Original Article

Type and Origin of the Gallium Deposits in Mainland China

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Abstract

With the continuous development of science and technology and the progress of human society, the important roles of more and more rare metals are being discovered. Gallium, the subject of this paper, is one of many rare metals. It is not only listed as one of the critical/strategic metals by an increasing number of countries, but also receives increasing attention and importance. China is one of the most important producers of many rare metals and rare earth elements. However, due to geopolitical factors and other influences, the world's understanding of China's rare metals is limited or incomplete. Based on a summary of previous work by many other geologists, this paper classifies the known genetic and industrial types of gallium in China, lists representative deposits of each type and their geological characteristics, and preliminarily discusses their mineralization mechanisms. Gallium deposits can be divided into two main industrial categories: independent and associated/symbiotic. Currently, all human exploitation and utilization is of the latter; no independent gallium deposit has been discovered globally. Known associated and/or symbiotic gallium deposits cover two main genetic types: primary and secondary, endogenous and exogenous. Endogenous gallium deposits are closely related to igneous activity and metamorphism, while exogenous gallium deposits are related to sedimentation and volcanic activity. Whether endogenous or exogenous, primary or secondary gallium deposits, they are not clearly distinct; rather, they exist as mixed and/or combined, or transitional, co- and/or associated gallium deposits. That is, both endogenous and exogenous processes jointly contribute to the formation of the same gallium deposit. For example, after sedimentary compaction of secondary gallium deposits, and/or after preliminary enrichment in gallium-bearing coal seams, further enrichment occurs through endogenous metamorphism, forming mineable co- and/or associated gallium deposits. Clearly, the cumulative and/or combined effects of multiple mineralization processes more easily lead to the formation of economically valuable gallium deposits.

Keywords: Co- and/or associated gallium deposit, genetic type, primary/secondary, endogenous/exogenous process, emerging critical/strategic mineral resource, mainland China

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1. Introduction

Gallium, hailed as the "backbone of the electronics industry," is an emerging critical mineral resource and a key metal on the lists of many countries. Its unique physical and chemical properties give it broad application potential in a variety of fields. With the rapid development of information technology and the continued growth in global demand for high-performance materials, gallium's strategic importance has become increasingly prominent, making it one of the most sought-after mineral resources by various countries. The rise of new-generation communications, the Internet of Things, big data, and cloud computing has led to explosive growth in the electronics and information industry. As one of the core materials of this industry, the demand for gallium has also increased dramatically (Che et al., 2022; YiruShufang, 2024; Li and Song, 2025).

With the widest liquid temperature range of any metal, Gallium melts at just 29.78 °C but boils at 2,204.8 °C. Liquid gallium can penetrate other metals, corroding them and forming alloys. It has nearly zero vapor pressure at room temperature and is low in toxicity with antibacterial properties, making it environmentally friendly (Tu et al., 2004; Gunn, 2014; Feng and Meng, 2024). Gallium easily supercools. Solid gallium is bluish-white and soft with a density of 5.937 g/cm^3.

Gallium has a wide range of applications, including semiconductor materials, optoelectronic materials, solar cells, alloy materials, medical devices, and magnetic materials. The largest application area is the emerging semiconductor industry, accounting for over 80% of total gallium consumption; followed by solar cells, medical materials, LEDs, and optical equipment (Li and Wang, 2020; YiruShufang, 2024; Li and Song, 2025).

Gallium nitride, gallium arsenide, and gallium phosphide are all gallium-containing semiconductor materials, and germanium semiconductors also contain gallium. As a second-generation semiconductor material, gallium arsenide is known as the "aristocrat of semiconductors" due to its high price. Gallium arsenide possesses better electronic properties than silicon: lower noise and higher electron mobility, and is widely used in remote control devices, mobile phones, DVD computer peripherals, lighting, and solar cells, among many other optoelectronic fields (Tu et al., 2004; Li and Wang, 2020; Che et al., 2022; YiruShufang, 2024; Li and Song, 2025).

Gallium, along with various other metals such as indium, thallium, tin, bismuth, and zinc, can form a series of low-melting-point alloys. These alloys are used in the production of temperature control equipment, mercury substitutes in instruments, special coatings for metallic materials, and cooling circuit materials in the electronics and nuclear industries (Tu et al., 2004; Zhao et al., 2017; Li and Wang, 2020; Che et al., 2022; Feng and Meng, 2024; YiruShufang, 2024; Li and Song, 2025; Xinlang Finance, 2025). Indium-gallium alloys containing 25% indium melt into a liquid state at 16 °C and can be used to manufacture sensing devices for automatic fire extinguishing systems. Gallium, along with copper, nickel, tin, and gold, can form cold welding fluxes for welding irregularly shaped, thin-walled materials that are difficult to weld with common materials, especially in cold

welding environments between metals and between metals and ceramics. Gallium arsenide (GaAs) solar cells possess characteristics such as high heat resistance, radiation resistance, and high photoelectric conversion efficiency, making them commonly used in aerospace and military fields. Copper-indium-gallium-selenium (CIGS) alloys are used to fabricate thin-film solar cells, offering advantages such as low production and usage costs and high photoelectric conversion efficiency, making them a popular choice among various solar cell products.

Gallium metal and its compounds are also widely used in biomedical fields such as antibacterial and bacteriostatic applications, biomedical imaging, medical filling materials, medical diagnostics, and disease treatment (Tu et al., 2004; Zhao et al., 2017; Li and Wang, 2020; Che et al., 2022; Feng and Meng, 2024; YiruShufang, 2024; Li and Song, 2025; Xinlang Finance, 2025). As a novel imaging agent, gallium can provide patients with entirely new information about their conditions. Gallium has a strong reflective effect on light; liquid gallium exhibits high reflectivity for light within a certain wavelength range while also adhering well to glass surfaces. This property makes gallium a suitable material for manufacturing specialized optical lenses. Gallium alloys can be used in medical devices and materials; for example, leveraging their physicochemical properties and non-toxic, non-irritating nature, gallium alloys are used as fillings and restorative materials for teeth. Indium-gallium alloy thermometers can be used in medical diagnostics; for instance, gallium citrate can be used for positive tumour imaging and the diagnosis of tumours in the lung, liver, spleen, and lymphatic system.

Based on previous research on gallium deposits in mainland China by other geologists, this paper comprehensively classifies their genetic types, summarizes the geological and geochemical characteristics of each type, and briefly discusses their formation mechanisms. It is intended as a reference for researchers interested in studying the genesis of global gallium deposits and finding more similar deposits, thus contributing to the sustainable development of human society.

2. Existence form and current resource status

Gallium, primarily existing as an associated and/or symbiotic mineral, is extremely unevenly distributed globally, making extraction difficult. Known gallium deposits worldwide are concentrated in a few countries and regions. Given gallium's increasingly important strategic value, major global powers are intensifying their competition for and strategic positioning in gallium resources, striving to enhance their competitiveness and influence in the gallium industry chain through policy support, technological research and development, and international cooperation (Yiru Shufang, 2024; Li and Song, 2025).

Although gallium is the most abundant rare metal in the Earth's crust (15 μg/g), independent gallium minerals are rare. Gallium exists in nature mostly as isomorphous and/or adsorbed forms, with very few concentrated as independent minerals. Currently, only 10 independent gallium minerals have been discovered globally, the vast majority of which are found in Africa, with the majority of these found in the Tsumeb deposit in Namibia (Wen et al., 2020; Feng and Meng, 2024; Li and Song, 2025. Table 1).

Table 1. Limited independent Ga minerals and major Ga-rich minerals (After Zhao et al., 2017; Feng and Meng, 2024; Sina Finance, 2025)

Mineral	Chemical formular	Ga %	Origin
Tsumgallite	GaO(OH)	67.9	Tsumeb, Namibia
Sohngeite	$Ga(OH)_3$	57.8	Tsumeb, Namibia
Gallite	$CuGaS_2$	35.3	Tsumeb, Namibia and Lubumbashi, DR Congo
Camevallite	Cu_3GaS_4	18.0	Tsumeb, Namibia
Gallobeudantite	$PbGa_3[(AsO_4),SO_4)]_2(OH)_6$	19.3	Tsumeb, Namibia
Richardsite	Zn_2CuGaS_4	17.8	Gem Mines near Merelani, Tanzania
Unnamed gallium sulfide	$(Cu,Fe,Zn)GaS_4$	-	Africa
Ishiharaite	(Cu,Ga,Fe,In,Zn)S	-	Capillitas, Argentina
Zincobriartite	$(Cu_2(Zn,Fe)(Ge,Ga)S_4$	-	Kipushi, DR Congo
Galloplumbogummite	$Pb(Ga,Al,Ge)_3(PO_4)_2(OH)_6$	-	Tsumeb, Namibia

Like most other rare metals on the Earth, gallium is currently known to exist in the form of associated and/or symbiotic minerals. According to incomplete statistics, over 50% of global gallium comes from bauxite, less than 40% from zinc deposits, and the remaining less than 10% from other various deposits. Global gallium resources amount to approximately 230,000 tons, with China accounting for about 80% of this (Ren, 2006; Wen et al., 2020; Che et al., 2022; Zhang et al., 2022; Feng and Meng, 2024; Li and Song, 2025). The global prospective gallium reserves exceed 1 million tons, the vast majority of which are associated with bauxite deposits, mainly distributed in Africa, Oceania, South America, and Asia. Some gallium is also associated with lead-zinc deposits, mainly distributed in Austria, Canada, China, Italy, Poland, and the United States, such as the Tri State and Upper Mississippi deposits in the United States, and lead-zinc deposits in Sichuan, Yunnan, and Guizhou provinces of China (Table 2).

Table 2. Gallium resources in mainland China (modified from Feng and Meng, 2024 and Sina Finance, 2025)

Province (Autonomous region)	Gallium resources (tons)
Guangxi	11,974.80
Jiangxi	6,808.71
Guizhou	5,074.00
Shanxi	3,050.07
Xinjiang	1,045.55
Other provinces and autonomous regions combined	912.44
National total	28,865.57

Currently, global gallium reserves are about 279,300 tons, of which China has 190,000 tons, Africa 53,900 tons, Europe 19,500 tons, South America 11,400 tons, and the United States 4,500 tons (Table 2).

China has abundant gallium reserves and resources, ranking first in the world (Ning et al., 2023; Feng and Meng, 2024; Li and Song, 2025). Ga-rich bauxite is largely found in Guangxi, Henan, Guizhou, and Shanxi (91.46% of total), while Ga-rich coal occurs mainly in Shanxi, Inner Mongolia, Xinjiang, Shaanxi, and Guizhou (80.4%) provinces and/or

autonomous regions. China's super-large coal-associated gallium deposit was discovered in 2006 in Inner Mongolia. Ga-bearing zinc deposits are mainly distributed in southern provinces such as Guizhou, Yunnan, Sichuan, Hunan, Guangdong, and Jiangxi provinces and/or autonomous regions (Table 2).

3. Deposit type

3.1 Industrial type

Like most other rare metal deposits, gallium deposits in mainland China can be divided into two industrial types: independent and associated/symbiotic (Table 3). However, to date, no independent gallium deposit has been discovered worldwide, but numerous associated/symbiotic gallium deposits of different origin have been found. Over time, independent gallium deposits may be discovered, similar to those found for the rare elements tellurium and selenium (Yin and Shi, 2020; Yin, 2025), to meet the increasing demand for rare metals in human society.

3.2 Genetic type

3.2.1 Primary exogenous

Primary exogenous gallium deposits, also known as sedimentary gallium deposits, are the most important gallium resources that humans can exploit and utilize for a considerable period of time. Gallium mineralization and enrichment occur in different forms under varying physicochemical conditions. Under reducing conditions, the ionic radius of gallium in a 6-coordinate configuration is similar to that of elements such as Zn, Sn, Cu, Fe, and Sb in sulfide deposits, especially Zn. This leads to sphalerite in sulfide deposits becoming the primary enrichment carrier for gallium (Ren, 2006; Wen et al., 2020; Che et al., 2022; Zhang et al., 2022; Feng and Meng, 2024; Li and Song, 2025). Under oxidizing conditions, the geochemical properties of gallium are similar to those of aluminium and iron, especially aluminium, exhibiting strong lithophile properties, which allows gallium to participate extensively in various mineralization processes.

The most industrially significant associated/symbiotic gallium deposits in mainland China include three types: bauxite type (Luo et al., 2023), lead-zinc type (Deng et al., 2002), and coal type (Bai et al., 2007; Qin et al., 2009; Ding et al., 2023; Ning et al., 2023) (Table 3). These are described below.

3.2.1.1 Bauxite-type gallium deposit

According to the U.S. Geological Survey in 2024 (Li and Song, 2025; Xinlang Finance, 2025), global bauxite resources are estimated at between 55 billion and 75 billion tons, with a gallium metal exceeding 1 million tons, and are currently being utilized comprehensively. Global bauxite deposits are mainly distributed between 30°N and 30°S latitude in Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%), and other regions (6%).

Table 3. Type and characteristics of gallium deposits in mainland China

Deposit type					Dominant deposit type/characteristics	Representative gallium deposit	Data source
Industrial	Genetic						
Independent	associated/symbiotic	Primary	Endogenous	Greisen	Ga-containing mica.	Less	Wen et al., 2020
				Pneumatolytic-hydrothermal	Nb, Ta-bearing alkaline granite	Ga-containing mica and feldspar	Dasongpo, Tengchong, Yunnan, China
					Pb-Zn polymetallic sulfide deposit	Ga-containing sphalerite	Fankou and Honggou Pb-Zn deposits in China
					Pyrite-type Cu deposit	Ga-containing sphalerite and chlorite	Northwest China
					Alunite deposit	Ga-containing alum stone	The Fanshan deposit, Zhejiang, China
					MVT	Including Pb, Zn, Cu, Ag, Ga, and As	Carbonatite Pb-Zn Deposit
				Intrusive	V, Ti magnetite deposit	Ga-containing titanium magnetite	Panzhihua V-Ti magnetite deposit
					Alkaline complex	Ga-containing nepheline	Less
				Pegmatite	Rare metal granite pegmatite	Ga-containing spodumene, lepidolite, feldspar	Pegmatite in Jiangxi, China
					alkaline granite pegmatite	Ga-containing nepheline, biotite, zeolite, feldspar	Less
				Metamorphic	Mica schist	Mica schist	Luozha complex in southern Tibet, China
			*PSH	Bauxite	Boehmite	Ga-containing boehmite	Guangxi, western Henan and Guizhou, China
			**EEM	SPCB***	Ga-Nb-REEs	Secondary paleoweathered basalt in Yunnan-Guizhou, China	
				Metamorphosed coal		Ga-containing coal	Shanxi, Inner Mongolia, China
			Exogenous	Sedimenary	Sedimentary iron deposit	Ga-containing hydroxide	Metamorphosed sedimentary Fe-bearing quartzite
					Bauxite deposit	Ga-containing boehmite	Guangxi, western Henan and Guizhou, China
					Coal	Ga-containing boehmite and kaolinite, etc.	The Junggar coal deposit in Inner Mongolia, China
					CCGMT*****		Yunnan and Guizhou, China
		Secondary	Sediment				

Note: *PSH - Primary secondary hybrid (joint) transitional type; **EEM - Endogenous-exogenous mixed (combined) transitional type; SPCB***: Secondary paleoweathering crust-type gallium polymetallic deposits in basalt; CCGMT*****: Carbonate-clay gallium multimetallic type.

Most bauxite deposits are lateritic and located in equatorial regions such as Guinea, Australia, Brazil, and India. Guinea holds the largest share of global reserves, followed by Vietnam, Australia, Brazil, and Jamaica, while China—mainly with karst-type bauxite—has smaller reserves and relies on imports for gallium production, making it sensitive to global market fluctuations.

Bauxite forms through weathering in warm, humid climates and contains 20-80 μg/g gallium (about 59 μg/g on average). Over 90% of primary gallium is recovered during alumina production. Due to similar geochemical behavior, gallium and aluminium accumulate together in bauxite, with gallium mainly substituting for aluminium in minerals such as gibbsite, diaspore, and boehmite. The Al/Ga ratio is commonly used to indicate enrichment.

Bauxite is classified as karst and/or lateritic. Karst bauxite contains 20-80 μg/g gallium, while lateritic bauxite contains 40-80 μg/g. Gallium is typically adsorbed in lateritic bauxite and may occur as GaO(OH) in karst bauxite, though overall contents are similar.

Gallium content in bauxite is generally 50-250 μg/g, 3-16 times higher than the crustal Clarke value of gallium. China's bauxite deposits are predominantly sedimentary, followed by cumulate, with lateritic bauxite being the least common. In bauxite dominated by gibbsite, gallium content is almost universally at industrial grade. These bauxite deposits were formed during the Carboniferous and Permian periods and are widely distributed in Shanxi, Guizhou, and Guangxi provinces and/or autonomous regions. Gallium content in western Henan bauxite ranges from 50-250 μg/g, with gibbsite being the primary gallium-bearing mineral, followed by kaolinite and iron-titanium minerals. Gallium grade in Guizhou bauxite is generally 122-127 μg/g, and the ore-bearing rock series is a combination of bauxite, along with iron ore, pyrite, refractory clay, and coal.

Regarding the origin of gallium in bauxite, Lu et al. believe that gallium in North China bauxite mainly originates from ancient continental aluminosilicate rocks rather than from the underlying carbonate basement (Zhao et al., 2017). Conversely, Wu believes that gallium mainly originates from the basement carbonate rocks (Zhang et al., 2022). Liu believes that gallium in Guizhou bauxite mainly originates from the argillaceous material in ancient island silicate rocks and basement carbonate rocks. In silicate rocks, gallium mainly substitutes for aluminium in feldspar. Feldspar easily transforms into kaolinite during lateritic transformation, with Ga and Al entering the kaolinite lattice together, and a small portion entering gibbsite. During weathering, the properties of gallium depend almost entirely on the solubility of kaolinite and gibbsite. In weathering solutions, Ga and Al generally exist in the forms of $Ga(OH)_3$ and $Al(OH)_3$. When the pH is 3-7, $Ga(OH)_3$ is more soluble than $Al(OH)_3$. During lateritic alteration, large quantities of gibbsite and kaolinite are formed in the acidic medium, resulting in significant iron loss, while Ga and Al remain stable within the residual weathered minerals. Most sedimentary bauxite deposits are formed by the transport and deposition of lateritic weathering crusts. Because gallium is more easily leached than aluminium, the upper Ga migrates downwards and accumulates in the lower honeycomb and earthy ores. This is likely why most gallium in western Henan bauxite deposits is hosted in earthy and honeycomb ores.

In a sense, this type of symbiotic/associated bauxite-type gallium deposit should be considered a mixed or transitional type of primary exogenous and secondary exogenous gallium deposits.

3.2.1.2 Coal-type gallium deposit

Presumably due to the adsorption of gallium by carbon, numerous studies (Bai et al., 2007; Qin et al., 2009; Ding et al., 2023; Ning et al., 2023; Feng and Meng, 2024; Li and Song, 2025) have shown that, although commercial gallium mining in coal mines has not yet been achieved due to technological limitations, Coal deposits contain over 10 million tons of gallium (industrial grade ~50 μg/g), with several super-large deposits identified in Inner Mongolia and Shanxi of China.

Gallium occurs in both inorganic and organic forms, mainly substituting in aluminium-bearing minerals like boehmite and kaolinite, though it can also be hosted in minerals such as illite, sphalerite, and feldspar. It is less abundant in organic matter and mainly associated with vitrinite.

Recovery is typically from coal combustion fly ash, but due to environmental concerns, low concentrations, and high costs, only China has achieved pilot-scale extraction. Thus, coal-hosted gallium is considered a potential future resource.

The industrial grade of gallium deposits in coal mines is 30 μg/g, while the gallium content in coal is generally 10-30 μg/g. Dai et al. (2006) reported gallium contents as high as 30-70 μg/g in the Junggar coalfield in Inner Mongolia, making it one of the newly discovered super-large gallium deposits in recent years.

The primary Ga-bearing mineral, gibbsite, was formed during peat accumulation when trihydrate colloidal solutions from ore-bearing weathered crust-type bauxite uplifted in the northern part of the basin were transported short distances into the peat swamp. It was dehydrated and coagulated through compaction during the peat accumulation stage and early diagenesis.

In some highly metamorphosed coals (such as the Daqingshan coalfield in Inner Mongolia), gallium is carried by gibbsite and kaolinite. To some extent, this associated/symbiotic coal-type gallium deposit is a mixed or transitional type of primary exogenous (sedimentary) and primary endogenous (metamorphic) gallium deposit.

3.2.1.3 Sediment-hosted massive sulfide type

Sphalerite can contain 0.01%-0.02% gallium, making lead-zinc deposits an important source, though actual recovery is limited by current technology. Gallium content is higher in low-temperature sphalerite (100-1000 μg/g) and much lower in high-temperature forms (<10 μg/g), and it may also occur in pyrite. Industrially, gallium is often recovered as a by-product of zinc sulfide processing.

Gallium content varies by deposit type, averaging 42 μg/g in Mississippi Valley-type (MVT) and 19 μg/g in volcanic-hosted massive sulfide (VHMS) deposits, with lower levels in other types. Although MVT and VHMS deposits make up a relatively small share of global lead-zinc resources, they are significant sources of gallium due to their higher concentrations.

3.2.2 Primary endogenous type

3.2.2.1 Volcanic-hosted massive sulfide type

Global zinc reserves are estimated at 1.9 billion tons, primarily located in Australia, China, Russia, and Peru. Despite these vast reserves, progress in extracting and utilizing gallium from zinc ore has been slow. Canada, Japan, Slovakia, and the United States have long recovered gallium from zinc scrap, and China has also begun recovering gallium from zinc smelting by-products. The main metallic minerals in lead-zinc deposits, such as galena, pyrite, and pyrrhotite, generally have very low gallium content, while sphalerite has higher levels, indicating that sphalerite is the most important Ga-bearing mineral. Not all lead-zinc deposits are Ga-rich. Magmatic lead-zinc deposits have very low gallium content. Ga-rich lead-zinc deposits are mostly hydrothermal sedimentary and/or sedimentary-modified types, such as the Fankou and Taolin deposits in mainland China, where the ore contains 30-60 μg/g of gallium, and the sphalerite contains more than 100 μg/g of gallium. These types of deposits generally have lower mineralization temperatures, and the sources of ore-forming materials are more complex than those of magmatic-hydrothermal deposits. Although gallium is chalcophilic, the fact that it is selectively enriched in certain deposits of a particular genetic type of lead-zinc deposit indicates that gallium enrichment in lead-zinc deposits is subject to more complex controls. The gallium content in MVT-type lead-zinc deposits varies considerably. For example, in the Fule deposit in the Sichuan, Yunnan, and Guizhou lead-zinc ore clusters, the gallium content in sphalerite ranges from 4.8 to 358 μg/g, with an average of 87 μg/g.

3.2.2.2 Metamorphosed (superimposed) type

This is a newly discovered symbiotic/associated gallium deposit. Located in the eastern Himalayan belt, the Lhozha magmatic-metamorphic complex intrudes into the southern Tibetan detached system (Gao et al., 2023). On the northeastern side of the intrusion, mica schist is xenografted by tourmaline-bearing leucogranite. The mica schist, mainly composed of phlogopite, chlorite, and minor biotite, contains high levels of Al_2O_3, K_2O, total FeO, MgO, and TiO, and is enriched in key metals such as Li, Rb, Cs, Ti, and Ga. Single-mineral chemical analysis indicates that the phlogopite in the mica schist is similar to that in the whole schist, also enriched in Li-Rb-Cs-Ga. These critical metals substitute for K in the phlogopite in isomorphous forms. Zircon geochronology results show widespread clastic ages and Cenozoic metamorphic events in the area. Previous studies suggest that the mica schist in the Lhozha area, originally a sedimentary rock, was xenografted and underwent low-grade metamorphism during the emplacement of the leucogranite.

The enrichment of rare metals thallium and gallium in metamorphosed sedimentary rocks of the Himalayan orogenic belt indicates that this region is expected to become one of the most important potential areas for the future mining of critical metals such as rare elements in mainland China. Globally, there is a need to strengthen the investigation and research on the mineralization potential of the critical metals in metamorphosed sedimentary rocks of all orogenic belts.

Other known gallium deposits associated with metamorphism include carbonate clay-type lithium-gallium-rare earth deposits (Wen et al., 2020a; Ma and Chen, 2024). However, current research on these deposits is still inadequate, and therefore, little is known about them thus far.

3.2.3 Secondary exogenous type

These gallium deposits include the weathered and eroded residual bauxite type and karst type mentioned above. These associated/symbiotic bauxite gallium deposits are not formed by a single mineralization process, but rather by a combination of secondary and primary geological processes; therefore, they are also referred to in this paper as combined and/or mixed transitional types (Table 3).

3.2.4 Primary/secondary and/or mixed endogenous/exogenous type

3.2.4.1 Carbonate-clay gallium multimetallic type (CCGMT)

The CCGMT deposit is characterized by its large mineralization scale, stable distribution, and low development and utilization costs (Wen et al., 2020a). Newly discovered clay-type lithium-REE polymetallic mineralized claystone strata in southwestern China include the Lower Carboniferous Jiujialu Formation (C1j) in Guizhou province and the Lower Permian Daoshitou Formation (P1d) in central Yunnan province. C1j, formed in the early to middle Early Carboniferous, is a lithological assemblage dominated by claystone, accompanied by bauxite claystone, ferruginous claystone, bauxite, and pyrite, with localized coal seams. It is an important bauxite-bearing stratum in Guizhou Province, China. P1d, formed in the Early Permian, is a coastal-lacustrine sedimentary assemblage consisting of sandstone and shale interbedded with limestone lenses, bauxite, and low-quality coal seams, generally 5-20 m thick, mainly distributed in the Kunming, Yuxi, Wuding, and Yiliang areas of central Yunnan. C1j and P1d claystones are classified into four types, developing from bottom to top: ① incompletely weathered iron-aluminous claystones during sedimentation and diagenesis, hard in texture and with high iron content; ② dense massive aluminous claystones; ③ oolitic aluminous claystones; ④ loose, earthy claystones, with strong near-surface weathering and leaching (Wen et al., 2020a).

In carbonate clay-type Li-Ga-REE deposits developed in the Yunnan-Guizhou provinces of mainland China, the ore-forming materials of Li-rich claystones have a relatively singular source, possibly originating from underlying impure carbonate rocks (Wen et al., 2020a; Wen et al., 2022). Due to limitations in mining conditions and extraction technology, the resources in carbonate clay-type lithium-gallium-rare earth deposits cannot yet be converted into reserves and cannot be truly put into production (Wang et al., 2022).

Studies of different types of Ga-rich deposits show that gallium generally tends to be enriched in a few specific minerals. In bauxite-type deposits, gallium is hosted in gibbsite; in lead-zinc ore-type deposits, gallium is mainly enriched in sphalerite; and in coal-type deposits, gallium is mainly found in gibbsite and diaspore. This seems to indicate that gallium enrichment has obvious mineralization specificity and mineral specificity.

3.2.4.2 Secondary paleoweathered crust-type gallium polymetallic deposits in basalt

The secondary paleoweathered crust of the basalts at the base of the Xuanwei Formation in the Yunnan-Guizhou region, located within the western and eastern metallogenic belts of the Upper Yangtze, is generally rich in metals such as niobium, rare earth elements, and gallium, all reaching industrial grades. This constitutes a rare metal enrichment layer, where rare earth elements and rare metals coexist, possessing enormous resource potential and significant economic value (Wen et al., 2020a).

The origin of the ore-forming materials in the Xuanwei Formation's niobium-gallium-rare earth deposits has been a long-standing point of contention in academic circles. The main viewpoints suggest: ① originating from the Kangdian Paleoland; ② from the acidic rocks at the top of the Emeishan Igneous Province beneath the Xuanwei Formation; ③ from the mixing of volcanic ash and hydrothermal fluids.

The Yunnan-Guizhou region possesses numerous areas of exceptionally high enrichment in rare earth elements and dispersed elements (Wang et al., 2020). Furthermore, this region widely distributes high-titanium, alkali-rich basalts, providing a rich ore-forming basis. Studies have shown that during the period of 257.2-254.6 Ma, claystones rich in rare and rare earth metals originated from the erosion zone within the Emeishan Large Igneous Province, and their metallic minerals mainly came from syenite, with a small amount from high-Ti basalt and felsic igneous rocks (Tian et al., 2023).

4. Gallium prospective area in mainland China

In recent years, with the development and advancement of detection technology, new Ga-rich deposits and/or mineralized areas have been continuously discovered. For example, gallium enrichment has been found in metamorphosed sedimentary rocks of the Himalayan orogenic belt. Furthermore, according to a report from China's Ministry of Natural Resources, a super-large rare earth metal weathered crust deposit containing 10,818 tons of gallium has been discovered in southern Yunnan, China.

It should be noted that although many gallium deposits have been discovered, very few actually meet the economic and technical standards for exploitation.

Researchers have concluded that the extraordinary enrichment of indium, germanium, gallium, niobium, and rare earth elements on the western margin of the Yangtze Plate in China has a certain material basis and internal mechanism, and have systematically proposed a "supergene weathered-sedimentary rare metal mineralization system," constructing a mineralization model for rare metals.

5. Discussion

Known gallium mineralization in mainland China exhibits diverse genetic and industrial types, including primary and secondary, exogenous and endogenous processes. There are also transitional and/or combined types formed by the combined effects of endogenous and exogenous, primary and secondary processes. Generally, one type initially enriches gallium, followed by further enrichment into mineralized deposits by subsequent geological

mineralization. In other words, its mineralization is characterized by multiple phases and stages, rather than being formed overnight by a single mineralization process.

The combined and superimposed alteration by weathering, erosion, sedimentation, igneous activity, and metamorphism is a major characteristic of gallium mineralization in mainland China. Because of this, it is sometimes difficult to classify a specific gallium mineralization into a particular genetic type, as they are often the result of the combined superposition of multiple geological processes from different geological periods.

Currently, most known gallium mineralization in China, especially the newly discovered ones, are concentrated in western China, particularly the Qinghai-Tibet Plateau and its surrounding areas. In other words, large-scale orogenic movements are the primary driving force behind the enrichment of numerous rare metals, including gallium, and rare earth element metals. An orogenic process often involves various scales and types of tectonic activity—igneous activity, metamorphism, sedimentation, and weathering and erosion. This is one of the main reasons why gallium mineralization is associated with multiple geological processes.

The known types of associated/symbiotic gallium deposits in mainland China, especially the genetic types newly discovered in the last two years, offer important insights for finding similar genetically derived gallium deposits in other parts of the world.
It is believed that in the near future, mainland China may be the first to discover independent gallium deposits in the Qinghai-Tibet Plateau and its surrounding areas, just as independent tellurium and selenium deposits were first discovered in the country (Yin and Shi, 2020; Yin, 2025).

Environments with multiple overlapping geological processes are most likely and suitable for occurrence in various orogenic belts. Therefore, orogenic belts are primary prospective areas for finding gallium and other rare metal deposits.

6. Conclusions

Globally known gallium deposits, especially associated/symbiotic gallium deposits, exhibit a wide variety of genetic types. The formation of these deposits is related to almost all known geological processes, such as orogenic movements, igneous magmatic activity, sedimentation, metamorphism, and even weathering and erosion.

Upon closer examination, the formation of many associated/symbiotic gallium deposits is not the result of a single geological process, but rather the result of two or more combined processes. Often, the first geological process initially enriches the associated/symbiotic gallium mineralization, and on this basis, a second and subsequent series of geological processes further enrich and modify the gallium mineralization. In other words, the economically viable mining scale of rare metals like gallium is the result of the combined enrichment by two or more geological processes.

In many cases, the mineralization of rare metals, including gallium, is the result of the combined effects of primary/secondary and exogenous/endogenous geological processes, rather than simply the result of one or a few endogenous mineralization processes.

For the enrichment of rare metals, the boundary between endogenous and exogenous mineralization is no longer clear. This is because the abundance of these metals in the Earth's crust is so low that they are difficult to concentrate into mineral deposits without a combination of endogenous and exogenous, or even primary and secondary, processes. For these reasons, orogenic belts are the optimal geological settings for finding mineralized zones of rare metals such as gallium.

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Data availability

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

Declaration of competing interest

The author declares that he has no 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.