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## Geology and mineralization of quartz vein-type and altered rock-type gold deposits in the Linglong gold orefield (916 t), Jiaodong Peninsula, China: A review

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### ABSTRACT

The Jiaodong Peninsula in North China Craton as the world's third largest gold metallogenic region, holding gold deposits primarily of the altered rock type and the quartz vein type. The Linglong gold orefield, with 916 t of proven gold resources presently, is a typical birthplace of quartz vein-type gold deposits in the Jiaodong Peninsula and develops altered rock type gold deposits. This study elaborated on the characteristics of deposits and the spatial distributions of orebodies in the Linglong gold orefield, analyzing control factors, geochemical characteristics, mineralization era, and mineralization mechanism. Comprehensive research has found that: The altered rock-type gold deposits have gentle dip angle and large scale, fine grain size of the gold ore, low average ore grades, low metal sulfide content, which is about 1/3 compared to the quartz vein-type gold deposits. Their gold minerals primarily occur as intercrystalline gold. In contrast, the quartz vein-type gold deposits occur in the steeply dipping tensile fissures in the footwall of main faults. Their orebodies exhibit steep dip angles and small scales but high average ore grades and metal sulfide content, with gold minerals primarily occurring as inclusion gold. The Linglong gold orefield experienced gold mineralization at about 120 Ma, with ore-forming fluids belonging to a moderate- to high-temperature, low-salinity, and reducing  $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}\pm\text{CH}_4$  system. The ore-forming fluid mainly comes from the mixture of magmatic water and meteoric water. The ore-forming materials primarily originated from the lower crust, supplemented by some mantle-derived components. The comprehensive analysis leads to the following conclusions: Extensive crust-mantle mixing provided thermodynamic conditions, migration pathways, and partial fluid sources for ore-forming fluid activity in the Jiaodong region. The rapid magma ascent led to the formation of detachment faults and associated tensile structures in the shallow crust, which create favorable space for fluid migration and the enrichment and precipitation of ore-forming elements. The pressure fluctuation of fluids arising from changes in the dip angles of faults is the main cause of the stepped metallogenic pattern. The quartz vein- and altered rock-type gold deposits are the product of the same metallogenic event under different metallogenic modes and tectonic locations. Based on the deep metallogenic regularity, this study established a geological-geophysical prospecting model for altered rock-type gold deposits, of which the critical factors include ore-hosting faults, high-precision geophysical exploration, and a stepped metallogenic pattern.

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## 1. Introduction

Jiaodong Peninsula, the foremost gold production base in China, ranks first nationwide in order of both gold reserves and gold production, with cumulative proven gold resources of over 5000 t (Song MC et al., 2018a). The gold deposits in the Jiaodong Peninsula are primarily of the altered rock type in fracture zones (the Jiaojia type) and the quartz vein type (the Linglong type), which account for 94% of the total gold resources of the peninsula (Song MC et al., 2014, 2020a). The Linglong gold orefield, where the Linglong gold deposits are designated, is well-known for quartz vein-type gold deposits. So far, the resources of altered rock-type gold deposits in fracture zones have significantly exceeded those of quartz vein-type gold deposits, changing the framework of deposit types within the Linglong gold orefield (Zhang PJ et al., 2015; Li SY et al., 2022; Song MC et al., 2022). As revealed by systematic exploration and research, major orebodies in several separate gold mining areas in the Linglong gold orefield are interconnected, forming a giant gold deposit with resources of over 500 t—the Taishang-Shuiwangzhuang giant gold deposit.

Jiaodong gold deposits belong to a Late Mesozoic giant gold metallogenic province within the Precambrian metamorphic basement. They may represent a unique genetic type of gold deposits that have not been fully described and defined (Goldfarb RJ and Santosh M, 2014; Deng J et al., 2023). As the only region in Jiaodong where large-scale altered rock-type gold deposits coexist with quartz vein-type gold deposits, the Linglong gold orefield serves as a natural laboratory for investigating the unique gold mineralization type in Jiaodong. Previous comprehensive studies achieved many advances in research on the deposit characteristics, metallogenic geological conditions, ore-controlling structures, metallogenic regularity, metallogenic epoch, and genetic mechanisms of the Linglong gold orefield (Li SX et al., 2007; Song MC et al., 2010; Lü GX et al., 2013; Deng J et al., 2015; Zhang PJ et al., 2015; Song YX et al., 2017; Liu GD et al., 2017; Li J et al., 2021a; He DY et al., 2024; Qiu KF et al., 2024), providing a significant basis for geologists to delve into the origin of Jiaodong gold deposits. This study detailed the characteristics of deposits and the spatial distribution of orebodies in the Linglong gold orefield and summarized the previous geochemical and isotopic dating results of the deposits. It analyzed the relationship between the gold deposits of the quartz vein and altered rock types, the influence of faults on mineralization, and mineralization-related problems. Moreover, it established a geological-geophysical prospecting model for altered rock-type gold deposits. This study is expected to assist in deeply understanding the metallogenic regularity and mechanisms of Jiaodong gold deposits and serve as a guide for deep prospecting.

## 2. Regional geological setting

Geotectonically, the Jiaodong Peninsula lies at the

junction of the southeastern margin of the North China Craton and the eastern end of the Dabie-Sulu Orogenic Belt (Fig. 1a). The Linglong gold orefield, situated in the Jiaobei uplift on the southeastern margin of the North China Craton, is adjacent to the Jiaolai Basin in the south and the Weihai uplift in the east. The Jiaobei uplift is primarily composed of Precambrian metamorphic rocks and Mesozoic intrusive rocks. Quaternary unconsolidated sediments are distributed along the coast and rivers in the northwestern Linglong gold orefield. The Jiaolai Basin, predominantly comprising Cretaceous volcanic-sedimentary rocks, is a Mesozoic continental basin superimposed on the Jiaobei and Weihai uplifts. The Weihai uplift, at the northeastern end of the Dabie-Sulu ultrahigh-pressure metamorphic belt, mainly encompasses Neoproterozoic granitic gneisses, containing many Triassic ultrahigh-pressure metamorphic eclogites and extensively distributed Mesozoic granitoids (Fig. 1b; Song MC et al., 2023a, 2023b).

### 2.1. Geological setting of the Jiaobei uplift

The Precambrian metamorphic rocks in the Jiaobei uplift consist primarily of the Meso- to Neoarchean granite-greenstone belt and the Proterozoic metamorphic strata.

The Mesozoic strata within the Jiaobei uplift are primarily distributed in the Jiaolai Basin, scattered over some small basins like Zangjiazhuang. These strata are Cretaceous continental volcanic-sedimentary strata, consisting of the Laiyang, Qingshan, and Wangshi groups.

The Jiaodong region experienced intense Mesozoic magmatic activity, leading to the formation of extensive intermediate-acid intrusive rocks. The intrusive rocks in the Jiaobei uplift primarily include Jurassic monzogranites (Linglong-type granites), Early Cretaceous granodiorites (Guojialing-type granites), Early Cretaceous diorites (Liulinzhuang-type high-Mg diorites), Early Cretaceous monzodiorite-quartz monzonite-monzogranite series (Weideshan-type granites), and Early Cretaceous syenogranites (Laoshan-type granites). The intermediate to mafic to acid veins primarily encompass the lamprophyre, diorite porphyrite, monzonite, and granite porphyry veins (Song MC et al., 2023b).

The Jiaobei uplift holds well-developed fault structures, mostly having a NE-NNE strike and, to a lesser extent, nearly EW and NW-NNW strikes. The NE-NNE-trending faults are the foremost ore-controlling faults in the Jiaodong region. Among them, the NNE-trending Zhaoping, Jiaojia, and Sanshandao faults, which run almost in parallel, control the distribution of most gold deposits in northwestern Jiaodong. These three faults are located roughly near the contact zone between the Early Precambrian metamorphic rocks (the hanging wall of the faults) and the Late Mesozoic granites (the footwall of the faults). Their dip angles reduce gradually from shallow to deep layers, showing a listric pattern. Furthermore, the three faults are characteristic of detachment

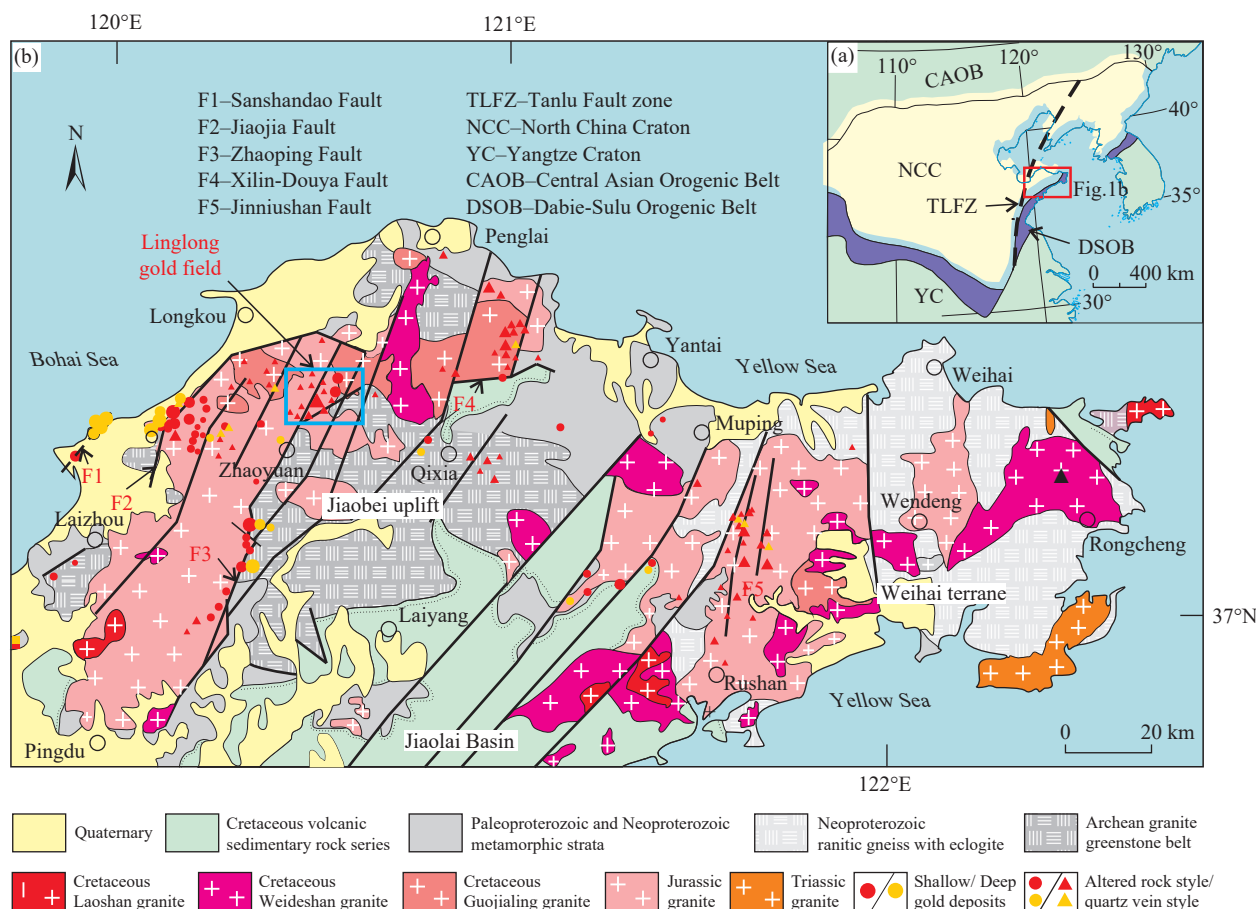


**Fig. 1.** Regional geological sketch map and gold deposit distribution map of the Jiaodong Peninsula (after Song MC et al., 2020b).

faults. The Linglong gold orefield is situated in the footwall of the northern segment of the Zhaoping fault. As the largest gold ore-controlling fault exposed in the Jiaobei uplift, the Zhaoping fault is approximately 120 km long and 150–200 m wide, with a dip direction of SE-E and dip angles ranging from 30° to 70°. Planarly, the Zhaoping fault displays a wavy distribution with a constantly changing strike. As shown in the fault profile, its dip angle presents a listric, stepped pattern characterized by upper steep and lower gentle angles and alternating steep and gentle angles. The northern segment of the Zhaoping fault is divided into the Jiuqujiangjia and Potouqing faults near the Linglong gold orefield (Fig. 2a).

## 2.2. Geological setting of the Linglong gold orefield

### 2.2.1. Major geological bodies

The Linglong gold orefield, located within the Jiuqu-Linglong area of northeastern Zhaoyuan and the northern segment of the Zhaoping fault, covers an area of approximately 60 km<sup>2</sup> (Fig. 2a). Major geological units in the orefield include Early Precambrian metamorphic rocks (Figs. 3a, b) and Jurassic Luanjiahe- (Fig. 3c) and Linglong-type granites (Fig. 3d), with intermediate to mafic and acid veins widely distributed. Besides, Guojialing-type granites (the Guojialing pluton; Fig. 3e) and Weideshan-type granites (the Aishan pluton) containing dioritic enclaves are extensively exposed in the northeastern Linglong gold orefield (Fig. 3f).

The Luanjiahe pluton (consisting of Luanjiahe-type granites) occurs as a composite batholith distributed in the NWW direction. It intrudes into the Neoproterozoic Qixia gneiss suite (TTGs) in the southeast and is in fault contact with Linglong-type granites in the northwest. This pluton consists predominately of grayish-white medium- to coarse-grained monzogranites, exhibiting medium- to coarse-grained granitic or porphyroid textures and massive structures. Its major minerals encompass plagioclases, alkaline feldspar, quartz, biotite, and a small amount of muscovite, characterized by extensive primary muscovite. Its accessory minerals include magnetite, pyrite, apatite, epidote, geikielite, monazite, and zircon.

The Linglong-type granites distributed in the Linglong gold orefield are known as the Guojialing pluton. This pluton consists of medium-grained gneissic porphyritic biotite monzogranites. It is light grayish-white, manifesting medium- to fine-grained textures and gneissic structures. Its major minerals include plagioclase, potash feldspar, quartz, and biotite, along with trace amounts of accessory minerals such as garnet, zircon, and titanite. Its phenocrysts primarily comprise plagioclase, with a content of about 10% and a long radius of mostly about 1 cm.

The Guojialing pluton (consisting of Guojialing-type granites) consists of porphyritic hornblende granodiorites. It is grayish-white, exhibiting porphyroid textures and massive structures. Its matrix demonstrates medium- to fine-grained

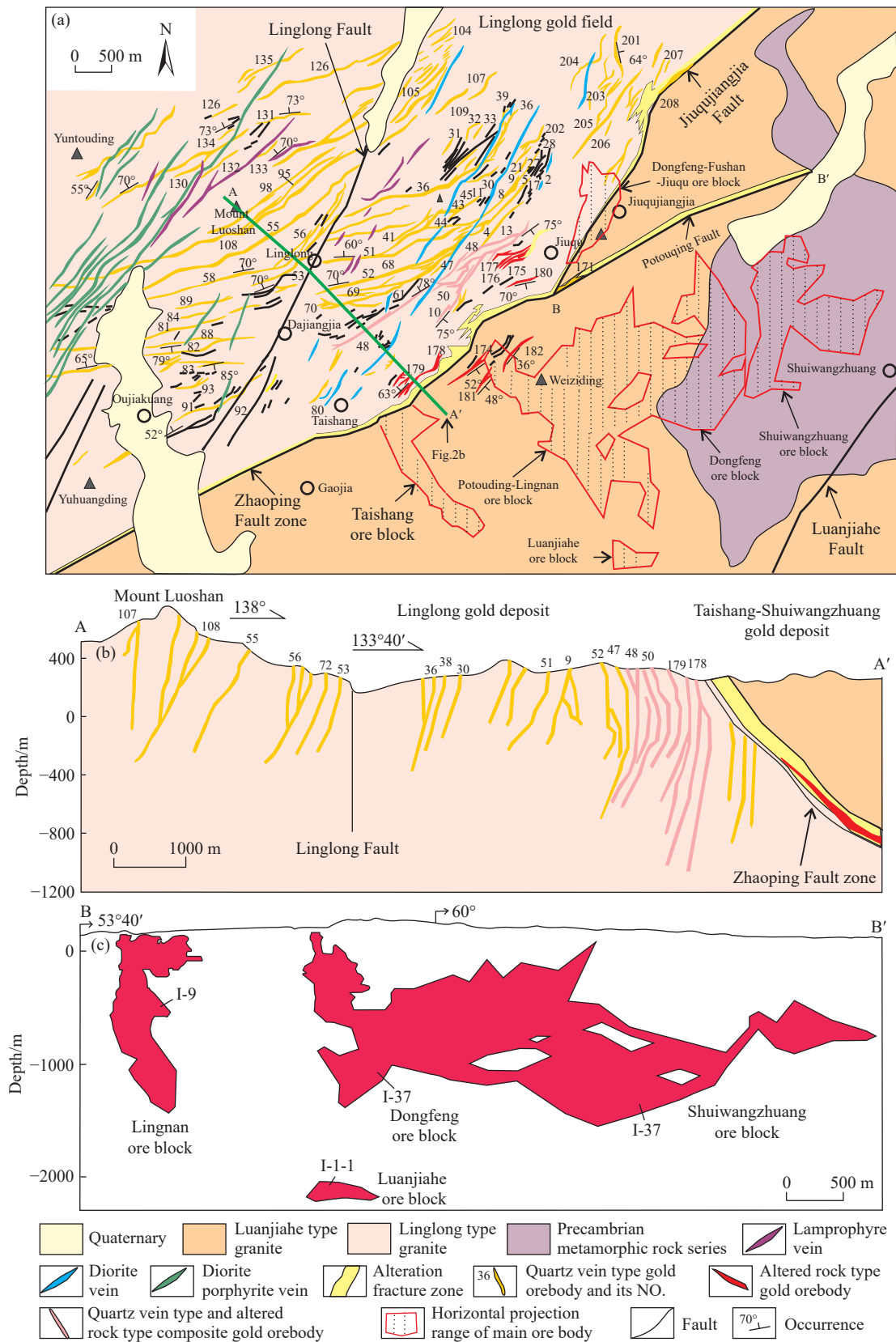


**Fig. 2.** a–Geological sketch map; b–sections map; c–vertical projection map of the Linglong gold orefield.

granitic textures, bearing fine-grained dioritic enclaves. The major minerals of the Guojiadian pluton include plagioclase, potash feldspar, and quartz, along with trace amounts of hornblende and biotite. Its accessory minerals include zircon,

titanite, and apatite. Its phenocrysts primarily consist of potash feldspar, with grain sizes of 3–5 cm.

The Aishan pluton (consisting of Weideshan-type granites) comprises porphyritic hornblende granodiorites. It is

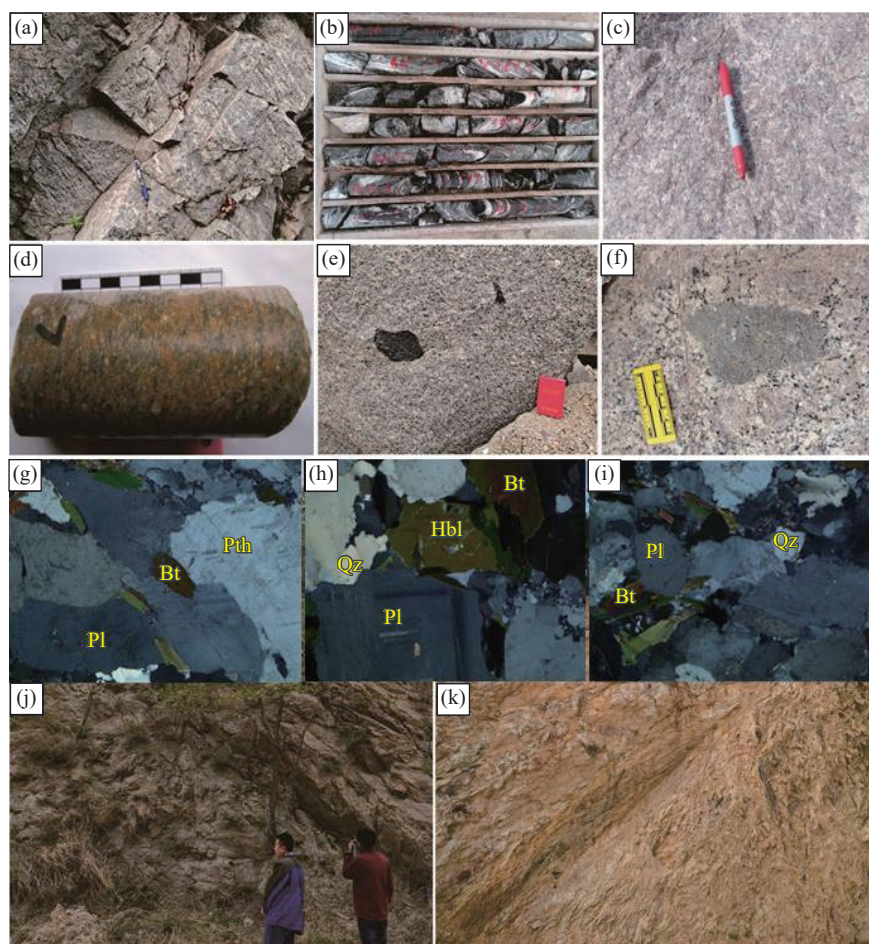


**Fig. 3.** Photos showing the primary surrounding rocks and ore-controlling faults in the Linglong gold orefield. Early Precambrian metamorphic rock series: a–tonalite gneiss; b–metamorphic rocks. Mesozoic granites: c–Luanjiahe-type granite; d, g–Linglong-type granite; e, h–Guojialing-type granite and its dark inclusions; f, i–Weideshan-type granite and its dioritic inclusions (Aishan pluton). Main fault planes: j–Potouqing fault; k–Jiuqujiangjia fault (to the north of Jiuqujiangjia Village). Qz–Quartz; Pth–Perthite; Pl–Plagioclase; Bt–Biotite; Hbl–hornblende.

grayish-white, exhibiting porphyroid textures and massive structures. It contains many dioritic enclaves with long radii of 3–20 cm. Its major minerals include plagioclase, potash feldspar, quartz, hornblende, and a minor amount of biotite, and its accessory minerals encompass zircon, titanite, and apatite. Its plagioclase phenocrysts manifest long radii of 3–5 cm, with kaolinization commonly visible.

#### 2.2.2. Ore-hosting faults

The ore-controlling faults in the Linglong gold orefield include the Potouqing (Fig. 3g) and Jiuqujiangjia faults (Fig. 3h), as well as the associated and derived NE- and NNE-trending secondary faults on their footwall. The Linglong and Luanjiahe faults in the orefield, experiencing no mineralization and alteration, are post-mineralization faults.

The Potouqing fault can be divided into the eastern and western segments. The western segment is a part of the Zhaoping fault before it branches. This segment has strikes ranging from 50° to 70°, a dip direction of SE, and a dip angle of about 40°. It is approximately 8000 m long and 33–82 m wide (up to 300 m locally), with a drilling-controlled maximum length along the dip direction of 3725 m (not pinching out yet) and a vertical depth of 2310 m. The eastern segment of the Potouqing fault is the southeastern branch of

the Zhaoping fault. This segment exhibits a dip direction of SE and dip angles varying from 28° to 45° (average: 33°). It is approximately 5500 m long and 10–330 m wide (up to 500 m locally), with a drilling-controlled maximum length along the dip direction of 3958 m and a maximum vertical depth of 2086 m. Continuous, stable major fracture planes are found in the central part of the main fault, marked by grayish-black fault gouges (thickness: 10–140 cm). The Jiuqujiangjia fault is the northwestern branch of the Zhaoping fault. It has a strike of 33°, a dip direction of SE, and dip angles varying from 23° to 60°. It is approximately 6100 m long and 40–80 m wide (up to 400 m locally), with a drilling-controlled maximum length along the dip direction of 4993 m and a maximum vertical depth of 2827 m.

The associated and derived secondary ore-hosting faults in the footwall of the main faults scatter from NE to SWW on a horizontal plane, forming a broom-like style. These faults are densely distributed, with up to 254 fault alteration zones that are over 50 m long occurring within the Dakaitou ore block. These faults have strikes ranging between 40° and 80°, a dip direction of NW, and dip angles varying from 50° to 90°. Except for a few that dip steeply in the SE direction, these faults change in a gentle wave pattern along their strikes and deepening directions.

### 2.2.3. Mineralized alteration zones

The Linglong gold orefield is the foremost region producing quartz vein-type gold deposits in the Jiaodong Peninsula. More than 700 gold-bearing quartz veins and altered rock veins (both hereinafter referred to as ore veins), running roughly in parallel, have been identified in the footwall of the Zhaoping fault. They contain over 40 ore veins with proven gold resources, with surrounding rocks all identified as Linglong-type granites. There are many veins of diorite, diorite porphyrite, lamprophyre, and granite porphyry near the ore veins. These ore veins are concentrated, forming vein swarms (Fig. 2a).

The Potouqing and Jiuqujiangjia fault zones, two large-scale mineralized alteration zones, host most of the altered rock-type gold deposits in fracture zones in the Jiaodong region. They are generally 100–500 m thick, up to 1 km locally. Their altered rocks primarily include (beresitized) phyllic cataclasites (sericitolite), beresitized granitic cataclasites, and phyllic granites with phyllic alteration, exhibiting zonal distributions near the major fracture planes. Generally, a cataclasite zone with phyllic alteration, a granitic cataclasite zone with phyllic alteration, and a granite zone with phyllic alteration are distributed sequentially in the hanging wall of major fracture planes. In contrast, a beresitized cataclasite zone, a beresitized granitic cataclasite zone, and a beresitized granite zone are distributed sequentially in the footwall of major fracture planes. Fault gouges with a thickness of several centimeters are commonly found along the major fracture planes, with gold orebodies primarily occurring in the alteration zones in the footwall of the fault gouges. The alteration zones generally host Luanjiahe-type granites and Early Precambrian metamorphic rocks in the hanging wall and Linglong-type granites in the footwall.

## 3. Characteristics of quartz vein- and altered rock-type gold deposits

### 3.1. Quartz vein-type gold deposits

#### 3.1.1. Characteristics of orebodies

The gold deposits dominated by quartz veins in the Linglong gold orefield include the Linglong (consisting of Dongshan, Xishan, Nandawa, Oujiakuang, Dongfeng, Jiuqu, and Dakaitou ore blocks), Nanrenjian, Dazhuangzi, and Niucaojian gold deposits. Their orebodies are composed of individual quartz veins or vein swarms. The quartz veins exhibit simple morphologies such as thick, thin, lentoid, and lensoid shapes, branching locally. At the pinchout ends of orebodies, individual quartz veins generally transition into stockwork veins. The orebodies are generally tens to hundreds of meters long, with large ones having lengths surpassing 1000 m and a maximum width of up to 40 m. The average grade of the quartz vein-type gold deposit in Linglong orefield is  $5.20 \times 10^{-6}$ , and it exhibits a large variation in gold grade, with the highest reaching  $620.81 \times 10^{-6}$ . The characteristics of typical orebodies (such as No. 108 vein, No. 4 vein, No. 9

vein, No. 2–4 vein of No. 175 vein swarm, No. 47–1 vein, No. 53–1 vein) are stated as follows: The veins with a length of 775 m to 3900 m, a depth extent along its dip direction of 360 m to 1043 m, thicknesses from 0.2 m to 10 m, strikes between  $40^\circ$  and  $80^\circ$ , a dip direction of NW, and dip angles varying from  $45^\circ$  to  $88^\circ$ . The veins bend in a gentle wave pattern along the strike and dip direction, bifurcating locally. The ores primarily include gold-bearing quartz veins and pyritized quartz veins, with a small quantity of gold-bearing beresites visible.

#### 3.1.2. Characteristics of ores

The ores of quartz vein-type gold deposits primarily include gold-bearing quartz veins and pyritized quartz veins (Figs. 4a–c), accompanied by a minor quantity of gold-bearing altered rocks. The major ore minerals encompass electrum, native gold, pyrite, and chalcopyrite, followed by pyrrhotite, sphalerite, galena, magnetite, and specularite, as well as trace amounts of native copper, native silver (Ag), bjelkite, marcasite, bornite, molybdenite, and hematite. The secondary minerals include limonite and azurite. The gangue minerals predominantly include quartz and sericite, followed by calcite and plagioclase, as well as minor amounts of chlorite, epidote, and fluorite. Among these, pyrite, chalcopyrite, and pyrrhotite are major gold-carrying minerals.

The ore textures primarily include granular, cataclastic, and relict textures, followed by metasomatic corrosion, poikilitic, interstitial, and emulsion textures. The ore structures are dominated by dense massive and disseminated structures, followed by dotted, stockwork, and brecciated structures.

The beneficial component in ores is gold, the associated beneficial components include silver, copper, and sulfur, and hazardous elements encompass lead, zinc, and arsenic. Besides, the ores contain trace amounts of dispersed elements such as gallium (Ga), beryllium (Be), titanium (Ti), and vanadium (V). The gold grade of the orebodies varies significantly, with a maximum of up to  $620.81 \times 10^{-6}$  and coefficients of variation ranging from 100% to 200%, suggesting uneven variations in the beneficial components. Additionally, the orebodies exhibit average grades of Ag, S, Cu, Pb, Zn, and As of  $8.02 \times 10^{-6}$ , 7.84%, 0.15%, 0.06%, 0.04%, and 0.006%, respectively.

#### 3.1.3. Characteristics of gold minerals

Gold-bearing minerals in the quartz vein-type gold deposits consist of electrum, native gold, and native silver, which account for 73.71%, 25.82%, and 0.47%, respectively. The gold and silver minerals in the ores are granular (56.83%), irregular (33.64%), flaky (7.29%), and columnar (2.24%) in shape. The gold minerals have fineness ranging from 700 to 900, averaging 769.24. The gold and silver minerals are primarily fine-grained (from 0.5 mm to 0.2 mm; 88.58%) and microgranular (below 0.5  $\mu\text{m}$ ; 9.19%), with a minor quantity of coarse-grained gold (above 0.2 mm; 2.23%).

Gold and silver minerals primarily occur in three forms:

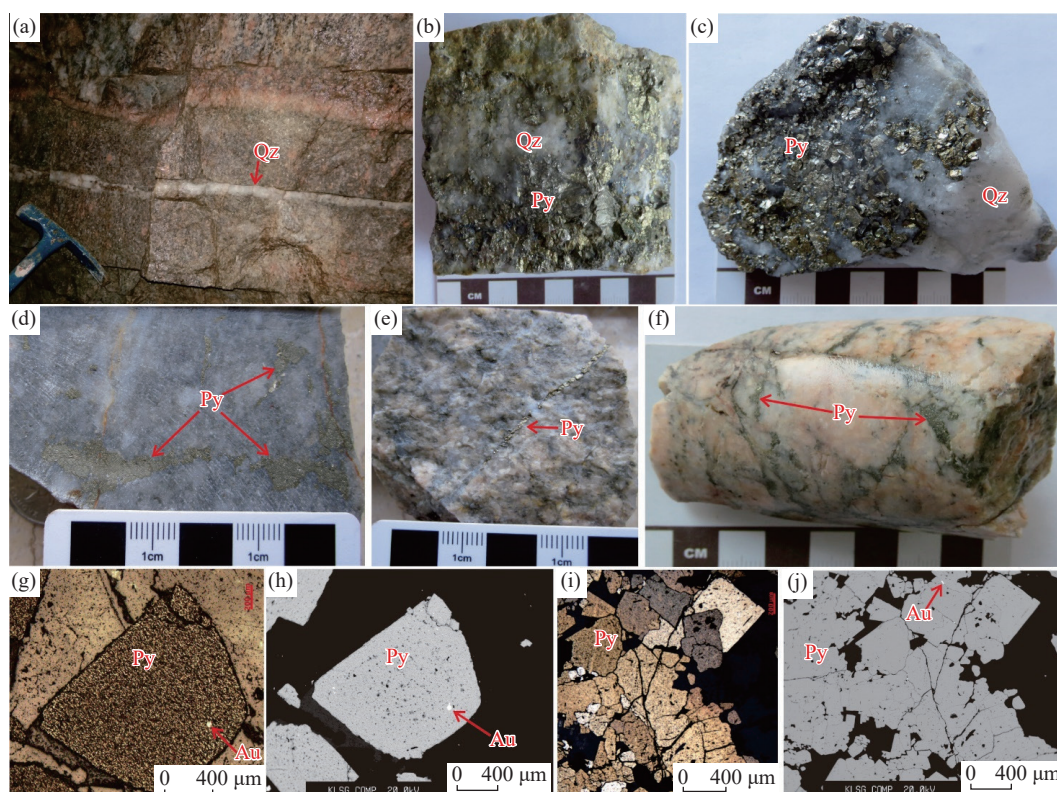


**Fig. 4.** Mineralization characteristics of the Linglong gold orefield. a–c—Quartz vein-type gold ores (a, b—collected from the Linglong-Xishan ore block at a depth of –50 m; c—collected from the Linglong-Xishan ore block at a depth of –230 m); d–f—altered rock-type gold ores (collected from Shuiwangzhuang gold deposit; d—beresitized cataclasite; e—beresitized granitic cataclasite; f—beresitized granite); g, h—automorphic pyrite and inclusion gold grains (h corresponding to the BSE photo); i, j—automorphic to hypautomorphic pyrite aggregates and fissure gold grains (j corresponding to the BSE photo). Qz—Quartz; Py—Pyrite; Au—Gold.

(1) Inclusion gold, distributed as inclusions in pyrite, chalcopyrite, quartz, and sphalerite crystals; (2) fissure gold, distributed along mineral fissures; (3) intercrystalline gold, distributed along the interstices of various minerals. They account for 82.64%, 13.59%, and 3.77% of the total mineral particles, respectively. The particle sizes of the gold and silver minerals reduce with the depth. These minerals are closely associated with metal sulfides. Specifically, fine-grained pyrite aggregates and chalcopyrite are the most enriched in gold and silver, while cubic pyrite exhibits the lowest gold and silver contents.

#### 3.1.4. Mineralization stages

Based on the paragenetic relationships of minerals, the mineralization process of the quartz vein-type gold deposits can be divided into four stages, i.e., the potassic and phyllic alteration stage, quartz-pyrite stage, gold-polymetallic sulfide stage, and carbonate stage. For the first stage, potassic and phyllic alternations occurred on both sides of veins, with resulting minerals primarily including potash feldspar, sericite, and quartz. Quartz formed in this stage is ivory, anhedral, coarse-grained (from 1.5 mm to 2 mm), and transparent, with clean surfaces. For the quartz-pyrite stage, the resulting quartz is smoky gray, and the metal minerals primarily include pyrite, along with minor amounts of chalcopyrite, pyrrhotite, electrum, and native gold. The gold-polymetallic sulfide stage witnessed the formation of

extensive gold and silver minerals and sulfides, with major metal minerals encompassing pyrite, chalcopyrite, galena, sphalerite, porphyrite, pyrrhotite, native gold, and kustelite. The carbonation stage witnessed the formation of carbonate minerals such as calcite, along with minor amounts of quartz and chlorite.

#### 3.2. Altered rock-type gold deposits

Altered rock-type gold deposits occur in the main fault zone of the Zhaoping fault. In previous explorations, these deposits were divided into the Taishang, Lingnan, Luanjiahe, Dongfeng No. 171 vein, Shuiwangzhuang, Lijiazhuang, and Fushan (Dongfeng) deposits (Figs. 2a, c). However, comprehensive research reveals that the major orebodies of these deposits are interconnected or superimposed, forming a giant gold deposit with gold resources of 600 t, i.e. the Taishang-Shuiwangzhuang giant gold deposit.

##### 3.2.1. Characteristics of orebodies

A total of 426 orebodies were delineated in the Taishang-Shuiwangzhuang gold deposit. These orebodies mostly occur in the beresitized cataclasite zone and the beresitized granitic cataclasite zone, both close to the major fracture plane in the footwall of the Zhaoping fault, with a few distributed above the major fracture plane. The two branches of the Zhaoping fault control different orebodies. Specifically, the main part of

the Zhaoping fault and the Potouqing fault control the Nos. I-9 and I-37 orebodies in the Lingnan mining area, the No. 1 orebody in the Shuiwangzhuang mining area, the No. 171-1 orebody in the Dongfeng mining area, and the No. I-1-1 orebody in the Luanjiahe mining area. The Jiuqujiangjia fault controls the No. 208 veined orebody in the Fushan mining area and the No. 2 orebody in the Shuiwangzhuang mining area (Fig. 5).

**No. I-9 orebody:** This orebody, distributed within the Lingnan mining area, occurs in the beresitized cataclasite zone and the beresitized granitic cataclasite zone, with drilling-controlled elevations ranging from +150 m to −1500 m, a maximum strike length of 800 m, and a maximum length along its dip direction of 2192 m (Figs. 6, 7). This orebody is stratoid/veined in shape, characterized by branching and combination, swelling and shrinkage, as well as pinchout and recurrence. It has strikes ranging from 12° to 96° (average: 70°), a dip direction of SE, and dip angles varying between 31° and 56°. It is 5.47 m thick on average, with an average grade of  $2.87 \times 10^{-6}$ .

**No. I-37 orebody:** This orebody is distributed in the Lingnan mining area (the former No. I-37 orebody), the Dongfeng mining area (the former No. 171-1 orebody), and the Lijiazhuang mining area (the former No. 1 orebody). Governed by the Potouqing fault, it occurs within the beresitized cataclasite zone and the beresitized granitic cataclasite zone. It has a length of 4700 m, a maximum drilling-controlled elevation of −1600 m, and a maximum drilling-controlled length along the dip direction of 3100 m (Figs. 6, 7). This orebody emerges as large veins, being stratoid locally. It spreads in a gentle wave pattern along its strike and dip direction, with branching and combination, as well as swelling and shrinkage. This orebody has strikes of 28°–63° (average: 57°), a dip direction of SE, and dip angles of 25°–51°. It is 13.11 m thick on average, with an average grade of  $2.97 \times 10^{-6}$ .

**No. I-1-1 orebody:** This orebody, with burial depths

ranging from 2260 m to 2477 m, ranks as the orebody with the largest burial depth identified so far. It exhibits a maximum drilling-controlled strike length of 673 m and a maximum length along its dip direction of 472 m. It primarily occurs within the beresitized cataclasite zone and the beresitized granitic cataclasite zone below the major fracture plane. This orebody is veined in shape. With the characteristics of branching and combination, as well as swelling and shrinkage, this orebody extends in a gentle wave pattern along its strike and dip direction. It has a strike of 54°, a dip direction of SE, and dip angles from 10° to 40° (average: 26°) (Figs. 6, 7). It is 12.64 m thick on average, with an average grade of  $7.24 \times 10^{-6}$ .

As illustrated in the grade, thickness, and grade  $\times$  thickness contour maps (Fig. 8), the aforementioned orebodies exhibit segmental mineralization enrichment along their strikes and dip directions. Specifically, along their strikes, the first, second, and third enrichment ore sections are the No. I-9 orebody, the left part of the No. I-37 orebody, and the right part of the No. I-37 orebody, respectively. Along their dip directions, the first, second, and third mineralization enrichment zones are distributed between the surface and an elevation of about −600 m, part with elevations between −800 m and −1500 m, and part with elevations less than −1600 m, respectively. Correspondingly, their ore-controlling faults have average dip angles of about 39°, 34°, and 26°, respectively. Two enrichment ore sections show intervals with the absence of ores or weak mineralization of generally 100–200 m. Furthermore, the second enrichment ore section exhibits a larger orebody scale than the first enrichment ore section. The third enrichment ore section has not yet been completely determined by drilling, with its deep part having huge potential for prospecting.

### 3.2.2. Characteristics of ores

Primary ores of the altered rock-type gold deposits include fine-grained, disseminated, beresitized cataclasites (Fig. 4d);

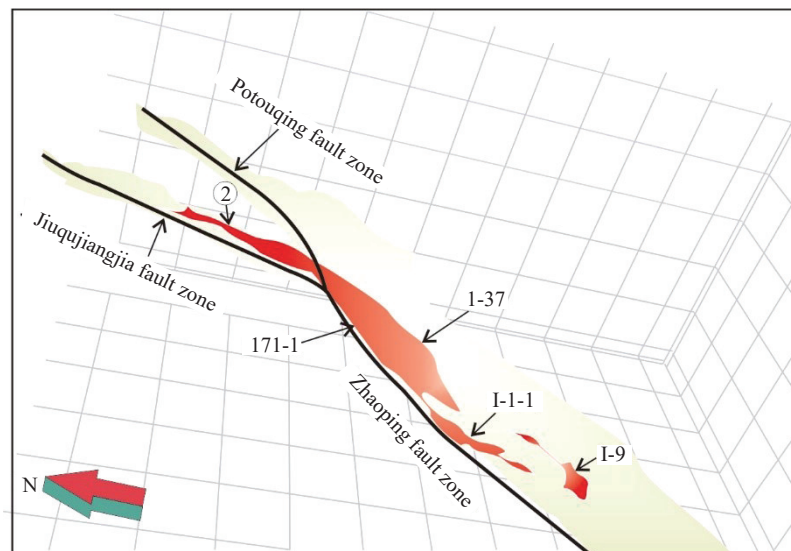


**Fig. 5.** Three-dimensional distribution of the Potouqing and Jiuqujiangjia faults and the orebodies they governed.

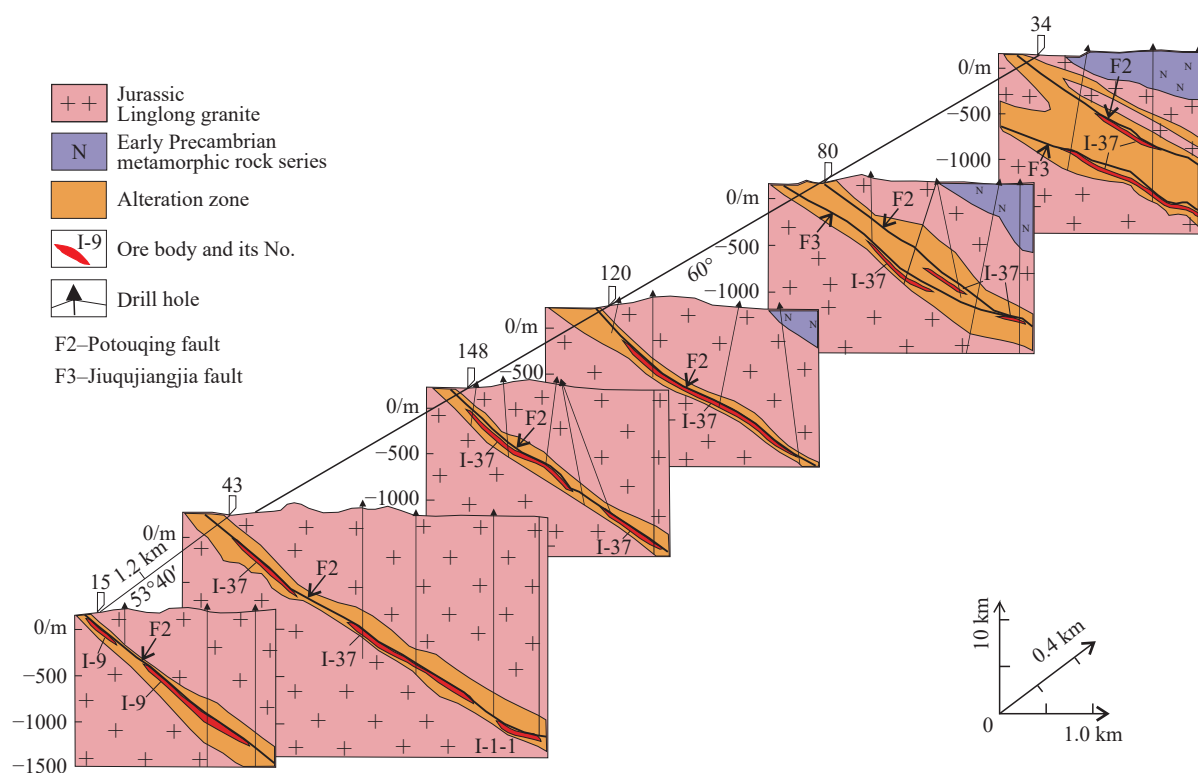


Fig. 6. Combined sections of exploration lines in the Taishang-Shuiwangzhuang gold deposit.

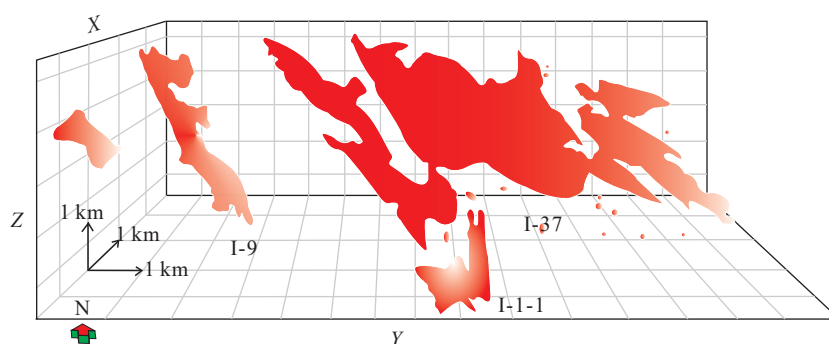


Fig. 7. Three-dimensional models of primary orebodies in the Taishang-Shuiwangzhuang gold deposit.

disseminated, veinlet, and stockwork beresitized granitic cataclasites (Fig. 4e), and veinlet beresitized granites (Fig. 4f). They are dominated by the former two types, which account for about 95% of the total. The primary ores have an average sulfur content of 2.26%, suggesting an industrial type of low-sulfur gold ores.

The ore textures are dominated by granular textures, followed by cataclastic and interstitial textures, as well as poikilitic and emulsion textures. The ore structures consist primarily of veinlet-disseminated, disseminated, and veinlet/stockwork structures, succeeded by dotted and lumpy structures.

Regarding the ore minerals, the native metals are dominated by electrum, followed by native gold and silver. The metal sulfides primarily include pyrite, followed by chalcopyrite, galena, sphalerite, and a minor amount of pyrrhotite. The gangue minerals primarily encompass quartz, sericite, and feldspar (Table 1). The beneficial components in

ores are dominated by gold, and the associated beneficial components are silver and sulfur, with an average silver grade of  $7.47 \times 10^{-6}$ . Elements like copper, lead, and zinc, as well as associated hazardous element arsenic, all show low contents (Table 2). From the shallow to the deep parts of the altered rock-type gold deposits, the silver and sulfur contents decrease while the gold-to-silver ratio increases (Table 2).

### 3.2.3. Characteristics of gold minerals

Based on a large number of mineralogical observations, electron probe and backscattered electron imaging analysis were used to obtain information on the composition, particle size occurrence, and color of gold minerals in the Linglong gold field. Gold minerals primarily occur as intercrystalline gold, followed by inclusion gold and a trace amount of fissure gold, which account for 56.11%, 34.87%, and 9.02%, respectively (Figs. 9a, b). The intercrystalline gold is predominantly found in the interstices of pyrite and quartz,

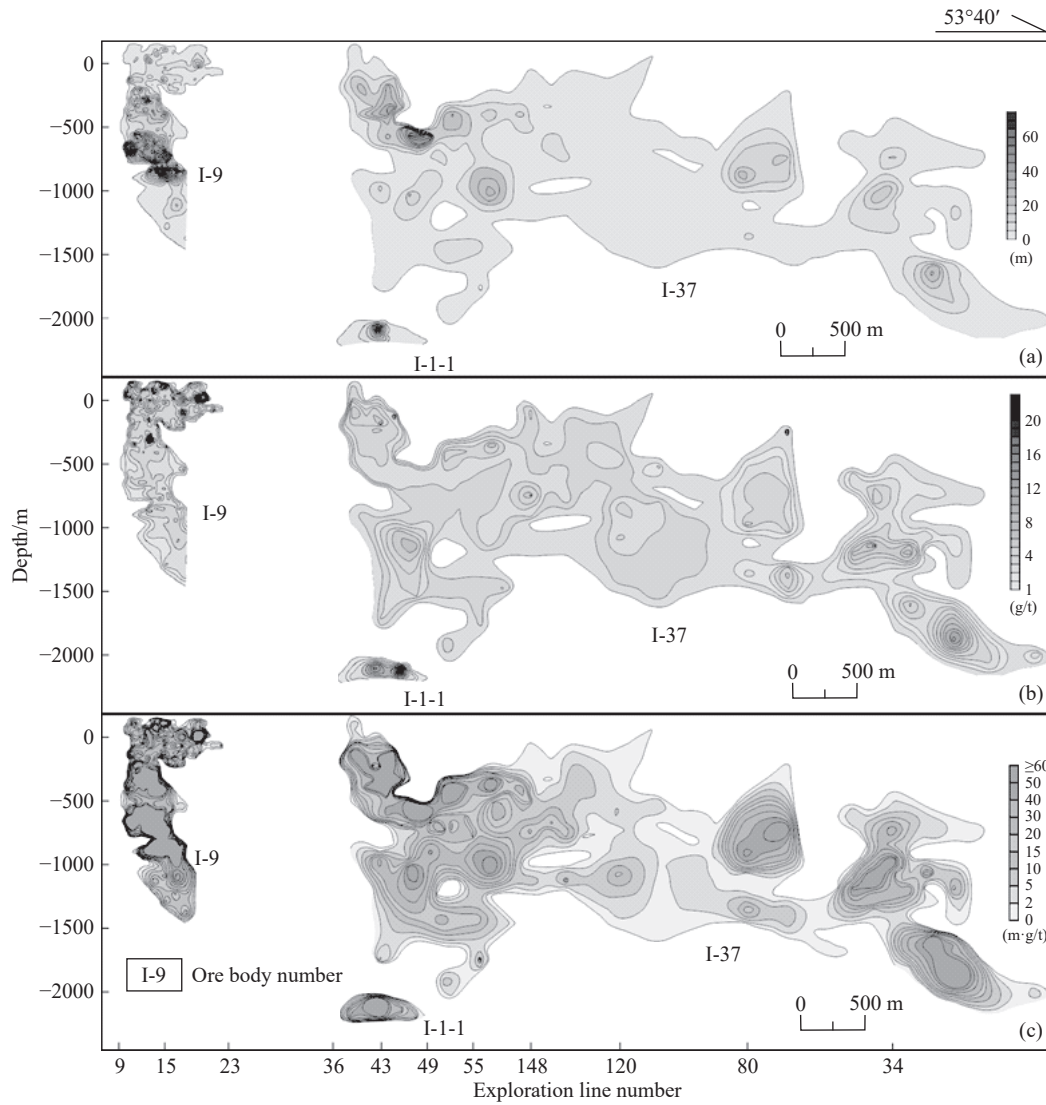


**Fig. 8.** Contour maps showing the vertical thicknesses and gold grades of the Taishang-Shuiwangzhuang gold deposit. a–Isopach map; b–gold grade contour map; c–grade × thickness contour map.

**Table 1.** Mineral composition of ores in the Taishang-Shuiwangzhuang gold deposit.

| Relative content | Category Ore mineral                                 |                                                                   |                                  | Gangue mineral                                                  |
|------------------|------------------------------------------------------|-------------------------------------------------------------------|----------------------------------|-----------------------------------------------------------------|
|                  | Native metal                                         | Metal sulfide                                                     | Others                           |                                                                 |
| Major            | Electrum                                             | Pyrite                                                            |                                  | Quartz, sericite, feldspar                                      |
| Secondary        | Native gold, silver                                  | Chalcopyrite, galena, sphalerite                                  |                                  | Calcite, dolomite                                               |
| Trace amount     | Natural bismuth, hessite, altaite, tellurobismuthite | Pyrrhotite, tetrahedrite, bornite, argentite, matildite, cosalite | Specularite, magnetite, siderite | Chlorite, apatite, zircon, titanite, epidote, rutile, leucoxene |

**Table 2.** Average contents of gold and related components at different depths.

| Deposit           | Au/ $10^{-6}$ | Ag/ $10^{-6}$ | S/%  | Cu/% | Pb/% | Zn/% | As/ $10^{-6}$ | Au/Ag ratio |
|-------------------|---------------|---------------|------|------|------|------|---------------|-------------|
| Above –500 m      | 3.30          | 8.13          | 2.45 | 0.05 | 0.08 | 0.08 | 11.20         | 1 : 2.46    |
| –500 m to –1500 m | 2.92          | 6.14          | 1.88 | 0.03 | 0.04 | 0.03 | 24.29         | 1 : 2.10    |
| Below –1500 m     | 5.10          | 5.88          | 1.82 | 0.05 | 0.05 | 0.05 | 0.06          | 1 : 1.15    |
| Average           | 3.39          | 7.47          | 2.26 | 0.04 | 0.07 | 0.07 | 18.23         | 1 : 2.20    |

whereas the inclusion gold content increases significantly in parts with elevations less than –1500 m. The gold minerals primarily consist of electrum (59%) and native gold (40%). Their fineness varies from 508 to 955 (average: 770), dominated by a range between 600 and 900. They are

principally fine-grained and microgranular, primarily showing a granular morphology. From the first to the third gold mineral enrichment zones from shallow to deep parts, the gold minerals exhibit increasing fineness (Fig. 9c), slightly increasing microgranular and fine-grained gold content (Fig. 9d),

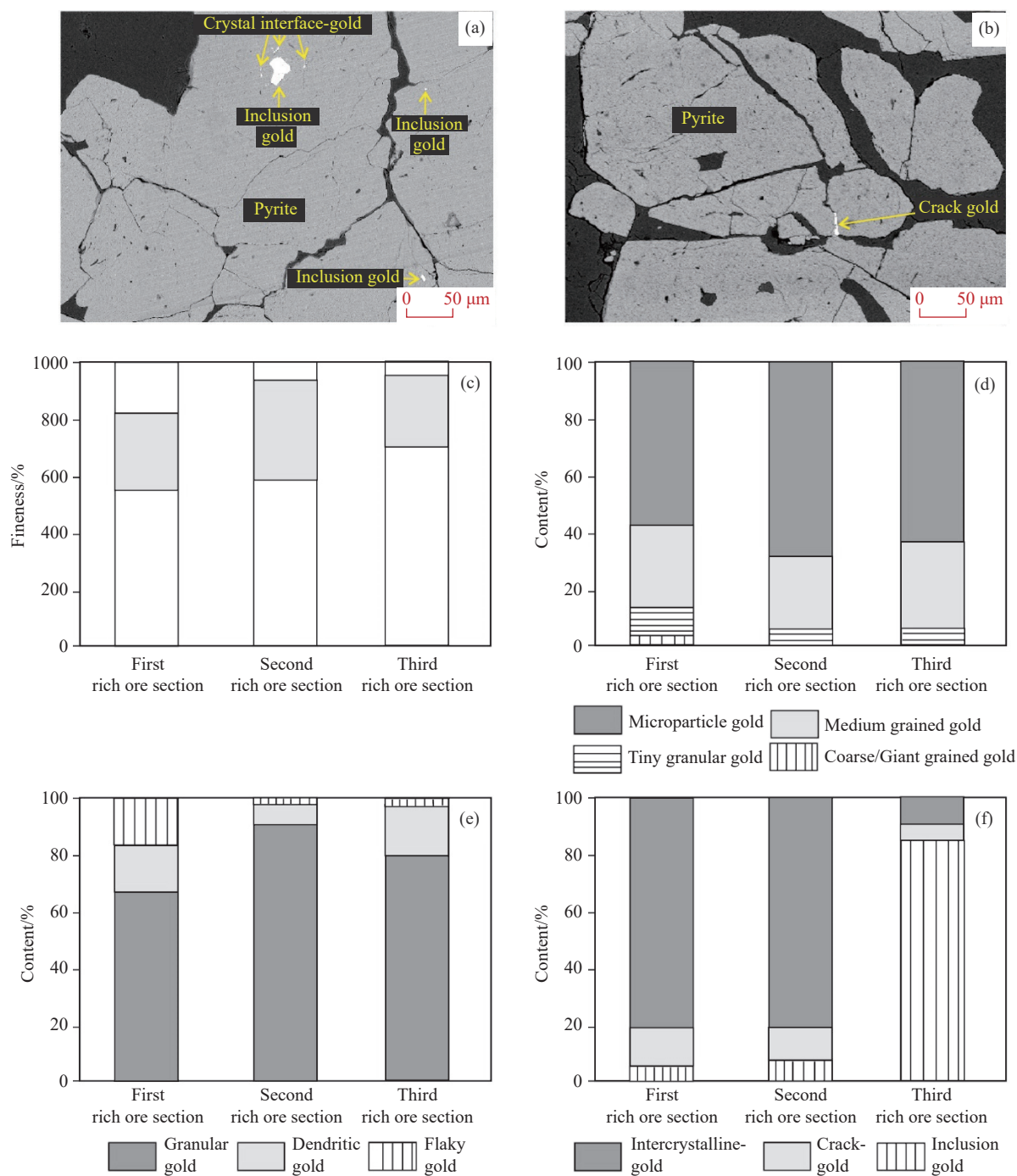


**Fig. 9.** Statistical histograms of gold mineral characteristics. a, b—Gold minerals occurring in pyrite; c—histogram showing the gold mineral fineness; d—histogram showing the particle size of gold minerals; e—histogram showing the morphologies of gold minerals; f—histogram showing the occurrence states of gold minerals.

gradually decreasing flaky gold content (Fig. 9e), and significantly decreasing intergranular and fissure gold content (Fig. 9f).

### 3.2.4. Mineralization stages

Based on the assemblages, textures, and structures of minerals, as well as the intersecting relationships of hydrothermal veins, the altered rock-type gold deposits can be divided into four metallogenic stages (Fig. 10): The pyrite-sericitolite stage (stage I), the gold-quartz-pyrite stage (stage II), the gold-quartz-polymetallic sulfide stage (stage III), and

the quartz-carbonate stage (stage IV). In stage I, the main paragenetic minerals included quartz, sericite, and pyrite. The quartz is white. The pyrite is coarse-grained and exhibits weak gold mineralization, mostly occurring as pyritized quartz veins. In stage II, the major paragenetic minerals include pyrite, and quartz, with minor amounts of sericite, native gold, and electrum. They are veinlet, stockwork, and veinlet-disseminated in shape, occurring within fractured alteration zones. Stage III, the main period for the formation of polymetallic sulfides, witnessed the formation of substantial quantities of gold and silver minerals. The metal

sulfides are dominated by pyrite, followed by minor amounts of chalcopyrite, galena, and sphalerite. Stage IV witnessed the formation of carbonate minerals, as well as quartz, sericite, and a minor amount of pyrite, with gold mineralization almost lacking. The carbonate minerals generally intersect and are superimposed as ore veins upon the veins formed in the former three stages. Stages II and III are the primary gold metallogenic stages.

### 3.3. Proven gold resources

So far, the Linglong gold orefield has had 916 t of cumulative proven gold resources (Table 3), including 170.8 t from the quartz vein-type gold deposits and 745.2 t from the altered rock-type gold deposits. Systematic investigations and research have discovered that major orebodies of the altered rock-type gold deposits, such as Shuiwangzhuang, Luanjiahe, deep Dongfeng, Lijiazhuang, and Lingnan deposits, that have been successively identified in the Potouqing and Jiuqujiangjia fault zones are interconnected with or superimposed upon each other, forming the Taishang-Shuiwangzhuang giant gold deposit with gold resources of up to 628 t.

## 4. Coupling relationships between orebodies and mineralization types

The main faults in the Linglong gold orefield include the Potouqing and Jiuqujiangjia faults. Their footwall primarily hosts Linglong-type granites, exhibiting the occurrence of many quartz veins and intermediate to mafic veins, as well as small-scale faults and fractures, which are comparatively concentrated in the NE direction while slight scattering in the SW direction. These veins and small-scale faults and fractures, together with the main faults, form a broom-like pattern. The hanging wall of the main faults is primarily composed of Luanjiahe-type granites, followed by a few Neoproterozoic Qixia gneiss suites, with the absence of veins and fractures. The altered rock-type gold deposits in the Linglong gold orefield primarily occur within the Potouqing and Jiuqujiangjia faults, whereas the quartz vein-type gold deposits in the orefield principally occur in quartz veins in the footwall of main faults.

### 4.1. Spatial relationships of major orebodies in the altered rock-type gold deposits

Further investigations have deepened the understanding of

| Stage<br>Minerals | I<br>Pyrite- sericite | II<br>Gold-Quartz-Pyrite | III<br>Gold-Quartz-<br>polymetallic<br>sulfides | IV<br>Quartz-Carbonate |
|-------------------|-----------------------|--------------------------|-------------------------------------------------|------------------------|
| Sericite          | —————                 |                          | —————                                           |                        |
| Pyrite            | —————                 | —————                    | —————                                           |                        |
| Quartz            | —————                 | —————                    | —————                                           | —————                  |
| Chalcopyrite      |                       |                          | —————                                           |                        |
| Siderite          |                       |                          |                                                 | —————                  |
| Pyrrhotite        |                       | —————                    |                                                 |                        |
| Gold              |                       | —————                    | —————                                           |                        |
| Sphalerite        |                       |                          | —————                                           |                        |
| Galena            |                       |                          | —————                                           |                        |
| Chlorite          |                       |                          | —————                                           | —————                  |
| Carbonate         |                       |                          |                                                 | —————                  |

**Fig. 10.** Mineralization stages and mineral generation sequence of altered rock-type gold deposits in the Linglong gold orefield.

**Table 3.** Statistics of the types and scales of gold deposits in the Linglong gold orefield.

| No. | Deposit name                             | Gold resources/t | Deposit scale | Deposit type      |
|-----|------------------------------------------|------------------|---------------|-------------------|
| 1   | Linglong gold deposit                    | 129.2            | Superlarge    | Quartz vein type  |
| 2   | Nanrenjian gold deposit                  | 9.1              | Medium        |                   |
| 3   | Dazhuangzi gold deposit                  | 4.8              | Small         |                   |
| 4   | Niucaojian gold deposit                  | 4.5              | Small         |                   |
| 5   | Qianjian gold deposit                    | 23.2             | Large         | Altered rock type |
| 6   | Lingnan gold deposit                     | 240.1            | Superlarge    |                   |
| 7   | Shuiwangzhuang gold deposit              | 186.1            | Superlarge    |                   |
| 8   | No. 171 ore vein of the Dongfeng deposit | 173.4            | Superlarge    |                   |
| 9   | Lijiazhuang gold deposit                 | 17.0             | Large         |                   |
| 10  | Luanjiahe gold deposit                   | 41.8             | Large         |                   |
| 11  | Dongfeng gold deposit                    | 71.0             | Large         |                   |
| 12  | Daqinjiangzongxi gold deposit            | 15.8             | Medium        |                   |

the spatial distributions of orebodies in the Linglong gold orefield. Early geologists generally considered that the Linglong gold orefield is composed of several independent quartz veins, with individual orebodies characterized by small scales and small depth extent (Li SX et al., 2007). Since the end of the 20<sup>th</sup> century, altered rock-type gold deposits in fracture zones have been identified, with orebody scales and depths far surpassing those of the quartz vein-type gold deposits. However, due to the lack of exchange of data from various exploration areas, previous geologists treated altered rock-type gold deposits in fracture zones within different exploration areas as independent large- and medium-sized deposits in their explorations and research (Li SX et al., 2007; Zhang PJ et al., 2015). In the deep prospecting in recent years, the drilling-controlled burial depths of altered rock-type gold deposits in fracture zones have reached 2500 m, with two boreholes with depths over 3000 m having even been drilled. This establishes the Linglong gold orefield as an area with the greatest exploration depth in the Jiaodong Peninsula. The deep prospecting results and previous exploration achievements have laid the foundation for gaining a deep understanding of the spatial distributions of orebodies in this orefield.

As revealed by a comprehensive study on the spatial distributions of altered rock-type gold orebodies in the Taishang-Shuiwangzhuang area, the orebodies are all governed by the Zhaoping fault and its branches. Along the strike of the fault, the No. I-2 orebody in the Lingnan mining area and the No. 171-1 orebody in the Dongfeng mining area are interconnected across exploration lines Nos. 55–148, and the No. 171-1 orebody and the No. 2 orebody in the Shuiwangzhuang mining area are interconnected across exploration lines Nos. 80–120. Moreover, the major orebodies of the Taishang and Lingnan mining areas exhibit a horizontal interval of approximately 1 km (Fig. 2). Profiles show that the orebodies governed by the Potouqing and Jiuqujiangjia faults are superimposed vertically, with shallow small orebodies dictated by the secondary fissures in the footwall of the faults.

Orebodies in various mining areas occur in the same continuous mineralized alteration zone, which serves as a link between these orebodies. The 3000.58-m-deep borehole in the Shuiwangzhuang ore block and the corresponding No. 34 exploration line reveal the continuity of the mineralized alteration zone and the relationships between orebodies (Fig. 11). The 3000.58-m-borehole reveals trondhjemites at depths from 0 to 10 m, granites phyllic alteration from 10 m to 1940 m, granitic cataclasites phyllic alteration from 1940 m to 2300 m, granitic cataclasites phyllic alteration from 2300 m to 2810 m, and fine-grained monzogranites from 2900 m to 3000 m. At a depth of –2000 m, an altered fracture zone of the Potouqing fault was identified, revealing continuous gold mineralization with a thickness of about 50 m. At a depth of around –2700 m, an altered fracture zone (about 156 m thick) of the Jiuqujiangjia fault was discovered. Its major lithologies include granites phyllic alteration and granitic cataclasites phyllic alteration, with ores found in one sample. The spatial distributions of the orebodies and the mineralized alteration zone indicate the significant continuity of orebodies in various mining areas of the Taishang-Shuiwangzhuang gold deposit, which, therefore, is a continuous giant gold deposit.

#### 4.2. Relationships between altered rock-type orebodies and changes in fault attitudes

The orebodies in the Linglong gold orefield are all governed by fault structures. Previous researchers put forward various ore-controlling regularity of faults, such as the cube of fault attitudes on the pitch and en echelon of orebodies, as well as the control of ores  $\lambda$ -shaped structures, en echelon structure assemblages, conjugated faults/fractures, and obliquely or reversely reactivated faults. Moreover, early researchers established that intersections between EW-striking basement tectonic zones and NNE-NE-striking superficial faults were favorable for the occurrence of large to super-large gold deposits (Deng J et al., 2019; Wang SR et al., 2020). The aforementioned understanding was derived from

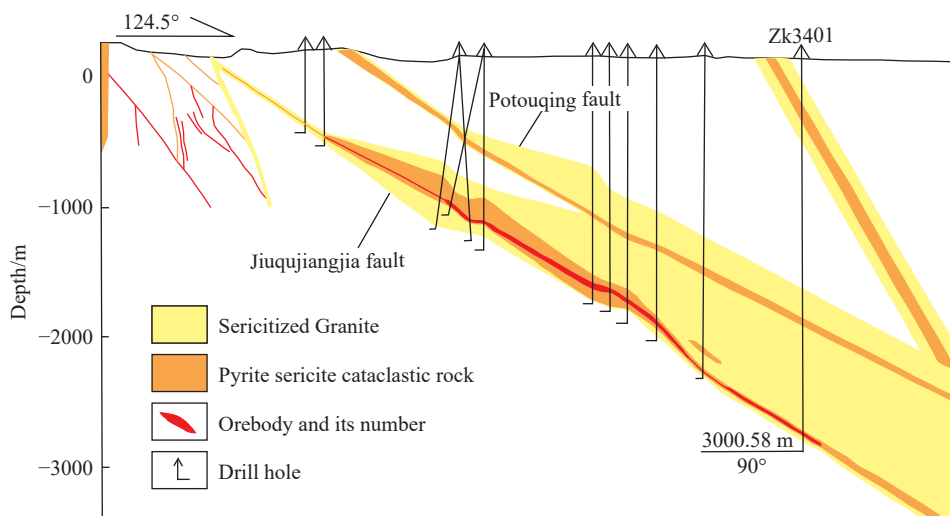


Fig. 11. Geological section of the No. 34 exploration line in the Shuiwangzhuang ore block.

data on the surface and shallow explorations of gold deposits. The gradually abundant deep exploration outcomes and the demand for deep exploration have jointly made it increasingly critical to investigate the deep ore-controlling regularity of faults. Recent studies have revealed that large-scale altered rock-type gold deposits frequently occur in parts with changes in fault dip angles, forming a stepped metallogenic pattern (Song MC et al., 2012). As suggested by the three-dimensional morphological analysis of the Dayingezhuang gold deposit in the Zhaoping fault zone, gold orebodies primarily occur in fault zones with slopes ranging from 20° to 40° (Mao XC et al., 2019).

As indicated by deep explorations and this study, the Jiuqujiangjia and Potouqing faults, which control the Taishang-Shuiwangzhuang gold deposit, show a listric pattern where dip angles are deep in shallow parts and gradually decrease toward deep parts. As stated above, within the current drilling-controlled range, the first, second, and third mineralization enrichment zones from shallow to deep parts of the giant deposit exhibit fault dip angles of approximately 39°, 34°, and 26°, respectively. The ore-controlling faults are wavy faults that dip gently and exhibit constantly varying attitudes, similar to the Sanshandao and Jiaojia faults (Song MC et al., 2012, 2021a). Using the three-dimensional model of the Taishang-Shuiwangzhuang giant gold deposit established based on borehole data, this study extracted the ore-controlling fault planes and calculated the changing rates of the fault dip angles. Generally, the ore-controlling faults exhibit slight changes in their dip angles, with changing rates concentrated in a range from 0 to 0.54 (Fig. 12). By superposing the grade × thickness contours of orebodies onto the map showing the changing rates of the dip angles, this study found that the distribution of orebodies agrees roughly with areas showing significant changes in fault dip angles and that the mineralization enrichment zones with dense contours

align well the areas. This finding implies that a higher changing rate of fault dip angles is associated with a high degree of mineralization enrichment (Fig. 12).

In the mineralization enrichment zones, as indicated by the grade × thickness contours of orebodies (upper right part in Fig. 12), a profile was determined by cutting along the dip directions of faults, and then the fault dip angles and the grade × thickness of orebodies were extracted at an interval of 20 m from shallow to deep parts. Consequently, the relationship between the grade × thickness of orebodies and the fault dip angle was plotted (Fig. 13).

The diagram reveals that there is roughly a negative correlation between the fault dip angle and the degree of mineralization enrichment (expressed by grade × thickness). Within elevations ranging from 80 m to −300 m and less than −1520 m, fault dip angles are relatively high, varying in a range of 30°–45°, corresponding to low degrees of mineralization enrichment or even zero mineralization. At elevations from −300 m to −1520 m, fault dip angles reduce sharply to 22°–30°, corresponding to significantly enhanced degrees of mineralization enrichment. Accordingly, the grade × thickness values of orebodies range from 22.95 m·g/t to 115.92 m·g/t (average: 71.99 m·g/t). Hence, parts with decreasing or gentle fault dip angles exhibit high-degree mineralization enrichment, with a higher difference in the fault dip angle corresponding to a higher degree of mineralization enrichment. As a result, the major orebodies of the gold deposits show a stepped spatial distribution from the shallow to the deep parts.

The stepped distribution of gold orebodies serves as an effective guide for deep prospecting. The exploration of the Lingnan mining area reveals significant segmental mineralization enrichment of orebodies from shallow to deep parts. Specifically, the orebodies in the first and second ore enrichment sections exhibit lengths along their dip directions

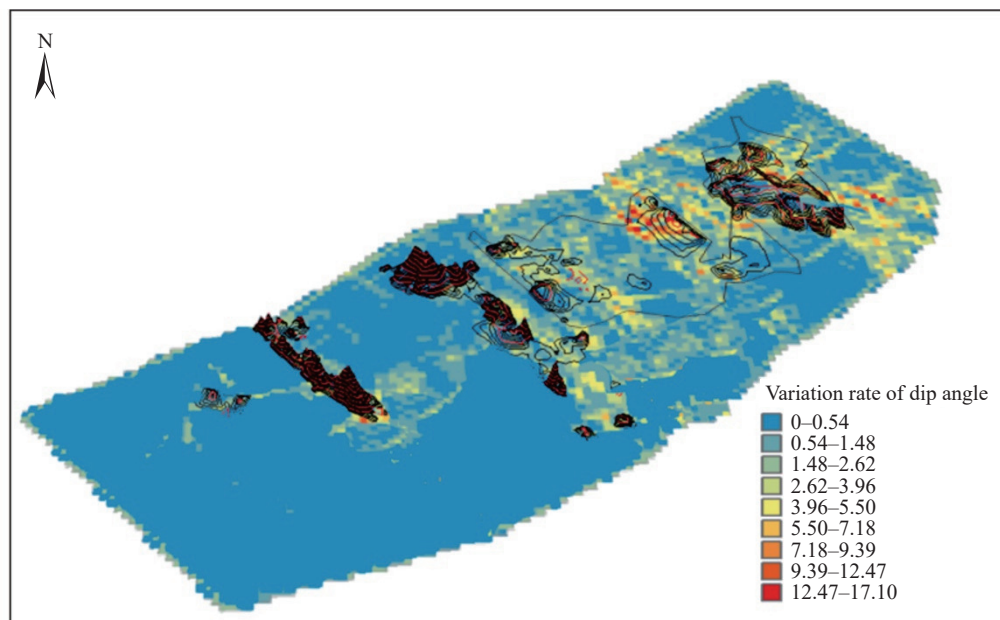


Fig. 12. Changing rates of ore-controlling faults' dip angles in the Taishang-Shuiwangzhuang giant gold deposit.

of about 1 km, and these orebodies are separated by weak-mineralization or zero-ore parts with lengths along their dip directions ranging between 700 m and 1000 m. Thick, large-scale orebodies in the ore enrichment sections all occur in parts with low fault dip angles. As forecast using the stepped metallogenic pattern, another ore-bearing step may exist at depths ranging from –2000 m to –2200 m. The verification shows that the third ore enrichment section was first discovered deep in the Jiadong region (Fig. 14).

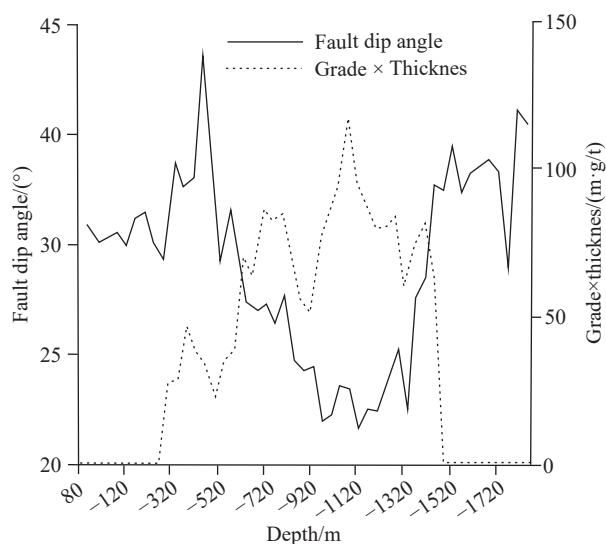


Fig. 13. Fault dip angle vs. grade × thickness.

The stepped metallogenic pattern of altered rock-type gold deposits is attributable to the fluid pressure fluctuations caused by changes in fault dip angles. The water-rock interactions, fluid immiscibility, and fluid mixing are considered critical factors in gold precipitation (Zhang L et al., 2020), while pressure fluctuations are the internal cause of fluid immiscibility (Yang LQ et al., 2014a). As ore-forming fluids migrate from deep to gently dipping segments, their pressure sharply decreases and their flow rates reduce, leading to fluid unloading and gold precipitation. Some researchers consider that the ore-forming parts are closely related to stress concentration. For a normal fault, parts with gradually decreasing dip angles are subjected to more intense normal stress compared to steep segments, making them more prone to experience stress concentration, which can hinder the further dislocation of faults while sealing fluids swarming from deep parts. Consequently, the fluid pressure constantly increases. As the fluid pressure reaches a certain value, hydrofracturing of rocks will occur, leading to the formation of brittle fractures. In this case, the fluid pressure in fractures drops instantly, and the fluids will boil or undergo evaporation, resulting in gold precipitation (Cheng NN et al., 2018).

#### 4.3. Relationships gold deposits of the altered rock and quartz vein types

Gold deposits of the altered rock and quartz vein types, two industrial types of gold deposits established by geologists

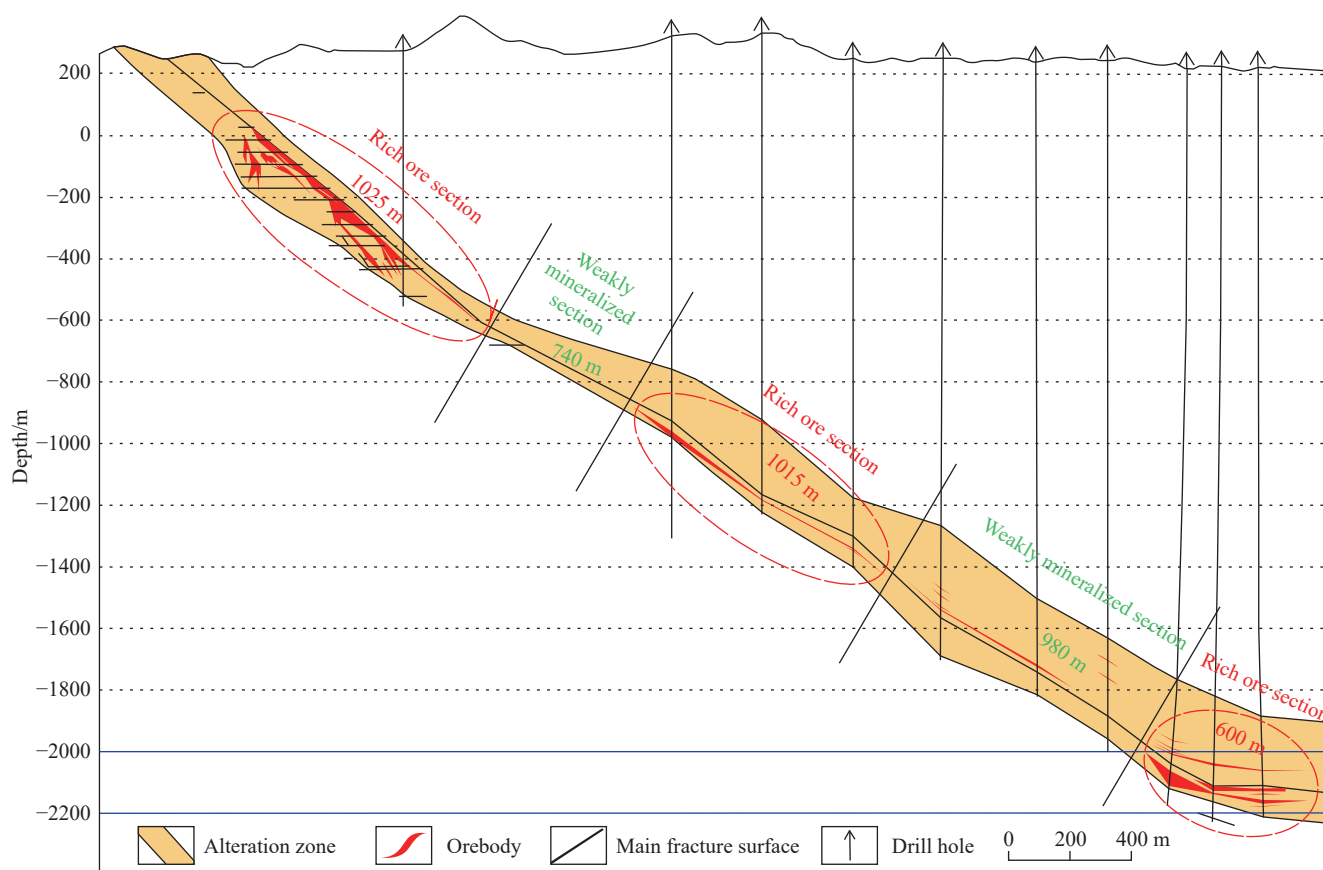


Fig. 14. Sketch map showing the geological section of the No. 43 exploration line in the Lingnan mining area.

in their practices, are two basic mineralization types of Jiaodong gold deposits. Increasingly abundant exploration and research results allow for constantly deepening the understanding of the relationships between both types of gold deposits. For instance, regarding the metallogenic epochs and origins of the deposits, it was believed previously that both types of gold deposits were formed in multiple phases due to various origins and were governed by different fault systems (Yang ZF et al., 1998; Shen YC et al., 2001; Zhang LC et al., 2002a, 2002b; Song MC et al., 2018a; Deng J et al., 2020b). For the spatial distribution of mineralization types, it was primarily considered that the gold deposits of the altered rock and quartz vein types exhibited a vertical distribution, with the former lying below the latter (Zhu FS et al., 1980; Fan YX et al., 1984; Wang Y et al., 1988; Liu LD et al., 1989; Shi YC et al., 2005). Some other researchers held that the two types of gold deposits primarily displayed a horizontal zoning pattern (Li JX et al., 1999; Wang JC et al., 2003; Lü GX et al., 2013). In contrast, the present popular understanding is that both types were formed in the same metallogenic epoch, had the same origin and ore-forming material source, and belong to the same tectonic system and that they exhibit different mineralization types due to varying tectonic conditions (e.g., nature, scale, and intensity) and mineralization modes (e.g., diffusion, infiltration, metasomatism, or filling) (Zhang PJ et al., 2015; Song MC et al., 2018a; Deng J et al., 2020a). Despite their significantly different metallogenic characteristics, their genetic mechanisms show close internal relations.

A comparative study shows that both types of gold deposits in the Linglong gold orefield differ in orebody characteristics and ore-hosting positions. Specifically, the altered rock-type gold deposits feature small dip angles, large scales, and low average ore grades, with orebodies occurring in large-scale, gently dipping fracture zones. In addition, both types of gold deposits vary in the characteristics of ore minerals and gold minerals. Ores in the quartz vein-type gold deposits exhibit significantly higher metal sulfide content, with an average S content more than three times that of ores in the altered rock-type gold deposits. In the quartz vein-type gold deposits, gold minerals primarily occur as inclusion gold and are mostly fine-grained, with fineness lower than that of altered rock-type gold deposits (Feng YC et al., 2023). In contrast, the gold minerals in altered rock-type gold deposits mainly occur as intercrystalline gold and are mostly microgranular. These differences indicate that both types of gold deposits exhibit different physical and chemical conditions for mineralization. The geochemical characteristics of the deposits (as detailed below) indicate that both types of gold deposits demonstrate roughly the same characteristics of fluid inclusions and stable isotopes, indicative of the same sources of fluids and ore-forming materials. Their differences are as follows: (1) The fluid inclusions of the altered rock-type gold deposits, formed during the mineralization, exhibit simple types, low salinity, and low temperature; (2) the quartz vein-type gold deposits tend to show the H-O isotopic

characteristics of magmatic water, while the altered rock-type gold deposits likely exhibit the H-O isotopic characteristics of atmospheric precipitation; and (3) ores in the quartz vein-type gold deposits exhibit similar S isotopic composition characteristics to the Neoarchean metamorphic rock series, while ores in the altered rock-type gold deposits possess the S isotopic characteristics of the Late Mesozoic granitoids and mafic dikes (Song MC et al., 2013). Additionally, the quartz vein-type gold deposits exhibit the coexistence of CO<sub>2</sub>-H<sub>2</sub>O inclusions and two-phase H<sub>2</sub>O solution inclusions, with consistent homogenization temperature distributions, within quartz of the main metallogenic period. In contrast, the altered vein-type gold deposits exhibit relatively simple fluid inclusions, dominated by CO<sub>2</sub>-H<sub>2</sub>O inclusions, within quartz of the main metallogenic period (Wen BJ et al., 2015). These different geochemical characteristics between both types of gold deposits are supposed to be related to the different metallogenic mechanisms. For the quartz vein-type gold deposits, gold precipitated due to the phase separation of ore-forming fluids, with ore-forming fluids and material sources preserving more characteristics of the sources. In contrast, the mineralization of the altered rock-type gold deposits is governed by the water-rock interaction between fluids and surrounding rocks, with stable isotopic compositions prominently affected by surrounding rocks.

Regarding spatial distribution, orebodies of both types of gold deposits are usually independently distributed, with their coexistence also visible in the same ore vein. Altered rocks frequently emerge at the edges, heads, and pinchout parts of the tails of quartz vein-type orebodies, while quartz vein-type orebodies are often visible in the footwall of altered rock-type orebodies. In the Linglong gold orefield, the orebodies occurring along the Jiuqujiangjia and Potouqing faults are all altered rock-type orebodies, while the numerous ore veins in the Linglong-type granites in the footwall of the faults exhibit the distribution of both altered rock-type gold mineralization and the gold mineralization dominated by the quartz vein type. For instance, the Nos. 108, 45–51, and 9 vein swarms mainly show the gold mineralization of the quartz vein type, while the Nos. 10–48 vein swarms exhibit the gold mineralization of the transitional type between quartz vein and altered rock types. Altered rock-type ore veins primarily occur near main faults, while quartz vein-type ore veins are mainly found far from main faults. In ore veins composed of both altered rocks and quartz veins, the quartz veins are generally concentrated as veinlets stockwork veins. They are surrounded by altered rocks, with widths generally less than 1 m (widths of quartz veins in typical quartz vein-type gold deposits: > 1 m or even tens of meters). The presence of gold deposits containing both altered rocks and quartz veins indicates the genetic connection between altered rocks and quartz veins (Zhang PJ et al., 2015). The profile of the Linglong gold orefield (Fig. 2b) distinctly presents the spatial distribution of gold deposits of the altered rock and quartz vein types. Specifically, altered rock-type gold deposits occur in main faults, while quartz vein-type gold deposits are found

in the footwall of the main faults. The activity nature shows that the Zhaoping fault is a large-scale transtensional fault possessing the properties of a detachment fault, with the faults and fissures whose footwall is filled with quartz veins serving as the ancillary tensile structures of its main fault (Lü GX et al., 2013; Zhang PJ et al., 2015). This means that the spatial distribution of gold mineralization types is related to their tectonic locations. Specifically, altered rock-type gold deposits are governed by main faults with developed cataclasites, while quartz vein-type gold deposits are dictated by secondary tensile fissures in the footwall of main faults. Therefore, vertically, the deposits of the altered rock and quartz vein types do not exhibit superimposition but reflect the locations and properties of structures. They were formed due to different fluid-structure coupling relationships at different structural locations or in sections with different structural properties in the same structural system. The altered rock-type gold deposits were formed under slow fluid seepage, fluid dissipation surpassing recharge, and water-rock interactions in faults with developed cataclasites, while the quartz vein-type gold deposits result from rapid fluid inflow, fluid recharge exceeding dissipation, and fluid phase separation in the tensile fissures lacking cataclasites.

## 5. Mineralization and prospecting model

### 5.1. Metallogenic epochs

The lack of minerals that can be directly used for gold dating led to many disputes about metallogenic epochs of Jiaodong gold deposits in the past. Early researchers ever considered that Jiaodong gold deposits were formed during the Archean or the Proterozoic. Later, the theory of multi-stage mineralization was proposed, holding that the Archean, Proterozoic, and Mesozoic were all important mineralization epochs (Li SX et al., 2007). Some researchers believed that Jiaodong gold deposits experienced three metallogenic events at 150 Ma, 120–110 Ma, and 100–110 Ma (Ding ZJ et al., 2015). In recent years, researchers have carried out much isotopic dating of Jiaodong gold deposits (Yang JH et al., 2000; Li JW et al. 2003, 2006; Li QL et al., 2008; Yang LQ et al., 2014a, 2017; Cai YC et al., 2018; Xue JL et al., 2019; Yuan ZZ et al., 2019; Deng J et al., 2020a; Sai SX et al., 2020; Zhang L et al., 2020). As indicated by massive high-precision data obtained using  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of altered minerals (muscovites/sericites), *in-situ* U-Pb dating of hydrothermal minerals (monazites), and Rb-Sr dating of single-grain pyrites, Jiaodong gold deposits have a main gold metallogenic epoch of  $120\pm 2$  Ma, a short geological period. The latest test results also demonstrate that a small number of quartz vein-type gold deposits in the Muping-Rushan area in the east Jiaodong Peninsula were possibly formed about 5 Ma later than the large-scale mineralization of Jiaodong gold deposits (Deng J et al., 2020a).

Researchers have also conducted many tests on the metallogenic epochs of deposits in the Linglong gold orefield. Before 2000, the data were mostly obtained using the Rb-Sr

and K-Ar dating of altered minerals (sericites/hydromuscovites) or fluid inclusions. These data varied in a wide range ( $126.5\pm 5.7$  Ma to  $71.86\pm 9.6$  Ma; Luo WC et al., 1987; Zhang ZH et al., 1993; Lü GX et al., 1993; Li HQ et al., 1994), leading to many disputes about the metallogenic epoch. Using the SHRIMP zircon U-Pb dating method, some researchers determined the post-mineralization isotopic age of felsic porphyry veins in the Linglong gold deposit and the pre-mineralization isotopic age of Guojialing-type granites near the Linglong gold orefield at  $120\pm 2$  Ma and  $126\pm 2$  Ma, respectively, strictly constraining the gold mineralization period within 126–120 Ma (Wang LG et al., 1998). Since 2000, the obtained ages of the Linglong gold orefield include the whole-rock Rb-Sr isochron ages of ores at  $125.5\pm 6.7$  Ma (Wang ZY et al., 2016), the Rb-Sr isochron ages of single-particle pyrite at  $121.6\pm 8.1$  Ma, from  $122.0\pm 11$  Ma to  $123.0\pm 4.2$  Ma, and  $120.6\pm 0.9$  Ma (Yang JH et al., 2000, 2001; Li QL et al., 2008), and the LA-ICPMS/SHRIMP U-Pb ages of hydrothermal monazites at  $121.4\pm 1.8$  Ma,  $119.1\pm 1.4$  Ma, and  $120.0\pm 4.6$  Ma (Lin ZW, 2019; Deng J et al., 2020a).

Presently, it is well established that the age of hydrothermal monazites can reflect the metallogenic epoch of gold (Deng J et al., 2020a). The highly consistent published ages of hydrothermal monazites in the Jiaodong region (Ma WD et al., 2017; Yang KF et al., 2018; Feng K et al., 2020; Deng J et al., 2020a) corroborate the reliability of this method. Three samples from the Linglong gold deposit yielded LA-ICPMS U-Pb ages of hydrothermal monazites from  $121.4\pm 1.8$  Ma to  $119.1\pm 1.4$  Ma, which align with the ages of hydrothermal monazites in most of the Jiaodong gold deposits. Therefore, this study proposes that the gold mineralization of the quartz vein and altered rock types in the Linglong gold orefield was concentrated at  $120\pm 2$  Ma, excluding the possibility of multi-stage or long-term mineralization.

### 5.2. Ore-forming fluids and material sources

#### 5.2.1. Nature of ore-forming fluids

The ore-forming fluids of the Linglong gold orefield belong to a reducing  $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}\pm\text{CH}_4$  fluid system with a medium-high temperature and low salinity. The temperature measurement of fluid inclusions shows that the mineralization temperature is mainly concentrated between  $158^\circ\text{C}$  and  $360^\circ\text{C}$ , and the salinity is mainly concentrated between 0.2% and 14.6% (Table 4; Fan HR et al., 2005; Zhang ZQ et al., 2007; Wang L et al., 2010; Li HK et al., 2012; Yang LQ et al., 2016a; Guo LN et al., 2020; Li J et al., 2021a). Their fluid inclusions, generally small (3–10  $\mu\text{m}$  primarily), can be primarily categorized into pure  $\text{CO}_2$  inclusions, two-phase  $\text{CO}_2$ - $\text{H}_2\text{O}$  inclusions, and pure  $\text{H}_2\text{O}$  inclusions, with multi-phase fluid inclusions containing NaCl or other daughter minerals also visible. The fluid inclusions of quartz vein- and altered rock-type ores exhibit similar characteristics overall, with slight differences. Compared to the quartz vein-type ores, the altered rock-type ores exhibit simpler fluid inclusion

**Table 4. Fluid inclusion characteristics of quartz from the Linglong gold orefield.**

| Ore block       | Mineralization type | Fluid inclusion type                                                                                                                                                                    | Major characteristics of the fluids in the metallogenic period                                                                                                                           | Reference             |
|-----------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| Linglong        | Quartz vein type    | Three types: Two-phase H <sub>2</sub> O-CO <sub>2</sub> , CO <sub>2</sub> -rich, and H <sub>2</sub> O-rich inclusions                                                                   | H <sub>2</sub> O-NaCl-CO <sub>2</sub> ±CH <sub>4</sub> fluids with medium temperatures (290°C–340°C), low salinity (4%–7%), rich CO <sub>2</sub> , and a trace amount of CH <sub>4</sub> | Guo LN et al., 2020   |
|                 |                     | Three types: Gas-liquid two-phase, three-phase CO <sub>2</sub> -bearing, and pure gas inclusions                                                                                        | CO <sub>2</sub> -bearing H <sub>2</sub> O-CO <sub>2</sub> -NaCl±CH <sub>4</sub> fluids with medium-high temperatures (244.3°C–328.4°C) and low salinity (2.5%–9.6%)                      | Wang L et al., 2010   |
|                 |                     | Five types: Pure CO <sub>2</sub> two-phase, two-phase, CO <sub>2</sub> -rich multi-phase, liquid phase-rich H <sub>2</sub> O solution, pure gas phase, and pure liquid phase inclusions | H <sub>2</sub> O-CO <sub>2</sub> -NaCl fluids with medium-high temperatures (180°C–360°C) and low salinity (3.0%–14.6%)                                                                  | Zhang ZQ et al., 2007 |
|                 |                     | Three types: Two-phase H <sub>2</sub> O-CO <sub>2</sub> H <sub>2</sub> O-CO <sub>2</sub> ±CH <sub>4</sub> , and H <sub>2</sub> O solution inclusions                                    | Main ore-forming temperature 210°C–335°C, low salinity (<11%) H <sub>2</sub> OCO <sub>2</sub> NaCl±CH <sub>4</sub> inclusions                                                            | Fan HR et al., 2005   |
| Linglong-Xishan |                     | Three types: H <sub>2</sub> O solution, two-phase H <sub>2</sub> O-CO <sub>2</sub> , and three-phase H <sub>2</sub> O-CO <sub>2</sub> inclusions                                        | H <sub>2</sub> O-CO <sub>2</sub> -NaCl fluids with medium-high temperatures (205°C–345°C) and low salinity (4.18%–8.55%)                                                                 | Li HG et al., 2012    |
| Taishang        | Altered rock type   | Three types: Two-phase H <sub>2</sub> O-rich gas-liquid, two-phase CO <sub>2</sub> -rich gas-liquid, and CO <sub>2</sub> inclusions                                                     | H <sub>2</sub> O-CO <sub>2</sub> -NaCl±CH <sub>4</sub> fluids with medium to high temperatures (158°C–336°C), low salinity (0.2%–9.1%), and rich CO <sub>2</sub>                         | Yang LQ et al., 2016a |
| Shuiwangzhuang  |                     | Three types: Two-phase gas-liquid, CO <sub>2</sub> -bearing, and daughter mineral-bearing inclusions                                                                                    | H <sub>2</sub> O-CO <sub>2</sub> -NaCl±CH <sub>4</sub> fluids with medium-high temperatures (290°C–350°C) and low salinity (1.2%–13.8%),                                                 | Li J et al., 2021a    |

types. For the altered rock-type ores, the fluids of the metallogenic period demonstrated greatly varying salinity and temperature, whose minimum values, however, were lower than those of the quartz vein-type ores.

#### 5.2.2. Source of ore-forming fluids

The ore-forming fluids in quartz fluid inclusions of the Linglong gold orefield exhibit  $\delta D$  and  $\delta^{18}O$  values varying primarily from –93‰ to –54‰ and from 1.4‰ to 9.89‰, respectively (Table 5).

In contrast, the quartz vein- and altered rock-type gold deposits demonstrate  $\delta D$  values varying from –93‰ to –54‰ and from –91.7‰ to –78.8‰, respectively. As shown in the  $\delta D$  vs.  $\delta^{18}O$  diagram (Fig. 15), the H-O isotopic compositions fall within the zones of magmatic water and metamorphic water and between each zone and the meteoric water line, mostly between the magmatic water zone and meteoric water line. The quartz vein- and altered rock-type ores present roughly the same H-O isotopic composition, except that the latter exhibit narrower variation ranges of  $\delta D$  and  $\delta^{18}O$  values and that, in the  $\delta D$  vs.  $\delta^{18}O$  diagram, the data points of quartz vein-type ores fall closer to the magmatic water zone while those of altered rock-type gold deposits are closer to the meteoric water line. As indicated by the C-O isotopic data of calcites forming in the late metallogenic stage of quartz vein-type ores, their  $\delta^{13}C$  values vary from –6.4‰ to –3.4‰ (Table 5), falling within the range of the  $\delta^{13}C$  values of carbonates forming in the late metallogenic stage of altered rock-type ores in the Sanshandao gold orefield (Song MC et al., 2021a, b). The phenomenon that the  $\delta^{13}C$  values approach those of igneous rocks/a magmatic system (–3‰ to –30‰) and the mantle carbon pool (–5‰ to –7‰; Hoefs J, 1997) indicates that the carbon in the fluids is derived from a magmatic system or the mantle.

Jiaodong gold deposits experienced extensive magmatic

activity during their mineralization, leading to the formation of mafic dikes, mantle-derived diorites, mantle- and crustal-derived granites (such as Weideshan-type granites), and bimodal volcanic rocks (the Qingshan Group). This indicates intense crust-mantle interactions. Therefore, it can be concluded that the magmatic fluids for mineralization in the Jiaodong gold deposits might be sourced from the fluid system in the process of crust-mantle interactions.

#### 5.2.3. Source of ore-forming materials

##### (i) S isotopes

Presently, the source of sulfur in the Jiaodong gold deposits remains highly controversial. Some researchers hold that the sulfur is primarily inherited from the sulfur isotopes of the ore-hosting surrounding rocks, originating from the Early Precambrian metamorphic complexes in the Jiaodong Peninsula initially and from the Late Mesozoic granitoids finally (Li SX et al., 2007; Yang LQ et al., 2014b). Some consider that the high  $\delta^{34}S$  values of Jiaodong gold deposits are related to the subduction of the Neoproterozoic high-sulfur deposits in the Yangtze Craton to the lithospheric mantle of the North China Craton (Deng J et al., 2020b). Some believe that  $^{34}S$  might originate from devolatilization during plate subduction (Feng K et al., 2020). Some believe that sulfur and sulfurophilic elements are transferred from the subducted slab to the overlying mantle wedge through aqueous melts or devolatilized fluids (He DY et al., 2024). Additionally, some studies propose that the sulfur primarily originated from mantle-derived magmatic sulfur and is mixed with crust-derived sulfur (Li J et al., 2020, 2021b).

Ores in the Linglong gold orefield exhibit  $\delta^{34}S$  value ranging from 2.9‰ to 9.8‰ (Table 6). Among them, the quartz vein- and altered rock-type ores display  $\delta^{34}S$  values from 2.9‰ to 9.8‰ (average: 7.3‰) and from 5.9‰ to 8.5‰ (average: 7.2‰), respectively. They show roughly the same

Table 5. Carbon, hydrogen, and oxygen isotopic compositions of quartz and calcite in the Linglong gold orefield.

| Ore block<br>(vein)/mineralization type | $\delta D_{\text{water}}/\text{‰}$ | $\delta^{18}O_{\text{water}}/\text{‰}$ | References           | Ore block<br>(vein)/mineralization type | $\delta D_{\text{water}}/\text{‰}$ | $\delta^{18}O_{\text{water}}/\text{‰}$ | Reference             |
|-----------------------------------------|------------------------------------|----------------------------------------|----------------------|-----------------------------------------|------------------------------------|----------------------------------------|-----------------------|
| No. 47 vein/quartz vein                 | -51.8                              |                                        | Wang L et al., 2010  | Xishan/quartz vein                      | 3.69                               |                                        | Chen GY et al., 1993  |
|                                         | -69.7                              |                                        |                      |                                         | 7.75                               |                                        |                       |
|                                         | -76                                |                                        |                      |                                         | 7.15                               |                                        |                       |
|                                         | -70.9                              |                                        |                      |                                         | 7.66                               |                                        |                       |
|                                         | -66.3                              |                                        |                      |                                         | 7.6                                |                                        |                       |
| Linglong/quartz vein                    | -71.3                              | 6.43                                   | Li SX et al., 2007   | Linglong/quartz vein                    | -58                                | 7.2                                    | Zhang LG et al., 1994 |
|                                         | -65                                | 6.17                                   |                      |                                         | -54                                | 7.2                                    |                       |
|                                         | -73.3                              | 1.88                                   |                      |                                         | -64                                | 6.1                                    |                       |
|                                         | -53.5                              | 6.89                                   |                      | No. 51 vein/quartz vein                 | -85                                | 4.2                                    |                       |
|                                         | -64.2                              | 5.21                                   |                      | No. 53 vein/quartz vein                 | -76                                | 4                                      |                       |
|                                         | -53.7                              | 5.79                                   |                      | No. 53 vein/quartz vein                 | -67.5                              | 5.7                                    |                       |
|                                         | -68.2                              | 5.3                                    |                      | No. 108 vein/quartz vein                | -62.5                              | 5.4                                    | Du XJ et al., 1988    |
|                                         | -73.1                              | 4.5                                    |                      | No. 52 vein/quartz vein                 | -75.6                              | 6.9                                    | Wang BC et al., 1986  |
|                                         | -55.1                              | 1.4                                    |                      | No. 108 vein/quartz vein                | -75.2                              | 7.4                                    |                       |
|                                         | -76                                | 4                                      | Yang ZF et al., 1991 | Linglong/quartz vein                    | -63—57                             | 6.0–9.3                                | Guo LN et al., 2020   |
|                                         | -93                                | 3.2                                    |                      | Shuiwangzhuang/altered rock             | -91.7                              | 2.57                                   | Li J et al., 2021a    |
|                                         | -76                                | 4.3                                    |                      |                                         | -89.1                              | 3.56                                   |                       |
|                                         | -62                                | 3.8                                    |                      |                                         | -82.6                              | 4.95                                   |                       |
|                                         | -64                                | 6.1                                    |                      |                                         | -87.5                              | 5.05                                   |                       |
|                                         | -54                                | 7.2                                    |                      |                                         | -89.3                              | 5.65                                   |                       |
|                                         | -58                                | 7.2                                    |                      |                                         | -86.3                              | 3.96                                   |                       |
|                                         | -75                                | 4.9                                    | Yang ZF et al., 1998 |                                         | -87                                | 4.82                                   |                       |
|                                         | -57.91                             | 1.45                                   | Li ZL et al., 1990   | Taishang/altered rock                   | -78.8                              | 4.97                                   | Zhou FY et al., 1991  |
|                                         | -67.53                             | 5.04                                   |                      |                                         | -90.71                             | 9.89                                   |                       |
|                                         | -61.8—75.97                        | 8.4–8.9                                | Qiu YS et al., 1988  |                                         |                                    |                                        |                       |
| Ore block/mineralization type           | $\delta^{13}C\text{‰}$             | $\delta^{18}O\text{‰}$                 | Reference            | Ore block/mineralization type           | $\delta^{13}C\text{‰}$             | $\delta^{18}O\text{‰}$                 | Reference             |
| Linglong/quartz vein                    | -6.4                               | 12                                     | Mao JW et al., 2002  | Linglong/quartz vein                    | -3.4                               | 11.4                                   | Mao JW et al., 2002   |
|                                         | -6.4                               | 12                                     |                      |                                         | -5.4                               | 11.6                                   | Li ZL et al., 1993    |
|                                         | -5.5                               | 11.7                                   |                      |                                         | -4.4                               | 10.5                                   |                       |
|                                         | -5.5                               | 11.9                                   |                      |                                         | -5.1                               | 11.6                                   |                       |

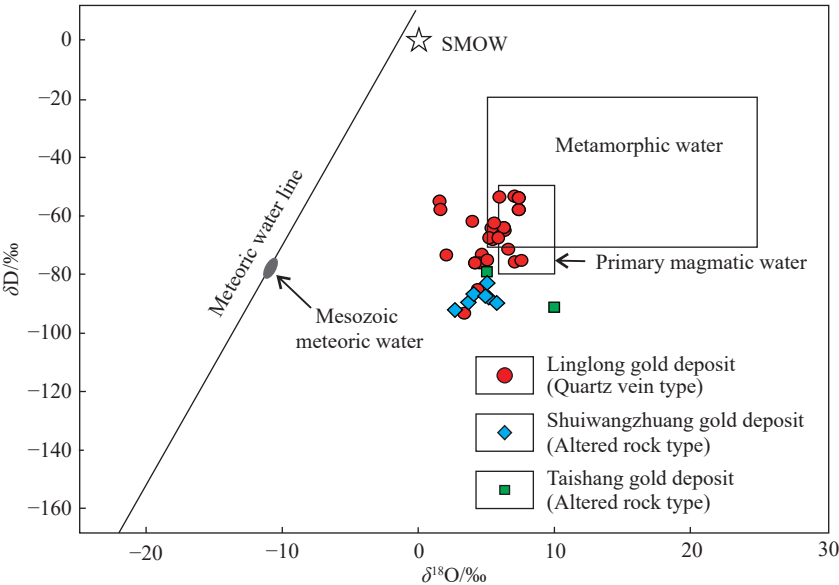


Fig. 15.  $\delta D$  vs.  $\delta^{18}O$  values of ore-forming fluids in the Linglong gold orefield (the base map modified from Taylor HP, 1974; Sheppard SMF, 1986).

average  $\delta^{34}\text{S}$  value, except that the former exhibits a significantly wider range of  $\delta^{34}\text{S}$  values and some significantly lower  $\delta^{34}\text{S}$  values. As revealed by the sulfur isotopic composition of ore-hosting surrounding rocks (Table 5), the Neoarchean TTG series exhibit the lowest  $\delta^{34}\text{S}$  values, which vary in a narrow range from 1.0‰ to 3.0‰; the Neoarchean Jiaodong Group demonstrates  $\delta^{34}\text{S}$  value varying in a wider range from 0 to 15.4‰ (average: 5.0‰); the Paleoproterozoic Jingshan and Fenzishan groups display the highest  $\delta^{34}\text{S}$  values, which range from 8.2‰ to 13.6‰; the Late Mesozoic granitoids show  $\delta^{34}\text{S}$  value varying from 3.8‰ to 16.0‰, and intermediate to mafic dikes exhibit  $\delta^{34}\text{S}$  values ranging between 5.3‰ and 10.8‰. The gold deposits exhibit significantly lower  $\delta^{34}\text{S}$  values than the Jingshan and Fenzishan groups with marine deposits as protolith. In contrast, their  $\delta^{34}\text{S}$  values are higher than those of TTGs formed by crustal remelting and overlap a lot with those of the Jiaodong Group and Late Mesozoic magmatic rocks. The  $\delta^{34}\text{S}$  values of the quartz vein-type ores vary in a wide range, roughly consistent with those of intermediate to mafic dikes. The altered rock-type ores exhibit relatively concentrated  $\delta^{34}\text{S}$  values, which are nearly identical to those of the Guojialing- and Linglong-type granites. These findings indicate that there is a certain genetic relationship between gold mineralization

and surrounding rocks. The low  $\delta^{34}\text{S}$  values of the quartz vein-type gold deposits indicate the possible mixing with deep mantle-derived fluids, while the S isotope characteristics of the altered rock-type gold deposits are more contributable to the interactions between fluids and surrounding rocks (Fig. 16).

#### (ii) Pb isotopes

The Linglong gold orefield exhibits stable Pb isotopic composition (Table 7), with  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios ranging from 17.142 to 17.523 (average: 17.319),  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios from 15.406 to 15.594 (average: 15.301), and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios from 37.607 to 38.271 (average: 37.364). The quartz vein-type ores exhibit generally the same Pb isotopic composition as the altered rock-type ores, except that the  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ , and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios of the altered rock-type ores are more stable and vary in narrower ranges. The source characteristic value of Pb isotopes,  $\mu$  ( $^{238}\text{U}/^{204}\text{Pb}$ ), is distributed in a relatively narrow range of 9.230–9.590, with an average of 9.397, higher than the  $\mu$  value of normal lead (8.686–9.238) and mantle-derived lead (7.3–8.0) and close to the  $\mu$  values of crust-derived lead (9.58). This indicates the stable sources of ore-forming materials. The ores exhibit  $\mu$  values close to those of intermediate to mafic dikes (9–9.4; average: 9.2), Guojialing-type granites (9.2–9.86; average: 9.40), Linglong-type granites (8.52–9.51; average: 9.18), and

**Table 6. Sulfur isotopic compositions of the Linglong gold orefield in the Jiaodong Peninsula.**

| Deposit or surrounding rocks                  | $\delta^{34}\text{S}$ value/‰ (*: determined using LA-MC-ICPMS)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Range/‰   | Average/‰ | Sample number | Reference                                                                                                                                        |
|-----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|-----------|---------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Linglong gold orefield/quartz vein type       | 7.8, 7.0, 8.3, 7.8, 7.9, 7.7, 8.3, 7.6, 8.5, 7.5, 7.0, 8.6, 7.2, 6.4, 7.3, 7.4;<br>3.3, 2.9, 3.4, 4.3, 4.5, 4.4, 5.7;<br>(8.3, 7.8, 7.9, 7.4, 7.4, 6.2, 6.3, 6.5, 6.3, 6.1, 8.5, 7.0, 6.3, 6.9, 7.2, 6.4, 6.4, 6.9, 7.2, 4.9, 6.8, 5.3, 7.1, 6.1, 7.9, 6.6, 6.8, 5.8, 5.9, 8.1, 7.3, 6.0, 5.9, 6.4, 6.9;<br>7.7, 8.0, 8.3, 8.1, 8.4, 8.9, 8.6, 7.6, 8.1, 8.5, 9.4, 8.8, 8.1, 7.9, 8.2, 8.4, 8.0, 7.2, 9.4, 8.4, 8.5, 8.0, 8.5, 7.9, 7.4, 7.0, 7.6, 6.7, 7.1, 6.5, 6.3, 9.4, 9.8, 8.8, 8.6, 9.3, 9.5, 8.1, 8.2, 8.6, 8.6, 8.2, 8.4, 8.6, 8.5, 8.2, 9.1, 8.1, 8.3, 8.5, 8.8, 9.2, 7.0, 8.1, 8.2, 9.1, 8.3, 8.2, 8.8, 9.2, 9.6, 8.5, 8.1, 8.0, 8.4, 8.6, 8.9, 5.9, 4.2, 4.0)* | 2.9–9.8   | 7.4       | 23+105*       | Hou ML et al., 2006;<br>Wang L et al., 2010;<br>Lin ZW et al., 2019*;<br>Cheng HY et al., 2019*                                                  |
| Taishang gold field/quartz vein type          | 7.2, 6.8, 7.4, 6.3, 4.5, 5.7, 6.6, 7.8, 8.0, 7.3, 7.2, 6.4, 7.3, 6.2, 6.3, 7.5, 7.9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 4.5–8.0   | 6.8       | 17            | Yang LQ et al., 2016a                                                                                                                            |
| Taishang gold field/altered rock type         | 6.3, 6.8, 7.3, 5.9, 6.4, 7.1, 7.9, 6.8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 5.9–7.9   | 6.8       | 8             |                                                                                                                                                  |
| Shuiwangzhuang gold deposit/Altered rock type | 7.5, 8.0, 7.5, 8.1, 7.0, 8.5, 7.4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 7.0–8.5   | 7.7       | 7             | Li J et al., 2021a                                                                                                                               |
| Jiaodong Group                                | 1.0, 1.5, 1.1, 1.7, 1.3, 1.0; 5.6, 8.2, 10.8, 12.4, 15.4; 6.9, 9.4, 7.8; 1.8, 2.1; 6.1, 7.8, 7.5, 7.0, 7.4, 7.3, 2.2, 1.2, 0.0, 1.7; 7.8, 7.5, 7.0, 7.4, 7.3, 6.1, 2.2, 1.2, 0.0, 1.7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 0.0–15.4  | 5.0       | 36            | Lin ZW et al., 2019;<br>Qiu YS et al., 1992;<br>Zhang C et al., 2014;<br>Tian JP et al., 2020;<br>Huang DY et al., 1994;<br>Wang YW et al., 2002 |
| Jingshan Ggroup                               | 10.7, 9.9, 9.8, 9.3, 9.8, 9.8, 10.0, 8.2, 12.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 8.2–12.0  | 9.9       | 9             | Zhang ZR et al., 1999                                                                                                                            |
| Fenzishan Group                               | 11.3, 13.0, 10.6, 11.4, 13.0, 12.0, 13.6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 10.6–13.6 | 12.1      | 7             | Lin ZW et al., 2019                                                                                                                              |
| TTG series                                    | 2.4, 2.3, 2.8, 3.0, 1.0, 1.6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 1.0–3.0   | 2.2       | 6             | Lin ZW et al., 2019                                                                                                                              |
| Kunyushan granite                             | 15.3, 3.8; 14.9, 8.5, 3.9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 3.8–15.3  | 9.3       | 5             | An JT et al., 1988;<br>Zhang SG et al., 1990                                                                                                     |
| Guojialing granite                            | 6.0, 7.2, 7.8, 6.4, 9.2, 16.0, 7.4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 6.0–16.0  | 8.6       | 7             | Zhang C et al., 2014                                                                                                                             |
| Linglong granite                              | 7.9, 8.2, 8.3, 8.4, 8.2, 8.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 7.9–8.4   | 8.1       | 6             | Mao JW et al., 2005                                                                                                                              |
| Intermediate to mafic dike                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 5.3–10.8  | 6.9       | 6             | Huang DY et al., 1994                                                                                                                            |

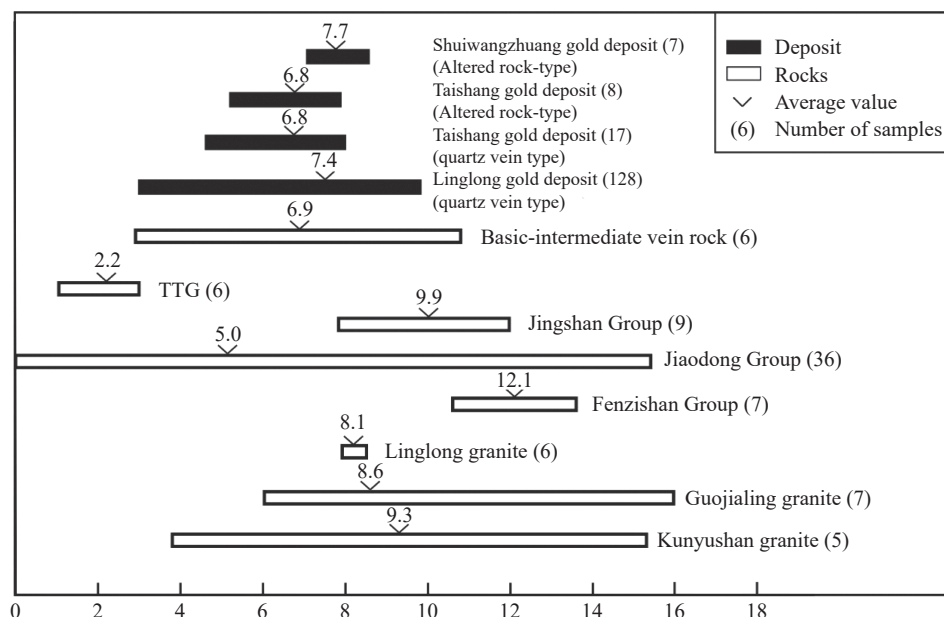


**Fig. 16.** Diagrams showing the sulfur isotopic compositions of typical gold deposits and primary ore-hosting surrounding rocks in the Linglong gold orefield, Jiaodong Peninsula.

the Jiaodong Group (8.7–9.4; average: 9.1; Ma GG et al., 2011), especially intermediate to mafic dikes and Guojialing-type granites.

As depicted in the discriminant diagram of the tectonic setting (Zartman RE et al., 1981; Fig. 17), samples fell in the zone of the lower crust, consistent with the projection range of Pb isotope data of Jiaodong gold deposits. Both findings indicate the characteristics of lead derived from the lower crust.

The comprehensive analysis of the S and Pb isotopic compositions reveals that the ore-forming materials primarily originate from the lower crust, supplemented by some mantle-derived components. The ores exhibit main isotopic compositions consistent with the direct ore-hosting surrounding rocks. Given that the Linglong- and Guojialing-type granites were mainly formed by the partial melting of Early Precambrian metamorphic rocks, it can be inferred that the ore-forming materials were predominantly derived from the metamorphic basement of the Jiaodong Peninsula, i.e., the Early Precambrian accretionary metamorphic complexes activated and reconstructed during the Mesozoic (Yang LQ et al., 2014b).

### 5.3. Gold precipitation mechanisms

As revealed by the simulation calculations of changes in the sulfide mineral assemblages and studies on the *in-situ* S isotopes of fluid inclusions and pyrite, the water-rock interactions and fluid immiscibility reduce the total S content in ore-forming fluids in Jiaodong gold deposits, making gold-sulfur complexes unstable and further leading to gold precipitation (Li XH et al., 2018; Feng K et al., 2020; Zhang YW et al., 2020; Hu HL et al., 2020a, 2020b). The temperature drop during water/rock interactions and fluid mixing leads to the supersaturation and precipitation of gold

in the ore-forming fluids (Cai YC et al., 2018), while pressure fluctuations serve as the main cause of fluid immiscibility (Yang LQ et al., 2016a, b; Liu JC et al., 2018). For the quartz vein-type gold deposits, the fluid immiscibility caused by periodic fluid pressure fluctuations is the key mechanism behind the effective precipitation of visible gold (Sai SX et al., 2020). For the altered rock-type gold deposits, intense water/rock interactions between ore-forming fluids and surrounding rocks alter the physical and chemical properties of ore-forming fluids and induce gold precipitation (Fan HR et al., 2003; Wen BJ et al., 2015; Xu WG et al., 2016). Additionally, the effects of water/rock interactions on hydrothermal alteration and gold mineralization vary with the temperature. At higher temperatures (above 400°C), water/rock interactions have minor effects on gold precipitation, which is associated with pyrrhotite rather than pyrite. At low temperatures (about 300°C), gold mineralization is directly related to pyrite precipitation (Xu WG et al., 2016).

### 5.4. Metallogenic mechanisms and modes

The Linglong gold orefield, with the Linglong pluton as ore-hosting geological bodies, hosts many mafic, intermediate to mafic, and acid veins, with the Guojialing and Aishan plutons exposed in the northeast. These magmatic rocks, formed during the Late Mesozoic, are closely associated with the gold deposits temporally and spatially. The Linglong pluton is composed of granites formed by crustal remelting at 160–150 Ma, whereas the Guojialing pluton comprises granites formed by the crystallization differentiation of mixed crust- and mantle-derived magmas at 130–125 Ma. Both the Linglong and Guojialing plutons exhibit the geochemical characteristics of adakites. The Aishan pluton, with isotopic ages ranging from 125 Ma to 114 Ma (Goss S et al., 2010;

**Table 7. Lead isotopic compositions and their characteristic parameters of the Linglong gold orefield.**

| Mineralization type | Ore block (vein) | $^{206}\text{Pb}/^{204}\text{Pb}$ | $^{207}\text{Pb}/^{204}\text{Pb}$ | $^{208}\text{Pb}/^{204}\text{Pb}$ | $\mu$ | $\Delta\beta$ | $\Delta\gamma$ | Data sources         |
|---------------------|------------------|-----------------------------------|-----------------------------------|-----------------------------------|-------|---------------|----------------|----------------------|
| Quartz vein         | No. 50 vein      | 17.238                            | 15.472                            | 37.883                            | 9.37  | 9.26          | 11.02          | Ma GG et al., 2011   |
|                     | No. 47 vein      | 17.481                            | 15.519                            | 38.04                             | 9.43  | 12.33         | 15.21          |                      |
|                     | Dakaitou         | 17.411                            | 15.506                            | 38.053                            | 9.41  | 11.48         | 15.56          |                      |
|                     | Houdi            | 17.3                              | 15.465                            | 37.892                            | 9.35  | 8.81          | 11.26          | Li ZL et al., 1993   |
|                     | Fushan           | 17.358                            | 15.567                            | 38.213                            | 9.55  | 15.46         | 19.83          |                      |
|                     | No. 61 vein      | 17.206                            | 15.448                            | 37.829                            | 9.33  | 7.7           | 9.58           |                      |
|                     |                  | 17.27                             | 15.442                            | 37.808                            | 9.31  | 7.31          | 9.02           |                      |
|                     | Xishan           | 17.195                            | 15.422                            | 37.731                            | 9.28  | 6             | 6.97           |                      |
|                     |                  | 17.379                            | 15.588                            | 8.271                             | 9.59  | 16.83         | 21.38          |                      |
|                     | No. 51 vein      | 17.337                            | 15.46                             | 37.866                            | 9.33  | 8.48          | 10.57          |                      |
|                     | No. 108 vein     | 17.171                            | 15.414                            | 37.691                            | 9.27  | 5.48          | 5.9            |                      |
|                     |                  | 17.267                            | 15.446                            | 37.785                            | 9.31  | 7.57          | 8.41           |                      |
|                     |                  | 17.292                            | 15.535                            | 38.061                            | 9.5   | 13.37         | 15.77          |                      |
|                     | No. 56 vein      | 17.215                            | 15.437                            | 37.787                            | 9.31  | 6.98          | 8.46           | Yang ZF et al., 1998 |
|                     | No. 55 vein      | 17.233                            | 5.5                               | 38.008                            | 9.43  | 11.09         | 14.36          |                      |
|                     |                  | 17.169                            | 15.415                            | 37.691                            | 9.27  | 5.54          | 5.9            |                      |
|                     |                  | 17.142                            | 15.425                            | 37.72                             | 9.29  | 6.2           | 6.67           |                      |
|                     |                  | 17.275                            | 15.406                            | 37.731                            | 9.23  | 4.96          | 6.97           |                      |
|                     |                  | 17.203                            | 15.43                             | 37.751                            | 9.29  | 6.52          | 7.5            |                      |
|                     |                  | 17.274                            | 15.548                            | 38.154                            | 9.53  | 14.22         | 18.25          |                      |
|                     | No. 61 vein      | 17.34                             | 15.573                            | 38.151                            | 9.57  | 15.85         | 18.17          |                      |
|                     | No. 83 vein      | 17.18                             | 15.423                            | 37.703                            | 9.28  | 6.07          | 6.22           |                      |
|                     | Linglong         | 17.403                            | 15.507                            | 38.03                             | 9.42  | 11.55         | 14.95          | Zhou XH et al., 2002 |
|                     |                  | 17.262                            | 15.487                            | 37.93                             | 9.4   | 10.24         | 12.28          |                      |
|                     |                  | 17.242                            | 15.488                            | 37.917                            | 9.41  | 10.31         | 11.93          |                      |
|                     |                  | 17.367                            | 15.547                            | 38.122                            | 9.51  | 14.16         | 17.4           |                      |
|                     |                  | 17.461                            | 15.539                            | 38.069                            | 9.47  | 13.63         | 15.99          |                      |
|                     |                  | 17.477                            | 15.542                            | 38.077                            | 9.48  | 13.83         | 16.2           |                      |
|                     |                  | 17.523                            | 15.594                            | 38.237                            | 9.58  | 17.22         | 20.47          |                      |
|                     | Linglong-Xishan  | 17.327                            | 15.483                            | 37.992                            |       |               |                | Lin ZW et al., 2019  |
|                     |                  | 17.410                            | 15.516                            | 38.084                            |       |               |                |                      |
|                     |                  | 17.361                            | 15.497                            | 38.006                            |       |               |                |                      |
|                     |                  | 17.408                            | 15.502                            | 38.044                            |       |               |                |                      |
|                     |                  | 17.321                            | 15.519                            | 38.027                            |       |               |                |                      |
|                     |                  | 17.204                            | 15.484                            | 37.871                            |       |               |                |                      |
|                     |                  | 17.252                            | 15.482                            | 37.934                            |       |               |                |                      |
|                     |                  | 17.306                            | 15.495                            | 37.933                            |       |               |                |                      |
|                     |                  | 17.298                            | 15.481                            | 37.648                            |       |               |                |                      |
|                     |                  | 17.299                            | 15.486                            | 37.607                            |       |               |                |                      |
| Altered rock        | Lingnan          | 17.337                            | 15.502                            | 38.002                            |       |               |                | Lin ZW et al., 2019  |
|                     |                  | 17.331                            | 15.493                            | 37.818                            |       |               |                |                      |
|                     |                  | 17.329                            | 15.493                            | 37.765                            |       |               |                |                      |
|                     |                  | 17.301                            | 15.478                            | 37.614                            |       |               |                |                      |
|                     |                  | 17.336                            | 15.505                            | 38.000                            |       |               |                |                      |
|                     |                  | 17.335                            | 15.511                            | 37.974                            |       |               |                |                      |
|                     |                  | 17.340                            | 15.500                            | 38.000                            |       |               |                |                      |
|                     |                  | 17.423                            | 15.533                            | 38.081                            |       |               |                |                      |
|                     |                  | 17.458                            | 15.578                            | 38.204                            |       |               |                |                      |
|                     |                  | 17.361                            | 15.508                            | 38.003                            |       |               |                |                      |
|                     |                  | 17.389                            | 15.512                            | 38.030                            |       |               |                |                      |
|                     |                  | 17.374                            | 15.501                            | 37.958                            |       |               |                |                      |
|                     |                  | 17.430                            | 15.533                            | 38.107                            |       |               |                |                      |

Song MC et al., 2020b), consists of mixed crust- and mantle-derived granites dominated by a crustal origin, manifesting the geochemical characteristics of volcanic arc granites. The diorite veins in the Linglong gold orefield have K-Ar isotopic ages ranging from 132.5 Ma to 122.6 Ma (Yang JH et al.,

2004), and the granite porphyries exhibit a SHRIMP U-Pb age of 120 Ma (Wang LG et al., 1998). The early mafic veins possess the typical geochemical characteristics of island arcs, with magmas originating from the partial melting of the ancient enriched lithospheric mantle metasomatized by fluid-

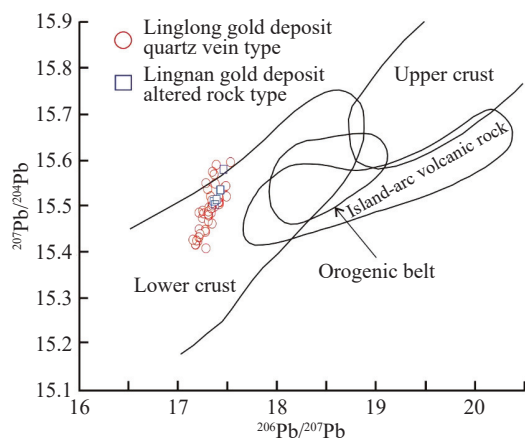


**Fig. 17.** Discriminant diagram for the tectonic environment of lead isotopes in ores in the Linglong gold orefield (the base map modified from Zartman RE and Doe BR, 1981).

rich melts. In contrast, the late mafic veins have the geochemical characteristics of oceanic island basalts, suggesting that they might be derived from the partial melting of the lithospheric mantle (Ma L et al., 2014; Deng J et al., 2019). The spatio-temporal correlation between magmatic activity and gold mineralization indicates genetic connections between the metallogenic progress and the diagenesis- and mineralization-related tectonic settings.

During the Late Jurassic, the extensive crustal remelting in the Jiaodong Peninsula led to the formation of Linglong-type granites. It is generally established that S-type granites were formed by the anatexis arising from intense crustal shortening and thickening in a compressive tectonic environment (Wang DZ et al., 2002). The formation of extensive Linglong S-type granites implies that the Jiaodong region experienced tectonic compression, shortening, and transformations, as well as crustal thickening, during the Late Jurassic. This event is related to the post-collision compression between North China and Yangtze plates and the subduction of the Paleo-Pacific or Izanagi plate toward Eurasia (Zhang YQ et al., 2007). During the Cretaceous, the ancient North China Craton was destroyed by the subduction and retreat of the Paleo-Pacific Plate, causing substantial lithospheric and crustal thinning (Zhu RQ et al., 2011). Meanwhile, extensive magmatic activity and extensional tectonics occurred in the eastern North China Craton (including the Jiaodong region), leading to the formation of a thermal uplifting-extensional tectonic system (Song MC et al., 2018b, 2021b; Li J et al., 2021b). During the Cretaceous, the crust in the Jiaodong region was uplifted rapidly. Studies have shown that the Linglong, Guojialing, and the Aishan plutons were emplaced at depths from 10 km to 15 km (Zhang HF et al., 2006), about 13 km (Dou JZ et al., 2015), and less than 3.5 km (Zhang HF et al., 2006), respectively. This suggests that the Linglong and Guojialing plutons experienced intense uplift and denudation during the emplacement of the Aishan pluton. Over a period of 40 Ma from its emplacement at about 155 Ma to the emplacement of the Aishan pluton at about 115 Ma, the Linglong-type granites underwent uplift and denudation with thicknesses of 7 km and

above. In contrast, the Guojialing pluton experienced uplift and denudation at a depth of up to 10 km within a period of about 10 Ma (Dou JZ et al., 2015), which has been reduced to 4 km at maximum since 110 Ma. Hence, significant crustal uplift occurred in the Jiaodong region at around 120 Ma. The large-scale activity of crust- and mantle-derived mixed magmas during the Early Cretaceous provided thermodynamic conditions, fluid migration channels, and partial fluid sources for ore-forming fluid activity. The rapid uplift of magmas strongly propped up shallow surrounding rocks, leading to the emergence of numerous tensile structures in the Linglong-type granites formed earlier and the formation of detachment faults along weak structural planes such as the boundaries between Linglong-type granites and Early Precambrian metamorphic rocks. All these created favorable spaces for the enrichment and mineralization of ore-forming fluids. Within the dominant detachment fault zones, ore-forming fluids flowed slowly along the interstices of loose cataclasites, forming altered rock-type gold deposits under the action of water-rock interactions. On the footwall of the dominant detachment faults, ore-forming fluids filled fractures via the action of pumping, forming quartz vein-type gold deposits. Within the dominant detachment faults, as the ore-forming fluids flowed from deep to shallow parts through the fault plane parts with sharply reduced dip angles, the fluid pressure significantly reduced, followed by gold unloading and mineralization in gentle fault segments (Fig. 18). Consequently, a stepped metallogenic mode has been formed (Song MC et al., 2012).

Overall, the gold deposits in the Jiaodong region were formed in a back-arc extensional setting resulting from the subduction of the Pacific Plate (Yang LQ et al., 2014b, 2018) at the peak of the significant lithospheric thinning in eastern China, the destruction of the North China Craton, and continental rifting. The back-arc extensional setting, differing from the settings of the collisional orogenic belts, subduction accretionary wedges, and intracontinental orogenic belts of typical orogenic gold deposits and being distinguished from the environment within a convergent plate of a gold deposit associated with intrusive rocks, was formed by the thermal uplifting-extensional mineralization. The lithospheric thinning and crust-mantle interactions during the Late Mesozoic induced extensive magmatic and fluid activity. The fluids, along with the ore-forming materials they extracted from the lower crust, formed a uniform ore-forming fluid pool. Concurrently, the crustal extension and the rapid magma ascent led to the formation of extensional structures in the shallow crust. As a result, the ore-forming fluids migrated to the detachment fault system of the middle-to-upper crust, culminating in precipitation mineralization.

##### 5.5. Geological-geophysical prospecting model for deep gold deposits

A conventional prospecting method for superficial gold deposits in the Jiaodong region involves the following steps:

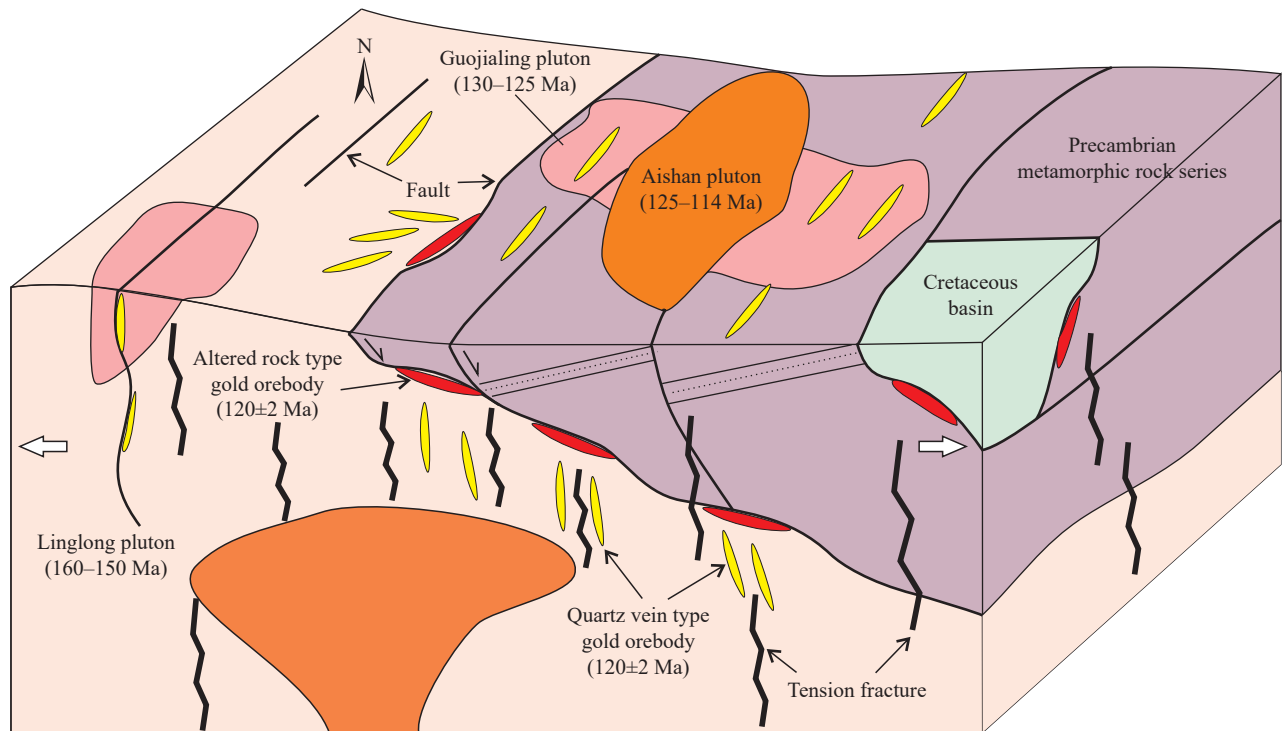


**Fig. 18.** Metallogenic modes of the Linglong gold orefield.

(1) Fault structures and mineralized alteration zones are delineated through geological mapping; (2) anomalies are identified using induced-polarization (IP) composite profiling, IP sounding, and soil and rock geochemical explorations; (3) prospecting centering on favorable metallogenic structures and geophysical and geochemical anomalies is performed through reconnaissance surveys. In summary, this method allows for prospecting centering around metallogenic structures and anomalies (Li SX et al., 2007). The conventional geological-geophysical prospecting model for gold deposits, functioning based on the electrical property contrast between the mineralized alteration zones of gold and their surrounding rocks, delineates anomalies using IP-dominated geophysical methods, and then prospecting is achieved by discovering anomalies through drilling (Li SX et al., 2007). However, deep gold orebodies, overlain by rock strata with thicknesses of hundreds of meters and exhibiting relatively small scales, which led to strongly suppressed anomaly signals, cannot be detected using the conventional method for superficial gold deposits.

A metallogenic geological mode serves as an important basis for deep prospecting. Based on the ore-controlling regularity of faults and the physical properties of rocks, as well as extensive explorations and repeated tests, this study proposed a deep stepped prospecting model consisting of ore-hosting faults, high-precision geophysical exploration, and a stepped metallogenic pattern. This model allows for the exploration of altered rock-type gold deposits by detecting ore-hosting faults' steps with changes in fault dip angles using methods such as frequency-domain electromagnetics and reflection seismic exploration. In other words, this model involves determining the depth extent and changes in deep

attitudes of ore-hosting fault zones through high-precision fine-scale geophysical exploration, delineating deep targets of gold deposits based on the stepped metallogenic pattern, and then confirming the target areas through deep drilling. The geophysical anomaly indicators for the steps of deep ore-hosting faults that can be identified jointly using methods like gravity and magnetic surveys, controlled source audio-frequency magnetotellurics (CSAMT), magnetotelluric sounding (MT), wide-field electromagnetic method (WFEM), and reflection seismic exploration include: (1) Gravity and magnetic values: The linear gradient zones with gravity anomalies (especially the parts with sudden changes) and the beadlike/elongate zones with high-amplitude magnetic anomalies (especially the turning parts of magnetic anomaly contours) are metallogenic favorable parts; (2) Resistivity: Zones with high- and low-amplitude resistivity anomalies serve as indicators of fracture zones, with U- or lying-S-shaped apparent resistivity contours formed by their synchronous downward bending indicate favorable parts for the occurrence of deep gold deposits; (3) Polarizability: The high-amplitude anomalies of apparent polarizability, apparent charging rate, and time constant, as well as the low-amplitude anomalies of correlation coefficients, indicate favorable parts for the occurrence of gold orebodies; (4) Seismic reflected waves: Faults exhibit wavy reflected waves on fault planes, with the turning parts and parts with decreasing dip angles of fault zones, as reflected by reflected waves, are favorable parts for the occurrence of deep gold deposits (Song MC et al., 2021c).

Based on the aforementioned geological-geophysical prospecting model for deep gold deposits, geophysical surveys using methods such as CSAMT, spectral induced

polarization (SIP), and gravity and magnetic exploration were conducted along the section of the No. 42 exploration line in the Shuiwangzhuang mining area (Fig. 19). These surveys allow for the discovery of the deep features of the Potouqing and Jiuqujiangjia faults and the identification of deep ore-hosting parts (Song MC et al., 2021c). The obtained gravity and magnetic anomalies reflected the Potouqing and Jiuqujiangjia faults, as well as the wide alteration zone between them (Figs. 19a, b). The magnetic anomalies to the east of the No. 8000 survey point (the hanging wall of the fault zone) exhibited stable, gentle curves with low values, reflecting the Early Precambrian metamorphic basement. The magnetic anomalies to the west of the No. 8000 survey point changed dramatically, with two associated positive and negative magnetic anomalies reflecting fault structures. From west to east, the section exhibited a secondary gravity high, followed by a gradual decrease in the gravity anomaly amplitude. This indicates the presence of remnant Early

Precambrian metamorphic rocks in the central part of the section, with the Linglong pluton found toward the west. The surface in the western part of the section witnesses the distribution of Linglong-type monzogranites, with the moderate-amplitude gravity anomalies indicating the possible presence of high-density metamorphic rocks in the deep part of the Linglong pluton. As illustrated by the cross-sectional diagram of CSAMT-derived resistivity contours, the gradient zones with increasing resistivity contour values signify the emergence of a fault alteration zone (Fig. 19c). This zone exhibited a dip direction of SE and a gentle dip angle, characteristic of the deep attitude of the fault alteration zone. As inferred from the stepped metallogenic pattern, the parts with significant fluctuations, increasing spacing, sudden changes, and gentle dips of resistivity contours are metallogenic favorable parts. On the cross-sectional diagram of SIP-derived resistivity contours, the high- and low-resistivity gradient zones that directionally extend are

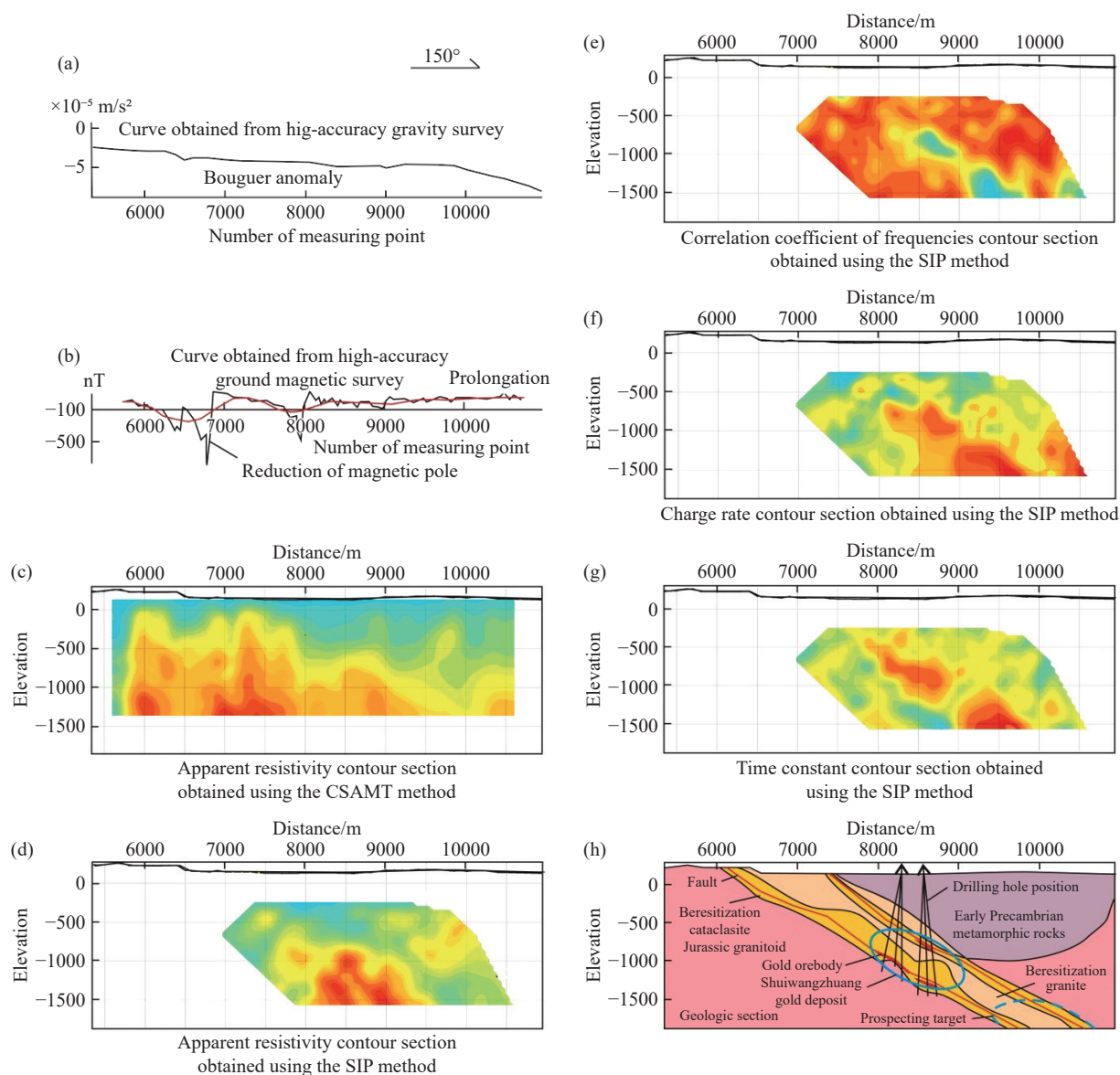


**Fig. 19.** Comprehensive geological-geophysical section of the No. 42 exploration line in the Shuiwangzhuang mining area (after Song MC et al., 2021c).

indicative of fault zones. Meanwhile, the turning points of the gradient zones, as well as the parts with sudden changes in the extension direction of the zones are parts with gentle fault dip angles, serving as favorable sites for mineralization (Fig. 19d). As displayed by contours of other SIP-derived parameters, the alteration zones of the Potouqing and Jiuqujiangjia faults exhibit anomalies of high charging rates, high time constants, and low-frequency correlation coefficients (Figs. 19e–g). These anomalies of the three parameters well aligned, with the locations and extension trends of the anomaly zones indicating the deep characteristics of the fault alteration zone. In the areas surveyed previously, the ore-bearing zone constrained at depths ranging from 1000 m to 1500 m along the No. 42 exploration line coincides completely with the above-stated polarizability anomalies (Fig. 19h). Furthermore, the high-amplitude polarizability anomalies in the area between the Nos. 9000 and 9500 survey points do not close within the exploration depth range. Hence, this area was delineated as a deep target area. Late deep drilling verification unveiled thick, large-scale gold orebodies at a depth of about 2000 m.

## 6. Conclusions

(i) The Linglong gold orefield primarily exhibits two mineralization types: The quartz vein type and the altered rock type. The altered rock-type deposits are governed by generally gently dipping main faults, whereas the quartz vein-type deposits occur in the steeply dipping tensional fissures in the footwall of the main faults. The gold orefield hosts cumulative proven gold resources of 916 t. Multiple altered rock-type gold deposits in the orefield, previously considered to be independent, are found to jointly constitute a continuous giant gold deposit—the Taishang-Shuiwangzhuang giant gold deposit in actuality, with gold resources of more than 600 t.

(ii) The orebodies of the Taishang-Shuiwangzhuang giant gold deposit governed by main faults are characterized by segmental mineralization enrichment along both their strikes and dip directions, forming three mineralization enrichment zones within a vertical range of 2500 m. Faults dictating the deposit occurrence exhibit a wavy distribution due to their constantly varying dip angles, with the mineralization enrichment zones primarily occurring in parts with changes in fault dip angles. The fluctuations in fluid pressure caused by changes in fault dip angles led to a stepped metallogenic pattern of the gold orebodies.

(iii) The quartz vein- and altered rock-type gold deposits, despite differing significantly in orebody characteristics, ore-hosting parts, and ore/gold mineral characteristics, share roughly identical H-O-S-Pb isotopic compositions and fluid inclusion characteristics. This suggests that both types of deposits were formed due to different fluid-structure coupling relationships at different structural locations or in sections with different structural properties in the same structural system.

(iv) The lithospheric mantle upwelling and craton

destruction during the Early Cretaceous resulted in extensive activity of crust- and mantle-derived mixed magmas in the Jiaodong region, which provides thermodynamic conditions, migration pathways, and partial fluid sources for ore-forming fluid activity. The rapid magma ascent led to the formation of detachment faults and associated tensile structures in the shallow crust, creating favorable spaces for fluid accumulation and mineralization. In fault parts where dip angles change sharply and then reduce, the fluid pressure fluctuated more significantly, leading to gold precipitation and mineralization.

(v) The geological-geophysical prospecting model for gold deposits in depth, with key factors including metallogenic structural zones, high-precision geophysical exploration, and a stepped metallogenic pattern, serves as an effective method for deep prospecting of altered rock-type gold deposits.

## CRedit authorship contribution statement

Jie Li and Ming-chun Song conceived the ideas. Wen Zhang, Ji-lei Gao, Zhen-liang Yang, Yong-qing Wang, and Jia-meng Fan participated in field surveys. Xiu-zhang Li, Mei-yun Wang, Li-peng Zhang, Shi-yong Li, Huai-hong Wang, and Yu-xin Xiong conducted data processing. Wen-xuan Hu and Tian-hui Bai reviewed and edited the manuscript.

## Declaration of competing interest

The authors declare that they have no conflicts of interest.

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