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The ore prospecting prediction model for the Huili copper orefield in Sichuan Province, China*

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Abstract. The prediction theory and methodology of ore prospecting were developed from an in-depth study of 129 typical deposits in China. It has been verified to be an effective method that is particularly suitable for the initial ore prospecting. In this method, the internal and external factors of metallogenesis are combined together to construct a geological model of prospecting prediction, which consists of metallogenic geological body, metallogenic structure, metallogenic structural plane and metallogenic characteristics. The Huili area is located in the western margin of the Yangtze Plate, where the regional metallogenic geological conditions are superior, and a series of unique iron-copper deposits were formed. In recent years, great breakthroughs and progress have been made in the deep and peripheral areas of the Huili copper orefield. Herein, we take the Huili copper orefield as a typical example to illustrate the specific application of this method in deep ore prospecting of hydrothermal deposits. The metallogenic geological body is the ore-hosting volcanic rocks (albitite in the Hekou Group), and the main metallogenic structure and structural planes are interfaces between basic (intermediate) volcanic rocks and sedimentary rocks and the possible volcanic vent. Combined with the summary of metallogenic characteristics, we constructed a geological model for ore prospecting in the Huili copper orefield.

Keywords: ore prospecting prediction model, mineral exploration, Huili copper orefield, volcanogenic massive sulfide deposits

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Научная статья
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Модель прогнозирования поисково-разведочных работ на меднорудном месторождении Хойли в провинции Сычуань, Китай*

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Резюме. На основе глубокого изучения 129 типичных месторождений Китая была разработана теория прогнозов и методология разведки руд и подтверждено, что это эффективный метод, особенно подходящий для начальных этапов разведки руды. В этом методе внутренние и внешние факторы металлогенеза объединяются для построения геологической модели прогноза поисковых работ, которая включает металлогеническое геологическое тело, металлогеническую структуру, металлогеническую структурную плоскость и металлогенические характеристики. Район Хойли расположен на западной окраине плиты Янцзы, где региональные металлогенические геологические условия превосходны, в связи с чем здесь сформировалась серия уникальных железно-медных месторождений. В последние годы большие успехи были достигнуты в глубоких и периферийных областях меднорудного месторождения Хойли. В статье меднорудное месторождение Хойли обсуждается в качестве типичного примера, позволяющего проиллюстрировать конкретное применение разработанного метода при поисках глубоких руд гидротермальных месторождений. Металлогеническое геологическое тело – это рудовмещающие вулканические породы (альбитит в группе Хэкоу), а основная металлогеническая структура и структурные плоскости представляют собой границы раздела между основными (средними) вулканическими породами, осадочными породами и возможным вулканическим жерлом. В сочетании с обзором металлогенических характеристик авторы построили геологическую модель для разведки руд на меднорудном месторождении Хойли.

Ключевые слова: модель прогноза поисково-разведочных работ, разведка полезных ископаемых, меднорудное месторождение Хойли, вулканогенные месторождения массивных сульфидных руд

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Introduction

Since the 21st century, with ore prospecting turning deep, the orientation prognosis of deeply concealed orebody has turned to be the scientific frontier of current ore prospecting and prediction worldwide, and it is also one of the main difficulties and hot research topics in the fields of deposit exploration and mineral deposits. Over the

years, many domestic experts and scholars have proposed various metallogenic prediction theories and methods. Here are some representative ones. (1) There are similar analogy and geological anomaly theories [1–5]. According to natural theories and laws, it is considered that similar geological environments and metallogenic conditions could form similar deposits. (2) Deposit

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metallogenic series theory [6–8]. This theory mainly focuses on a group of deposit type combinations whose formation time, location, and genesis are closely related under the dominant geological mineralization in a specific geological period and geological environment. (3) Metallogenic system theory [9]. It organically combines the tectonic system, fluid system, chemical reaction, and deposit localization mechanism. It analyzes all the geological elements and the metallogenic process that control the formation, variation, and preservation of the deposit and the integration of the deposit series and anomaly series in terms of the dynamic evolution of mineralization. (4) Ore deposit model theory [10]. It conducts genetic model research for different minerals and ore deposit types and uses the genetic model of known deposits to carry out the metallogenic prediction and guide prospecting and exploration in unknown areas. (5) Prospecting prediction theory and methodology in exploration area [11–13]. Since the beginning of the 21st century, through implementing the national crisis mine prospecting project, especially the in-depth study of 129 representative deposits over five years, the scientific research team headed by Professor Ye Tianzhu, has made great efforts in theory and method of large-scale prospecting prediction. Combining the theories of geochemistry, mineralogy, and mineral deposit with the examples of major types of mineral deposits, a framework of exploration-area prospecting prediction theory and methodology is successfully constructed. Starting from combining internal factors (geochemical characteristics of elements) and the external factors (types of geological processes) of mineralization, a geological model of prospecting prediction is constructed, mainly composed of a metallogenic geological body metallogenic structure, metallogenic structural plane, and metallogenic characteristics. This method-technology system is supported by geochemistry theory, mineral deposit theory, element geochemistry experiment data, and mineral experiment data and formed based on many typical deposit research data and exploration project practice verification. It is an effective method especially suitable for initial prospecting and exploration. Summarizing and integrating the achievements obtained, they compiled the Prospecting

Prediction Theory and Methodology in Exploration Area [12, 13], which systematically summarized the fundamental prospecting prediction theories, and initially established prospecting prediction models for China's 25 main deposit types. This method has been tested in practice and preliminarily solved the critical problem of mineral exploration. Located in the western margin of the Yangtze Plate, the Huili area of Sichuan Province has superior metallogenic geological conditions, and formed a series of unique iron-copper deposits. In recent years, using the prospecting prediction theory and methodology in exploration area, major prospecting breakthroughs and progress have been achieved in the deep and periphery of the Huili copper orefield. Here taking it as a typical example, we expound the prospecting prediction theory and methodology and its application process in order to start further research and discussion on improving the success rate of deep prospecting.

Regional geology

The Huili area is located in the middle section of the SN-trending Sichuan – Yunnan passive continental margin rift system in the western margin of the Yangtze Plate (Fig. 1, a). This rift system is more than 1200 km long from north to south and about 150–250 km wide from east to west. The northern section extends in a NE-SW direction. It lies between the Longmenshan fault (Beichuan – Yingxiu) and the Longquanshan fault on the west side of the central Sichuan continental core. The middle section (Xichang area) and southern section (central Yunnan area) situated between the Anninghe – Lvzhijiang fault, the Leibo fault, and Xiaojiang fault extends in SN direction, with some areas crossing the Xiaojiang fault eastward to the Liupanshui fault zone in western Guizhou [14].

Except for the Ordovician and Carboniferous strata, the strata ranging from Paleoproterozoic to Cenozoic are distributed, especially the Proterozoic and Mesozoic strata. The regional strata mainly consist of Pre-Sinian, Sinian to Silurian, Permian, Triassic to Cretaceous, and Cenozoic. Among them, the pre-Sinian Hekou Group is the main copper-bearing horizon in this region (Fig. 1, b). The Hekou Group is a marine volcanic sedimentary rock series deposited in a continental

Fig. 1 Geotectonic location of the Huili area (modified from [20]) (a);

Geological sketch map of the Huili ore field (modified from [21]) (b)

Рис. 1. Геотектоническое положение района Хойли (по источнику [20] с изменениями) (a)
и геологическая схематическая карта рудного поля Хойли (по источнику [21] с изменениями) (b)

margin rift environment. According to its eruption characteristics, it can be divided into three tectonic cycles, namely, Dayingshan Formation, Luodang Formation, and Changchong Formation, which are composed of a series of metamorphic clastic rocks and volcanic rocks. Previous geochronology studies show that the Hekou Group was formed in the early Proterozoic (ca. 1700 Ma: [15–19]). The magmatic activity in this region is intense and has the characteristics of multi-cycle and multi-period, including the Jinning, Chengjiang, Variscan, and Indosinian periods. A series of anticlinoria, synclinoria, and thrust faults dominated by EW orientation followed by SN strike were formed due to the superposition of different periods and different types of tectonic events since the Huili period. Therefore, this region has a double-layer structure, with the lower layer forming the lower fold basement and developing the EW-striking fold and the upper layer constituting the upper fold basement and developing the SN-striking fold.

Deposit geology

The Huili copper orefield is located in Huili County, Sichuan Province. It is an essential large copper deposit in SW China and is the most extensive copper production base in Sichuan Province. Structurally, it lies on the west side of the southern part of the secondary Shuangshibaixiang anticline, which belongs to the southern limb of the Hekou anticlinorium (Fig. 1, *b*). In the past decades, more than ten major ore deposits (spots) have been discovered, including two large deposits (Luodang and Hongnipo), two medium-sized deposits (Shilong and Laoyanghantangou), with the rest of small deposits and spots. The cumulative proven copper resources of this orefield reach 1.74 million tons.

The Paleoproterozoic Hekou Group, Mesoproterozoic Huili Group, and Triassic Baiguowan Formation are widespread in this region. The bottom of the Hekou Group is intruded extensively by gabbro, and no underlying strata are seen. The Tongan Formation of the Huili Group is exposed in the west of the region and is in fault contact with the Hekou Group. The Baiguowan Formation is predominantly distributed in the southern part of the mining district, with sporadic distribution in the northwest corner of the district. They

are controlled by SN-trending fault and are unconformable with the underlying Hekou Group. The Hekou Group is a set of volcanic-sedimentary metamorphic rocks, the main ore-bearing formation in this area. Based on the formation characteristics, it can be divided into three different volcanic eruption-sedimentary cycles. Each cycle starts with normal deposition and ends with the end of volcanic eruption deposition. The earliest volcanic eruptions were mainly potassic, rich in potassium and poor in sodium, including potassium feldspar quartz granulite and potassium feldspar-bearing quartz albitite. The last volcanic eruption contains more sodium but less potassium, such as albite granulite and quartz albitite. All volcanic eruptions show in the three cycles of the formation the characteristics of underdeveloped agglomerates. That indicates that the volcanic eruptions in this area are dominated by a relatively quiet fissure-type eruption, which is consistent with the fact that volcanic rocks distribute alongside the F_1 . Huili orefield is located between the regional nearly SN-trending F_{13} and F_{29} . F_{13} is a reverse fault, striking $10\text{--}20^\circ$ NE and dipping $70\text{--}85^\circ$. Its hanging wall has the nature of shifting northward. F_{29} is also a reverse fault, with strike of 30° NE and a decreasing dip angle from $70\text{--}85^\circ$ on surface to $30\text{--}40^\circ$ in the deep. Between F_{13} and F_{29} , the gentle Shuangshibaixiang anticline and the Hongnipo syncline have similar orientation of 20° NE, and are separated by nearly EW-striking F_1 . The east and west ends of F_1 are restricted by F_{13} and F_{27} , respectively, with a strike of $60\text{--}80^\circ$, a fracture width of 10–30 m and a maximum vertical fault distance of 325 m. It has the nature of reverse fault in the early period, and the nature of normal fault in the later period. The strata of the west limb of the Shuangshibaixiang anticline incline to the southwest, dipping $30\text{--}40^\circ$, while the strata of the east limb of it incline to the southeast, dipping $30\text{--}40^\circ$. The southern part of the Shuangshibaixiang anticline comprises a series of small anticlines and synclines, mainly including Luodang anticline, Laoyanghantangou syncline, Laohushan anticline, Xiaochang syncline, Zhaizhiqing anticline from west to east. To the eastern part of the Hongnipo syncline, there are the small Xinlaochang anticline and Shilong syncline (Fig. 1, *b*).

The magmatic activity is intense and widely distributed in Huili orefield. The Hekou volcanic rocks constitute the ore-bearing horizon of this district. The intrusive rocks exposed here are mainly gabbro, followed by basic dyke rocks, intrusive breccias, etc. Gabbro is a basic intrusion that is widely exposed in this area. There are more than a dozen gabbro rock masses, dykes, and sills here. Gabbro swarm is dark green, with fiber columnar, gabbro, diabasic textures, and a massive structure. Its distribution is mainly controlled by faults. The gabbro intruded along with F_1 and the intersection of F_1 and F_{13} and was exposed in the area of Luodang – Laohushan – Laoyanghantangou – Shilong (Fig. 1, *b*). Granite porphyry is relatively rare in the vicinity of the mining district. It is light flesh red, with a holocrystalline porphyritic texture. The fissure caused by stress is filled with quartz veins. Besides, many late dykes within the mining area, including diabase, diorite, and lamprophyre, with thickness ranging from tens of centimeters to several meters. They are widely distributed, controlled by faults, joints, and fissures. Moreover, it is worth noting that they are obliquely interspersed with stratification, crosscut, and destroy orebodies.

The Luodang deposit is located in the area constrained by Laoyatian in the west, Sirentai-qiao in the east, Shaofangliangzi in the north, and Lantianwan F_1 in the south. Copper orebodies mainly occur in the upper and middle part of the Luodang Formation, with the economic ones primarily hosted in quartz albitite and biotite quartz schist. The upper ore-bearing section is mainly distributed in the axis of the Huili syncline, where the Luodang orebody occurs. The ore-bearing rocks are mainly interbedded biotite quartz schist and quartz albitite. The copper reserves in this section account for more than 50 % of the entire mining district. The middle ore-bearing section is widely distributed in the district. However, no economic copper orebody has been discovered. The ore-hosting rock is dominated by thick gray massive quartz albitite with a small amount of muscovite quartz schist. The ore-bearing rocks in the lower section consist of abundant garnet biotite schist and minor quartz albitite, and mica schist. They are gray with palimpsest texture and massive structure. There are only a few surface outcrops of copper orebodies in the Luodang

deposit, and most of them are concealed or semi-concealed. Whereas. The orebodies in this block have relatively good stability and extensibility, distributing within an area of 1900 m long from east to west and 900 m wide from north to south. There are 32 orebodies in this block, four of which are longer than 1000 m. The thickness of them ranges from 3 to 20 m. The scale of them varies greatly, extending from 80 to 1960 m in a strike, from 43 to 525 m of the average single orebody in inclination, and from 1.6 to 30.71 m in average vertical thickness (Fig. 2). In addition, these orebodies show obvious expansion, contraction, and cross compound phenomena. Ore mineralization is relatively uniform in this block. The copper grade is general 0.67–1.26 %, with an average of about 0.9 %.

Construction of the geological model of prospecting prediction

The genetic type of the Huili orefield. Study on the Huili orefield began in the early 1990s. Since then, a lot of research has been carried out in terms of deposit geology, geochemistry, diagenesis and mineralization age, ore-forming fluids, and ore-forming material sources [15, 18, 19, 23–38]. In the beginning, most researchers proposed that the Huili copper deposit is a VMS-type deposit on the basis of being syngenetic with the marine volcanic hosting strata, stratiform and stratoid orebodies, abundant strata-bound sulfide minerals, sulfur and lead isotope showing ore-forming materials derived from the Hekou Group [22, 27, 28]. Some researchers also suggested that the Jinning movement and diabase emplacement might have promoted the reactivation and enrichment of metallogenic elements [30, 39]. Besides, since 2000, some scholars have put forward that the Huili copper orefield is an IOCG deposit based on the evidence of strong albitization, large amounts of Ti-poor magnetite and enrichment of Co, Au, P, F, REE, etc. Subsequently, much more attention has been paid to the possible IOCG properties of the Huili orefield. To date, numerous studies have shown that the Huili orefield possesses the characteristics of representative IOCG deposit, including extension environment of intraplate rift, magmatic and stratigraphic sources of ore-forming fluids, and materials [32], extensively pervasive Na, Na-Ca and K

Fig. 2. Cross section VIII of the Luodang district (modified from [22])

Рис. 2. Поперечный разрез VIII района Луодан (по источнику [22] с изменениями)

alteration characteristics¹, and multi-stage nature of mineralization² [18, 19, 29, 32, 33, 35, 36].

Determination of metallogenic geological body. The metallogenic geological body refers to the physical carrier of the mineralization process that forms the major minerals, up to industrial grade, in the main ore-forming stage. It consists of geological formation and forming environment, and also refers to natural rock assemblage and rock-controlling structure, and is closely related to the formation of the deposit in terms of time, space, and genesis [13, 40]. Therefore, only when it is clearly defined can the spatial location of deep and peripheral blind deposits and / or orebodies be predicted more accurately, which will provide significant guidance for further prospecting and exploration.

Temporal and spatial relationship between metallogenic geological body and ore deposits:

Temporally, the formation ages of ore-bearing volcanic rocks and orebodies are ca. 1.68 Ma and ca. 1.67 Ma, respectively, indicating mineralization is roughly coeval with diagenesis. Spatially, it is found that orebodies are often concomitant with volcanic rocks. They are hosted either in the volcanic rocks or in the sedimentary rocks near the contact zone between the two (Fig. 2).

Material source relationship between metallogenic geological body and ore deposits: The chondrite-normalized REE patterns for pyrite from banded ores are similar to those of basic (intermediate) volcanic rocks. Sulfur isotope studies suggest that sulfur was mainly derived from rocks mentioned above, with a contribution of seawater sulfates. The initial ⁸⁷Sr / ⁸⁶Sr value is 0.712 [41], which is roughly consistent with the values (ranging from 0.71614 to 0.718937) of ore-hosting volcanic rocks at the time of minera-

¹ Zhu Z. Lala iron oxide copper gold deposit: metallogenic epoch and metal sources: Ph.D. thesis. Chengdu: Chengdu University of Technology, 2011.

² Greentree M. Tectonostratigraphic analysis of the Proterozoic Kangdian iron oxide-copper province South-West China: Ph.D. thesis. Perth: University of Western Australia, 2007.

lization³, suggesting that the ore-forming materials were sourced from basic-intermediate volcanic rocks in the Hekou Group. Moreover, the sulfides have highly radiogenic lead isotopic ratios, with $^{206}\text{Pb} / ^{204}\text{Pb}$ and $^{208}\text{Pb} / ^{204}\text{Pb}$ ranging from 17.687 to 67.289 and from 36.533 to 63.573 (unpublished data), respectively, indicative of the source of volcanic rocks enriched in uranium, thorium, and radiogenic lead in the Hekou Group.

Above all, the metallogenic geological body is basic (intermediate) volcanic rock formed from the Paleoproterozoic submarine volcanic eruption and/or overflow, which provided ore-forming materials and heat energy for seawater convection.

Metallogenic structure and structural plane. The study on metallogenic structure and structural planes is aimed to determine the spatial location, distribution, morphology, occurrence of the orebodies and so on, which is of great significance for prospecting and prediction. Metallogenic structures are generally structures that are usually active at the same time as mineralization, including those that existed before mineralization and reactivated during mineralization and those that formed during mineralization. The metallogenic structural planes refer to the dominant or recessive discontinuous interfaces of petrophysical and petrochemical properties [13]. They can be divided into three types, namely, primary metallogenic structural planes, secondary metallogenic structural planes and physicochemical condition conversion planes. The first type includes lithological interfaces, geological body interfaces and structural planes formed by gravity, stress, heat and thermal fluids. The second type consists of fold, fault, joint, fissure and so on. The third type generally includes conversion interfaces of temperature, pH and Eh.

The most important metallogenic structures and structural planes are a set of primary metallogenic structural planes, referring to the lithological interfaces between basic-intermediate volcanic rocks (metamorphosed into albitite) and sedimentary rocks (metamorphosed into schist). Volcanic channel facies products found in the

Luodang open pit, such as volcanic breccia and collapsed breccia indicate that here may exist a volcanic vent, which is also a primary metallogenic structural plane. As the western extension of the Baotaichang – Jiulong deep fault, F_1 controlled the distribution of ore-bearing rocks and the extension and enrichment of orebodies, and served as a channel for gabbro emplacement, suggesting that it is a syngenetic fault. In addition, the dramatically lithological change, abundant siderite and interbedded slump accumulation rocks indicate that F_{29} is also a syngenetic fault.

Metallogenic characteristics. The process of mineralization is very complex, and its products are diverse. The characteristics that can directly indicate the spatial location of the orebody and has critical importance for prospecting prediction is referred to as metallogenic characteristics. What's more, they must be unquestionably geological facts confirmed by macro and micro means [13].

(1) The orebodies are chiefly stratiform, straitoid and lenticular, with occurrence roughly consistent with stratigraphic bedding, showing typical strata-bound features. The ore-hosting rocks are mainly quartz albitite, biotite quartz schist, muscovite quartz schist and marble (Fig. 2).

(2) Ore types include laminated, massive, brecciated and veined ores (Fig. 3, a–d). Ore minerals are mainly chalcopyrite, pyrite and magnetite, followed by molybdenite, hematite, glaucodot, sphalerite, etc., with occasional native gold (Fig. 3, e–h). Gangue minerals consist mainly of quartz, calcite, albite, biotite, muscovite, chlorite, etc. Ore textures are chiefly subhedral to euhedral granular texture, metasomatic texture, poikilitic texture, cataclastic texture, with scarce exsolution texture and sieve texture. The ore structures are dominated by lamellar structure, massive structure, brecciated structure and vein structure.

(3) The laminar and massive orebodies have relatively weak alteration, which are mainly characterized by silicification, carbonation, chloritization, albitization, biotitization, and tourmalinization (Fig. 3, i–l).

³ He D. Petrological and geochemical characteristics of the Lala copper deposit in Sichuan province: Ph.D. thesis. Guiyang: Institute of Geochemistry, Chinese Academy of Sciences, 2009.

Fig. 3. Photomicrographs showing the typical metallogenic characteristics:

a – features of laminated ores, showing sulfides parallel to foliation; b – features of massive ores; c – features of brecciated ores, with sulfides cementing volcanic breccia; d – features of veined ores, showing sulfide vein filling fissures; e – subhedral to euhedral magnetite; f – subhedral to euhedral pyrite; g – molybdenite and pyrite replaced by chalcopyrite; h – cataclastic glaucofane and pyrite replaced by chalcopyrite; i – carbonation and silicification alteration; j – chloritization alteration; k – albization alteration; l – tourmalinization alteration

Mt – magnetite; Ccp – chalcopyrite; Py – pyrite; Mot – molybdenite; God – glaucofane; Sp – sphalerite;

Br – breccia; Qz – quartz; Ms – muscovite; Bt – biotite; Chl – chlorite; Cal – calcite; Ab – albite; Tur – tourmaline

Рис. 3. Микрофотографии, демонстрирующие типичные металлогенетические характеристики:

a – характерные особенности слоистых руд, в которых сульфиды расположены параллельно слоистости;

b – характерные особенности массивных руд; c – характерные особенности брекчированных руд

с цементирующими вулканическую брекцию сульфидами; d – характерные особенности жильных руд,

где сульфидные прожилки заполняют трещины; e – магнетит от гелидиоморфного до идиоморфного;

f – пирит от гелидиоморфного до идиоморфного; g – молибденит и пирит, замещенный халькопиритом;

h – катакластический глаукофан и пирит, замещенный халькопиритом; i – изменение карбонизации

и окварцевания; j – изменение хлоритизации; k – изменение альбитизации; l – изменение турмалинизации

Mt – магнетит; Ccp – халькопирит; Py – пирит; Mot – молибденит; God – глаукофан; Sp – сфалерит;

Br – брекчия; Qz – кварц; Ms – мусковит; Bt – биотит; Chl – хлорит; Cal – кальцит; Ab – альбит; Tur – турмалин

Prospecting prediction geological model.

Guided by the prospecting prediction theory and methodology, the prospecting prediction geological model (Fig. 4) is eventually constructed based on the determination of the metallogenic geological body, metallogenic structure, and metallogenic structural planes and summaries of the metallogenic characteristics. In the volcanic-exhalative-sedimentary period, multiple continuous volcanic eruptions brought a large number of valuable components, which are directly spilled out onto the seabed with lava flow and volcanic debris. They were then transported and accumulated into submarine basins or slopes and finally

formed the ore-bearing volcanic sedimentary formations or source beds.

Conclusions

The significant mineralization event associated with marine volcanism has been recognized in this area, corresponding to breakups of the Columbia.

The metallogenic geological body is the ore-bearing volcanic rocks (albitite in the Hekou Group). The structural planes are mainly the interfaces between basic-intermediate rocks and sedimentary rocks and possible volcanic vents, which are primary metallogenic structural planes.

Fig. 4. Prospecting prediction geological model of the Huili orefield

Рис. 4. Прогнозно-разведочная геологическая модель рудного месторождения Хойли

After summarizing metallogenic characteristics, the geological model of prospecting prediction in

the Huili copper exploration area has been constructed.

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