Article

A Geological-Geophysical Prospecting Model for Deep-Seated Gold Deposits in the Jiaodong Peninsula, China

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Abstract: The North China Craton is one of China's major gold-producing areas. Breakthroughs have been continually made in deep prospecting at depths of 500–2000 m in the Jiaodong Peninsula, and geophysical methods have played an important role. Given that the geophysical signals of deep-seated gold deposits are difficult to detect, due to their thick overburden layers, conventional geophysical methods are not suitable for deep prospecting. Therefore, this study upgrades the geological-geophysical prospecting model, which is based on the deep metallogenic model and geophysical method of large exploration depths. Based on the analysis of the metallogenic geological factors of the altered-rock-type gold deposits in the fracture zones of the Jiaodong Peninsula, this study proposes that the gold deposits are controlled by large-scale faults, generally occur near the contact interfaces between the Early Precambrian metamorphic rock series and Mesozoic granitoids, and exhibit a stepped metallogenic model. This model then becomes the prerequisite and basic condition for deep prospecting by geophysical methods. For this reason, the traditional geophysical model, which focuses on the exploration of shallow mineralization anomalies, is transformed into a comprehensive multi-parameter geological-geophysical qualitative prospecting model highlighting the exploration of ore-controlling structural planes. The model adopts various frequency domain methods (e.g., CSAMT, AMT, WFEM), reflection seismology, and other methods to detect the deep geological structure. The characteristics of parameters such as gravity and magnetism, resistivity, polarizability, and the seismic reflection spectrum are applied to identify the ore-controlling fault location and dip angle change, and to estimate the ore-bearing location according to the stepped metallogenic model. The prospecting demonstration of deep-seated gold deposits in the Shuiwangzhuang mining area indicates the effectiveness of the comprehensive model. The comprehensive deep prospecting model effectively solves the problem of deep prospecting of gold deposits controlled by faults, promotes the great breakthrough of deep prospecting in the Jiaodong Peninsula, and provides an important technology demonstration for deep prospecting throughout China.

Keywords: deep-seated gold deposit; geological-geophysical prospecting model; geophysical prospecting indicator; stepped metallogenic model; ore-controlling fault; Jiaodong Peninsula

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1. Introduction

With its accumulated proven gold resources of greater than 5000 tonnes, the Jiaodong Peninsula ranks as the world's third largest gold concentration area. In addition, it is also the area which leads in carrying out deep prospecting and achieving breakthroughs

in China. Deep prospecting in the Jiaodong Peninsula began in the 20th century, and view breakthroughs have been achieved in the 21st century. During the exploration of deep-seated gold deposits in the Sizhuang mining area in Laizhou City from 2002 to 2006, a total of 51.83 tonnes of gold reserves was detected at borehole depths in the range of 625.16–1015.26 m, which is the first significant achievement ever made in deep prospecting in China. Since then, deep-seated super-large gold deposits have been successively detected under non- or weakly mineralized sections with a vertical thickness of 150–200 m below the shallow gold deposits such as Jiaojia and Matang. After this time, breakthroughs have been continually made in deep prospecting in the Jiaodong Peninsula. These are dominated by more than 40 gold deposits of medium-scale and above, at depths of 500–2000 m, and over 3000 tonnes of newly added gold reserves have been obtained. Furthermore, it has been revealed that many shallow gold deposits in the Sanshandao and Jiaojia areas, which had been previously considered to be independent, are in fact interconnected into one deposit in the deep area. With their total reserves exceeding 1000 tonnes, these two areas are the only kiloton class super-giant gold deposits in China [1].

With the intensification of mineral exploration and development, the amounts of residual superficial metal mineral resources have increasingly decreased. Therefore, deep prospecting has become an important direction for mineral resource exploration in developed countries. However, due to the high burial depth and weak information of deep mineral resources reflected on the ground surface, it is difficult to obtain information regarding deep mineralization by implementing conventional techniques such as surface geological exploration, geophysical exploration, geochemical exploration, and remote sensing. For this reason, exploration technology has become a key factor restricting deep prospecting. The difficulty with deep prospecting lies in how to break through vertical non- or weakly mineralized intervals under the natural pinch-out of superficial ores, so as to obtain effective information regarding the deep ore-hosting locations. Therefore, it is necessary to deepen the research on the deep metallogenic regularity and ore-controlling factors and explore new prospecting methods.

Previous studies have mainly focused on the systematic summary of the application of geophysical techniques in shallow gold prospecting [2]. Although some studies have been carried out regarding the geophysical methods for deep prospecting in the Jiaodong Peninsula [3–5], the geophysical methods for deep prospecting there have yet to be comprehensively and systematically analyzed. In particular, deep prospecting using geophysical-geological methods combined with geological methods has yet to be thoroughly studied. All of these have restricted the effective application of geophysical methods in deep prospecting and the development of geophysical techniques [6–15]. This paper analyzes the occurrence regularity of deep-seated gold deposits and the prerequisite of geophysical prospecting and proposes the geological-geophysical prospecting model for deep prospecting of the altered-rock-type gold deposits in fracture zones based on effective geophysical methods adopted in deep prospecting in the Jiaodong Peninsula. Next, it discusses the application principles of the prospecting model and the applicability of relevant methods. The purposes of the paper are to deepen the research on deep prospecting methods, and to provide effective techniques for promoting the implementation of the prospecting strategy of “prospecting deep deposits” in East China.

2. Overview of Metallogenic Geological Background and Prospecting Methods of Superficial Gold Deposits

2.1. Overview of Geology and Gold Mineralization in the Jiaodong Peninsula

The Jiaodong Peninsula lies on the southeastern margin of the North China Craton and at the northeastern end of the Dabie-Sulu ultrahigh pressure (UHP) metamorphic belt, with the Jiaobei and Weihai terranes in the western and eastern parts of the area, falling within the North China Craton and Sulu UHP metamorphic belt, respectively. In addition, the Jiaolai Basin is superimposed on the Jiaobei terrane and the southern part of the Weihai terrane (Figure 1). The Jiaobei terrane mainly consists of Neoproterozoic granite-greenstone belts and Paleoproterozoic-Neoproterozoic metamorphic strata, whereas the Weihai terrane

is mainly composed of Neoproterozoic granitic gneiss bearing UHP eclogites, and the Jiaolai Basin mainly includes Cretaceous volcanic-sedimentary rock series. Jurassic-Cretaceous granitic intrusive rocks are widely emplaced throughout the Jiaobei and Weihai terranes, whereas a small number of Triassic granitoids are only exposed in the Weihai terrane. Faults are highly developed in the Jiaodong Peninsula, among which the NE-NNE-trending faults are the most developed, followed by the nearly EW-NEE-trending faults. Furthermore, the EW-trending faults are sporadically exposed on the ground surface. The gold deposits found in the Jiaodong Peninsula are mainly controlled by the NE-NNE faults, including the Sanshandao, Jiaojia, Zhaoping, Xilin-Douya, and Jinniushan faults.

Figure 1. Regional geological sketch and gold deposit distribution of the Jiaodong Peninsula [16]. 1—Quaternary; 2—Cretaceous; 3—Paleoproterozoic and Neoproterozoic; 4—Neoproterozoic bearing eclogite granitic gneiss; 5—Archean granite-greenstone belt; 6—Cretaceous Laotian granite; 7—Cretaceous Weideshan granite; 8—Cretaceous Guojialing granite; 9—Jurassic Linglong granite; 10—Triassic granitoids; 11—Geological boundary of conformity/unconformity; 12—Fault; 13—Shallow gold deposits (very large and large/medium-scale and small); 14—Deep-seated gold deposits (very large and large/medium-scale and small); 15—Gold deposit of altered-rock-type/quartz-vein-type/alterred-breccia-type.

There are more than 200 gold deposits with proven resources present in the Jiaodong Peninsula, with gold resources of greater than 5000 tonnes. The gold deposits found in the area are mainly distributed in and around the Jiaobei terrane. The gold mineralization types in the gold deposits mainly include the altered rock type in the fracture zones and quartz vein type, along with a small amount of altered breccia type, altered conglomerate type, interlayer decollement and detachment zone type, and pyrite-carbonate vein type. The ore-hosting surrounding rocks mainly include Jurassic Linglong granite, Cretaceous Guojialing granite, and Early Precambrian metamorphic rocks. In addition, a small number of gold deposits also occur in the Cretaceous Laiyang Group at the bottom of the Jiaolai Basin. The tectonic magmatic background related to gold mineralization in the Jiaodong Peninsula during the late Mesozoic has been studied extensively by previous researchers [17–22]. In addition, deep prospecting carried out since the beginning of the 21st century has led to the discovery of more than 3000 tonnes of proven gold resources at a depth range of

600–2000 m in deep deposits, exceeding the previously proven gold resources at depths of 500 m and less.

2.2. Prospecting Methods of Superficial Gold Deposits

The prospecting methods of superficial deposits used in the Jiaodong Peninsula mainly include geological, geochemical, and geophysical methods. Among them, geological methods mainly serve to delineate ore-prospecting target areas or directly discover orebodies according to ore-bearing regularity and prospecting indicators. Based on a large number of studies on gold mineralization [23–34], the main ore-bearing regularity and prospecting indicators are proposed as follows: the ore-bearing regularity of faults; the altered mineral indicators characterized by pyrite sericites and quartz veins; the equal-distance distribution laws of deposits; the laws of deposit paragenesis and ore deposit type zoning; and the pitch, pinch-out, and reappearance and arrangement laws of the orebodies.

Geochemical methods include the geochemical surveys of secondary and primary halos. The geochemical survey of secondary halos has played an important role in regional metallogenetic prediction and target area selection in the Jiaodong Peninsula. Its objectives are to delineate the geochemical anomalies of gold and the elements associated with gold mineralization, and to select ore-prospecting target areas through 1:200,000 and 1:50,000 stream sediment surveys and 1:10,000 soil surveys. The geochemical survey of primary halos mainly seeks to delineate metallogenetic target areas, and provide bases for the arrangement of exploration engineering through 1:50,000 bedrock geochemical prospecting surveys and 1:10,000 and 1:5000 surveys of bedrock geochemical prospecting area and sections. The indicative elements used for the gold prospecting in geochemical exploration in the Jiaodong Peninsula mainly include Au, Ag, As, Cu, Pb, Zn, Sb, Bi, Hg, and Mo, and gold orebodies can be effectively discovered based on the zoning of primary halos of these 10 elements. In greater detail, the inner-zone, mesozone, and outer-zone elements of the horizontal zones in the primary halos are as follows: The inner-zone elements include Au, Ag, As, and Bi, and exhibit strong positive anomalies of Au, Ag, As, and Bi and weak positive anomalies of Cu, Pb and Zn. The mesozone elements exhibit strong positive anomalies of Cu, Pb, and Zn and weak anomalies of Au, Ag, As, and Bi. Finally, the outer-zone elements show positive anomalies of Hg and Mo and weak anomalies of Au, Ag, and Bi [2].

Electrical prospecting is the most common geophysical method used for gold prospecting in the Jiaodong Peninsula. Among the electrical prospecting methods, the resistivity method is mainly used to search and trace the high-resistance orebodies of quartz-vein-type, whereas the induced polarization method is mainly used to identify the sulfide-rich altered rock orebodies with polarizability of 2–5% [2]. The altered-rock-type gold deposits in fracture zones in the Jiaodong Peninsula are controlled by large-scale regional faults. The hanging and foot walls of the ore-controlling faults consist of Early Precambrian metamorphic rock series and Late Mesozoic granites, respectively, and the two differ greatly in terms of magnetism. Therefore, magnetic prospecting is also commonly used for gold prospecting in the area. Gravity prospecting is mainly used to study regional geological structures and determine the locations and scale of faults. A tongue-shaped irregular gravity gradient zone extending westwards is considered an important geophysical indicator for the prospecting of altered-rock-type gold deposits in the fracture zones of the Jiaodong Peninsula [2].

2.3. Geological-Geophysical Prospecting Model of Superficial Gold Deposits

Geophysical methods have played an important role in the prospecting of superficial gold deposits in the Jiaodong Peninsula, and some gold deposits with thin overburden layers have been discovered there based on the anomalies revealed by geophysical methods. The geological-geophysical prospecting model established for the Jiaojia type gold deposits (the altered-rock-type in the fracture zones) is briefly described as follows [2].

2.3.1. Physical Property Models of Geological Bodies Related to Gold Deposits

- (1) Low-polarization, high-density, high-magnetism, and finite homogeneous half-space low-resistance bodies are the reflection of Neoproterozoic metagabbro (Table 1);
- (2) Low-polarization, high-density, low-magnetism, and finite homogeneous half-space low-resistance bodies are the manifestation of Neoproterozoic TTG gneisses;
- (3) Low-polarization, low-density, low-magnetism, and finite homogeneous half-space high-resistance bodies are the reflection of Linglong granite;
- (4) Low-polarization, low-density, medium- and high-magnetism, and finite homogeneous half-space high-resistance bodies are the manifestation of Guojialing granite;
- (5) Low-magnetism, low-density, high-polarization, and medium- and high-resistance bodies in the shape of infinitely deep and inclined plates are the manifestation of altered fracture zones with weak mineralization (such as sericitization, pyritization and silicification) at the periphery of the orebodies;
- (6) Medium- and high-polarization, low-density, low-magnetism, and medium- and high-resistance orebodies in the shape of definitely deep and inclined plates are the reflection of the orebodies.

Table 1. Physical property characteristics of major geological bodies related to gold deposits in the Jiaodong Peninsula.

Parameters Lithology	η (Polarizability)/%		ρ (Resistivity)/ $\Omega \cdot m$		σ (Density)/ g/m^3		κ (Susceptibility)/ $\times 10^{-6} 4\pi$ SI		J_r (Remanent Magnetization)/ $\times 10^{-3}$ A/m	
	Relative Change	Variation Range	Relative Change	Variation Range	Relative Change	Variation Range	Relative Change	Variation Range	Relative Change	Variation Range
Metagabbro	Low	3.0–4.0	Low	$n \times 10^{-3}$ 10–300	High	2.87	High	500–4000	High	5–1000
Gneiss	Low	3.0–4.0	Low	$n \times 10^{-3}$ 10–300	High	2.87	Low	30–80	Low	5–10
Linglong granite	Low	4.0–5.0	High	2500–4000	Low	2.58	Low	5–100	Low	1–10
Guojialing granite	Low	4.0–5.0	High	2500–4000	Low	2.58	Medium-high	50–200	Medium-high	5–15
Fractured altered rock	Low-medium	6.0–8.0	Slightly low	600–850	Low	2.50	Low	5–10	Low	0–2
Orebody and mineralized altered rock	High	20–25	Medium-high	1000–2000	Low	2.62–2.75	Low	5–15	Low	0–5

2.3.2. Geophysical Prospecting Models for Superficial Gold Deposits

- (1) Gold deposits in the fractured, altered contact zone between metagabbro and Linglong granite. Their physical property model is the combination of the a, c, e, and f types. The gravity and magnetism above orebodies appear as gradient zones with contour values gradually increasing and accompanied by low values. These correspond to the characteristics of high polarization and secondary high resistance (Figure 2a).
- (2) Gold deposits in the fractured altered contact zone between TTG gneiss and Linglong granite. Their physical property model is the combination of the b, c, e, and f types. The gravity and magnetism above orebodies exhibit the characteristics of transitional zones with contour values decreasing and magnetic anomalous values increasing, and are accompanied by low anomalous values. These correspond to the characteristics of high polarization anomalies and secondary high resistance (Figure 2b).
- (3) Gold deposits in the fractured altered contact zone between Linglong granite and Guojialing granite. Their physical property model is the combination of the c, d, e, and f types. These exhibit weak low gravity values above the orebodies, and correspond to the characteristics of weak magnetic gradient zones, high polarization anomalies, and low resistance (Figure 2c).
- (4) Gold deposits in the fractured altered zone type inside the Linglong granite. Their physical property model is the combination of the c, e, f, and c types. These exhibit weak low gravity and magnetism values above the orebodies. They correspond to high-induced polarization anomalies and low-resistance anomalies (Figure 2d).

Figure 2. Geological-geophysical prospecting model for altered-rock-type gold deposits in the fracture zones of the Jiaodong Peninsula. (a) Cangshang gold deposit. (b) Jiaojia gold deposit. (c) Hedong gold deposit. (d) Wangershan gold deposit. 1—Quaternary; 2—Linglong granite; 3—Early Precambrian metamorphic rock series; 4—Guojialing granodiorites; 5—Altered fractured zone; 6—Low-polarization, high-magnetism, high-density, and low-resistance body; 7—Low-polarization, low-magnetism, high-density, and low-resistance body; 8—Low-polarization, low-magnetism, low-density, and high-resistance body; 9—Low-polarization, medium-high-magnetism, low-density, and high-resistance body; 10—High-polarization, low-magnetism, low-density, and medium-high-resistance body; 11—Medium-high-polarization, low-magnetism, low-density, and medium-high-resistance body.

3. Stepped Metallogenic Model of Deep-Seated Gold Deposits

3.1. Stepped Metallogenic Model of Deep-Seated Gold Deposits

The precise understanding of the occurrence characteristics and regularity of deep-seated gold deposits is the basis and prerequisite of deep prospecting, and a practical metallogenic model is an important basis for the establishment of a prospecting model. The stepped metallogenic model of deep-seated gold deposits in the Jiaodong Peninsula is a key basis for the building of a multi-parameter geological-geophysical prospecting model for deep-seated gold deposits in the area. As discovered through massive prospecting practices, the dip angle of ore-hosting faults of the altered-rock-type gold deposits in the fracture zones of the Jiaodong Peninsula constantly changes from shallow to deep parts, exhibiting shovel-shaped and stepped distribution characteristics. Accordingly, the gold bodies are distributed in a stepped pattern, the details of which are as follows:

- (1) With the dip angle changing in an alternate steep and gentle manner along the dip direction, the ore-controlling faults exhibit stepped distribution characteristics;
- (2) Due to the intermittent enrichment of mineralization from shallow to deep parts, multiple metallogenic spaces are formed;
- (3) Thick and large orebodies tend to be distributed in the turning parts of steep and gentle dip angles and sections with gentle dip angles;
- (4) There is limited vertical interval bearing no gold between two adjacent metallogenic steps within a given metallogenic region.

These distribution characteristics of altered-rock-type gold deposits reflect the natural occurrence law of deep-seated orebodies, indicating the overall stepped distribution characteristics of orebodies from shallow to deep parts. Therefore, these are referred to as the stepped metallogenic model of deep deposits [35]. According to relevant studies, the ore-hosting structures of quartz-vein-type gold deposits are contrary to those of altered-rock-type gold deposits. In greater detail, quartz-vein-type gold deposits are mainly controlled by steep faults. The sections of the steep faults with a high dip angle expand, and are favorable parts to the filling of quartz veins. Thick and large gold orebodies mainly occur in the steep parts of the faults (i.e., the sections where the stepped dip angle of faults is high) (Figure 3). Different ore-controlling fault zones or mining areas significantly differ in terms of the scale, interval distance and dip angle of ore-bearing steps. For example, the vertical distance between shallow steps and deep steps in the northern offshore mining area of the Sanshandao area is approximately 400 m, whereas that in the Jiaojia mining area is 150–550 m [35]. In addition, large ore-bearing steps frequently contain secondary ore-bearing steps with a slightly changing dip angle, featuring relatively thin orebodies and poor mineralization. The stepped metallogenic model provides the prerequisite of core technology and identifiable targets for deep prospecting.

Figure 3. A stepped distribution pattern of deep-seated gold deposits [36].

3.2. Mechanisms of the Stepped Metallogenic Model

The stepped metallogenic model of deep-seated gold deposits is a comprehensive reflection of tectonic activities and mineralization. Throughout the process of cutting geological bodies, faults frequently extend along rock layers when encountering relatively plastic rock layers or geological body interfaces. However, in most cases they directly cut through the rock layers when encountering relatively brittle rock layers, due to the non-uniform lithology and structure of the geological bodies. As a result, the dip angle with alternate steep and gentle changes is formed. For a normal fault, its steep sections consist of open space of tension, whereas its gentle sections are semi-open shear spaces. It is difficult for fluids to be stored in the open spaces. For a reverse fault, its slope sections are extruded and closed spaces, whereas its plateau sections are semi-open shear spaces. It is difficult for fluids to flow into extruded closed spaces. Therefore, the gentle sections of faults are favorable spaces for the metasomatic mineralization of fluids due to their shear property.

Faults with a gentle dip angle are prone to forming the physical and chemical interfaces for fluid mineralization. Suitable physical and chemical conditions are necessary for ore-bearing fluids to become unloaded, precipitated and enriched. The minerals in the ore-forming fluids in the crust can only be precipitated and mineralized under suitable temperature and pressure conditions near the geochemical and physical-chemical interfaces at a certain depth. Faults with low dip angles or gentle ups and downs possess relatively stable physical and chemical conditions. Furthermore, they form a small included angle with the physical and chemical interfaces suitable for mineralization, or continuously ap-

pear or interpenetrate near these interfaces, which is conducive to mineral precipitation. In addition, they tend to develop along the interfaces between different geological bodies, and the hanging and foot walls of the faults differ in terms of lithology and structure. Therefore, they appear as geological interfaces with different physical and chemical conditions. When such interfaces are located within the depth range with specific temperature and pressure conditions, they overlap or even control metallogenic physical-chemical interfaces to a certain extent, and thus become the most favorable metallogenic parts. This is an important reason why ore occurs in faults with low dip angles.

The pressure of fluids in fault sections with different dip angles is the decisive factor in the stepped ore-hosting pattern. When migrating along steep fault sections, the deep ore-bearing hydrothermal fluids rise from high-pressure areas to low-pressure areas and thus quickly diffuse, which is unfavorable for the enrichment and mineralization of fluids. When migrating along gentle fault sections, ore-forming fluids slowly and transversely flow under relatively constant pressure and temperature conditions. Furthermore, fault gouge barriers in the metallogenic fault zones are present in the Jiaodong Peninsula. For this reason, ore-forming materials are likely to be enriched and mineralized. Therefore, orebodies mainly occur in the gentle sections of faults. In addition, the influencing factors of the migration and enrichment of ore-forming fluids also include the porosity and permeability of the tectonic rocks of faults [37,38].

Faults with various properties and attitude types are developed in the Jiaodong Peninsula, and the gold mineralization types controlled by faults mainly include the altered-rock-type in fracture zones and quartz-vein-type throughout the area. The altered-rock-type gold deposits in the fracture zones are mainly controlled by regional large-scale faults that which are generally gentle. Ore-controlling faults have great potential for deep prospecting, where mineralization is mostly distributed in a stepped pattern. The multi-parameter geological-geophysical prospecting model of deep-seated gold deposits proposed in this paper is mainly applicable to the deep prospecting of altered-rock-type gold deposits in the fracture zones. Many strike-slip faults, such as the Taocun and Luanjiahe faults, are also present in the Jiaodong Peninsula. However, these faults possess flat fault surfaces and high dip angles, with no distinct alternate steep and gentle changes. Therefore, all of these faults bear no ore, indicating that the changing dip angle of faults is a necessary condition for gold enrichment in the Jiaodong Peninsula.

4. Prospecting Methods and Instruments

4.1. Geophysical Prerequisite for Deep Prospecting

The basic geological prerequisite for geophysical prospecting is that the differences in the physical properties of rocks and ores are closely related to corresponding mineral types. The difficulty in the prospecting of deep-seated gold deposits in the Jiaodong Peninsula is that the orebody-related information reflected on the Earth's surface is very weak due to the large burial depth of the deposits, thus conventional geophysical methods and prospecting concepts are not suitable there. For example, the induced polarization method has played an important role in the prospecting of superficial gold deposits in the Jiaodong Peninsula, due to the fact that the gold orebodies in the area contain large numbers of sulfides which are liable to cause induced polarization anomalies. However, sulfide anomalies caused by deeply buried orebodies are strongly suppressed by thick overburden layers and cannot be detected using the conventional induced polarization method. For deep prospecting, it is necessary to study the occurrence regularity of orebodies, so as to determine the mineralization-related differences in the physical properties of geological bodies and to improve the methods and techniques and select the instruments and methods with a large detection depth and high resolution. As indicated by the massive prospecting results, the notable differences in the physical properties of geological bodies which are closely related to the gold deposits in spaces throughout the Jiaodong Peninsula serve as an important geophysical prerequisite for deep prospecting in the area. The major ore-hosting geological

bodies of the gold deposits in the Jiaodong Peninsula and their differences in physical properties are described as follows:

- (1) The deposits occur in large-scale regional fault zones. The major ore-controlling faults in northwest Jiaodong include the Sanshandao, Jiaojia, and Zhaoping faults, with respective lengths of 12 km, 60 km and 120 km, and widths of 20–500 m [2]. Compared with the original rocks, the density, resistivity and magnetism of the fault zones are notably lower, whereas the polarizability of the fault zones is notably higher, and generally increases by more than 7% [2]. The gravity, magnetic, and resistivity anomalies are distributed in moniform and stripped patterns. In the case of the high silicification of rocks in the fault zones, the resistivity of the fault zones will not significantly decrease. When the fault zones are filled with late basic and ultrabasic dykes, their magnetism will significantly increase.
- (2) Many gold deposits lie in the contact zones between the Early Precambrian metamorphic rocks and Mesozoic granites, which differ notably in terms of resistivity, polarizability, and magnetism (Table 1).
- (3) The Early Precambrian metamorphic rocks are closely related to the gold deposits; thus, the distribution areas of metamorphic rock series are the stratigraphic basis for deep prospecting. Compared with the Mesozoic granitoids, the Early Precambrian metamorphic rocks are characterized by high density, low resistance, low polarization, and uneven and greatly varying magnetism.
- (4) The concentration areas of the gold deposits are generally distributed inside, on the edges of, and in the surrounding areas of the complex rock masses composed of Linglong and Guojialing granite. This type of rock association is characterized by relatively high resistance, low polarization, and low density. In addition, the Linglong granite exhibits low magnetic susceptibility, whereas the Guojialing granite possesses medium-high magnetic susceptibility. In terms of gravity anomalies, the concentration areas are located on the edges of the areas with low gravity anomalous values (i.e., the transitional zones between high and low gravity anomalous values) and within the contact zones between large-scale low and high gravity anomalies. In addition, the edges of small-scale blocky and moniform positive magnetic anomalies are areas which are favorable to deep-seated gold mineralization. In terms of resistivity, the concentration areas are located at the typical interfaces between electric fields with high and low resistance.

4.2. High Precision Gravity and Magnetic Exploration Method

Gravity measurement was carried out using a CG-5 high-precision flow quartz spring gravimeter with a working point distance of 200 m. Lattice calibration was carried out before formal work, and the static, dynamic and instrument consistency tests were carried out before and after work.

For the magnetic measurement, a GSM-19T proton magnetometer produced by GEM of Canada was adopted, with a working distance of 100 m. The instrument noise level, probe consistency, host consistency, and instrument consistency were measured before and after the formal production.

GeolPAS V4.5 was used for potential field conversion, map compilation, and joint inversion of gravity and magnetic data.

4.3. Electromagnetic Prospecting Method

The CSAMT, MT, and SIP measuring methods were carried out using a V8 multi-functional electric device produced by Phoenix Geophysical Co. of Canada. Prior to the formal work, all instruments and magnetic bars were calibrated, and instrument consistency, stability and parallel tests were performed.

For the CSAMT measurement device, a 1 to 6 scalar measurement mode with working frequency ranging from 9600 to 1 Hz was adopted, and two components were observed

(E_x and H_y). The transceiver distance ranged from 6.5 to 7.5 km, with transmitting and receiving dipole moment distances of 1500 m and 40 m, respectively.

The MT measuring electrode was arranged in a “+” shape. The measuring point distance ranged from 200 to 300 m, acquisition time from 6 to 8 h, and frequency band from 920 to 0.35 Hz.

The SIP measurement and observation device which was used was a dipole–dipole observation system, with measuring point and dipole distances of 50 m and 100 m, respectively. The distance between two points ranged from 100 to 300 m. The isolation coefficient was from 4 to 39, and the measuring frequency band ranged from 0.0156 to 256 Hz.

For the wide-field electromagnetic (WFEM) measurement, an SGY-2 wide area electromagnetic instrument produced by Hunan Geosun Hi-Technology Co., Ltd. was used. The measurement was input into a set of transmitting equipment and three sets receiving equipment. The field data were collected in 11, 9, 7, 5, 3, and 1 frequency groups, with a total of 40 frequency bands was adopted. The transceiver distance was 15 km, and the pole distance was 50 m. The consistency comparison tests were conducted on all receivers before and after initialization, and the receivers, transmitters, and ancillary equipment were regularly tested.

4.4. Reflection Seismic Exploration Methods

The 428XL multi-channel telemetry digital seismometer produced by Sercel Co. of France was used for reflection seismic exploration. The detector uses a 10 Hz low frequency detector (model number: 20DX-10). The sampling interval was 1.0 ms, and the recording length was 15 s. This method adopts a 6000-20-20-20-6000 observation system, with double-line acquisition, and line spacing of 20 m. By means of intermediate exciting and bilateral asymmetric receiving, 601 channels were received and 120 times coverage was carried out. The excitation method is used in a single well; the well depth is 18–20 m, and the excitation dosage is 8 kg. The receiving system adopts 6 detectors in a series combination, centralized stacking, and being buried underground.

4.5. Technical Methods Applicable to Different Interference Conditions

The industrial and agricultural production in the Jiaodong Peninsula are highly developed, and the sound intensities in different exploration areas differ quite widely. According to the detection depth, resolution, prospecting cost, and resistance to interference of various methods, the following combinations of technical methods applicable to various sound intensities are adopted in the prospecting of gold deposits in the Jiaodong Peninsula (Table 2).

Table 2. Combinations of geophysical technical methods for detecting deep-seated gold deposits in the gold concentration areas of the Jiaodong Peninsula.

Exploration Target	Sound Intensity	Effective Method	Optimal Combination	
			Noise Condition	Combination of Methods
Ore-controlling structural plane	Medium (weak) noise	CSAMT AMT WFEM	Weak noise	AMT + gravity prospecting
		Seismic exploration Gravity prospecting	Medium noise	CSAMT/WFEM + gravity prospecting
	Strong noise	Gravity prospecting Seismic exploration WFEM	Combination of dominant gravity prospecting and seismic exploration and auxiliary WFEM method	
Highly polarized body (mineralized alteration zone)	Medium (weak) noise	SIP		

Under weak sound intensities in the prospecting areas, the combination of dominant AMT (or CSAMT or WFEM) and auxiliary gravity prospecting and seismic exploration was adopted.

Under medium sound intensities in the prospecting areas, the AMT method adopted under weak noise conditions was replaced with either the CSAMT or WFEM method, both of which have stronger resistance to interference. Therefore, the combination of dominant CSAMT or WFEM and auxiliary gravity prospecting and seismic exploration was adopted.

Under strong sound intensities, conventional electromagnetic methods were not effective, thus the combination of the dominant gravity prospecting and auxiliary seismic exploration and WFEM method was adopted.

The main exploration targets of the above method combination were ore-controlling structural planes (ore-controlling faults). Meanwhile the spectral-induced polarization (SIP) method was used to detect deep-seated highly polarized bodies. With this method, the induced polarization effects of the deep geological bodies could be inferred through data processing and inversion interpretation, and thus highly polarized bodies were delineated.

5. Results: Prospecting Model for Deep-Seated Gold Deposits and Application Demonstration

5.1. Multi-Parameter Geological-Geophysical Prospecting Model for Deep-Seated Gold Deposits

For the deep prospecting of the altered-rock-type gold deposits in the fracture zones of the Jiaodong Peninsula, the stepped ore-hosting model was taken as the theoretical basis, the physical characteristics of rocks and ores as the prerequisite, and the geophysical method combination and corresponding geophysical prospecting indicators was taken as the means. Next, a qualitative geological-geophysical prospecting model used to identify deep-seated gold bodies according to multiple parameters was then established, based on the experimental studies and application practices in the prospecting of typical deep-seated gold deposits (Figure 4). Taking the geological and physical characteristics of the No. 320 exploration line of the Shaling gold deposit as a typical case, the geophysical prospecting indicators of deep-seated gold deposits are summarized as follows (Figure 4a,b).

Figure 4. Multi-parameter geological-geophysical prospecting model for deep-seated gold deposits. (a) Geological section along No. 320 exploratory line in Shaling gold deposit. (b) Physical properties of fractured altered-rock-type gold deposit. (c) Curve diagram of ΔT anomaly. (d) Curve diagram of Bouguer gravity anomaly. (e) Profile of apparent resistivity for the CSAMT. (f) Profile of 2D inverse of wide field electromagnetic method. (g) Profile of correlation coefficient of frequencies for the SIP. (h) Reflection seismic profile. (i) 3D geological model.

5.1.1. Characteristics of Gravity and Magnetic Fields

As indicated by the metallogenic geological characteristics of the altered-rock-type gold deposits in the fracture zones, most of the gold deposits are seated in the fault zones developing along the contact zones between metamorphic rock series and granites (Figure 4a). The areas favorable to the occurrence of gold deposits include the turning parts of the major fault plane's attitude, local expansion parts of faults, and the intersections of faults running in different directions. In terms of the gravity and magnetic fields, the linear gravity anomaly gradient zones (particularly their turning areas) are the areas which are conducive to mineralization. The magnetic field is characterized by moniform and banded zones of high magnetic anomalies. In particular, the turning areas (bulges and depressions) of the magnetic anomaly contours are the areas which are most favorable to mineralization.

The Linglong granite is characterized by a low, gentle and stable magnetic field and low gravity anomalies, whereas the metamorphic rocks are characterized by local high magnetic and gravity anomalies against the background of a low and gentle magnetic field. The ΔT (magnetic anomaly) values of the magnetic field show the transition from a low negative magnetic field, which varies locally to a stable low negative magnetic field (Figure 4c), with ΔT positive anomalies commonly appearing near fracture zones of faults. The gravity anomalies Δg (gravity anomaly) contours as gravity gradient or transitional zones with increasing contour values (Figure 4d), and these are zones which are favorable to mineralization.

5.1.2. Resistivity Anomalies

The gold deposits are generally distributed in zones with weak tectonic stress where metamorphic rocks are in contact with granites. The Linglong granite is characterized by high resistance anomalies, and the metamorphic rocks by medium-low anomalies. The ore-hosting fault zones appear as the gradient zones, with resistance changing from low to high in the profile of apparent resistivity for the CSAMT (Figure 4e), and their resistivity contour density is about twice that of the side with relatively low resistance. At the same time, they exhibit low-resistance zones within high-resistance areas on the WFEM section (Figure 4f), and the resistivity values are generally below $800 \Omega \cdot m$. In addition, the changes in the angle at which the gradient zones (or low-resistance zones) extend toward the deep parts correspond to the inclination characteristics of the fault zones. When the angle exhibits high-to-low turning characteristics, then apparent resistivity contours at the turning parts are sparse and synchronously curved downward, showing a U-shaped or S-shaped mark, thus indicating that the alteration zones of the faults are becoming gentle. The fault parts with a decreasing dip angle indicated by the turning parts of the gradient zone are favorable to the occurrence of deep-seated gold deposits.

5.1.3. Polarizability Anomalies

It is difficult for the time-domain-induced polarization method to achieve a prospecting depth of greater than 1 km, whereas the SIP method can be used to realize a detection depth of up to 2 km by adjusting the electrode array coefficient and transmitting power [3,4]. The following four SIP parameters were obtained by means of inversion of the measured complex resistivity spectrum: complex resistivity (ρ_a), apparent chargeability (ma), relaxation time constant (ta), and frequency-dependence coefficient (ca). The high-value anomalies of ρ_a , ma and ta and low-value anomalies with the interlacing distribution of ca are indicators of the enrichment of metal sulphides or favorable locations for gold ore bodies (Figure 4g). The ρ_a value of the strongly mineralized alteration site is less than $200 \Omega \cdot m$ and the respective amplitude ranges of ma , ta and ca are 10–20%, 15–50 s and 0.4–0.7%.

5.1.4. Characteristics of Seismic Reflection

Faults appear as undulating reflected waves on fault planes. The waves reflected by metamorphic rocks exhibit poor continuity of in-phase axes, bifurcation, and mergence, whereas the reflected waves in different directions intersect obliquely and appear in the form of upward arcs (Figure 4h). The Mesozoic rock masses show weak reflection, with earthworm-shaped, wavy, and arched in-phase axes. At the same time, the waves reflected by the Mesozoic rock masses are short in terms of lateral continuity or show blank reflection areas. All of these factors make it difficult to form continuously traceable reflected waves inside the Mesozoic rock masses, thus reflecting the non-layered and uneven internal structure of the rock masses. The turning parts of fault zones and gentle fault sections indicated by the reflected waves are the areas which are favorable to the occurrence of deep-seated gold deposits.

5.1.5. 3D Spatial Characteristics

Within the 3D view of a given fault system, the ore-controlling faults show the characteristics of shovel-shaped curved surfaces along their dip directions. Meanwhile, the dip angle in the upper part of the fault plane is steep and gradually decreases toward the deep parts (Figure 4i). Concave and convex surfaces are alternately distributed across the fault planes.

5.2. Demonstration of Geophysical Prospecting of Deep-Seated Gold Deposits in the Shuiwangzhuang Mining Area, Jiaodong Peninsula

The Shuiwangzhuang gold deposit occurs in the northern section of the Zhaoping fault, which bifurcates into the Potouqing and Jiuqujiangjia faults which strike to the NE and dip to the SE in the deposit area. Aside from the small number of orebodies occurring in the Potouqing fault in the east, the major orebodies of the deposit appear in the Jiuqujiangjia fault in the west. The Shuiwangzhuang gold deposit possesses proven gold resources of more than 170 tonnes, and its mineralization type is altered-rock-type gold deposits in fractured zones. The No. 2 major orebody of the deposit occurs in the beresitized cataclasite and beresitized granitic cataclasite zones, under the main fault plane, with an occurrence elevation of −851 to −2173 m. In addition, the orebodies found in the Shuiwangzhuang gold deposit are distributed in the shape of a large vein, with an average strike of 20°, a dip direction of southeast, and dip angles of 15–35°. Moreover, they have a maximum length of 2560 m along the strike, a maximum depth of 2080 m along the dip direction, a burial depth of 1349 m, an average thickness of 5.46 m, and an average ore grade of 4.27 g/t [39].

Geophysical section Y3 was arranged along the No. 42 exploration line of the Shuiwangzhuang mining area to carry out CSAMT, SIP, gravity, and magnetic surveys. The frequency of the SIP method used on the Y3 section ranges from 0.0156 to 256 Hz. The geophysical inference and interpretation clearly revealed the deep extension and morphological characteristics of the Potouqing and Jiuqujiangjia faults (Figure 5).

Both gravity and magnetic anomalies can reflect the Potouqing and Jiuqujiangjia faults and the wide alteration zone between them (Figure 5a,b). After reaching the second highest value, the gravity along section Y3 gradually decreases from west to east, indicating that residual Early Precambrian metamorphic rocks are present in the middle part of the section and that the western part of the section is dominated by Linglong pluton. On the western side of the section, the ground surface is dominated by Linglong monzonitic granite, whereas the medium gravity anomalies indicate that high-density metamorphic rocks may be possibly distributed in the deep parts of the Linglong pluton. To the east of the No. 8000 measuring point (the hanging wall of the fault zones), the magnetic anomaly curve is stable and gentle, thereby reflecting the Early Precambrian metamorphic basement. To the west of the No. 8000 measuring point, the magnetic anomaly curve leaps and two accompanying positive and negative magnetic anomalies are the reflections of the faults.

Figure 5. Comprehensive geological-geophysical section Y3 of the Shuiwangzhuang gold deposit. (a) Curve obtained from high-accuracy gravity survey. (b) Curve obtained from high-accuracy ground magnetic survey. (c) Apparent resistivity contour section obtained using the CSAMT method. (d) Apparent resistivity contour section obtained using the SIP method. (e) Frequency-dependence coefficient contour section obtained using the SIP method. (f) Chargeability contour section obtained using the SIP method. (g) Relaxation time constant contour section obtained using the SIP method. (h) Geologic section.

On the resistivity contour section obtained using the CSAMT method (Figure 5c), the gradient zones with the contour values changing from low to high act as the sign of alteration zones in faults. The gradient zones dip southeastward at low dip angles, thus indicating the deep attitude characteristics of the alteration zones. According to the stepped metallogenic model, it can be inferred that the area which are favorable to mineralization include the areas where the resistivity contours fluctuate greatly; the areas where the spacing between resistivity contours increases; the turning areas between the steep and gentle sections of the gradient zones, and the gentle parts of gradient zones. On the resistivity contour section obtained using the SIP method (Figure 5d), the directionally extending gradient zones with resistance changing from low to high act as the reflection of the fault zones. The areas where the gradient zones turn and where the turning areas of the extension direction of gradient zones correspond to the areas where the dip angles of the faults decrease. Therefore, these are the areas which are favorable to mineralization. On the contour sections of other parameters measured using the SIP method (Figure 5e–g), the alteration zones of the Potouqing and Jiuqujiangjia faults appear as highly apparent chargeability anomalies, high relaxation time constant anomalies, and low frequency-dependent coefficient anomalies that correspond closely to one another. In addition, the positions and extension trends of the anomaly zones indicate the deep characteristics of the alteration zones of the faults. A geological section was inferred and interpreted based on the

above geophysical characteristics, and has been verified through deep drilling (Figure 5h). At the same time, the deep prospecting target areas have been delineated at an elevation of approximately -1000 m and depth of about -1800 m, respectively, according to the multi-parameter geological-geophysical prospecting model of deep-seated gold deposits. Finally, the Shuiwangzhuang gold deposit has been detected in the former prospecting target area according to drilling, whereas the latter target area requires further exploration.

6. Conclusions

The breakthroughs made in deep prospecting in the Jiaodong Peninsula have resulted from the organic combination of experience accumulation, theoretical improvement, and technical advancement. In greater detail, the deep extension destinations of known metallogenic fault zones were selected as the prospecting target areas by virtue of long-term practical experience, whereas the optimal metallogenic space and prospecting targets were determined based on the new understanding of deep metallogenic regularity, and the deep favorable ore-hosting parts were delineated using the geophysical techniques with high precision and a large prospecting depth. The establishment and application of a geological-geophysical model for deep prospecting is the key technology required to break through the bottlenecks in deep prospecting in the Jiaodong Peninsula. The following conclusions are drawn from this study on the geological-geophysical prospecting model for deep prospecting of gold deposits in the Jiaodong Peninsula:

- (1) The ideas and methods of deep prospecting differ significantly from those of shallow prospecting. The traditional shallow gold prospecting in the Jiaodong Peninsula mainly involves using the time domain electric method to delineate the mineralized anomaly body, whereas for deep-seated gold prospecting the frequency domain electromagnetic method and reflection seismic method are mainly adopted to determine the extension characteristics of the ore-controlling faults in the deep areas.
- (2) The gold deposits in the Jiaodong Peninsula are controlled by large-scale regional faults. The orebodies are mainly distributed throughout the turning areas of steep to gentle dip angles. The ore-hosting faults developed along the contact interfaces between the Early Precambrian metamorphic rocks and Mesozoic granitoids exhibit a stepped metallogenic model in the downward direction. This model provides a technical premise and key exploration target for the geophysical exploration of deep-seated gold deposits.
- (3) The key indicators of multi-parameter geological-geophysical prospecting model to identify deep-seated gold deposits include the following: stepped metallogenic model; gravity gradient zones, beaded and elongated high magnetic anomaly zones; turning part of high- and low- resistance zones; high-value anomalies of complex resistivity, apparent chargeability and relaxation time constant; low-value anomalies of frequency-dependence coefficient; and undulating seismic reflection waves.
- (4) Through the demonstration of geophysical exploration of deep-seated gold deposit in the Shuiwangzhuang mining area, the deep prospecting target area has been delineated at the elevation depth of -1000 m, and has been verified by drilling.

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