8.2.1. Ore deposits formed during crustal magmatism and related hydrothermal processes: Formation, beneficiation, and the environmental and social considerations of utilization

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Abstract:

Crustal magmatic systems that form volcanoes also produce mineral deposits that are important sources of critical metals. These include porphyry, epithermal, skarn, iron-oxide-copper-gold, and Carlin-type mineral deposits that form by magmatic-hydrothermal processes, magmatic sulfide deposits that form by purely igneous processes, and pegmatite deposits that form by both processes. These mineral deposits are important sources of copper, gold, iron, lead, lithium, nickel, platinum-group-elements (platinum, palladium, rhodium, ruthenium, osmium, iridium), molybdenum, silver, selenium, tantalum, tellurium, tungsten, tin and zinc. These metals are fundamental to equitable global development, and it is essential to understand the geological processes that form these mineral deposits in order to explore for and discover new deposits to replace those that have been utilized. This chapter provides an overview of these mineral deposit types, including how they form, how metals are extracted from them (mineral beneficiation), the environmental impacts of mining and mineral production, and the importance of community and regulatory considerations for responsible mining.

Key Words: critical metals, pegmatite, porphyry, epithermal, skarn, copper, gold, responsible mining, corporate social responsibility (CSR); environmental, social, governance (ESG); social license to operate (SLO), tin, tungsten, molybdenum, mineral beneficiation, Indigenous

Introduction

The tools, technology and energy production that support society are made of minerals [1, 2]. These minerals are mined from mineral deposits, many of which form in and around volcanoes and their intrusive underpinnings. For example, porphyry-type deposits, which are the primary global source of copper, form in subduction zone environments from volatile-rich magmas that explosively release hydrothermal fluids containing copper and other metals when they rise through the crust, depositing these metals within the surrounding rock as the fluids cool and pressure decreases (Fig. 8.2.1.1). If this metal-rich hydrothermal fluid infiltrates limestone it will deposit metals to form skarn deposits, which are the primary global source of tungsten, as the fluid cools and changes composition because of chemical reactions with carbonate minerals in the host rock. Pegmatite deposits, which are an important global source of lithium and the only source of cesium and tantalum, form during late stage differentiation of felsic magmas when compositionally evolved volatile- and incompatible-element-rich melt fills fractures in the surrounding rock and crystallizes.

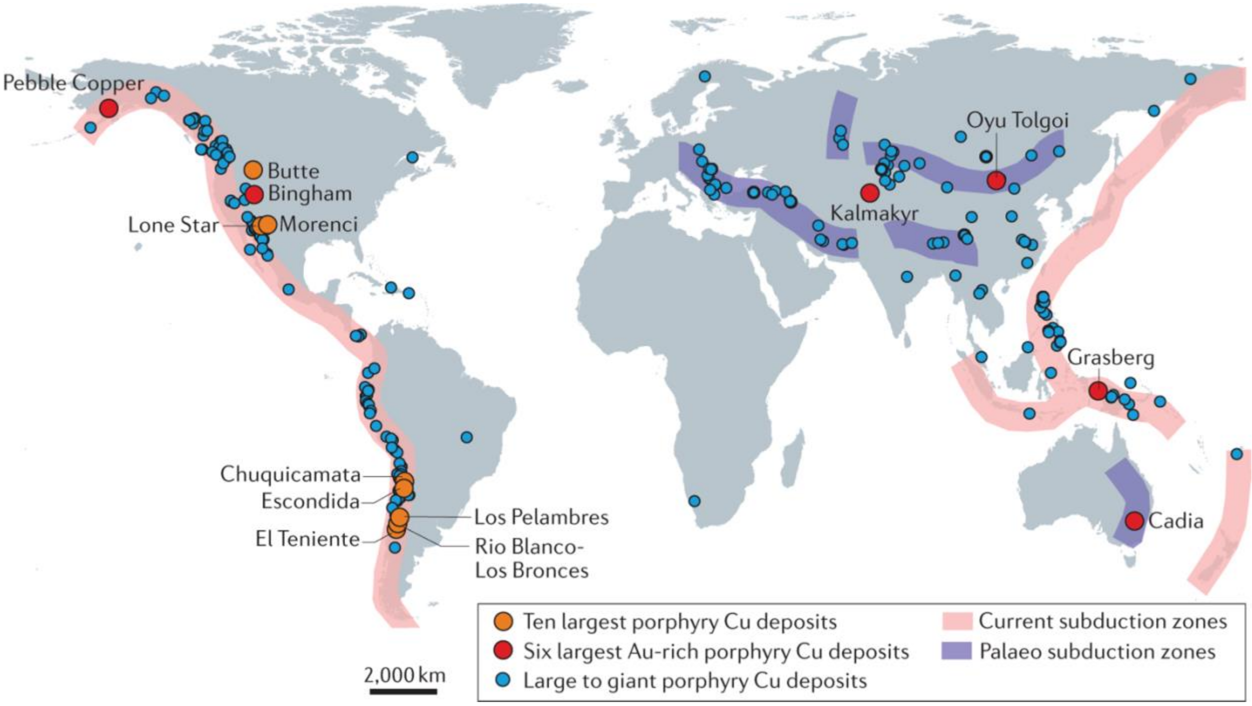


FIGURE 8.2.1.1. Porphyry-type deposits enriched in copper, gold, molybdenum and silver form from magmas generated in subduction zone environments. Credit: [3]

As global consumption of minerals continues to grow at a rate that is faster than that of human population growth (Fig. 8.2.1.2), it is essential to understand the geological processes that form these mineral deposits in order to explore for and discover new deposits to replace those that have been utilized [4]. This is fundamental to achieving the United Nations Sustainable Development Goals (SDG) because minerals are required to manufacture affordable and clean sources of energy, provide access to clean water and sanitation, build sustainable cities and communities , provide nutrients for life on land and life below water, manufacture technology for digital education, and build healthcare infrastructure. This goal of this chapter is to help readers gain insight into the factors that control the geological formation and distribution of mineral deposits formed in crustal magmatic systems. Mineral exploration is also discussed, as well as mineral extraction and production, the environmental impacts of extraction and production, and the crucial roles for community participation, government regulation and public opinion in determining whether a mineral deposit can be utilized

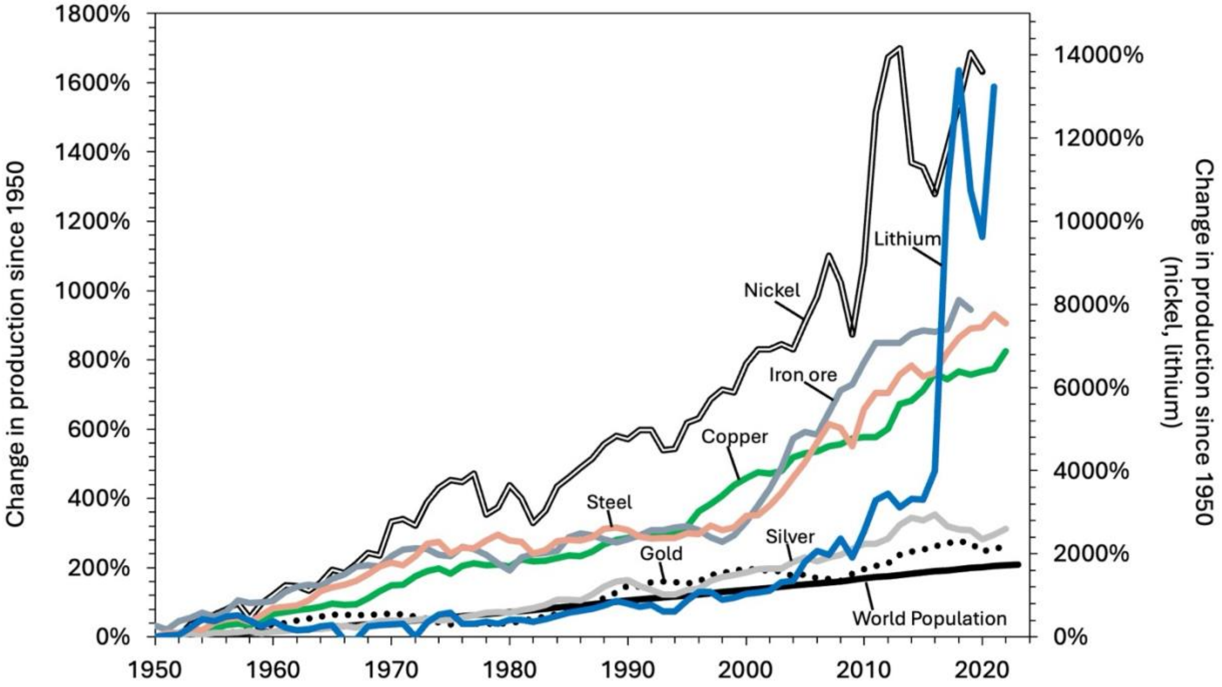


FIGURE 8.2.1.2. Change in world population and primary mine production of copper, gold, iron, lithium, nickel, steel and silver relative to 1950 (all data from the US Geological Survey).
Credit: Adam Simon

Mineral Deposits and Ore Deposits

A mineral deposit is a place in Earth's crust where geologic processes have concentrated one or more minerals at abundances greater than the average crust. For example, the average concentration of copper in rocks that make up Earth's crust is about 0.003 weight percent whereas the rock mined at a copper deposit contains typically about 0.5–1 weight percent copper (Fig. 8.2.1.3). This means that the rocks in a copper deposit contain about 300 times more copper than in unmineralized rocks. This increased concentration of copper allows a mining company to extract the metal at a cost that is less than its selling price. We call such a profitable mineral deposit an ore deposit. Thus, all ore deposits are mineral deposits, but the reverse is not true. The market value for a particular metal, together with current mining technology along with the ability to gain permits to mine a mineral deposit, referred to as the social license to operate, determine whether a mineral deposit can be mined profitably. If markets or technologies change, new deposits may become profitable, or old deposits may no longer make money. Economic geologists study mineral deposits, in particular focusing on the natural processes that concentrate ore minerals to make an ore deposit. Understanding these processes is important for developing models that guide exploration for new deposits and ensure a sustainable supply of mineral resources. Many different processes can concentrate minerals and create ores [1]. In the rest of this chapter, we will discuss several mineral deposits related to magmas and the environmental and social considerations that increasingly play the deterministic role in the extraction of minerals.

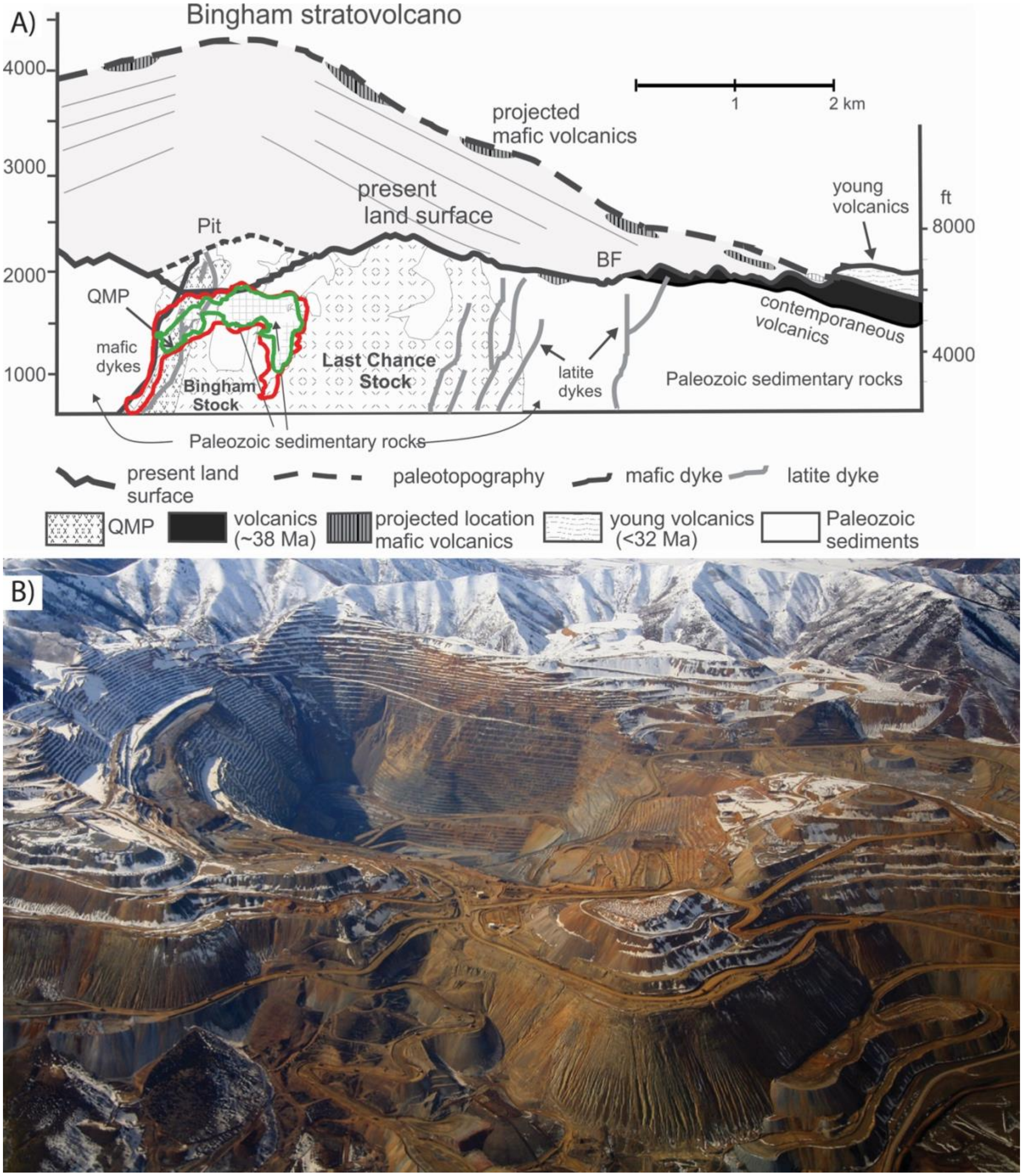


FIGURE 8.2.1.3. A) Paleographic reconstruction of the Bingham stratovolcano at 38 million years ago. The copper ore body is outlined in red. Rocks within the red and green areas contain >0.35 and >0.75 weight percent copper. Elevation in meters. B) view of the open pit mine, which is 4 kilometers (2.5 miles) wide and 1210 meters (0.75 miles) deep, covering 770 hectares (1900 acres, or 3.0 square miles). Credit: A) Keiko Hattori [4]. B) Doc Searls. CC BY 2.0 https://upload.wikimedia.org/wikipedia/commons/1/1d/Bingham_Canyon_mine_2016.jpg

Mineral Exploration

The basic function of mineral exploration is to replace deposits that have been utilized. The demand for minerals is so great that even large mineral deposits are exhausted rapidly, making it necessary to search constantly for new ones. For example, the average life of a large copper mine is a few decades. This is why we call mineral deposits nonrenewable resources. It follows that we must think of Earth as having a fixed inventory of minerals to supply our needs. Geological exploration works because most mineral deposits form in specific geological environments by processes that are clearly evident in the rock. By studying deposits that have already been discovered, geologists learn about these environments and processes and then look for similar deposits elsewhere. Exploration involves geological, geochemical, and geophysical methods. Geological methods are based on the host-rock features and the understanding of ore-forming processes of the many different deposit types. A commodity may be present in several different types of mineral deposits. Each deposit type has distinctive geological features (e.g., tectonic setting, host rocks, mineralization style, ore and waste mineralogy, alteration types, textures, orebody shape, structures, degree of metamorphism, controls of orebodies, zonation in alteration and mineralization, etc.). Hence, exploration strategies are different for different types of deposits.

Geochemical exploration relies on the principle that nature works as hard to destroy mineral deposits as it does to create them. This natural destruction often leaves a geochemical signature in the soils above or around a mineral deposit. Hydrothermal alteration, which forms when hot water reacts with adjacent rocks, changes their mineral and chemical composition. Altered rocks usually contain minerals in a zonal arrangement that can be used to vector toward the center of the mineral system. Geochemical exploration surveys also use other natural features, such as plants and animals (e.g., mound-building termites) whose roots or nests reach deep into the underlying regolith, as well as lakes and swamps. In areas where glaciers have covered the bedrock with sand and gravel, these can be sampled for traces of ore scraped from the underlying rock. Weathering of metal sulfide minerals forms mercury and sulfur gases that can be detected in surveys. Regional geochemical surveys help locate these areas, as well as facilitating exploration and aiding strategic planning. Geophysical exploration involves measuring physical properties of rocks and minerals, including magnetic, electric, electromagnetic, radiometric, short to long-wavelength infra-red spectral, density/gravity features, and the speed of seismic waves, passing through rocks. Such features can be detected on the ground, or from an airplane or satellite (remote sensing). Exploration models integrate geological, geochemical, and geophysical data in order to understand the ore-forming process and reduce the size of an exploration area.

Exploration begins at the continent or country scale over very large areas and is progressively reduced to a regional scale of tens to hundreds of square kilometers by considering information on known deposits, tectonic settings, large-scale geophysical and geochemical surveys, remote sensing and geologic mapping. Combined with statistical analysis of metal endowment by deposit type, exploration maturity and estimated remaining metal endowment, as well as business risk criteria (e.g., infrastructure, safety, corruption, legal title, administration favorability, etc.), district- and project-scale targets are defined. Project-scale exploration then identifies prospects of a few square kilometers or less to determine specific locations that can subsequently be drilled to provide additional information. This can involve digging trenches and pits to expose rocks beneath soil cover and conducting high-resolution geochemical and geophysical surveys. The composition of rocks recovered by drilling provides definitive data that confirms the presence or absence of a mineral deposit. If a drill hole intersects a significant length of ore, it is called the discovery hole, and subsequent holes are drilled outward from this hole to determine the total size and shape of an ore body.

The concentrations of the target metal among all drill core samples are evaluated to determine a total deposit value based on current and forecasted market prices for the metal. This is followed by an initial financial appraisal of the costs to build and operate a mine, considering yearly metal production, capital expenditure and discount rates, mining and milling costs, administration and grade control costs, mine dilution and recovery factors, royalties and corporate tax rate, metal prices, and the cost of a reclamation fund. The product of these calculations is an estimation of the ore reserve, which is the amount of confirmed metal in the deposit that can be extracted at a profit, and the resource, which includes reserves plus any undiscovered deposits, regardless of economic or engineering factors. If a decision is made to continue after considering all of this information, the next steps involve a prefeasibility study that involves additional drilling to increase the level of certainty for the total amount of metal, metallurgical study of the ore to determine optimal ore extraction methods and metal recovery rates, preliminary mining planning, environmental geology, and hydrogeology. Simultaneously, work will be carried out to secure the mining license. All of these stages of exploration and mine planning may several years if there are no setbacks. However, setbacks are common, and a project may change hands several times before a decision is made, often with hiatuses.

The best exploration success rate (to discovery) is at best a few percent. Using copper as an example, in the period between 2001 to 2010, about 20 new copper deposits of at least 0.1 Mt were discovered each year globally. From 2015 to 2022 this decreased to less than 10 per year. The success rate of discovering a virgin occurrence of at least 0.1 Mt was around 1 in 2500 for the period 2001 to 2010 and is now about 1 in 5000. The rate of success for a copper occurrence becoming an economically viable deposit is between 1 in 100 and 1 in 800 [5].

Crustal Ore Deposits

Magmatic sulfide deposits

Magmatic nickel-copper sulfide deposits supply about 60% and 3% of the world's nickel and copper, respectively, and are significant sources of platinum-group-elements as well as byproduct cobalt and gold (Fig. 8.2.1.4). The principal ore minerals are sulfides such as pyrrhotite, pentlandite and chalcopyrite. Classification schemes that are based on the form and composition of host rocks normally include classes such as meteorite impact-related, flood basalts, high-magnesium basalts, anorthosites – troctolites, komatiite, ferropicrite and Alaskan-type. These deposits form in mantle-derived mafic and ultramafic magmas by the separation of silicate melt into two immiscible melts of different composition as the magma cools (Fig. 8.2.1.4; see Part 2 Chapter 3.3). One persists as a silicate melt whereas the other is a sulfide melt into which siderophilic metals preferentially partition during the unmixing process. In order for mafic magmas to reach sulfide saturation prior to the point where large amounts of Ni-bearing olivine have crystallized and sequestered nickel, interaction with sulfur-bearing crust is usually necessary. In the case of the magmatic sulfide deposits associated with the Sudbury Igneous Complex, Canada, the impact of a 10- to 16-km diameter meteorite or comet produced a 250 km-wide crater that contained a large volume of superheated melt from which immiscible sulfide melt formed, sequestered metals, and gravitationally accumulated at the bottom of the magma chamber. These deposits typically contain between 0.7 and 3 and 0.2 and 2 percent nickel and copper, respectively. Deposits typically contain from a few hundred thousand to a few tens of millions of tonnes of sulfide ore although there are some much larger deposits. For example, Sudbury, Noril'sk (Russia) and the Duluth

Complex (USA) contain 1645 million metric tons, 1903 million metric tons, and 8000 million metric tons of sulfide-rich ore, respectively.

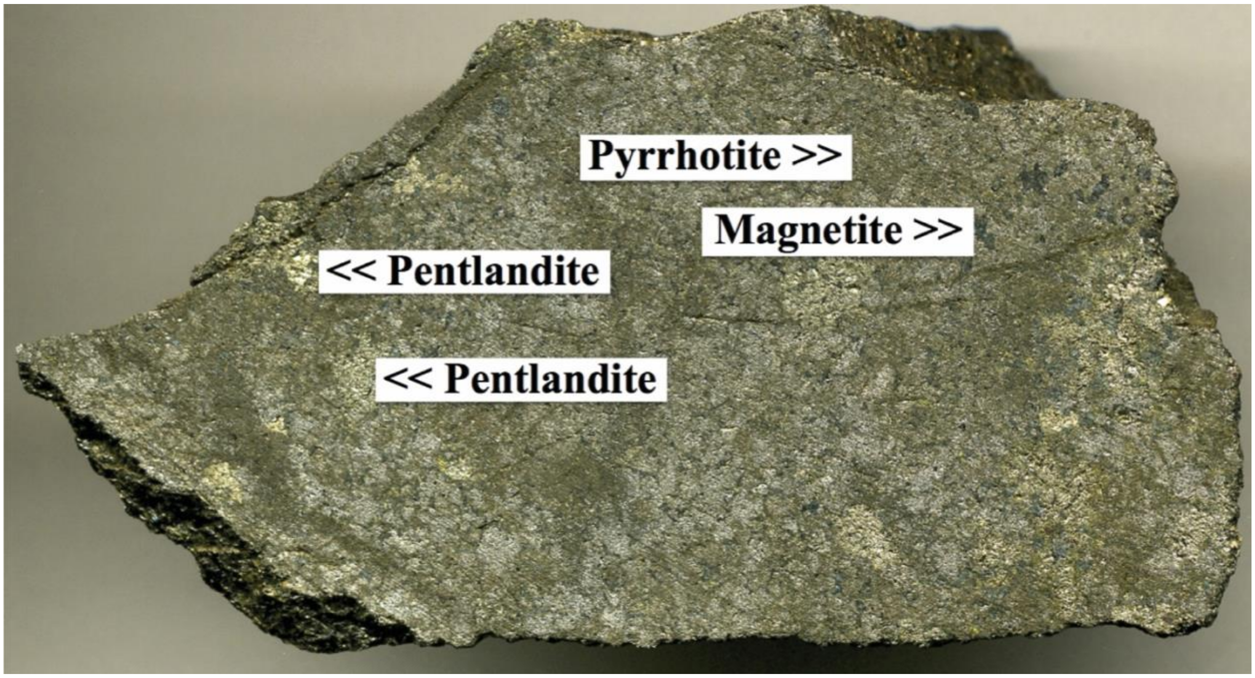


FIGURE 8.2.1.4. Pentlandite in pyrrhotite from the Sudbury Impact Structure in Ontario, Canada. (field of view 8.35 cm across) Pentlandite = $(Fe,Ni)_9S_8$; pyrrhotite = $Fe_{1-X}S$; magnetite = Fe_3O_4. Credit: James St. John, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons

Magmatic platinum-group-element deposits supply more than 95% of global platinum, palladium and rhodium. These deposits are characterized by the presence of disseminated sulfide minerals in layered mafic intrusions with the richest deposits occurring in relatively thin layers or "reefs" within large, layered intrusions (see Part 2 Chapter 3.3). The world's largest deposits are all located in southern Africa, with two layers of the Bushveld Igneous Complex (Merensky Reef and UG2 Chromitite) in South Africa in production, as well as the Great Dyke of Zimbabwe. The platinum-group-element reefs in deposits in the Bushveld and Stillwater igneous complexes, as well as the Great Dyke, are typically low in sulfide abundance (<3 volume percent), although the platinum group elements are strongly associated with sulfide minerals and occur as platinum-group-element sulfide minerals, or as spatially associated tellurides, bismuthinides, arsenides or alloys. The J-M Reef of the Stillwater Complex, USA, is another low-sulfide but high-platinum group element deposit currently being mined. In some cases, palladium may occur primarily in solid solution with platinum. Sulfur is thought to have played a primary role in the concentration and localization of the platinum group elements. Enrichment of platinum group elements may occur in a number of different rock types. For example, the sequence of rocks that defines the Merensky Reef (anorthosite, lower chromitite - pegmatoidal feldspathic pyroxenite/norite, upper chromitite) is quite distinct from the package of rocks that define the J-M Reef of the Stillwater Complex (troctolite, gabbronorite, norite). There are two general models that have evolved for the generation of platinum-group-element-enriched horizons in layered intrusions. The first invokes the attainment of sulfide saturation in the magma chamber during crystallization of mafic to ultramafic silicate melt (see Part 2 Chapter 3.3). The second invokes reaction of platinum-group-element-sulfides with late-stage magmatic-hydrothermal fluids that preferentially mobilize copper and sulfur, thereby increasing the residual concentration of the platinum group elements. There is also evidence supporting a role for the assimilation of country rocks to form these deposits.

Pegmatite deposits

Granitic lithium-cesium-tantalite (LCT) pegmatite deposits supply about 25% of the world's lithium and almost all of cesium and tantalum, as well as tin, beryllium, tantalum, boron, fluorine, phosphorus, manganese, gallium, hafnium and rubidium in some deposits [6]. These pegmatites form by melting of lithium-rich sedimentary rocks or by extreme differentiation of low calcium granites. Lithium-cesium-tantalite pegmatites exhibit compositional zonation and range from relatively homogeneous pegmatites, such as Whabouchi (Quebec, Canada) to highly zoned lithium-cesium-tantalite pegmatites, such as those in Cape Cross and Brandberg (Namibia). Zoned pegmatites can contain as many as eleven distinct mineralogical zones (although more typically they contain five zones). Most pegmatites have an innermost massive quartz zone grading into feldspar-dominated zones containing variable proportions of minerals dominated by tantalum, tin, beryllium, cesium and lithium, through to a mica-rich outer zone and a tourmaline–mica dominated margin. The origin of zoning in pegmatites has been variously proposed to result from sequential crystallization of a single fluid, multiple injections of different compositional fluids, or alteration of an initial pegmatite assemblage by later hydrothermal fluids. Large crystals are typical of pegmatites (Fig. 8.2.1.5).

The outer rim of a zoned pegmatite is usually on the order of centimeters wide, with millimeter-size crystals in contact with the host rock where crystallization rates were presumably faster. The inner part of a zoned pegmatite is generally tens of centimeters to meters in width and the grain size is much larger (up to meters) in length. The inner portion of the pegmatite is mainly quartz, feldspar and occasionally semi-precious gemstones such as tourmaline. The intermediate zone is mineralogically more diverse and includes several minerals of economic importance, such as muscovite, beryl, spodumene, amblygonite, lepidolite and columbite–tantalite. The crystals in the intermediate zone can reach several meters in length. Although not currently of significant economic importance, niobium-yttrium-fluorine (NYF) pegmatites are characterized by enrichment in niobium, titanium, yttrium, rare earth elements (REE), zirconium, uranium, thorium and fluorine. These pegmatites are typically associated with and often hosted within metaluminous to alkaline (locally peralkaline) anorogenic A-type granite plutons formed in continental or ocean rift zones. Late-stage alteration of niobium-yttrium-fluorine pegmatites by, typically F- and CO_2-rich fluid, has been interpreted to indicate the presence of immiscible silicate and fluoride melts that subsequently crystallized to form the pegmatites. Please see Chapter 8.4.1 for a discussion of additional lithium resources in volcanic systems.

FIGURE 8.2.1.5. A single, giant of spodumene ($LiAl(SiO_3)_2$) in the Plumbago North pegmatite deposit, Maine, USA. The vertically-oriented crystal in the center of the photo has dimensions of 4.5 × 0.9 × 0.6 meter (15 x 3 x 2 feet).

Credit: William B. Simmons

Porphyry-type deposits

Porphyry-type deposits supply about 75% of the world's copper as well as significant amounts of gold, molybdenum, silver in addition to byproduct rhenium and tellurium [7]. These systems are large volume (hundreds of million tonnes of ore) accumulations of low-grade (typically <1 weight percent copper) ore minerals associated with intrusive rocks at mid- to shallow-crustal depths above subduction zones at convergent plate boundaries (Fig. 8.2.1.6a, c). As such, their distribution often parallels active and fossil volcanic chains, forming metallogenic belts that span over hundreds of kilometers (Fig. 8.2.1.1 see Part 2 Chapter 2.1). Although porphyry-type systems formed since the Archean, younger examples from Cenozoic times (66 million years ago) are most abundantly preserved. Some of the best examples of porphyry provinces globally are the Andean margin of South America, where Chile hosts the largest porphyry copper deposit on Earth (Río Blanco-Los Bronces; >200 Mt contained Cu) and the two largest copper producing mines (Escondida and Collahuasi at about 1.1 and 0.6 Million tonnes copper per year, respectively). In addition, in the western United States, the Bingham Canyon mine has produced 19 million tons of copper, creating the deepest man-made hole, and the Southwest Pacific region hosts the Grasberg porphyry copper-gold deposit in Indonesia that has produced 13 million tonnes copper and 46 million Troy ounces (1,430 tonnes) gold.

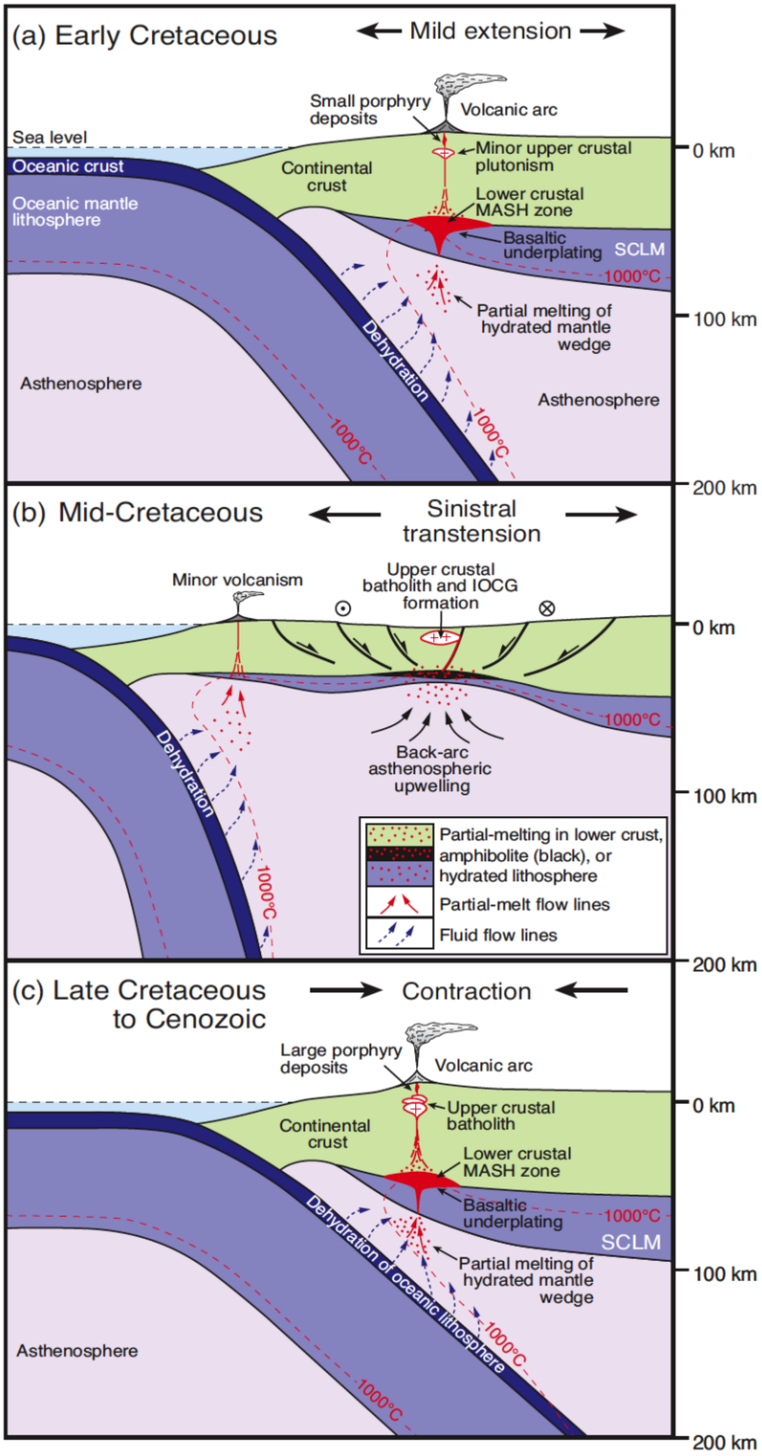


Fig. 8.2.1.6. Subduction zone environment applicable to northern Chile, where porphyry, epithermal and IOCG deposits formed. Credit: [8]

The name "porphyry" derives the porphyritic texture of the host rock, characterized by larger crystals (typically <0.5 cm) known as phenocrysts surrounded by a finer-grained groundmass (Fig. 8.2.1.7). Such porphyritic texture forms when magma ascends through the Earth's crust, cooling slowly and allowing phenocrysts to grow over an extended period (see Part 1 Chapters 2.3 and 5.2). Then, as magma gets closer to the surface, it cools faster such that the remaining crystals do not have enough time to grow big, resulting in the formation of a finer-grained groundmass. As magma ascends from a high-pressure and high-temperature environment to a comparatively cooler and less pressurized, shallower sub-volcanic environment, it cools and begins to solidify, forming crystals. Under these new pressure and temperature conditions, the magma loses its ability to retain its dissolved water and volatile load, which escapes from the magma, akin to the release of gas when opening a soda. This process, commonly referred to as "volatile exsolution", is a fundamental step driving the generation of porphyry deposits (see Part 1 Chapters 2.2 and 5.1). During this process, anions such as chlorine and sulfur along with cations such as copper, gold, molybdenum, silver, and other metals are efficiently incorporated into the exsolved volatile phase, giving rise to metal-enriched magmatic-hydrothermal fluid.

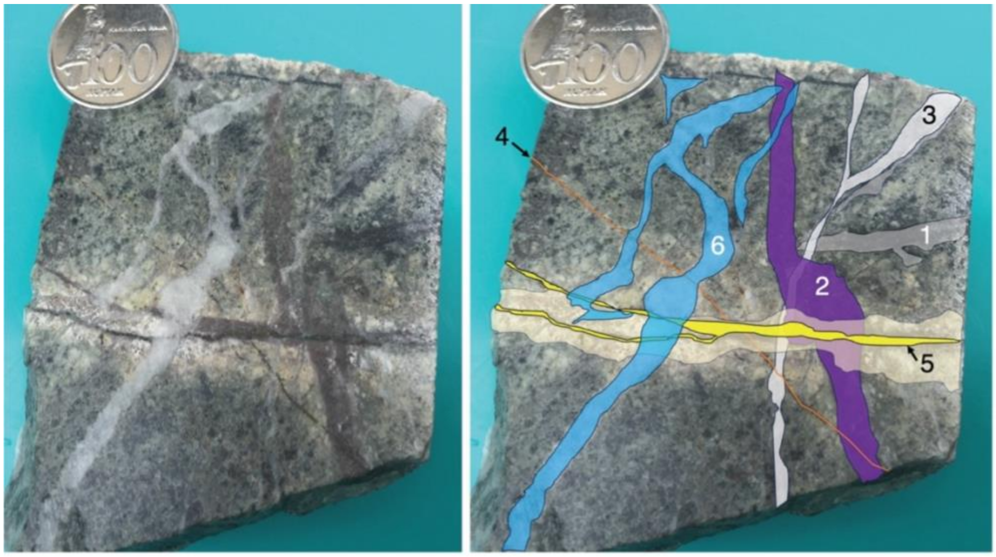


FIGURE 8.2.1.7. Hand sample from Sungai Mak porphyry deposit, Sulawesi (Indonesia) with stockwork veining (left) as indicated (right): 1) 1- to 3-mm banded magnetite-bt veinlets with pervasive bt alteration; 2) cut by light gray quartz vein; 3) cut by dark/purple-gray vein with pervasive chlorite-weak white mica alteration; 4) cut by chalcopyrite "paint" vein; 5) cut by pyrite-quartz vein with white mica halo; 6) cut by anhydrite-only vein. Credit: Antonio Arribas

Fracture zones in the rock overlying the magma reservoir allow the metal-rich fluids to explosively escape from the magma where decreases in pressure and temperature cause phase separation (or boiling) of the originally one-phase fluid into a dense and saline aqueous fluid known as brine, and a coexisting vapor phase. The dense brine commonly remains at greater depths, closer to the magmatic heat source, and is responsible for the formation of the high-temperature porphyry-type ore environment. By contrast, the lower-density vapor phase migrates upward to the epithermal environment, discussed below. This process affects ore metal distribution, mineralization styles, and alteration minerals. Copper and molybdenum, for example, reside in deeper, hotter porphyry environments near the magma source, whereas gold and silver are transported by magmatic liquids or vapors to shallow crustal levels. A spatial association between deep porphyry-type mineralization transitioning to shallow epithermal mineralization has been recognized in volcanic terrains worldwide, suggesting a genetic linkage.

During continuous upward and outward fluid circulation in both environments, cooling by reaction with surrounding rocks and/or mixing with circulating groundwater produces a series of chemical reactions, changes in physical conditions, and mineralogical transformations that result in the precipitation of ore minerals. Thus, fluid circulation in the porphyry environment results in ore precipitation, forming disseminations when reacting with permeable surrounding rocks and, most commonly, forming networks of interconnected veins known as stockwork, which is the signature of the copper mineralization in porphyry systems (Fig. 8.2.1.7). Such crosscutting veins are the product of ascending waves of high-pressure fluid released from the magma chamber. They are mostly composed of quartz, with variable amounts of sulfide minerals such as chalcopyrite, molybdenite, and pyrite. Accompanying alteration minerals typically display a zonation depending on the temperature (proximity to the heat source) and acidity of the ascending fluids. This can vary from a deep zone dominated by potassium-bearing minerals (such as K-feldspar and biotite) to an intermediate zone, where K-Al-rich micas and quartz are abundant, to a shallower lithocap of aluminosilicates and sulfates formed in a hypogene acid environment dominated by condensation of magmatic volatiles into groundwaters [7]. A more peripheral zone dominated by lower temperature minerals such as epidote, calcite, and albite(at deeper levels) and chlorite, calcite and clays , at shallower levels, forms an envelope around the porphyry system. The preservation of this zoned ore-forming system is useful for the successful discovery of economically viable deposits. Post-ore formation processes, such as tectonic uplift, erosion, and volcanic edifice collapse, are crucial for exposing porphyry and epithermal systems. Understanding these processes enhances the potential for successful mineral discovery.

Epithermal gold and silver deposits

Epithermal deposits supply about 10% and as much as 20% of the global gold and silver supply, respectively. Epithermal deposits are discussed in Chapter 8.3.3 and the brief summary here is based on [9]. Epithermal deposits form from magmatic-hydrothermal and meteoric-dominated geothermal fluids, typically at <1 km depth, and are broadly grouped according to tectonic setting and mineralogy. One endmember style, hosted by acid-leached rock within the lithocap, contains 10-90 volume percent sulfides and formed from magmatic-hydrothermal fluid that evolved from calc-alkaline andesitic-dacitic magmas in arcs characterized by near-neutral stress states or mild extension. Deposits that formed from oxidized magmas are enriched in gold-silver, copper and arsenic-antimony and important sulfide minerals are high sulfidation-state enargite, luzonite, famatinite and covellite. Type examples include El Indio, Chile and Yanacocha, Peru. Deposits associated with reduced magmas are enriched in silver, antimony and tin and the important sulfide minerals are acanthite and stibnite. The type example is Potosí, Bolivia. A variation on this style of epithermal deposit is enriched in gold-silver, zinc, lead and copper, and is common on the margins of the acid-leached rock lithocap. These deposits are associated with sulfide minerals that include sphalerite, galena, tetrahedrite-tennantite and chalcopyrite. Type examples include the gold-rich Baguio deposit in the Philippines and the silver-rich Fresnillo deposit in Mexico. A distinctly different style of epithermal deposit is enriched in gold with minor silver. Deposits associated with sub-alkaline bimodal basaltic and rhyolitic magmas typically contain less than 2 volume percent sulfides, including minor arsenopyrite, sphalerite, galena, tetrahedrite-tennantite, chalcopyrite, sometimes pyrrhotite, and selenide minerals. Deposits associated with alkali basaltic to trachytic magmas typically contain 2 to 10 volume percent of the same sulfide assemblage, with abundant telluride minerals are abundant.

Deposit sizes in the epithermal environment range from tens of thousands to greater than one billion metric tons of ore, with average gold contents in narrow veins that can be up to 30 grams per ton, and silver contents often exceeding this by approximately one to two orders of magnitude. Because of their shallow depth of formation, most preserved epithermal deposits are geologically young, having formed in the Cenozoic era. For example, the Ladolam epithermal deposit in Papua New Guinea formed about four hundred thousand years ago within the crater of an active volcanic system. Despite being rare, epithermal deposits such as those in the Deseado Massif in Patagonia that formed about 150 million years ago have survived erosion due to prior burial, preserving features such as silica sinters, indicate ancient subaerial hydrothermal activity.

Iron oxide-copper-gold deposits

Iron oxide-copper gold deposits (IOCG) deposits supply about 5% of the world's copper as well as byproduct gold, with some deposits also producing uranium, cobalt and rare earth elements. These systems contain thousands to millions of tonnes ore with 0.2 to 5 percent copper and 0.1 to 1.5 grams of gold per tonne. Two types of IOCG deposits are recognized. The first group corresponds to Archean and Proterozoic deposits associated with an orogenic to post-orogenic tectonic setting in a continental crust inboard of craton margins where small degrees of partial melting of metasomatized lithospheric mantle formed volatile-, copper- and gold-enriched magmas of alkaline affinity. The second group occurs in the Chilean and Peruvian Andes formed during the Mesozoic (Upper Jurassic to Lower Cretaceous) within a continental margin magmatic arc [10]. These deposits formed during or immediately after extensional deformation in the back-arc and are associated with times of steeper subduction (Fig. 8.2.1.6b). The IOCG deposits of the Andean belt are clearly related to an active volcanic arc. Notably, the continental crust precursor to IOCG mineralization in the Andes was thinner than that associated with the formation of porphyry-type deposits. This reduction in crustal thickness was caused by extensional deformation in the back-arc where thinned continental crust led to melting of metasomatized subcontinental lithospheric mantle, resulting in IOCG mineralization.

Almost all IOCG deposits occur within volcano-sedimentary basinal host rocks that have been metamorphosed at low to medium grades either before or during IOCG mineralization. Host rocks include metasedimentary, metavolcanic, and mafic to felsic igneous rocks. Copper occurs primarily as chalcopyrite and bornite, rarely as covelline (e.g., Salobo in Carajas, Brazil). Pyrite and pyrrhotite are minor. Hydrothermal alteration is volumetrically more extensive than porphyry-type deposits and reflects the higher temperatures of formation of IOCG deposits. Alteration stages vary from early sodic-calcic with the formation of minerals such as albite, scapolite or quartz to a calcic-ferric alteration represented by minerals such as magnetite (and/or hematite) together with actinolite and apatite. Copper mineralization is associated with a potassic-ferric alteration facies that overprints previous events and is spatially more restricted to higher temperatures zones. This alteration type is associated with minerals such as magnetite, biotite and K-feldspar, and at lower temperatures it can be associated with hematite, K-feldspar or calcite. Late-stage, volumetrically minor hydrolytic (acid) alteration forms in the upper and proximal portions of the deposit with minerals such as sericite and chlorite.

The styles of mineralization in IOCG deposits are controlled by structures and host rock permeability. Mineralized hydrothermal breccias are common (Fig. 8.2.1.8a) and, if the host rock is permeable enough, mineralization will precipitate following a favorable lithological horizon forming a "manto" type deposit. Mineralization in volcanic-sedimentary rocks often closely emulates the original stratification of the host (Fig. 8.2.1.8b). Ore fluids in IOCG deposits were hypersaline and contained high concentrations of iron and copper (and other metals) but contained two to three orders of magnitude less sulfur than porphyry-type ore fluids, evidenced by the occurrence of significantly less pyrite (FeS_2) in IOCG deposits. The abundances of stable isotopes of copper, iron, oxygen and sulfur indicate that the ore fluid was dominantly magmatic-hydrothermal, with evidence in some deposits for the addition of chlorine and some metals from evaporite sequences.

FIGURE 8.2.1.8. Examples of IOCG mineralization styles. (A) Mineralized hydrothermal breccia with chalcopyrite ($CuFeS_2$), photo from the Sossego mine in the Carajas district, Brazil. (B) Lithological controlled IOCG mineralization with iron oxides (magnetite and hematite), photo from the Santo Domingo IOCG deposit, Atacama region, Chile. Credit: Irene del Real.

Skarn deposits

Skarn deposits supply about 70% of global tungsten, are a major source of tin, gold, copper, zinc, lead, silver, molybdenum and iron, and a source of other critical metals including boron, beryllium, bismuth, cadmium, cobalt, gallium, germanium, indium, niobium, tantalum, rhenium, rare earth elements, antimony and uranium, plus gemstones and industrial minerals such as jade, wollastonite, fluorite, quartz crystals, and diopside. Skarns most commonly occur in the contact zone between intrusive magma and carbonate wallrocks. Skarns may extend away from the contact for several kilometers along faults and along favorable lithological boundaries between carbonates and siliciclastic sedimentary rocks and volcanic rocks, between chert and mafic lavas, and in certain carbonate beds. Lesser skarns may occur along the contact of an older intrusion and carbonates. Skarns may replace also igneous rocks. These skarns are magmatic-hydrothermal and contain most of the metals. Metamorphic hydrothermal skarns may contain tungsten and/or gold. Other minor skarns occur in regional metamorphic rocks without water involvement are mined for wollastonite and other industrial minerals.

Skarns in calcium-rich host rocks, referred to as calcic skarns, form through a sequence of events beginning with contact metamorphism (no water involvement) of rocks surrounding a magma body, followed by the evolution of metal-rich magmatic-hydrothermal fluid from the magma and infiltration of this fluid into the host rocks at high temperatures, typically >550 °C. Reaction of the high-temperature fluid with calcium-rich host rock results in the formation of minerals including garnet, pyroxene, wollastonite, rhodonite, and sometimes minor scapolite. Metals remain dissolved in the fluid during this early fluid-rock reaction due to the high temperatures and salinities of the ore fluids. Continued fluid-rock reaction at <550 °C alters earlier-formed minerals and replaces them with epidote, amphibole, vesuvianite, ilvaite, scapolite, quartz, and/or iron and tungsten oxides including specular hematite, magnetite, mushketovite, wolframite, and/or scheelite. Continued cooling of the ore fluid results in precipitation of most metals, and formation of assemblages of quartz, carbonate (calcite, and sometimes siderite, ankerite, rhodochrosite, dolomite), chlorite, biotite, K-feldspar, fluorite, sulfides-sulfosalts, electrum, and cassiterite (Fig. 8.2.1.9).

Skarns formed in dolomitic limestone, referred to as magnesian skarns, will include a greater abundance of magnesium-rich silicate minerals such as periclase in the contact metamorphic marble, and magnesium-rich olivine (forsterite), magnesium-rich pyroxene (diopside), wollastonite, and minor garnet as an alteration product of high-temperature, >550 °C, alteration. At temperatures <550 °C, fluid-rock reactions produce humite, clinohumite, chondrodite, and slightly later phlogopite. Continued cooling of the ore fluid produces serpentine with lesser talc, chlorite, quartz, carbonate, and brucite. Magnesian skarns may contain significant boron and more magnetite than calcic skarns.

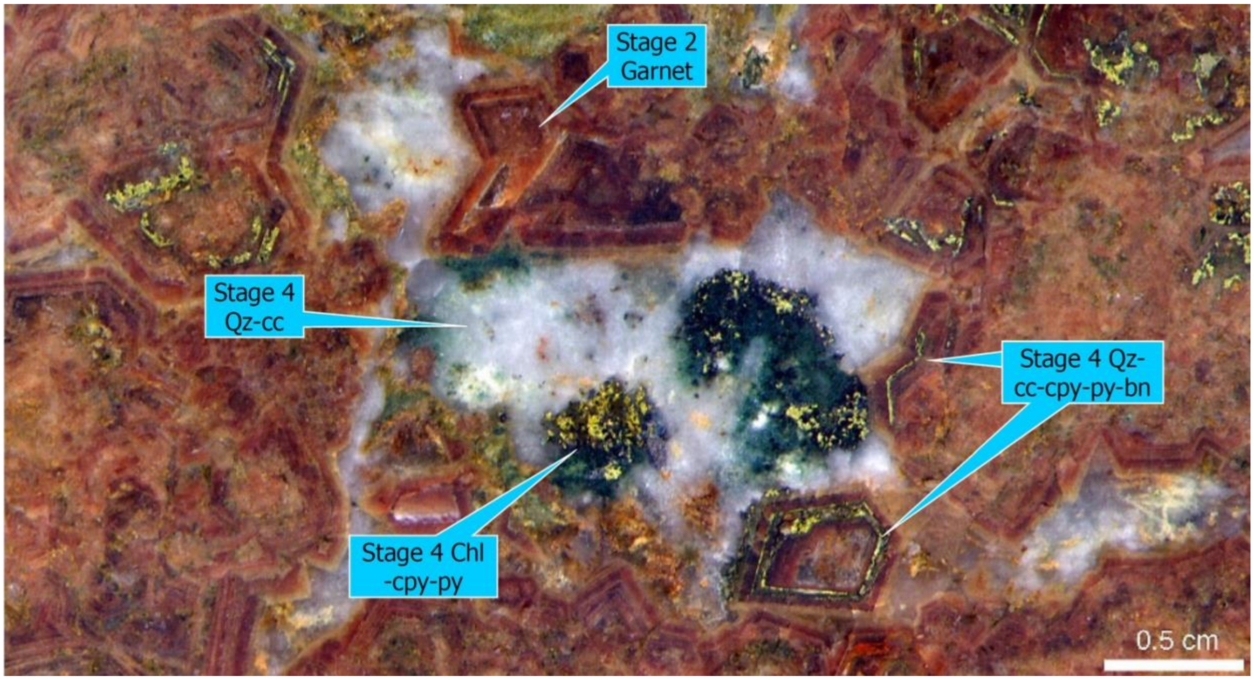


FIGURE 8.2.1.9. A typical calcic skarn showing a moderate-temperature Stage 4 assemblage (chlorite-quartz-calcite-chalcopyrite-pyrite-bornite) filling the interstices of high-temperature (>550 °C) Stage 2 garnet grains, and selectively replacing some zones in garnet. Qz: quartz; Chl: chlorite; Cc: calcite; cpy: chalcopyrite; py: pyrite; bn: bornite. Credit: Zhaoshan Chang

Metal abundances within skarns vary as a function of the redox state and degree of fractionation of the causative magma. In skarns formed from oxidized and less fractionated magma, molybdenum is enriched near the magma-country rock contact and with increasing distance from this contact mineralization is zoned in the order copper, zinc, lead, silver, and manganese or arsenic. Magnetite is abundant, reflecting the iron-rich nature of the ore fluid, while iron is also required for the formation of garnet and/or pyroxene. At a district/camp scale, a skarn may transition to porphyry- or greisen-type deposits in the causative intrusion, then to a carbonate replacement deposit, and finally to Carlin-type or Carlin-like deposits beyond the skarn. Carbonate replacement deposits may transition to intermediate-sulfidation epithermal deposits where carbonates are overlaid by volcanic rocks.

Carlin-type gold deposits

Carlin-type gold deposits in the western United States supply about 5% of global gold and represent the largest accumulation of gold on Earth after the Witwatersrand in South Africa. Carlin-type deposits formed in sedimentary rocks during the Eocene, from 42 to 36 Ma, temporally and spatially correlated with the southwest sweep of volcanism through the Great Basin of the western United States. Carlin-type deposits occur along five main trends: the north-northwest striking Carlin and Battle Mountain trends, the northeast striking Getchell trend, and the roughly north striking Alligator Ridge and Jerritt Canyon trends.

Carlin-type deposits occur as replacement-style ore, characterized by fine-grained gold-bearing pyrite disseminated primarily in sedimentary rock. The sedimentary host rock mostly comprise shelf and slope carbonate and siliciclastic rocks that formed on the passive margin of the western edge of North America. Some of these sedimentary rocks are carbonaceous black shales where syn-sedimentary pyrite precipitated due to bacterial decomposition of organic matter in an anoxic environment.

Compressional tectonism began in the region around 370 million years ago during the Antler orogeny, which caused deep water siliciclastic rocks to be thrust eastward on top of the slope and shelf rocks. A second compressional event about 270 million years ago called the Sonoma orogeny formed the Golconda thrust. Both thrust faults juxtaposed relatively impermeable siliciclastic rocks over carbonates, creating aquitards that focused later hydrothermal fluids into the more permeable and reactive units beneath the thrusts. Continued compression led to additional crustal shortening in the region, as well as episodes of subduction-related magmatism in the Jurassic and Cretaceous.

In the Eocene, a transition to an extensional tectonic regime inverted the earlier compressional structures and created conduits for the flow of low-temperature (<300°C), low-salinity hydrothermal fluids that also contained carbon dioxide and hydrogen sulfide. The fluids were acidic, leading to decarbonization of the carbonate rocks, thereby creating secondary porosity and permeability. Ore-stage hydrothermal pyrite precipitated onto the margins of earlier, mostly diagenetic pyrite in the host rocks. The hydrothermal pyrite comprises very thin, micron-scale rims with feathery or fuzzy margins that extend as tendrils into the host rock. The gold is “invisible,” occurring as sub-microscopic gold nanoparticles and in the crystal lattice of hydrothermal pyrite. Late ore-stage orpiment and realgar are prevalent, alongside lesser stibnite, and minor galkhaite, fluorite, cinnabar, sphalerite, and tellurides. The ore fluids carried arsenic, antimony, and gold, but relatively little silver, copper, or other base metals.

High spatial resolution analyses of pyrite reveal that the gold occurs in nanoscale arsenic-rich zones, but the gold:arsenic ratios are inconsistent. The sulfur isotopic signatures of the most gold-rich zones are similar to the sulfur isotopic signatures of Eocene magmas and sulfide ore minerals at Eocene magmatic-hydrothermal gold deposits in the Great Basin. This has been interpreted to indicate that Carlin-type deposits formed from magmatic-hydrothermal fluids that exsolved from Eocene calc-alkaline magmas. Deposits with similar characteristics are known in other places such as the Yukon, Canada, southern China, Indonesia, Iran, and Malaysia, but it remains uncertain whether they formed from the same processes as the giant Carlin-type deposits in Nevada.

Simulating ore-forming processes in the laboratory

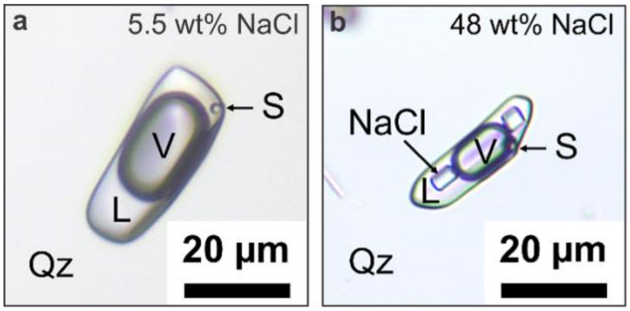
The foundation of our understanding of phase equilibrium in magmatic and associated hydrothermal systems lies in observations made by performing experiments over the range of pressure (*P*) -

temperature (*T*) conditions attending the formation of mineral deposits. Such experiments are used to determine what phases (e.g., minerals, silicate melt, fluid) are stable at certain pressure and temperature conditions in a specific system and what their compositions are. Such data serve as a foundation for thermodynamic models that predict phase equilibrium in such systems.

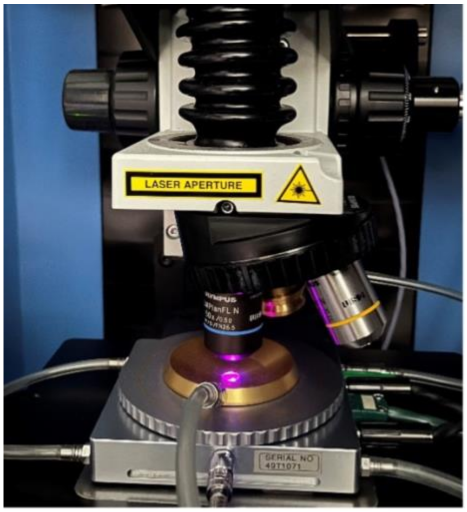
Experimental techniques can be classified based on the timing of observations. These are most commonly made *ex situ* at ambient conditions after the termination of the experiment. Certain methodologies also facilitate direct, *in situ* observations during the experiment. In the case of *ex situ* experiments, the experimental system is enclosed in an inert container with ductile walls, most commonly made of noble metals. This capsule is sealed and placed into an apparatus that allows the generation of the elevated pressure (P) and temperature (T) conditions of interest. In the ideal case, the container does not react with the phase assemblage in the experimental system and allows the transmission of pressure. The capsule is held at the targeted P-T conditions for a sufficient amount of time to reach equilibrium (commonly days to weeks) and subsequently quenched in the hope that during rapid cooling, the phases retain the composition they attained at the experimental *P-T* conditions. This is followed by in situ microanalysis of the resulting phases with techniques such as electron probe microanalysis (EPMA), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), Secondary Ion Mass Spectrometry (SIMS) and X-ray absorption spectroscopy (XAS) or molecular spectrometric techniques. Experiments with non-quenchable phases, such as solute-bearing aqueous fluids representing for example the ore-forming fluids in hydrothermal systems or the vapor bubbles in magmas, pose a particular challenge. To be able to obtain their equilibrium composition, such fluids have to be representatively sampled at the experimental *P-T* conditions or observed and analyzed *in situ*. At magmatic *P-T* conditions, a creative way that has been invented for representative sampling is the trapping of the fluid phase in the form of fluid inclusions in minerals, most commonly quartz. In such experiments, a quartz cylinder is placed in the capsule, and it is fractured by a thermal shock after equilibrium has been attained. The fluid then penetrates the fractures, which subsequently heal to minimize surface energy leading to the formation of isolated microscopic-sized enclosed pockets of fluids, or fluid inclusions. Such inclusions can later be analyzed, most commonly by LA-ICP-MS. In addition, the speciation of various elements (i.e. their valency) in the fluid can be determined by molecular spectrometric methods, most commonly Raman spectrometry, either at ambient conditions or at elevated *P-T* by reheating the inclusions in a microscope heating stage under the Raman spectrometer (See How to box).

How to Box:

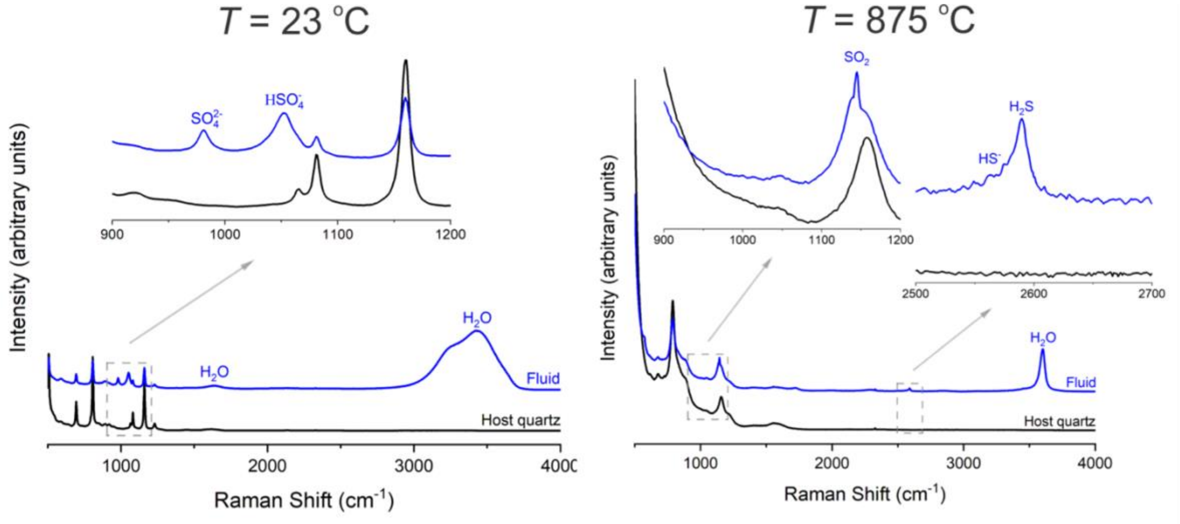
How to determine the speciation of sulfur in deep magmatic fluids?



At first, experiments are conducted in externally heated pressure vessels at controlled *P, T* and redox conditions. The salt and S-bearing aqueous fluid phase in these experiments is trapped after the attainment of equilibrium in the form of synthetic fluid inclusions in quartz. Panel **a** shows a synthetic fluid inclusion (SFI) formed from a low-salinity fluid at *P*=200 MPa and *T*=875 °C, typical conditions of upper crustal magma reservoirs. The originally single-phase fluid unmixes to a liquid phase (L) and a vapor bubble (V) upon cooling, in addition some solid elemental sulfur (S) has precipitated. Panel **b** shows a fluid inclusion formed from a high-salinity fluid, which also precipitated a salt crystal upon cooling to ambient *T*.



Subsequently, such SFI are reheated in a microscope heating stage to their entrapment *T*, and the *P* inside the inclusion increases also close to the entrapment *P* due to the nearly constant volume of the SFI. At the experimental *P*-*T* conditions, Raman spectra are collected to identify and quantify various S species.



The resulting Raman spectra highlight the importance of *in situ* measurements at elevated *P-T*. In the quenched fluid at 23 °C, S is present as aqueous HSO_4^- and SO_4^{2-} species and as elemental solid S, whereas at 875 °C, it forms predominantly SO_2, H_2S and HS^-. Note that the blue spectra were obtained from the fluid phase + host quartz, whereas the black spectra show the signal from the host quartz only as reference.

This leads us to the class of *in situ* experimentation, where the studied system is observed directly during the experiment visually and/or by various spectrometric techniques using electromagnetic radiation that can penetrate the walls of the system container (e.g. Raman spectrometry, XAS). These techniques may facilitate the determination of the bulk composition of the equilibrium phases and also provide information on the structure of solids or the speciation of elements in any of the stable phases.

Regarding the experimental apparatuses employed, for *ex situ* experimentation on phase equilibrium in volcanic systems at upper crustal pressures, gas-pressurized vessels are most commonly used. These can be heated either internally or externally. In internally heated pressure vessel apparatuses (IHPV), a relatively large-volume vessel is pressurized with argon gas and the pressurized volume includes a tubular resistance heater, within which the capsule is contained. In externally-heated pressure vessel apparatus (EHPV), a tubular pressure vessel made of special alloys contains the experimental capsule and is pressurized with argon gas. In turn, the whole assembly is heated together in a tube furnace (Fig. 8.2.1.10). In both types of apparatus, we can attain up to several thousand times atmospheric pressure and temperatures up to 1200°C. *In situ* experiments at the *P-T* conditions of shallow crustal magma storage are restricted to synthetic fluid inclusions (See How to Box) or with certain limitations to diamond anvil cell experiments where a special glassy carbon-lined pressure vessel is developed for in situ XAS.

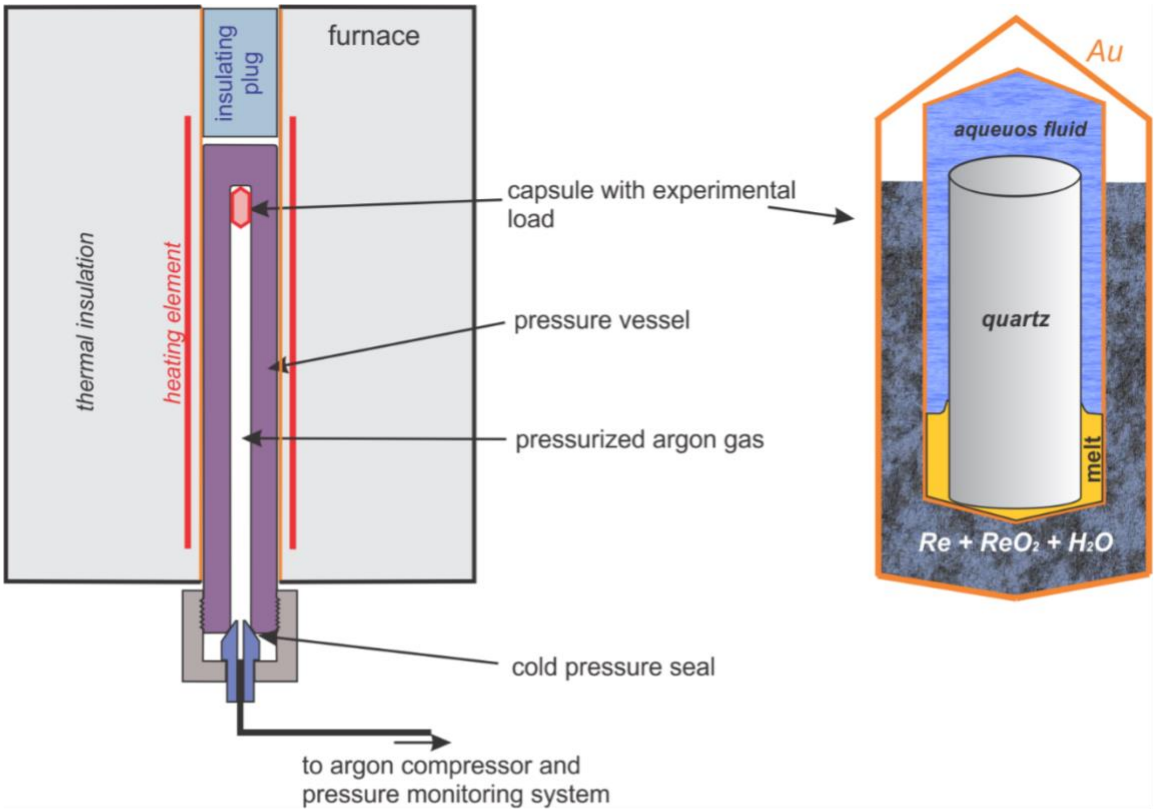


FIGURE 8.2.1.10.
Schematic drawing of an externally-heated pressure vessel apparatus (left) and a gold metal capsule prepared for an experiment to study the partitioning of elements between aqueous fluid and silicate melt by using the synthetic fluid inclusion technique (right).
Credit: Zoltan Zajacz

Insights from High-Pressure Experiments

Magmatic phase equilibrium is the first key phenomenon with relevance to ore genesis that we can study by experiments. For example, experiments have shown that amphibole and garnet are stable phases during the crystallization of hydrous arc magmas in deep crustal magma reservoirs, while plagioclase is destabilized by the presence of dissolved water in the silicate melt. This leads to specific geochemical signatures in the residual melt, such as high strontium/yttrium ratios. Magma differentiation at greater crustal depths also leads to the concentration of volatile constituents such as water, sulfur and chlorine in the residual melt, which in turn play a critical role in the generation of ore fluids after the ascent of these melts to the upper crust. This explains the positive correlation observed between the fertility of arc magmas for magmatic hydrothermal copper-gold-molybdenum deposits and their characteristic strontium/yttrium ratio.

Magmas may reach saturation in a solid and/or liquid sulfide phase, the latter effectively sequestering the chalcophile metal budget of the melt. This is the process that produced large magmatic sulfide deposits in layered mafic intrusions, such as the Sudbury meteorite impact 1.85 billion years ago. However, such sulfides may form also in hydrous arc magmatic systems, although their role in the regulation of magma fertility during magmatic hydrothermal ore genesis is debated. They may sequester the metal budget of the magma leading to infertility, or their metal budget may be recycled during fluid exsolution from the magma and transferred to the associated hydrothermal systems leading to increased ore fertility. Either way, understanding how economically important metals partition between sulfides and silicate melts is essential for assessing the role of magmatic sulfide saturation in ore genesis. This has been studied experimentally, and the results showed that chalcophile elements such as copper, gold, platinum and palladium are effectively sequestered by magmatic sulfides, whereas others such as molybdenum, tin, tungsten, lead, and zinc do not partition strongly enough into sulfides to be significantly affected by magmatic sulfide saturation.

Saturation of a fluid phase is a pre-requisite for the transfer of ore metals from magmas into hydrothermal systems associated with them. To model this process, the solubility of volatile constituents in silicate melts must be quantitatively determined. High-pressure experiments revealed the strong positive effect of pressure on volatile solubilities in silicate melts and allows the construction of solubility models for water and carbon dioxide with predictive capability over a broad range of *P, T* and melt composition. Silicate melts can dissolve as much as several weight percent (weight percent) water at upper crustal pressures and well above 10% at lower crustal pressures. The solubility of CO_2 is about one order of magnitude, or a factor of 10, lower; thus, carbon dioxide saturation may trigger fluid exsolution in an early stage of magma evolution. As soon as a fluid phase has formed, volatile and metallic elements partition between this fluid and the associated silicate melt. Their fluid/melt partition coefficients are controlled by melt composition, *P, T,* and in the case of metals, the presence of ligands that combine with the cationic metals to form stable aqueous complexes. Chlorine and sulfur are common minor constituents of magmas and are the most common ligands for metal complexation, for example as the chloride ion (Cl^-) or bisulfide ion (HS^-). Consequently, to be able to model ore metal extraction from magmas, one first needs to quantify how chlorine and sulfur partitions between the fluid and the melt phases as a function of *P, T,* melt composition, and in the case of sulfur, redox conditions. Numerous experimental studies have been conducted to quantify these relationships. One of most important observations is that chlorine partitions strongly to the fluid only from felsic melts, restricting the efficient fluid extraction of chloride-complexed metals, such as copper, to late stages of magma crystallization. Another important experimental outcome highlights the redox-dependent partitioning of sulfur, which favors the fluid phase much more strongly in its reduced state (HS^- or S^{2-}) than in its oxidized state (S^{4+} or S^{6+}). Sulfur transfer to the fluid is particularly important, because sulfur is the element that facilitates the precipitation of metal sulfides in the associated hydrothermal systems. Indeed, experimental results in combination with model calculations have shown that at greater crustal pressures, a significant fraction of the oxidized sulfur budget of a magma may be withheld by primary magmatic anhydrite. Such anhydrite, in combination with vapor bubbles retained in the magma, may, for example, be the source of the “excess sulfur” phenomenon often observed during the eruption of intermediate to felsic magmas. “Excess sulfur” refers to significantly more sulfur being emitted into the atmosphere than was dissolved in the silicate melt phase to start with.

The final critical process to consider during the magmatic history of ore forming systems is the partitioning of ore metals into the fluid phase. Since the analysis of fluid inclusions by LA-ICP-MS became possible, most experimental studies aiming to quantify metal partitioning have been using the synthetic fluid inclusion technique. Aqueous fluids with various volatile and solute components, analogue to those found in natural fluid saturated magmas, were equilibrated with silicate melts of various composition. The fluids were trapped at the experimental *P-T* conditions as inclusions in quartz, with the compositions being subsequently determined by LA-ICP-MS. At the termination of such experiments, the silicate melt quenches to a glass, the composition of which is also determined. By comparing the composition of the fluid and melt phases, fluid/melt partition coefficients can be derived. Such studies have shown for example that effective transfer of copper, silver, molybdenum, tin, indium, platinum and palladium to the fluid phase requires the presence of significant amount of chlorine to form aqueous complexes with these metals, whereas gold is more effectively transported in the form of bisulfide complexes even at magmatic temperatures.

Mineral beneficiation and environmental considerations

Mineral Beneficiation

Mineral deposits require some form of processing or beneficiation in order to extract the minerals and metals. Several possibilities for this exist and is dependent on the occurrence of the minerals and host constituents and the form that they are beneficial in. Typically, most ores require some form of crushing and grinding to a suitable size for further processing. Grinding the crushed material further into finer particles increases the surface area for chemical reactions during subsequent steps. The most common and historically important step in mineral processing is gravity separation, that exploits the density difference between minerals. This technique is useful for separating heavy minerals, like sulfides, from lighter gangue minerals or for concentrating metals, like gold, away from the gangue material. There are many options for this including; jigs, shaking tables, spiral concentrator and spiral cones.

Where the minerals of interest are fine-grained or intimately associated with waste materials (or gangue), a common method for separation is Froth Flotation that is based on their hydrophobicity. In this process, finely ground ore is mixed with water and chemicals called collectors, which selectively bind to the surface of the desired minerals, allowing them to be separated from the gangue. Another common method of separation is based on the separation of magnetic minerals from non-magnetic minerals (termed Magnetic Separation). This method exploits the magnetic properties of minerals, utilizing magnetic fields. Magnetic separation is particularly useful with iron, ores of niobium and tantalum, and many of the rare earth element minerals.

Where a metal is held within a mineral lattice, the separation of the metal from the uneconomic components requires separation. A common method is the leaching of the metals using a solvent. Sulfuric Acid leaching is commonly used for extracting metals like copper, zinc, and nickel whereas Hydrochloric Acid is commonly used for rare earths and an alkaline cyanide solution for gold and silver. In general, the solvent dissolves the mineral host and complexes the metal of interest. Other gangue phases show only limited solubility and hence the separation. A more extreme version of this is to melt the rock material in a Smelter and then separate out the metal of interest in a magmatic type metal soup. This is also used in refining crude metal precipitates to saleable products as well.

To collect the metal from solution a form of precipitation is required, this traditionally is through formation of an insoluble phase, but this has largely been replaced by membrane or solvent technology to collect, concentrate and then precipitate a purer metal product that be solved; for example, in the beneficiation of copper using an immiscible organic solvent to separate copper from the aqueous sulfuric acid solution and then electrowinning to produce the copper anode plates. These beneficiation methods can be used individually or more commonly in combination depending on the specific characteristics of the mineral deposit and the desired minerals to be extracted. Additionally, environmental considerations and economic feasibility play crucial roles in selecting the appropriate beneficiation process.

Environmental issues

The development of any mine or mineral deposit comes with a degree of environmental degradation. Modern mining methods seek to minimize or mitigate these impacts. The most obvious impact from open-pit mining and waste rock disposal is sterilization of land for further use and the resulting devaluation of that land. In addition, in some climates mining can also result in land degradation, soil erosion, deforestation, and alteration of landforms. The disturbance of land surfaces can have long-term effects on ecosystem productivity and soil fertility. This can also lead to loss of habitat for fauna and flora decreasing the population or occurrence of both in extreme cases leading to extinction through loss of habitat and fragmentation of ecosystems. Such impacts can also lead to adverse visual impacts, particularly in areas with pristine natural scenery.

One of the more visible issues with mining is the impact on local water resources, especially with deposits containing sulfide minerals that can generate Acid Rock Drainage-Metal Leaching (ARDML) waters when exposed to air or water. This can occur in waste rock or process waste facility, or on exposed open pit walls. During mining, exposed material within the mine may react with water, with some minerals being oxidized to produce acid that can modify the chemical composition of water. Most commonly, exposure of iron sulfide minerals – particularly pyrite (FeS_2) and marcasite – to water and air (O_2) produces acid (H^+), sulfates SO_4^{2-} and aqueous ferrous iron (Fe^{2+}) shown by the following chemical reaction.

$$FeS_2 + \frac{7}{2}O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+$$

In evaluating acid-generation potential, the objective is to balance processes that generate acidic environments with those that can neutralize acid. Any test work must reflect the actual mineralogical reactions that will likely occur at the mine in question.

Water has many uses in mining and processing activities. Mine waters originate as groundwater or rainwater, which undergo chemical modification in situ through mineral-water reactions. Mine water here refers to any runoff or flow through a portion of a mine site, and/or that has had contact with any of the mine workings. Water quality is now heavily regulated and closely managed at a mine, in terms of use, interaction, and discharge. The understanding of the water management system for a mining operation is a critical component of mining environmental management. An assessment of global impacts to water resources shows that the largest contributor globally is agriculture, but mining can be a local or regionally important factor. In some locations, such as parts of northern Chile, mining operations are no longer permitted if they do not have an alternative water supply such as desalinated seawater, since local water sources are over exploited.

Scientific understanding of the processes that lead to poor water quality of drainage from metal mines generates the basis for guidelines and regulatory limits. Rapid and relatively inexpensive multi-element analyses of water samples allow the concentration of contaminants to be measured, helping to quantify and understand rock-water reactions. Mineralogical analysis is used to identify primary minerals, such as sulfides that tend to oxidize and produce acid drainage, and carbonates that may provide neutralization capacity; in addition, secondary minerals may armor sulfide minerals from oxidation or may sequester some metals. Mining and processing operations can release particulate matter, sulfur dioxide (SO_2), nitrogen oxides (NOx), and other air pollutants into the atmosphere from excess vehicle traffic, power generation, mineral beneficiation and blasting of rock. These pollutants can contribute to air quality degradation and have adverse effects on human health and the environment.

Communities near mining operations may be exposed to environmental contaminants from mining activities, leading to potential health risks such as respiratory problems, neurological disorders, and heavy metal poisoning. Dust emissions, water contamination, and exposure to hazardous chemicals are primary concerns. Social problems may also occur due to temporary high paid jobs leading to rapid expansion of remote settlements and then loss of this employment when the mine closes.

A modern concern for mining is the long-term management of tailings, the waste material generated from mineral processing. This process is crucial to prevent environmental contamination. Improper storage and disposal of tailings can result in the release of toxic substances and pose risks to aquatic ecosystems and human health, and in some cases result in catastrophic accidents such as the Samarco incident in Brazil, the Williamson Mine in Tanzania and the Jagersfontein Mine in South Africa in 2022, the Tieli dam failure in China in 2020, the Córrego do Feijão Mine in Brumadinho, Brazil, in 2019, the Cadia Mine in Australia in 2018, the Germano Mine in Mariana, Brazil, in 2015, the Padcal Mine in the Philippines in 2012, and the São Francisco dam failure in Miraí, Brazil, in 2007 [11].

Global standards of tailings management are now proposed. Addressing these environmental issues requires comprehensive planning, mitigation measures, and regulatory oversight throughout the lifecycle of mining operations for such resources. Implementing best practices in environmental management, such as minimizing waste generation, adopting cleaner production technologies, and engaging in reclamation and restoration efforts, can help mitigate the adverse impacts on the environment and surrounding communities. Additionally, stakeholder engagement, including consultation with local communities and Indigenous groups, is essential to ensure that environmental concerns are adequately addressed, and sustainable development goals are met. A change in resource focus has led to many tailings been identified as potential new resources for critical metals. Less common is the utilization of waste rock and low-grade ore as potentially economic feed due to changes in metal prices and improved metallurgy. A critical aspect of addressing environmental challenges and reducing environmental impact involves engagement with communities, government and society and involving them in the development, implementation, and monitoring of options for mitigation of environmental effects. The confidence of society is essential to the delivery of long-term sustainable plans.

Social, environmental and regulatory considerations

Responsible Mineral Developments

The notion of responsible mining was born from a recognition of the negative impacts and positive potential of the extractive sector. The mining industry has a responsibility to mitigate its impacts, and most companies now recognize they have obligations to the societies in which they operate, beyond financial viability [12, 13]. Responsible mining is inherent to corporate policies and practices that fall under the purview of corporate social responsibility (CSR), as well as the economic corollary of environmental, social, and governance (ESG). Responsible mining is also inscribed in the broader sourcing apparatus, in which companies intend to address risks and problems in their supply chains.

The scope of responsible mining is vast and contentious. While the most visible aspects encompass environmental and social issues, a holistic approach includes taxation systems, labor rights, transparency and traceability, and tailings and closure management. The concept also materializes differently between industrial, large-scale mining (LSM) and artisanal and small-scale mining (ASM) operations with significantly diverse operating and risk profiles. Thus, strategies for responsible mining need to be tailored to the type of operations, the socio-economic realities of the communities surrounding the projects, and the environmental specificities of the area. The concept should also encompass less visible aspects of a mining operations, such as the type of ore extracted, the timeframe from exploration to exploitation to closure, as well as the historical imbalances between communities, governments, and the mining industry.

The Relevance of Communities

Mining is geographically restricted to the locations where minerals are found in the Earth. This often leads to mining projects operating close to communities. The relationship between mining and communities also extends beyond immediate geographical boundaries, with mining projects having far reaching, regional, national, or even global economic, social, and environmental impacts. Mining is often done through two different approaches, each with its own set of characteristics, advantages, and challenges. Large-scale mining typically involves the use of advanced technologies, substantial capital investment, and operations that span vast areas. These operations are often undertaken by multinational corporations and require significant infrastructure, including machinery, transportation networks, and processing facilities. Large-scale mining projects have the capacity to extract significant quantities of minerals efficiently, making them well-suited for meeting the demands of global markets.

Alternatively, ASM typically involves little or no mechanization. Some of these operations take place in remote or economically marginalized locations, where access to formal employment opportunities is limited. However, ASM increasingly occurs in areas with intense industrial production of metals. For example, a fifth of the global production of cobalt comes from small operations in the Democratic Republic of the Congo. Vilified for its devastating impacts on individual miners and its often-illicit structure, ASM nonetheless provides a crucial source of income for community members and their families and can contribute to poverty alleviation and local development. However, these operations also present challenges, including limited access to financing and technical support, inadequate safety standards, and environmental degradation. The large-scale and artisanal- and small-scale mining sectors generally operate separately, but they are intimately linked. Artisanal and small-scale miners often operate adjacent to or on LSM concessions, having been there before LSM operations began or moving into an area once a deposit is identified. This cohabitation is often complex and has pushed companies and governments to take actions to mitigate harms.

Social, Economic, and Environmental Impacts and Communities

If developed in a socially, economically, and environmentally conscious way, mining can have positive impacts. It provides jobs, develops infrastructure like roads that can benefit local communities, and it contributes to a country’s economy through taxes and royalties. In regions where employment opportunities are limited, mining can be a source of income for local residents, at least during the life span of the operations. Large mining companies often invest in programs and initiatives aimed at improving education, healthcare, and other essential services in the communities where they operate, thereby contributing to local development.

However, mining is also disruptive to local communities and can have negative impacts. Entire communities can be displaced by mining activities, while mining-dependent communities may face challenges with boom-and-bust cycles, where income and economic prosperity are closely tied to fluctuations in commodity prices. This can create instability and vulnerability, as communities become overly reliant on a single industry that is susceptible to market volatility. The construction of a mine can lead to an influx of outsiders to small and remote communities leading to social disruption and straining local infrastructure and services by increasing housing costs and crime rates. Additionally, often the economic benefits of mining accrue disproportionately to multinational corporations and national governments, exacerbating social inequalities and further marginalizing local communities. Environmental degradation caused by mining activities can have long-lasting consequences, affecting agricultural productivity, tourism, and other sectors dependent on healthy ecosystems. For Indigenous and other communities, whose cultures and identities are intimately tied to the land, destruction of sacred sites and resources can undermine Indigenous land rights and have profound social and spiritual effects.

Regulatory Framework

The regulatory framework plays a crucial role in ensuring that mining developments are conducted responsibly, balance the interests of stakeholders, safeguard the environment, and promote sustainable development. Regulations governing the mining sector typically encompass a wide range of issues, including environmental protection, health and safety standards, Indigenous and community rights, land use, and revenue management.

Environmental regulations are important in ensuring that mining companies minimize harm to ecosystems, biodiversity, and natural resources and are held responsible for current and future issues. These regulations usually require companies to conduct Environmental Impact Assessments (EIAs), develop mitigation plans, and obtain permits before commencing mining operations. They may also specify standards for waste management and disposal, water treatment, and reclamation to ensure the restoration of affected landscapes post-mining. Health and safety regulations protect workers and communities living near mining sites. These regulations may establish standards for workplace safety, occupational health, and emergency preparedness and may also require companies to provide training, protective equipment, and medical services to employees and nearby residents.

Human rights are another key consideration within the regulatory framework. Regulations may mandate consultation with and the consent of Indigenous peoples before granting permits for mining projects, in accordance with national standards such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). In particular, free, prior, and informed consent (FPIC) is an established framework that should guide engagements with Indigenous communities, giving them more power to orient and potentially reject a project. Regulations may also require companies to negotiate agreements with Indigenous communities to ensure that they receive fair compensation, benefits, and opportunities for participation.

Effective enforcement and oversight mechanisms are essential for ensuring compliance with regulatory requirements and holding companies accountable for their actions. Regulatory agencies responsible for overseeing the mining sector must have adequate resources, expertise, and independence to monitor and enforce compliance with environmental, health and safety, and social standards. In many cases of developing countries, the rules exist, but the lack of financial and human capacities may limit their implementation.

Stakeholder Engagement and Participation

Meaningful engagement and consultation with affected communities, as well as participation from Indigenous and marginalized groups, is essential to ensure that their voices are heard and that their rights are protected and respected in decision-making processes related to mining projects. Meaningful engagement goes beyond mere information sharing or token gestures of consultation; it involves fostering genuine dialogue, building trust, and empowering local communities to participate actively in decision-making processes that affect their lives and livelihoods. This is required in, for example, Peru, where mining companies are obligated to obtain approval from the competent authorities of their environmental impact assessment (EIA), which must provide specific details for a community participation program and execution, before a project can be started [14].

Consultation with affected communities should occur early in the mining stage and be conducted in a transparent and inclusive manner, allowing community members to express their concerns, priorities, and aspirations regarding a proposed project. This involves providing information about the project's potential impacts, risk, and benefits in a language and format that is understandable. Meaningful consultation also requires active listening, respect for diverse perspectives, and a willingness to consider alternative viewpoints, even if they challenge the interests of the mining company.

Community participation entails involving local stakeholders in the design, implementation, and monitoring of mining projects and empowering them to contribute to decision-making processes and shape outcomes in ways that reflect their priorities and values. This may involve establishing community advisory committees, conducting regular meetings and workshops, and facilitating capacity building initiatives to enhance the skills and knowledge of community members. By engaging communities as partners rather than passive recipients of development initiatives, mining companies may leverage local expertise, cultural insights, and traditional knowledge to co-create solutions that are socially, culturally, and environmentally appropriate.

The role of Indigenous peoples in mining developments is complex and multifaceted, shaped by historical injustices, cultural values, and legal frameworks governing land rights and resource management. Indigenous communities often inhabit territories rich in natural resources targeted for mining activities, placing them at the forefront of debates over land ownership, environmental protection, and socio-economic development. Mining companies must engage in genuine dialogue, build trust, and establish mutually beneficial partnerships with Indigenous people based on principles of equity, reciprocity, and shared benefits.

Social License to Operate

Social license to operate (SLO), a concept ideated and introduced to the world by mining executive Jim Cooney at a World Bank conference in 1997 [16], is a critical concept in the mining industry, reflecting the understanding that a mining company's legitimacy and right to conduct mining activities are contingent on its relationship with the communities and stakeholders affected by its operations. Although SLO refers to the acceptance and approval of a mining project by its stakeholders more generally, local community stakeholders are often the arbiters of SLO. There is no legal permission or regulatory compliance associated with SLO.

Gaining and maintaining SLO is essential for mining projects. Without the support and participation of local communities, companies may face opposition through protests and legal challenges that can disrupt operations, delay project timelines, and damage company reputations. A lack of SLO can also undermine investor confidence and lead to financial losses for mining companies, as shareholders are increasingly prioritizing sustainability and social responsibility in their investment decisions. Building SLO requires proactive engagement with stakeholders throughout all stages of the mining project lifecycle, from exploration and development to closure and reclamation. Companies must demonstrate their commitment to economic growth by implementing best practices in environmental management, social impact assessments, and community development.

Recent and needed advances

Mining companies are struggling to discover new mineral deposits at a time when society needs increased mine production for economic development and the transition to renewable energy infrastructure. The precipitous decline in mineral deposit discovery signals that exploration strategies of the past are not working. Exploration desperately needs innovation. Artificial intelligence and machine learning will certainly help improve mineral exploration, but they are not a panacea considering that mining companies have been using these computational technologies since they were developed. Mineral discovery is a chain of tough probabilities. Discovery of a mineral occurrence must be followed by drilling and preliminary economic and engineering assessment to confirm a potential mineral resource. Further drilling, economic evaluation, engineering, and metallurgical assessment are required to develop an ore reserve that can serve as the basis for building a mining operation. With the right macro-economic conditions including a higher copper price, there are also mineral resources that lie at depths deeper than the ~500 meters below surface that are currently being explored. Deeper underground mining is feasible by block caving and remote operation methods that are safe and environmentally friendly can be used to develop these copper resources. Deep mines will have a much smaller surface environmental imprint than current surface mines. If we begin to explore for deeper deposits, discovery rates could increase. Also, there are substantial mineral resources contained in surface stockpiles. For example, one multinational mining company estimates they have over 17 million tonnes of copper in waste stockpiles previously thought to be unrecoverable. With advancements in leaching techniques, this copper can become part of the global supply chain. Because it was previously mined, the production is low-cost and has a lower carbon footprint.

Summary

This chapter provides an overview of the formation of mineral deposits formed during crustal magmatism and related hydrothermal processes. Magmatic sulfide deposits are the primary source of platinum-group elements as well as significant source of nickel and copper. Porphyry deposits are the primary source of copper and molybdenum and significant suppliers of byproducts such as gold, silver, rhenium and tellurium. Epithermal deposits are important sources of gold and silver and byproducts such as copper, lead, zinc and mercury. Iron oxide-copper-gold deposits are important sources of their namesake metals as well as byproducts sch as cobalt, silver, rare earth elements and uranium in some deposits. Skarn deposits are an important source of iron, copper, tin, tungsten, zinc lead, and gold. Carlin-type gold deposits are important gold producers. Each of these mineral deposit types will continue to play an important role in supplying metals for global development. Understanding how these mineral deposits form is important to inform exploration programs to discover new mineral deposits to replace current deposits that become exhausted and to increase supply to meet growing demand.

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