Original Article

Geology and genetic types of the primary rhenium deposits in Mainland China

Jian Zhao Yin [1,2,3] Ⓛ

Abstract

The unique physical and chemical properties of the rare element rhenium make it have increasingly extensive and indispensable uses in many modern high-tech fields such as national defense, aerospace, petrochemical industry, electronic materials, quantum computing and ultra-high temperature emitters, and medicine. For this reason, many countries, especially Western developed countries, have listed rhenium as one of the critical metals or strategic minerals for protection and restriction. Due to the heterogeneity of the distribution of chemical elements throughout the earth, compared with similar minerals in other continents, the rhenium deposits in mainland China have both similarities and unique features. For example, mainland China has the only independent rhenium deposit in the world so far. At the same time, mainland China also has associated and/or symbiotic rhenium ore types that most countries in the world have. China's large-scale rhenium exploration, research and application started late. But it has developed rapidly in the past 10-20 years. This article summarizes the geological characteristics of the rhenium deposits discovered in mainland China in recent times and divides their genetic and industrial types.

Key words: rhenium deposit; mainland China; application; market; geology; genetic type

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Affiliation Info: [1] Orient Resources Ltd., Canada; [2] Wuhan Institute of Technology, Wuhan 430205, China; [3] College of Earth Sciences, Jilin University, Changchun 130061, China

Authors' Contact Info: Yin, JZ: jzyin7@jlu.edu.cn

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Corresponding Aurhor Ⓛ: Yin, JZ, PhD, PGeo, Professor; Email: jzyin7@jlu.edu.cn

1. Introduction

As early as 1871, the founder of the periodic table, Russian chemist Dmitri Mendeleev, brilliantly predicted that there was a "manganese-like" element with an atomic weight of 190 in nature. In 1913, the British genius physicist Henry Moseley further predicted the new elements 43, 61, 72 and 75 that had not yet been discovered in the periodic table at that time, among which 75 was Re that was later discovered. In 1925, German chemists Walter Noddack, Ida Tacke and Otto Berg used X-rays to discover the belated element 75 in platinum ore and columbite, and named the newly discovered element Rhenium after the Rhine River, where Ada was born. Rhenium thus became the last natural element discovered in the periodic table. In 1928, German scientist Nordak separated and obtained the first 1 g of rhenium metal in human history from 660 kg of molybdenite in the laboratory1-3. However, the large-scale production of rhenium began two years later in 1930.

Rhenium, a rare metal that has long been unknown to the world, has rapidly attracted widespread attention in the past 20-30 years due to the highly developed modern science and technology and its wide application in many high-tech fields. Many countries have even listed it as a critical metal for protection.

2. Chemical and physical properties, uses, production and market of rhenium

2.1 Chemical and physical properties

As a highly dispersed and therefore extremely rare element, rhenium has an abundance of only one billionth of an order of magnitude; namely, 10^{-9} in the Earth's crust (Table 1), which is lower than the content of any rare earth element in the periodic table. Re has similar atomic and ionic radii to Mo and Cu, and therefore coexists and thrives with these two metals[3-6]. The highly electronegative metallic rhenium crystal belongs to the hexagonal system, with a unit cell edge length a_0 of 2.760 Å and c_0 of 4.458 Å, and is most stable with a 4-valent cation. Therefore, rhenium mainly coexists and/or associates with molybdenite and various copper sulfides, and mostly appears in these minerals in the form of isomorphous impurities. Indeed, rhenium is mainly distributed in countries rich in copper and molybdenum ore resources. Although there are reports that independent rhenium deposits have been discovered in mainland China, most of the Re metal currently used by humans is mainly enriched and separated and purified from by-products such as soot and waste acid from the smelting of Mo and Cu ores.

Table 1. Abundance of rhenium in various rocks from the Earth (modified from Zhou et. al.[5])

Sample source	wB/10^{-9}	
	Range	Average
The Earth's Core		291
Primitive mantle		0.27
Depleted mantle		0.12
Oceanic crust		0.96
Continental crust		2
Ultrabasic rocks (peridotite)	0.003~1.15	
Basic rocks (gabbro, diabase, basalt)	0.36~1.5	
Intermediate rocks (diorite, monzonite, andesite)	＜0.5	
Acidic rocks (such as granite, porphyry, rhyolite)	0.22~1.14	
MORB	0.33~1.47	0.93
OIB	0.1~0.642	0.35
Common shale	9~51	
Black shale	56~285	
Sulfide-rich mineralized black shale	Up to 33,000	
Anoxic sediments	2~127	50
Oxygen-containing sediments	＜0.1	

There are very few known rhenium minerals (Table 2). The first rhenium mineral discovered in the world, dzhezkasganite, comes from the Dzhezkasgan sandstone copper deposit in central Kazakhstan. Later, some rhenium minerals were found in the graphite-rich pyroxene rocks of the Stillwater complex in the United States[3-7]. Then, pure rhenium mineral rheniite was found in the Kudriavy crater in the Kuril Islands of the Far East in Russia. This is also the only pure rhenium mineral found in the world so far[7].

Table 2. Known minerals of rhenium in the world (modified from Zhou et. al.[5])

Origin	Country	Mineral name	Chemical formula
Zhazgan sandstone Cu deposit	Kazakhstan	Dzjezkazganite	$CuReS_2$
Zhazgan sandstone Cu-Mo deposit		-	$Cu(Re, Mo)S_4$
Voronov Bor, Rybozero Cu-Mo eposit	Russia	Osmium-cupreous rheniite	$(Re, Cu, Os, Fe)S_2$
Sublimates of Kudryavyi volcano; Sugraly sandstone uranium deposit in Uzbekistan; Copper-bearing shale in Mansfeld Cu mine in Germany	Japan, Uzbekistan, Germany	Rheniite	ReS_2
-	Finland	Tarkianite	$(Cu, Fe)(Re, Mo)_4S_8$
Danba Yangliuping Cu-Ni deposit	China	-	$(Re, Cu, Os, Fe, Ni, Pb)S_2$
	China	-	$(Re, Cu, Fe)S_2$
Northern Arizona	USA	Oxided rhenium	Re_2O_7
Transbaikal tungsten deposit	The former USSR	Native rhenium	Re or Re0
Meteorites	-	Ruthenium-rhenium ore	$Re_{97}Ru_3$
Stillwater ultrabasic intrusion	USA	Rhenium sulfide	Re_2S_3
Coldwell complex in Canada	Canada	-	$(Re, Mo, Fe, Cu)S_3$, $Re(Mo, Cu, Fe)_2S_3$
-	Switzerland or Italy	-	$(Pb_{0.87}Sr_{0.83}Y_{0.43})(Ti_{14.4}Fe_{6.05}Re_{0.23}Mn_{0.23})O_{38}$
Ni-rich ultrabasic rock in Njuggtraskliden and Caledonian uranium-mineralized quartzite in Solvbacktjarn	Sweden	-	$Cu(Re_3, Mo)S_8$

As one of the few rare metals on the Earth, silvery white rhenium is hard, has high resistivity, is resistant to high temperatures and corrosion, wear and stretch. It has a melting point of 3,180 °C and a boiling point of 5,627 °C. Its melting point ranks third among all elements, only after W and Ta. Its boiling point is the highest among all known metals. The density of rhenium is 21.04 g/cm^3, ranking fourth among all metals. Its resistivity is 3.84 times that of tungsten. Its elastic modulus and mechanical properties are close to iron[3-7].

2.2 Use

The unique physical and chemical properties of rhenium make it widely used in defense, aerospace, petrochemical industry, electronic materials including quantum computing, ultra-high temperature emitters, and medicine. For example, it is widely used to make electrodes, thermocouples, high temperature and corrosion resistant alloys, and as a catalyst, etc.[2-7].

When rhenium is added as an additive to alloys such as tungsten, molybdenum and chromium, the strength and plasticity of these metal alloys are significantly improved. Therefore, high-temperature alloys such as rhenium-tungsten, rhenium-molybdenum and rhenium-nickel are widely used in industries such as aerospace and electronics. Ta and W alloys with Re added are the most high-temperature resistant metal alloys known so far. For example, the Re-W thermocouple can measure a high temperature of up to 3,100 ℃. The cathode of the electron tube made of Re-W alloy has a lifespan 100 times longer than that of ordinary tungsten electron tubes. The ultra-high temperature emitter material with Re added can increase the discharge effect of hot electrons by 20%. The parts such as aircraft engine turbine blades, combustion chambers and jet nozzles with Re added have greatly improved their deformation resistance and creep resistance under long-term high temperature and high pressure, and extended their service life.

The creep life of nickel-based single crystal high-temperature alloys with 3% to 6% rhenium added is increased by a full 10 times. In a sense, the addition of rhenium determines the service life and quality of one or several generations of single crystal blades, and these blade materials directly determine the service life and quality of one or several generations of engines. This phenomenon is called the "rhenium effect" by scientists. According to statistics, 80% of the world's rhenium is currently used in the aviation engine industry. Rhenium is therefore of great strategic significance in national defense and the military, and is also called "aviation metal", "a super metal", "a strategic metal" or "rocket engine bone strengthening powder"[1-7].

The first application of rhenium began in the 1960s when Chevron and UOP Inc. jointly invented a rhenium-containing catalyst for oil processing. This rhenium-platinum alloy catalyst not only improved the depth of the reforming reaction, but also increased the productivity of gasoline, aromatics and hydrogen[1-5]. Since then, Re-Pt catalysts have been successfully launched and quickly and widely used in the oil industry, such as the production of lead-free and high-octane gasoline. This has ushered in a new era of "oil purification". Currently, about 90% of chemical products require rhenium and other catalysts. Once rhenium-platinum alloys appeared, they became very popular. The manufacture of high-efficiency catalysts and solar cells cannot be separated from the participation of rhenium. By the early 1970s, between 1978 and 1980, the sharp increase in rhenium demand caused its price to rise by three times. In the 1980s, people found that rhenium-nickel alloys had excellent properties of high temperature resistance, wear resistance and tensile resistance, making them the best choice for the production of single crystal blades for aviation. Rhenium alloy can withstand a weight of 117 tons without deformation. The engine nozzle made of it can withstand 100,000 thermal fatigue cycles, which is very suitable for producing parts for the most complex and harshest parts of aircraft engines. These key parts directly determine the performance and safety of aircraft engines.

In recent years, new biomedical metal materials with Re as an additive have greatly improved medical technology with their excellent performance, and have therefore been widely used in fields such as trauma repair and orthopedics. For example, "heart stent" surgical implants made of advanced medical metal material rhenium-molybdenum alloy still have good plasticity, resistance to physiological corrosion, fatigue resistance and wear resistance at high strength, thus benefiting patients and changing the human world. Rhenium can be seen in the fields of medicine, petrochemicals, and so on: high-speed rotating X-ray tube targets made of rhenium-tungsten alloy, radiopharmaceuticals for treating malignant tumors, long-life grids for microwave communications, heating tubes for space reactor cores, electric filaments for making special incandescent bulbs, shells of artificial satellites and rockets, protective plates for atomic reactors, evaporated metals used as ultra-high temperature heaters, and high-temperature coatings on rockets and missiles, etc.

2.3 Production and market

2.3.1 Global

Since 2011, global rhenium production has been in a state of fluctuation. In 2021, global rhenium production totaled 59 tons, a decrease of 0.3 tons from 2020. Global rhenium deposits are mainly concentrated in the United States, Chile and Poland, with a total production of 47.6 tons in 2021, accounting for about 80.7% of the global total production. The next rhenium producing countries are Uzbekistan, China, Kazakhstan and Armenia. Chile has the richest rhenium resources, followed by the United States, Russia, Kazakhstan, Armenia, Peru and Canada[3-4]. The rhenium resources and reserves in mainland China are relatively small thus far. The estimated rhenium metal pellet price averaged $1,070 per kilogram in 2023, a 5% decrease from the annual average price in 2022[8]. In 2023, apparent consumption in the United States was about 22% less than that in 2022. During 2023, the United States continued to rely on imports for much of its supply of rhenium. Canada, Chile, Germany, Kazakhstan, and Poland supplied most of the imported rhenium. Imports of APR decreased by an estimated 44% in 2023 compared with those in 2022. Imports of rhenium metal decreased by an estimated 8% in 2023 compared with those in 2022. Estimated world rhenium production in 2023 increased slightly compared with that in 2022.

The United States and Germany continued to be the leading secondary rhenium producers. Secondary rhenium production also took place in Canada, Estonia, France, Japan, Poland, and Russia. Industry sources estimated that approximately 25,000 kilograms of secondary rhenium was produced worldwide in 2023. There were no primary rhenium projects in 2023 that were expected to significantly contribute to rhenium availability in the immediate future[8].

About 90% of the world's rhenium metal is produced in porphyry deposits. The proven rhenium reserves are about 2,400 tons, mainly distributed in Northern Europe, Central Asia, North America and South America. From the perspective of global metallogenic belts, rhenium-containing deposits are concentrated in the Western Pacific metallogenic belt, the Tethys metallogenic belt, the Central Asia-Mongolia metallogenic belt and the Indian Craton metallogenic area[3-4]. Chile, which has 50% of the world's rhenium production, is the world's largest rhenium supplier. Other major producers include the United States and Poland. China's rhenium resources are not rich, with a reserve of 237 tons.

In terms of the development and utilization of rhenium metal, five countries, including the United States, the United Kingdom, France, Canada and Russia, can produce alloy steel containing rhenium.

2.3.2 China

The production of rhenium metal in mainland China has always been low, reaching 5.13 tons in 2021, and a year-on-year increase of 1.8%. The demand is 11.89 tons, a year-on-year increase of 5.64%. However, in terms of primary rhenium ore resources, the country has not yet systematically carried out rhenium resource evaluation and prospecting work, and only obtained some rhenium resources in the process of exploring molybdenum or copper-molybdenum deposits[3-4]. The sources of rhenium metal in mainland China include primary rhenium produced from mines and recycled rhenium. In 2021, the production of recycled rhenium metal in mainland China was 2,625 kilograms, accounting for 51.22% of the country's total rhenium production that year. Primary mines produced 2,500 kilograms of rhenium metal, accounting for 48.78%[9-10].

Affected by the decline in product prices, the market size of the rhenium industry in mainland China has shown a gradual downward trend: the country's rhenium market size was about RMB 488 million in 2014, and it quickly fell to RMB 207 million in 2021. In terms of rhenium metal consumption, the country mainly focuses on the two most important uses, high-temperature alloys and catalysts. In 2021, the demand for rhenium in the catalyst field in mainland China reached 62%, while the high-temperature assistant alloy field accounted for 14.64%[3-4].

It is worth mentioning that China began to extract rhenium from molybdenum concentrate roasting dust in the 1960s. Generally, molybdenite concentrate contains 0.001%-0.031% rhenium. To extract 1kg of rhenium, it is usually necessary to process 1000-2000 tons of related ores. Obviously, the investment is very huge. At present, there are two main processes for extracting rhenium: wet method and pyrometallurgy. According to some data, the amount of rhenium lost from the waste acid of copper smelting industry in China is 200~500 kg per year[1,4], which is an astonishing waste.

Compared with developed countries in the world, the rhenium industry in mainland China is still in its infancy. And its development and utilization are heavily dependent on the development and utilization of host ore deposits, and it will take some time to form a scale. In other words, rhenium ore resources still have a large development space in mainland China.

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3. Geographical distribution and geology of rhenium deposits in mainland China

3.1 Geographical distribution

In recent years, with the increasing attention paid to strategic emerging minerals, or so-called critical minerals in the West, mainland China has successively discovered considerable natural rhenium resources in the Zhanling molybdenum deposit in Jingxian County, Anhui; the Lala copper deposit in Sichuan; and the Laochang porphyry molybdenum deposit in Lancang, Yunnan (Table 3). In 2008, an independent sandstone rhenium deposit was discovered in Muchuan, Sichuan. Two years later, in 2010, the Huanglongpu molybdenum deposit in Luonan County, Shaanxi was discovered. At that time, it was reported that the “reserves” of associated rhenium ore in the Huanglongpu molybdenum deposit were about 176 tons, accounting for about 7% of the global reserves, second only to Chile, the United States, Russia and Kazakhstan[3-5]. It should be pointed out that the so-called “reserves” here should be low-level resources, not real reserves. The news media in mainland China and even scientific research institutions engaged in pure theoretical research often do not understand the huge difference between the terms “resources” and “reserves”. In 2017, 30 tons of associated rhenium was discovered in the Zhanling molybdenum deposit in Jingxian County, Anhui Province. This number should also be a low-level resource volume, rather than a real reserve in the Western industry.

Table 3. Known paragenetic/associated rhenium deposits in mainland China (modified from Zhou et. al.[5])

Province	Deposit	Type	Commodity	Age	Average Mo grade	Min. Re in Moly*	Max. Re in Moly	Average Re in Moly	Total ore	Total Mo metal	Average Re grade	Total Re metal
(Region)				Ma	%	10^{-6}			Mt	10,000 tons	g/t	ton
Anhui	Shapinggou	Pohphyry	Mo-Cu	108.1	0.144	2.41	15.7	8.58	1582	245.9	0.012	20
Heilongjiang	Duobaoshan		Cu-Mo	474.5	0.02~0.03	353.9	729.4	492	951	15.22	0.149	142
Hubei	Jiguanzui	Skarn	Cu-Au	138		425.7	1 152	734.9				
	Tonglushan		Cu-Au	137		261.4	665.4	385.7		0.68		3
Inner Mongolia	Bainaimiao	Pohphyry	Cu-Mo-Au	433.95	0.106	134.2	254.3	201.9	11.04	1.17	0.181	2
	Wunugetushan		Cu-Mo	171.6	0.015	215.8	919.8	512.8	435	45	0.077	33
Jilin	Daheishan		Mo	169	0.081	24.15	42.8	33.7	1045	149.72	0.002	2
Jiangxi	Dexing		Cu	171	0.016	172.3	591.4	358	1825	27.2	0.057	105
	Taqian	Skarn	W-Mo	162		19.17	87.7	43.7		1.59		1
	Tongkengzhang	Pohphyry	Mo	1 347	0.13	1 125	1 338	1 256	1	0.13	1	2
	Xiongjiashan, Jinxi		Mo	155		171.3	614.5	450				
Liaoning	Xiaojiayingzi	Skarn	Mo-Fe	161.4	0.23	21.75	163.1	64.3	8.87	10.05	0.148	1
	Yangjiazhangzi		Mo	189		33.8	53.1	43.5		26.18		11
Shaanxi	Huanglongpu	C - vein	Mo-Pb	222	0.1	71	260	135	120	12	0.133	16
	Jinduicheng	Pohphyry	Mo	138	0.106	4.2	26	14.46	1 089	97.1	0.026	28
	Nannihu-Sandaozhuang	Skarn	W-Mo	144	0.143	9	51	23.33	1 033.6	147.8	0.033	34
Sichuan	Muchuan	Sandstone	Cu-Mo-Re									
Tibet	Chengba	Skarn	Cu-Mo	58.5		84.6	461.3	252	899.1			
	Jiama	Pohphyry	Cu-Mo-	14.3		61.66	2 232	185.5		60		111
		Skarn	Pb-Zn									
	Jigongcun	Quartz vein	Mo	22.5	0.13	1410	1 691	1 525	48.8	6.34	3.47	166.3
	Lakange	Pohphyry	Cu	13		343.6	837.5	538				
	Nuri	Skarn	Cu-Mo-W	24.1	0.073	285	605.5	417	134.6	2.86	0.304	41
	Qulong	Pohphyry	Cu-Mo	16	0.032	306	1 218.2	616	1 517	45.7	0.197	299
	Tinggong	Pohphyry	Cu-Mo	16		225.7	922.7	486		1.05		5
	Xiongcun	Pohphyry	Cu-Mo-Au	166		1 615	12 182	4 146				
Xinjiang	Donggebi	Pohphyry	Mo	211.7	0.113	6.54	84.2	35.4	350.24	39.6	0.04	14
	Boluokenu	Skarn	Cu-Mo	288.1		54.3	77.8	64.4				
	Xilekuduke	Pohphyry	Cu-Mo	329.2		118	572.1	317				
	Zhajisitan	Sandstone	Re-U									
Yunnan	Pulong	Pohphyry	Cu-Mo-Au	213	0.004	239.8	379.3	318.5	271.93	4.72	0.013	3
	Machangqing	Pohphyry	Cu-Mo-Au	34.6	0.093	34.1	63.9	49.1	58.9	5.48	0.051	3

Note: Moly - Molybdenite; C-vein - Carbonate vein.

One fact is that the rhenium resources in mainland China are still relatively scarce, with low resource and reserves. The reserves of rhenium are less than 300 tons, accounting for only about 7% of the global total[5]. Of course, another fact is that mainland China has made some progress in the exploration, mining and utilization of rhenium in recent years, and the annual output of some rhenium mines is about two tons[5]. As for the currently known production areas, the rhenium deposits in mainland China are mainly distributed in the following major regions:

- **Southwest:** Southwest China is the main production area of primary rhenium deposits in China. The so-called southwest here refers to Sichuan, Yunnan, Guizhou and Tibet. Sichuan Province is one of the most important rhenium production areas in the southwest. These rhenium deposits are mainly distributed in Ganzi and Aba in the province. The Happy Peak or Xilefeng rhenium deposit in Yunnan Province is one of the largest rhenium deposits in mainland China. In addition, some other mines in the southwest also produce a small amount of rhenium, but the total output is relatively low.

• **Northeast China:** Northeast China is one of the regions with high rhenium production in mainland China, mainly distributed in Jilin, Liaoning, Heilongjiang and some neighboring provinces, such as some silver deposits in Inner Mongolia. Among them, Xinmin City, Liaoning Province is one of the main production areas of rhenium in Northeast China, and the rhenium ore produced is of good quality. However, the total rhenium production in Jilin and Heilongjiang provinces, which are also located in the Northeast, is relatively low.

• **Central China:** Some rhenium deposits have also been found in Henan, Shaanxi, Hubei, Hunan, and Yingtan, Jiangxi Province, which are rich in tungsten, molybdenum and copper ores. However, they are all small in scale[3-5].

• **Other regions:** In addition to the aforementioned regions, a small number of rhenium deposits have also been found in other regions of mainland China, such as Jiangsu, Fujian, and some silver deposits in Gansu, but they are also small in scale[3-6].

Overall, the known rhenium deposits in mainland China are widely distributed. However, these rhenium deposits are geographically remote and scattered, with poor infrastructure in the locations of the deposits, difficult mining, and high production costs. Affected by these factors, the overall rhenium ore production in mainland China is relatively low.

3.2 Deposit geology

The representative rhenium deposits and their geology discovered in mainland China are as follows:

- **Sichuan Muchuan-Mabian Re-Cu-Mo polymetallic deposit**

The sedimentary rocks of the Shaximiao Formation of the Middle Jurassic in the Sichuan Basin are traditionally important oil and gas production strata in southwest China, and are also a potential area for the development of various sedimentary deposits. The 1:50,000 regional geological surveys that began in the mid-twentieth century and the 1:10,000 comprehensive geochemical profiles survey projects in key work areas such as the rhenium-bearing rock series in recent years have unveiled the mystery of rhenium mineralization in the basin. Wu et al. conducted profile surveys, geological mapping, and dissections of typical deposits and showings in the Shaximiao Formation, supplemented by rock and mineral identification, multi-element chemical analysis, and lithology combination characteristics. He studied the sedimentary environment, material sources, and paleoclimate of the Shaximiao Formation, its typical deposits, showings, and rhenium-bearing rock series. In his master's thesis titled "Study on the Geological Conditions of Rhenium Mineralization in Mabian-Muchuan Area, Leshan City, Sichuan Province" completed in 2018[11], he concluded that under the action of epigenetic geology, rhenium migrates in the form of oxygen complexes dissolved in water. When a large amount of organic matter, feldspar and quartz particles and ore-forming materials are deposited in rivers and intermittent lakes at the same time, the organic matter in the water body adsorbs ore-forming materials copper, molybdenum and rhenium and deposits. During the mineralizing process, a large amount of H_2S gas released by the decomposition of organic matter dissolves in water to produce a large amount of sulfur-containing solution, causing the deposition environment to change from an oxidizing state to a partially reducing state, so that sulfur-loving elements such as Mo, Cu and Re combine with S to form molybdenite and hydrous colloidal molybdenite ($MoS_2 \bullet nH_2O$), in which a considerable part of rhenium enters molybdenite, colloidal molybdenite and sulfide molybdenite in an isomorphous form.

In fact, as early as 1958, researchers noticed this type of mineralization and linked it with key words such as igneous action, hydrothermal activity, greisenization, ore-bearing quartz, and contact metamorphism[12]. The origin of the mineralization is self-evident. More than 20 years later[13-19], more researchers conducted more in-depth research on the geological characteristics and mineralization era of the mineralization. Among them, Shao concluded after studying the deposit that the occurrence state of rhenium in nature has not yet been fully clarified, and the geochemical characteristics of rhenium are also poorly understood[13]. At present, it is only known that basic igneous rocks contain more rhenium than acidic igneous rocks, and pegmatites contain more rhenium than their parent magma. Columbite, yttrium silicon beryllium ore, and tantalite in pegmatite veins all contain a certain concentration of rhenium, but it is most enriched in the hydrothermal stage after the magmatic period. It is generally believed that rhenium is mainly enriched in copper-molybdenum and copper deposits. This also seems to hint at the origin of the mineralization.

Shu believes that the mineralization geotectonic conditions, geological characteristics of the deposits, and ore-controlling factors of this rhenium mineralization belt are unique[14]. In the period of depression with deep regional dissection and distribution of algal reef ore source layers, the areas where northeast-trending tension-shear faults are developed or connected with them are all prospective areas for rhenium mineralization.

Some scholars have also found through research that this type of molybdenum-bearing sandstone is a new type of mineralization, namely sedimentary sandstone-type rhenium-molybdenum (osmium) mineralization[16]. The X-ray powder diffraction analysis shows that the fine-grained flaky molybdenum-bearing mineral is crystalline molybdenite. High-precision mass spectrometry analysis found that molybdenite contains dispersed Re, Os and platinum group elements, and the Os content is very high, which has important comprehensive utilization value. High-precision Re-Os isotope dating proves that the formation age of molybdenite is the same as that of host sandstone of the Mesozoic red bed basin. In addition, no signs of hydrothermal activity or tectonic influence were found at the time, so the preliminary conclusion that molybdenite is of syngenetic sedimentary origin was drawn.

Hao conducted scanning electron microscopy, energy spectrum and organic carbon isotope analysis on the bitumen closely related to rhenium and molybdenum enrichment and concluded that the mineralized sandstone in the mining area is the product of the delta front distributary channel sedimentary environment, rather than the relatively low-energy reduction distributary bay sedimentary environment, nor is it enriched by oxidation-reduction under surface conditions[17]. The bitumen in the deposit was formed by thermal cracking of the underlying Triassic Xujiahe Formation ancient oil reservoir. The extraordinary enrichment of rhenium and molybdenum has a close spatial and genetic relationship with the organic matter in the ancient oil reservoir.

Fan et al. conducted rhenium analysis on a large number of rocks and ores in this area and concluded that the mineralized layers in the central part of the Sichuan Basin are mainly rhenium and molybdenum, the eastern part is mainly rhenium, molybdenum and copper, and the southern part is mainly copper, rhenium and silver[20]. That is, there is a geochemical zoning phenomenon in the study area.

- **Huanglongpu Re-Mo carbonate vein-type deposit in east Qinling**

This deposit is a typical representative of the above-mentioned rhenium province in the central part of mainland China, and is also a relatively rare type of rhenium mineralization style. As the only carbonate vein-type Re-Mo deposit in the world[21], the Huanglongpu Re-Mo ore field is located in the western section of the East Qinling metallogenic belt on the southern edge of the North China Platform, and is spatially controlled by the Lushi-Machaoying fault zone. Carbonate vein-type Re-Mo deposits are closely related to the Indosinian magmatic activity. The structure provides a favorable ore-bearing space, and the surrounding rock provides a small amount of ore-forming materials, forming the NW-trending Yuantou-Nianziping Re-Mo polymetallic mineralization belt and the NE-trending Xiping-Qinlinggou Cu-Mo mineralization belt. The Re and Mo contents are generally positively correlated. The ore-forming fluids are mainly magmatic hydrothermal fluids of the medium-high temperature silicate-carbonate-sulfate system. The ore-forming materials are mainly derived from mantle-derived igneous magma, which belongs to the late Indosinian orogeny and has roughly experienced three major mineralization periods.

Huang concluded that molybdenite is the main carrier mineral of rhenium[23]. In different types of molybdenum deposits in the eastern Qinling region, the average content of Re in molybdenite is mostly between 10 and 20 ppm, but the molybdenite in the Huanglongpu carbonate vein-type molybdenum (lead) deposit has an average Re content of up to 152.5 ppm. Rhenium in molybdenite exists in the form of isomorphic substitution for molybdenum. The difference in rhenium content in molybdenite of these deposits mainly depends on the content of original rhenium in the ore-forming hot fluid. Molybdenite polytypes include 2H type and 2H+3R mixed type. Rhenium content and mineralization temperature have no effect on molybdenite polytype, so molybdenite polytype has no typical significance for molybdenum ore type.

The Comprehensive Research Team of the Shaanxi Geological Bureau conducted a study on the mineralization of the intermediate-acidic rock mass in the Shipo-Huanglongpu area of Luonan from 1979 to 1982, and concluded that there were at least two molybdenum mineralization periods in the Huanglongpu-Jinduicheng area. The eastern part of the study area is a favorable area for finding iron, molybdenum and copper, while the western part is a favorable area for finding molybdenum, rhenium and sulfur deposits.

The Ministry of Natural Resources’ released report titled “"Resource Verification Report of Shanghe Molybdenum Deposit in Dashigou Deposit Section of Huanglongpu Molybdenum Ore Field in Luonan County, Shaanxi Province” shows that the molybdenum ore resources have increased from the original 51,000 tons to 128,500 tons. The newly discovered associated ore has a rhenium metal content of 176.11 tons, making it the largest rhenium ore producing area in China[24]. The Re content of the Dashigou molybdenum deposit ranks first among the molybdenum deposits in the eastern Qinling Mountains in Shaanxi, and is also among the top in similar deposits in the country[25-26].

- **Jigongcun Re-Mo deposit in Tibet**

The Jigongcun Re-Mo deposit in Qushui County, Tibet, is a quartz vein-type rhenium deposit with a prominent rhenium-rich feature[27]. The rock mass in the area is mainly granodiorite and quartz diorite with an age of 51.8 ± 0.5 Ma, and the mineralization age of the deposit is 21.8 ± 6.2 Ma. The hydrothermal alteration distributed in the fault zone and the rock mass on both sides is potashization, epidote-chloriteization and pyrite-sericite quartzization from deep to shallow. The mineralization can be divided into quartz-potassium feldspar-anhydrite stage, quartz-pyrite stage, quartz-molybdenite stage, quartz-galena stage, and molybdenum epigenetic oxidation stage from early to late. Among them, rhenium and molybdenum are mainly developed in the quartz-molybdenite stage. The rhenium-containing metal minerals are mainly molybdenite, followed by U-Ti oxides and bismuth tellurides. The Re content in molybdenite is mostly between 0.10% and 0.30%, with a maximum of 0.88% and an average of about 0.20%. The Re content in molybdenite is (1334-2148) $\times 10^{-6}$, with an average of 1606 $\times 10^{-6}$. The Re content in U-Ti oxide is 0.02% on average, with a maximum of 0.07%. The Re content in bismuth-telluride is 0.13%-0.19%, with an average of about 0.15%. The ore-forming fluid in the mining area belongs to the CO_2-H_2O-NaCl system, mainly H_2O solution inclusions (L1 and L2) and CO_2-H_2O inclusions (C1 and C2). Among them, L1, C1 and C2 fluid inclusions are the main ones, followed by a small amount of L2 and single-phase fluid inclusions. The homogenization temperature range of each stage of the ore body Ⅰ1 is: 251.4～311.4 ℃ in the quartz-pyrite stage, 232.2～295.7 ℃ in the quartz-molybdenite stage, and 180.7～239.4 ℃ in the quartz-galena stage. The quartz-potassium feldspar-anhydrite stage in the ore body Ⅱ1 is 263.0～325.6 ℃, quartz-pyrite stage is 246.5～303.5 ℃, quartz-molybdenite stage is 201.0～270.0 ℃, and quartz-galena stage is 180.0～218.5 ℃. From the early stage of mineralization to the late stage of mineralization, the ore-forming fluid showed an evolution trend from medium temperature and medium salinity to low temperature and low salinity.

The Jigongcun molybdenum deposit in Tibet is a typical rhenium-rich molybdenum deposit[5], with an estimated molybdenum ore content of 48.8 million tons, molybdenum metal content of 63,400 tons, and an average molybdenum grade of 0.13%. The rhenium metal content is 166.33 tons, with an average grade of 3.47×10^{-6}. The ore body is mainly vein-like and occurs in the ductile shear zone in the granodiorite, with a time difference of about 30 Ma between diagenesis and mineralization. Hydrothermal alteration mainly includes silicification, sericitization, kaolinization, etc., but is limited to the granodiorite in and on both sides of the fault. Molybdenite is mainly vein-like and thin-film-like in quartz vein fissures or in the altered granodiorite at the edge of the fault in the form of dissemination. The mineral assemblage is mainly pyrite-quartz, molybdenite ± pyrite ± galena-quartz, with very small amounts of chalcopyrite, Bi-Te sulfide, U-Ti oxide, etc. Rhenium is mainly found in molybdenite, and trace amounts of rhenium are also found in sulfides such as chalcopyrite.

- **The Zagestan sandstone-type Re-U deposit in Xinjiang**

The Zajistan sandstone-type U-Re-Se-Mo polymetallic deposit in the Yili Basin of Xinjiang was called the 511 uranium deposit during the "secret era" in mainland China[5-6,28]. The uranium ore bodies are produced in the interlayer oxidation-reduction transition zone in the Jurassic Shuixigou Group lithic quartz sandstone and feldspar lithic sandstone, and are of epigenetic alluvial origin. Rhenium minerals, which exist in the form of rhenium sulfides or metal organic compounds combined with humus, are enriched in the front line of the interlayer oxidation zone and its inner and outer sides in a vesicular shape, which is roughly consistent with the distribution range of the uranium ore bodies, but biased towards the reduction zone. Selenium is enriched in the inner side of the front line of the interlayer oxidation zone in a lens shape, biased towards the oxidation zone. The uranium ore contains abundant strawberry-shaped, star-shaped colloidal pyrite, organic matter and charcoal, as well as a small amount of pyrrhotite, marcasite and limonite. Uranium appears in the form of microscopic particles of uranium-containing minerals such as pitchblende and uraninite, or is present in sandstone in an adsorbed form. Rhenium may migrate with water between oxygen-containing layers in the form of Re7^{+} ion complexes, and be enriched in the interlayer oxidation-reduction transition zone under the reduction of organic matter and sulfur. U is highly positively correlated with associated elements such as Re, Mo, and Se. The average content of Re in uranium ore is 0.71×10^{-6}, Mo 54.16×10^{-6}, and Se 1.40×10^{-6}.

4. Characteristics of rhenium ore in Mainland China

In recent years, mainland China has achieved remarkable results in the exploration of rhenium deposits. New associated rhenium deposits have been discovered in Guizhou, Hubei, Henan and other provinces, as well as independent rhenium mineralization zones suspected to be dominated by rhenium, namely sedimentary sandstone rhenium deposits in Muchuan, Sichuan (Table 3-5). As of the end of 2021, China has obtained a total of 787.41 tons of rhenium ore resources[28].

Table 4. A brief statistical table of rhenium deposits discovered in mainland China （modified from Huang et. al.[28]）

Series #	Province/region	City	County	Depopsit name	Cumulative resource (t)	Average grade (%)
1	Inner Mongolia	Chifeng	Al Horqin Banner	Laojiagou Mo	6	0.004 125
2	Liaoning	Huludao	Lianshan District	Lingqian Mo	1.29	0.005 100
3	Liaoning	Huludao		XintaimenMo	7	
4	Heilongjiang	Heihe	Nenjiang County	Duobaoshan Cu-Mo	75	
5	Heilongjiang			Tongshan Cu	24	
6	Jiangsu	Zhenjiang	Jurong City	Tongshan Mo-Cu	2	1.000 000
7	Fujian	Nanping	Wuyishan City	Pingdi	5.29	
8	Henan	Luoyang	Luanchuan	Luotuoshan pyrite	1.5	0.003 600
9	Henan			Sandaozhuang Mo-W	33.38	300～0.002
10	Henan			Lengshui-Chitudian Mo-Pb-Zn	146	0.001 000
11	Henan	Xinyang	Guangshan	Qianechong Mo	15.14	0.140 000
12	Hubei	Huangshi	Daye City	Houtoushan Mo-Cu	1	0.034 000
13	Hunan	Chenzhou	Guiyang	Baoshan	6	
14	Hunan	Changsha	Liuyang City	Longwangpai	78.3	0.000 600
15	Tibet	Lhasa	Qushui	Jigongcun Mo	164.31	
16	Shaanxi	Weinan	Hua	JinduichengMo	41.85	0.000 327
17		Shangluo	Luonan	Xigou Mo	7.24	
18				Huanglongpu Mo	53.82	

Table 5. A brief geology & geochemistry of the rhenium deposits in mainland China（modified from Huang et al.[28]）

Origin	Deposit	Commodity	Type	Metallogenic epoch			Dominant commodity			Re		Mining situation
				Orogeny	Age (Ma)	Dating method	Commodity	Resource (10,000 t)	Size	Resource (t)	Size	
Jinxian, Anhui	Chenling Mo	Mo, Cu, Re	Porphyry	Yanshan			Mo	6.21	Medium	29.42	Medium	No
Yanqing, Beijing	Dakezhuang Mo	Mo, Re	Continental volcanic		137.6±3.7	Molybdenite	Mo	1.04		0.38	Small	No
Wuyishan, Fujian	Pingdi Mo	Mo, Pb, Re	Magmatic hydrothermal		107.4±3.3	Re-Os	Mo	2461	Small	5.29	Medium	Yes
Gutian, Fujian	Xichao Mo	Mo, Re	Porphyry		113.4±0.9	Molybdenite Re-Os	Mo	0.25		1.52	Small	Stopped
Enping-Yangchun, Hubei	Chunwan Mo	Mo, Re	Porphyry				Mo	21.24	Medium	40.25	Medium	No
Yangchun, Hubei	Shilu Cu-Mo	Cu, Mo, Ag, Re	Skarn		104.34±0.66	Molybdenite	Cu, Mo	28.97；		2.887	Small	Stopped
Kaiyang, Guizhou	Baimadong Hg	Mo, Hg, Tl, V Re, Ga, B, Sb	Epithermal Hydrothermal				Hg	2.4232		20	Medium	Unknown
Luanchuan, Henan	Luotuoshan pyrite	S, Cu, Zn, W, Re	Skarn		137.1～138.4	Molybdenite Rb-Sr	S	756.9 Ore	Large	1.5	Small	Yes
	Nannihu Mo-W	Mo, W, Re	Porphyry-skarn		143.4～146.5	Molybdenite Re-Os	Mo, W	67.6910； 0.6061	Large	30.79	Medium	Yes
	Sandaozhuang W	Mo, W W, Mo, Re	Skarn		143.4～146.5	Molybdenite Re-Os	Mo, W	77.36； 51.12	Large	22		Yes
	Shangfanggou Mo	Mo, Re	Porphyry-skarn		144.8±2.1	Molybdenite Re-Os	Mo	72.23		81.258	Large	Yes
Guangshan, Henan	Qianechong Mo	Mo, Ag, Re	Porphyry		128.7±7.3	Molybdenite Re-Os	Mo	50.738 8		15.14	Medium	Yes
Nenjiang, Heilongjiang	Duobaoshan Cu-Mo	Cu, Mo, Re Cu, Mo, Se, Re		Caledonian	475.1±5.1	Molybdenite Re-Os	Cu	315.05		75	Large	Yes
	Tongshan Cu	Cu, Mo, Au, Cd, Re			461±1	LA-ICP-MS Zircon U-Pb	Cu	32.983	Medium	24	Medium	Yes
Xunke, Heilongjiang	Cuihongshan polymetallic	Fe, Re, Mo, W, Zn, Cu, Pb, Sn, Cd, In, Se, Te	Skarn	Yanshan	201.6±1.4	Molybdenite Re-Os	Fe	6 865.82	Large	0.6	Small	Stopped
Daye, Hubei	Houtoushan Mo-Cu	Mo, Cu, Re	Magmatic hydrothermal				Mo, Cu	0.012 9； 0.094 0	Small	1.08		Yes
	Tongkoushan Cu	Cu, Mo, Ag, Se, Te, Re	Porphyry-skarn		143～129	Mica Ar-Ar	Cu	30.77	Medium	5.9	Medium	Yes
Yangxin, Hubei	Lijiawan Cu polymetallic	Cu, Au, Ag, Mo, S, Se, In, Cd			138～137	SHRIMP Zircon U-Pb	Cu	7.75	Small	0	Showing	Yes
Liuyang, Hunan	Longwangpai Mo-W	W, Mo, Re	Magmatic hydrothermal		146.3±1.8	Molybdenite Re-Os	W + Mo	2.67		78.3	Large	No
Yongji, Jilin	Daheishan Mo	Mo, Cu, S, Ga, Re	Porphyry		168.2±3.2	Molybdenite Re-Os	Mo	21.55	Large	3	Small	Yes
	Guokuidingzi Cu	Cu, Ag, Re, Ga, Ge	Magmatic hydrothermal		250±1.5	Molybdenite Re-Os	Cu	0.51	Small	0.4	Showing	Stopped
Jurong, Jiangsu	Tongshan Cu-Mo	Cu, Mo, Au, Ag, Re	Skarn		170	Garnet U-Pb	Cu, Mo	1.196 5； 0.514 4		4	Small	Yes
Huludao, Liaoning	Xintaimen Mo	Mo, Pb, Zn	Porphyry		183±3	Molybdenite Re-Os	Mo, Zn	0.069 9； 0.016 3		7	Medium	Yes
	Yangjiazhangzi Mo	Mo, Pb, Zn	Skarn		187～191	Molybdenite Re-Os	Mo	2.45	Medium	1.39	Small	Yes
Alukeerqin, Inner Mongolia	Laojiagou Mo	Mo, Re	Porphyry	Indosinian	234.9±3.1	Molybdenite Re-Os	Mo	8.321 9		5.728	Medium	No
Xinbaerhuyouqi, Inner Mongolia	Wunugetushan Cu-Mo	Mo, Cu, Re, Ag, Au			177.4±2.4	Molybdenite Re-Os	Mo, Cu	34.67； 130.24	Large	99.1	Large	Yes
Luonan, Shaanxi	Huanglongpu Mo	Pb, Mo, Fe Re, Te, Se	Skarn		221	Molybdenite Re-Os	Mo	12.2		53.82		Yes
	Mulonggou Fe	Fe, Mo, Cu, Zn, S		Yanshan	151±1	LA-ICP-MS Zircon U-Pb	Fe	1841.96	Medium	3.18	Small	Stopped
	Xigou Mo	Mo, Re	Magmatic hydrothermal	Indosinian	225.1±1.4	Molybdenite Re-Os	Mo	1.76		6.46	Medium	Yes
Huaxian, Shaanxi	Jinduicheng Mo	Mo, Cu, S, Se, Re	Porphyry	Yanshan	129～140	Molybdenite Re-Os	Mo	96.97	Large	118.7	Large	Yes
Sangrixian, Tibet	Mingze Cu polymetallic	Cu, Mo, Re		Himalayan	30.26±0.69	Molybdenite Re-Os	Cu, Mo	13.09； 6.23	Medium	16.64	Medium	No
Hami, Xinjiang	Jingerquan-Baishan Mo	Mo, Re, Ag		Indosinian	224.8±4.5	Molybdenite Re-Os	Mo	3.55		29.15		No
Chabuerxibo, Xinjiang	Langka U-Re	U, Re	Epithermal	Yanshan	J_2		U	0.459 96		21.7		Unknown

Most of the known rhenium deposits in mainland China are paragenetic and/or associated minerals of molybdenum and/or copper-molybdenum deposits. Relevant researchers have estimated that China's rhenium resources are about 4,000 tons by analyzing the Re-Os isotope data of molybdenite in 147 such deposits[28-31]. Among the more than 70 porphyry copper deposits counted, 10 of them have associated rhenium resources exceeding 50 tons (Table 3-5). There are 18 associated and/or paragenetic rhenium deposits in China, with a total rhenium resource of 669.12 tons, an increase of 39.5%.

From the perspective of rhenium mineralization age, most of the known rhenium deposits in mainland China were formed in the Jurassic, that is, during the Yanshan orogeny. The next ones were the Indosinian, Caledonian and Himalayan periods. This shows the important influence of Mesozoic plate tectonic movement on rhenium mineralization (Tables 3 and 5).

Some mainland Chinese scholars believe that China's rhenium ore production capacity has been significantly improved in recent years and has become the world's second largest producer of rhenium products[28]. However, the grade of China's rhenium ore is low, and its comprehensive utilization technology lags behind that of the international community. The secondary recycling and utilization of rhenium resources is still immature, and there is a problem of insufficient resource recycling and development and utilization scale. In addition, the rhenium industry in mainland China is still in its infancy, with breakthroughs to be made in the deep processing of rhenium mineral products and high-tech materials. Currently, it mainly relies on imports. However, China is strengthening cooperation with countries rich in rhenium mineral resources through the "Belt and Road" initiative to enhance its ability to obtain overseas rhenium mineral products.

Relevant scholars further pointed out that with technological advancement and increasing market demand, the demand for rhenium will continue to grow[28-31]. It is expected that in the next 10-20 years, the application of rhenium in China will become more diversified, and the demand for rhenium will therefore reach its peak. However, the country’s existing domestic rhenium resource reserves are difficult to meet demand. To this end, it is recommended that the Chinese government actively evaluate the potential of rhenium ore resources, improve comprehensive utilization technology, and strengthen the secondary recycling of rhenium. At the same time, a strategic reserve mechanism for rhenium will be established to ensure resource security and further improve the security of rhenium resources.

5. Types of primary rhenium deposits in mainland China

Based on the above information, the primary rhenium deposits currently known in mainland China can be divided into the following types (Table 6), which are briefly discussed below.

Table 6. Types of known primary rhenium deposits in mainland China

Industrial type	Genetic type	Metallogenic time		Potential commodity association
		Orogeny	Age (Ma)	
Associated/symbiotic	Porphyry	Caledonian, Indosinian , Yanshan, and/or Himalayan	30.3 - 475.0	Mo, Cu, Pb, Zn, Ag, Au, S, Cd, Re, Se, In, Ga, Te
	Skarn	Indosinian and Yanshan	137.1 - 221.0	W, Mo, Fe, S, Sn, Cd, In, Se, Te, Cu, Pb, Zn, Au, Ag, Re
	Continental volcanic	Yanshan	137.6 ± 3.7	Mo, Re
	Magmatic hydrothermal	Indosinian and/or Yanshan	107.4 - 250.0	Mo, Cu, Pb, W, Re, Ag, Ga, Ge
	Hydrothermal	Yanshan		Re, Ga, B, Sb, Hg
	Epithermal	Yanshan	104.34 ± 0.66	Cu, Mo, Ag, Re, Mo, Hg, Tl, V, U
	Carbonate vein	Yanshan, Indosinian	222	Mo, Pb, Re
	Quartz vein	Himalayan	22.5	Mo, Re
Independent (multimetal)	Sandstone	Yanshan	202.0 - 206.0	Re, Cu, Mo, Os, U

Compared with the similar minerals in other countries around the world, the primary rhenium deposits in mainland China have both the same or similar features, but also their own unique features.

As for the first category of associated and/or symbiotic rhenium deposits, mainland China and the world have the following genetic types: porphyry type, skarn type and the composite type of the two; magmatic hydrothermal type, other genetic hydrothermal type, and/or mixed type of different hydrothermal fluids; sandstone-type rhenium Re-Cu deposits including the (reduced-facies) sandstone strata-bound deposits, such as the Zhezkazgan sandstone copper deposit in Kazakhstan, and the Mansfield-type multi-element copper deposits in the Permian copper-bearing sandstone-shale in Eastern Europe, which contain extremely high rhenium, and rhenium has even been extracted from them; sandstone-type Re-U deposits, such as the uranium (scandium) sandstone deposits in the Colorado Plateau of the United States; sedimentary transformation-type associated rhenium deposits: under certain geological conditions, rhenium and/or its compounds are enriched and formed in certain sedimentary rocks through hydrothermal activities generated by deep buried rock bodies; volcanic rock-type rhenium deposits; and rhenium mineralization in black shales, such as the high content of rhenium and platinum group found in the Devonian black shales in the Yukon region of Canada[32], and similar rhenium mineralization has also been found in Hunan and Guizhou, China. In a sense, this rhenium-bearing black shale-type rhenium mineralization may be an independent rhenium deposit similar to the sandstone-type rhenium mineralization in mainland China.

Similarly, in terms of the first category of associated and/or symbiotic rhenium mineralization, mainland China has discovered genetic types that have not yet been discovered in other countries, such as carbonate vein type, quartz vein type and epithermal rhenium mineralization. Of course, this difference may be largely a matter of time, that is, the international community may find it soon. In addition, differences in the understanding or judgment criteria of the genetic type of rhenium mineralization will also cause this temporary result.

The greater difference between the known rhenium mineralization in mainland China and the international community lies in the so-called independent rhenium mineralization in mainland China. This is actually the discovery of rhenium polymetallic mineralization in China, which has not been discovered or reported overseas so far. Of course, this so-called independent rhenium mineralization in mainland China still needs more exploration work to verify. The fact is that this so-called independent rhenium mineralization is polymetallic mineralization, not independent rhenium mineralization in the pure sense.

However, some sources believe that the skarn-type Merlin molybdenum-rhenium deposit in Queensland, Australia is one of the few independent rhenium deposits, with a rhenium grade of up to 22.7 g/t. However, compared with other types of deposits, the total reserves of this rhenium deposit are relatively small[33].

In terms of the mineralization era, the known rhenium mineralization in mainland China is also different from that in the international community. In general, the mineralization era of the global rhenium-rich deposits spans a wider range, from the Paleoproterozoic to the Cenozoic, but mainly in the Cenozoic and Mesozoic, among which the Himalayan and Yanshanian are the most developed, followed by the Caledonian and Indosinian. In terms of origin, global rhenium mineralization is mainly distributed in the Circum-Pacific metallogenic belt and the Tethys metallogenic belt. Among them, the most representative rhenium deposits formed in the Himalayan period are the most, such as the Cerro Verde (62 Ma) in Peru, Bingham (37 Ma) in the United States, Maronia (29 Ma) in Greece, Sar Cheshmeh (12.5 Ma) in Iran, and the El Teniente (5.4 Ma) porphyry copper-molybdenum deposit in Chile. Representative deposits of the Caledonian period include the Aksug porphyry copper-molybdenum mine (403 Ma) in Russia. There is also a very small number of rhenium deposits formed in the Paleoproterozoic, such as the Merlin molybdenum-rhenium deposit (1,528 Ma) in Australia.

The known rhenium mineralization in mainland China mainly occurred in the Yanshanian period, with representative deposits such as the porphyry copper-molybdenum polymetallic deposit in Xiongcun, Tibet (166 Ma), the porphyry copper deposit in Dexing, Jiangxi (171 Ma), the Jinduicheng in Shaanxi (138 Ma) and the Daheishan porphyry molybdenum deposit in Jilin (169 Ma). The second is the Indosinian period, with representative deposits such as the porphyry molybdenum deposit in the East Gobi of Xinjiang (211.7 Ma) and the carbonate vein-type molybdenum-lead deposit in Huanglongpu, Shaanxi (222 Ma). The third is the Himalayan period, such as the quartz vein-type molybdenum deposit in Jigongcun, Tibet (22.5 Ma); and the Caledonian period, such as the Bainaimiao porphyry copper-molybdenum polymetallic deposit in Inner Mongolia (433.9 Ma) and the Duobaoshan porphyry copper-molybdenum deposit in Heilongjiang (474.5 Ma).

6. Discussion

The unique geographical location and rich geological structure of mainland China determine that the rhenium resources produced here have both similarities with similar resources in other continents around the world and their own uniqueness. This is consistent with the fact that the distribution of chemical elements on the entire earth, especially on the earth's surface, is uneven.

Similar to most rare elements in the world, rhenium in mainland China mainly appears in the form of associated and/or paragenetic minerals. The world's rhenium resources are mainly contained in porphyry copper and/or copper-molybdenum deposits, and the resource volume accounts for about 80%. Typical examples are the Ajo porphyry copper-molybdenum deposit in Arizona, USA and the Chuquicamada porphyry copper-molybdenum deposit in Chile. The same is true for mainland China: porphyry associated and/or paragenetic rhenium deposits are the main type, but not limited to copper or copper-molybdenum deposits. Rhenium mineralization in mainland China is associated and/or paragenetic with porphyry copper, copper-nickel, and copper-molybdenum deposits, and is also paragenetic and/or associated with porphyry lead and zinc deposits.

In this regard, more associated or symbiotic deposits will be discovered in the Yangtze River Basin, the Qinghai-Tibet Plateau, the Northwest and the three provinces of Northeast China in the near future,, which are rich in porphyry copper, copper-molybdenum and copper-nickel deposits. Some researchers have already noticed this[34].

An interesting phenomenon is that there is a significant difference in the average rhenium content in molybdenites formed by different orogenic movements: the rhenium content in molybdenites formed in the Himalayan and Yanshan periods is higher, followed by the Indosinian and Caledonian periods. In general, the newer the formation of molybdenite, the higher the rhenium content and the greater the resource reserves[35]. Golden et al. calculated the average rhenium content of molybdenite in molybdenum deposits formed in three geological periods around the world, which was 115×10^{-6} during 2,910~1,870 Ma, 335×10^{-6} .

Compared with traditional bulk minerals such as copper, lead, zinc and iron deposits, the exploration and research of rhenium deposits started much later. It is believed that more brand new and known types of rhenium deposits will be discovered over time. For example, trace amounts of rhenium have been found in ultramafic rocks in Ukraine in recent years, rhenium mineralization has been found in volcanic rocks in Hokkaido, Japan, in the fumaroles of Kudriave Volcano in Russia, and in mineralization related to platinum group elements in ultramafic rocks[36].

In the Ni-Mo-PGE sulfide-rich layers of the Lower Cambrian in southern China, the grade of rhenium in some areas has reached or even exceeded its industrial grade, with the highest rhenium in a single sample reaching 33×10^{-9}. There is every reason to believe that more new types of rhenium deposits will be discovered in the future[36].

7. Conclusions

The uneven distribution of various chemical elements on the earth itself, as well as the unique and colorful geological background of mainland China, determines that the primary rhenium deposits produced here have similarities with similar resources in other continents around the world, but also have their own uniqueness.

In particular, mainland China has the Qinghai-Tibet Plateau, which is still geologically very active, resulting in the frequent discovery of some minerals independent of the world in the western part of mainland China, such as the independent tellurium deposit discovered in 1993 and the newly discovered independent rhenium deposit in western Sichuan Province, part of the Plateau. This is the key difference between mainland China and other parts of the world. I believe that in the near future, more special mineralization types and minerals that will attract the attention of the international geological community will be discovered in the Qinghai-Tibet Plateau, including the rhenium deposit discussed in this article.

In addition to the Qinghai-Tibet Plateau, more and more associated and/or symbiotic rhenium deposits will be found in the Yangtze River Basin, Qinling Mountains, Northwest China and Northeast China, which are rich in porphyry copper, copper-molybdenum and copper-nickel deposits.

China's exploration, development, production and research on rare element rhenium deposits are still in the initial stage, and there is a lot of room for development in all aspects. At the same time, there is also room for improvement in the beneficiation, smelting and orderly development and control of the downstream market of rhenium ore products in the mainland.

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Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.