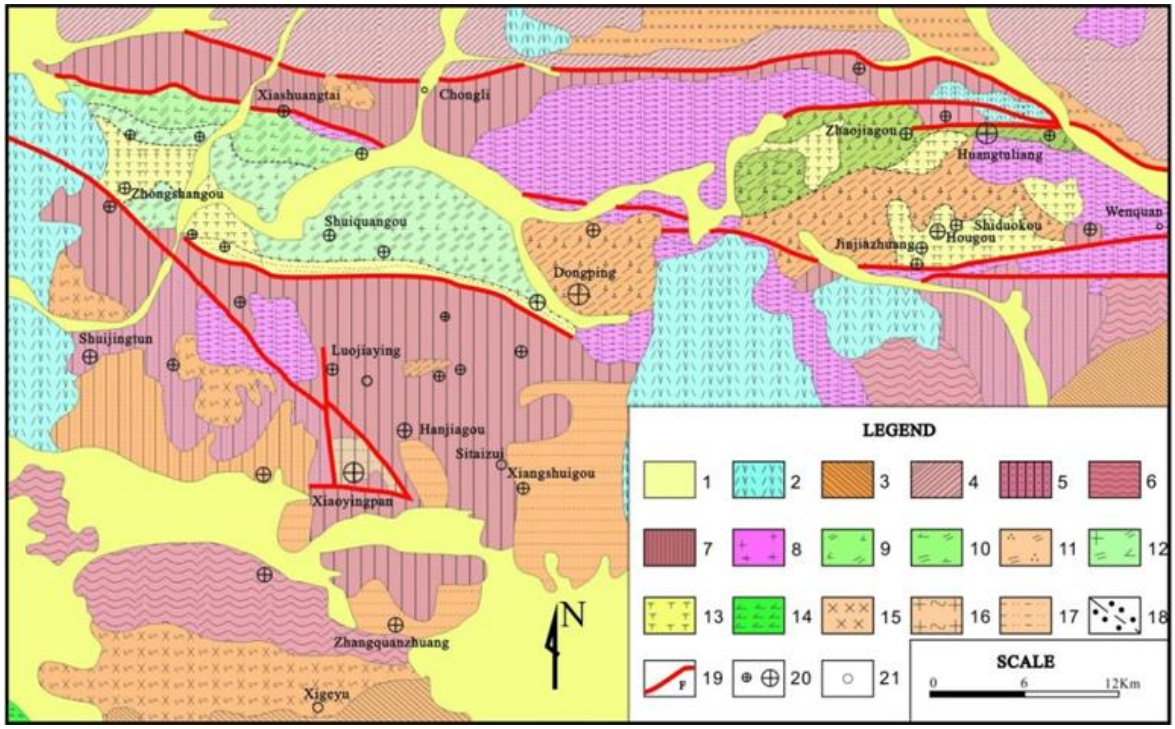


Figure 2. Simplified geological map of the gold deposits in the Zhangjiakou gold province (after Yin et al., 1995; 2021 & 2023)

1. Quaternary sediments; 2. Tuff conglomerate, sandstone and breccia of the hanging Jurassic system; 3. Sandstone, siltstone and dolomite of the Proterozoic Changcheng system; 4. Metamorphic granulite of the late Archean Hongqiyingzi Group; 5. Metamorphic granulite of the Aijiagou Formation of the Archean Sanggan Group; 6. Gneiss of the Shuidizhuang Formation of the Archean Sanggan Group; 7. Metamorphic granulite of the Jiagouhe Formation of the Archean Sanggan Group; 8. Granite of the Yanshan orogeny; 9. Amphibolite monzonite of the Hercynian orogeny; 10. Pyroxene amphibolite monzonite of the Hercynian orogeny; 11. Quartz monzonite of the Hercynian orogeny; 12. Amphibolite adamellite of the Hercynian orogeny; 13. Syenite of the Hercynian orogeny; 14. Pyroxenite of the Hercynian orogeny; 15. The Proterozoic granite-gneiss; 16. The Archean granite-gneiss; 17. The Archean metamorphic mica quartz diorite; 18. Marginal migmatization zone of the monzonite; 19. Fault and/or fault zone; 20. Small to large size gold deposits; 21. Town and/or village

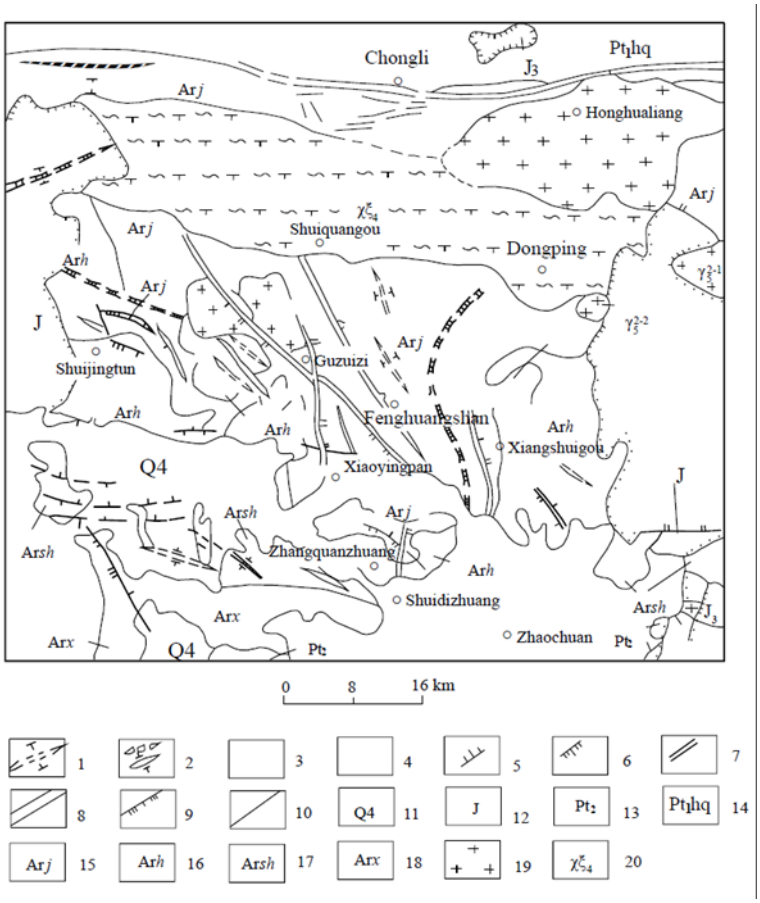


Figure 3. Structural outline of the Zhangjiakou gold province

1. Yanshanian syncline; 2. Early Precambrian third stage antediluvian folds; 3. Early Precambrian second stage reverse antediluvian folds; 4. Early Precambrian first stage reversed complex syncline (form) folds; 5. Himalayan fault zone; 6. Yanshanian fault zone; 7. Archean fault zone revived in the Yanshanian; 8. Deep and large fault zone since the Archean; 9. Archean fault zone; 10. Faults of unknown nature; 11. Quaternary; 12. Jurassic volcanic-sedimentary rocks; 13. Mesoproterozoic Changchengian marine sedimentary rocks; 14. Lower Proterozoic Hongqiyingzi Group; 15. Archean Sanggan Group Jiangouhe Formation metamorphic rocks; 16. Archean Sanggan Group Huajiaying Formation metamorphic rocks; 17. Archean Sanggan Group Shudizhuang Formation metamorphic rocks; 18. Metamorphic rocks of the Xigeyu Formation of the Archean Sanggan Group; 19. Yanshanian granite (porphyry); 20. Hercynian alkaline complex (unclassified)

2.1.1. Regional Structure

Zhangjiakou has a long geological history and complex geological structure. The Archean Sanggan Group metamorphic rocks have undergone multiple stages of tectonic action, forming different types and forms of geological structures (Figure 3) (Yin and Shi, 1995; Yin, 2019a; Wang et al., 2022; Yin and Shi, 2026 a & 2026b).

Regional fold

The metamorphic rocks of the Sanggan Group underwent three folding deformations in the Early Precambrian (Song et al., 1994; Yin and Shi, 1995). The first phase of folding formed a giant compound syncline in the metamorphic rocks of the Sanggan Group, with an axis nearly east-west, an axis plane dipping south, and strata reversed from south to north,

forming the basic structural framework of the Zhangjiakou area. Most researchers believe that this phase of folding occurred in the Archean, contemporaneous with the high-amphibolite-granulite metamorphic event in the region, and slightly earlier than the occurrence of the Chongli-Chicheng deep fault. The second-stage folds are a group of NW-NWW-trending, compound inverted anticlines, with axial planes inclined to the northeast or even lying flat. The sizes of the folds in this stage vary. The secondary tight folds with a scale of 10-100 m on both sides of the main anticline are extremely developed. The second-stage folds predate the migmatization of the area, which occurred at 2500-2400 Ma. The third-stage folds are a group of axially northwest or northwest-west-oriented compound folds formed by NE-SW compressional stress, which appear as wavy fold bundles widely distributed throughout the area, either parallel to each other or arranged in a staggered pattern. Their sizes vary, and a single anticline generally extends for 2-7 km. Among them, the backbone fold in this area is also the largest with the Hanjiagou anticline, which extends nearly 20 km along the axial direction (Figure 4). The Hanjiagou anticline is a wide and gentle wavy fold with a dip angle of about 30 degrees on both wings. The wavelength is generally several times greater than the wave height, and the axial plane is nearly vertical. It is one of the most clearly exposed and best preserved fold structures in the area.

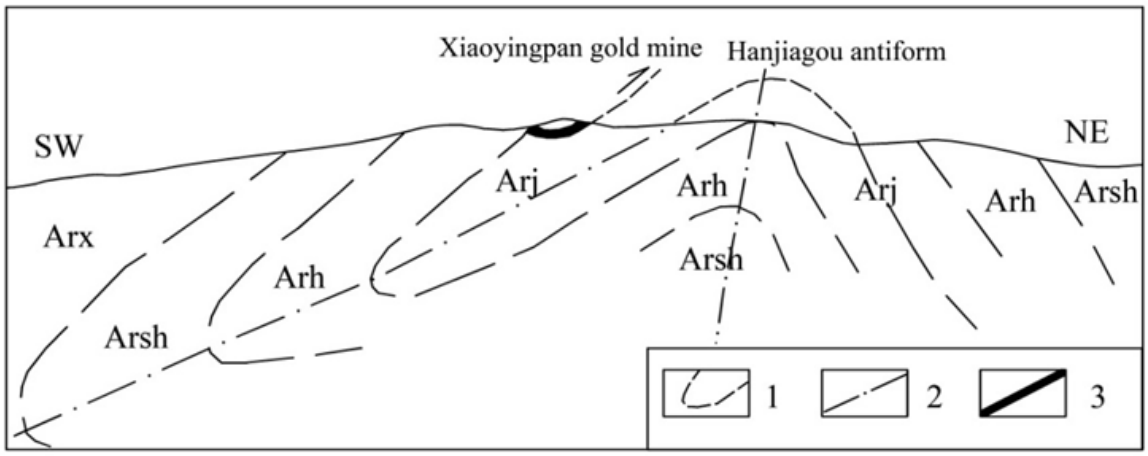


Figure 4. Ore-hosting structure of the Xiaoyingpan gold deposit in the Zhangjiakou gold province (Yin and Shi, 1995; Wang et al., 2022)]

1. Schistose of the host rock; 2. The fold axis plane; 3. Gold-bearing quartz vein/ore body

Regional fault

There are many faults and/or fault zones in the area, which can be divided into east-west faults, northwest faults and northeast faults according to their strike direction (Figures 1-3). The gold belt and ore fields are mainly controlled by the east-west Chongli-Chicheng deep fault, and the gold deposits and ore bodies are located in the secondary fault systems on both sides of the deep fault. The intersection of faults in different directions is often where gold deposits are concentrated. This is also one of the common characteristics of almost all endogenous gold deposits in the world.

• **East-west fault:** The Chongli-Chicheng deep fault zone, which is more than 500 kilometers long and 1-5 kilometers wide, is the most important first-order fault and gold-controlling structural zone in the North China Platform. As the dividing line between the Inner Mongolia axis and the Yanshan platform folded belt, the fault zone starts through Shangyi, Shizuizi, Chongli, Zhenningbao to

Chicheng in the west and turns north through Chengde and Beipiao to merge with the Kangbao-Weichang-Chifeng fault zone, forming an important gold metallogenic zone in northeastern China. The fault zone is composed of a series of densely parallel high-angle reverse faults, compression and crushing zones, and ductile shear zones. The rock strata close to the fault zone are nearly upright and some small mylonite belts are developed along the layers. The fault surface is roughly south-dipping, and the alteration foliation on both sides is strong. The rocks in the fault zone generally contain 0.01-0.40 g/t of gold, with the highest at 0.87 g/t (Yin and Shi, 1995). There are a series of Archean and Hercynian basic-ultrabasic rock bodies of varying sizes on both sides of the fault zone. Gravity field measurements have shown that the fault zone cuts deep below the Moho surface. The depth of the Moho surface in the Chongli area is 42-43 km (Dong, 1989; Song et al., 1994; Yin and Shi, 1995). This is a deep fault zone that has been active from the Archean Era through the Himalayan Period. The series of structures derived from it not only control a series of magmatic activities, but also control deformation, metamorphism, migmatization, and sedimentation of different ages and scales on both sides. All these geological processes provide power, heat, mineralizing materials, ore fluid migration channels, and ore-bearing space for the activation, migration, and enrichment of gold in this area, and ultimately create many different types of gold deposits in the Zhangjiakou gold province (Figure 5). On both sides of this fault zone stretching for more than 200 km, especially within 30 km on its south side, from the Erdaobei gold mine in Shangyi in the west to the Tulongshan gold mine in Chicheng in the east, there are more than 100 gold deposits and gold showings distributed intermittently (Figures 1-2).

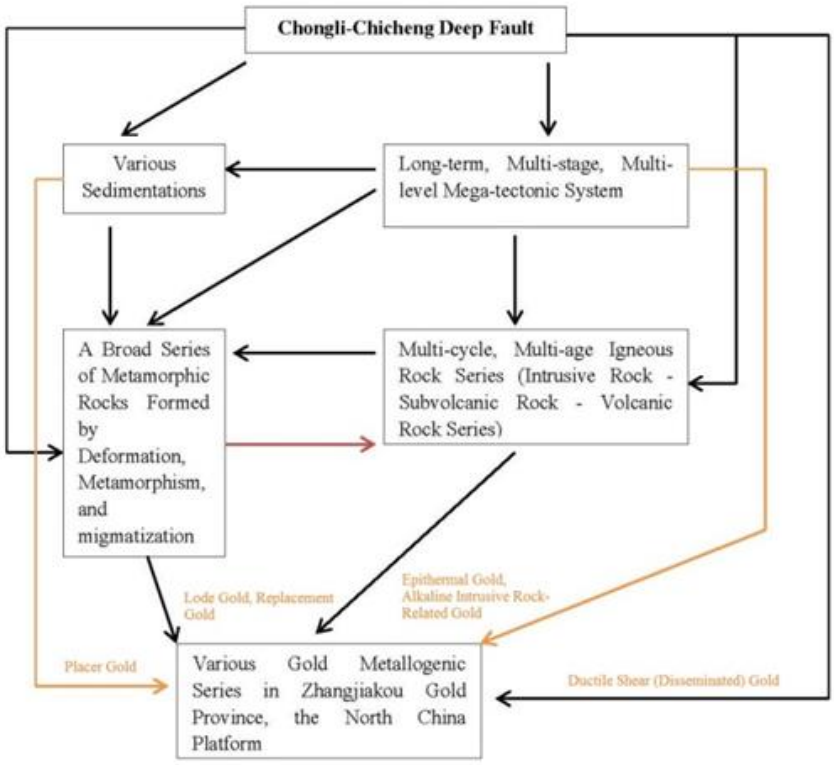


Figure 5. The extensive impact of the Chongli-Chicheng deep fault zone and its control over the Zhangjiakou gold province

The fault zone is mainly composed of early mylonite rocks, late tectonic breccias, marine sedimentary rocks of the lower part of the Mesoproterozoic Changcheng Group, and tectonic rocks of the Jurassic. Some sections are limonite-mineralized, and thin quartz veins are interspersed and filled along the fault zone. The mylonite is mainly composed of sericite, light red potassium feldspar, and quartz, the latter possessing an obvious wire drawing structure. These rocks with strong tectonic foliation are often distributed around some rigid blocks. The structure and rock deformation of the fault zone indicate that it has a history of multi-period and multi-stage activities (Wang, 1986; Dong, 1989; Hu et al., 1990; Zhang, 1990; Song et al., 1994; Yin and Shi, 1995; Xu et al., 2014). Its main activity periods are: the early stage, including the ductile shear thrust during the Late Archean Wutai Movement; the middle stage of the Proterozoic Jixian Movement, was revived and dominated by ductile-brittle thrust activities; the Hercynian stage, characterized by brittle deformation and the formation of a large number of tectonic breccias, accompanied by the emplacement of basic and ultrabasic rock bodies. Finally, the late stage, comprised of the Mesozoic and Cenozoic periods, was characterized by brittle normal fault activities.

• **NW-trending fault**: The northwest-trending faults are the most widely distributed, large-scale, and frequently active group of faults in the area. According to the occurrence, they can be divided into two groups: one group strikes NW310°-340°, dips to the northeast, and has a dip angle of 50°-80°. It is mainly distributed in the Zhangquanzhuang-Xiangshuigou area, containing many gold-bearing quartz veins and filled with various igneous dykes. The other group strikes NWW280°-310°, dips to the south, and has a dip angle of 60°-70°, which is mostly consistent with the occurrence of the strata. The faults are filled with gold-bearing quartz veins with very few igneous dykes. It is mainly distributed in the Shuijingtun-Sitaizui area. In the Xiaoyingpan-Zhangquanzhuang area, more than 200 gold-bearing quartz veins and intermediate-basic dykes distributed in the northwest are widely developed. This fact shows that the northwest-west-trending faults in the area have important mineralization and prospecting significance. The northwest-trending faults that are closely related to mineralization have the following characteristics: larger-scale faults often show traces of multi-stage activities, and the structures are inherited and accompanied by multi-stage hydrothermal superposition. Before gold mineralization, they were characterized by compression and torsion, and during the mineralization period, they were tensile and tension-torsion. The deposits and ore bodies are often controlled by secondary feather-shaped fissures. The various types of igneous dykes contained within them, including gabbro, diabase, lamprophyre, diorite porphyry, granite porphyry, and quartz porphyry, are mostly very developed due to the influence of later structures, and polymetallic mineralization is common. The top and bottom plates and surrounding rock of the fault are well hydrothermally altered, and sericitization, silicification, chloritization, and pyritization are common.

• **North-south fault**: According to their formation age and structural characteristics, the North-South fault can be divided into two categories: one is a large-scale multi-stage active fault, extending 3-7 km; the fracture zone constituting the fault is relatively wide at 20-30 m on average, with the widest area at 50-100 meters with an inclination of 50°-70°. It is filled with gold-bearing quartz veins or dykes and has developed various alterations, which were revived in the Yanshan orogeny and destroyed the existing ore bodies and/or cut through the dykes. The second category is the product of the Yanshan orogeny, with a small scale and obviously cuts various early geological bodies and ore bodies.

There are many ductile thrust structures and a klippe group in the area, some of which are closely related to the formation of gold deposits. For example, the main controlling ore structure of the Xiaoyingpan gold deposit discussed below is a typical representative of this type of ductile thrust structure.

2.1.2. Ore-bearing structure

The main ore-bearing structure of Xiaoyingpan gold deposit is a gentle wavy compression-shear structure, with an overall trend of 46° northeast, a dip to the southeast, and an average dip of 4° (Figure 6). The gently dipping gold-bearing quartz vein, i.e. the fault, is bounded by different lithologies of the hanging and foot walls: the hanging wall is composed of the older Archean Huajiaying Formation metamorphic rocks (Ar*h*), while the footwall belongs to the younger Jiangouhe Formation metamorphic rocks (Ar*j*). Most researchers theorized that (Wang, 1986; Dong, 1989; Hu et al., 1990; Zhang, 1990; Li, 1992; Song et al., 1994; Xu et al., 2014) this structure is an interlayer sliding or detachment zone. It is a compressive structure formed by relative sliding between the metamorphic rock layers of the Huajiaying Formation and Jiangouhe Formation of the Archean Sanggan Group during the compression and folding process. It was later filled with gold-bearing ore fluid to form the main ore body of the Xiaoyingpan gold deposit.

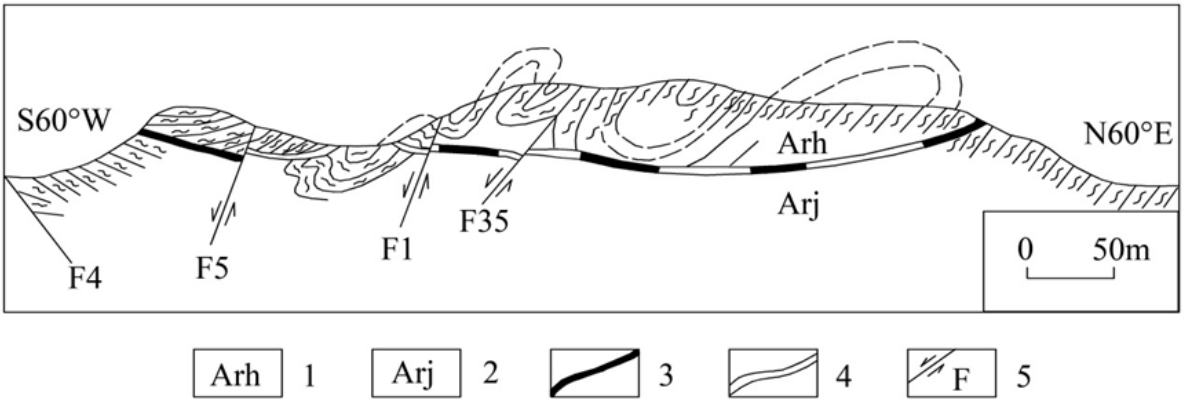


Figure 6. Cross section of the main ore-hosting structure of Xiaoyingpan gold deposit and its relationship with the surrounding rocks of both the hanging wall and the foot wall

1. Metamorphic rocks of the Huajiaying formation of the Archean Sanggan group; 2. Metamorphic rocks of the Jiangouhe formation of the Archean Sanggan group; 3. Gold-bearing quartz vein/ore body; 4. Altered rocks; 5. Fault

Field observations and studies have shown that the structure is mainly composed of mylonite rocks and is strongly altered, and the gold-bearing quartz veins are strictly confined within the mining area. The more than 30 gold-bearing quartz veins exposed on the surface that were originally identified were later proven to belong to the same vein belt through systematic exploration and were strictly controlled by the uneven compressional structure with convex and concave separations. After a detailed field study of this ore-bearing structure, the author of this article concluded that it is not an interlayer sliding zone or a slip zone, but a typical thrust-nappe ductile shear zone. The evidence is as follows: The overall occurrence of this large-scale gently inclined quartz vein-type ore body is not consistent with the overall occurrence of the gneissosity of the metamorphic rock strata in

the mining area, nor is it consistent with the trend of the folds in the area. No matter what kind of superposition the folds developed in the area have experienced, their trends are all NW, EW, and SN, and there are no NE-trending folds. The overall occurrence of the main ore body of the Xiaoyingpan gold deposit strikes 46 degrees north and dips to the southeast. Obviously, it is impossible for the existing fold structure to form such an occurrence of the ore body through interlayer sliding. Statistics of more than 500 occurrences of ore bodies in different parts of the mining area show that the dip angle of the ore body is generally 3°-5°, and locally 17°-21°. Statistics on the occurrence of the strata above and below the ore bodies in the area show that the strata in the mining area generally have an inclination of 20°-40° and can reach 50°-60° or even steeper locally. Obviously, the ore bodies and strata are in an oblique relationship, which is also proved by field observations. This oblique relationship cannot be explained by the view of interlayer sliding (debonding) zones.

It is almost universally recognized by relevant researchers that the turning end of a fold is often a favorable location for mineralization. This favorable location includes two main parts: the collapsed location and the compression cracks, especially the tension cracks. If the main mineralization structure of the Xiaoyingpan gold deposit is indeed a slip structure in the process of folding, then there should be ore bodies filled in the collapsed location and/or structural cracks at the turning end, but neither drilling nor open pit exploration have found the existence of such ore bodies. This proves instead that the mineralization structure is not an interlayer slip structure in the process of folding. Field drilling and open pit exploration also confirm the uneven mineralization structure, with a height difference of 20-30 m between the ore layers at the crest and trough and a wavelength difference of about 100 m, while the ore body is still continuous in the same layer (Song et al., 1994; Yin and Shi, 1995). It is hard to imagine that the ore-bearing space created by the interlayer sliding (decollement) during the folding process can create such a huge single ore body. As previously mentioned, the hanging and foot walls' lithology of the ore-bearing quartz veins is different, and the secondary small soft wrinkles and fold structures are developed in the metamorphic rocks of the hanging wall but not in the foot wall (Figure 6). If the structure where the ore body is located is indeed the interlayer sliding (decollement) between Arh and Arj, then the ore body should only be produced in this position. The reality is that this structure is only the location where the main ore body of the mining area is located. The gold ore body is not only produced in the contact zone between the Huajiaying Formation of the Sanggan Group and the Jiangouhe Formation metamorphic rocks, but are also produced in single Arh or Arj metamorphic rocks. This obviously cannot be explained by the interlayer sliding (decollement) structure between Arh and Arj to explain its ore-control mechanism.

Some researchers believe that the ore-bearing structure of the Xiaoyingpan gold deposit is part of the Qingbiankou-Xiaoyingpan thrust structure (Li, 1994). The two wings of this ductile thrust-nappe structure are tightly closed and small folds and secondary faults with inclined or upright axial surfaces are well developed, resulting in an intense deformation zone. A series of isoclinal inverted folds are developed in the middle zone between the root and the frontal zones. The axial surfaces of these folds are inclined to the root zone, and secondary faults are developed. The thrust-nappe structure is a rear-edge thrust fault system that is imbricate fan-shaped and has forward extension characteristics. . Blastomylonites are developed in the Dongwangshan-Zhoudingtun-Geyubao area, which are the product of early ductile thrust deformation and later transformation such as static recrystallization. Its external system is the Archean granulite facies terrane, which is a component of the early

deeper crust that was exposed to the surface through thrust uplift. Its scale is estimated to be more than 100 km, and the thrust distance may be several kilometers. This thrust structure has the characteristics of multiple periods of activity, and it may be revived in the later period (Zhang, 1984; Xu et al., 1997; Wang et al., 2021; Zhen et al., 2021).

Thrust faults are well developed in the Huajiaying Formation (Ar*h*), the main ore body's hanging wall in the Xiaoyingpan gold deposit. As secondary structures of the hanging wall, these thrust faults are either oblique to the surrounding rock or occur along the layer and become interlayer faults. In this regard, the main ore-bearing structure of the area cannot be consistent or parallel to the occurrence of the surrounding rock, otherwise its secondary faults will not occur along the layer. This proves from one aspect that the main ore-bearing structure is not what has previously been called an interlayer sliding. Both these small-scale thrust faults and the main ore body are upturned about 25° north, and the occurrence gradually slows down towards the south. In the Sandaogou open-pit mining area of the Xiaoyingpan deposit, you can see almost vertical strata and ore-bearing layers upturned to the north. This shows that the overall movement direction of the thrust structure is from south to north. The remaining scratches, steps, and directional mylonite structures on the hillside to the west of the Sandaogou mining area also confirm this.

Mylonite is widely developed in both the hanging and foot walls of the ore-bearing structure in the Xiaoyingpan West mining area, especially in the foot wall. This indicates that the thrust nappe structure is a ductile shear zone. There is also sugar-like quartz with slight iron staining and yellow-brown and brown in the mining area, and the quartz grains are of different sizes. According to Bonnemaison and Houssou et al (Bonnemaison, 1986; Houssou et al., 2017), this kind of extremely fine, milky white or even colorless and transparent sugar granular quartz, which sometimes has a jasper- or chalcedony-like appearance, is composed of microcrystalline quartz (1 - n μm) aggregates. This microcrystalline quartz aggregate is the result of the reprecipitation of silicon dioxide after the original existing mineral-free milky white quartz formed a solution through mylonitization. Essentially, the mineral-free quartz vein plays the role of sugar granular quartz matrix. Sugar granular quartz is a "lithology" that is conducive to capturing gold and is the result of ductile shear. In other words, sugar granular quartz can be used as an identification mark for the existence of ductile shear zones.

In summary, the ore-bearing structure of the Xiaoyingpan gold deposit is a gently inclined, thrust-nappe ductile shear zone. The general direction of the thrust is from south to north. From a regional perspective, along with the aforementioned first-stage closed isoclinal folds, a series of thrust-nappe ductile shear zones developed in the Zhangjiakou area. In addition to the above-mentioned Xiaoyingpan main ore-bearing and Chongli-Chicheng giant thrust-nappe ductile shear zones, there are also the Shizuizi-Xishuangtai and Dalingbao-Tianjiayao thrust-nappe structures. In this geological environment where thrust-nappe action is generally developed, the possibility of the development of thrust-nappe ductile shear zones in the Xiaoyingpan area is far greater than interlayer sliding.

Based on the interaction between different geological phenomena in the field and the characteristics of the Xiaoyingpan gold deposit's main ore-bearing structure, and by comparing them with faults at different stages in the region while accounting for the isotopic ages of existing geological events (Table 1), it should be effective to examine the formation age and development evolution of the ore-bearing structure.

Table 1. The key geological events in Zhangjiakou gold province

Major Geological Events in the Region		Relative Geological Period	Isotopic age
		Early → Late	Ma
Early	Volcano-sedimentary processes and mafic and ultramafic intrusions	….	>2800
	High-amphibolite-granulite metamorphism (Chongli-Chicheng	….	2790 ± 155
	(deep fault begins to be active)		
	Regional migmatization	….	2500-2400
	Amphibolite-facies retrograde metamorphism	….	2400
	Greenschist-amphibolite retrograde metamorphism	….	1800-1500
	Localized migmatization	….	600-450
	Main dike emplacement	….	380-242
	Alkaline complex emplacement	….	273-203
	Mineralization of major gold deposits	….	260-150
Late	Part of the porphyritic granite emplacement	…	188-156
Data source	Zhang, 1984; Wang, 1986; Zhang, 1986; Gao & Gao, 1988; Dong, 1989; Hu et al., 1990; Zhang & Wang, 1990; Zheng, 1990; Gao, 1991; Li, 1992; Hu, 1994; Li and Peng, 1994; Wu, 1995; Yin and Shi, 1995; Mo, 1996; Wu, 1997; Xu et al., 1997; Niu et al., 2009; Zhao et al., 2010; Liu, 2014; Xu et al., 2014; Zhen et al., 2021		

Through a detailed study of the Xiaoyingpan gold deposit and regional structures, some researchers have concluded that its main controlling structure is one of a series of faults that occurred with the first phase of folding. In other words, the ore-bearing structure of the deposit occurred during the Wutai Movement at the end of the Archean Era (Ye and Qian, 1994; Bai, 2018). Judging from the deformation characteristics of the ore-bearing structure and its hanging rock strata, it is similar to the Chongli-Chicheng giant thrust nappe ductile shear zone. Therefore, the author agrees with this view. Judging from the different fillings in the fault zone, this is also a multi-stage active fault zone. The fault has since been reactivated, and the gold-bearing quartz veins have been strongly broken and transformed.

The main ore-bearing structure of the Xiaoyingpan gold deposit is a fault that occurred in the late Archean and was active many times across different geological periods. The three main evolutionary stages of the fault and their characteristics are as follows: ① Early ductile deformation began in the late Archean, and thus the characteristic mylonite is formed. The rock is transformed from high amphibolite phase to granulite phase through ductile shearing to greenschist phase. The typical mineral combination is sericite + chlorite + quartz ± feldspar. ② The mid-term brittle-ductile or ductile-brittle deformation stage occurred in the Hercynian period. Uneven strain occurred in the area due to the differences in the rock types that underwent tectonic activation in different sections, some of which were continuous non-uniform strains while others were discontinuous non-uniform strains. In this way, hardening occurred through plastic deformation in some sections, where the rock's mechanical properties changed from toughness (plasticity or viscosity) to brittleness. This caused the ductile shear zones formed under the same time, space, and physical and chemical conditions to show different characteristics of toughness or brittleness in different sections. Fractures in brittle sections lead to the filling of quartz veins, or the pre-existing quartz veins are fractured and gold-bearing hydrothermal fluids flow in to form quartz vein-type ore bodies. In the ductile stage or section, sugar-like gold-bearing quartz veins and altered rock-type gold mineralization are formed. This also explains why there are two types of gold ores in the Xiaoyingpan deposit. ③The late transformation that occurred in the early Yanshan orogeny was brittle deformation, which was mainly manifested in the

strong crushing and transformation of the existing ore body, causing dislocation and complicating its occurrence. At the same time, white quartz and carbonate veins without ore were generated. This post-ore-forming transformation stage created good conditions for the late oxidation and secondary enrichment of the ore in the mining area, and also created conditions for the formation of local placer gold deposits.

In summary, the main ore-bearing structure of the Xiaoyingpan gold deposit has multi-stage and multi-phase activity characteristics and exhibits different structural properties. This structural feature leads to multi-stage and multi-phase gold mineralization, as well as different mineralization styles, namely quartz vein, replacement, and oxidized secondary enrichment.

The Dongping gold deposit in Zhangjiakou area is related to a large-scale alkaline complex intrusion (Figures 2-3). Its ore bodies and veins are also clearly controlled by various structures (Figures 7-8) (Song and Guo, 1992; Yin, 1994i; Li and Jin, 2000; Zhang et al., 2000; Jiang et al., 2012; Wang et al., 2021; Chao et al., 2022).

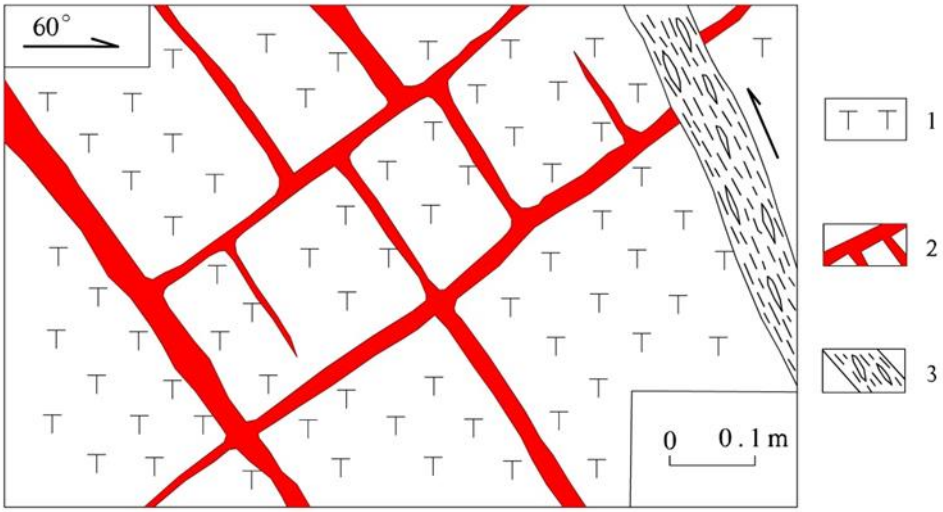


Figure 7. Sketch map of grid-like quartz stockwork veins in Dongping gold mine (#36 Drift, 1503 Level; after Yin and Shi, 1995 and Chao et al., 2022)

1. potassium feldspar altered monzonite; 2. grid-like quartz stockwork vein (Q1); 3.fault

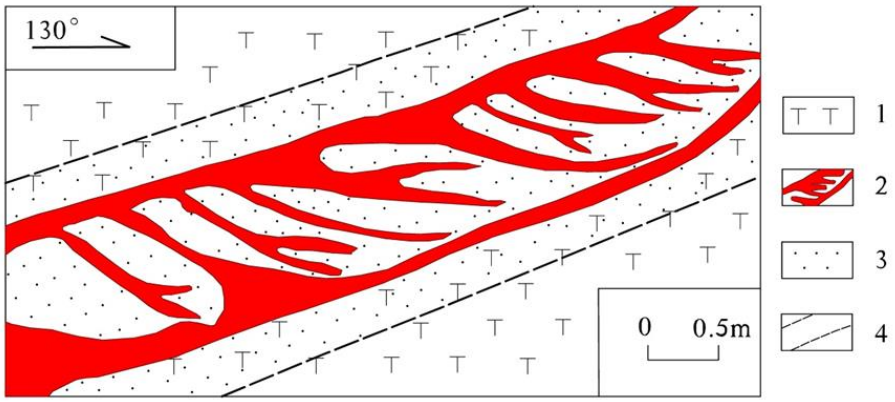


Figure 8. Sketch map of quartz vein (Q3) formed in the third paragenetic stage in Dongping gold deposit (on the roof, 1464 Level; after Yin and Shi, 1995 and Chao et al., 2022)

1. monzonite; 2. quartz vein (Q3); 3. potassium feldspar altered monzonite; 4. ore body range

2.2. Gold deposits and structures in the Mesozoic orogenic belt on the west coast of Canada

The Cariboo gold mining district, located in the east-central region of British Columbia, Canada, has been a historically significant gold rush district on the Pacific coast of western North America since at least 1858. Large-scale gold rush mining occurred in this region prior to the 1930s, since which exploration and mining of hard rock gold have been the main focus. To this day, it is still an important gold-producing area in North America with hard rock gold as the main exploration and mining target. At the same time, placer gold mining of different scales still flourishes. During the Great Depression in the 1920s, the Cariboo gold mining district thrived in spite of the broader severe economic decline. The British Columbia government even had plans to move the provincial government to Barkerville, a small town that was the epicenter of the Cariboo gold mining district. Although this move did not come to fruition, Barkerville, which is still famous for its role in the BC gold rush, has become a provincial park and is still favored by tourists from all over the world. Among the many projects in the park, the most popular one is the gold panning show. The luckiest tourists will harvest a small amount of real gold nuggets among the "fool's gold" pyrite that was put in the sediment beforehand.

According to relevant statistics, recorded gold production from the Cariboo gold mining district totals some 5.0 million ounces, including an estimated 3.0 million ounces from placer mining from 101 creeks and rivers, and 2.0 million ounces from lode gold mining (Yin, 2018a; Yin, 2019a).

The mining district lies approximately 80 km east of Quesnel, 120 km southeast of Prince George, and 500 km north of Vancouver. It is situated within the Quesnel Highlands on the eastern edge of the Interior Plateau. The highlands have an average width and length of approximately 50 km and 160 km respectively (Yin and Daignault, 2007 & 2008). The Quesnel Highlands are the remnants of a rolling plateau formed initially from bedrocks lain down as the ancient North American Plate moved westwards, colliding with offshore seabed and island groups. The bedrocks were then overlain by lava flows emanating from Chilcotin volcanoes that filled the lowlands between the Coast and Cariboo Mountains. These remnants rise gradually from roughly 1,500 m above sea level in the west to more

than 1,900 m above sea level in the east, and become progressively more dissected with elevation. Located between the Coast and northern Rocky Mountains, the district is within the Southern Cordillera region, as defined by the Geological Survey of Canada for the purpose of describing seismic risk (Bowman, 1889; Johnston and Uglow, 1926; Richards, 1948).

Situated within the Cariboo gold belt (Figure 9), the district encompasses (from northwest to southeast) the former producing Hardscrabble tungsten-gold mine and the Mosquito Creek (MGM), Aurum, and Island Mountain gold mines (IGM), located on the northwest of the Jack of Clubs Lake. The IGM (1934-1967) and MGM (1980-1983) produced 603,800 ounces of gold from approximately 1.35 million tons of quartz-type ore with an average grade of 12.0 g/t gold and replacement ore with an average grade of 23.0 g/t gold. The Cariboo Gold Quartz mine (CGQ), situated on southeast of the Jack of Clubs Lake (Figures 9), produced 1.68 million tons grading 12.7 g/to gold from 1933 to 1959, primarily from quartz veins. Additionally, the belt also contains the Bonanza Ledge gold mine, the Cariboo Thompson gold & silver mine, and the Cariboo Hudson gold mine (Skerl, 1948; Struik, 1986; Rhys, 2001; Yin, 2009 & 2010).

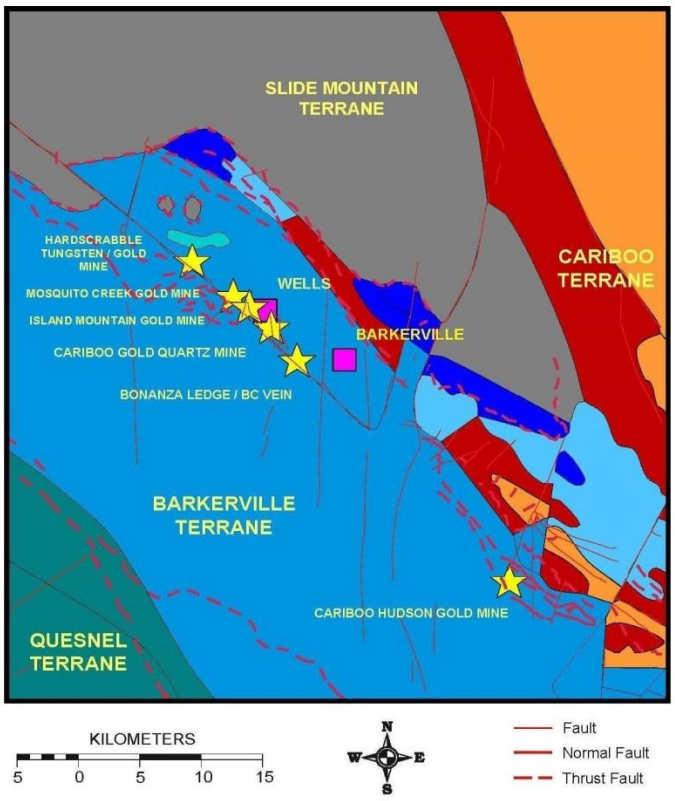


Figure 9. Regional geology of the Cariboo gold mining district (After Yin, 2018a)

The region lies within the Barkerville terrane consisting of a late Proterozoic and/or Paleozoic sequence of continental shelf and slope deposits developed adjacent to the craton

of Ancestral North America, and includes clastic sedimentary rocks along with lesser amounts of volcanic rocks and carbonates. As part of the Omineca belt of the Canadian Cordillera, it is structurally the lowest exposed stratigraphic sequence in area, and is more deformed and metamorphosed than adjacent terranes (Rhys, 2001; Yin, 2009 & 2010). Rocks of the Snowshoe group in the district have been metamorphosed to lower greenschist facies, generally of lower metamorphic grade than other sequences in the Barkerville terrane. Rocks of the Barkerville terrane were subjected to an early period of ductile deformation that resulted in westward-directed, asymmetrical folds plunging shallowly to the northwest. Post metamorphic open folds with upright cleavage are superimposed on earlier structures. During the late Cretaceous to early Tertiary, the terrane was disrupted by northwest trending dextral strike-slip faults such as the Willow fault, a major strike-slip fault of unknown displacement that has been mapped through Mount Tom, Island Mountain, Cow Mountain and Richfield Mountain in the Barkerville area (Struik, 1986). The north striking cross faults are an important control for the gold vein mineralization (Rhys, 2001). Stratigraphic position, host rock lithologies, and proximity to north-striking fault zones are important guides to the different styles of gold mineralization recognized in the district. Historical production has been from mesothermal pyrite-bearing quartz vein systems that cut turbiditic rocks, and from semi-massive to massive pyrite replacement type bodies that occur in carbonate-rich rocks structurally higher but stratigraphically lower in the sequence (Skerl, 1948; Struik, 1986; Rhys, 2001). The area is underlain by a northwest striking, moderately northeast dipping sequence of rocks on the steep, overturned limb of a southwest-verging antiform (Figures 9), which in turn, is on the northeast flank of the Island Mountain anticlinorium. Structure in the district is briefly discussed as follows (Rhys, 2001; Yin, 2011):

•**Deformation and folding**: at least three phases of folding and fabric development occur in the region and are responsible for the major regional map patterns. The early deformation event records significant, ductile penetrative shortening. Deformation 2 is associated with a spaced to penetrative northeast-dipping foliation. The youngest deformation results in spaced, northwest trending, and steeply dipping crenulation cleavage in the region.

•**Faults**: faults and shear zones developed in the region are of several generations and orientations. These include the north trending and moderate to steep east-dipping faults; for example, the No. 1, Rainbow, Sanders, Lowhee, Goldfinch, Waoming and Marie faults. The strike faults are a northwest-trending, and moderate to steep northeast-dipping (45° - 80°) set of faults, likely the oldest in the area; one of the most important strike faults is the BC fault zone, localized mainly in the BC Argillite Unit and occupied by the BC quartz vein.

There are five principal types of lode gold deposits in the district; namely, auriferous pyrite replacement, including replacement in limestone and in calcareous clastic rock; pyrite-quartz vein/veinlet lode gold, including strike vein, diagonal vein, orthogonal vein, and quartz veinlets; basalt-hosted auriferous pyrrhotite-pyrite lode gold; and associated gold in porphyry copper styles (Table 2) (Yin, 2018a & 2019a).

Table 2. Lode gold deposit type in the Cariboo gold mining district (Yin, 2018a & 2019a)

Lode gold type	Sub-type	Representative gold deposit
Auriferous pyrite replacement	Limestone hosted	Mosquito Creek, Aurum, Island and Cow Mountain gold deposit
	Clastic rock hosted	Bonanza Ledge gold deposit on the Barkerville Mountain
Basalt-hosted gold-bearing pyrrhotite-pyrite lode gold	N/A	QR gold deposit
Auriferous pyrite-quartz vein/veinlet lode gold	Strike quartz vein	BC Vein on Barkerville & Cow Mountains
	Diagonal quartz vein	Hardscrabble W-Au Mine, Island, Cow and Barkerville Mountains
	Orthogonal quartz vein	Island, Cow and Barkerville Mountains; Cariboo Thompson & Cariboo Hudson Gold Mines
	Quart veinlet	Island, Cow and Barkerville Mountains
Associated gold in porphyry copper	N/A	Mount Polly porphyry copper

As the most important type of gold deposit in the area, quartz vein-type gold mineralization is completely controlled by faults of different properties and occurrences. Most important in this case refers to gold deposits with the largest mineralization scale, the most gold produced, and are still being explored and mined today.

3. Close spatiotemporal relationship between structure and gold mineralization

By examining the relationship between different types of gold deposits and structures around the world, we can generally establish the following common rules: the two have the same or very similar temporal and spatial distributions, and they are also inseparable in space. The tectonic system's scale, level, stress type, and activity period determine the scale of gold belts, ore fields, deposits, and ore bodies, and even the type of gold mineralization.

Within the same fault system, faults of different levels play different controlling roles in the formation of gold deposits, and can be viewed as having their own division of labor. The first-level deep faults in the fault zone not only control the formation of mineralization parent rocks closely related to the formation of gold deposits, but also directly or indirectly control the migration of mineralization materials and gold-bearing fluids, and ultimately direct the formation and distribution of the gold deposit belt in the area (Figure 1-3,5,9). Secondary faults control the distribution of different gold fields in the same gold belt. As for tertiary faults, they specifically control the formation and distribution of specific deposits in a certain gold field.

There is no doubt that the empty areas at the turning ends of the folds and associated cracks and fractures are also favorable locations for the production of gold deposits and gold ore bodies. The Ø-shaped structure formed by the intersection of linear and circular structures is also a favorable location for gold mineralization (Yin, 1996). Depending on the sizes of the circular and the linear structures, the Ø-shaped structure at their intersection controls either some gold ore fields (large-scale Ø-shaped structure) or some gold deposits (small-scale Ø-shaped structure).

Similar to the above-mentioned Ø-shaped structures, the intersection of two or more linear structures and depending on their size the intersection of linear structures and folds, also control the formation of gold ore fields and/or deposits. Similarly, the intersection of two or more ring structures is also a favorable condition for the formation of gold mineralization. The scale of these ring structures also determines the scale of the relevant gold ore fields and/or deposits, and by association determines the output form of the relevant gold ore bodies.

The mechanical properties of faults or fissures at different levels (tensile, compressive, compression-torsion, tension-torsion, shear, brittle, ductile, brittle-ductile or ductile-brittle, etc.) also control the scale and output pattern of gold mineralized belts, ore fields, ore deposits, and to an extent ore structure and texture.

The number of fault activities also controls the scale and output pattern of the same gold belt, ore field, ore deposit, and ore body to a certain extent. Similarly, the number of fault system activities also controls more specific gold mineralization elements such as the stage, mineralization intensity, and ore structure to a certain extent.

In short, structural association indirectly or directly controls the occurrence, development, and completion of gold mineralization by controlling the three major diagenetic processes closely related to mineralization, especially igneous activities.

4. Discussion: the deep mechanism between structure and mineralization

Fundamentally speaking, the ultimate question of mineral deposit research is a very complex and extremely difficult one to answer: Where is the deposit, and why is it here instead of elsewhere? The traditional mineral deposit theory gives a vague and general description: given a certain tectonic position and a specific structural-magmatic-sedimentary background, certain P, T, Eh, pH, mineralizers and their concentrations and other factors control the formation of mineral deposits. This is an answer largely without substance.

Theoretically, the answers to all problems in nature ultimately come down to a series of scientific principles based on mathematics, physics, and chemistry.

However, the complexity of the ore forming control factors in nature is difficult to accurately summarize using the same language of mathematical and physical formulas and/or chemical reaction equations. Among the many ore-controlling factors, some variables seem to be certain, while others exist in a state of non-integer dimension: the ore-forming hydrothermal system is a complex nonlinear, non-equilibrium system.

Due to the existence of certain nonlinear fluctuation factors, it is impossible to fully and meticulously characterize the variables of a mineralization process under current scientific and technological conditions. In a specific mining area, even between structures of the same level and type, there will be differences in mineralization capacity due to the different surrounding rock conditions. One part is completely mineralized, another part is locally mineralized, and even more parts are not mineralized at all. Even under the same surrounding rock conditions, two structural systems, or even different parts of the same

structural system, can result in two completely different results of mineralization or non-mineralization due to some very inconspicuous factors.

Nevertheless, in-depth exploration of the intrinsic mechanism of structural control over gold mineralization still has very important economic value and theoretical significance.

According to the dissipative structure theory, a nonlinear open system far from equilibrium will constantly exchange matter and energy with the outside world. When the change of an individual parameter in the system reaches a certain threshold, the system will undergo a mutation, i.e., a non-equilibrium phase transition through fluctuations, and transform from the original chaotic disordered state to an ordered state in time, space, or function [58]. Geologists have studied the branch theories of dissipative structure formed by nonlinear dynamics, such as bifurcation, cynergetics, and catastrophe theory (Yu, 1981 & 1987; Li, 1989; Wu and Lin, 1992; Yang et al., 1993; Yin, 1996), in addition to the non-equilibrium and nonlinear problems that are common in geological processes. They point to the transformation from mineralization to mineral deposits, which is essentially the result of the development of dissipative structures from steady-state instability to a state far from equilibrium ((Yu, 1981 & 1987).

The occurrence of mineralization results from the development of localized dissipative structure and length of coherence. There are a large number of nonlinear coherent effects in the fault system. When the ore-forming fluid reaches some nonlinear low-pressure expansion zones, mutation phenomena cause hydrothermal boiling, nonlinear rapid decrease in solubility, cross-catalysis, and convergence between alteration and mineralization, which are all obvious nonlinear coherent effects. The fault-ore-forming system is a dissipative structure far from equilibrium, which provides the necessary conditions for mineralization.

The formation of dissipative structure requires two conditions that are internal and external to the system: internal conditions that constitute the self-organization conditions of dissipative structure, and external conditions such as certain mineralization forces that trigger and maintain the occurrence of self-organization, including magmatic events, geothermal gradients, and the maintenance of certain material compensation guarantees. The generation of dissipative structure is the result of thermodynamic instability caused by order parameters exceeding a certain critical value. At this time, even a small disturbance can cause the state of the system to transition to the dissipative structure branch (Figure 10). This branching phenomenon destroys the original uniform symmetry of the system, which are the so-called symmetry-breaking instabilities. The essence of mineralization is the combination of conditions and transformational mechanism of the non-equilibrium steady-state instability without ore into a dissipative, ore-forming structure.

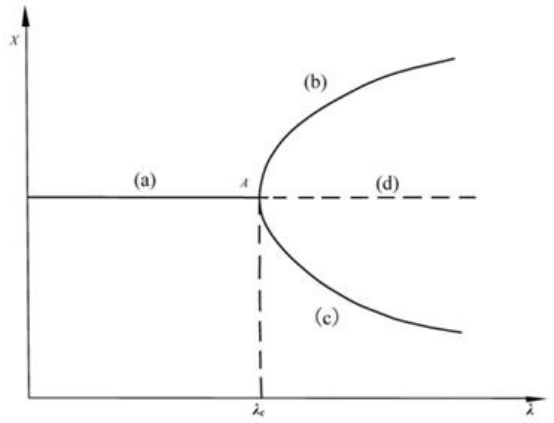


Figure 10. Stability and bifurcation of solutions of reaction-diffusion equations (After Yu, 1987)

X represents the amplitude of the solution of the equation, and the solid line and the dotted line represent the stable solution and the unstable solution, respectively; λ_c is the critical value of λ; *A* is the branch point; a and d represent thermodynamic branch, b and c represent its branches

Ore accumulation is spatially localized, i.e., the localization of dissipative structures. The emergence of prospective mineralization areas is a reflection of localized dissipative structures. Whether various mineralization factors can enter a coordinated state together is the key to mineralization. When a large amount of minerals enter the localized dissipative structure, they are precipitated and mineralized due to the action of state attractors, i.e., expansion zones or favorable ore-controlling spaces. Some ore-bearing spaces have accumulated minerals many times, and some ore-forming hydrothermal fluids have pulsed up and formed minerals many times. This inheritance can occur between multiple mineralizations over a long period of time, such as tens or hundreds of millions of years. The ore source exists for a long time in the mineralization concentration area, and localized dissipative structures appear many times in favorable spatial locations under the action of multiple external forces. This favorable space can be as large as a mineralization belt or as small as a specific ore-gathering structure.

In short, the control of structure on gold and other mineralization is essentially the formation of localized dissipative structures that are conducive to the occurrence of gold deposits. The formation of any mineralization zone on earth is the result of the development and evolution of a grand dynamic system in geological history. It is a unified whole of geological-metallogenic processes and their time-space structures that have been formed and constantly changed. The spatial zoning of strata, structures, igneous rocks, and ore deposits, the formation of mineralization zones, and the establishment of mineralization periods all come from the self-organization process occurring in a macroscopic homogeneous system and the resulting time-space ordered structure, namely dissipative structure.

The dynamic response of the geochemical system to disturbances both inside and outside the system and its relative stability are the root causes of the system's self-organization process and the formation of ordered space-time structures. The emergence of multiple

non-equilibrium steady states (where the space-time symmetry of the system remains unchanged) in the geochemical cycle of crustal evolution, the occurrence of periodic chemical oscillations (time-ordered structure "limit cycle", time asymmetry) in the process of magma crystallization, and the division of regional mineralization prospect areas (space-ordered structure "localized dissipative structure", space asymmetry) are open physical and chemical systems in a non-equilibrium state. They generally undergo dynamic evolution, self-organization processes, and form space-time dissipative structures. They are generated because the system's local time and space domains do not respond in time to inside and outside disturbances and are pushed away from equilibrium, thus causing the non-equilibrium steady state to become unstable. The multi-order of successive bifurcation of dissipative structures determines the formation of mineralization zones on the earth's surface (Yu, 1981 & 1987; Li, 1989; Wu and Lin, 1992; Yang et al., 1993; Yin, 1996).

The identification procedure of ore-aggregating dissipative structures is to identify and find open systems for energy and material exchange. More specifically, it is to find deep structures and rising channels of magma and fluids, and discover the ore-forming forces that ensure the supply of materials and energy, such as geothermal anomalies, magma, and tectonic activities. It's also important to look for ore-forming "attractors" such as expansion zones and favorable ore-controlling spaces, and traces of nonlinear coherence effects or specific alteration and geochemical element combinations, and pay special attention to their scale and intensity. The length of coherence can then be reviewed to estimate the potential of ore deposits. The length of coherence refers to the linear length of the system that breaks symmetry and forms a dissipative structure when the rise and fall increases at the critical point and the steady state become unstable.

Large structures are often closely related to the formation of large and super-large mineral deposits. Large structures that penetrate the entire crust and even reach the mantle lithosphere provide energy for geological processes such as magmatic activity. Changes in the thermal state of the crust or lithosphere, such as the rise of mantle plumes, can also cause the activation of existing large structures. The continuity of large faults and the decompression induced by faults will cause deep superheated materials to melt due to pressure release, thereby further inducing diagenesis and mineralization. Some special types of faults, such as the ductile shear system deep in the crust, not only provide some metamorphic fluids, but also help to extract mineralizing materials from the surrounding rocks under reducing conditions and tectonic pumping. The brittle-ductile tectonic conversion system in the middle of the crust and the open brittle fracture network system in the upper crust provide channels for ore fluid convection and places for ore-forming materials to precipitate, thus forming shear zone-type ore bodies related to fragmented mylonite and vein-like ore bodies related to open fracture systems, respectively [65-66].

Many micro-disseminate type gold deposits in the Yunnan, Guizhou, and Guangxi Provinces of China are generally believed to have been formed on the basis of initial gold enrichment during syngenetic sedimentation, followed by subsequent enrichment through hydrothermal transformation along faults, such as replacement and filling.

In the relatively active period of some faults, such as syngenetic faults, the faults assist the conduction of ore-bearing fluids through seismic pumping, expansion, and re-rupture of mineralized zones. When the applied stress is close to the rock's breaking strength, the

expansion effect causes a series of microcracks in the rock that are parallel or approximately parallel to the fault plane, thereby increasing the fault's conductivity. If the fluid potential gradient is parallel to the fault plane, the fluid will flow preferentially along the syngenetic fault zone. Usually, the expansion effect is strongest in the area of maximum tensile stress. Re-rupture of mineralized zones occurs in the middle and late stage of diagenesis, which reconnects the cracks blocked by cement and enhances the fault's ability to conduct fluids and heat energy. The seismic pumping effect was first proposed by Scholz in 1974 (Zhai et al., 1997).

Fault movement releases stress in the fault zone, compresses the rock back to its pre-expansion state, and the fluid that originally filled the expansion gap is squeezed out and flows upward along the fault zone. The driving, drainage, excretion, and mineral accumulation of hydrothermal fluids by syngenetic faults are necessary conditions for the formation of hydrothermal sedimentary deposits. Syngenetic faults of different orientations and scales intersect and divide large basins to produce secondary small basins, resulting in differences in the bottom topography, hydrodynamics, hydrogeochemistry, and physical chemistry in the basin, thus creating a favorable space for the accumulation of large amounts of minerals.

The main fault belt in south China’s Yunkai gold province also clearly controls the distribution of gold mineralization belts (Chen, 1994). Approximately 95% of the 130 gold deposits are located in various faults. The shape and occurrence of gold deposits are generally similar to specific sections of the fault structure, or depend on the shape and occurrence of its secondary fault. Brecciated gold ore is developed in fault breccia or compression fracture zones of brittle fracture, and the brecciated ore is mostly the surrounding rock from both sides of the structure. Gold mineralization is mostly developed in cementing materials including siliceous, iron-manganese, etc. Vein gold ore is often produced in brittle fractures or in secondary fractures beside them. The gold ore structure in the ductile fault is mainly banded and disseminated, and the ore structure includes mylonitic structure and anisotropic granular structure. The bands in banded gold ore are primarily formed by the directional arrangement of minerals such as quartz, mica, and calcite that have been elongated due to plastic deformation. The intensity of gold mineralization is positively correlated with the intensity of fault activity. In structures with large fault scale, developed tectonic rocks, and multi-stage activity characteristics (especially those with early ductility and late brittleness), the intensity of gold mineralization is strong. Otherwise, it is weak.

Fault zones are mutation zones of rock mechanical properties and physical and chemical conditions. Where pores and cracks are developed, rock and mineral particles are small but the surface area is large, which will have a greater absorption function for ore-bearing hydrothermal fluids. This is conducive to the interaction between the ore-bearing hydrothermal fluids and tectonic rocks to produce alteration and mineralization. With the continued action of geo-stress and the further development of tectonic rocks, the migration, convergence, and precipitation of ore-bearing hydrothermal fluids will continue. If the fault is revived, multi-stage and multi-epoch gold mineralization may occur.

The Dongwujiazi and Paishanlou gold deposits in western Liaoning Province are close to each other and belong to the eastern section of the North China Platform’s northern margin.

and are both produced in late Archean metamorphic rocks. However, as a representative of quartz vein-type gold deposits, the Dongwujiazi gold deposit is quite different from the ductile shear zone-type represented by the Paishanlou gold deposit in terms of mineralization mechanism, age, and characteristics. Some researchers believe (Zhou et al., 2015) that the difference in local tectonic environment has caused these two different types of gold deposits. This sharp contrast can be well explained based on the "wave conduction" theory.

The three major faults in the northwest Shandong Province of China control more than 80% of the gold reserves in Jiaodong gold province (Liu, 2015). The tectonic stress field in the mining area was characterized by NW-W compression before mineralization, resulting in a NNE-trending compressional fault zone; during the mineralization period, it was characterized by NW-W extension, with two groups of faults in the nearly N-S and NE directions opening and being filled with ore fluids; after mineralization, it was characterized by NNW-W compression, forming a grid-like structural fluid-conducting system (Chen, 2010). The secondary faults of the Tanlu fault are the ore-controlling and ore-guiding structures of the Jiaodong gold province. The shallow tension-shear fractures produced by the right-lateral strike-slip faults in the late Yanshanian period are ore-containing structures. The expansion effect caused by the tension-fracture deformation is the driving force for the "pumping" of deep ore fluids to invade and fill (Zhao et al., 1996). The structure of the Jiaodong gold province in the mineralization period has the characteristics of multi-level ore control. The NEE-trending Taishan-type structure controls the distribution of the Jiaodong gold province, and the NNE-trending regional shear zone controls the output location of the gold ore field. The nature of the fault controls the gold mineralization style. The occurrence of the fault zone controls the inclination and lateral inclination of the ore body. The migration characteristics of the hanging and foot walls of the shear structure and the combination of faults control the distribution pattern of the veins. The structural deformation lithofacies zone controls the geochemical characteristics of the structure. The structure in the main mineralization stage shows the characteristics of stress relaxation and tension (Lu et al., 2007).

The latest research reveals that the multiple eruptions of the Icelandic volcanic system between 2023 and 2024 did not come from a single magma reservoir, but from multiple reservoirs with different chemical compositions (Simon et al., 2024). This shows the complexity and dynamics of the mid-crustal magma domain, and is of great significance to build a more accurate and profound understanding of the mineralization mechanism of magma. For a long time, scientists generally believed that most basalt eruptions on oceanic islands and mid-ocean ridges were supplied by a single magma reservoir located in the middle crust or shallow crust, and therefore believed that the magma had been fully mixed underground before the eruption. The materials produced by the Icelandic volcanic eruption possess significant heterogeneity in chemical composition. The differences in the isotopic ratios of K_2O/TiO_2, $^{87}Sr/^{86}Sr$, and $^{143}Nd/^{144}Nd$ and the ratios of incompatible elements all point to the existence of multiple magma reservoirs with different chemical compositions beneath the Icelandic volcano. Additionally, changes in the geochemical characteristics of rocks in different eruption events indicate that these magma reservoirs are not static, but instead undergo complex dynamic evolution processes, including magma injection, mixing, and differentiation.

From this, it can be inferred that deep faults cause the melting and mixing of rocks of different compositions at different depths in the earth's crust, further promoting chemical reactions between these substances, thereby greatly promoting the occurrence and development of various mineralizations and the formation of mineral deposits.

6. Conclusions

The “dissipative structure” reframes mineralization as a mathematical and physical problem, linking it to the stability and bifurcation of reaction–diffusion equations that describe its time evolution. Mineralization is essentially the transformation of a non-equilibrium, non-mineralized state into a stable dissipative structure, driven largely by geological features such as faults.

Beyond serving as pathways and storage for ore-forming materials, faults influence mineralization through key physical and chemical effects. Deep, large faults cause decompression, triggering melting, magmatic activity, and mineralization. They also facilitate fluid movement through seismic pumping, fracturing, and expansion. Long-term tectonic activity sustains geothermal anomalies, hydrothermal systems, and favorable geochemical conditions, while repeated fault activity enhances the accumulation and enrichment of ore materials, increasing the likelihood of large gold deposits.

Deep faults also induce crustal melting and mixing of rocks at different depths, creating conditions for chemical reactions, migration, and re-enrichment of ore-forming materials. Within fault systems, different levels play distinct roles: major deep faults act as channels for magma and mineralizing materials, forming specific types of gold deposits depending on rock composition, while smaller faults control the distribution of ore fields, deposits, and ore bodies.

Finally, structural characteristics—such as mechanical properties, activity, and rock types—govern the intensity and stages of mineralization. Post-mineralization tectonic processes further reshape deposits, often transforming primary gold deposits into placer deposits.

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Data availability

The data that support the findings of this study are available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.