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Characteristics and Exploitation of Rare Earth, Rare Metal, and Rare-Scattered Element Minerals in China

Wang Denghong, Sun Yan, Dai Hongzhang, Guo Weiming, Zhao Zhi, Zhao Ting, Li Jiankang, Wang Chenghui, Huang Fan, Yu Yang, Li Dexian

Key Laboratory of Metallogeny and Mineral Assessment, Ministry of Natural Resources of the PRC, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China

Abstract: China is a country rich in rare earth, rare metal, and rare-scattered element (RRR) minerals, and is a major producer and exporter. However, owing to backward deep-processing technologies, high environmental costs, poor strategic awareness, and other reasons, China does not yet play a prominent role in the global RRR minerals market. As China has entered a critical period, in which the technological innovation drives the social development, the availability of RRR minerals have become vital due to their unlimited potential for innovation. In this paper, based on data accumulated during the investigation and prospecting of RRR minerals from 2011 onwards, we briefly summarize the main characteristics of the RRR minerals, provide some suggestions for their development and utilization, and further emphasize the fundamental idea that "rare earth should be regulated, rare metal should be found when needed, and rare-scattered elements should be used wisely".
Keywords: rare earth, rare metal, and rare-scattered element minerals; resource characteristics; exploitation

1 Main characteristics of rare metal mineral resources in China, and suggestions for their exploitation and utilization

With the exception of strontium, rare metals extracted in China are not competitive in the global market due to the state in which they occur, and the type of the deposits. The trade structure of rare metals is mainly that of low-end exports and high-end imports. It is urgent to strengthen the prospecting, adjust the industrial structure, and widen the fields of application.

1.1 Lithium (Li)

Lithium is mainly used in atomic energy and for producing special alloys. Special glass and batteries based on new energies are called "energy metals" because of their extensive application, especially in lithium batteries. They are not only the high-end materials necessary for high-tech emerging industries, but also the routine materials necessary for the daily life of ordinary people [1].

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Corresponding author: Wang Denghong, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Researcher and Doctoral Supervisor. Major research field is mineral resources research. E-mail: wangdenghong@vip.sina.com
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According to the geological origin, lithium deposits can be divided into four types: the granitic pegmatite type, the brine type, the greisenization granitic type, and the Li-rich clay type. The brine type is the most relevant type of lithium deposit; on the other hand, the granitic pegmatite type can be exploited comprehensively thanks to the presence of associated rare elements, while the clay rock type lithium deposit should be regarded as a "potential" resource.

For the development and utilization of lithium resources, the most difficult and revolutionary application of lithium is that as the basic raw material of controllable nuclear fusion in civil power generation. According to a calculation by scientists, the energy released from 1 kg of lithium by thermonuclear reactions is equivalent to that released from more than 20,000 t of high-quality coal. The Jiajika spodumene deposit in Sichuan Province, China, is the richest in ^{6}Li of all lithium ores in the world. Its strategic significance is very high and should be paid great attention to. The main metallogenic belt and the potential for lithium mining in China are located as follows: a salt lake type lithium metallogenic belt in the Qinghai-Tibet Plateau; a pegmatite type rare metal metallogenic belt in Altay, Xinjiang; a pegmatite type rare metal metallogenic belt in western Sichuan; and a niobium-tantalum-lithium metallogenic belt in southern China (including the Moufushan-Jiuling-Wugongshan area, the Nanling belt, and the Wuyishan belt).

In view of the current trend, featuring the rapid development of new energy and new materials industries, a strong demand of high-end lithium products, such as battery-grade lithium carbonate, has surged, especially for power batteries, and special engineering plastics. At present, China's lithium products are mainly represented by industrial-grade lithium carbonate, lithium hydroxide, and other traditional lithium products with simple industrial processing and low added value. In the processing of high-end lithium products, there is still a large gap between China and the international advanced level, as well as a shortage of supply, due to which a large amount of import is necessary. The level of deep-processing technology determines the competitiveness of enterprises, and also determines the international competitiveness of the Chinese lithium industry. Therefore, speeding up the development of lithium resources in China, increasing the types of lithium products, upgrading the product structure, developing all kinds of high-end lithium products, and enhancing the overall competitiveness have become urgent tasks for the lithium industry in China.

1.2 Beryllium (Be)

Beryllium, mainly in the form of beryllium copper alloy or beryllium metal, is widely used in aviation, and in aerospace and nuclear reactor fields. It is a necessary strategic metal mineral resource for the development of new industries. Beryllium copper alloys have a wide range of civil applications. For instance, springs made of beryllium bronze can be compressed hundreds of millions times. In addition, beryllium has a good corrosion resistance, high-temperature strength, high thermal conductivity, as well as excellent radiation penetration, neutron moderation, reflection, and infrared reflection properties.

The granitic pegmatite ore type is the most important source of beryllium, and large reserves exist. Other types of Be deposits include the skarn-type beryllium ore, the volcanic hydrothermal beryllium ore, the greisen-type beryllium ore, and the quartz vein beryllium deposit.

Beryllium resources are abundant in China, and are distributed in 14 provinces and autonomous regions. The known beryllium reserves in China are mainly associated with lithium, tantalum, and niobium ores (48%), followed by rare earth (27%) and tungsten ores (20%). The granitic pegmatite type is the most relevant beryllium ore type in China, which accounts for about half of the total reserves, and mainly occurs in Xinjiang, Sichuan, and Yunnan. Hydrothermal quartz vein-type beryllium ores are characterized by medium scale, high grade, and coarse mineral crystallization, and are mainly found in south-central and eastern China. The granite-type beryllium ore is mostly found in geosyncline fold belts, mainly of the Mesozoic era, such as the Askart beryllium deposit in Qinghe County, Xinjiang, or associated with other rare metals (e.g., tantalum and niobium), such as in the 414 deposit in Yichuan, Jiangxi Province. Beryllium mineral resources in China have a highly clustered distribution, with few isolated deposits and many associated deposits, and are characterized by low grade and large reserves.

The dependence of China on beryllium imported from abroad is high, therefore it is urgent to strengthen the ore prospecting. Beryllium deposits in the rare metal metallogenic belts in Altay, Xinjiang, and in western Sichuan still have potential for further prospecting. However, the beryllium deposits related to light-colored granites in Tibet, and the skarn or skarn-like beryllium deposits in their contact zones are similar to the beryllium deposits in the Mufushan area of Hunan, Hubei, and Jiangxi provinces. Regarding the former, there have been progresses in prospecting in recent years, and therefore it can be treated as a resource reserve [2]. The resources of tungsten ores

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in China are very abundant, and beryllium is often produced together with tungsten, thus it is worth paying attention to finding independent beryllium ores in tungsten mining areas. This is a realistic new direction for prospecting, at least in the Qinling Mountains. There are independent tungsten veins, as well associated tungsten-beryllium ores and independent beryllium ore bodies. The tungsten-tin-beryllium polymetallic metallogenic belts such as the eastern Qinling, western Yunnan (e.g., the Mahuaping W-Be deposit), and southeast Yunnan (e.g., the Malipo ore field) all occur with similar conditions, and have a great potential for prospecting. In the Nanling tungsten-tin polymetallic metallogenic belt, other types can be identified according to the theory of the mineralization series. The volcanic rock-type beryllium deposits discovered in Dawan in Xiapu, Fujian, in the southeast coast, and in northwest edge of the Junggar basin, have given new vitality to the exploration of beryllium deposits in recent years.

1.3 Niobium and Tantalum (Nb, Ta)

The niobium-tantalum has excellent properties such as a high melting point, good ductility, low steam pressure, strong corrosion resistance, and high thermal conductivity. It is an important raw material for electronics, atomic energy, aerospace, iron and steel, and the chemical industry. It is widely used in the development of emerging industries. Niobium-tantalum resources are mainly derived from carbonatite weathering crust-type deposits, granites and granitic pegmatite deposits, and placer deposits containing niobiobite-tantalite, the most important of which is the carbonatite weathering crust type. China's tantalum resource endowment is poor, large-scale open-pit mines are relatively few, and independent niobium ores have not been found. Because the industrial-grade indicators specified by China for tantalum-niobium deposits of granite type and granitic pegmatite type are too low [3], tantalum reserves and base reserves are difficult to develop in practice although they are large [4]. Therefore, large quantities of niobium and tantalum still need to be imported.

The characteristics of niobium-tantalum ore resources in China are as follows: (1) the known niobium deposits are distributed in 17 provinces of China, yet they are highly concentrated in Inner Mongolia and Hubei, which account for 95.5% of the country's niobium resources; (2) the Nb-Ta grade of the niobium ores used in China is low, much lower than that of the foreign niobium-tantalum ores; (3) the associated minerals are complex and difficult to concentrate and smelt; (4) the mineral resources are very large, but the resources and reserves available for use are very few. Therefore, it is necessary to increase the efforts to find ores which are high-grade, and easy to mine and separate. On the one hand, it is necessary to search for new resources in the old mining areas, such as in the 414 deposit in Yichun, in the Geyuan deposit in Hengfeng, Jiangxi Province, in the Nanping area, Fujian province, etc. On the other hand, it is also necessary to scale up the comprehensive studies on the resources in the Baerzhe niobium-rare earth deposit in the Daxinganling metallogenic belt, in the Miaoya Niobium-rare earth carbonate-type deposit in Zhushan, Hubei Province, in the Duanfengshan pegmatite-type tantalum-niobium deposit in Tongcheng Hubei Province, and in the newly discovered rare metal deposits (such as Zhaojinggou in Wuchuan County, Inner Mongolia), so as to make a breakthrough in the large tonnage and high-grade niobium-tantalum deposits.

The main characteristic of the niobium-tantalum is its remarkable heat resistance, thanks to which it is regarded as a rare and high-melting-point metal. High-purity Nb_2O_5 (> 99.9%) is mainly used in the high-tech field, whereas more than 60% of tantalum metals in the world are used in the manufacture of electronic products [5]. Brazil is the world's largest producer of niobium, while Australia is the largest producer of tantalum. China's large-scale cemented carbide producing group, represented by Ningxia Orient Tantalum Industry Co., Ltd., and many enterprises producing and utilizing tantalum-niobium and its alloys have come to form a complete industrial system, which includes all the steps from mining, smelting, and processing, to the final application. The manufacturing scale, process technology, production equipment, testing means, and the product quality of these enterprises have reached a new level, allowing China to step into the world's top ranks of tantalum products production and application.

The United States, Russia, and China have always given great importance to the strategic significance of niobium and tantalum. With the development of new industries, the emphasis on niobium and tantalum will increase unabated. China has not done enough in this respect. On the one hand, the existing resources are not managed appropriately. For instance, the coastal sand mines in Hainan have been carelessly excavated, which not only depleted the resources, but also destroyed the environment. On the other hand, not enough attention is paid to the basic geological work, such as the study of the ore-forming condition and the ore-forming rule; moreover, the potential of the resources is unknown, the progress of ore prospecting is not great, and the issue of a sustainable development is becoming more prominent. It is urgent to strengthen the geological prospecting, study the rational exploitation and utilization of the existing resources, increase the investment, and increase the degree of protection of the source.

1.4 Zirconium (Zr)

Zirconium is regarded as a “rare metal”, because pure zirconium is difficult to smelt. Therefore, it is important to search for high-grade zirconium raw materials, and at the same time it is necessary to put more effort into metallurgical innovation. China’s zirconium ore resources can be divided into two categories: placer deposits and hard rock-type zircon deposits. The known reserves are only 5×10^5 t, which is less than 1% of the global zirconium resources. Most of the zirconium resources in foreign countries come from coastal placer mines, while placer zirconium occurs rarely in China, hence the structure of the Zr resources in China is also unfavorable.

Placer zircon deposits are distributed in the southeast coast of China, with the southern coast of Guangdong and the east coast of Hainan Island being the areas with the highest concentration of deposits, while hard rock deposits are scattered in Inner Mongolia and in the southern provinces and regions. The provinces with proven reserves of more than 1×10^5 t are the Inner Mongolia, Hainan, Guangdong, Yunnan, and Guangxi, which account for 97.6% of the country’s reserves. Hainan is the largest source of placer Zr, accounting for 67% of the country’s reserves, but most of them have been consumed, and the remaining resources are no longer being exploited in order to protect the environment.

Zirconium metal is ranked into grades: the industrial grade and the grade for the atomic energy sector. In addition, some high-quality zircon crystals with appropriate weight, transparent or of bright color, can be used as a gem-quality raw material.

The characteristics of the zircon deposits resource in China are as follows: uneven distribution and relatively concentrated reserves; not very rich ores with the presence of more associated minerals; complete types of deposits with regular distribution; easy to mine deposit, clustered, and suitable of comprehensive exploitation and utilization; slightly high levels of radioactivity.

The zirconium ore resources in China are not competitive in the market. Almost all the hard rock deposits are low-grade associated deposits, while the coastal placer deposits are mainly distributed in areas subjected to environmental protection. These two types are precisely the main types of zirconium mines in China. To guarantee the national security strategically, the following strategies are proposed. (1) Priority should be given to the investigation of placer resources in coastal areas not subjected to environmental protection or infrastructure areas. Investigation and evaluation of overburden resources must be carried out according to the regulations, and resources should be recovered first, and only then construction should be carried out. (2) Carrying out the prospecting work of high-grade zirconium ores is possible in the distribution area of low-grade hard rock type primary ores, and a breakthrough in ore prospecting is also possible. (3) The best type of Zr ores in the world associated with the weathering crust should be explored in the areas with suitable ore-forming geological conditions. (4) The management should be strengthened, based on domestic production, to import appropriately, restrict the export, and avoid vicious competition. (5) The technological innovation and theoretical innovation should be strengthened, to improve the efficiency in the utilization of the existing resources, and to improve the product structure.

1.5 Hafnium (Hf)

Hafnium is a dispersed element in rare metals, or a rare metal in dispersed elements. The amount of hafnium is small, but it is an essential raw material in the high-tech field. Around 85% of the world’s hafnium is used for control rods and emergency shutdown rods in nuclear reactors, while 3% is utilized as an alloy additive. Hafnium is often associated with zirconium, but zirconium used as a nuclear reactor structural material must be removed from hafnium in order to ensure a neutron capture cross-section of 0.18 barns. The production of hafnium sponges in China began in 1966, which are mainly used as the control rod for nuclear submarines and nuclear reactor cores.

The types of hafnium deposits in China include the marine sedimentary type (coastal placer type), the fluvial alluvial type, the weathering crust and residual slope type, the alkaline granite type, and the pegmatite type. However, the formation of independent deposits with low grade is difficult, and the industrial raw materials are mainly zircons.

The following suggestions are made: (1) to strengthen the comprehensive utilization of hafnium, especially the comprehensive investigation and evaluation of hafnium associated with zirconium; (2) to strengthen the research

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in basic disciplines and marginal disciplines of resources development and comprehensive utilization, and disclose new fields; (3) to improve continuously the technical methods for studying the material composition of the deposits; (4) to apply the new advances in science and industry technology to the geological work, to improve the recovery rate and the industrial utilization rate of hafnium; (5) to identify the resources, and to establish the raw material base; (6) to make great efforts to improve the quality of hafnium products and carry out protective development; (7) to establish and improve the corresponding scientific research institutions to improve the level of application and research & development; (8) to strengthen the comprehensive evaluation in geological exploration work. Furthermore, attention should be paid to recycling the scrap metal and to the related environmental protection.

1.6 Strontium (Sr)

The main raw materials from which strontium is extracted are the celestite and the strontium siderite. As of 2011, China's celestite reserves were 1.545×10^7 t, accounting for 69.4% of the world's known strontium reserves. The known celestite strontium deposits are mainly large-scale and super-large single strontium deposits, accounting for 87% of the total reserves. Qinghai Province accounts for 95.6% of the country's celestite reserves, followed by Chongqing, Jiangsu, and Yunnan. Strontium thiophosphate in the Shifang phosphate ore in Sichuan Province, strontium associated with lead-zinc ore in Jinding, Yunnan, and co-associated strontium in brine have also been comprehensively utilized to a certain extent.

China is the world's leading producer of strontium products, accounting for about 40% of world's production in 2013, more than 80% of which is exported. Strontium carbonate is the most important strontium compound in strontium products, accounting for 80% [6] of the total strontium products. At present, the annual production capacity of strontium carbonate in the world is about 4×10^5 t, and China accounts for about 2.6×10^5 t. China is rich in strontium resources, yet some issues are currently limiting the development of the related industry, which are detailed as follows. (1) The development situation is grim. Because of mining of the rich ores while abandoning the lean ores, the loss rate is high, and the waste of resources has become more serious. Since strontium mines in China have been exploited for many years, they have entered the tail-mining period one by one. (2) The quality of the products is low, so strontium ores of high quality must be imported. At present, attention is paid to the comprehensive utilization of the resources, both in China and abroad. The following suggestions are made: (1) to strengthen the management of strontium mining and strontium chemical production to protect strontium resources; (2) to adjust the industrial structure, and restrict the direct export of ores; (3) to increase the importance of the comprehensive evaluation of associated strontium ores; (4) to strengthen the knowledge on the ore-forming theory of strontium ores and estimate the yields; (5) to widen the fields of application of strontium, and actively develop high-end products.

1.7 Rubidium and Cesium (Rb, Cs)

Rubidium and cesium have excellent optical and electrical properties, and are widely used in emerging industries. There are no independent rubidium minerals in nature. Rubidium is mainly extracted from Li-mica, Fe-Li-mica, and carnallite, and is part of the "dispersed elements" category of rare metals. There are 13 major rubidium and cesium deposits in China. Among them, 5 are considered super-large, 2 are large, 1 is medium-sized, and 5 are small. The quality of rubidium ores in China is far inferior to that in foreign countries. For example, the ore-grade of Rb_2O in the Tanco deposit at Bernic Lake in Canada is 1.0%, while that in the 414 deposit in Yichun, Jiangxi Province, China, is only 0.22%.

The main types of rubidium deposits are: (1) the lithium mica albite granite type; (2) the granitic pegmatite and amazonite-bearing granite types; (3) rubidium in muscovite and lithium mica formed by the mineralization of tungsten and tin veins in granitic rocks (which can sometimes meet the industrial requirements); and (4) salt deposits. The main types of cesium deposits include: (1) the lepidolite-albite granite type; (2) the pegmatite type; (3) cesium in minerals such as ferromanite and muscovite in tungsten and tin veins and mica; (4) potash deposits; (5) the salt lake type; (6) modern hot springs. At present, industrial-level exploitation mainly occurs for cesium-bearing pegmatite, accounting for 98% of the total reserves, and is distributed mainly in the Altay region of Xinjiang and Yichun in Jiangxi. The reserves of cesium in lithium mica in Yichun account for more than 40% of China's cesium reserves, which make them the largest in the country. Since 1958, the Xinjiang Institute of Metallurgy has been using cesium garnet from Altay to produce cesium chloride in small batches. The annual production of cesium chloride with 99% purity is about 2 t. Rubidium and cesium do not occur in mines independently, thus they are generally recovered as co-associated components from other deposits.

The rubidium and cesium resources in China are characterized by a wide distribution and by the presence of many types of deposits, but also by a concentration of resources and metallogenic ages, by the presence of few independent deposits, and by a difficult exploitation and utilization. When developing rubidium ores in China, we should pay attention to: (1) make full use of the tailings resources of the existing mines; (2) strengthen the research on the mineral processing technology of the low-grade rubidium ore resources, in order to identify the high-grade rubidium source of mica type; (3) evaluate the availability of cesium resources in the salt lakes in Tibet; (4) strengthen the comprehensive utilization of rubidium and cesium resources, and improve the related standards of rubidium and cesium industrial production in China. Although the reserves of cesium in China are among the highest in the world, most of them are associated with cesium in lithium mica, while the reserves of cesium garnet ores are relatively small, and the resources are low. The endowment is not good.

2 Main characteristics of rare earth mineral resources in China, and suggestions for exploitation and utilization

Rare earth minerals are widely used in information technology, biotechnology, energy technology and other high-tech fields, as well as in national defense construction. They also play an important role in the transformation, innovation, and upgrading of some traditional industries, such as in agriculture, in the chemical industry, and in the manufacturing of building materials.

China is the richest country in rare earth resources. However, in recent years, due to over-exploitation and unrestricted low-cost sales, China’s rare earth reserves have progressively decreased. China has made an indelible contribution to the development of new industries in the world, yet China has been unfairly treated under the WTO system, and its own strategic significance for rare earth resources has not been fully understood. Abnormal production and smuggling are very serious. To this end, China has had to introduce a series of protective mining development policies and measures.

The regional distribution of rare earth mineral deposits in China is multi-faceted, and relatively concentrated. At present, over a thousand deposits and ore spots have been discovered in more than two thirds of Chinese provinces (including the autonomous regions); however, 98% of the total rare earth resources in the country are distributed in Inner Mongolia, Jiangxi, Guangdong, Sichuan, and Shandong, forming a “north-light and south-heavy” resource pattern. Among them, the middle-weight and heavy rare earths are mainly concentrated in the Nanling area at the junction of Jiangxi, Hunan, Guangdong, and Guangxi, and the ion-adsorption type of rare earths ore is the most abundant one. This type of rare earth ore is easy to mine, and the minerals are easy to extract. Thus, Nanling has also become an important middle-weight and heavy rare earth production base in China as well as worldwide. Since 2011, a series of progresses have been made in the geological survey, mineral administration, resource evaluation, and environmental assessment of ion-adsorbed rare earth deposits [7]. Rare earth deposits have also been discovered in Guangxi, Guangdong, Yunnan, Fujian, Zhejiang, and other provinces, and their rare earth reserves may exceed that of Jiangxi. Light rare earth minerals are mainly found in North China (Bayan Obo in Inner Mongolia and Chishan in Shandong) and in southwestern China (Liangshan in Sichuan and Chuxiong and Dehong in Yunnan).

For a long time, China’s rare earth industry has been small, scattered, chaotic, poor, and affected by very prominent other issues. By 2013, more than 100 rare earth smelting enterprises have been established in China, the annual total capacity of which is about 3×10^5 t, while the average annual capacity of each enterprise is only about 3000 t, therefore the problem of low-level repeated construction is prominent.

It is worth noting that China currently ranks first in three rare earths-related rankings, i.e., in terms of the amount of reserves, the production scale, and the processing and export volumes. However, the deep processing and application technology of rare earths in China is far from being the first in the world. The production and application of high-tech and high-value-added rare earth products lags far behind those of the United States, Japan, and other developed countries. There is oil in the Middle East and rare earths in China. Therefore, people all over the country give great importance to the exploitation and utilization of this precious resource, which should be considered a strategic asset comparable to oil. A number of suggestions are provided, which are detailed as follows. (1) Rare earths are a precious strategic mineral resource (and a resource in general) of China, as well as of the world. Protecting China’s rare earth resources means to protect the resources for all mankind. It is of great significance to establish a global community with a shared future for the world based on rare earth minerals. (2)

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China exports rare earths, yet it is difficult for China to import high-end technology for deep processing of rare earths and its derivatives. China cannot simply "buy and sell" rare earths in the free market, another solution must be found. It is suggested that new breakthroughs should be made through the mode of cooperation based on "technology + resources", and high importance should be especially given to heavy rare earths. (3) Independently of how the international market changes, China must have its own strategic positioning and layout, and must innovate independently rather than following the global trend. (4) It is suggested to increase the total amount of mining, and to control and regulate the exports [8]. (5) It is advised to strengthen the research and development of dual-use products. For instance, the exploitation of military technology for civilian uses might greatly improve the overall level of rare earth development and utilization in China, and might in turn create new opportunities for the research and development of high-end rare earth products.

3 Characteristics of mineral resources of scattered elements in China, and suggestions for exploitation and utilization

China is rich in scattered elements; however, many issues exist in relation to their exploitation, such as a low level of research, unclear resources, lack of exploitation and utilization standards, product simplicity, backward technical route, and a great concern on environmental pollution. There is still a large gap before the goal of "wisely use" can be achieved.

3.1 Indium (In)

The independent mineral of indium is very rare in nature, and the formation of independent deposits is difficult [9]. Industrial exploitation mainly originates from by-product recovery during the smelting process of hematite, lead-zinc, and tungsten-tin ores. Indium mainly occurs in sphalerite, but it can be obtained easily only when tin and zinc are co-associated and zinc is enriched on a large scale. Indium is expected to be a scarcer strategic resource than rare earths, and is more difficult to find. The enrichment of indium is specific to deposit types, and mainly occurs in cassiterite-sulfide and tin-rich lead-zinc deposits, although it may also be enriched in bauxite deposits. Indium is mainly distributed in 15 provinces and autonomous regions in China. Among them, Yunnan and Guangxi accounts for 40% and 31% of the country's total indium reserves, respectively.

In the last ten years, more and more attention has been paid to indium thanks to its excellent performance in the high-precision industrial technology. China has the largest geological reserves of indium in the world, with a global share of about 50%. It has been estimated that the reserves of indium amount to 9,600 t. China has been recovering indium since 1954. By 2006, its indium production capacity reached 657 t, making it the largest producer of indium. However, the industrial chain of indium has remained below the requirements for the production of high-purity indium, and the introduction of foreign core technologies has not brought enough development.

From the point of view of the global mineral resource strategy, the following suggestions are made. (1) The actual and strategic values of indium should be re-recognized at the national level. The State Administration of Customs and Taxation should reposition indium, which is currently categorized in the column of base metals. (2) The export tax rebate for indium should be abolished in international trade and commerce. (3) State reserves should be established to encourage non-governmental reserves to enhance the people's awareness and attention to rare and precious metals. (4) The government should promote the development of China's indium processing industry, especially to strengthen the support for the development of emerging industries. (5) Governments at all levels should implement a licensing system for the production and export of indium.

3.2 Gallium (Ga)

In recent years, gallium has become a new favorite in the electronics industry, and is known as "the new grain of semiconductor materials". By the end of 2008, the resource reserves of gallium in China were 1.366×10^5 t, accounting for about 75% of the world total. Guangxi, Guizhou, Henan, Shanxi, and Yunnan account altogether for 88.2% of the country's reserves. Gallium in the Panzhihua V-Ti magnetite deposit in Sichuan Province accounts for 41%–42% of the world's reserves alone, and for 54%–55% of China's reserves, followed by the Dexing Copper Mine, which accounts for 15% of the country's reserves. However, both Panzhihua and Dexing reserves are largely useless because of their low grade. At present, ultra-pure gallium has been successfully prepared in China, and a production line of 15 t of ultra-pure gallium has been built [10].

Although the production of gallium in China ranks high in the world, most of the gallium is exported as a raw material. China is the major exporter of gallium raw materials in the world, and an important importer of high-end products and manufactured products of gallium at the same time. The following recommendations are made. (1) It is suggested to continue to fully recover the gallium resources. China must value the strategy highly, and have corresponding measures in policy, also in respect to strategic reserves. (2) It is advised to restrict the export of gallium resources, and at the same time to improve the technology level of the production of high-end gallium products in China. (3) Finally, it is suggested to encourage innovation, research, and development of new products, provide policy and tax support, and change the advantage in terms of resources into an economic, technical, and talent advantage.

3.3 Germanium (Ge)

Germanium resources in the world are relatively small. According to the current world consumption, they are enough only for the next 40 years. China is the country with the second largest germanium resources in the world, with about 35 known germanium mineral sites, with reserves of about 3,500 t. These reserves are mainly distributed in Guangdong, Yunnan, Inner Mongolia, Jilin, Shanxi, Guangxi, Guizhou, and in other 12 provinces (accounting for 96% of the total Ge reserves). There are mainly placer lead deposits (e.g., the Huize in Yunnan, and the Hezhang lead-zinc deposit in Guizhou), sedimentary remodeling deposits (e.g., the Fankou lead-zinc deposit in Guangdong), and hydrothermal alternation deposits (e.g., the Shuikoushan lead-zinc deposit in Hunan) in China with relatively high germanium content. Yunnan Province is rich in germanium resources, mainly distributed in lead and zinc deposits, and in germanium-bearing lignite deposits, which currently rank first in the country.

Germanium is a strategic material for optical information technology, and can be used in solar germanium cells on satellites. An increasing attention has been paid to the application of germanium in health care. For instance, organic germanium drugs can make a breakthrough in the medical field mainly because of their low toxicity (slight or non-toxic), as well as their anti-cancer and immune effects on the human body. At present, China and the United States basically monopolize the germanium resources in the world, but the export volume of China is more than 70% of the total export volume worldwide. However, most of the export is represented by low value-added primary raw material products. These primary products have become strategic reserve resources in other countries, or raw materials for the refined and deep processing of products. If China do not limit the export of germanium, there will be a shortage of germanium resources in China. It is suggested that a quota system for the export of germanium should be established.

3.4 Cadmium (Cd)

Cadmium and zinc share a common geochemical behavior in nature, thus cadmium is mainly associated with zinc ores. China is rich in cadmium resources, mainly in Yunnan, Sichuan, Guangdong, Guangxi, Hunan, Gansu, Inner Mongolia, Qinghai, and Jiangxi. The Jinding Pb-Zn deposit in Lanping, Yunnan is an ultra-large cadmium-associated deposit in China. The Niujiaotang zinc deposit in Duyun, Guizhou Province, is a deposit with the highest known cadmium content at present, and is one of the rare large independent cadmium deposits in the world. The Dulong cadmium-rich tin polymetallic deposit in Yunnan contains thousands of tonnes of cadmium, and it is considered a large-scale deposit. In the Dachang ore field, in Guangxi, the most important cadmium source comes from the sphalerite, and the overall cadmium resource amounts to more than 10,000 t.

Cd-Hg agents formed by elemental cadmium and mercury soften when heated, yet they are hard at human body temperature. This “liquid metal” or “deformable metal” has received both military and civilian attention. Cadmium alloys play an important role in the national defense industry. Cadmium rods can regulate the speed of the chain reaction in nuclear reactors. The United States listed cadmium as a strategic reserve stock, with a reserve target of 5370 t.

In recent years, environmental problems caused by cadmium, which is toxic for organisms, have become the research focus of many scholars. The high content of cadmium in the environment in areas where zinc ores occur will be a common problem, to which more attention must be paid. Mining activities lead to the release of elemental cadmium, which enters the underground water environment and can lead to cadmium pollution. In agricultural production, sewage irrigation can cause cadmium pollution in soil.

In summary, it is necessary to ascertain the distribution of cadmium from the geological background, including its occurrence in the deposit and its general distribution in rocks, in order to fully recover Cd while mining

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lead-zinc ores. This should be carried out not only to ensure the comprehensive utilization of cadmium resources, but also to reduce the release of cadmium into the environment. At the same time, it is necessary to strengthen innovative research involving cadmium in the high-tech field, and expand its field of application. In particular, the research and development of the "liquid metal" should be strengthened. It must be considered that only a safe utilization of Cd can reduce the likelihood of environmental pollution.

3.5 Thallium (Tl)

Thallium is a typical dispersed element occurring in the crust. It is mainly isomorphous and has a colloidal adsorption state. An independent mineral form of thallium exists [11]; however, independent deposits of thallium are only reported in China. A mercury-thallium deposit has been found in Laimuchang, Guizhou Province, an arsenic-thallium deposit has been found in Nanhua, Yunnan, and a thallium deposit has been found in Xiangquan, Anhui Province. In fact, thallium is widely found in polymetallic deposits, such as in the Yunfu pyrite deposit and in the Fankou lead-zinc deposit in Guangdong, in the Jinding lead-zinc deposit in Yunnan, and so on. Thallium in the dust of lead-zinc mine smelter is also a main source for thallium recovery.

Thallium reserves in China rank first in the world. Thallium is the dominant resource in China, but the demand for thallium is very small. In 2009, the annual consumption of thallium worldwide was only 15 t. The technology for the utilization of thallium in Chinese industry lags behind that of other countries, and thallium is mainly used in the fields of the high-tech and chemical industries, with annual demands of 225 kg and 24 kg, respectively.

Low-temperature hydrothermal deposits in southwest China generally contain thallium. Because of weathering, thallium will contaminate water, soil, vegetation, and air. The following suggestions are made: (1) the distribution of Tl in nature should be investigated and removed completely to avoid contamination; (2) besides planting turf in tailing sand reservoirs, the composition of groundwater should also be monitored for a long time, and the source of the pollution should be eliminated by means of a comprehensive recovery and utilization; (3) since the mobility of thallium in dust is very high, dust removal is the key to prevent thallium pollution, and attention should be paid to the recovery of thallium from the industrial processes of sulfuric acid and cement production.

3.6 Tellurium (Te)

Tellurium is a rare and dispersed element whose content in the earth's crust is very low. Nonetheless, tellurium is widely used and is an important element, and its demand is steadily increasing. Tellurium is mainly dispersed in chalcopyrite, pyrite, galena, sphalerite, and other minerals in sulfide and gold-bearing quartz vein deposits. The industrial tellurium is mainly recovered from the anode slime of electrolytic refining processes of copper and lead.

About 30 tellurite deposits have been found in China, and the Chinese reserves of tellurium rank third in the world. They are mainly located in Guangdong (42% of the country's total), Jiangxi (41%), and Gansu (11%). Tellurite deposits in China are concentrated in hydrothermal polymetallic deposits, skarn-type copper deposits, and magmatic copper-nickel sulfide deposits. The Dabaoshan deposit in Guangdong, the Chengmenshan deposit in Jiangxi, and the Baijiazuizi deposit in Gansu Province are the three largest tellurium-associated deposits in China, accounting for 94% of the total reserves of associated tellurium in China. The first independent tellurite ore in the world was discovered in August 1991 in Dashuigou, Shimian County, Sichuan Province, China [12].

More than half of the tellurium production is utilized in the metallurgical industry. The main areas in which the consumption is growing are those of the photoelectric instruments-lasers, the photodiodes, and the optical receivers. Being a country rich in tellurium resources, China must give importance to the development and utilization of such resources, not only by strengthening the protection, management, supervision of the development, and utilization of tellurium resources, but also by relying on the scientific and technological progress. It is urgent to improve the level of utilization of tellurium resources, and to avoid an excessive and poorly organized export of low-end products.

3.7 Rhenium (Re)

Rhenium is a rare metal element on the earth and is not easy to become enriched in a number of geological processes. Important rhenium-bearing deposits include: (1) porphyry copper (molybdenum) and porphyry molybdenum deposits; (2) hydrothermal uranium-molybdenum deposits; (3) molybdenum-bearing and vanadium-bearing copper-shale and sulfur-siliceous shale deposits; (4) independent rhenium deposits [13]; (5) rhenium-bearing magmatic copper-nickel deposits, chromite deposits, platinum deposits; (6) rhenium-bearing wolframite deposits; (7) rhenium-copper sandstone and uranium-rhenium-copper sandstone deposits; (8) rhenium-copper-carbon shale-type copper deposits.

Rhenium, known as a "strategic metal" and an "aviation metal", has a wide range of applications, such as in jet engine components, gas turbine engines, and quantum computers. The application of rhenium in aero-generators has always been lacking in China's high-end equipment manufacturing industry, which has been forcing China to import aircraft generators for a long time.

China has the largest sources of rhenium, and almost all of them are associated with molybdenum deposits, which are concentrated in Jinduicheng, Shaanxi Province, and in Luanchuan, Henan Province, accounting for 90% of the total reserves of rhenium in China. An independent rhenium ore was found in the Muchuan area of Sichuan Province, and the predicted amount of resource was 50 t.

Because of the strong dispersion of rhenium and its rare occurrence as an independent mineral, most mines rarely recover rhenium while mining the main elements, resulting in a waste of rhenium resources. The following suggestions are made: (1) to investigate the occurrence of rhenium in nature, and especially strengthen the exploration and evaluation of associated rhenium resources; (2) to study the mechanism of rhenium enrichment and mineralization; (3) to strengthen the study of the ore-forming patterns of rhenium-bearing deposits; (4) to increase the verification of the presence of rhenium in the mining areas of the existing metal mines as well as in the metal deposits under exploration; (5) to improve the overall level of utilization and develop the technology for recovering different types of rhenium ores; (6) to strengthen the research and development of rhenium deep processing products; (7) to strengthen the strategic research on the rhenium resource.

3.8 Selenium (Se)

Selenium is a semi-metallic element, similar in nature to sulfur, but with stronger metallicity. The highest content of selenium is found in carbonaceous siliceous rocks, where it can reach concentrations up to 8590 ppm [14]. The supernormal enrichment and mineralization of selenium in nature occur only in Pacajake, Bolivia, and in Yutangba, China. Selenium enrichment is often found in siliceous rock formations. At present, the identified selenium ore resources mainly include four types: "distant" selenide vein deposits; unconformable surface type deposits; sandstone type copper-uranium deposits; and continental volcanic rock type low-temperature gold-silver deposits.

By the end of 2007, the reserves of Se in China were 15,600 t. The reserves of selenium in 18 provinces were mainly distributed in Gansu, Guangdong, Heilongjiang, Hubei, and Qinghai provinces (accounting for 79.3% of the country's total). Among the known selenium reserves, magmatic Cu-Ni sulfide deposits account for more than half of the total selenium reserves, which are mainly associated resources [1].

The most prominent characteristic of selenium is that its conductivity under visible light increases thousands of times compared to that in darkness. Therefore, it is widely used in the glass, electronic, optical and metallurgical industries. Selenium is an important trace element in the ecological environment. Excess or deficiency of selenium in the environment will lead to diseases. On the other hand, a high concentration of selenium endangers the growth and development of crops, reduces the yield, and leads to the abnormal development and even death of animal embryos. Selenium is a necessary trace element in the human body. Deficiency of selenium or excessive intake of selenium both are harmful to the human health.

Se-rich soils in China are common, but their distribution is very uneven. According to the characteristics of landscape geochemistry, the distribution of Se in soil, and the distribution of Se-rich soils in different states, and in accordance with the principle of "taking measures according to both the local conditions and the comprehensive exploitation", we should focus on the research and development of each Se-rich soil area.

4 Discussion and conclusion

As early as 1950, the American Congress passed the *Defense Production Act*, requiring the government to convert rare metals into quartermaster production and reserves. Subsequently, Russia, South Korea, Japan, the European Union, and other countries also have classified the main "RRR metals" as strategic resources to ensure a stable supply. In recent years, also China has issued a series of documents and policies to support the development and comprehensive utilization of "RRR resources" and strengthen the storage and protection of lithium and rare earth elements. However, the strategic orientation of the "RRR minerals" is not yet clear enough, as the motivation for innovation is insufficient, and raw materials or primary products are currently the most sold ones. It is recommended that the system be more comprehensive, the strategic problems of "RRR resources" in China deeply

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studied, the exploration of resources emphasized, the technology of extracting resources strengthened, and the efforts in research and development of new products applied in the high-end sector.

As far as rare earth elements are concerned, an effort should be put into informing common people that rare earths are precious, and private enterprises should be encouraged to participate in the research and development of rare earth-related products. At the same time, measures should be taken to protect China's rare earth resources, especially ion-adsorbed rare earths, so that "rare earths can be managed". Regarding the rare metals, there have been encouraging breakthroughs in recent years about lithium ore prospecting in places such as Jiajika in Sichuan [1,7]. On the other hand, there have not been fundamental breakthroughs in the prospecting of beryllium, tantalum, zirconium and other rare metals. There is a strong dependence on the import from foreign countries; therefore, there is an urgent need to increase the ore prospecting efforts, starting from the rule of "rare but normal" in China. This goal can be achieved by careful deployment, scientific projects, and increased investments, so that "rare can be found." Finally, regarding the scattered metals, China is rich in both co-associated resources and independently recoverable resources. Independent tellurite, independent thallium ores, and independent selenite, which are not found in foreign countries, can be found in China in the form of "scattered but undispersed" ores. However, the level of research on scattered elements in China is very low, the amount of resources is unclear, and there is a lack of standardization in their development and utilization. Therefore, on the one hand, normative management should be strengthened and, on the other hand, innovation should be carried out. By taking the scattered metals in the high-tech field product innovation as a guide, the "scattered but used well/wisely" condition can be achieved. Product development of scattered elements can be considered to be the point with most innovation. However, the Chinese product is simple, the technical route is not advanced, and the originality and the revolutionary research and development ideas are lacking. These conditions result in the overconsumption of thallium, gallium, germanium, indium, tellurium in the form of both dispersed and rare raw materials (which is also causing environmental pollution), with the consequence that, even though the export is large, the profit remains small.

References

[1] Wang D H, Liu L J, Liu X X, et al. Main types and research trends of energy metallic resources in China [J]. Journal of Guilin University of Technology, 2016, 36(1): 21–29. Chinese.

[2] Shao J N, Tao W P, et al. Requirements manual for mineral resources industry [M]. Beijing: Geological Publishing House, 2011. Chinese.

[3] Chen Q S, Yu W J, Zhang Y F, et al. Considerations on the strengthening of the mineral resources reserve [J]. China Mining Magazine, 2015, 24(1): 20–24. Chinese.

[4] He J L. Progress of tantalum and niobium industry in China [J]. Strategic Study of CAE, 2003, 5(5): 40–46. Chinese.

[5] Li S W. Tantalum niobium resources and production status [J]. China Nonferrous Metallurgy, 2008 (1): 38–47. Chinese.

[6] Wang J Q. Exploration and application of strontium resource in Qinghai Province [J]. Inorganic Chemicals Industry, 2004, 36(1): 15–16. Chinese.

[7] Wang D H, Wang R J, Sun Y. et al. A review of achievements in the three-type rare mineral resources (rare resources, rare earth and rare scattered resources) survey in China [J]. Acta Geoscientica Sinica, 2016, 37(5): 587–598. Chinese.

[8] Huang X W, Li H W, Wang C F, et al. Development status and research progress in rare earth industry in China [J]. Chinese Journal of Rare Metals, 2007, 31(3): 279–288. Chinese.

[9] Tu G Z, Gao Z M, Hu R Z, et al. Geochemistry and metallogenic mechanism of dispersed elements [M]. Beijing: Geological Publishing House, 2004. Chinese.

[10] Fan J H. Research and industrialization of super pure gallium [J]. Journal of Guangdong Non-ferrous Metals, 2006, 16(2): 92–99. Chinese.

[11] Li D X, Gao Z M, Zhu Y X, et al. Thallium-bearing minerals and vegetaiont prospecting for thallium [J]. Geology and Prospecting, 2003, 39(5): 44–48. Chinese.

[12] Chen Y C, Yin J Z, Zhou J X, et al. Geological characteristics of Dashuigou tellurium ore deposit in Shimian County, Sichuan Province, China [J]. Scientia Geologica Sinica, 1994, 29(2): 165–167. Chinese.

[13] Bin Z Y, Liu J H, Ran J M. Production, application and market of rhenium [J]. Hunan Nonfreeous Metals, 2005, 21(3): 7–10. Chinese.

[14] Zheng B S, Hong Y T, Zhao W, et al. Selenium rich carbonaceous siliceous rocks and endemic selenium poisoning in Western Hubei [J]. Chinese Science Bulletin, 1992 (11): 1027–1029. Chinese.