Mineral resources, while principally nonrenewable, are generally placed in two main categories: **metallic** (containing metals) or **nonmetallic** (containing other useful materials). Most mining is focused on metallic minerals. A significant part of the advancement of human society has been developing the knowledge and technologies that yielded metal from the Earth and allowed the machines, buildings, and monetary systems that dominate our world today. The location and recovery of these metals have been a key facet of the study of geology since its inception. Every element across the periodic table has specific applications in human civilization. Metallic mineral mining is the source of many of these elements.
16.3.1: Types of Metallic Mineral Deposits

The number of ways that minerals and their associated elements concentrate to form ore deposits are too complex and numerous to fully review in this text. However, entire careers are built around them. Some of the more common types of these deposits are described, along with their associated elemental concentrations and world-class occurrences.

Magmatic Processes

![Layered intrusion of dark chromium-bearing minerals, Bushveld Complex, South Africa](image)

Crystallization and differentiation (see chapter 4) of a magmatic body can cause the concentration of certain minerals and elements. **Layered intrusion** (typically ultramafic to mafic) can be host to deposits that contain copper, nickel, platinum-palladium-rhodium, and chromium. The Stillwater Complex in Montana is an example of an economic layered mafic intrusion [30]. Associated deposit types can contain chromium or titanium-vanadium. The largest magmatic deposits in the world are the chromite deposits in the Bushveld Igneous Complex in South Africa [31]. Rocks of the Bushveld Igneous Complex have an areal extent larger than the state of Utah. The chromite occurs in layers, which resemble sedimentary layers, except this occurred within a crystallizing magma chamber.

![This pegmatite from Brazil contains lithium-rich green elbaite (a tourmaline) and purple lepidolite (a mica).](image)

Water and other volatiles that are not incorporated into mineral crystals while a magma crystallizes become concentrated around the margins of these crystallizing magmas. Ions in these hot fluids are very mobile and can form exceptionally large
crystals. Once crystallized, masses of these large crystals are called **pegmatites** that form from the concentration of magma fluids near the end of crystallization when nearly the entire magma body has crystallized. In addition to minerals that are predominant in the main igneous mass, such as quartz, feldspar, and mica, pegmatite bodies may also contain very large crystals of unusual minerals that contain rare elements like beryllium, lithium, tantalum, niobium, and tin, as well as native elements like gold [32]. Such pegmatites are ores of these metals.

Figure 1: Schematic diagram of a kimberlite pipe.

An unusual magmatic process is a **kimberlite** pipe, which is a volcanic conduit that transports ultramafic magma from depths in the mantle to the surface. Diamonds, which are formed at great temperature and depth, are transported this way to locations where they can be mined. The process that emplaced these kimberlite (ultramafic) rocks is no longer common on Earth, and most of the known deposits are Archean [33].

**Hydrothermal Processes**

Figure 2: The complex chemistry around mid-ocean ridges.
Fluids rising from crystallizing magmatic bodies or heated by the geothermal gradient cause a wide range of geochemical reactions that can form a variety of mineral deposits. The most active hydrothermal process today produces volcanogenic massive sulfide (VMS) deposits, which form from black smoker activity near mid-ocean ridges all over the world, and commonly contain copper, zinc, lead, gold, and silver when found on the surface [34]. The largest of these deposits occur in Precambrian age rocks. The Jerome deposit in central Arizona is a good example.

Another type of deposit which draws on heated water from magma is a porphyry deposit. This is not to be confused with the igneous texture porphyritic, although the name is derived from the porphyritic texture that is nearly always present in the igneous rocks in a porphyry deposit. Several types of porphyry deposits exist: porphyry copper, porphyry molybdenum, and porphyry tin. They are characterized by the presence of low-grade disseminated ore minerals closely associated with intermediate and felsic intrusive rocks over a very large area [35]. Porphyry deposits are typically the largest mines on Earth. One of the largest, richest, and possibly best-studied mines in the world is Utah’s Bingham Canyon open-pit mine, which has had over 100 years of high production of several elements including copper, gold, molybdenum, and silver. Associated underground carbonate replacement deposits have produced lead, zinc, gold, silver, and copper [36]. Past open pit production at this mine was dominated by copper and gold from chalcopyrite and bornite. Gold occurs in minor quantities in the copper-bearing mineral, but the large scale of production makes Bingham Canyon one of the largest gold mines in the U.S. Future production may be more copper and molybdenum (molybdnite) from deeper underground mines.
The majority of porphyry copper deposits owe their economic value to concentration by weathering processes occurring millions of years after the hosting intrusion called supergene enrichment. These occur once the hydrothermal event has ceased and the ore body has been uplifted, eroded, and exposed to oxidation [37]. When the upper pyrite-rich portion of the deposit is exposed to rain, pyrite in the oxidizing zone creates an extremely acid condition which dissolves copper out of copper minerals such as chalcopyrite, converting the chalcopyrite to iron oxides like hematite or goethite. The copper is carried downward in the solution until it arrives at the groundwater table and a reducing environment where the copper precipitates, converting primary copper minerals into secondary higher-copper content minerals. Chalcopyrite (35% Cu) is converted to bornite (63% Cu) and ultimately chalcocite (80% Cu). Without this enriched zone (2 to 5 times higher in copper content than the main deposit) most porphyry copper deposits would not be economic.

Figure (\(\PageIndex{1}\)): Garnet-augite skarn from Italy.

If limestone or other calcareous sedimentary rocks are present adjacent to the magmatic body, then another type of ore deposit called a skarn deposit can form. These metamorphic rocks form as magma-derived, highly saline metalliferous fluids react with carbonate rocks, creating calcium-magnesium-silicate minerals like pyroxene, amphibole, and garnet, as well as high-grade zones of iron, copper, and zinc minerals and gold [38]. Intrusions that are genetically related to the intrusion that made the Bingham Canyon deposit have also produced copper-gold skarns that were mined by the early European settlers in Utah [39; 40]. Metamorphism of iron and/or sulfide deposits commonly results in an increase in grain size that makes separation of gangue from the desired sulfide or oxide minerals much easier.
Sediment-hosted disseminated gold deposits consist of low concentrations of microscopic gold as inclusions and disseminated atoms in pyrite crystals. These are formed via low-level hydrothermal reactions (generally in the realm of diagenesis) that occur in certain rock types, namely muddy carbonates and limey mudstones. This hydrothermal alteration is generally far-removed from a magma source but can be found in extended rocks with a high geothermal gradient. The earliest locally mined deposit of this type was the Mercur deposit in the Oquirrh Mountains of Utah where almost one million ounces of gold were recovered between 1890 and 1917. In the 1960s a metallurgical process using cyanide was developed for these types of low-grade ores. These deposits are also called Carlin-type deposits because the disseminated deposit near Carlin, Nevada is where the new technology was first applied and because the first definitive scientific studies were conducted there \[41\]. Gold was introduced by hydrothermal fluids which reacted with silty calcareous rocks, removing carbonate, creating additional permeability, and adding silica and gold-bearing pyrite in the pore space between grains. The Betze-Post mine and the Gold Quarry mine on the “Carlin Trend” are two of the largest of the disseminated gold deposits in Nevada. Similar deposits, but not as large, have been found in China, Iran, and Macedonia \[42\].
Geochemical processes that occur at or near the surface without the aid of magma also concentrate metals, but to a lesser degree than hydrothermal processes. One of the main reactions is redox (short for reduction/oxidation) chemistry, which has to do with the amount of available oxygen in a system. Places where oxygen is plentiful, as in the atmosphere today, are considered oxidizing environments, while oxygen-poor environments are considered reducing. Uranium deposition is an example of redox mobilization. Uranium is soluble in oxidizing groundwater environments and precipitates as uraninite when reducing conditions are encountered. Many of the deposits across the Colorado Plateau (e.g. Moab, Utah) were formed by this method [43].

Redox reactions were also responsible for the creation of banded iron formations (BIFs), which are interbedded layers of iron oxide (hematite and magnetite), chert, and shale beds. These deposits formed early in the Earth’s history as the atmosphere was becoming oxygenated. Cyclic oxygenation of iron-rich waters initiated the precipitation of the iron beds. Because BIFs are generally Precambrian in age, they are only found in some of the older exposed rocks in the United States, in the upper peninsula of Michigan and northeastern Minnesota [44].

Deep, saline, connate fluids (trapped in the pore spaces), within sedimentary basins may be highly metalliferous. When expelled outward and upward during basin compaction, these fluids may form lead and zinc deposits in limestone by replacement or by filling open spaces (caves, faults) and in sandstone by filling pore spaces. The most famous of these are called Mississippi Valley-type deposits [44]. Also known as carbonate-hosted replacement deposits, they are large deposits of
galena and sphalerite (lead and zinc ores) which form from fluids in the temperature range of 100 to 200°C. Although they are named for occurrences along the Mississippi River Valley in the United States, they are found worldwide.

**Sediment-hosted copper** deposits occurring in sandstones, shales, and marls are enormous in size and their contained resources are comparable to porphyry copper deposits. These were most-likely formed diagenetically by groundwater fluids in highly-permeable rocks [45]. Well-known examples are the Kupferschiefer in Europe, which has an areal coverage of >500,000 Km², and the Zambian Copper Belt in Africa.

![A sample of bauxite. Note the unweathered igneous rock in the center.](image)

Deep and intense weathering of soils and mineral deposits exposed at the surface can result in the formation of surficial deposits. **Bauxite**, an ore of aluminum, is preserved in karst topography and laterites (soils formed in wet tropical environments) [46]. Aluminum concentrates in soils as feldspar and ferromagnesian minerals in igneous and metamorphic rocks undergo chemical weathering processes. Weathering of ultramafic rocks results in the formation of nickel-rich soils and weathering of magnetite and hematite in banded iron formation results in the formation of goethite, a friable mineral that is easily mined for its iron content.

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**Surficial Physical Processes**

![Lithified heavy mineral sand (dark layers) from a beach deposit in India.](image)
At the earth’s surface, the physical process of mass wasting or fluid movement concentrates high-density minerals by hydraulic sorting. When these minerals are concentrated in streams, rivers, and beaches, they are called **placer** deposits, whether in modern sands or ancient lithified rocks [47]. Native gold, native platinum, zircon, ilmenite, rutile, magnetite, diamonds, and other gemstones can be found in placers. Humans have mimicked this natural process to recover gold manually by gold panning and by mechanized means such as dredging.

### 16.3.2: Environmental Impacts of Metallic Mineral Mining

![Figure 1: Acid mine drainage in the Rio Tinto, Spain.](image)

The primary impact of metallic mineral mining comes from the mining itself, including disturbance of the land surface, covering of landscapes by tailings impoundments, and increased mass wasting by accelerated erosion [48]. In addition, many metal deposits contain pyrite, an uneconomic sulfide mineral placed on waste dumps, which may generate **acid rock drainage** (ARD) during weathering. In the presence of oxygenated water, sulfides such as pyrite react undergo complex reactions to release metal ions and hydrogen ions, lowering pH to highly acidic levels. Mining and processing of mined materials typically increase the surface area to volume ratio in the material, causing reactions to occur even faster than what would occur naturally. If not managed properly, these reactions may lead to acidification of streams and groundwater plumes that can carry dissolved toxic metals. In mines where limestone is a waste rock of carbonate minerals like calcite or dolomite are present, their acid-neutralizing potential helps reduce the likelihood of generating ARD. Although this is a natural process too, it is very important to isolate mine dumps and tailings from oxygenated water, both to prevent the dissolution of sulfides and subsequent percolation of the sulfate-rich water into waterways. Industry has taken great strides in preventing contamination in recent decades, but earlier mining projects are still causing problems with local ecosystems.
16.3.3: Nonmetallic Mineral Deposits

While receiving much less attention, nonmetallic mineral resources (also known as industrial minerals) are just as vital to ancient and modern society as metallic minerals. The most basic of these is building stone. Limestone, travertine, granite, slate, and marble are common building stones and have been quarried for centuries. Even today, building stones from slate roof tiles to granite countertops are very popular. Especially-pure limestone is ground up, processed, and reformed as plaster, cement, and concrete. Some nonmetallic mineral resources are not mineral specific; nearly any rock or mineral can be used. This is generally called aggregate and is used in concrete, roads, and foundations. Gravel is one of the more common aggregates.

Evaporites

Evaporite deposits form in restricted basins, such as the Great Salt Lake or the Dead Sea, where evaporation of water exceeds
the recharge of water into the basin [49]. As the waters evaporate, soluble minerals are concentrated and become supersaturated, at which point they precipitate from the now highly-saline waters. If these conditions persist for long stretches of time, thick deposits of rock salt and rock gypsum and other minerals can accumulate (see chapter 5).

Figure \((\PageIndex{1})\): Hanksite, \(\text{Na}_{22}\text{K}(\text{SO}_4)_{9}(\text{CO}_3)_{2}\text{Cl}\), one of the few minerals that is considered a carbonate and a sulfate

Evaporite minerals like halite are used in our food as common table salt. Salt was a vitally important economic resource prior to refrigeration as a food preservative. While still used in food, now it is mainly mined as a chemical agent, water softener, or a de-icer for roads. Gypsum is a common nonmetallic mineral used as a building material, being the main component of drywall. It is also used as a fertilizer. Other evaporites include sylvite (potassium chloride) and bischofite (magnesium chloride), both of which are used in agriculture, medicine, food processing, and other applications. Potash, a group of highly soluble potassium-bearing evaporite minerals, is used as a fertilizer. In hyperarid locations, even rarer and more complex evaporites, like borax, trona, ulexite, and hanksite, are found and mined. They can be found in such localities as Searles Dry Lake and Death Valley, California, and in ancient evaporite deposits of the Green River Formation of Utah and Wyoming.

**Phosphorous**

Figure \((\PageIndex{1})\): Apatite from Mexico.
Phosphorus is an essential element that occurs in the mineral apatite, which is found in trace amounts in common igneous rocks. Phosphorite rock, which is formed in sedimentary environments in the ocean [50], contains abundant apatite and is mined to make fertilizer. Without phosphorus, life as we know it is not possible. Phosphorous is a major component of bone and a key component of DNA. Bone ash and guano are natural sources of phosphorus.

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