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Advantages of Copper Resources and Prospects for Their Exploitation and Utilization in Tibet

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Abstract: Copper resources play an important role in the development of the national economy. However, there is a large gap between the supply and demand of copper resources in China. Tibet has the most abundant copper resources in China; therefore, the scientific and rational exploitation of copper resources in Tibet plays a very important role in ensuring a sustainable supply of copper resources in China. The distribution characteristics of the copper resources in Tibet and the advantages and disadvantages of exploiting these copper resources are summarized herein. Furthermore, this study proposes that we should adhere to the scientific development concept, construct green development bases for copper resources in the major metallogenic belts in Tibet, accelerate scientific exploration and orderly development of copper resources, correctly handle the relation between resource development and environment protection, and consider the economic, social, and environmental benefits brought about by the exploitation of copper resources to promote the steady development of Tibetan society and achieve the goal of targeted poverty alleviation.
Keywords: copper resources; exploitation and utilization; Tibet

1 Introduction

Copper is widely used as a basic raw material in modern industries and is an essential material basis for economic and social development due to its extensive applications. The development and utilization degree of copper resources is closely related with the economic development level and technological progress. In addition, copper can optimally reflect the development of the real economy and act as the “barometer” of the macroeconomy [1]. According to the forecast of the Research Center for Strategy of Global Mineral Resources, Chinese Academy of Geological Sciences, the demand for refined copper production in China will be 7.5×10^6 t–8×10^6 t in 2020 and 6.5×10^6 t–7.5×10^6 t in 2025 and will be larger than the supply. In the short run, the gap between the supply and demand will expand further [2]. Moreover, the overall resource scenario is not optimistic.

Tibet, known as the “roof of the world,” is located in the southwest of China, accounting for 12.5% of the total national territory. Its complicated geological structure and evolution, especially the intense magmatic activities since the Mesozoic and Cenozoic, have resulted in extremely favorable conditions for copper mineralization. Due to

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several breakthroughs in prospecting in recent years, Tibet has become the province with the most copper resources in China. Currently, the proven copper reserves in Tibet account for more than half of China's copper reserves [3,4], making Tibet an important strategic reserve base for copper resources in China. The rational development and utilization of copper resources in Tibet may change the current situation, where the resources in Eastern China are becoming increasingly exhausted, form a good pattern of complementary national resources, enhance the guarantee degree of copper resources in China, and ensure the economic security of China. In addition, the development and utilization of copper resources will have an important strategic significance in further promoting the development of the Tibetan industrial economy, supporting the benign growth of local related industries, and maintaining peace and stability in ethnic autonomous regions.

However, the ecosystem in Tibet is very fragile. If the corresponding areas undergo large-scale, disorderly mining, the resulting damage to the ecological environment will be difficult to recover from in a short term; moreover, this will not be conducive to the sustainable development of the mining economy. In addition, the relatively backward infrastructure construction and regional technical and economic conditions in Tibet have increased the cost of mining development. Therefore, after summarizing the distribution of copper resources in Tibet, this paper puts forward several suggestions concerning the development and utilization of the important strategic resources in the aforementioned areas and prospects for the development and utilization of copper resources in Tibet.

2 Reserves, distributions, and features of copper resources in Tibet

2.1 Overview of the reserves

Tibet is located in the Tethys–Himalayan metallogenic domain, which is one of the three major metallogenic domains worldwide. Tibet has a complex geological structure and evolutionary history; the intense magmatic activities since the Mesozoic and Cenozoic created favorable metallogenic conditions for the formation of copper deposits, especially porphyry-type copper deposits. Currently, 390 copper deposits have been discovered in Tibet, including 17 (super) large-scale deposits and 6 medium-scale deposits. The proven copper ore reserves exceed 5.3×10^7 t, ranking top in China, and copper is one of the dominant minerals in Tibet [3,5]. Of these deposits, single deposits on the scale of 10 million tonnes include the Tiegelongnan copper deposit [6] and the Qulong copper deposit [7]. The copper resource reserves of these single ore deposits rank among the top 10 copper reserves in Asia.

Currently, the identified copper deposits are primarily distributed in three large-scale copper–iron-polymetallic metallogenic belts with important industrial prospects [8,9]; these belts are 1) the Yulong copper metallogenic belt in the "Sanjiang" area of Eastern Tibet [10], 2) the Gangdese metallogenic belt in the center of Tibet [11], and 3) the Bangongco–Nujiang metallogenic belt in the northwest of Tibet [12,13]. All three metallogenic belts have (super) large copper deposits.

2.2 Deposit distributions and metallogenic belts

2.2.1 Yulong copper metallogenic belt

The Yulong copper metallogenic belt is located in the "Sanjiang" area in Eastern Tibet, from Xiariduo in Chamdo County in the north to Mamupu in Markam County in the south. The belt is approximately 250 km in length and 40 km in width. It extends from northwest to southeast. Deposits include the Narigongma porphyry copper deposit in Qinghai Province to the northwest, and the Hongshan, Xuejiping, Pulang, Machangjing, and Beiya deposits in Western Yunnan from Markam County to the south. The deposit types are primarily porphyry and skarn Cu–Mo deposits, with the Yulong Cu–Mo deposit as a representative, including large- and medium-sized deposits such as Zanaga, Mangzong, Duoxiasongduo, and Malasongduo, in which the mineralization age is primarily 40–35 Ma (Eocene), closely related to porphyry Cu–Mo–Au mineralization under the mechanism of late collision conversion mineralization in the continent–continent collision process between India and Asia [14]. The resources of the main copper deposits in the Yulong copper metallogenic belt are listed in Table 1.

2.2.2 Gangdese copper metallogenic belt

The Gangdese copper metallogenic belt is primarily located in the center of Tibet, where the social economy is most developed and the transportation is most convenient in Tibet. From Ngamring County in Shigatse City in the west to Gyaca County in Nyingchi City in the east, the belt spreads in a nearly east–west direction with a length of 550 km from east to west and a width of 10 km from north to south. It is dominated by porphyry, porphyry–skarn, or skarn type Cu–Mo (polymetallic) deposits. A total of 12 Cu–Mo or Cu-polymetallic deposits of industrial significance have been discovered in its eastern section. From west to east, the deposits are the Jiru, Bairong,

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Chongjiang, Tinggong, Zongxun, Dabu, Lakange, Qulong, Jiama, Xiangbeishan, Xiamari, and Chuibaizi [15]. Copper deposits such as Qulong and Jiama have a metallogenic age range of 20–14 Ma (Miocene). Their formation is closely related to the metallogenesis that occurred during the continent–continent collision between India and Asia. The number of research studies on the middle and west Gangdese is relatively small. These deposits are primarily porphyry-type copper–gold deposits and copper deposits. The middle section is represented by the Xiongcun copper–gold deposit, with a mineralization age of 172–160 Ma (Middle Jurassic), which represents subduction mineralization in the Middle Jurassic. The western section is represented by the Zhunuo copper deposit, with a metallogenic age of 13 Ma (Miocene), which is consistent with the porphyry deposits forming under the background of the main collision in the eastern segment of the Gangdese metallogenic belt. The main copper deposit resources in the Gangdese copper metallogenic belt are listed in Table 2.

Table 1. Mineral reserves of the copper deposits in the Yulong copper metallogenic belt.

Deposit	Copper reserves	Associated minerals and reserves
Yulong	6.5×10^6 t	Fe: 1.267×10^7 t, Mo: 4×10^5 t
Zhanaga	4.23×10^5 t	Mo: 2400 t
Mangzong	9.1×10^5 t	Mo: 2.5×10^4 t
Duoxiasongduo	8.9×10^5 t	Mo: 5.1×10^4 t, Ag: 2529 t
Malasongduo	1.508×10^6 t	Mo: 6×10^4 t

Table 2. Mineral reserves of copper deposits in the Gangdese copper metallogenic belt.

Deposit	Copper reserves	Associated minerals and reserves
Qulong	$>1 \times 10^7$ t	Mo: 5×10^5 t
Jiama	7.5×10^6 t	Mo: 7×10^5 t, Pb + Zn > 1.7×10^6 t, associated Au: 170 t, associated Ag: 1×10^4 t
Xiongcun	2.37×10^6 t	Associated Au: 213 t, associated Ag: 1093 t
Bangpu	1.2×10^6 t	Mo: 4.54×10^5 t
Nuri	5.1×10^5 t	Mo: 3.2×10^4 t, WO_3: 1.9×10^5 t
Zhunuo	2.3×10^6 t	Mo: 4×10^4 t , associated Au: 33.8 t, associated Ag: 999 t
Tinggong	3.4×10^5 t	Mo: 3.7×10^4 t, associated Au: 23 t, associated Ag: 1249 t
Chongjiang	5×10^5 t	Mo: 2.7×10^4 t, associated Au: 36 t, associated Ag: 814 t
Bairong–Gangjiang	1.86×10^6 t	Mo: 1.7×10^5 t

2.2.3 Bangongco–Nujiang copper metallogenic belt

The Bangongco–Nujiang copper metallogenic belt is located in Northwest Tibet, from Ge'gyai County in the Ngari Prefecture in the west to Baingoin County in the Naqu region in the east, with a total length of 800 km from east to west and a width of 50 km from north to south. Represented by the Tiegelongnan, Duobuza, and Bolong Cu–Au deposits (collectively referred to as the "Duolong Cu deposit"), the deposit types are primarily porphyry-epithermal and porphyry–skarn Cu–Au deposits. The mineralization ages are primarily 125–90 Ma (Cretaceous). Its mineralization is related to the continental margin arc formed by the subduction of the Neo-Tethys oceanic crust at the continental margin [6]. The main copper deposit resources in the Bangongco–Nujiang copper metallogenic belt are listed in Table 3.

2.3 Deposit characteristics

Copper deposits are widely distributed and abundant in Tibet. Most of these deposits are related to Mesozoic and Cenozoic magmatism. The deposit types include porphyry, skarn, epithermal, sedimentary metamorphism, sedimentary, and weathering crust types. In addition to porphyry–skarn deposits formed under collision and extension, island arc porphyry copper–gold deposits, high sulfidation epithermal copper–gold deposits, and low sulfidation epithermal silver–gold–lead deposits have become important copper-polymetallic deposit types in Tibet, due to new discoveries in recent years. Copper deposits formed in Yanshanian are primarily distributed on both sides of Bangongco–Nujiang suture zone, which is closely related to tectonic–magmatic events caused by the evolution of the Bangongco–Nujiang Ocean. The copper deposits that formed during the Himalayan period are primarily distributed in the southern Gangdese metallogenic belt on the northern side of the Yarlung Zangbo River suture zone and the northern Qiangtang–Chamdo metallogenic belt in the “Sanjiang” area of Eastern Tibet, which are closely related to the tectonic–magmatic events caused by the evolution of the Yarlung Zangbo River Ocean. The deposits occur in clusters or alignments. In specific metallogenic belts, these deposits are characterized by their large numbers, large scales, various types, and rich co-associated elements (molybdenum, gold, silver, lead, and zinc). In addition, rare or dispersed elements, such as indium, gallium, germanium, thallium, rhenium, selenium, and tellurium, and a large number of elements, such as sulfur, nickel, cobalt, bismuth, and arsenic, are available for comprehensive use.

Table 3. Mineral reserves of copper deposits in the Bangongco–Nujiang copper metallogenic belt.

Deposit	Copper reserves	Associated minerals and reserves
Tiegelongnan	1.098×10^7 t	Au: 37 t, Ag: 2609 t
Duobuza	2.95×10^6 t	Au: 93 t
Bolong	2.72×10^6 t	Au: 126 t
Naruo	2.51×10^6 t	Au: 82 t, Ag: 873 t
Nating	1.56×10^6 t	Au: 118 t

3 Exploitation of copper resources in Tibet

3.1 Significance of resource exploitation in Tibet

Tibet is especially abundant in copper, iron, zinc, chromium, and other mineral resources. A series of world-class copper deposits have been discovered. Some are in the exploration stage. Several copper resource bases have been set up one after another, playing an important role in ensuring the sustainable supply of copper resources in China.

With the development of the domestic economy in China, the number of newly discovered copper deposits has dramatically decreased. The mineral resources in East China are becoming increasingly exhausted, and the reserve resources are seriously insufficient. Copper is one of the main minerals contributing to the national economic growth, and the growth ratio of copper consumption to copper reserves has shown a negative trend [15]. Scientific and reasonable exploration and development of copper will therefore play an important role in the development of China’s national economy.

There are abundant copper resources in Tibet; unfortunately, copper ion pollution is often caused after ore bodies are exposed or leached out to the surface by underground water, e.g., the “Kongque River” in Qulong, formed in the lower reaches of the Yulong copper mine area and the Qulong copper mine area, and the dystrophication in the Demingding mine area, formed naturally after the ore bodies were exposed to erosion at the surface. The proper exploitation and utilization of copper resources in Tibet will help reduce secondary unnatural pollution caused by the formation of these ore bodies.

3.2 Status of exploitation and utilization

Currently, there are 32 officially recorded non-associated copper deposits and 13 associated copper deposits in Tibet. Large-scale copper deposits that have complete infrastructures and are undergoing mining or recently mined include the Qulong copper deposit, the Zhunuo copper deposit, the Yulong copper deposit, the Jiama copper-polymetallic deposit, the Tinggong copper deposit, and the Xiongcun gold copper deposit [16]. The planned copper mining projects include the Duolong copper deposit. The main mining enterprises currently engaged in copper mine exploitation in Tibet are listed in Table 4.

With respect to this development, the Xiongcun copper mine project in Xietongmen County has been listed by the government of the Tibet Autonomous Region as a key construction project and a key productivity layout and industrial planning project in the 12th Five-Year Plan and has been established as an important component of the nonferrous metal industrial base in Central Tibet. When the phase II project of the Qulong mining area is completed and implemented, it will become the modern green nonferrous metal mine with updated automation, highest altitude, largest domestic scale, and most advanced processing equipment in the world.

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Table 4. Mining enterprises engaged in copper mine development in Tibet.

Mining enterprises	Deposit	Mining rights	Reserves	Planned production capacity	Main shareholders
Julong Mining Ltd., Tibet	Qulong, Zhunuo	Julong Mining Co., Ltd., Tibet	Cu: 1.3×10^7 t, Mo: 3.564×10^5 t	3×10^5 t/d (raw ore)	Zangge Potash Fertilizer Ltd., Golmud
Western Mining Ltd.	Yulong	Yulong Copper Mining Co., Ltd., Tibet	Cu: 6.5×10^6 t	1×10^5 t/a (refined product)	Western Mining Ltd.: 58%
China National Gold Group Ltd.	Jiama	Huatailong Mining Development Co., Ltd., Tibet	Cu: 7.5×10^6 t, Au: 170 t	1.65×10^7 t/a (raw ore)	China National Gold Group Ltd.: 51%
Tibet Mining Ltd.	Tinggong	Neim County Copper Mining Development Co., Ltd.	Cu: 1.37×10^6 t	1.5×10^6 t/a (raw ore)	Tibet Mining Ltd.: 90%
Jinchuan Group Ltd.	Xiongcun-I	Tianyuan Mining Co., Ltd., Tibet	Cu: 8.7×10^5 t, associated Au: 120 t, associated Ag: 778 t	1.2×10^7 t/a (raw ore)	Jinchuan Group Ltd.: 55%
CHINALCO Tibet Mining Ltd.	Tiegelongnan, Naruo	Jinlong Mining Co., Ltd., Tibet	Cu: 1.349×10^7 t, associated Au: 119 t, associated Ag: 3482 t	Preparation	CHINALCO Tibet Mining Ltd.: 66%
Hongda Group Ltd., Sichuan	Duobuza, Bolong, Nating	Hongda (Duolong) Mining Ltd., Tibet	Cu: 6.9×10^6 t, associated Au: 304 t	Preparation	Hongda Group Ltd., Sichuan: 40%, Hongda LTD., Sichuan: 30%

3.3 Advantages and disadvantages of development

3.3.1 Advantages

The geological conditions for mineralization are superior in Tibet compared to other regions, and the natural resources of the area are unique. Tibet is located in the eastern section of the Tethys–Himalayan metallogenic domain. Due to the collision between the Indian and Asian continents and the subduction and extinction of the Bangongco–Nujiang Ocean, the copper deposits in Tibet exhibit a sufficiently large size, young metallogenic epoch, varied types, and excellent preservation. The proven copper reserves in the three metallogenic belts in Tibet exceed 5.3×10^7 t [3], accounting for more than 60% of the total copper resources in China, and the preliminarily proven copper, molybdenum, lead and zinc, associated gold, and silver resources amount to 7×10^7 t, 2.9×10^6 t, 1.4×10^7 t, 1000 t, and 42 000 t, respectively, making Tibet unique in its resource endowment.

There is a complete mechanism for policy guarantee. In 2010 and 2015, the 5th and 6th Working Conferences on Tibet held by the Central Government decreed the long-term construction of Tibet to be an important principle and provided policy guarantees and major project supports such as fiscal levies, financing, investments, personnel, and aid for Tibet. The intensity of infrastructure construction further increased, and the regional technological and economic conditions will subsequently be greatly improved. *The Outline of the Thirteen Five-Year Plan for National Economic and Social Development in Tibet Autonomous Region* proposes to “strengthen basic geologic and mineral exploration, build an important strategic resource reserve base, develop the industrial chain of smelting and deep processing of superior minerals, and promote efficient utilization of mineral resources.” The new mode of cooperation between provinces, ministries, and enterprises in mineral exploration implemented since 2012 provides policy guarantees and support for relevant mining enterprises to engage in mineral exploration and investment in the region.

Copper mines and related industries will boost the economy and employment in Tibet. Once Tibet can achieve a production capacity of 4×10^5 t of refined copper, the output value will exceed 20 billion yuan. Copper-related mining, beneficiation, metallurgy, and transportation industries can drive the growth of the GDP of Tibet by at least 50 billion yuan. The reasonable deployment and construction of copper resource development bases in the three major copper metallogenic belts may realize a reasonable distribution of copper resource production capacity, make unique contributions to employment absorption, stable development, and targeted poverty alleviation, and provide important resource guarantees for China to cope with complex international situations.

3.3.2 Disadvantages

Tibet, with its fragile ecological environment, is located in a plateau region with over 60% of the area consisting of frozen soil and nearly 30% consisting of infertile land. The ecosystem is immature with weak erosion resistance and serious desertification. In addition, major and large Chinese rivers originate in this region and it is called "China's water tower;" therefore, it has always been a key area for ecological environmental protection. If mining activities are not strictly controlled, disordered mining activities will damage the ecological environment of the plateau.

Regional technological and economic conditions in Tibet are lagging behind those in the rest of China. In contrast to the well-developed economy in Eastern China, the power infrastructure construction of Tibet is backward. Until 2017, the total installed capacity of the local power grid in Tibet was 2.807×10^6 kW and the power generation capacity of the local power grid was 5.844×10^9 kW·h. This level can only ensure the electrical uses of the local economy, social development, and people's demand for production and living. The industrial power is also occasionally rationed to feed the livelihood needs of the people.

The cost of mineral resource exploration and mining exploitation is high. Infrastructure construction is still an important factor restricting the exploration and exploitation of mineral resources in Tibet. Infrastructure facilities such as transportation and communication still need to be strengthened. In addition, it is still difficult to exploit and utilize some associated minerals, resulting in high costs for mineral resource exploration and mining exploitation.

The labor force structure is one-fold. Tibet is located in the southwest of the Qinghai–Tibet Plateau. Areas above an altitude of 4000 m account for 85.1% of the total area of the region. Tibet is known as the "Roof of the World" and the "Third Pole." Laborers from the remaining parts of China who enter this area feel an obvious sense of displacement. Tibet has a local resident population of 3.3054 million people, a small population with relatively low levels of education and few skilled workers. The labor force is obviously insufficient, which also imposes an impact on mining exploitation.

4 Prospects for exploitation and utilization

Mineral resources are an important part of land resources and an important foundation for national economic construction. Tibet is endowed with abundant copper resources. Scientific and reasonable exploitation and utilization of copper resources are important means to realize the requirements of the 6th Working Conference on Tibet held by the Central Government, namely, "enriching the people and prospering the Tibetan areas, building the area in the long term, promoting the well-being of people of all ethnic groups, and accelerating the pace of comprehensively building a well-off society in Tibet." Meanwhile, it can improve the utilization pattern of copper resources in China. Therefore, based on the reality in Tibet, this paper makes the following suggestions concerning the exploitation and utilization of copper resources.

4.1 Ensure the minimum production capacity of the three major copper metallogenic belts, realize regional coordinated development of copper resource, and ensure the safety of copper resources in China

The three major metallogenic belts in Tibet may achieve a certain production capacity within 5 years. Based on the development of the Yulong copper mine, Eastern Tibet will realize a daily processing of 1×10^5 t of copper ores. The three major mineral deposits of Jiama, Qulong, and Xiongcun are the main green development mines in Central Tibet, with an annual output of 3.5×10^5 t of refined product, ensuring the security of copper resources in China. In Western Tibet, the first area to be developed will be the Gaerqiong–Galale district. The gold resources in this district are greater than 70 t, and the prospective resources are up to 100 t. The transportation conditions in this district are relatively good. The economic development of the Gaerqiong–Galale district will play an important role in the social economy development of the Ngari Prefecture. On the premise of mature conditions, priority should be given to the development of the Tiegelongnan copper–gold deposit in the Duolong district.

It is suggested that the construction plan of the Western Tibet (Nagqu–Shiquanhe) railway should be started as soon as possible, which not only will promote the exploitation of copper-rich polymetallic mineral resources in Western Tibet and promote local employment but also will have important military significance. This is of obvious importance to the security of the India–China border.

4.2 Increase macro-control, improve the efficiency of copper resource exploitation, and lead resource exploitation in an orderly manner

Tibet is located in a remote area, and its transportation system has not yet been fully established. If ore mining and

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primary smelting are conducted without the development of local copper refining industry and copper processing industry, it will not only cause waste with respect to transportation but will also affect the development benefits of the copper resources. While building the copper resource reserve bases, we need to start to formulate a construction plan for the local copper industry system as soon as possible.

According to the *Standardization Conditions for Copper Smelting Industry* issued by the Ministry of Industry and Information Technology on April 14, 2014, higher requirements have been put forward for the scale, technology, and environmental protection capabilities of the newly built copper smelting projects. The document encourages enterprises to simultaneously process copper concentrates and secondary copper-containing resources, with a smelting capacity of over 1×10^5 t/a (inclusive). It is suggested that while the local copper industry system is planned, leading enterprises should be encouraged to build smelting projects in suitable areas via alliances between giant companies with unified production and unified pollution treatments to minimize the impact on the environment.

4.3 Realize the coordinated development of resource exploration and exploitation and environmental protection

Tibet, due to its high altitude, low oxygen concentration, and strong ultraviolet radiation, has a special natural environment and extremely fragile ecology. Before exploring the copper resources in Tibet, attention should first be paid to avoiding factors that can damage the plateau environment. For example, water, land, biological, and other resources as well as geological disasters caused by mining should be considered [17]. An emphasis should be placed on the following aspects.

Adhering to the Scientific Outlook on Development and the green development concept of respecting, conforming to, and protecting nature, we should not only strengthen restrictions and management in terms of policies but also enhance the environmental protection awareness of mining enterprises themselves. Further, we should develop new technologies to allow green exploration of mineral resources and mining exploration and strictly control ecological and industrial indicators.

The copper deposits in Tibet are primarily porphyry and related deposit types with shallow burial depths suitable for strip mining. Therefore, in future mine designs, the former extensive exploration and development approach should be changed and the waste rock pile sites and tailing reservoirs in mining areas should be rationally planned to increase the land utilization and prevent the destruction of land resources [18].

In the copper smelting process, pyrometallurgy, as a traditional copper smelting strategy, is currently the main copper production method and is suitable for copper sulfide. Hydrometallurgy includes sulfuric acid leaching–extraction–electrowinning and bacterial leaching methods and is considered in the industry to be a mature, low-cost, and low-risk technology [19]. For example, the Morenci Cu–Mo deposit in Arizona, USA, has implemented “zero emissions” in the mining area, which means that all waste liquids are recycled, therefore achieving positive environmental benefits. In addition, the bacterial leaching process has been successfully applied in the mining areas of Dabaoshan in Guangdong and Zijinshan in Fujian. Compared to traditional pyrometallurgy, the hydrometallurgical copper production method has advantages such as simple processing, low cost, high recovery degree of comprehensive metal, and no sulfur dioxide pollution, as well as having a stronger capability of processing low-grade complex ores and copper-containing waste ores. Meanwhile, in Tibet, where water and electricity are scarce and traffic conditions are inconvenient, electrolytic copper can be produced locally, saving approximately 80% of the freight costs [20]. Therefore, it is necessary to vigorously promote this environmentally friendly copper smelting method in Tibet, where environmental requirements are increasingly strict and regional technological and economic conditions are underdeveloped.

Acidic wastewater formed during copper mining may easily pollute downstream water bodies. Real-time monitoring of the industrial “three waste” (i.e., waste gas, waste water, and waste residual) emission indexes should be strengthened during mining to prevent environmental safety accidents.

The environmental impact of copper development in Tibet can be minimized and several new mining enterprises for green development can be built if the abovementioned technical treatments are implemented. Based on the domestic and international experience, the impact of high-standard green mining exploitation on the environment is controllable and limited. It is necessary to change the traditional understanding that “mining exploitation will definitely destroy the environment.” Chile and Peru in South America, with the largest-scale copper deposits in the world, account for more than half of the worldwide copper production capacity. The exploitation of resources there not only has made great contributions to these countries but also has completely changed the local economic outlook and community development. For example, the largest porphyry copper deposits in Chile, the Los Bronces–Rio

Blanco Cu–Au deposit (with 2.2×10^8 t of metal copper reserves) and the El Teniente Cu–Au deposit (with 1.2×10^8 t of metal copper reserves), are located approximately 100 km and 120 km, respectively, northeast of the Chilean capital of Santiago. The exploitation and utilization of these deposits did not cause environmental problems in the capital region but rather supported the economic development of the country and even controlled the lifeblood of the copper resource supply worldwide.

4.4 Further strengthen investments in resource exploration and ascertain the resources in Tibet

In recent years, great progress has been made in the exploration of copper resources in Tibet. Several world-class deposits and metallogenic belts have been identified, and the amount of resources discovered has increased significantly. However, the current economic base reserves are small and the overall resource supply is low, far from meeting the demands of mining development. Therefore, it is necessary to further strengthen investments in resource exploration and statistically evaluate the resources in Tibet.

There are three key directions for mineral resource exploration: (1) conduct supplementary exploration of known mining areas, improve the exploration level of mining areas, and increase economic basic reserves; (2) intensify the exploration in deep and peripheral locations for second prospecting spaces; and (3) strengthen the exploration intensity and metallogenic prediction of new areas in key metallogenic belts to find new ore districts.

The biggest problem of exploration investment lies in the shortage of funds. We need to make full use of policy levers to encourage mining enterprises to increase exploration investment, speed up the construction of the mining rights market, and increase the proportion of commercial exploration funds in the exploration area. Meanwhile, we should increase social capital via investment promotion, bid auctions, listings, and other means. National and provincial geological exploration funds should focus on public welfare exploration so as to attract more commercial exploration funds with corresponding exploration results.

When setting up mining rights, priority should be given with respect to the scale of copper mines and the minimum mining scale of mines, so as to guide mining enterprises in areas with concentrated mineralization to gradually realize joint reorganizations and to integrate and form joint-stock mining companies with intensive and large-scale operations. Small deposits or ore occurrences with limited resources that cannot be developed on a large scale often cause destruction and the waste of resources, and the environmental cost is usually relatively high. Therefore, such mining enterprises should be discouraged.

4.5 Optimize the mining designs of copper deposits and promote the comprehensive utilization of mineral resources

The amounts of non-biological solid substances required to produce one tonne of raw copper ore, refined product, and crude copper are 2.5 t, 100 t, and 450 t, respectively, and the amounts of water required are 0.35 t, 25 t, and 200 t, respectively [21]. Therefore, to optimize and reduce the material input for copper production, we should start with an optimization of the copper mining design and reduce the energy consumption in mineral processing and smelting as much as possible.

The current determination of ore body boundaries in China is based on industrial indicators such as the cutoff grade, the minimum industrial grade, and the rock eliminating thickness, which lack economic connotations. The determination of industrial indexes for copper resources should be based on economic benefits. According to the technical performance of ore processing and the 10-year average price of copper in the international market, the corresponding design institutes should issue recommendations for industrial indicators.

Most copper deposits in Tibet possess associated minerals, and there are few independent copper deposits. In the process of exploitation and utilization, the comprehensive utilization of the associated minerals should be strengthened. In accordance with the principle of "making the fullest use," gold, silver, and molybdenum as well as the lead and zinc concomitants in porphyry–skarn–epithermal deposits should be comprehensively utilized in an all-round and mandatory way, so as to firmly make full use of resources, increase the value of associated minerals, and ensure green and environmentally friendly exploitation.

5 Conclusions

Tibet has abundant copper resources; copper is one of the most important dominant minerals in the Qinghai–Tibet Plateau and has received strong policy support. However, due to factors such as its fragile ecological environment, poor infrastructure, high development cost, unreasonable labor structure, and few basic economic reserves, low-grade copper ore bodies are difficult to mine in a short term, which means the overall guarantee degree of

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resources is not high. All these factors limit the exploitation and utilization of copper resources in Tibet. Scientific and reasonable exploitation and utilization of copper resources in Tibet are of significance for ensuring a reasonable distribution pattern and sustainable supply of copper resources in China, promoting the construction of the natural ecological civilization, and stimulating the economy and employment in Tibet.

To scientifically and rationally exploit and utilize the copper resources in Tibet, we should change the traditional method of exploitation and strengthen macro-control from the viewpoints of the environmental, economic, and social benefits of resources. By optimizing the mining design of copper mines, adopting environmentally friendly smelting technology, and handling the relationship between mineral resource exploration, mining exploitation, and environmental protection, we can build new copper exploitation bases using green exploration, development, and smelting to improve the benefits of resource exploitation and ensure coordinated development between the environment and economy.

The construction of green copper resource exploitation bases in the major copper metallogenic belts in Tibet can provide an important resource guarantee for China to deal with the complicated international situation and achieve a reasonable distribution of domestic copper resource production capacity. Meanwhile, it can also benefit the economy, society, and environment via the exploitation of copper resources, promote the stable development of Tibet, and realize the targeted poverty alleviation.

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