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Porfyrová ložiska Cu-Au ve světě a v Mongolsku
Porphyry Cu-Au deposits in the world and in Mongolia

Bakalářská práce
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Prague, May 15, 2019

V Praze, 15.8.2019

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SUMMARY

Copper played crucial roles throughout the history for at least 10,000 years and was an important part of the industrial revolution. Copper has specific chemical and physical attributes. Thanks to its abilities, copper is one of the most demanded metals in the industrialized world. Copper is widely used to produce various products, such as electrical and electronic products, construction, industrial equipment and other general products. Occurrence of Cu in the Earth's crust is around 50 ppm. Copper bearing minerals are discussed later, but Cu can be found in pure "native" form.

Porphyry Cu deposits supply more than a half of world Cu production. Regions with the most abundant PCDs are the Andes of South American, North American Cordillera and southwestern Pacific region. Europe, Africa a central Asia host some significant deposits.

Review-based bachelor thesis "Porphyry Cu-Au deposits in the world and Mongolia" discusses variety of aspects of global porphyry deposits regarding their metal association, geology, global abundance, and genesis in the first part. Next part discusses briefly the Mongolian copper production and regional geology and final part discusses characteristics of two Mongolian gold-rich porphyry Cu deposits, Oyu-Tolgoi and Kharmagtai.

ABSTRAKT

Měď hrála klíčovou roli v historii po dobu nejméně 10 000 let a byla důležitou součástí průmyslové revoluce. Měď má specifické chemické a fyzikální vlastnosti, díky kterým je jedním z nejpoptávanějších kovů v průmyslovém světě. Měď je široce využívána v různých odvětvích průmyslu, při produkci elektrických a elektronických výrobků, ve stavebnictví, v průmyslových zařízeních a v dalších obecných aplikacích. Výskyt Cu v zemské kůře je kolem 50 ppm. Minerály obsahující měď jsou pojednávané dále ale měď se vyskytuje i v přírodní formě.

Víc než polovina světové produkce mědi pochází z porfyrových ložisek. Porfyrová ložiska mědi jsou nejhojnější v následujících regionech, jihoamerické Andy, severoamerická Cordillera a jihozápadní Pacifik. Některá významná ložiska se nachází též v Evropě, Africe a střední Asii.

Rešeršní bakalářská práce „Porfyrová ložiska Cu-Au ve světě a Mongolsku“ pojednává v prvé části o různých aspektech porfyrových ložisek celkově, včetně užitkových kovů, geologie, globální distribuce a geneze. Další část stručně pojednává o mongolské produkci mědi a regionální geologii. Závěrečná část se dvěma mongolským porfyrovým ložiskům bohatým na zlato, ložiskům Oyu-Tolgoi a Kharmagtai.

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Contents

LIST OF ABBREVIATIONS

CAOB – Central Asian Orogenic Belt

Gt – Gigaton, billion tons

ICMM – International Council on Mining and Metals

MMHI – Ministry of Mining and Heavy Industry

MRPAM – Mineral Resources and Petroleum Authority of Mongolia

Mt – megaton, million tons

OT – Oyu-Tolgoi

Oz – ounce

PCD(s) – Porphyry Copper Deposit(s)

PGE – Platinum Group Elements

ppb – parts per billion

ppm – parts per million

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1. INTRODUCTION

Copper is a flexible and ductile metallic element that is an excellent conductor of heat and electricity. Copper is also resistant to corrosion and antimicrobial. Equipment is the largest copper end-use sector, followed by building construction and infrastructure. Global demand for this metal has tripled in the last 50 years and now porphyry Cu deposits supply nearly three-quarters of the world's copper, one-fifth of gold and 95% of Molybdenum. Demand for copper is believed to grow further and it can be met by discovering new deposits, technical improvements and recycling. The mean undiscovered total for porphyry deposits in the world is 3,100 Mt. Understanding porphyry deposits' genesis, geology and other characteristics can be essential to new discoveries. Porphyry copper deposits are found worldwide in a different location with various geological environments. Porphyry deposits are not only the main sources of Cu and Mo but also significant sources of Au and Re. Open-pit and underground (block-caving and room-pillar) mining techniques are used to exploit PCDs. The world's largest mined copper producing country is Chile, where the largest porphyry deposits are found, while the biggest copper importing country is China.

Copper is an important contributor to the national economies of developed and developing countries. Copper production takes a huge part in Mongolia's economy and export, as their neighbor, China, is the world's largest copper importing country. Some large porphyry Cu deposits and giant Oyu-Tolgoi porphyry Cu deposit in Mongolia are in operation to commit to the country's copper production and exporting. The biggest open-pit mine in Mongolia is Erdenet-Ovoo porphyry Cu-Mo deposit in the north. In southern Mongolia, there are several porphyry deposits, including Tsagaan-Suvarga Cu-Mo deposit, Kharmagtai Au-rich porphyry deposit and the richest and largest porphyry Cu-Au system in Mongolia, Oyu-Tolgoi. Currently, there are 2 concentrators in Mongolia to produce final products for export, one in Oyu-Tolgoi mine and other one in Erdenet-Ovoo mine. These two concentrators are capable to produce more concentrates than they do now. The country's economy could benefit from new porphyry Cu discoveries if they perform to their full capacity.

Such studies on porphyry deposits can be applied to exploration methods. Only 33% of the Mongolian territory have a geological mapping of 1:50000 scale. By the time, when more detailed geological mappings will be done, a better understanding of porphyry deposits will be needed for new discoveries.

2. DEFINITION OF PORPHYRY DEPOSITS

2.1. Definition of Cu porphyry deposits

Porphyry Cu deposits are low-grade (mostly less than 1 wt.% Cu) and large-tonnage (mostly about 40-50 Mt ores) deposits exploited by open-pit, block-caving and other mining techniques, where disseminated Cu bearing sulfide minerals are emplaced in a system of fractured stockwork veinlets. The ore body typically resembles a vertically elongated clumsy cylinder with a width of around 2 km. Other common characteristics of porphyry Cu deposits are an extensive hydrothermal alteration of host rocks, fracture-controlled stockwork ore mineralization, genetic and spatial relation to felsic to intermediate porphyritic intrusions, shallow depth of formation (< 5-6 km, usually in between 1-2.5 km) and multiple hydrothermal and magmatic (i.e. intrusive) events.

The forms of many porphyry Cu deposits mimic their host intrusions, thus cylindrical stocks typically host cylindrical orebodies, whereas laterally extensive dikes give rise to the orebodies with similar narrow, elongated shapes. Several porphyry stocks within about 2 km area are counted as a single deposit. Group of porphyry Cu deposits creates Porphyry Cu System. **Porphyry Cu systems** are defined as large volumes (10-100 km^3) of hydrothermally altered rock centered on porphyry Cu stocks that may also contain other deposit types, like skarn, carbonate-replacement, sediment-hosted, and high- and intermediate-sulfidation epithermal base and precious metal mineralization (Sillitoe, 2010). One of the hallmarks of porphyry Cu systems is magmatic arc near subduction zones at convergent plates, though some systems occur post-collisional and other tectonic settings. Porphyry Cu systems show a marked tendency to occur in linear, typically orogen-parallel belts, which range from a few tens to hundreds and even thousands of kilometers long, as an example The Andes of western South America (Sillitoe, 2010).

Porphyry Cu deposits contain typically large (hundreds of million tonnes), low- to medium-grade (less than 1% of Cu), epigenetic, disseminated stockwork and hypogene economic orebodies (Sinclair, 2000). This is a result of development in modern technology, of which ability to operate large open-pit mining, block-caving or bulk-mining techniques, for a large amount of ore or deposits at greater depths. Another method that took copper mining and producing industry to the next level is “froth flotation”(Misra, 2000).

Three main subtypes of Porphyry deposits are discriminated, based on ore-body-morphology, geological setting and depth of formation: 1) plutonic subtype 2) volcanic (or subvolcanic) subtype and 3) classic subtype. Plutonic subtype occurs in batholithic settings with mineralization occurring in one or more phases of the plutonic host rock. Volcanic subtype occurs in the roots of volcanoes, with mineralization both in volcanic rock and related plutons and classic subtype occurs with high-level, post-orogenic stocks that intrude unrelated host rock. Mineralization may occur within the stockwork or the host rock, sometimes in both. Most of the Cenozoic PCDs are classified as “classic” subtype.

Another way to classify porphyry Cu deposits is to group them based on their primary product and major byproduct (e.g.: porphyry Cu, porphyry Cu-Au, porphyry Cu-Mo).

2.2. Definition of Au-rich porphyry Cu deposits

Gold abundance in PCDs varies so much. The definition of Au-rich porphyry deposits was originally based on Au/Mo ratio, with no reference to their Cu content. This resulted in the suggestion that Au-rich deposits occur largely in island arc setting (e.g. Oyu-Tolgoi, Mongolia; Kesler et al., 2002). Later, based on long-term-Au production from porphyry Cu systems, a value of 0.4 g/t Au was proposed by Sillitoe as a lower limit for porphyry Cu-Au deposit (Kesler et al., 2002). The ratio of Au/Mo is greater than 30 (Singer and Cox, 1987).

3. METAL ASSOCIATION, ORE GRADE, BULK TONNAGE

3.1. Metal association

Different types of porphyry Cu deposits (i.e. Cu, Cu-Au, Cu-Mo) show various association with other metals. Gold-rich porphyry Cu deposits are more likely to contain more platinum group elements (PGEs), while Mo-rich deposits are not. Porphyry Cu deposits are not only home to Cu, Mo and Au, but also host other metals such as Ag, Pt, Pd, Pb, Zn as either economical or uneconomical by-products.

3.1.1. Gold

According to Sillitoe (1993) as cited in (Misra, 2000), all porphyry Cu deposits contain some Au and many carry high enough concentration for recovery as coproduct or byproduct, especially after the surge in the gold price in the 1970s. Figure 1. shows the Au price chart during the 70s till present. Actual Au price is around 1400 \$/oz (5.8.2019 – 1469\$). Gold occurs typically within the porphyry stocks (as part of the porphyry-type ores), alternatively high sulfidation Cu-Au ores tend to overlap some porphyry Cu-Au systems (Laznicka, 2006). As mentioned before Au content in PCDs is around 0.4 g/t. Some PCDs (Grasberg, Indonesia; Oyu-Tolgoi, Mongolia and Bingham, Utah) are richer than average. Grasberg contains several hundred million tons (Mt) averaging 1.5 g/t Au (Sillitoe, 1973). In deposits, where main ore is associated with early potassic alteration (such as Grasberg and Bingham), native Au is found mostly as 5-100 μm inclusions. Other forms of Au, usually with tellurides and bismuth, have been reported, but very rare. Bornite and chalcopyrite are preferred hosts for Au. In deposits mentioned above, Au is associated more with bornite than chalcopyrite (Kesler et al., 2002).

Source: INET BFA

Figure 1. Gold price chart during last 50 years. Blue circle indicates Au price surge in the 1970s (source INET BFA)

3.1.2. Molybdenum

As mentioned before porphyry Cu-Au deposits mostly occur in island-arc settings, while porphyry Cu-Mo deposits are common in continental margin settings. Main Mo bearing sulfide is molybdenite (MoS_2).

Elements present as an admixture in molybdenite (Re, Se and Te), may present valuable byproducts of molybdenite concentrates. Porphyry Cu-Mo deposits Erdenet-Ovoo, Mongolia, which was emplaced along the active continental margin of the Siberian Craton, originally contained 0.27 Mt of Mo with 0.025 wt.% Mo ore grade (Seltmann et al., 2014). Porphyry Mo deposits have ore grade in the range of 0.05 to 0.2 wt.% Mo, while the ore-grade median in porphyry Cu-Mo deposits is 0.016 wt.% Mo, according to Panteleyev (1995). Highest ore-grades of Porphyry Mo deposits are found in Climax (0.24 wt.% Mo) and Henderson (0.17 wt.% Mo) deposits in Colorado, USA. These Mo-rich porphyry deposits also contain W (tungsten) and Sn as byproducts and they are called Climax-type Mo-rich deposits (Kirkham and Sinclair, 1972).

3.1.3.Silver

One of the minor byproducts, other than Au and Mo, is silver in porphyry Cu deposits. Study of fluid inclusions from quartz veinlets in K silicate alteration zones at Grasberg and Bajo de la Alumbrera shows that high salinity brine contains most of the Zn, Pb and Ag. Concentrations are even greater than Cu in a brine (Sillitoe, 2000).

3.1.4.Platinum and Palladium

Samples from 33 porphyry Cu deposits were investigated for platinum-group elements and minerals, 6 of 7 deposits, where a higher amount of Pt and Pd was found, were emplaced in island-arc settings. The trend in this result reveals that Au-rich PCDs tend to host a higher amount of Pt and Pd. PGE are related to the presence of merenskyite, sperrylite and a solid solution of merenskyite-moncheite. These minerals in samples are found as inclusions in chalcopyrite and within Au grains as Pd tellurides in some other deposits. Grades of PGEs in these deposits are low, less than 1 g/t (Tarkian and Stribrny, 1999).

3.2. Ore Grade

One of the main porphyry Cu deposits' characteristics is low grade. Typical hypogene porphyry Cu deposits have average ore grade of 0.5 wt.% to 1.5 wt.% Cu, <0.01 wt.% to 0.04 wt.% Mo and 0.01 to 1.5 g/t Au (Sillitoe, 2010). More detailed classification of Cooke et al. (2005) discriminates: low grade (less than 0.5 wt.% Cu), moderate grade (0.5-0.75 wt.% Cu) and high grade (more than 0.75 wt.% Cu) deposits. When it comes to porphyry Cu-Au subtype deposit, the average Au grade is about 0.4 g/t. Average ore grades of Cu, Mo and Au in porphyry Cu-Au, Cu-Mo and Cu-Au-Mo, are summarized in Table 1.

Table 1. Average ore grade of Cu, Au and Mo in porphyry Cu-Au, Cu-Au-Mo and Cu-Mo deposits (after Singer et al., 2005).

	Porphyry Cu-Au	Porphyry Cu-Au-Mo	Porphyry Cu-Mo
Cu grade (wt.% Cu)	0.44	0.45	0.45
Mo grade (wt.% Mo)	0.003	0.014	0.025
Au grade (g/t Au)	0.40	0.12	0.015

3.3. Bulk Tonnage

Large tonnage is one of the main characteristics in Porphyry Cu deposits. According to Lowell (1994) (in Misra, 2000), an ore body should have at least 20 Mt of ore and minimum ore grade as mentioned above, to qualify as a porphyry Cu deposit. Most of the porphyry Cu deposits have an average of 40-50 million tonnes and the most giant deposits contain more than 500 Mt of ore. Even some deposits have greater than Gt of ore. The largest known PCDs to date are located at Chuquicamata and El Teniente, both in Chile. Each deposit has a total of around 10 billion tonnes of ore including proved, probable and possible reserves. An interesting fact about bulk tonnages in PCDs was discussed by Kesler et al. (2002) that with one exception of the Grasberg deposit, most porphyry Cu-Au deposits have higher ore grades and lower total ore tonnages than porphyry Cu-Mo deposits. Singer (1995) classified porphyry deposits into 'Giant' and 'Supergiant' groups depending on their Cu reserve. Giant deposits have at least 2 million tonnes of Cu reserve and Supergiant deposits have at least 24 Mt of Cu reserve. Similarly, Giant and Supergiant Cu-Au porphyry deposits contain more than 100 or 1200 tons of Au reserves, respectively. The more detailed classification was proposed by Clark (1993). He suggests 7 groups, such as small, moderate, large, very large, giant, supergiant and the largest (Clark, 1993 in Cooke et al., 2005). Grade vs tonnage graph for each porphyry subtypes is summarized in figure 2.

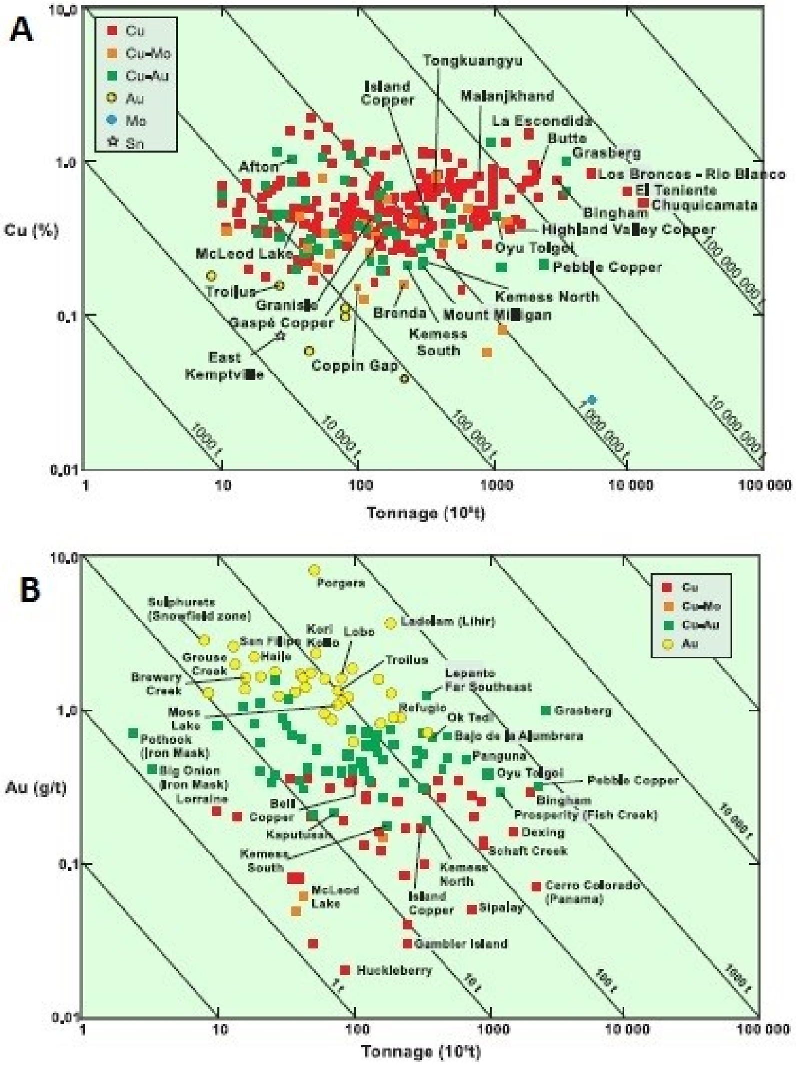

Figure 2. Grade vs Tonnage for each porphyry subtypes. A) Copper grade (wt.%) vs tonnage (10^6 t). B) Gold grade (g/t) vs tonnage (Sinclair, 2000).

4. GEOLOGY

Most porphyry Cu deposits are distributed along convergent plate boundaries and island-arc settings that resulted from collisional and subductional events. The deposits are typically associated with relatively younger intrusions within slightly older magmatic environments. Ages tend to be Mesozoic and Cenozoic, although some are dated back to an earlier period (Sun et al., 2017). Some characteristics in regional geology of porphyry Cu systems are discussed in this paragraph and details will be discussed further in individual sections. Porphyry Cu systems tend to occur in linear, typically orogen-parallel belts, which range from a few tens to thousands of kilometers long, as an example The Andes of western South America and the Apuseni-Banat-Timok-Srednogorie belt of Romania, Serbia and Bulgaria (Sillitoe, 2010). Porphyry Cu systems are generated mainly in magmatic arc environments. Some investigators proposed the importance of the intersection between continental transverse fault zone or lineaments and arc parallel structures for porphyry Cu formation in (Sillitoe, 2010). As an example, geologic settings of three porphyry Cu-Au deposits from different areas of the world are mentioned below.

Batu Hijau, Indonesia

Indonesian Au-rich porphyry deposit Batu Hijau is associated with a Middle Miocene to Middle Pliocene age intermediate intrusive sequence that was emplaced into Early to Middle Miocene age volcaniclastic rocks of the Sunda-Banda arc (Kesler et al., 2002).

Skouries, Greece

Porphyry Cu-Au deposit in northern Greek is associated with monzonite porphyries of Early Oligocene age that were emplaced into Paleozoic rocks rather than coeval arc volcanic and volcaniclastic rocks (Kesler et al., 2002)

Oyu-Tolgoi, Mongolia

Mongolian porphyry Cu-Au deposit in the southern Gobi is in the middle to late Paleozoic Gurvansaikhan terrane, which contains basaltic to dacitic volcanic and sedimentary rocks of island-arc affinity. It is intruded by Late Devonian and Early Carboniferous granitoids. Near Oyu-Tolgoi deposit, another major intrusion is detected and it is Na-alkalic granite complex of Early Permian age (Hedenquist et al., 2006).

4.1. Morphological subtypes

Depending on its geology, morphology and formation depth, porphyry Cu deposits are divided into three groups, such as Classic, Volcanic and Plutonic. According to Sutherland (1976), as cited in (Singer, 1999), ***classic-type deposits*** are centered around small cylindrical plutons. They are commonly associated with breccia pipes and have concentric zones of alteration and mineralization. Coeval volcanic rocks are commonly absent in these deposits.

Volcanic-type deposits are related to irregular or dike igneous bodies that have intruded coevally and at least partly that same volcanic pile. Volcanic-type deposits have more concentration of Au, while plutonic-type porphyry deposits have more contents of Mo (Singer, 1999). ***Plutonic-type deposits*** are found in large plutonic to batholithic intrusions at relatively deep levels. Host rocks are phaneritic coarse-grained to porphyritic.

Volcanic-type deposits tend to be emplaced at shallow depths and/or roots of volcanoes and as mentioned above plutonic-type deposits occur deeper. Depth also defines whether Au- or Mo-rich porphyry Cu deposit to be formed (Singer, 1999). According to Berger (2008), porphyry Cu subtype deposits form at average depth of 1.5 to 4 km, although according to B. Sutherland (1976) average depth of porphyry Cu deposits' formation is around 4 to 5 km, as cited in (Berger et al., 2008).

Large deposits with more than 100 Mt of ore are commonly related to large intrusions or intrusive complexes that are about 5 km in diameter. Smaller deposits are related to smaller plutons, which are less than 1 km in diameter (Misra, 2000).

4.2. Petrography of host intrusions

Porphyry Cu deposits are intrusion-related mineralized hydrothermal systems the most abundant host intrusions are granite, granodiorite, tonalite, quartz monzodiorite and diorite. Even monzonite, quartz-monzodiorite and syenite are typical host rock types. Numerous authors agree that PCDs are normally hosted by I-type granitoids (Panteleyev, 1995). Porphyry Cu deposits tend to be associated with intrusions such as batholith, dikes, sills, veins, veinlets and stocks.

Based on results of chemical analysis, intrusions of porphyry deposits generally represent intermediate to a felsic differentiated member of the calc-alkaline magma series, such as quartz diorite – quartz – monzonite – granodiorite. The most common intrusions in continental margin areas of Western South and North America are granodiorites and quartz monzonites. Whereas, the most abundant and typical intrusions found in PCDs within island-arc settings (Southwestern Pacific and some in Central Asia) are lower-potassium quartz diorite intrusions. Island-arc intrusions also include granodiorites, quartz monzonite and syenites. Porphyry Cu intrusions related to island-arc setting lack *k-feldspar* phenocrysts (Misra, 2000), but in the case of Oyu-Tolgoi, intrusions contain 35-50 vol % *feldspar* phenocrysts (Hedenquist et al., 2006). Gold-rich porphyry Cu deposits are related to porphyry intrusions that belong to I-type and magnetite series suites. Sillitoe (1979) explained that their host intrusions are highly oxidized, sulfur-poor representatives of magnetite series (Sillitoe, 2000).

4.3. Mineralization

4.3.1. Mineralization

Porphyry Cu deposits have their ores in the form of sulfides, that are typically pyrite, chalcopyrite, bornite and molybdenite. According to Sinclair (2000), typical porphyry Cu-Au ore minerals are chalcopyrite, bornite, chalcocite, tennantite and enargite. Associated minerals are pyrite, arsenopyrite, magnetite, quartz, biotite, k-feldspar, anhydrite, epidote, chlorite, albite, calcite, fluorite and garnet. Mineralized zones usually occur in three different ways, some occur only within the main intrusive stock, some only within peripheral wall rocks or they occur in a combination of both. They tend to form in veins, veinlets, stockwork, fractured zone and breccia pipe. Most of the orebodies are surrounded by pyrite rich halos. Mineralization in porphyry Cu deposits can be subdivided also into hypogene and supergene. Generalized mineralization zoning pattern for porphyry Cu deposits is shown in figure 3.

4.3.2. Hypogene mineralization

The most abundant shape of the orebody is a steep-walled cylindrical cone. Near flat cylindrical cone shapes are also known alongside some gently dipping tabular shapes. Mineralization in porphyry Cu deposits tends to occur in concentric zones. Sometimes in the center, there is a barren and/or low-grade chalcopyrite or molybdenite. Mineralization is mostly disseminated. Outward from the center, pyrite mineralization increases and form so-called pyrite-rich halo (Evans, 1993). As an example, primary hypogene mineralization at the Rosario Cu deposit is dominated by chalcopyrite, while bornite (secondary) is disseminated in veins. Chalcopyrite-rich concentric zones change to pyrite-rich zone outward. The most abundant mineral is bornite in the deposit (almost 50% of sulfide minerals; Porter, 2002).

4.3.3. Supergene effects in mineralization

Supergene effects are processes near the ground surface or at shallow depths. Nearly all porphyry Cu deposits, especially those in the continental margin, possess a capping of supergene alteration and enrichment above hypogene sulfide mineralization. Leaching of metal from oxidation zone is controlled by the amount of H_2SO_4 acid produced by oxidation of sulfides, depending on total sulfide (pyrite) content. Characteristic Cu minerals for this zone are chalcocite and covellite (Misra, 2000). For example, at Rosario deposit, chalcopyrite and bornite were leached by groundwater and this supergene enrichment created irregular zones of Cu oxides. Volcanic rocks of these leached zones were bleached and show some argillization including iron oxides with chrysocolla and brochantite mineralization (Porter, 2002). Some other key minerals in supergene mineralization zone, near advanced argillic alteration zone, are quartz, dickite and kaolinite and other sulfide assemblages are enargite-, chalcocite- and covellite-pyrite (Sillitoe, 2010).

4.3.4. Au-mineralization in porphyry Cu-Au deposits

Gold contents in porphyry Cu-Au deposits correlate well with the intensity of A-type quartz veinlets. Gold contents tend to increase downward over a distance of some hundreds of meters in many Au-rich porphyry deposits and in some deposits increases upward. Gold in porphyry deposits is mainly fine-grained and present as a native metal. Gold is mostly associated with pyrite, when the deposits are pyrite-poor, it is associated with chalcopyrite. Sometimes Au grade intergrown with bornite is much higher than others. Some precious metals are related to Au mineralization in porphyry deposits, such as Ag, sperrylite and merenskyite of PGE (especially Pd).

4.4. Hydrothermal alteration

Hydrothermal alteration (Fig.3.) is a general term used for processes by which rock-forming minerals are altered with the help of heated aqueous fluids in fractures and grain boundaries. The hydrothermal alteration has different zones based on their assemblage of minerals and classified into groups based on their mode of occurrence and According to Titley (1982 as cited in (Misra, 2000)), there are different types of hydrothermal alterations based on their mode of occurrence. Hydrothermal alteration can be divided into three groups as *selectively pervasive, pervasive* and *localized along veins and veinlets.* Many different factors influence the degree, extent and type of hypogene hydrothermal alterations, such as temperature, pressure, mineralogy of host rocks, permeability of host rocks and chemistry of hydrothermal fluids. ***Selective pervasive alteration*** results in recrystallization or conversion to new minerals (specific minerals) without destroying original rock textures. Examples include biotite to recrystallized biotite, feldspar phenocrysts to kaolinite, chlorite or epidote and conversion of hornblende or biotite to chlorite. ***Pervasive alteration*** is associated with amount of fractured host rocks and chemical composition of hydrothermal fluids. The result is the destruction of minerals and texture of host rocks and the formation of new minerals. ***Vein-veinlet alteration*** is the most common and obvious type of alteration in porphyry Cu systems. (Misra, 2000)

Based on mineral assemblages, hydrothermal alteration rocks are classified into four basic types of alteration zonings: ***potassic*** (K-silicate, inner zone), ***phyllic*** (sericitic), ***argillic*** and ***propylitic*** (outer zone). Other types of hydrothermal alteration zones and some subtypes within basic alteration zones are named depending on their mineral assemblages, such as sodic-calcic (Na-Ca) alteration zone, advanced argillic, intermediate argillic, chlorite-sericite zone and others. These basic hydrothermal alteration zones are emplaced upward from the bottom. According to Sillitoe (2010), sericitic (phyllic) alteration is more abundant in porphyry Cu-Mo deposits, whereas chlorite-sericite alteration develops preferentially in porphyry Cu-Au deposits. Potassic alteration zone is mostly centered and the deepest alteration zone is typically Ca-Na alteration zone, which is below K-alteration zone. Generalized alteration zoning pattern for porphyry Cu deposits is shown in figure 3.

4.4.1.Potassic zone

Characteristic minerals of the potassic alteration (Fig.3.) are K-feldspar (orthoclase), biotite, quartz and sericite (muscovite). K-feldspar and quartz are stable as original rock-filling minerals and as vein-filling constituents, although K-feldspar can be a product of alteration after plagioclase. Magmatic biotite is altered to a more magnesian variety and the iron released from the alteration of biotite or more mafic minerals then biotite goes to form a small amount of some minerals, such as magnetite, pyrite and chalcopyrite. According to Sillitoe (2010), biotite is the predominant alteration mineral in relatively mafic porphyry intrusions and host rocks, whereas K-feldspar abundance increases in more felsic, granodioritic to quartz monzonitic settings. Potassic alteration is the most prominent in or near porphyry centers (Misra, 2000). Anhydrite may be prominent in this zone. Other possible minerals are actinolite, epidote, sericite, andalusite, albite, carbonate, tourmaline, magnetite and sulfide assemblages are pyrite-chalcopyrite, chalcopyrite (+bornite, chalcocite), according to (Sillitoe, 2010).

4.4.2.Phyllic zone

Phyllic alteration zone can also be called “zone of sericitization” or “sericitic” alteration zone (Fig.3.). Characteristic mineral assemblages of phyllic zone are sericite, quartz and pyrite. Phyllic zone usually carries minor chlorite, illite, rutile and pyrophyllite, meanwhile, carbonates and anhydrite are rare, according to Evans (1993). When the phyllic zone is present, it possesses the greatest development of disseminated and veinlets of pyrite. Phyllic alteration zone involves extensive leaching of sodium, calcium and magnesium and may lead to complete replacement of aluminosilicate minerals by sericite and quartz. (Misra., 2000).

4.4.3.Argillic zone

The argillic zone is not always present. When present, it is characterized by assemblages containing clay minerals (kaolinite near orebody, montmorillonite far away from orebody). Pyrite is major sulfide and it could be accompanied by minor amounts of chalcopyrite, bornite, enargite and tennantite. Even though pyrite is predominant in the argillic zone, it is less abundant than in the phyllic zone. It usually occurs in veinlets than disseminated. K-feldspar is almost not affected. (Evans, 1993). The argillic zone in porphyry Cu systems is either late, supergene and pervasive or is shallow hypogene, according to Misra (2000).

4.4.4.Propylitic zone

Characteristic mineral assemblage in propylitic zone consists of chlorite, calcite, epidote, pyrite and albite. This outmost alteration zone (Fig.3.) in porphyry Cu systems is always present. Primary mafic minerals (biotite, hornblende) are partially or wholly altered to chlorite and carbonate. Plagioclase may be unaffected (Evans, 1993). Other possible minerals in propylitic zone are actinolite, hematite, magnetite and some other sulfide assemblages are sphalerite and galena (Sillitoe, 2010). Propylitic, phyllic and argillic alteration assemblages are quite resistant to low-grade metamorphism, but only phyllic alteration assemblages are likely to survive medium- to high-grade metamorphism (Misra, 2000).

4.4.5. Ca-Na alteration zone

The Ca-Na alteration zone is more abundant in Au-rich porphyry Cu systems than Cu only or Cu-Mo systems. Ca-Na zone is formed in greater depth (Fig. 3.) alongside propylitic and below K alteration zones, although it is not always present. Sodic-calcic alteration is commonly magnetite bearing but mostly is sulfide and metal-poor alteration zone. Na-Ca zone can sometimes host mineralization in Au-rich deposits. Key minerals in this zone are albite/oligoclase, actinolite and magnetite alongside other minerals such as diopside, epidote and garnet (Sillitoe, 2010)

4.4.6. Advanced argillic zone

Characteristic mineral assemblage within the advanced argillic zone is quartz, alunite and kaolinite, ±dickite and pyrophyllite. Some other minerals are diaspore, andalusite, zunyite, corundum, topaz and specularite. Principal sulfide assemblage in this zone is pyrite-enargite, pyrite-chalcocite and pyrite-covellite (Sillitoe, 2010).

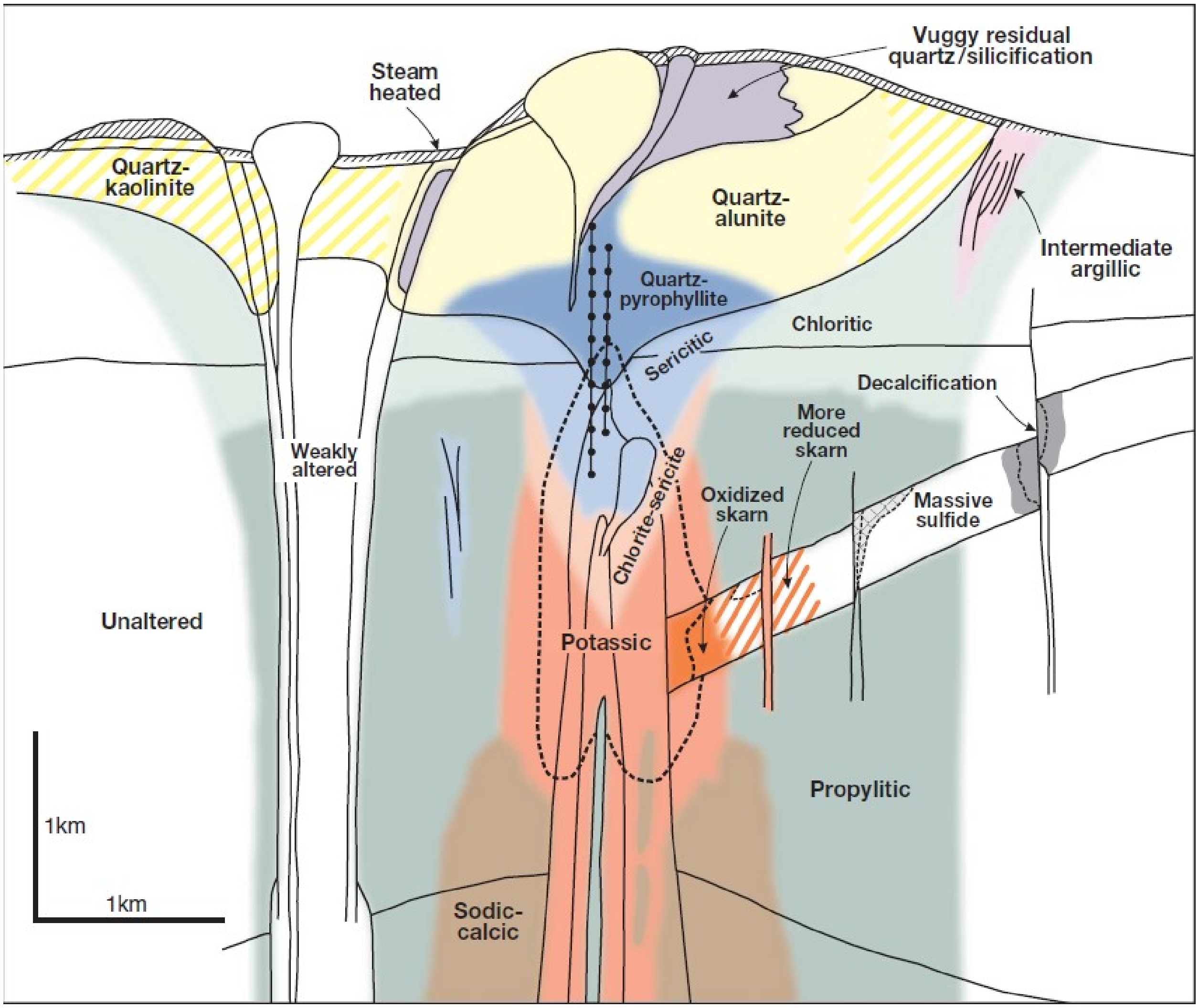

Figure 3. Generalized alteration-mineralization zoning pattern for porphyry Cu deposits (Sillitoe, 2010)

4.5. Hydrothermal Fluids

Magma contributes heat, magmatic fluid and metals to the hydrothermal system. Ore forming potential of these magmas depends on timing and composition of magmatic fluids and this potential is recorded in fluid inclusions. The earliest classification for fluid inclusion was done by Nash (1976 as cited in Cooke et al., 2013). These three common fluid inclusions are two-phase fluid inclusions with high liquid/vapor ratio; fluid inclusions with low L/V ratio; and inclusions containing halite. Less common inclusions in PCD contain liquid, vapor CO_2 and aqueous phase. In some PCDs, the earliest and deepest veins contain high-temperature (500 ºC) two-phase (liquid-vapor) vapor-rich fluid inclusions that have moderate salinities. These are low- to intermediate-density primary magmatic-hydrothermal fluids of crystallizing intrusive complex. With the help of modern advanced technology, some studies identified extreme base metal concentration in high-temperature brines, vapors and intermediate-density fluids. This triggered a debate on the main transport of metals in porphyry stockworks (Cooke et al., 2013). Although Bodnar (1995 as cited in Berger et al., 2008) summarized evidence that the source of metals in porphyry systems is magmatic fluid, of which inclusions are mostly found in quartz veins.

Porphyry Cu systems are generated in vapor-dominated geothermal systems involving circulation of meteoric fluids (200 to 400 ºC with around 5 wt.% NaCl dissolved) above a magmatic heat source, with direct contribution of fluids or metals from the magma, according to White et al. (1971, as cited in Sillitoe, 1973). Convection provides an efficient mechanism for delivery of large amounts of an aqueous phase, in the form of bubble-rich magma, throughout the magma chambers to the basal parts of the porphyry stocks or dike swarms. Parental magmas need to be water-rich (more than 4%) and oxidized to maximize the metal contents of the aqueous phase. High water contents help magmas to be saturated with the aqueous phase and high oxidation state prevents magmatic sulfide precipitation, which loses metals before they partition into the aqueous phase. Nevertheless, resorption of any sulfide melt during an ascent of oxidized magmatic fluids can make a huge contribution to metal budgets (Sillitoe, 2010).

Homogenization temperatures of fluid inclusions in porphyry Cu deposits vary from 100 to 900 ºC (Cooke et al., 2013). Magmatic fluids about 600 to 700 ºC hot with more than 40 wt.% salinity (NaCl, KCl) are important during earlier stages of PCD ore formation.

5. GLOBAL DISTRIBUTION OF PORPHYRY COPPER DEPOSITS

5.1. Geographical distribution of porphyry copper deposits

Porphyry Cu deposits occur throughout the world in a series of extensive and relatively linear provinces. Most porphyry Cu deposits are associated with Mesozoic to Cenozoic orogenic belts in continental plate margin or island-arc settings. Global distribution of porphyry Cu deposits is shown in Fig.4. majority of porphyry Cu deposits are found in four post-Paleozoic orogenic belts: a) the western American belt; b) the southwest Pacific belt; c) the Caribbean belt; and d) the Alpine belt. The western American belt, which contains the greatest concentration of porphyry Cu deposits, contain the Andes (Chile, Peru, Argentina), southwestern USA and Canadian Cordillera. Many of giant and supergiant porphyry Cu deposits are concentrated here. The southwest Pacific belt also hosts plenty of porphyry Cu deposits in the regions of Philippines, Indonesia and other countries. Central Asian countries (Uzbekistan, Kazakhstan, Kyrgyzstan, Mongolia and others) host other large and giant deposits (Misra, 2000).

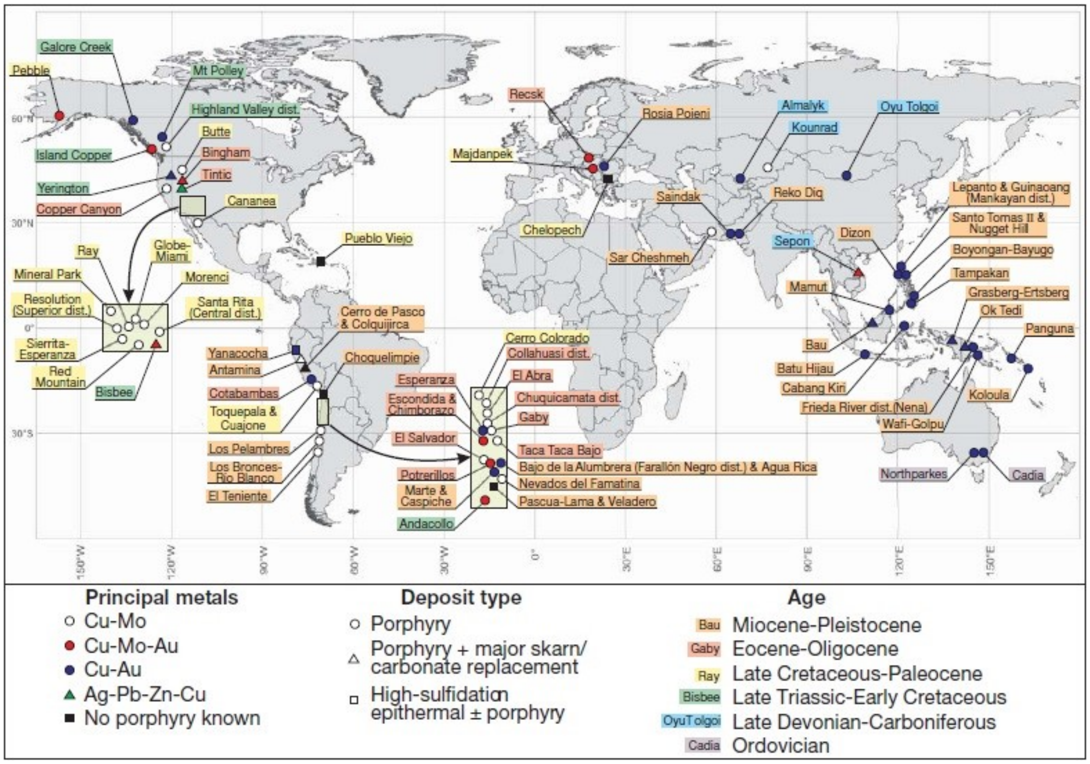

Figure 4. Global distribution of porphyry related deposits shown on map. Principal metals, deposit types and ages are included (Sillitoe, 2010)

5.2. Temporal distribution of porphyry copper deposits

Porphyry Cu systems are, although were generated worldwide since Archean, relatively young, probably because younger arc terranes are normally the least eroded. according to Sillitoe (2010). Most of them are Mesozoic to Cenozoic of age as mentioned above, but some deposits are Ordovician, Devonian and Carboniferous. Figure 4 shows age distribution of porphyry Cu deposits globally and histogram in figure 5 shows peak periods for development of porphyry Cu deposits globally as well. According to the histogram, majority of deposits are Jurassic or younger in age (Sinclair, 2000).

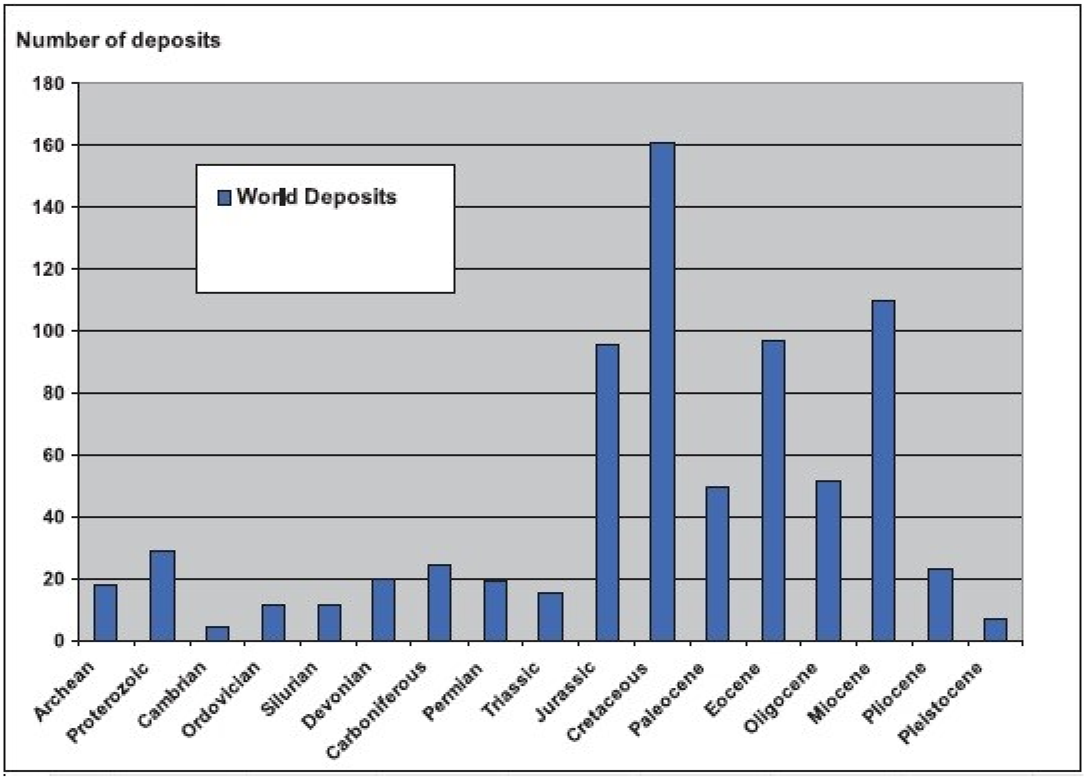

Figure 5. Histogram shows temporal distribution of global porphyry Cu deposits (Sinclair, 2000).

5.3. Tectonic environment/setting

Most porphyry Cu deposits form in subduction-related magmatic arcs along convergent plate margins in continental and oceanic island-arc settings (Sillitoe, 1973). Some deposits also occur in other tectonic environments, such as arc-continental collision settings, syn- or post-collisional zone settings and intra-continental rift or extensional environments, according to Richards (2009) (Gao et al., 2018). Magmatic arcs constructed arcs during contractional tectonism and, hence, deficient in volcanic products tend to host the largest and highest-grade deposits (Sillitoe, 2014). Majority of giant world-class porphyry deposits, including El Teniente, Chuquicamata, Bingham, Grasberg, Kalmakyr and Oyu-Tolgoi, occur in relatively narrow extensive metallogenic domains, such as the Circum-Pacific (the Nipponides), the Tethyan (the Tethysides, porphyry deposits in the Tethyan are mostly formed in post-subduction times during post-collisional extensions (figure.6a) and the Central Asian (the Altaids) metallogenic domain. It is agreed that oceanic slab subduction (figure.6b) plays a key role in the formation of porphyry Cu deposits. The formation starts with metasomatism in the mantle wedge, which leads to the production of magma with high oxidation state and water content. Metals and sulfides are separated from this magma (Wan et al., 2017). As mentioned before, Au-rich and Mo-rich porphyry Cu deposits tend to occur in intra-oceanic arc settings and continental arc environments, respectively (Gao et al., 2018).

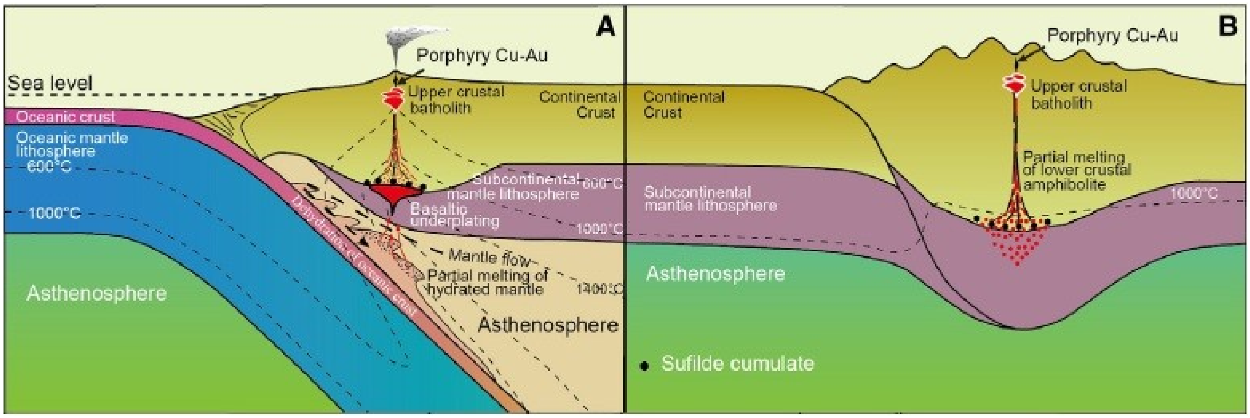

Figure 6. Idealized tectonic settings showing preferred environments for formation of porphyry deposits. A) continental magmatic arc is thickened by subduction of oceanic crust and B) continental magmatic arc is thickened by subduction of continental crust (modified from Groves 1998 in Wan et al., 2017)

7. GENETIC MODEL

Porphyry Cu systems typically spread upper 4 km or more of the crust. Centrally located stocks are connected downward to parental magma chamber at depths of about 5-15 km. Parental chambers are the sources of both magmas and high-temperature, high-pressure metalliferous fluids throughout system development. Field observation and theoretical calculations suggest that parental chambers with a volume of 50 km^3 or more are capable of releasing enough fluid to form porphyry Cu systems (Sillitoe, 2010).

7.1. Early porphyry Cu system evolution

As mentioned before, although hypersaline magmatic liquids are crucial during the early stages of porphyry Cu formation, Sillitoe (2010) suggested that hypersaline liquids are important along with the large volume of lower density vapor during mineralization. In many cases, vapor can contain an appreciable amount of Cu, Au, Ag and S, plus As, Sb, Te and B. on the other hand Hypersaline liquid can contain Fe, Zn, Pb, Mn and possibly Mo. Earlier it was assumed that transport of Cu and Au was in the form of chloride complexes in the hypersaline liquid, but recent experiments and fluid inclusion studies show that vapor phase can act as transporting agents of Cu and Au (Sillitoe, 2010).

As porphyry Cu systems cool through 700º to 550º C temperature range, single-phase liquid or coexisting hypersaline and vapor can initiate potassic alteration and perhaps the first metal precipitation in and around early porphyry intrusions. When vapor expands and decompresses upward, the solubility of metals transported in vapor decreases. Such a decrease in solubility leads to precipitation of Cu-Fe sulfides together with Au and can account for the formation of Au-rich porphyry Cu deposits. The voluminous vapor separates from the coexisting hypersaline liquid due to its low density and ascends buoyantly into the rock column just above porphyry intrusions (Sillitoe, 2010).

7.2. Late porphyry Cu system evolution

As the underlying parental magma chambers solidify and magma convection ceases, heat flux and aqueous fluid supply to the overlying porphyry Cu systems are reduced. The low-salinity liquid appears to be responsible for the formation of the chlorite-sericite and sericitic alteration, as well as advanced argillic alteration and mineralization of Cu and Au in the lithocaps. The admixture of magmatic and meteoric fluids is also necessary to produce sericitic alteration. Meteoric water had formerly important role in the porphyry Cu genetic models. Late stages are sometimes associated with shallower mineralization and formation of porphyry related other deposits (Sillitoe, 2010)

By the time that the late-mineral porphyry phases are added to porphyry Cu stocks or dike swarms, a fluid ascent from magma chambers ends and metal availability is too limited to generate mineralization (Sillitoe, 2010).

8. PORPHYRY COPPER DEPOSITS IN MONGOLIA

Mongolia is considered as ‘mining-dependent’ country according to the International Council on Mining and Metals (ICMM). The country’s mining industry is responsible for 90% of total export and about 20% of gross domestic product (GDP; MRPAM, 2016), according to annual report 2018 published by Mineral Resource and Petroleum Authority of Mongolia (MRPAM). Copper is one of the most important metals in the mining industry of Mongolia, with total economical Cu reserves of 50 Mt. More than half (38.2 Mt) of it is discovered in 4 porphyry Cu-Au and Cu-Mo deposits. The country produced 1.3 Mt Cu and 20 tons of Au in 2018, according to annual report 2018 published by the Ministry of Mining and Heavy Industry (MMHI, 2018). A large amount of Mongolian copper reserve is detected in Cu-Au or Cu-Mo porphyry deposits in northern and mainly in southern Mongolia. There are three main Cu metallogenic belts in Mongolian territory: The Northern Mongolian, Central Mongolian and the Southern Mongolian metallogenic belt. Copper mineralization in Mongolia is subdivided into some types, such as magmatic, volcanic-hosted massive sulfides, basalt-hosted, sedimentary rock- and shale-hosted, skarn type and porphyry Cu mineralization. There are currently known more than 70 porphyry Cu mineralization occurrences and 6 known porphyry Cu deposits (Enkhjargal and Jargalan, 2016). Oyu-Tolgoi (Fig. 8.) is a supergiant porphyry Cu-Au system that consists of several local deposits with the largest Cu, Au and ore reserve in Mongolia. Deposit is operated by a Canadian company, Turquoise Hill Resource, who stated that the company produced 159 000 tons of Cu and 8 tons of Au in their 2018 annual report (Report OT, 2018). The biggest open-pit mine, Erdenet-Ovoo porphyry Cu-Mo deposit, produces about 130 000 tons of Cu and 4000 tons of Mo on average per year, according to their latest annual report 2014 (www.erdenettoday.mn, 10.8.2019). Oyu-Tolgoi mine project in southern Mongolian Gobi is run by a joint venture of Turquoise Hill Resource (Rio Tinto) and Mongolian Government. Open-pit mining (Fig. 8.) started operating since 2013, and underground mining was planned to start by 2020, but there is a possibility of a delay.

8.1. Geology of Mongolia

Mongolia belongs to Central Asian Orogenic Belt (CAOB) and current appearance was approximately formed around the closure of Mongol-Okhotsk Ocean during Late Jurassic, during which Siberian block and northeast Chinese Block converged each other. Territory of Mongolia is subdivided into two larger domains, northern-central and southern, by Main Mongolian Lineament (Fig.7) or Ural-Mongolian Lineament, which is the largest overthrust fault in the country (Porter, 2016). As mentioned in the previous chapter, there are three main Cu metallogenic belts: northern, central and southern. The southern Cu metallogenic belt hosts more than half of Mongolian porphyry deposits, including Oyu-Tolgoi, Tsagaan-Suvarga and Kharmagtai (Fig.7). the southern belt consists of six island arc terranes, such as Baitag, Edren, Mandal-Ovoo, Khashaat, Enshoo and Gurvansaikhan terrane (Enkhjargal and Jargalan, 2016). As shown in figure.7, the Edren terrane is home to few porphyry Cu deposits and the Gurvansaikhan terrane, in the center of southern domain, is currently the home to major porphyry Cu deposits, therefore has a potential to host next deposits.

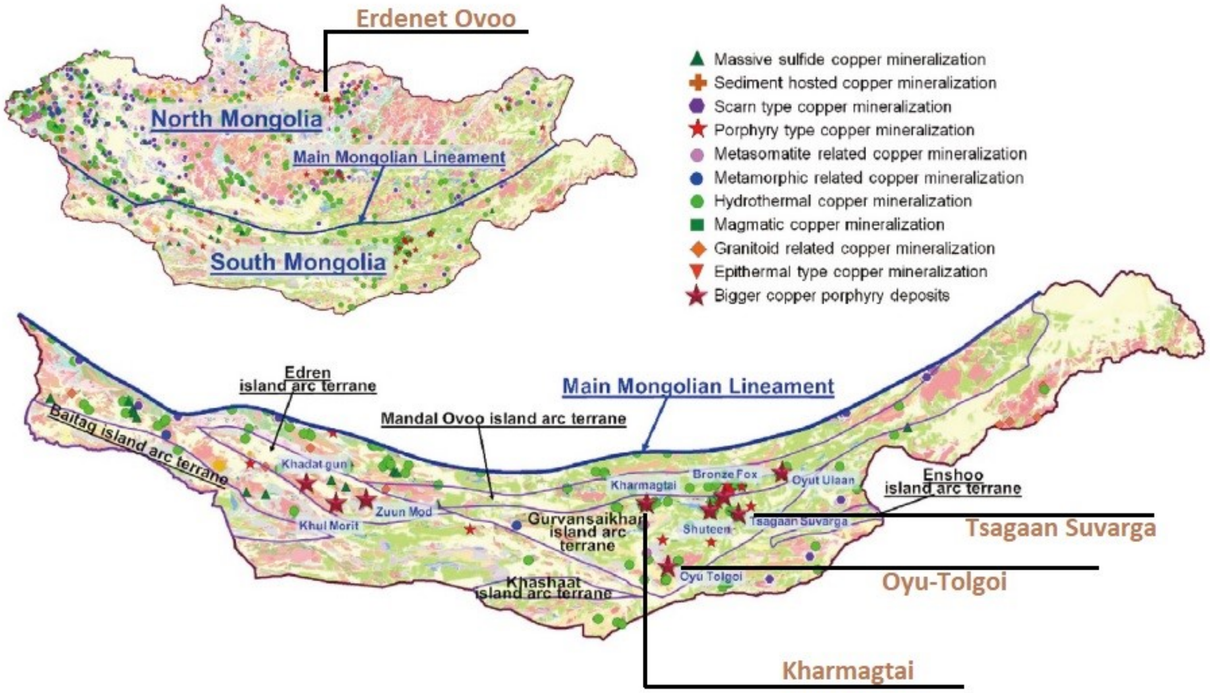

Figure 7. Distribution of Cu mineralization in southern Mongolia, including major porphyry Cu deposit (Enkhjargal and Jargalan, 2016).

8.2. Oyu-Tolgoi

Oyu-Tolgoi porphyry Cu-Au system is in the South Gobi region of Mongolia, approximately 550 km south from the capital city Ulaanbaatar and 80 km north from the Chinese border. System is a cluster of five main deposits that are at 22 km long north-northeast-trending zone (Perello, 2001). From north to south, the deposits comprise Hugo Dummett, divided into north and south Hugo, the southern Oyu-Tolgoi cluster of the Central, South and Southwest Oyu deposits and Heruga and Heruga North (Porter, 2016). They occur in a middle to late Paleozoic arc terrane and are associated with Late Devonian quartz monzodiorite intrusions. The Hugo Dummett deposits are the deepest and characterized by high-grade Cu and Au mineralization associated with intense quartz veining and several phases of quartz monzodiorite intruded into basaltic volcanic host rocks. Sulfide minerals here are bornite-chalcopyrite in the core and pyrite (+enargite and covellite) upward at shallower depths. High-sulfidation state at Oyu-Tolgoi is hosted by advanced argillic alteration mineral associations (Porter, 2016).

8.2.1. Grade and Tonnage

According to Rio Tinto Annual Report (2015), total measured + indicated + inferred resource + reserves of Oyu-Tolgoi porphyry Cu-Au system amounted to 6.382 Gt @ 0.67 wt.% Cu, 0.29 g/t Au, of which 1.494 Gt @ 0.85 wt.% Cu, 0.31 g/t Au, 1.23 g/t Ag were proven + probable reserves. This resource amounts to 42.76 Mt of contained Cu and 1850 t of Au. The northern-most Hugo Dummett deposits are the largest and richest deposits discovered to date. The North Hugo deposit contains proven + probable reserves of 499 Mt @ 1.65 Cu, 0.35 g/t Au and 3.39 g/t Ag, whilst Heruga deposit, which includes Mo zone, contains total resources 1.817 Gt @ 0.39 wt.% Cu, 0.36 g/t Au, 1.40 g/t Ag and 113 ppm (=0.64% Cu $_{\text{equivalent}}$) Mo (Porter, 2016).

8.2.2. Characteristics of gold at Oyu-Tolgoi porphyry Cu-Au district

Individual deposits of Oyu-Tolgoi system show slightly different characteristics of Au. Based on Au (g/t) to Cu (%) ratio, Hugo Dummett deposits have the lowest, whereas Southwest Oyu and Heruga deposits have 0.8 to 3:1 or more ratios of Au/Cu. Higher Au/ Cu ratios in Oyu-Tolgoi system were mostly associated with biotite or biotite-magnetite alteration (Porter, 2016)

Gold at **Hugo North** occurs mostly as micro inclusions of electrum (8-28 wt.% Ag) or at grain boundaries of sulfide minerals, mainly bornite and tennantite. Upper parts of Hugo Dummett have a lower density of veins and this resulted in a lower grade of Au and Cu as well. Bornite-rich zone overlying the deep core of main quartz-monzodiorite intrusion contains moderate to a higher grade of Au. Gold is well associated with sulfides particularly bornite and chalcopyrite. Most native gold grains are less than 10 µm. An electron microprobe study, done by Oyunchimeg (2008 in Porter, 2016), shows that gold is commonly >95% pure in porphyry deposits and is also present in base metal veins (Porter, 2016).

Serious lack of Au (<30 ppb Au) occurs in **Central Oyu** deposit, where 80 vol.% of the copper occurs as disseminated covellite. Oyu-Tolgoi porphyry system's only significant high-sulfidation mineralization is in this area. **Southwest Oyu** (Fig.8.) deposit is Au-rich porphyry system with high-grade (>1 g/t Au) core. Gold grain is fine and intergrown with chalcopyrite as vein fills. Like other areas, Au is found as inclusions or at boundaries of sulfides or gangue minerals. High Au (g/t) to Cu (%) ratio of 3:1 was identified (Porter, 2016). In contrast, **South Oyu** (Fig.8.) has a low Au/Cu ratio, which is 0.4 (Hedenquist et al., 2006).

The highest Au (g/t) to Cu (%) ratio in the **Heruga** area was more than 10:1 in the deeper levels where gold is associated with biotite alteration. Gold inclusions are found at boundaries or in thinner veins. Most characters are similar to other deposits in Oyu-Tolgoi porphyry Cu-Au system (Porter, 2016).

Figure 8. Oyu-Tolgoi open-pit mine (source: gettyimages.com, 19.8.2019)

8.3. Kharmagtai

The Kharmagtai porphyry Cu-Au district is located in the southern Gobi Desert of Mongolia and near the margin of the Mandal Ovoo terrane and the Gurvansaikhan Terrane. The district is about 430 km south of the capital city Ulaanbaatar and 160 km northeast from Oyu-Tolgoi porphyry Cu-Au system. In 1976, prospecting was undertaken in the south Gobi and Mongolian and Russian identified porphyry-related Cu-Au-Mo mineralization and tourmaline-associated Au mineralization at Kharmagtai deposit. The Kharmagtai districts located in the southern Mongolian magmatic belt, which comprises mid-Paleozoic, arc-related, calc-alkaline to potassic calc-alkaline igneous complexes. The Gurvansaikhan terrane, where Oyu-Tolgoi, Kharmagtai and other porphyry deposits are located, is within this mid-Paleozoic old Kazakh-Mongol magmatic arc. Preliminary Re-Os (Stein, 2003) dates of 330.2±1.0 Ma have been determined for Kharmagtai district (Kirwin et al., 2005). Preliminary geological mapping shows that most of the area is comprised of a Devonian volcaniclastic sedimentary rock, which has been intruded by Carboniferous monzodiorite and diorite bodies. Most of the intrusive rocks display some degree of hydrothermal alteration. Petrological studies show that the diorite porphyries contain phenocrysts of plagioclase, hornblende, quartz, magnetite and zircon matrix (Kirwin et al., 2005). The district consists of four main mineralized areas: **Zesen uul** (Copper hill), **Altan uul** (Golden hill), **Tsagaan sudal** (White vein) and **Chunt**. The Kharmagtai porphyry district is still in its exploration stage and exploration activity is undergoing by Xanadu Mine company and according to official reports, the company is working to discover new gold-rich deposit at greater depths (Xanadu Mines Ltd, Media release, 2018)

8.3.1. Grade and Tonnage

Average grades at the Kharmagtai range between 0.64-0.84 wt.% Cu, 0.4-4.1 g/t Au, and 5-23 g/t Ag. Kharmagtai Cu-Au deposits have mineable measured + proven + probable reserves of 18 Mt of ores including 88000 t of Cu and 13500 t of Au. It has the total measured + indicated + inferred resource + reserves of 68 Mt ores with 260000 t of Cu and 25000 t of Au. The mineralization area Altan Tolgoi (Golden hill),200 m below the surface, has an average grade of 0.318 wt.% Cu and 0.281 g/t Au (MRPAM, 2016a).

8.3.2. Hydrothermal Alteration at Copper Hill area of Kharmagtai district

The Copper Hill (Zesen uul) is one of the main four mineralized areas of Kharmagtai porphyry Cu-Au district. Petrological studies carried out by Mason (2003 as cited in Kirwin et al., 2005) indicate that all rocks within the Copper Hill area have suffered some degree of hydrothermal alteration. It is mostly associated with fracturing and veining during multiphase events. The potassic alteration has affected most of the porphyries and some of the sedimentary rocks that are intruded by monzodiorite. Two slightly different K-alterations are detected in altered metasediments and porphyries. Potassic alteration in metasediments contains mineral assemblage of albite + biotite + magnetite + quartz + pyrite. Meanwhile, K-alteration in porphyries contains an assemblage of albite or K-feldspar + quartz + magnetite + biotite + trace chalcopyrite + apatite. Primary porphyry textures are usually well preserved except in zones with high-intensity K-feldspar alteration where porphyry textures are completely destroyed. Propylitic or phyllic alteration overprints precursor potassic assemblages. Propylitic alteration preserved texture and is characterized by an assemblage of chlorite ± calcite ± pyrite while phyllic alteration destroyed the texture and is characterized by an assemblage of sericite + pyrite + quartz ± chlorite ± tourmaline ± chalcopyrite ± gold (Kirwin et al., 2005).

9. DISCUSSION

Porphyry Cu deposits in Oyu-Tolgoi system, Tsagaan-Suvarga and Kharmagtai deposits are relatively older than the average age of PCDs. Some PCDs with similar characteristics, such as same advanced argillic, Au-grade and similar magnetite bearing K-silicate alteration, are found in Canada, Papua New Guinea and other countries, although these foreign deposits differ from Oyu-Tolgoi by their younger ages, Mesozoic to Cenozoic. Central Oyu deposit's environment that chalcocite blanket is also similar to giant examples of Chuquicamata and Escondida deposits (Perello, 2001). Oyu-Tolgoi has also same calc-alkalic magma series as 65% of other Au-rich PCDs. Among the world's largest PCDs, Oyu-Tolgoi porphyry system was the oldest in the list, about 360 million years older than 22 of 25 deposits. Oyu-Tolgoi has average tonnage among them but was the 5th highest Cu-grade and the 3rd highest Au-grade deposit (Cooke et al., 2005). Some low-grade copper values have been found in sand, gravel and clay, while laminations of chrysocolla and copper wad associated with argillization are found. Shallower deposits (south and central Oyu deposits) in Oyu-Tolgoi system have a less common type of alteration zone, pervasive destructed early K-silicate alteration. Several samples from Oyu-Tolgoi have witnessed some exotic copper mineralization. (Perello, 2001), while Kharmagtai porphyry Cu-Au deposit usually has relatively well-preserved porphyry texture for its pervasive alteration (Kirwin et al., 2005). When mineral assemblages of alteration zones in Kharmagtai deposit were compared to what a normal PCD would contain, the Mongolian deposit slightly differs by an abundance of chlorite and tourmaline in phyllic alteration and absence of K-feldspar in K-silicate alteration zone within metasediments. Unlike Oyu-Tolgoi and other typical PCDs, no high-sulfidation lithocaps have been identified in the Kharmagtai porphyry district. Even these two Mongolian Au-rich porphyry districts are in same Gurvansaikhan terrane, Kharmagtai has diorite porphyry as the main host rock for copper-gold mineralization and Oyu-Tolgoi's main host rock is monzodiorite (Kirwin et al., 2005).

10. CONCLUSION

Porphyry copper deposits are studied more and understood well compared to other porphyry related deposits. But more studies can be beneficial to the usage of gathered information of geology and genetic models, so one can apply suitable geophysical and geochemical techniques and benefit from the increased potential to discover new deposits. PCDs share following main characteristics, such as large tonnage, low-grade, formation within island-arc or continental magmatic arc near subduction-related convergent plates, disseminated sulfide mineralization in stockwork, breccia pipes and dikes, vein and veinlets. Main regions with significant PCDs abundances are North American Cordillera, Andes, Southwestern Pacific and Central Asian orogenic belt, although PCDs are abundant worldwide. By-products, gold, molybdenum and other metals, increase the economic importance. Today PCDs supply nearly three quarters of world Cu demand and large amounts of other by-products. Improvements in modern technology allow lower-grade deposits to be exploited economically. Shallower deposits can be exploited mostly by using open-pit mines and underground mining, block caving and room-pillar methods, are used to exploit deeper and richer orebodies. Copper concentrate processing method, froth-flotation, also played a crucial role in the importance of PCDs.

Mongolia’s economy is dependent more on the mining industry than any other sector. The mining industry in the country is responsible for more than 90% of foreign trade and almost a quarter of total gross domestic product. Copper production is one of the contributors alongside coal. Porphyry Cu-Au or Cu-Mo deposits account for far more than a half of its Cu production each year and large amounts of Au, Mo and other metals.

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