
Research article

Types and metallogenic indices of porphyry (Cu) polymetallic deposits based on tectonic settings

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Abstract: Cu plays an irreplaceable and important role in many aspects of modern society. One of the most important sources of Cu is porphyry Cu polymetallic deposits (PCPDs), which are large in size and low in grade. The formation of porphyry polymetallic deposits (PPDs), including PCPDs, is associated with two different tectonic settings, namely, the oceanic subduction zone and the continental collision zone, including the intracontinental orogenic belts. In this paper, the deposits formed in these two settings are referred to as the oceanic type and the continental type, respectively. Deposits formed under the two different tectonic settings share certain common characteristics, yet they also display distinct geological and geochemical features. Drawing on a global review of the spatiotemporal distribution and mineralization ages of both oceanic and continental PPDs, and synthesizing information on their geology, geochemistry, mineralization processes, and specialized ore controls—such as the degree of magma differentiation and oxidizability—the authors summarize the metallogenic indicators and potential exploration targets for these PPDs through the lens of modern scientific and technological advances. Key diagnostic tools include characteristic minerals (e.g., hornblende) that reflect the extent of magma differentiation, as well as specific lithochemical and geochemical parameters, such as oxygen fugacity and/or magmatic oxidizability (ΔFMQ), ratios like Zr/Hf, La/Ta, Y/Ho, La/Nb, K/Rb, LREE/HREE, Rb/Sr, Rb/Ba, A/CNK, Zr+Nb+Ce+Y, V/Sc, Zn/Fe, $\text{Fe}^{3+}/\Sigma\text{Fe}$, and Eu/Eu*, along with decoupling of twin element pairs (mainly Nb-Ta and Zr-Hf) and tetrad effects in REE patterns. Undoubtedly, a comprehensive analysis of the above

lithochemical and geochemical values in porphyry bodies represents a key approach for assessing whether a given porphyry intrusion hosts minerals and, if so, what types of metals it may contain.

Keywords: metallogenic indices; special ore controls; lithochemical/geochemical values; porphyry Cu polymetallic deposits (PCPDs); porphyry polymetallic deposits (PPDs) including PCPDs; oceanic; continental

1. Introduction

Cu metal plays an almost irreplaceable role in many industries, including electricity, electronics, automobiles (especially new energy vehicle batteries), motorcycles, bulk appliances, construction, medical care, machinery, renewable energy infrastructure (e.g., wind turbines, photovoltaic systems, solar panels, nuclear power, and hydrogen energy), the military, and marine engineering, with applications from trains to ships and airplanes, extending from key components of traditional industries to high-tech fields. One of the most important sources of Cu is PCPDs of an enormous size (Figure 1) [1]. Almost all continents in the world have their own representative world-class PCPDs, most of which are associated and/or symbiotic with a variety of other metals such as Au, Mo, W, Sn, Pb, Zn, Ag, Fe, Te, Re, Co, Se, and Pt, and non-metals S and As. Porphyry deposits, as the main source of metal Cu and an important source of metals such as Au, Sn, W, Fe, and Mo, constitute a continuous polymetallic metallogenic series from porphyry Cu, Au, and Mo to porphyry Cu-Mo, Cu-Au, and Pb-Zn-Ag deposits. Therefore, this article uniformly uses the term porphyry Cu polymetallic deposits and/or porphyry polymetallic deposits, hereinafter referred to as PCPD/PCPDs and/or PPD/PPDs.

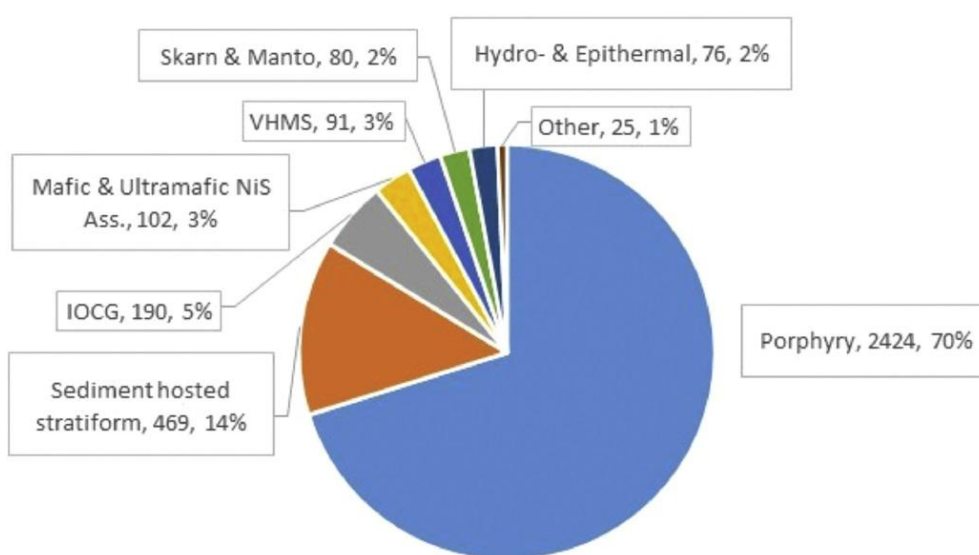


Figure 1. Resource importance for different Cu deposit types (Mt & %) [1].

Among all known types of Cu mineralization in nature, PCPDs are the largest in scale, and their reserves and resources account for the largest proportion of all types of Cu deposits. The

intermediate-acidic shallow porphyries not only provide nearly 75% of the world's Cu but also produce 90% of the world's Mo, 20% of Au, and most of the rare metal rhenium, as well as many other metals such as W, Pb, Zn, and Ag [2]. Among the 10 most important Cu deposits with newly added resources in the world in the past decade, 8 are of porphyry and genetic types, closely related to these porphyries, and only 2 are sedimentary and/or metamorphic Cu deposits. These 10 world-class Cu deposits are ranked from highest to lowest in terms of known resources or reserves as follows: the Kamo-a-Kakula sedimentary Cu deposit in the Democratic Republic of the Congo (with a production of 437,061 metric tons in 2024), the Huru massive sulfide-porphyry Cu deposit in Indonesia, the Cascabel carbonate metasomatic-epithelial-porphyry-skarn Cu-Mo deposit in Ecuador, the Enciero porphyry Cu deposit, the Cachorro porphyry Cu deposit and the Lahuifa porphyry Cu-Mo deposit in Chile, the Winu metamorphic sedimentary Cu-Au-Ag deposit and the Karawa porphyry-skarn Cu deposit in Australia, the Tato hydrothermal-porphyry-volcanic massive sulfide Cu deposit in Canada, and the Porvenir porphyry Cu deposit in Ecuador [2]. Cu exploration accounts for about 23% of the world's total investment in solid mineral exploration. China lists Cu as one of its critical minerals, and Cu has always been one of the main minerals invested by relevant Chinese departments in prospecting and exploration [3]. During the 14th Five-Year Plan period, Tibet, China, has added more than 20 million tons of Cu resources, with a predicted resource potential of 150 million tons. Through deep prospecting, the Duobaoshan Cu mine in Heilongjiang, China, has added 3.65 million tons of Cu resources. The Julong Cu mine in Tibet, owned by Zijin Mining Group, is expected to achieve an annual production of 170,000 tons in 2025, making it the largest Cu mine in China and also the world's largest, lowest-grade, and highest-altitude Cu mine. Despite this, Cu resources in China have the shortcomings of low grade and difficult development. As a result, the country's rapid economic development has kept its dependence on foreign Cu metals above 70% for a long time [2]. As of now, China's domestic Cu production is still relatively low, and most of the Cu needs to be imported from Chile, Peru, Australia, and other countries.

At present, there is a vast amount of research literature on PPDs worldwide. However, most of the research is limited to the geology and ore-forming models of specific local deposits or PPDs in a certain region [4–9], and there is a relative lack of macroscopic understanding and overall grasp of the ore-forming mechanisms of such deposits worldwide. On the basis of summarizing worldwide research results, this article classifies the global porphyry metallogenic system into two categories (oceanic and continental crust types) and summarizes the geology and geochemistry of the two types of PPDs, especially the rock chemical parameters of each type of deposit. Therefore, it is expected that when searching for PPDs, the best mineralized porphyry body can be selected by analyzing these prospecting parameters, which can achieve twice the result with half the effort and save exploration time and capital investment.

2. Spatiotemporal distribution

In terms of geotectonic setting, PPDs are often distributed at the margins of two types of convergent plates: oceanic subduction belts and continental collision belts. In other words, there are two metallogenic models for this type of deposit: oceanic and continental.

2.1. Oceanic

Substantial evidence indicates that magmatic arcs—comprising both island arcs and continental arcs—serve as the primary setting for the formation of PPDs, a role that has earned them the designation “subduction zone factories”. In fact, 97% of the world’s giant porphyry Cu (Mo, Au) deposits are generated in such environments [10]. Classic oceanic porphyry metallogenic provinces are predominantly located along the western Pacific coast. For instance, the island arcs of Indonesia and the Philippines mainly host porphyry Cu and Cu-Au deposits, exemplified by Batu Hijau in Indonesia and Lepanto-FSE in the Philippines. In contrast, classic continental arc metallogenic provinces are chiefly distributed along the eastern Pacific coast, encompassing the Arizona province in the southwestern United States, the northern Mexican province, and the northern and central Chilean provinces. These regions primarily yield porphyry Cu and Mo deposits, with notable examples including Chuquicamata, La Escondida, and El Teniente in Chile, as well as Bajo de la Alumbrera and Marte in Argentina. Although porphyry Mo deposits do occur in rift settings (such as the Climaix type), the vast majority are still found in magmatic arcs, particularly in continental arc environments (i.e., the quartz monzonite type).

More specifically, porphyry Cu and Mo deposits are mainly distributed in thick continental arcs, while porphyry Cu and Au deposits are mainly formed in medium-thick island and continental arcs, especially during the short extension period of these geological tectonic units [11–13].

At present, the consensus is that large-scale and super-large PCPDs with important economic value are mostly distributed in ocean-continent (ocean) subduction boundaries such as island arcs and continental arcs [14,15]. Their ore-forming parent magma is closely related to subduction. Over the past century, based on extensive geological observations and detailed, comprehensive research, Western scholars have established the well-known magmatic arc PCPD mineralization model (Figure 2) and achieved major breakthroughs in the exploration of porphyry deposits in the Pacific Rim.

The long-dominant ocean mainstream model holds that metal-bearing magma from the mantle wedge above the subduction plate differentiates in the deep earth, forming large PCPDs (Figure 2a). However, a major challenge facing this model is how PCPDs are formed in relatively flat subduction plates. In this case, the mantle wedge is reduced or even absent, so where do Cu and other ore-forming materials come from?

Lamont et al. studied the Laramide porphyry province in Arizona, USA, which was formed by the flat subduction of the Farallon Plate under the North American Plate about 80–40 million years ago. They found that the melting and Cu polymetallic mineralization of the ancient Proterozoic crust, rather than the mantle wedge, contributed to the formation of these PCPDs (Figure 2b) [16], thus further improving the oceanic model of PPDs. Lamont et al. concluded that flat subduction may occur when the subduction plate is young, warm, buoyant, and abnormally thick, or when the plate advances faster than it retreats. Flat subduction is usually associated with large-scale tectonic processes, including crustal thickening, changes in the thermal structure of the upper plate, and inland migration of magmatism, extending hundreds of kilometers away from the trench. Some giant PCPDs on the planet, such as Resolution in Arizona, USA, and Río Blanco and Escondida in Chile, were formed in a flat subduction tectonic setting. This structure accounts for about 10% of all subduction zones in the world. The PCPDs in Arizona are derived from the ancient Proterozoic crust,

which is more than 500 million years old, rather than from the younger mantle [16]. The garnet-clinopyroxene combination minerals entrained in the lava are consistent with the origin of the Proterozoic lower crust and contain Cu sulfides, which further supports that Cu was enriched in the crust long before the Laramide orogeny. The front edge of the subduction oceanic Farallon plate introduced a large amount of water directly from the underlying plate into the lower crust, inducing a process called water flux melting and leading to asynchronous heating of the crust, causing local melting of the Proterozoic basement to produce magma that rose to the upper crust and formed PCPDs (Figure 2b). The melting time determined by U-Th-Pb chronology coincides with the peak period of PCPD formation, supporting this view. This new oceanic PCPD mineralization model not only improves the traditional model but also solves the problem of the formation of PCPDs in flat subduction settings worldwide, highlighting the important role of fluids in crustal melting and the formation of PCPDs.

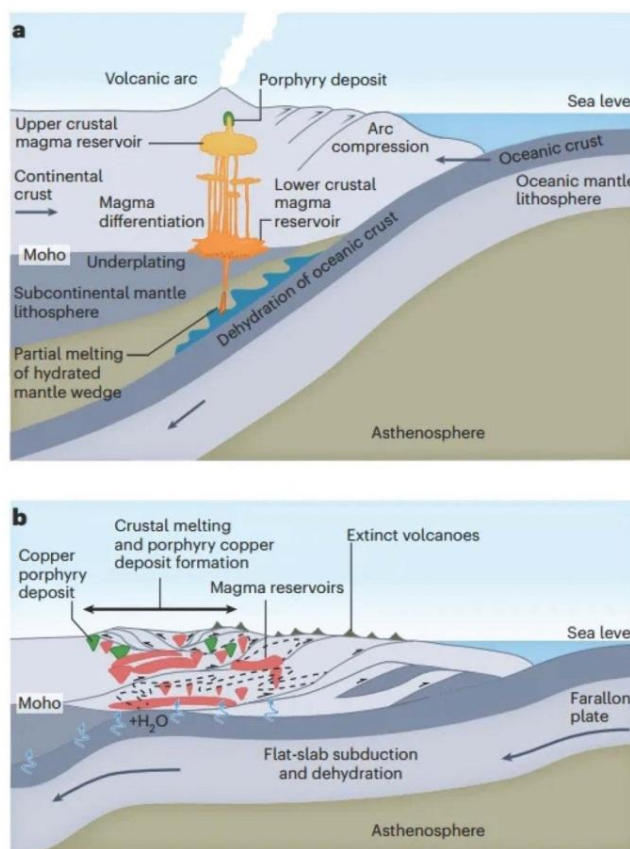


Figure 2. Two oceanic (sub-oceanic) models for the formation of PCPDs [15,16]. a) Partial melting of hydrous mantle peridotite above the subduction zone leads to the generation of Cu-bearing magmas [15]. b) Volatiles from the subduction slab trigger water-flux crustal melting, granite magmatism, and the formation of porphyry Cu polymetallic ores during flat subduction [16]. Here, forced flow into the mantle wedge is cut off, and volatiles derived from the slab (H₂O, CO₂, Cl, and S) pass straight into the base of the crust, triggering water-fluxed crustal anatexis, granitic magmatism, and, potentially, PCD formation.

Oceanic magmatic arcs primarily host porphyry Cu-Au or Au-rich Cu deposits (in island arc settings), as well as porphyry Cu-Mo and Mo deposits (in continental arc settings). Based on their metal assemblages, oceanic PPDs are classified into Cu, Mo, and Au deposit types, along with transitional varieties such as Cu-Mo, Cu-Au, and Cu-Mo-Au. More specifically, porphyry Cu deposits containing Au > 0.4 g/t are termed porphyry Cu-Au deposits, whereas those with Au < 0.4 g/t are referred to as Au-rich porphyry Cu deposits [5,10].

2.2. *Continental*

Despite advances, the improved oceanic porphyry mineralization model remains incomplete, as it faces substantial challenges from continental collision zones, including those hosting intracontinental PPDs. Over the past three decades, numerous PPDs have been discovered within the Alpine-Himalayan Tethys continent–continent collision zone, notably represented by China's Gangdise belt. Examples include the Gangdise and Yulong porphyry Cu polymetallic belts in the Qinghai-Tibet Plateau continental collision zone, the West Tethys porphyry Cu polymetallic belt in the Miocene continental collision zone, the Qinling giant porphyry Mo polymetallic belt in the Qinling continental collision belt, the Dexing porphyry Cu-Au deposit in Jiangxi Province, and several porphyry Cu-Fe-Au deposits in the middle-lower Yangtze River region within the Yanshanian intracontinental setting of eastern China. Also notable are porphyry Au deposits (e.g., the Bilihe porphyry Au deposit in Inner Mongolia) and porphyry Pb-Zn-Ag deposits (e.g., the Lengshuikeng Pb-Zn-Ag deposit in Jiangxi Province) found in Yanshanian continental settings in China (Figure 3). These occurrences demonstrate that PPDs can form abundantly in non-arc environments, a phenomenon that the classic oceanic porphyry polymetallic mineralization model fails to adequately account for.

Since the beginning of this century—and even earlier—Chinese geologists have been actively investigating the geology and genesis of PPDs, carbonatite-type Mo deposits, and Au and Pb-Zn-Ag deposits within continental collision zones (such as those in the Qinghai-Tibet Plateau and the Tethyan region) and intracontinental settings (like the Qinling Orogenic Belt). In doing so, they have proposed conceptual models for mineralization and tectonic controls specific to PPDs in continental environments. Research findings indicate that, although continental collision and intracontinental PPDs share alteration and mineralization features with their oceanic counterparts, fundamental differences exist between the two in terms of geodynamic background, deep mineralization processes, magma origin and evolution, and sources of fluids and metals [4,10,17–21]. In continental collision zones, porphyry Cu, Cu-Mo, and Cu-Au deposits controlled by strike-slip fault systems in oblique collision zones develop during late tectonic transition stages, whereas porphyry Cu-Mo deposits governed by normal fault systems perpendicular to the collision zone are mainly formed in post-collisional crustal extension settings. In intracontinental orogenic settings, porphyry Cu-Au deposits appear in the early stage, followed by porphyry Pb-Zn-Ag deposits in the late stage; these are largely distributed along ancient but reactivated lithospheric discontinuity zones and controlled by grid-like fault systems [5,10]. In post-orogenic and/or orogenic extension environments, numerous porphyry Mo and Au deposits occur, chiefly around the margins of continental basement-cratons and controlled by reactivated lithospheric discontinuities. In China, large numbers of PPDs have been

generated within continent–continent collision orogenic belts (e.g., the Qinghai-Tibet Plateau and the Qinling orogenic belt), in intracontinental orogenic settings characterized by Yanshanian tectono-magmatic activation, and in non-orogenic or post-orogenic extensional environments marked by tectonic regime transitions (Figure 3). These deposits are distinct from oceanic PPDs globally in that they occur in non-arc settings (Table 1).

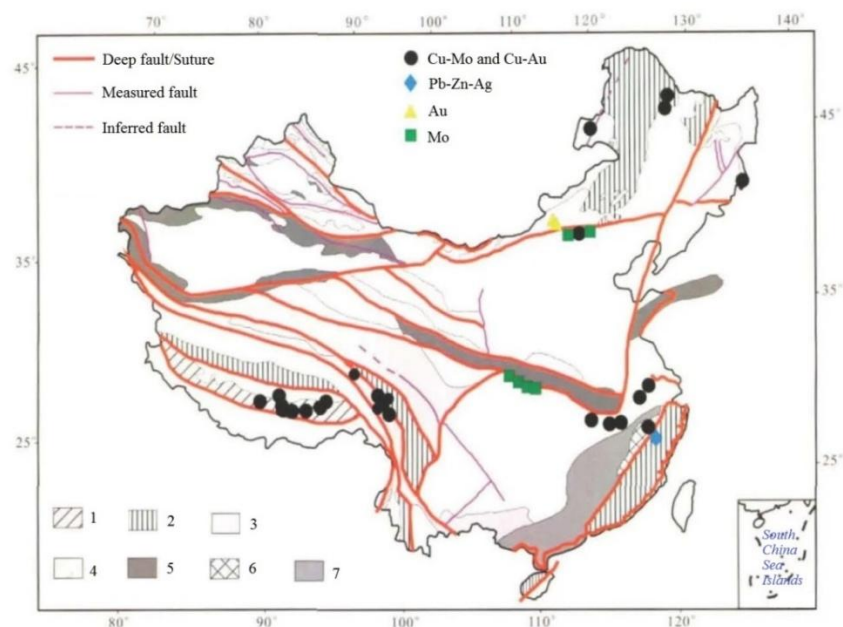


Figure 3. The tectonic framework of the Chinese mainland and continental PPDs [10]. Legend: 1. Cenozoic volcanic arc; 2. Mesozoic volcanic arc; 3. Mesozoic flysch belt; 4. Paleozoic volcanic arc; 5. Paleozoic flysch belt; 6. Proterozoic volcanic arc; 7. Proterozoic flysch belt.

2.2.1. Cu-Mo deposits

The continental porphyry Cu-Mo deposits in China are concentrated in the Qinghai-Tibet Plateau (Figure 3, Table 1) and extend discontinuously to the west to the Miocene collisional orogenic belt in West Asia, forming a world-class Tethyan-Himalayan PPD belt [18–21,29]. It is currently known that at least two PPDs belts have developed in the Qinghai-Tibet Plateau, namely the Yulong porphyry Cu belt in eastern Tibet and the Gangdise porphyry Cu belt in Tibet. The former is 300 km long and consists of four large Cu deposits and numerous ore-bearing porphyry bodies, with a Cu metal reserve of more than 10 million tons. Among them, the Yulong PPD has been widely studied for its huge Cu metal reserves (6.28 million tons) and relatively high grade (0.99% Cu) [5,10]. The latter extends about 350 km from east to west along the Gangdise belt and currently controls more than 20 million tons of metallic Cu resources. The Qulong porphyry deposit contains 7.8 million tons of Cu, ranking first in China. The ore belt is produced in the main collision zone of the India-Asia continent, and it was formed in a post-collision crust extension environment.

Table 1. Geology and geochemistry of oceanic and continental PPDs (modified after [22]).

Type	Oceanic		Continental				
Sub-type	High angle subduction	Flat-slab subduction	Continental collision	Intracontinental orogenic			
Ore-bearing porphyry	Mainly typical calc-alkaline quartz diorite, A small amount of granodiorite, quartz monzonite, and syenite	Mainly calc-alkaline granodiorite and quartz monzonite, with less high-potassium calc-alkaline	High-potassium calc-alkaline and shoshonitic porphyry	B-rich calc-alkaline granodiorite and monzogranite	Granodiorite and quartz diorite	Granite and granodiorite	Aluminum-supersaturated granite porphyry, equivalent to S-type granite
Metal	Cu, Cu-Au, Au, Cu-Mo, Mo, Cu-Mo-Au		Cu, Cu-Au, Cu-Mo	Au	Cu-Au (-Fe)	Mo, Mo-W, Mo-Fe	Pb-Zn-Ag
Alteration	potassic alteration, serification, argillization, and propylitization etc.		Followed the Lowell and Guilbert model silicification-serification, K alteration, propylitization	K alteration, silicification-serification, propylitization, strong argillization, chloritization, and tourmalinization	potassic alteration, silicification-serification, argillization, and propylitization	Calcium alteration, K alteration, silicification-serification, and propylitization	chloritization, serification, silicification, & carbonatization
Ore minerals	Mainly bornite, chalcopyrite and pyrite		Chalcopyrite, pyrite, molybdenite, native gold, bornite, galena, sphalerite, arsenite, chalcocite	Natural gold, electrum, pyrite, chalcopyrite, scheelite, and bornite	Pyrite, chalcopyrite, bornite, molybdenite, magnetite, native gold, hematite, galena and sphalerite	Pyrite & molybdenite, followed by scheelite, magnetite, chalcopyrite, sphalerite, galena, & pyrrhotite	Pyrite, sphalerite, galena, acanthite, and native silver

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Type	Oceanic		Continental				
Sub-type	High angle subduction	Flat-slab subduction	Continental collision	Intracontinental orogenic			
Lithochemistry & geochemistry	Na ₂ O/K ₂ O < 1.88		The adakite-like magmatic rocks	Adakite magma affinity	Adakite magma affinity	SiO ₂ > 70 %, F-rich, (N ₂ O+K ₂ O) > 8 %	High K & Si, Ca alkaline, high
	Sr-Nd isotopic composition close to that of MORB						
Mineralization age (Ma)	low radioactive Pb, ²⁰⁷ Pb/ ²⁰⁴ Pb < 15.55,		Na ₂ O/K ₂ O < 1.2, high ⁸⁷ Sr/ ⁸⁶ Sr) and low ¹⁴⁴ Nd/ ¹⁴³ Nd, ²⁰⁷ Pb/ ²⁰⁴ Pb > 15.55, high Rb/Sr & Ba/Sr ratio	εHf = 4.6~9.9	enriched radioactive Pb	εNd = 1.8~1.14, Mg [#] = 48~53	δ ¹⁸ O (>10‰), & high radioactive Pb
				Late Jurassic	153~106 & 166~177	130~145 & 116.5~115.5	172~159
Representative mineral deposit	Panguna, Batu Hijau, and Lepanto-FSE in the southwest Pacific	Bingham in the US, Refugio in the Central Andes, & Grasberg & Ok Tedi in Papua New Guinea	Yulong and Qulong porphyry deposits in Tibet, China	Hada Temple and Bilihe in Inner Mongolia, China	Dexing, Chengmenshan, and Tongshankou, etc. in Jiangxi-Hubei, China	Shangfanggou, Jinduicheng, & Nannihu in the Qinling Orogenic Belt of China	Lengshuikeng, Jiangxi, China
Data source	[9,12,15,16,19,25,26,29,30,34]		[2.5,6,9,10,12,15,17–21,23,24, 27–33,35–36]				

2.2.2. Cu-Au deposits

This type of deposit is mainly produced on the edge of the Yangtze Block, activated during the Yanshanian period in eastern China (Figure 3, Table 1). The Dexing porphyry Cu ore field in Jiangxi Province is developed on the southern edge, and the porphyry Cu-Fe-Au mineralized belt in the middle and lower Yangtze River is developed on the northern edge. The Cu reserves of the Dexing ore field reach 6 million tons [5,10]. The porphyry Cu-Au deposits in the middle and lower Yangtze River mineralized belt are produced in the ore clusters of eastern Hubei, Jiurui, Lucong, and Ningzhen, being mainly porphyry Cu-Au deposits, followed by porphyry Cu-Mo deposits.

2.2.3. Mo deposits

The continental porphyry Mo deposits are mainly produced in the East Qinling area on the southern edge of the North China Craton and the Yanliao area on the northern edge (Figure 3, Table 1). The East Qinling Mo ore belt, which is distributed in the NW–SE direction, starts from Luonan, Shaanxi, in the west and ends in Luanchuan, Henan, in the east. It is about 250 km long and 20–30 km wide, with its eastern section as wide as 50–60 km. The Shimen-Machaoying deep fault runs across the middle of the belt, dividing it into two sub-zones, the south and the north. According to the nature of the ore-bearing porphyries, these deposits can be subdivided into two types: porphyry Mo deposits related to small intrusives and porphyry Mo deposits related to large intrusives. The large and small intrusives related to mineralization are mostly produced at the intersection of two groups of structures in the northwest and northeast directions [6,23–24,36].

2.2.4. Au deposits

Continental porphyry Au deposits in China are currently found in Xianghuang Banner, Inner Mongolia. Representative deposits are the Hadamiao and Bilihe gold deposits, which are about 10 km apart (Figure 3, Table 1). They are all produced in the Mesozoic continental volcanic basin in the Bainaimiao-Xianghuang Banner metallogenic belt on the northern edge of the North China Platform. The emplacement of the porphyry body is controlled by secondary faults such as NW-trending Bilihe and/or EW-trending Hadamiao faults [7,9,37–40]. The porphyries related to mineralization were developed after the Late Jurassic, when the region had entered the intracontinental extension stage. Porphyries related to the formation of continental Au deposits in China are mostly produced in small upright and/or steeply inclined stocks, and a single deposit often has multiple mineralization centers. The ore body is mainly produced at the top of the ore-bearing porphyry (such as Bilihe) and in its internal contact zone with the surrounding rock (such as Hadamiao).

2.2.5. Pb-Zn-Ag deposits

This type of deposit is represented by the Lengshuikeng super-large Pb-Zn-Ag deposit in Jiangxi, China (Figure 3, Table 1). The deposit is located on the edge of the Yanshanian volcanic fault basin on the northern edge of the Cathaysia block and is controlled by NE and NNE thrust

nappe structures and their intersection with NW-trending extensional faults [41–43]. The ore-bearing intrusive is an ultra-shallow emplacement felsic porphyry system. The Lengshuikeng-type porphyry Pb-Zn-Ag deposit is characterized by a large number of cryptoexplosive breccias, often closely associated and/or coexisting with the “trinity” of non-ore quartz syenite porphyry (rhyo-porphyry) and post-ore potassium-granite porphyry. The ore-bearing porphyry is mainly a series of calc-alkaline and potassium-basalt rocks with high potassium, high silicon, and aluminum supersaturating.

2.3. Metallogenic epoch

Volcanic magmatic arcs can be classified into island arcs and continental arcs based on the presence or absence of back-arc basins. Island arcs result from steep, deep subduction of oceanic plates and are characterized by the development of back-arc extensional basins. Continental arcs, by contrast, arise from gentle subduction of oceanic plates, and their back-arc regions typically lack such extensional basins. Alternatively, these arcs may originate from continental collision and/or intracontinental orogenic settings. Consequently, the formation ages of PPDs and their associated intrusive rocks essentially coincide with the timing of oceanic and/or continental plate collision or orogenic activity [5,10].

Oceanic PPDs may occur in any era, though they are predominantly concentrated in the Cenozoic (approximately 65%) and Mesozoic (about 35%), with a particular peak in the Tertiary [17]. Paleozoic examples include Cadia Hill in Australia and Kal'makyr in Uzbekistan; Mesozoic deposits are represented by Fish Lake and Mount Polley in Canada; and Cenozoic occurrences include Grasberg, Bingham, Panguna, Bajo de la Alumbrera, Lepanto-FSE, and Refugio [5,10].

PPDs in continental collision zones span from the Mesozoic to the Cenozoic, but are chiefly Mesozoic in age. In China, such deposits were mainly formed during the Yanshanian period (Table 1). The principal lithogenic and mineralization ages for porphyry-skarn-epithermal deposits in Tibet are as follows: Early to Middle Jurassic (160–174 Ma) in the central Gangdise belt; Early Cretaceous (89–123 Ma) in the western Bangong Lake-Nujiang belt; Paleocene (50–65 Ma) and Oligocene-Miocene (14–23 Ma) in the eastern and western Gangdise belt; and Eocene (39–43 Ma) in the Yulong belt [19]. The Oligocene to Miocene post-collisional porphyry Cu deposits in the southern Tibetan Gangdise belt contain total copper resources exceeding 20 million metric tons (Mt) and are genetically linked to granodioritic to quartz monzogranitic porphyry intrusions that exhibit adakite-like signatures (e.g., $\text{Sr/Y} > 40$) [18]. In the eastern Gangdise belt, adakite-like magmatic rocks in the southern sub-belt range from ca. 38 to 18 Ma, whereas those in the northern sub-belt range from ca. 21 to 10 Ma. Mineralization ages for porphyry Cu deposits in the eastern Gangdise belt also show a south to north decreasing trend: deposits in the southern sub-belt are approximately 30 Ma, while those in the northern sub-belt are between 21 and 13 Ma.

3. Geology and geochemistry

Table 1 lists the key geology, lithochemistry, and geochemistry of various PCPDs and/or PPDs and is briefly described below.

3.1. Oceanic

The mineralized porphyries generally have an exposed area of less than 2 km². They are shallow (1–4 km) and multi-staged and multi-phased [17]. The cracks in the porphyries and surrounding rocks control the alteration and mineralization. The fluids that caused the alteration and mineralization in the early stage were mainly magmatic fluids, with a salinity of 30%–60% NaCl equiv. and a temperature of 400 to >600 °C [5,10,17]. The late alteration and mineralization fluids were mixed with the meteoritic water, with a salinity of <15% NaCl and a temperature drop of 200–400 °C. The alteration of the surrounding rocks of porphyry Cu deposits is very developed, ranging from hundreds to thousands of meters, with regular horizontal and vertical zoning, from the center of the rock to the outside: K-metasomation, greisenization, argillification, and propylitization [44]. However, the alteration of Au-rich porphyry Cu deposits is slightly different: The alteration of Au-rich porphyry Cu deposits is, spatially from bottom to top, Ca-Na metasomation, K-metasomation, propylitization, moderate-advanced argillification, and greisenization [45].

Veins in PPDs can be divided into three categories. Irregular-plate-shaped A veins were formed in the early stage of mineralization when the porphyry was not yet consolidated and are related to potassium alteration. B veins were formed when various porphyries were consolidated, and large-scale fracture events developed. Compared with A veins, B veins are far away from the porphyry body. D veins in the late stage of mineralization were formed by the addition of a large amount of rainwater to the ore-forming fluid. Compared with B veins, they are farther away from the porphyry body and cut through the early A and B veins. In addition, this type of vein has obvious feldspar decomposition alteration halos [17,44,45]. Au-rich PPDs also develop various types of veins during hydrothermal alteration, but they are slightly different from the A, B, and D veins developed in the classic PCPDs. Mineralization can be produced in porphyries or in nearby surrounding rocks, but most of it is produced in the contact zones between the two. The PPDs are accompanied by hydrothermal alteration zoning, also showing zonal distribution. From the center of porphyries to the periphery, the following is formed: low-grade core, rich ore shell, and rich pyrite shell. The ore is mainly produced in the form of dissemination and veinlet dissemination. The mineralization of most Au-rich porphyry Cu deposits is closely related to the Ca-Na and K alteration zones. The large number of micro-cracks and veinlets developed in the alteration zones controls the Au. The sulfides in the deposit are mainly bornite, chalcopyrite, and pyrite [17].

3.2. Continental

Continental PPDs often do not exist in isolation, but are one of several different genetic types in the same metallogenic series. For example, the Cu deposits in Tibet have become a typical porphyry-skarn-epithelial-thermal Cu polymetallic metallogenic series, and the northern section of the “three rivers” in eastern Tibet, the middle and eastern section of the Gangdise River, and the Bangong Lake-Nujiang porphyry-skarn-epithelial-thermal Cu polymetallic mineralization belt are typical representatives [5,46,47]. There are considerable Cu polymetallic resources in them. For example, the Xiongcu Cu (Au-Ag) deposit has a Cu resource of 2.38 million tons, 202 tons of associated gold, and 1,041 tons of associated silver. Cu (Au-Ag) deposits such as Tiegelongnan, Duobuza, and

Bolong have Cu resources exceeding 24 million tons, associated gold exceeding 500 tons, and associated silver exceeding 5,000 tons. The main deposits related to the thickening of the crust due to continental collision are skarn Pb-Zn (Cu-Au-Ag) deposits, such as Monyaa, Dongzhongla, Bangbule, and Chagler, as well as low-sulfidation epithermal Ag-Pb-Zn (Au) deposits. The main deposits related to continental collision and strike-slip are porphyry-skarn Cu-Mo-W deposits, such as the Yulong Cu-Mo-Au-W ore belt and the Nuri-Chengba Cu-Mo-W ore cluster. The main deposits related to the continental collision and extension background are porphyry-skarn Cu polymetallic deposits, such as the Julong Cu-Mo polymetallic deposit, the Jiama Cu polymetallic deposit, the Bangpu Mo-Cu polymetallic deposit, and the Junuo Cu-Mo deposit [5,46,47].

The fundamental geology of PPDs in the Chinese mainland can be summarized as follows. Ore-bearing porphyries are predominantly quartz diorite, diorite, and granodiorite, with rocks mainly of high-K calc-alkaline and potassic shoshonite affinity. Alteration progresses from early central potassic alteration and peripheral propylitization to late silicification-sericitization and medium--deep argillization. Mineralization evolves from early irregular veinlets and stockwork veins (type A) and planar veinlets (type B) to late cross-cutting veins (type D). Ore bodies are chiefly developed in the contact zones between porphyries and country rocks; some deposits are fully mineralized, with ore bodies generally taking cylindrical or hollow-cylindrical forms. Metal sulfides are mainly pyrite, chalcopyrite, molybdenite, and bornite, while oxides are primarily hematite and magnetite. Early mineralization assemblages consist of pyrite + chalcopyrite + molybdenite + magnetite, whereas late assemblages comprise pyrite + bornite + hematite. In the early stage, ore-forming fluids were predominantly high-temperature ($>400\text{ }^{\circ}\text{C}$) and high-salinity (34–53 wt% NaCl) magmatic waters; in the late stage, meteoric water was introduced, with temperatures dropping below $350\text{ }^{\circ}\text{C}$ and salinities decreasing to $<12\text{ wt\% NaCl}$. The $\delta^{34}\text{S}$ values of ores cluster around 0, indicating a deep-sourced origin [5,10,17,18,20,21]. Based on lithochemistry, geochemistry, Sr-Nd-Pb isotopic compositions, and mineralization assemblages of continental type ore-bearing porphyries, some researchers have identified four distinct ore-bearing porphyry magmatic systems (Table 2) [5,8,10,17,18,20,21]. These indices can serve as useful exploration indicators for PPDs.

Clearly, there are essential differences in geology, lithochemistry, geochemistry, and genesis between continental ore-bearing porphyries (COBP) and oceanic ore-bearing porphyries (OOBP), which are widespread globally. COBP are mostly high-K calc-alkaline and basaltic rocks, whereas OOBP are mainly calc-alkaline (high-angle island arcs) and high-K calc-alkaline (low-angle continental margin arcs). COBP magmas generally originate from crustal source rocks with varying basement properties, and their genesis relates to deep continental processes. OOBP magmas, by contrast, derive from mantle wedge regions modified by fluid metasomatism in subduction zones, closely linked to oceanic plate subduction. Continental Cu (Mo, Au)-bearing magmas typically originate from thickened juvenile mafic lower crust, with mantle-derived materials directly and/or indirectly participating in the magmatic system via underplating, seepage, and metasomatism [5,10]. Mo-bearing magmas usually stem from thickened ancient lower crust, while Pb-Zn-Ag-bearing magmas originate from ancient middle to lower crust. Au-bearing magmas mainly derive from intracontinental upper crust but have undergone variable degrees of mixing and/or incorporation of mantle-derived magma.

Table 2. Continental porphyry magmatic system and its lithochemistry and geochemistry.

Magma system			Cu (Mo & Au)-bearing	Mo-bearing	Pb-Zn-Ag-bearing	Au-bearing
Lithology			High-K calc-alkaliner and/or shoshonitic intermediate -acid poyphyry	High-K calcium alkaline and/or shosphoric granite porphyry and granodiorite porphyry	Al-supersaturated porphyry with medium-high oxidation comparable to S-type granite	Mainly B-rich granodiorite & granite porphyry, followed by alkali-ferromagnetic granite porphyry, comparable to type I granite
Lithochemistry & geochemistry	REE	LREE/HREE (LREE)	LREE/HREE fractionation	LREE-enriched	LREE-enriched	LREE-enriched
		La/Yb	17.2~63.9	14.8~95.8	9.1~11.2	9.0~13
		Eu negative anomaly	No	Complicated	Significant ($\delta\text{Eu} = 0.38\sim0.51$)	Varying degrees
		Y	$(2.9\sim16.9) \times 10^{-6}$	$(6.8\sim107.0) \times 10^{-6}$		$(12.8\sim29.0) \times 10^{-6}$
		Yb		$(0.43\sim11.8) \times 10^{-6}$		
	Rock composition	LaN/YbN	16 ~ 65	12 ~ 78		
		MREE		depleted		
		$\varepsilon\text{Nd} (t)$	1.8~1.14	12.4~18.4	-9.75 ~ -10.06	-1.0 ~ -3.6
		SiO ₂		High SiO ₂ , K, and F,	65.97%~76.39%	70%~72%
		Al ₂ O ₃		low (9.0%~13.8 %)	12.01%~19.62%	
		K ₂ O + Na ₂ O			4.28%~9.48%	
		K ₂ O			4.17%~8.25%	3.1%~3.6%
		K/(K + Na)			0.89~0.98	0.38~0.42
		Fe ₂ O ₃ /(Fe ₂ O ₃ + FeO)			0.5~0.8	
		A/KNC			1.18~3.86	
		Mg [#]	48 ~ 53			
		Sr/Y	19 ~ 186	27.5~216.2		5~11

Continued on next page

Magma system		Cu (Mo & Au)-bearing	Mo-bearing	Pb-Zn-Ag-bearing	Au-bearing
Isotope	Nb/Ta			11.44~15.67	11~13
	Ti, P, Nb, Ta & other HFSE		Depleted		Depleted
	K, Ba, Rb & other LILE		Relatively enriched		Relatively enriched
	Other			Al ₂ O ₃ > (K ₂ O + Na ₂ O + CaO)	Al ₂ O ₃ /(K ₂ O + Na ₂ O + CaO): 0.9–1.0
	⁸⁷ Sr/ ⁸⁶ Sr	0.6931~0.7329	0.7077~0.7629	0.7072~0.7169	0.7085~0.7120
	²⁰⁶ Pb/ ²⁰⁴ Pb		17.12~18.13	17.768~17.886	19.079~19.586
	²⁰⁷ Pb/ ²⁰⁴ Pb	>15.55	15.14~15.54	15.514~15.548	
	²⁰⁸ Pb/ ²⁰⁴ Pb		37.35~38.05	38.105~38.308	
	δ ¹⁸ O‰			10.70~13.30	
	Origin	Tibetan Plateau collision zone; Dexing, Jiangxi & the middle-lower Yangtze River, China	Qinling Molybdenum Belt, China	Lengshuikeng, Jiangxi, East China	Bilihe and Hadamiao areas, Inner Mongolia, China
Data source		[5,10,17–21,23,26,27,29,33–35,37,39,48]			

One factor contributing to the differences in PPDs between the two tectonic settings is that the collision between the Indian and Asian continents occurred only briefly in the early Cenozoic (approximately 55–45 Ma), and the Indian continental lithospheric plate did not subduct beneath the lithosphere in the hinterland of the Qinghai-Tibet Plateau [48]. Moreover, continental collision was largely confined to the limited area of the Himalayas and Gangdise, rather than affecting the entire Qinghai-Tibet Plateau.

4. Discussion: metallogenic process and control

For PPDs, including PCPDs, in addition to many well-known traditional ore control factors such as structure, magma, and host rock, there are also some unique controls that can be used as signs of prospecting and exploration. This article only discusses these unique mineralization processes and ore controls.

4.1. Metallogenic process

The latest research on the formation of oceanic PPDs is summarized as follows. The subducting oceanic plate undergoes large-scale dehydration as it transitions from blueschist to eclogite facies at

a depth of approximately 100 km [18–21,26–28,33–35,48]. The released solute-rich fluids metasomatize the overlying mantle wedge, inducing partial melting and generating calc-alkaline magma. Following MASH (melting, assimilation, storage, and homogenization) processes in the lower crust, a long-lived, stable magma chamber develops in the shallow crust, facilitating metal enrichment and the concentration and discharge of ore-forming fluids. Dehydration of the oceanic plate transports substantial amounts of water, sulfur, halogens, metals, and fluid-mobile large ion lithophile elements (LILE) into the mantle wedge. The significant addition of H₂O imparts high oxygen fugacity to the melts derived from the wedge mantle. Under such high fO_2 conditions, sulfur is predominantly dissolved in the magma as sulfate (approximately 1.5%), causing chalcophile elements like Cu and Au—which normally partition into sulfides—to behave as incompatible elements and become enriched in the silicate melt. Large volumes of fluid are exsolved from the shallowly emplaced felsic magma chamber and rise convectively to the chamber roof or stock apex, forming a fluid carapace. The fluid released from the deep magma chamber at about 700 °C and ≥ 1.2 Kbar is typically a supercritical fluid with a salinity of roughly 10 wt%. Upon ascent and decompression, this supercritical fluid undergoes phase separation into a high-salinity liquid-rich phase and a low-salinity vapor-rich phase; the former—the high-salinity liquid—is the primary carrier for metals such as Cu and Mo. Exsolved fluid salinity increases with pressure, and Cu solubility rises markedly with increasing fluid salinity. Consequently, higher pressures (generally ≥ 1 Kbar, i.e., depths ≥ 4 km) are highly favorable for Cu enrichment in the fluid during exsolution. The regular occurrence of large to super-large PPDs in clusters along island arcs or continental margin arcs has led to the establishment of the classic oceanic PPD metallogenic model (Figure 2).

Traditional theory holds that mineralization in porphyry-hydrothermal systems is typically completed within a few million years, generally around 1 Ma, with mineralization depths of 5–10 km and horizontal extents of 10–30 km [49]. However, Mottram et al. [50] applied carbonate U-Pb dating to carbonate minerals in a porphyry-hydrothermal system in the Yukon, Canada, and found that hydrothermal activity there persisted for as long as 50 million years (Figure 4).

This latest research confirmed that the relevant porphyry-epithelial fluid system and related mineralization have the following characteristics: A) Ultra-long hydrothermal activity process: The formation time of carbonate minerals in the deposit lasted from 77 million years ago to 19 million years ago, a total of 58 million years. B) Multi-stage mineralization: The earliest mineralization coincided with the formation time of the porphyry deposit, which occurred about 77 million years ago; thereafter, from about 74 million years ago to 19 million years ago, the deposit underwent multiple superimposed transformations of epithermal mineralization. C) Fluid movement under fault activity: The precipitation time of carbonate minerals is highly consistent with the activity time of the Daxi Fault, indicating that fault activity plays a vital role in the formation of the deposit. Fault activity not only provides a channel for the migration of magma and hydrothermal fluids but also continuously creates new infiltration space through fault sliding and brecciation, allowing hydrothermal activity to continue for a long geological period and form multi-stage mineralization. D) Transformation of early mineralization by epithermal action: The phenomenon of dissolution and transformation of early-formed sulfide minerals indicates that late epithermal fluids have played a certain role in transforming and enriching the early-formed porphyry deposits, and may have also affected the final scale and grade of the deposits.

4.2. Metallogenic control

More and more recent studies have shown that the high degree of magma differentiation and magma oxidation are key and special ore controls in the formation of various porphyry metal deposits.

4.2.1. Magma differentiation

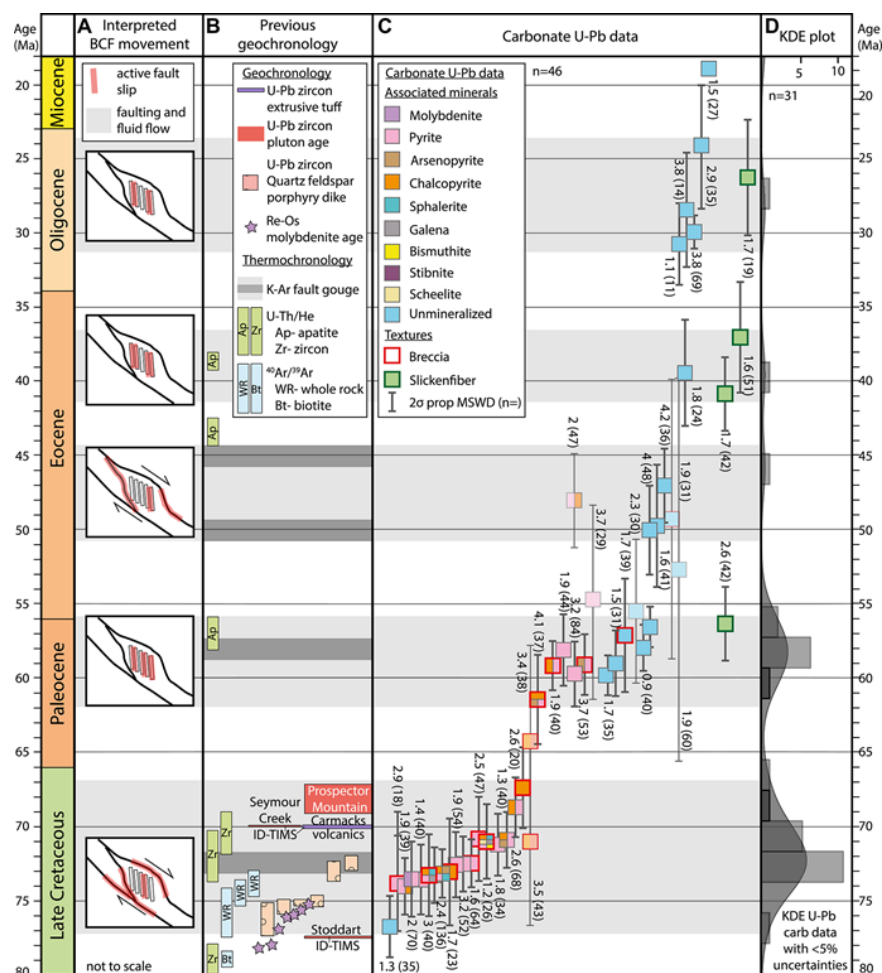


Figure 4. (A) Interpreted Big Creek fault (BCF) slip periods based on Mottram et al. [50] and including new interpretations from data presented here. (B) Previous geochronological and thermochronological constraints from the Revenue-Nucleus system, where U-Pb zircon ages are weighted average laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) dates, except where isotope dilution–thermal ionization mass spectrometry (ID-TIMS) age is stated. (C) Summary of in situ U-Pb carbonate geochronology data ($^{206}\text{Pb}/^{238}\text{U}$ intercept ages with 2σ propagated uncertainties and quoted mean square of weighted deviates, MSWD [$n = 1$]), colored for mineral association. Data with uncertainties $>5\%$ have been made transparent. (D) Kernel density estimate (KDE) and histogram showing main populations of data (binning = 2 Ma). Gray shading around main populations. Carb, carbonate.

Sulfide-rich, mantle-derived basic magma rises and intrudes into the lower crust, where it undergoes melting, assimilation, retention, homogenization, and fractional crystallization, ultimately producing water-rich, ore-bearing intermediate-to-felsic magmas [51,52]. During magma ascent and subsequent cooling crystallization, large-scale fluid exsolution occurs. Once sulfide solubility is reached, sulfides become saturated and crystallize within the magma. These metallic sulfides subsequently break down in the exsolved fluid, releasing substantial amounts of sulfur and metals into the ore-forming fluid. Cooling of this fluid then triggers metal precipitation. The exceptional enrichment of elements such as Cu typically takes place during the differentiation and evolution of mantle-derived magma and the ensuing magmatic-hydrothermal processes [51–53]. Geochemical evidence indicates that ore-forming felsic magmas originate from high-pressure differentiation of mafic parent magmas in the lower crust.

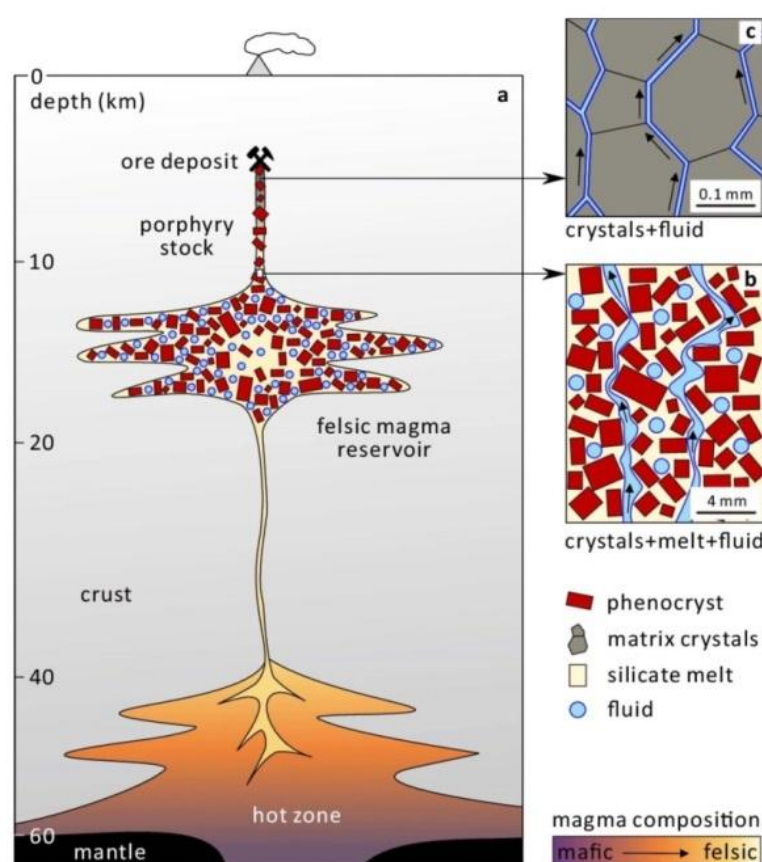


Figure 5. Cartoons illustrating the preferred model of magma evolution, fluid exsolution, and fluid transport processes involved in the formation of porphyry-type Cu (Au, Mo) deposits in the Sanjiang region (not to scale) [54]. a) Accumulation of lower-crustal, fertile magmas at mid-to upper crustal depths of 10–20 km, and exsolution of the ore-forming fluids at these depths during considerable crystallization of the magmas. b, c) Percolation of the fluids through a transient, interconnected fluid network in the porphyry magma. Notice that the residual melt at the top of the porphyry stock has already transformed into a finely-crystallized matrix due to decompression-induced H₂O loss.

Two main models have been proposed. The magma chamber model posits that ore-forming magma accumulates into a large magma chamber at upper crustal depths of about 4–10 km; as further crystallization proceeds, porphyry magma and ore-forming fluids are exsolved from this chamber, with mineralization occurring at its top. In contrast, the magma channel model argues that fluid exsolution begins already in the lower crust and continues as the magma rises, eventually leading to ore formation in the shallow crust without requiring an intermediate magma chamber [54]. The primary ore-forming materials within the magma have already entered the fluid phase at depths of 10–20 km, after which enormous volumes of ore-forming fluid migrate upward over distances of approximately 10 km (Figure 5).

Table 3. Discrimination factors of highly differentiated I-, S-, and A-type granites (modified after [33]).

Discriminator	Granite type		
	I	S	A
Characteristic minerals	Amphibole, aluminum-rich minerals, muscovite and garnet, etc.	Aluminum-rich minerals, cordierite and andalusite, etc.	Dark minerals such as arfvedsonite, etc.
10000Ga/Al	0.48–1.26	0.08–0.90	0.69–3.11
A/CNK	0.92–1.34	0.80–1.52	0.99–1.30
P ₂ O ₅	Negatively correlated with SiO ₂	Positively correlated with SiO ₂	n/a
Zr+Nb+Ce+Y	$(123.6–311.4) \times 10^{-6}$	$(97.00–307.43) \times 10^{-6}$	$(63.30–1965.83) \times 10^{-6}$
Diagenetic temperature (°C)	764	n/a	800–900
Y & Th-Rb evolution trend	Positive correlation	Negative correlation	n/a
Ga/Al-Zr evolution trend	Negative correlation	Negative correlation	Linear reduction

Highly fractionated granites not only serve as an important indicator of continental crustal maturity but are also closely linked to the formation of numerous significant mineral deposits, including non-ferrous, rare, and rare earth elements [33]. Yu et al. [55] and Wu et al. [56] further demonstrated that strong magma differentiation is a critical factor controlling rare metal mineralization. Highly fractionated granites are leucocratic or white granites that have undergone intense crystallization differentiation, representing the final products of highly evolved crustal fractionation. Their formation is governed by various physical and chemical factors, such as high temperature and volatile content. The protracted crystallization differentiation of magma often entails continuous enrichment of diverse ore-forming elements. In terms of characteristic elements and element ratios (Table 3), highly fractionated granites exhibit reduced Zr/Hf, La/Ta, Y/Ho, La/Nb, K/Rb, and LREE/HREE values, alongside elevated Rb/Sr and Rb/Ba ratios [33]. Highly fractionated I-type granites are enriched in minerals like muscovite and garnet; highly fractionated S-type granites contain abundant cordierite and andalusite; whereas highly fractionated A-type granites are characterized by dark minerals such as sodic amphibole (arfvedsonite). Lithochemically, in highly

fractionated I-type granites, SiO_2 , A/CNK , P_2O_5 , and $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ decrease, with Ga/Al-Zr showing a declining evolutionary trend. In highly fractionated S-type granites, SiO_2 , A/CNK , and P_2O_5 increase, while $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ decreases. For highly fractionated A-type granites, the lower limit of $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ is 350×10^{-6} , diagenetic temperatures exceed 800°C , and Ga/Al-Zr follows a linearly decreasing evolutionary path. The evolution of these highly fractionated granites is influenced by their viscosity, which in turn depends on major chemical components, temperature, texture, and the nature of surrounding rocks.

Some highly fractionated granites show special geochemistry of decoupling of twin element pairs (Nb-Ta and Zr-Hf) and tetrad effects of REEs [55,56]. The decoupling of twin elements Nb-Ta in highly fractionated granites is mainly caused by the fractional crystallization of minerals such as hornblende and biotite and the later F-rich fluid, while the decoupling of Zr-Hf is mainly controlled by the fractional crystallization of zircon. The tetrad effect of REEs in highly fractionated granites is formed by the melt-fluid and fluid-gas separation of magma that has undergone highly fractionated crystallization. The fractional crystallization of minerals such as monazite, allanite, xenotime, and zircon will lead to a decrease in the total amount of REEs and the ratio of light to heavy REEs, as well as a strong negative Eu anomaly. Some studies pointed out that the depth of magma differentiation may be a key factor affecting the differential distribution and mineralization potential of PPDs [12,13,57]. Many researchers have conducted experimental lithological studies on the occurrence of Cu, the distribution behavior of Cu in melt-mineral, melt-fluid, gas phase, high-salinity brine phase and liquid phase, and the solubility of Cu in fluids, and have come to the following main understandings [49,58–63]: The extraordinary enrichment of metallic Cu usually occurs in the differentiation evolution of mantle-derived magma and the subsequent magma-hydrothermal process. Cu mainly exists in the form of +1 valence in ore-forming hydrothermal fluids and melts above 100°C , and its specific complex form is affected by system composition, temperature, pressure, pH, H_2S fugacity, and salinity. The occurrence state of Cu in Cl-poor and S-silicic melts is $\text{CuO}_{0.5}$, and in high-temperature ($>300^\circ\text{C}$) acidic and medium-low salinity hydrothermal fluids, it is mainly $[\text{CuCl}]_0$, $[\text{CuCl}_2]^-$ and CuHS_0 ; in low-temperature ($<300^\circ\text{C}$) alkaline and medium-low salinity hydrothermal fluids, it is mainly $\text{Cu}(\text{HS})_2$ and CuHS_0 . In high-salinity brines, Cu^{2+} and Cu^+ easily complex with Cl to form high-coordination complexes. The overall trend of Cu distribution coefficient (D_{Cu}) is: D_{Cu} silicate mineral/melt ($0.007 \pm 0.002 \sim 0.82 \pm 0.08$) $< D_{\text{Cu}}$ Fe-Ti oxide/melt ($0.19 \pm 0.02 \sim 1.72 \pm 0.68$) $< D_{\text{Cu}}$ fluid/melt ($2 \sim 2698$) $< D_{\text{Cu}}$ high-salinity brine/gas phase ($2 \sim 7066$) $< D_{\text{Cu}}$ sulfide/melt ($180 \sim 42000$). The D_{Cu} value is used for simulation calculations of magmatic evolution and Cu polymetallic mineralization in porphyry systems.

Steam-phase fluids have a strong Cu-carrying capacity [59,61,62,64–66]. The solubility of Cu is significantly positively correlated with the pressure of the mineralization system ($300 \sim 1700$ MPa) and is as high as 25% and 2.3% in chlorine-containing and HS-containing hydrothermal fluids after the magmatic period. The partial melting of S-containing and S-poor mantle peridotites ($<10\% \sim 25\%$) can lead to significant enrichment of Cu in mantle-derived basic arc magma. Further decomposition of sulfides can promote the high enrichment of Cu in the mineralization fluid. The ore-forming fluid must carry at least $1000 \sim > 10,000$ ppm Cu to cause the precipitation of ore minerals such as chalcopyrite.

4.2.2. Magma oxidation

Growing evidence indicates that, regardless of the geotectonic setting in which PPDs form, the generation of large porphyry deposits requires ore-forming magmas with high oxygen fugacity, specifically $\Delta\text{FMQ} = +1$ to $+2$ [67]. Under such oxidizing conditions, sulfur is predominantly present as sulfate in the magma, which promotes the progressive enrichment of Cu and other chalcophile elements in silicate melts during magmatic evolution. High oxygen fugacity also helps explain why calc-alkaline magmas typically contain elevated concentrations of chalcophile elements [68]. Consequently, magma oxygen fugacity is used as a geochemical indicator for assessing porphyry mineralization potential and likely deposit scale. The high oxidizability of oceanic PPD ore-forming magmas is attributed to the significant contribution of the subducting oceanic plate to arc magmas. In contrast, the oxidizability of continental PPD ore-forming magmas may be linked to fractional crystallization of garnet and/or amphibole, combined with injection of mantle-derived potassic to ultrapotassic magmas, both of which can raise magma oxygen fugacity.

Wang et al. investigated the porphyry Cu-W deposits in the Gangdise belt of Tibet and concluded that water-rich, oxidized magmas with high Sr/Y ratios and abundant volatiles (e.g., S and Cl) formed in collisional settings are closely associated with PPD genesis [69]. Oxidizing conditions cause sulfur to exist mainly as SO_4^{2-} and/or SO_2 rather than S^{2-} , facilitating Cu transport and inhibiting early sulfide precipitation in the magmatic-hydrothermal system. High S and Cl contents promote the formation of metal complexes, enhancing metal mobility during magma hydrothermal evolution. Magmas with high Sr/Y ratios are generally considered to result from residues of garnet and/or amphibole during partial melting, high pressure fractional crystallization of these minerals, and interaction and fractional crystallization of asthenosphere-derived arc magmas with upper crustal materials. As a typical continental collision metallogenic belt in the southern Lhasa terrane of Tibet, the Gangdise porphyry Cu belt hosts PCPDs closely related to Miocene granites with high Sr/Y (>20) and high La/Yb (>20). Cu mineralized granites are derived from juvenile lower crust [zircon $\varepsilon\text{Hf}(t) > 5$, TDM < 600 Ma], whereas W mineralized granites have been contaminated by the ancient basement of the Lhasa terrane [$\varepsilon\text{Hf}(t) < 0$, TDM > 1000 Ma]. High oxygen fugacity promotes Cu mobility, whereas low oxygen fugacity combined with high F content favors W enrichment in residual melts. Magma oxygen fugacity and volatile content (H_2O , Cl, S, and F) are thus key factors controlling whether high Sr/Y granites produce Cu and/or W mineralization. Cu-forming magmas are highly oxidizing and Cl/S-rich, while W-forming magmas are highly reducing, F-rich, and Cl and S-poor. Zircon ΔFMQ values, Ce/Nd ratios, and Cl/ SO_3 contents of apatite and biotite can serve as effective discriminators between these two granite types.

Ai et al. analyzed globally published V/Sc ratios in arc magmas, along with partition coefficients of V and Sc between minerals and silicate melts [70]. By exploring the relationship between the V/Sc ratio and magma oxygen fugacity ($f\text{O}_2$), they evaluated the oxidation characteristics of magmas in arc crusts of varying thicknesses. Their results indicate that magnetite fractional crystallization is the primary factor reducing V/Sc ratios in residual magmas. The Mg# at the onset of magnetite crystallization shows a significant positive correlation with magma oxidizability. In mature island arcs and continental arcs with crustal thicknesses exceeding 20 km, magma oxygen fugacity tends to increase with crustal thickness, and differentiation of garnet and

hornblende further enhances magma oxidizability. In thin arcs with crustal thicknesses below 20 km, magmas exhibit higher oxidizability than those in thick arcs, probably due to greater input of oxidized materials from the subducting slab (Figure 6). These findings corroborate the conclusions of Loucks [71].

This suggests that subduction dynamics and crustal thickness play a critical role in determining the oxidation state of arc magmas and the formation of PCPDs [70]. Highly oxidized primitive arc magmas become sulfide-saturated owing to magnetite crystallization during the early stages of magmatic evolution. This process results in early Cu loss and is therefore unfavorable for PCPD formation. In thick arcs, however, magnetite crystallization is widely suppressed, allowing sulfide saturation to occur at late magmatic stages, which better preserves Cu mineralization potential in the evolving magma. The input of subduction-related materials and the auto oxidation of magma accompanying increasing crustal thickness jointly govern arc magma oxidizability. Highly oxidized thin arc magmas may not favor PPD formation, because high oxygen fugacity promotes early magnetite crystallization and sulfide saturation. By contrast, magmatic differentiation in thick crust delays magnetite crystallization, thereby retaining Cu mineralization potential in the magma. Magnetite crystallization plays a key role in controlling sulfide saturation and Cu content during magmatic evolution, particularly in the late stages, and thus aids in understanding the mineralization potential of arc-related porphyry magmas under varying crustal thicknesses.

The oxidative origin of ore-forming magmas for continental PPDs, such as those in the Qinghai-Tibet Plateau, is similar to that of oceanic PPDs and can be broadly divided into two categories: source oxidation and magma auto oxidation. Evaporitic and carbonate sediments were widely developed on the northern margin of the Indian plate during the Paleocene–Eocene [72], and mantle carbonate metasomatism has been identified through Os-Sr-Mg isotopes in Miocene ultrapotassic volcanic rocks of the Gangdise belt [73]. Following the collision of the Indian plate, these oxidized sediments underwent dehydration under high temperature and pressure, releasing oxidizing fluids that metasomatized the overlying lithospheric mantle, potentially generating a highly oxidized source region [29].

A systematic analysis of sulfur contents in apatite from magmatic rocks of varying ages in southern Tibet revealed a strong positive correlation between apatite sulfur content, crustal thickness, and geochemical indicators of garnet differentiation; sulfur content increased markedly after the India-Asia collision [26]. Because sulfur readily enters the apatite lattice, this suggests that garnet differentiation in a crustal thickening environment promotes magma auto oxidation, thereby generating high oxygen fugacity magmas conducive to continental PPD mineralization. Similar to subduction zone arc magmas, collision zone porphyry magmas also undergo extensive amphibole fractionation, so the auto oxidation effect induced by amphibole is equally applicable to collision zone porphyry magmas. Luo et al. conducted a systematic Fe isotope study on Gangdise porphyry magmas and proposed that Fe isotope fractionation caused by amphibole differentiation correlates positively with zircon-derived magma oxygen fugacity, indicating that amphibole fractionation can also produce magmatic oxidation effects in continental collision zones [32]. Additionally, because continental PPDs are usually closely associated in time and space with potassic-ultrapotassic magmas derived from metasomatized lithospheric mantle, the injection of such high oxygen fugacity magmas—for example,

Gangdise ultrapotassic rocks with $\Delta\text{FMQ} = +0.8$ to $+3.0$ [27]—into the porphyry mineralization system is also considered a possible cause of the high oxidation state of continental porphyry magmas.

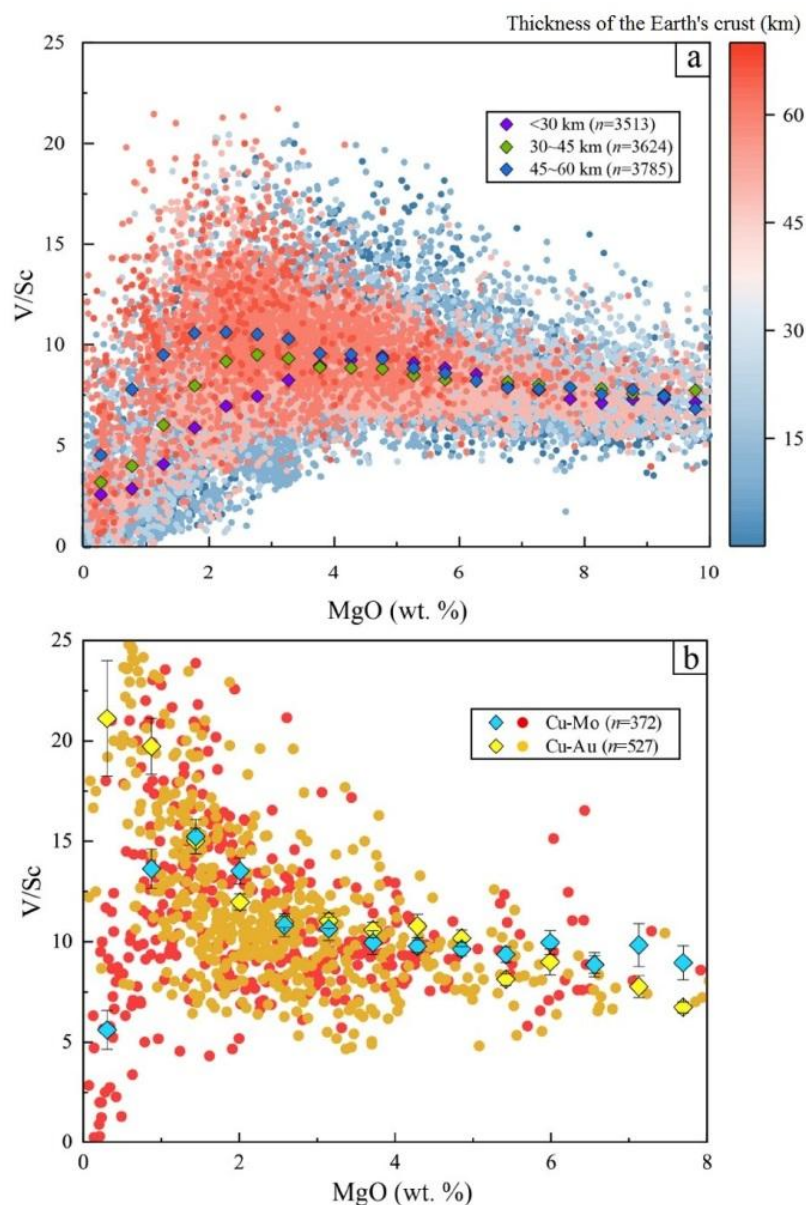


Figure 6. V/Sc variation patterns of oceanic PCPDs around the world [71]. a) V/Sc and MgO relationship of arc magmas worldwide. Circles are colored according to crust thickness, and diamonds of different colors represent the average V/Sc and MgO values for arc crust thickness <30 km, 30–45 km, and >45 km. b) V/Sc and MgO relationship of magmatic series related to PCPDs. Circles are colored according to deposit type, and diamonds of different colors represent the average V/Sc and MgO values for Cu-Mo and Cu-Au deposits. The average V/Sc values were calculated at data intervals of 0.5 wt% MgO, and 10% of the highest and 10% of the lowest values were removed from each MgO unit to reduce interference from extreme values.

Marine sulfate evaporites formed during the Great Oxidation Event, approximately 2.4 billion years ago, played a key role in the formation of a Cu-Ni sulfide deposit in South Africa [63]. Sulfur isotope analysis revealed a genetic link between magmatic sulfides and evaporites, indicating that the Great Oxidation Event not only altered atmospheric and oceanic oxidation states and sedimentary deposit types but also created a sedimentary sulfate reservoir that serves as an important sulfur source for magmatic deposits. This finding, which establishes a connection between the Great Oxidation Event and magmatic deposit formation, enhances our understanding of the link between magmatic oxidation and PPD genesis.

Studies of valence states of variable valence elements such as S and Fe in melt inclusions indicate that oxidation of fluids released by the subducting slab is common in the sub-arc mantle [74]. Arc magmas exhibit higher oxygen fugacity than mid-ocean ridge basalts ($\Delta\text{FMQ} = +0.5$ to $+3$ [67]). Kelley and Cottrell analyzed $\text{Fe}^{3+}/\Sigma\text{Fe}$ ratios in undegassed basaltic glasses worldwide and found that samples closer to subduction zones have higher $\text{Fe}^{3+}/\Sigma\text{Fe}$ ratios [75]. This ratio shows a good linear correlation with water content, suggesting that the mantle wedge metasomatized by the subducting slab is closely linked to arc magma oxidizability. Sub-arc mantle peridotite also has a higher oxygen fugacity than mid-ocean ridge and ocean island basalts [76], further indicating that arc magma oxidizability may originate in the mantle. Zhao et al. confirmed through statistical analysis of Cu/Zr ratios from over 100,000 arc volcanic rock samples worldwide that arc magma oxidizability derives from the mantle rather than from crustal magmatic evolution [77]. However, studies of many redox sensitive element ratios, including V/Sc, Zn/Fe, and Eu/Eu*, have found that primitive arc magmas have redox states similar to MORB, and that oxidizability may be progressively acquired during magmatic evolution [78,79]. After compiling V/Sc ratios from more than 20,000 Quaternary arc magmas worldwide, Ai et al. found that, regardless of whether the arc is thick or thin, V/Sc ratios increase during early magmatic evolution and decrease after magnetite saturation [70]. This indicates that oxygen fugacity changes during magma evolution and that magnetite saturation does not lead to a continuous increase in arc magma oxygen fugacity. Tang et al. proposed the “garnet redox filter” model by analyzing the global correlation between high-pressure garnet differentiation and calc-alkaline magma differentiation, and verified it using cumulates from Arizona, North America [79]. This model assumes that Fe-rich garnet has extremely low $\text{Fe}^{3+}/\Sigma\text{Fe}$ (<0.1), and that fractional crystallization of garnet at high pressure in the deep crust elevates the $\text{Fe}^{3+}/\Sigma\text{Fe}$ of the residual melt, thereby oxidizing the magma. Because Fe^{3+} has a higher bond strength, heavy Fe isotopes tend to partition into Fe^{3+} -bearing systems [25]. Therefore, Fe isotope fractionation during magma evolution can effectively record changes in magma redox state. After studying Fe isotope compositions of intrusive dykes from the northwestern Yangtze Platform and Andean arc volcanic rocks, Li et al. [28] and Du et al. [80] respectively confirmed the existence of the garnet redox filter. However, this model faces challenges from experimental petrology. Holycross and Cottrell measured the partitioning behavior of different Fe valences in garnet through fractional crystallization experiments and concluded that the partition coefficients for Fe^{2+} and Fe^{3+} in garnet are similar, so garnet differentiation cannot significantly alter magma redox state [81]. Tang et al., however, questioned several simulation details, including the failure to use Fe^{2+} partition coefficients derived from high-temperature and high-pressure experiments and the simulation results obtained after neglecting 50% crystallization [82].

Regardless of whether garnet exerts a redox filter effect, it can typically form only in thickened arc environments because garnet stability is strongly pressure dependent (>1.3 GPa [83,84]).

Hornblende is another widely abundant Fe-rich mineral in arc magma systems, with a stability field spanning a broader depth range within the crust. Studies have highlighted the important role of hornblende in arc magma evolution [84]. Compared with traditional trace element discrimination diagrams, the morphological coefficient (λ) of REE distribution patterns more effectively identifies hornblende versus garnet differentiation during magma evolution. Luo et al. compiled data from global magmatic arcs and, using the λ coefficient, identified hornblende differentiation characteristics in intermediate felsic magmatic rocks, especially island arc varieties [32]. Thus, hornblende differentiation in arc magma systems plays an extremely important role in arc magma oxidizability. A systematic study of deep hornblende cumulates from the Kohistan arc in Pakistan revealed that hornblende also has relatively low $\text{Fe}^{3+}/\Sigma\text{Fe}$ (0.2–0.3) [85]. Modeling shows that when the $\text{Fe}^{3+}/\Sigma\text{Fe}$ of the parental magma exceeds 0.2, amphibole fractional crystallization can increase the residual melt's $\text{Fe}^{3+}/\Sigma\text{Fe}$ by 0.1–0.3, and this capacity gradually strengthens as magma evolution proceeds. Another widely accepted explanation is that arc magmas are oxidizing due to their high water content. Loucks and Fiorentini emphasized, from the perspective of zircon trace elements, that water saturated degassing of water-rich arc magmas leads to an increase in magma oxygen fugacity [86].

4.2.3. Others

Kerrick et al. studied volcanic magmatic arcs and pointed out that tectonic settings characterized by crustal thickening, block uplift, and flattening or changes in subduction plate inclination are favorable for the generation of Au-rich porphyry Cu deposits [87]. The initiation and termination of flat-slab subduction, polarity reversal of subduction zones, and the cessation of subduction due to collision are all considered conducive to the formation of such deposits. Recent studies have found that many deposits formed during volcanic arc rifting, including Cerro Corona and Minas Conga in northern Peru, as well as the Marte, Lobo, Refugio, and Cerro Casale deposits in the Maricunga belt of northern Chile. This indicates that the formation of these deposits is closely linked to extensional structures. Corbett and Leach compared the effects of normal versus oblique convergence on island arc deposits and concluded that intrusion-related mineralization is particularly well developed in island arcs where normal convergence transitions to oblique convergence—that is, the transformation of tectonic regimes controls the formation of such deposits [4]. In continental collision settings, a range of tectonic systems, including large strike slip fault systems, develop alongside oblique collision, block movement, lithospheric delamination, and rifting, thereby controlling the formation of PPDs in continental orogenic belts at various crustal levels [88]. Intraplate compression shortens the crust and triggers intracontinental orogeny; in later stages, post-orogenic and/or non-orogenic lithospheric extension, or orogenic collapse, commonly occurs. The PPDs in the middle-lower Yangtze River region of China formed in a post-orogenic collapse setting [5].

Au-rich porphyry Cu deposits are mainly distributed in subduction-related volcanic magmatic arcs. Magma is a key factor in the formation of PPDs [45,89–91]. Subduction termination, shifts in plate margin stress regimes or plate rotation, lithospheric thickening, thermal rebound, mantle lithosphere delamination, and lithospheric extension may all induce melting and contribute to PPD

formation. Yan et al. compared the differences between Mesozoic basic magmatic rocks in the eastern and western sectors of the Nanling region, China, and their constraints on the spatial zonation of “eastern W and western Sn” mineralization [92]. The sustained activity of Mesozoic mantle-derived basic magma in this region provided essential heat for partial crustal melting and prolonged magma chamber evolution, which was an important factor in the differentiation and even mineralization of W- and Sn-forming magmas. Basic rocks in the eastern sector are mainly calc-alkaline and tholeiitic, whereas those in the western sector are chiefly alkaline. The spatial distribution—W-rich in the east and Sn-rich in the west—is primarily controlled by source composition, crust-mantle interaction, degree of differentiation, oxygen fugacity, and volatile content. Coincidentally, Ni et al. studied numerous granite-related metal deposits in Gejiu, Yunnan, China, and concluded that basalt may be the primary source of Cu mineralization in that region [31].

The degree of magmatic differentiation is proportional to mineralization. The enrichment of metals during magma crystallization differentiation can be effectively recorded by zircon. In Nanling granites, zircon $\delta^{94/90}\text{Zr}_{\text{IPGP}}$ values and metal (U, W, Sn) contents show synchronous trends [34], indicating that granitic magma crystallization differentiation itself can promote significant enrichment of ore-forming elements in residual melts, leading to mineralization. Zircon isotopes can thus trace the mineralization potential of highly fractionated granites, becoming an important tool for mineral prospecting and exploration.

In summary, lithochemical and geochemical indicators (Tables 1–3), such as magma oxygen fugacity or oxidizability ($\Delta\text{FMQ} = +2.0$ to $+2.8$ [93]), are important criteria for determining whether a porphyry body is mineralized. A similar indicator is the Ce(IV)/Ce(III) ratio in zircon [94]. Variations in the V/Sc ratio can also serve as a powerful tool for evaluating magma’s mineralization potential, particularly in the search for porphyry Cu-Au deposits.

5. Conclusions

PPDs, including PCPDs, are primarily generated in two types of geotectonic settings: oceanic and continental. The former can be further subdivided into high-angle subduction and flat-slab subduction, while the latter encompasses continental collision and intracontinental orogenic settings.

Metal-bearing magmas in the mantle wedge above high-angle subducting plates undergo differentiation to form PPDs at depth. The advance of flat-slab subduction leads to asynchronous crustal heating and triggers water flux melting, which can also induce localized melting and mineralization of ancient metal-bearing basement rocks. Different PPD types develop in marine magmatic arcs (island arcs) versus continental margin arcs: the former are dominated by Au-Cu and/or Au-rich Cu deposits, whereas the latter mainly host Cu-Mo and/or Mo deposits.

Continental PPDs in mainland China include Cu (-Mo, -Au), Mo, Au, Pb-Zn-Ag, Fe, and other mineral types, along with their corresponding magmatic systems, and thus exhibit a broader range of metal mineralization than their oceanic counterparts. Both oceanic and continental PPDs—including PCPDs—possess distinctive lithochemical and geochemical signatures. These trace element, REE, and isotopic parameters can serve as important indicators for assessing whether a porphyry body hosts mineralization and, if so, what metals it may contain.

The degree of granitic magma differentiation is a particularly important factor controlling the formation of various PPDs, with a positive correlation between differentiation degree and mineralization potential. Therefore, accurate identification of porphyry differentiation levels is a key criterion for evaluating its mineralized status. Diagnostic parameters include characteristic minerals (e.g., magnetite, hornblende, and garnet), lithochemical indices (such as A/CNK, P_2O_5 , and $Zr + Nb + Ce + Y$), decoupling of twin element pairs (notably Nb-Ta and Zr-Hf), REE tetrad effects, and other specialized geochemical values. Variations in the V/Sc ratio also offer a powerful tool for evaluating magma's mineralization potential, particularly in the exploration of porphyry Au-Cu deposits.

Certain indicators of high magma oxidation—such as oxygen fugacity ΔFMQ ($= +1$ to $+2$), Sr/Y ratios, and V/Sc ratios—are likewise important criteria for assessing whether a porphyry body is mineralized.

Author contributions

Supervision, conceptualization, methodology, resources, investigation, project administration, formal analysis, original draft preparation, writing, writing-review, and editing, JZ Yin; investigation, validation, funding acquisition, HY Shi. Both authors have read and agreed to the published version of the manuscript.

Funding

This project was supported by Zijin Mining Group, China and Orient Resources Ltd., Canada.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article

Acknowledgments

The authors are grateful to David Yin, Sean Daly, P.Geo, and James Sparling, P.Geo for reading and revising the manuscript.

Conflicts of interest

There is no conflict of interest concerning any governmental or private agencies and the publication has been approved by both of the co-authors.

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