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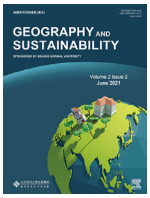

Perspective

Mineral Resource Science in China: Review and perspective

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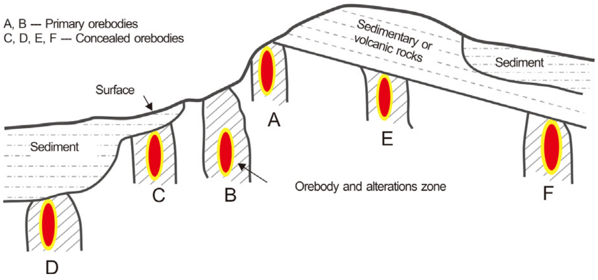
HIGHLIGHTS

- Mineral resources are essential to the prosperity and security of modern societies.
- Major advances of the research on mineral resources is summarized.
- Some key issues regarding ore-forming mechanism, exploration and utilization of major and critical mineral resources are proposed.
- Four potentially important research fields to be further developed in the future are suggested.

GRAPHICAL ABSTRACT



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ABSTRACT

Mineral resources are essential to prosperity and security of modern societies. How mineral resources can guarantee sustainable development of economy in countries, especially those developing countries, has long been a focus of attention of international communities. This paper provides a comprehensive summary for major advance of the research on mineral resources in past decades, and proposes some key issues regarding ore-forming mechanism, exploration and utilization of major and critical mineral resources. On the basis of these aspects, we also identify four priority science issues to be addressed in the future, including (1) mechanism of both metal circulation and extremely high concentration, (2) theories and technologies of prospecting deep-earth resources, (3) investigation of mineral resources in seafloor and polar regions, and (4) efficient, clean and recycling utilization of mineral resources. It can be expected that new advances in these four issues would tremendously promote the innovation of mineral resource science, and provide scientific and technologic support to meet the demand of mineral resources for human activities and the harmonious development of both mineral-resource exploration and ecological restoration.

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1. Introduction

Mineral resources are crucial material foundation for economic and social development. With progressive advances of global industrialization, especially those in developing countries, it is expected that global demand for mineral resources will continue to grow rapidly in the coming decades. Therefore, how to meet the global demand of major resources for sustainable development has been a focus of attention of international communities.

Prospecting of mineral resources has been evolved from experience to theory and technology in the past decades. Prospecting via theory and technology is guided by geological principles, and is aimed to determine where the ore bodies are located using advanced exploration techniques. Therefore, the innovation of mineral resource science is the only way to meet continual demand of resources for modern societies. In the past decades, a number of major breakthroughs on key scientific and technological issues concerning resource demands have greatly enriched the connotation of mineral resource science. The cycle of innovation-practice is an inexhaustible driving force to the progressive development of mineral resource science.

Mineral resource science is an important component of earth sciences and resource and environmental sciences, mainly focusing on the ore-forming mechanisms, exploration techniques, and utilization of mineral deposits (Hu et al., 2010). Different mineral resources may have formed at some particular stages in Earth's history and are usually associated with great geological and environmental events (Zhai, 2010). They are important proxies to reconstruct geological and environmental events and evolutionary processes of the Earth. Therefore, development of mineral resource science can not only promote earth and environmental sciences to reveal the mystery of the Earth and establish the theory of earth system science, but can also provide theoretical "cornerstone" to meet the resource demands of modern societies.

In general, there are four major trends for the demands of mineral resources in future China. They include (1) The total demand of mineral resources for sustainable development of economy and society will keep at a high level, and there is still a long way to go to ensure sufficient, stable and safe supply of major and basic mineral resources, (2) The global new technological revolution, advanced manufacturing and national defense security require profound changes of demand for the type and quality of mineral resources, and it is urgent to strengthen the theory research and exploration technology of strategic and critical metals, (3) Severe problems in ecologic environment and high-quality transformation and development of domestic economy urgently require to improve the utilization of mineral resources from extensive style to green, low-carbon and environment-friendly style, (4) The competition for resource control among countries is increasingly fierce, and the approach of "base in domestic and utilize overseas" will still be the basic strategy to ensure resource security of China.

Current supply and demand of mineral resources in China is very challenging (Zhai et al., 2019). It is difficult to change the severe situation of the lower per capita resource amount comparing with the world average level in a short term. Considering the consumption of 40 major types of mineral resources in China, 32 types are the highest consumption worldwide and 24 types account for more than 40% of the global total consumption (Fig. 1). The external dependence of 18 major and critical metals remains fairly high (40%-99%) (Fig. 2), threatening the country's economic security. In recent years, the strategic mineral resources such as rare earth elements (REE) and some rare dispersed elements in China show a declining trend in the proportion of global reserves. The superiority or position of China in supplying mineral resources is being challenged, weakening the international "discourse power". It is urgent to change such passive situation and strengthen scientific and technological innovation of mineral resources in China. We should first clarify the summation and global patterns of mineral resources. If China can break through a series of theory and technical bottlenecks in ore-forming mechanism, exploration, and development and utilization of resources, it would be eventually able to guarantee the demands of mineral resources and coordinate the relationship between resource development and ecological environment. Meanwhile, it is also necessary to promote the development of mineral resource discipline. In this review paper, we will first summarize recent progresses of mineral resource science, and then emphasize future research highlights, including key scientific and technological issues.

2. Priority Science issues in mineral resource science

2.1. Relationship between Earth system and metallogenic system

It is commonly thought that metallogenic system can be considered as a special component of Earth system in the prolonged history of the Earth, reflecting the fundamental controls of Earth's sphere-interaction and great geological events on the formation of diverse mineral deposits. While subduction-related metallogenesis remains to be the focus of many research studies, metallogeny associated with syn-collisional and intraplate setting has become new research highlights. More attention has also been paid to the comparative study of different metallogenic provinces and belts in a giant metallogenic domain. On the basis of acknowledge of source and deposition of metallic elements, precise ore-forming processes and evolution are critical for a better understanding of ore genesis. Metallogenic modelling tends to integrate different deposits or deposit types other than a single deposit, aiming to develop a model for regional metallogenic system.

2.2. Mineral exploration towards undercover and deep earth

With the development of mineral exploration, it is getting more and more difficult to discover mineral deposits in surface or near surface regions of the crust. Thus, going deeper from the known deposits or shifting towards undercover has become a new destination in current exploration projects (Fig. 3). Compared with exploring near surface and shallow-crustal level ore bodies, mineral exploration towards the deep crust and undercover is highly challenging, and needs to resolve a series of theoretical and technical problems.

In recent years, many countries with cutting-edge technology in mining industry have taken visionary plans to launch major research projects, set up research and development institutions, innovate mineralization theories, and develop deep exploration technologies. For example, Australia has launched projects like Uncover and AuScope to uncover the overburden area and reveal deep resources. The European Union (EU) has started the HiTech AlkCarb project to develop new geological models and sustainable exploration methods in the alkaline rocks-carbonatite complex. Canada has successfully accomplished the LithosProbe Program, where one of the major tasks was to test and develop reflection seismic methods for the deep mineral exploration. These deep-targeting programs have made significant progresses in understanding holistic mineralization processes, and developing new deep exploration technologies. The concept of mineral system has been developed and improved, and the mineral system-based targeting approach has been built. In addition, techniques such as seismic reflection of mineral deposits, three-dimensional electromagnetic detection and interpretation, and lithologic mapping, have also been developed, providing advanced technical solutions for mineral exploration at depth.

2.3. Critical minerals

Critical metals or critical minerals are new resource concepts in recent years, which refer to some mineral resources that are highly demanded in modern societies and also have high risk of safe supply. They include rare earth elements, rare metals, rare dispersed metals and rare precious metals (Zhai et al., 2019), as well as radioactive metals. These metals have unique physical, chemical and thermodynamic properties, and are irreplaceable in high-tech industry. It is predicted that global

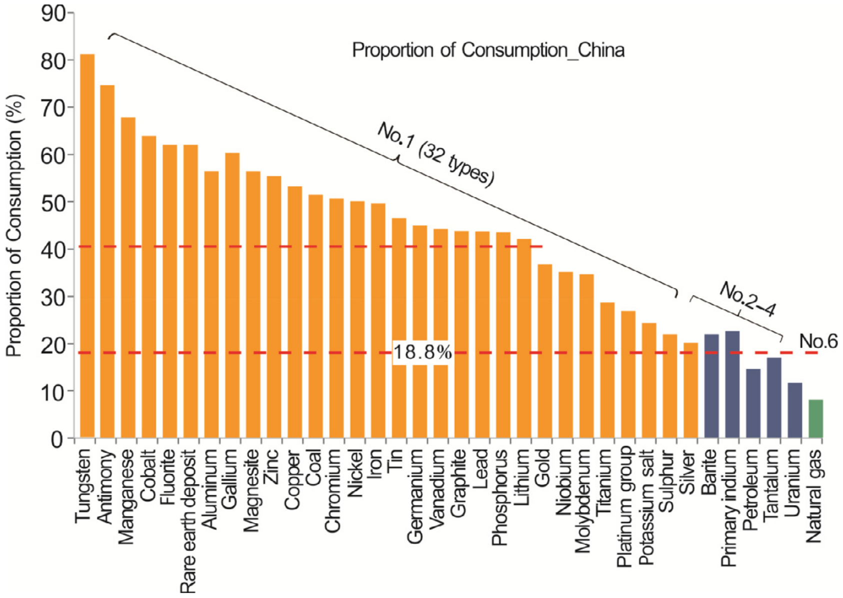

Fig. 1. Proportion of China's consumption of mineral resources in 2018.
Data from the Research Center for Strategy of Global Mineral Resources and Chinese Academy of Geological Sciences, 2019.

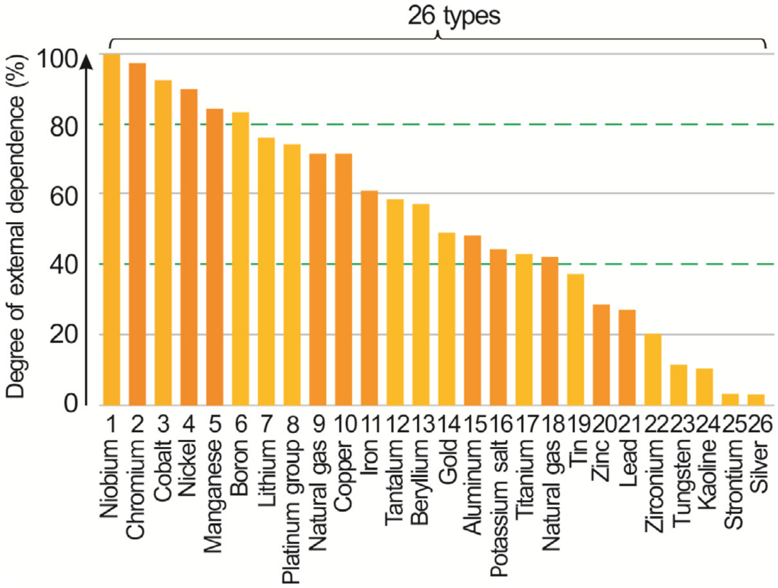

Fig. 2. The degree of external dependence of mineral resources of China in 2018.
Data from the Research Center for Strategy of Global Mineral Resources and Chinese Academy of Geological Sciences, 2019.

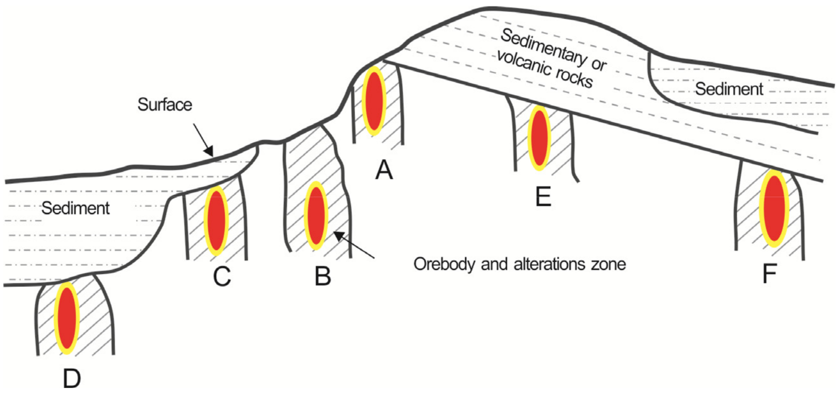

Fig. 3. The spatial distribution of various ore bodies, in which the concealed orebodies C, D, E and F are the main targets for the deep mineral exploration in the future (modified from Wang et al., 2016).

demands for critical metals will grow rapidly in the next decades, and the competion between supply and demand will become increasingly prominent. In the future, the international competition in mineral resources and science and technology will depend on who will control the resources of critical metals (Zhai et al., 2019). Many countries have realized that current research level of critical metal mineralization and related metallogenic theory and exploration technology cannot meet the requirement for rapid development and utilization of critical metals. In this scenario, some western countries and unions, such as the United States, EU, Japan and Australia, have made domestic development strategies and major research plans for critical metals. They have funded systematic studies on mineralization mechanism of critical metals, prospecting exploration and efficient utilization. Recent advances on these aspects have enhanced our understanding for critical metals and their global supply and demand patterns.

2.4. Mineral resources in the marine and polar regions

Nearly half of Earth's areal seabed is the "international seabed area". According to the United Nations Convention on the Law of the Sea, subsoil and its resources in the seabed are common to all mankind. As a strategic replacement area of mineral resources on land, deep sea areas have been surveyed and four types of mineral resources were discovered, *i.e.*, polymetallic manganese nodules, cobalt-rich crusts, hydrothermal sulfides, and REE-rich sediments (Liu et al., 2014). The ore reserves of the deep sea areas are expected to be huge, far beyond the total amounts of proved metal reserves of manganese, copper, nickel, cobalt, lead, zinc, rare earth and platinum-group elements on land, which provide potential for future mineral resources. Many countries, especially western countries, have strengthened the investigation and research for mineral resources in the seabed. It is also time for China to carry out more research and exploration on the resources in the seabed.

The mineral resources in polar regions have been discovered in both land and sea. More than 220 types of energy and mineral resources have been discovered in the Antarctic land, including coal, petroleum, natural gas, iron, copper, aluminum, lead, zinc, manganese, nickel, gold, silver, graphite, diamond, thorium, plutonium and uranium. These may nearly cover all known natural resources so far in the world, of which more than 30 types with important potential (Chinese Arctic and Antarctic Administration in State Oceanic Administration, 2016). The Arctic land also contains abundant energy and mineral resources, in particular those of coal, iron, gold, silver, copper, lead, zinc, nickel and molybdenum. The important energy resources in the Arctic seas and seas around Antarctica include mainly oil gas and natural gas hydrates. Due to the restriction of "The Protocol on Environmental Protection to the Antarctic Treaty" (signed in 1991 and put into force in 1998) and the sovereignty issue of the Arctic land, it is nearly impossible to explore the polar resources, especially those in the Antarctic land in the near decades. However, it is still necessary to carry out studies on the distribution, mineralization mechanism, and prospective reserves of the mineral resources in the polar regions for future development and utilization.

2.5. Clean and recycling utilization of mineral resources

Many western countries have launched intensive research on efficient utilization of clean energy and recycling of mineral resources. In particular, they have strengthened fundamental research and enhanced the capability of initial innovation, such as ecological environment, processing equipment, integrated innovation in the technology application, inter-connection between the product quality-performance and high-end manufacture. Moreover, artificial intelligence (AI) and information technology are also penetrated and connected with the development and utilization of mineral resources. On the contrary, mining industry in most developing countries is associated with low-level and inefficiency resource utilization, higher wastage, and severe ecological and environmental problems. A crucial mission for these countries is to seek an efficient way to utilize clean and recycled mineral resources via scientific and technological innovation.

2.6. Revolution of new technology in mineral resource science

The revolution of high-precision and high-sensitivity analytical techniques and experiments has greatly enhanced the development of mineral resource science. In recent years, a number of micro-beam analytical techniques, such as the ion microprobe (SIMS), proton microprobe (PIXE), and the laser ablation plasma mass spectrometry (LA-ICP-MS), have been developed to obtain accurate mineralization ages, to constrain the source of ore-forming metals and fluids, and to link the mineralization with coherent geological events. For example, the spatial distribution of elements and isotopic compositions in mineral scale of the ore samples can be used to decipher complex ore-forming processes of mineral deposits (Gopon et al., 2019), which otherwise are hardly recorded in the bulk compositions of the ores.

The innovation of exploration techniques has given rise to new metallogenic theory and new exploration techniques. The results of seismic wave velocity and electrical conductivity in the lithosphere and upper mantle show that the high-conductivity and low-velocity blocks in the upper mantle correspond well with the distribution of mineral deposits in the upper crust. A good example is that the diamond-bearing kimberlites in the Kaapvaal Craton, South Africa, are mainly distributed on the boundary of the high-resistivity and high-conductivity blocks. The low-velocity block is considered to be the enriched lithospheric mantle that was metasomatized by fluids and is likely the source of many important metallogenic systems. The mobile platform integrated geophysical exploration technology represented by the airborne gravity gradient survey is changing the traditional mineral exploration mode. It is now possible to provide rapid exploration and evaluation for large "inaccessible" areas. Meanwhile, the integrated gravity, magnetic and electrical three-dimensional inversion interpretation, joint inversion of multiple data types and three-dimensional mapping technology have greatly improved the accuracy of deep resource exploration, which is now able to explore the underground below 2000 m depth.

Exploration geochemical methods are developed to analyze element concentrations and states in micro scale, even nanometer or molecular scale. The development of penetrating geochemical exploration technology has significantly improved the successful rate of geochemical exploration for the deep mineral resources in overburden areas. The updated theories of geochemical exploration have been used in practice; the suspected geochemical anomaly model has been proven in real mines, and the large-scale multi-layer nested geochemical anomaly theory has become the basis of geochemical mapping and global-scale geochemical model.

New advanced technologies such as big data and artificial intelligence have also been applied to mineral exploration, which may lead to a new-round scientific and technological revolution in mineral resource science. Given the prospects on both "efficient exploration prediction" and "scientific ecological assessment", artificial intelligence and big data can be used to extract efficiently and analyze comprehensive data sets of mineral resources and exploration, generating a terminal intelligent operating system. In this fashion, highly artificial intelligence techniques of mineral resource exploration and development is expected to be established in the near future.

3. Research progresses in China

The understanding of the formation, successful exploration, and economic exploration of mineral resources is of critical importance to China's modernization. Here we present an overview on current states and major progresses of mineral resource science in China.

3.1. Metallogenic theory and metallogenic regularity

China is located in the junction of the paleo-Pacific, paleo-Asian and Tethyan metallogenic domains, which is an ideal natural laboratory for metallogenic theory innovation (National Natural Science Foundation of China and Chinese Academy of Sciences, 2020). The North China Craton, the Tibetan Gangdese, the Sanjiang-Tethys, and the central Asian orogens, the middle-lower reaches of the Yangtze River, and the South China Block are important metallogenic provinces in China and have been intensively investigated in the past decades. Recent advances in earth system science and experimental and analytical techniques have greatly promoted multi-disciplinary research on many important issues of metallogeny, such as timing and evolution of mineralization, sources and evolution of ore-forming fluids, transportation and enrichment of ore-forming metals, structure of metallogenic system, mineral deposit models, and tectonic settings and geodynamics related to regional mineralization. Significant achievement and great successes have been made in metallogeny and ore genesis associated with early evolution of cratonic blocks, destruction of the North China Craton, collisional orogeny from Precambrian to Phanerozoic, intracontinental tectonic reactivation, and plume-related magmatism (e.g., Wang et al., 2014; Hu et al., 2017; Zheng et al., 2019; Li et al., 2019; Mao et al., 2019; Hou et al., 2020; Jiang et al., 2020a,b; Zhai et al., 2020; Zhu and Sun, 2021). These progresses have greatly contributed to the metallogenic theories in a global system.

The understanding of the formation, distribution and evolution of mineral deposits is a key to the innovation of metallogenic theories. In the last decade, numerous studies have been carried out for many important types of mineral deposits in main metallogenic zones, unravelling metallogenic regularity in different levels and scales (e.g., Li et al., 2019). These studies revealed the spatial and temporal distribution of mineral deposits and linked the ore-related tectonic settings and metallogenic evolution, so that regional metallogenic series and metallogenic systems can be precisely defined (e.g., Yu et al., 2020). To date, a new-round of research and integration on the metallogenic regularity of important mineral resources and major geological units in China has been completed with a series of maps of metallogenic regularity of specific mineral resources, providing important foundation to evaluate mineral resources potential (e.g., Wang et al., 2014; Ye et al., 2016). Meanwhile, the metallogenic regularity of major mineral resources in neighboring countries, such as those in Central Asia and Southeast Asia, has also been investigated to ensure the successful mineral exploration in overseas.

Critical mineral resources in China, such as Li, Be, Nb, Ta, W, Sn, Ge, In, Ga, Re, Se, Cd, Te, Tl, REE, Ni, Co, Pt and U, have been systematically investigated in the past few decades. Important advances include identification of main deposit types, reconstruction of tectonic settings where the deposits occur, delineation of important metallogenic belts and their spatial and temporal distribution (Mao et al., 2019; Li et al., 2019; Zhai et al., 2019; Jiang et al., 2020a, b). Meanwhile, some new deposit types of critical mineral resources have been recognized (Wen et al., 2020; Jiang et al., 2020b). The outcomes of these researches have laid the foundation for further study of metallogenic theory, resource evaluation, and utilization of critical mineral resources. Furthermore, a Major Research Plan of the National Natural Science Foundation of China has recently been launched for the research on metallogeny and utilization of critical mineral resources.

In the last two decades, there were three profound trends in the study of metallogenic theory and metallogenic regularity. First, metallogenesis has been commonly interpreted in the context of earth system science. The roles of catastrophic geological events and the asthenosphere-lithosphere-atmosphere interactions on massive transport and unusual enrichment of metallic elements and large-scale mineralization have been eventually recognized (e.g., Hu et al., 2017; Zhai et al., 2020). Second, interdisciplinary research has increasingly promoted the innovation of continental metallogenic theory, such as the Gangdese porphyry Cu belt in the Tibetan plateau (Yang and Cooke, 2019; Hou et al., 2020). Third, studies of metallogenic theory and metallogenic regularity have made breakthroughs in mineral prospecting and exploration (e.g., Deng et al., 2019; Yu et al., 2020).

Although significant progresses have been made in the metallogenic theories in China, some key issues need to be further strengthened and emphasized, including (1) The role of global tectonics and geodynamics in a specific metallogenic belt or province should be examined, so that the ore genetic models established based on the mineral deposits in China can be well recognized worldwide, (2) The theoretical research of metallogenic mechanism should be integrated to enhance mineral exploration, (3) The research institutes should be encouraged to collaborate with mining companies, working on the issues that are really concernes by mining companies, and (4) Some subjects such as ore field-scale structure geology, ore mineralogy, experimental metallogeny, mineral exploration, metallogenic dynamics, and numerical simulation of ore-forming process, should be upgraded and oriented to facilitate the innovation of metallogenic theory and successful exploration.

3.2. Exploration and evaluation of mineral resources

In the past decade, China has made great breakthrough in prospecting ferrous metals, nonferrous metals, precious metals, rare earth elements and radioactive metals with the aid of metallogenic theories and decent financial supports for geological exploration (e.g., Ye et al., 2016; Chang and Goldfarb, 2019; Yu et al., 2020). The newly discovered gold reserves exceed 1,000 tons, including two giant and several large- to medium-sized deposits. These deposits were mainly formed during the late Paleozoic and Mesozoic in the Jiaodong Peninsula in the North China Craton, the Yangtze Block, and the southwestern Tianshan in the central Asian orogenic belt. Substantially high reserves of gold are also reported in some Cu-Au porphyry deposits, including the early Cretaceous Naruo deposit in the Tibetan Plateau and the Shaxi deposit in the Anhui province. The big breakthrough of prospecting porphyry copper deposit is the discovery of the Naruo and Qingcaoshan deposits in the Tibetan Plateau and the Chating deposit in Anhui province. Six newly discovered early Cretaceous porphyry molybdenum deposits are estimated to have the total ore reserves of more than 2.5 Mt. They are mainly located in the northern margin of the North China Craton and the central Asian orogenic belt. The most typical is the Caosiyao super-large molybdenum deposit in the Inner Mongolia.

The middle-lower reaches of the Yangtze River has been explored to host the early Cretaceous iron and tungsten deposits. They are mainly skarn deposits and contain over 500 Mt of Fe and 5 Mt WO_3. Eight large Pb-Zn deposits have been discovered in the Tibetan Plateau, Xinjiang, Guizhou and Gansu provinces, with the total Pb and Zn reserves of more than 48 Mt. Seventeen REE deposits have been discovered in Zhejiang, Jiangxi, Fujian and Yunnan provinces. They are either iron-oxide type or clay-adsorption type, with the total reserves of rare earth oxides being over 1.38 Mt.

Recent progresses on the uranium deposits in China extended the prospecting depth from <500 m to 500 to 2000 m. The scientific deep drilling programs accomplished a 2891-m-long borehole in the Xiangshan mountain and a 1709-m-long borehole in the south of Zhuguangshan mountain, and discovered economic uranium ore bodies and polymetallic mineralization in these two regions. In addition, a historic breakthrough has been made in the exploration of the sandstone-type uranium deposit in North China.

Despite these great breakthroughs, the numbers of newly discovered large and super-large deposits have been decreasing dramatically in the past decade compared with the first decade of this century. This is mainly caused by the shrunk financial support for exploration from China's government, more stringent environmental standards for exploration and exploitation, and less enthusiasm of capital markets for exploration. If there is no major adjustment for the policies in the future, these factors will be the main bottleneck to hamper new breakthrough of prospecting in China. Current exploration for major mineral resources in China is aimed to prospecting unknown deep underground and to explore critical mineral resources. The key to breakthrough in the mineral exploration in the next 10 to 15 years is to build a practical and efficient exploration system in China.

The scientific evaluation for metallogenic potential has been a hard task in the international community. In the past decade, new models and methods (digital model, nonlinear multi-information prospecting and prediction model, integrated information interpretation method, three-dimensional visualization quantitative evaluation method, computational information processing and prediction method) have been applied to assess some important mineral resources, advancing the capability of scientific evaluation of metallogenic potential in China. These can predict the metallogenic potential in four aspects, *i.e.*, localization, quantification, accuracy and availability. Twenty-six metallogenic belts and 325 important ore districts have been defined, while 47186 target areas for prospecting have been delineated in China. The ore reserves of 25 important mineral species beneath 500 m, 1000 m and 2000 m from the surface have been predicted. A massive, heterogeneous, multi-scale and multi-disciplinary database of metallogenic potential evaluation for the 25 mineral species in China has been established (e.g., Xiao et al., 2016), which can serve as a scientific foundation for the strategic plan of mineral resources in China.

Because effective diagnostic information of metallogeny at depth is hard to identify, the exploration and evaluation results for the mineral resources at depth become less reliable with the increase of exploration depth. Therefore, it is crucial to develop new prediction methods to reconstruct the spatial distribution of the mineral resources at the depth from 2000 to 4000 m below the surface.

3.3. Development of deep exploration of mineral resources

In order to cope with theoretical and technical challenges of deep exploration of mineral resources, China has successively carried out multi-scale deep exploration and metallogenic prediction research in the past decade. Within the framework of the metallogenic system theory, deep exploration is tightly integrated with the mineralization process and metallogenic prediction. The "traces" left by the mineralization are identified in different scales, and a new concept of multi-scale metallogenic prediction has been proposed.

On the regional scale, the deep lithospheric structure has been explored in several metallogenic belts in the Tibetan Gangdese, Central Asia, and South China. It is presumed that the deep processes of lithospheric tearing, delamination and subduction may have triggered metallogenic systems. Ore-forming melts/fluids may have been generated by the interaction of the lithosphere and asthenosphere. The distribution of metallogenic belts are likely controlled by the lithospheric structure and crustal block boundary. Based on these assumptions, a new method of regional metallogenic prediction, integrating deep exploration data, machine learning and artificial intelligence, is put forward. The three dimensional (3D) "transparent" exploration has been carried out in a scale of mineral deposit cluster. The 3D geological modeling technology is conducted in the metallogenic belts of the Tibetan Gangdese, East Junggar, and the middle-lower reaches of the Yangtze River, which is guided by the idea of "3D structure + mineralization model + integrated information" (Lü et al., 2017). With the implementation of the National Crisis Mine Special Project, a three-in-one prediction model of "metallogenic geological body, metallogenic structural plane and metallogenic characteristics" has been put forward based on a large number of deep exploration practice. These efforts effectively guide the deep exploration. In the scale of a mineral deposit, the deep exploration methods have catered to different types of deposits such as porphyry Cu (Mo) deposits, skarn Fe-Cu deposits, IOCG deposits, epithermal deposits and Jiaodong-type Au deposits. Great progress has been made in prospecting strata-bound and ductile shear zone deposits by seismic technology of metallic deposits.

In the past decade, China has made breakthroughs in the research and development of core technology and equipment for deep exploration. Major achievement include the high-precision microgravity sensor, high-precision digital gravimeter, software systems used in geophysical data processing and interpretation, and more than 10 new methods of deep exploration. The overall technical parameters of the technology and equipment stated above have reached or exceeded international levels. These progresses have significantly improved the research independency and international competitiveness of China in the deep exploration of mineral resources, getting rid of the dependence upon import softwares/hardwares, and further updating the theory of geophysical exploration.

However, there are still a lot of problems in the deep exploration in China, due to the complex evolution history of continents, interweaving mineralization stages and varied topography. These include (1) the ambiguous understanding of the spatial-temporal relationship and genetic link between the deep exploration results and the "trace" of mineral systems, (2) the lack of a multi-scale metallogenic prediction index system based on metallogenic system theory, and a deep prediction technology realm based on big data, machine learning and artificial intelligence, (3) the backward exploration technology of high-speed mobile platform missing the needs of deep exploration and evaluation in large areas, and (4) the three-dimensional exploration technology of gravity, magnetic, electric, electro-magnetic and inversion interpretation able to finely detect the mineral resources at depths ≥3000 m.

3.4. Polar and deep-sea resource survey

In the 1950s to 1980s, international scientific community conducted the survey of mineral resources in three metallogenic regions in the Antarctic continent, *i.e.*, the Antarctic Peninsula polymetallic (Cu, Pt, Au, Ag, Cr, Ni, Co, etc.) mineralization area, coal and polymetallic (U, Cu, Zn, Au, Ag, Sn, etc.) mineralization area near Transantarctic Mountains, and iron mineralization area in East Antarctic (also Cu, Mo, Pt and other nonferrous metals). Among them, the South Prince Charles iron mine near Chinese Zhongshan Station in East Antarctic continent, may be one of the largest super-large iron deposits in the world.

Due to the restriction of “The Protocol on Environmental Protection to the Antarctic Treaty”, the investigation of the Antarctic mineral resources conducted by international community has almost stalled in the past 30 years. Our investigation in this area is restricted to collect data in the literature, assessing the resource potential and mineralization. During the “Twelfth Five-Year Plan” period, a 1:25,000 geological mapping in sectional Lasman Hills was carried out to theoretically study the distribution of iron mineralization and its potential. In addition, a geological survey was conducted in the Permian-Triassic Emory Group sedimentary basins with high organic matter in the North Prince Charles Mountain, in order to constrain the distribution range, sedimentary sequence and provenance of the sedimentary basins. The organic matter and hydrates in the marine strata near the Antarctic have been preliminarily investigated. However, the investigation of the mineral resources in the Arctic land is limited to data collection in the literature.

After 40-year-long accumulation and development, China has made remarkable advances in the exploration of deep-sea resources, which include five exclusive exploration contract areas of deep-sea mineral resources in the Pacific Ocean and Indian Ocean, three of them for polymetallic nodules, one for cobalt-rich manganese crust and one for polymetallic sulfides. It makes China the owner of deep-sea contract areas with the most complete and numerous ore types in the world. In the past decade, China has made important progress in the deep-sea exploration of mineral resources, deep-sea key technology research and development, formulation of international deep-sea rules, and deep-sea metallogenic theory. Significant progress has been made in the exploration, resource evaluation and metallogenic regularities of the polymetallic nodules and cobalt-rich crust in the Pacific Contract area, providing important information for the better understanding of metal enrichment mechanism, microbial mineralization, isotope records of metals and paleo-ocean evolution (Fu and Wen, 2020). The development of typical high-temperature hydrothermal circulation modeling have illustrated the diversity of hydrothermal processes associated with detachment faults along the ultraslow spreading ridge and provided reliable evidence for the hydrothermal circulation system on the slow to ultra-slow ridges. Large-scale deep-sea REE metallogenic areas have been discovered in the centre of the Indian Ocean basin, southeastern Pacific Basin and Western Pacific Basin. Four REE-rich metallogenic belts have been preliminarily divided in the global scale. The investigation has been carried out for their tectonic setting, environmental background and REE enrichment mechanism. In addition, a series of underwater vehicle platforms and deep-sea acoustic, optical, electric, magnetic and other detection technologies and equipment have been successfully developed and widely applied for the deep-sea exploration of mineral resources.

In general, China conducted limited investigation and research on the mineral resources in polar region in the past 30 years. With the increasing demand for mineral resources, the research of mineral resources in polar region should be strengthened. In the Antarctic continent, it is necessary to equip with the instruments that are capable to investigate mineral resources. In the Arctic region, the investigation, development and utilization of mineral resources should be carried out through international cooperation to deepen the understanding of the potential and mineralization in polar region. In addition, three main problems are very serious in current deep-sea investigation and research on mineral resources, including (1) Most deep-sea survey instruments rely on import, lack of independent research and development, (2) The theoretical research of deep-sea mineralization is limited, lack of knowledge of deep-sea mineralization dynamics and temporal and spatial distribution of benthonic mineral products, and (3) There is lack of comparable research on the terrestrial and marine mineral products, so that the successful theory of terrestrial mineralization cannot be well referred to the exploration of marine mineralization. Additionally, more attention should be paid for the mineral resources in cosmic bodies like moon and planets, expanding and deepening our understanding of the potential and utilization of extraterrestrial mineral resources.

3.5. Efficient, clean and recycling utilization of mineral resources

In the last decade, China has been practicing the concept of innovative and green development. Breakthroughs have been made in the research and development of efficient and clean utilization technology and equipment. These have promoted the conservation and comprehensive utilization of the mineral resources in China (Zhang, 2016; Qi et al., 2019). The major advances in this field are listed below.

The mining and beneficiation technology of mining enterprises has been steadily improved, with new modes of equipment being invented and adopted. More attention has been paid for the recycling of low-grade ores, residual mineral deposits, by-product elements and tailings by mining enterprises. Waste water generated during mining and beneficiation has been recycled. Ecological restoration of the mines has been highly valued. The integrated utilization rates of mineral resources have been continuously improved. A number of green mines that meet the requirement of ecological civilization have been chosen to be the national green mine pilot units. Resource processing enterprises have focused on upgrading technology and developing advanced technologies and equipment in terms of efficient conversion, comprehensive utilization, energy conservation, and environmental protection. These have dramatically improved the efficiency of integrated utilization of mineral resources and reduced the energy consumption and pollutant emission.

The beneficiation processing of ferrous metals and by-product metals has been continuously improved. The techniques have been developed for fluidized roasting of low-grade ores, separation of V and Cr by sub-molten salt method, and efficient and clean utilization of V-rich Ti-magnetite, increasing the recovery rates of V, Ti and Cr by more than 20%. The progress has also been made in the techniques for solid waste reduction from the source.

The advanced production capacities of Cu, Pb and Zn in China account for 99%, 80%, and 87% of the global total capacities, respectively. Energy consumption for smelting has reached the advanced level in the world. The total discharge of heavy metals has been declining. The integrated utilization rates of major strategic mineral resources, such as Ni-Co laterites, have been significantly improved. The by-product Co has been also utilized.

The utilization of REE, Nb, Ta, Zr, Hf, etc., have been gradually shifted from extensive to refined mode. Recovery rates have been increased with the improved processes. Regular products have been eventually replaced with high-value and high-end products.

In addition, the integrated utilization of secondary resources such as metallurgical solid waste and urban minerals has been developed rapidly, enhancing the recycling and utilization rates of the mineral resources. This will reduce the exhaust of raw mineral resources.

Despite the advances mentioned above, the utilization level of the mineral resources in China still needs to be improved. It is of priority to focus on the integrated utilization of tailings, efficient conversion and green separation of critical metals, technology and equipment innovation for high-value products, and the mergence with online monitoring and big data. In addition, *in situ* development and utilization of unconventional resources in the ocean, moon, and planets are research frontiers.

4. Future research highlights

4.1. Key scientific and technological issues

China has long-term and huge demands for mineral resources, but also possesses great prospecting potential. To further enhance and guarantee the capacity of mineral resources in China and the supportive role of earth sciences in scientific and technological innovation, it is urgent to implement a series of large programs and individual investigator-driven innovation researches. This could promote the innovation of ore-forming and ore-prospecting theory, exploration technology, ore processing and metallurgical theory, basic theory of resource substitution and recycling utilization, and meet huge demands for mineral resources in China. This could also coordinate the development of exploration and utilization of mineral resources and ecological restoration and environmental protection, as well as the development of the mineral resources discipline. The key scientific and technological issues include:

(1) The cycling mechanism of ore-forming elements in the Earth, which is focused on the relationship of mineralization with the heterogeneity of continental components, interactions among core, mantle and crust, and great geological events in the Earth;
(2) Accumulation mechanism of extremely high concentration of ore-forming elements, which involves the types and features of sources, conditions of kinetical- and energetic-driven mechanism and activation-transport of source materials, and mechanism and factors controlling extremely high concentration of ore-forming elements;
(3) Prospecting models and exploration technology of mineral deposits, which are mainly focused on the prospecting ore formation models, refined geophysical and geochemical exploration techniques, and big data-driven, integrated AI prospecting;
(4) Theories and techniques related to high-efficient recycling and clean utilization of mineral resources, especially key techniques of free-waste mining and metallurgy, research and development of high-efficient, green metallurgical chemicals, advanced techniques of low-grade complex multi-metal prospecting, and recycling utilization techniques of industrial wastes.

4.2. Key research fields

4.2.1. Mechanism of cycling and extreme concentration of ore-forming elements

Metallogenic theories of major and critical mineral resources in main metallogenic belts and classical ore-forming systems should be developed in the four major tectonic regimes of the Earth, *i.e.*, pre-plate-tectonics, plate subduction, continent-continent collision and intraplate. Major topics of researches may include cycling of elements within the Earth, genetic links between great geological events and mineralization, processes involving element concentration and deposition, experimental modeling and tracing systems of element cycling, and global comparison of major metallogenic belts.

4.2.2. Deep exploration theory and technology of mineral resources

Deep exploration theory and techniques are aimed to discover mineral resources in the deep Earth. The key issues may include the multi-scale, 3D lithospheric structures of major metallogenic belts and the evolution of related ore-forming systems, prospecting and modeling of 3D fine structures in large mineral deposit clusters, deposit-scale index systems of predicting deep mineralization, integrative collection, treatment and interpretation techniques of active- and positive-source geophysical prospecting based on nodal seismograph, techniques and equipment of high-speed removable geophysical prospecting, collection, treatment and interpretation techniques of ground 3D electric magnetic survey (DCIP), and large-scale deep-penetration geochemical exploration techniques.

4.2.3. Investigation of mineral resources in the seabed and polar regions

Investigation of mineral resources in the seabed and polar regions carried out by China is far behind those of western countries. The key issues should be objective to the future competition in the mineral resources of the seabed and polar regions. These may involve investigations of tectonic settings of mineral deposits, mechanism and regularities of ore formation, and techniques and platform of exploration. Given the potential political issues in the seabed and polar regions, we should do our best to avoid unnecessary misunderstanding or detraction.

4.2.4. High-efficient, clean and recycling utilization of mineral resources

The utilization efficiency rates of mineral resources in China are remarkably lower than those in western countries. Scientific and technological innovation must be made to reveal the distribution of metals in ore minerals, to develop the theories of high-efficient clean utilization of by-products, low-grade ores and tailings, and the theories of recycling utilization of mining and industrial wastes. Given the high-quality development strategy in China, recycling cannot be only involved in mining and refining stages, but also should be considered in the waste disposal stage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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