Worldbuilding Pasta Metals Resources Patreon Preview

There's an old saying popular with some geologists, "If it can't be grown it has to be mined." Though crops, meat, fish, and lumber may sustain a simple society, much of the development of human civilization has been driven in part by resources extracted from minerals in Earth's crust. We'll be covering those today, particularly focusing on **metals** but including other mineral resources as well. For the moment I am excluding resources mainly used for energy generation (coal, oil, uranium, though I'll discuss how some uranium ore deposits form) as we'll discuss these in the next section (though much of what I'll say here will inform that discussion). Unlike the biological resources covered in the last section, these exist in finite quantities and cannot be produced except where they are already present (though with a couple wrinkles we'll discuss). Thus, the particular position of these resource deposits has often had huge political, strategic, economic, and social implications throughout history.

Charting out the availability of these resources is tricky, because we have to account for multiple processes often occurring millions or even billions of years apart:

- The **formation** of deposits, which sometimes involves multiple steps and occurs in different ways as the planet ages.
- The **exposure** of deposits at or near the surface, as they can form as deep as the mantle but the deepest mines today are just 4 kilometers deep (and prior to the development of geology even shallowly buried deposits were hard to identify).
- The **discovery** and **extraction** of deposits, as allowed for by advancing technology.

My approach here varies a bit, but in general I'll tackle these issues separately—formation and exposure first, extraction and technological advancement second—which adds a bit of redundancy but hopefully a bit more clarity as well.

Properly accounting for all of these requires a deep geological history, as we constructed back in Part Va, and detailed modern terrain, as we constructed in Part VIIc. Without those we could only speak in the broadest terms, so I'll be presuming you've followed a process generally similar to those tutorials.

As a final note, I've made an attempt here to be fairly comprehensive just to cover all possible bases, so this is a pretty long and detailed post even by my standards and I encourage you to skip around if you need or want to; if you're here because you're interested in the distribution of the most vital bronze age metals I don't expect you to stick around to learn the major current uses of every variety of clay.

Surface Geology

First off, we can get a head start on the "exposure" part of the equation by charting out the broad types of surface geology on our world; basically, what major events created the rock that is currently exposed at the surface (or at least in outcrops) in different parts of the world. Many of these regions will overlap at least partially, because different types of geology can be mixed in together; e.g. a region may be mostly covered in young sediment, but with a few outcrops of older rock. Just one outcrop containing a large mineral deposit can be a major source for some resources.

Cratons

The oldest parts of the crust, comparable to the Archean (4-2.5 billion years ago) cratons on Earth that likely formed before the onset of plate tectonics. As such, the processes that formed mineral deposits here will be very different from processes that are ongoing today. You'll recall we started with these back in Part Va, which gives us a good starting point here.

These can be subdivided into **shields**, where the ancient bedrock is exposed at or near the surface, usually due to uplift pushing up the rock or glacial activity scraping away all overlaying sediment; and **platforms**, where the craton is buried by deep sediment or other younger rock. Deposits formed in the cratonic rock are generally only accessible at shields (or other small outcrops), but some processes can carry minerals from the craton to the surface in platforms.

On the edges of the cratons (or within them, between older sections of crust), are **greenstone belts**, where repeated island arc collisions around the initial cratonic cores have formed belts of highly fractured and metamorphosed rocks, often including green chlorite and amphibole minerals. These are known for being particularly rich in precious metals.

Old Crust

These are areas of crust that are outside the cratons, but have remained largely untouched by orogenies and volcanism over the period of geological history simulated in Part Va—and that, as with the shields, have been exposed on the surface due to uplift or glacial activity.

In essence, this is crust intermediate in age between the cratons and the start of the simulated history, comparable to Proterozoic (2.5-0.54 billion years ago) crust on Earth (some sources count these as cratons as well, but for consistency I won't refer to them as such). The rock here formed in the transitional period between the young crust and modern plate tectonics, and between simple early life and complex life. It thus contains a range of deposit types formed by stages in that transition.

Active Orogenies

These were, of course, already broadly defined back in Part Va, though I'm marking them out more broadly here to include the whole area of deformation.

These are some of the youngest areas of the crust, comparable to Cenozoic (66-0 million years ago) orogenies on Earth. There are somewhat different mineral-forming processes at play in **subduction** (Andean- and Laramide-type in my taxonomy) and **collisional** (Ural- and Himalayan-type) orogenies, but bear in mind that all current collisional orogenies must have been subduction orogenies in the near past and should still have some minerals formed in that time. Subtler differences may also appear between orogenies formed on **island arcs**, on **continents**, and on continents but with a recent collision with an island arc. **Flat-slab subduction** (as in Laramide-type orogenies) and **slab rollback** (as in trailing-edge active margins, but also sometimes within Mediterranean-like closing seas) may also influence ore formation.

Old Orogenies

These were, again, already marked out in Part Va, though again I'm marking them more broadly here. Exclude regions that have been deformed or overrun by new orogenies or LIPs, or completely eroded down and buried in sediment.

These are older than the active orogenies, comparable to Paleozoic (541-252 million years ago) and Mesozoic (252-66 million years ago) orogenies on Earth. The minerals here formed in processes pretty similar to those ongoing in active orogenies today, but may have been altered or exposed by later erosion and weathering, and all of these orogenies have necessarily gone through the whole process of subduction and collision. Orogenies formed during collisions, especially with island arcs, may contain **ophiolites**, sections of ocean crust lifted onto continents that may contain ore deposits that don't often form on continents.

Igneous Provinces

This includes the large igneous provinces in Part Va—save for where they have been overridden by orogenies, or they have been completely buried—and hotspot trails over continents. The rocks here were formed by magma rising directly up from the mantle, which forms different minerals from the water-laden magma produced in orogenies.

Hotspots

Regions with ongoing hotspot volcanism. These areas will be mostly covered in recently formed ash and rock, which are relatively poor in useful resources compared to rock formed by orogenies or erosion and deposition.

Rifts

Areas with either active rifting now that has not yet opened an ocean basin or failed rifts that may still have some ongoing activity or did in the past.

Sedimentary Basins

Deep layers of sediment formed by long-term subsidence of the crust. Compression and cementation of sediment will tend to turn it into sedimentary rock within a few thousand years, but for simplicity I'll refer to that as "sediment" as well in this post. Some amount of sediment will tend to accumulate in any low-lying area, and certain ores might appear at any such locations, but deep basins mostly form in a few circumstances:

- Along passive margin coastlines (lacking subduction and orogenies).
- In and around rifts.
- In foreland and forearc basins alongside orogenies.
- Occasionally in the flat interiors of continents with prolonged periods of tectonic inactivity, particularly around cratons.

Somewhat different ore types will form in marine and freshwater (lakes, rivers, wetlands) sediment, but most sediments even within continental interiors will be marine sediments deposited at periods of high sea level (or shortly after subsidence when sediment hadn't piled back up to sea level yet) or at least an alternating mix of marine and freshwater sediment formed by fluctuating sea levels. Many continents have large interior sedimentary basins formed around former shallow seas, which would have been flanked by passive margins.

Ores and Deposits

All naturally-occuring elements can be found in low concentrations throughout the crust (and dissolved in the oceans), but separating them all out is usually uneconomical; instead we seek out **ores**, minerals containing desireable materials at concentrations sometimes hundreds to thousands of times greater than the average, or at least in a chemical form that makes their extraction and refinement easier.

None of these ores existed when Earth first formed; aside from the still-inaccessible iron core, the planet started out as a mostly homogenous mush of rocky minerals with metals mixed into their crystal structures. The only real variation was a general tendency for metals to sink deeper into the mantle—already putting us surface-dwellers at a disadvantage (some rare metals like gold and platinum may have been virtually absent from the primordial crust, and are only present today thanks to later delivery by meteorites). But since then, various geological processes have concentrated many metals and other mineral resources into different ores, and plate tectonics in particular has helped to both form ores and provide pathways for deeply buried ores to reach the surface. Thus, every resource has a story about how it transitioned from scattered impurities in the crust to a concentrated ore **deposit**.

The formation process also informs the **grade** of the resulting ore deposits—how concentrated the desireable materials are. Some formation processes will produce high-grade deposits composed mostly of metal-rich ores, but many will instead produce lower-grade deposits where crystals or pockets of ore are mixed in with other minerals (or the ore contains a low concentration of the desired material), thus requiring more work to extract even before they're refined.

Many resources—particularly metals—can be found in multiple types of ore deposits, and many ore deposits contain multiple resources, so for purposes of clarity I'll discuss formation of different types of ore deposits in this section, and then in the following sections I'll go over each resource and list the deposits they're found in (though this division applies moreso to metals, as nonmetal mineral resources more often have unique, exclusive deposits).

I'm going to try not to get too deep into the chemistry and mineralogy here, but that is a necessary element of this discussion, so let's start with a quick overview:

Earth's crust and mantle are predominantly composed of **silica** (SiO_2), as are those of all other rocky bodies. Silica can be found on its own as **quartz**, but usually forms a variety of **silicate** minerals, which often contain significant amounts of magnesium, iron, aluminum, calcium, sodium, and potassium, but are difficult to break down and so generally don't form good ores even of these most common metals, though they may be extracted for other uses. We can divide rocks and magmas into two major types (though it's really more of a continuous spectrum):

- **Mafic** rocks like **basalt** and **gabbro** that are a bit more rich in common metals (**ma**gnesium + **f**erric (rich in iron) = mafic). Most of the mantle and oceanic crust are mafic, and on the surface mafic rocks form mostly at rifts and hotspots, associated with **effusive** volcanism (mostly producing liquid lava flows).
- **Felsic** rocks like **granite** and **rhyolite** that are more silica-rich (**fel**dspar (a silicate mineral with aluminum and alkalis) + **si**lica (i.e. quartz) = felsic). Most of the continental crust is felsic, and felsic rocks form mostly at orogenies, associated with **explosive** volcanism (producing more ash).

Both mafic and felsic rocks are still mostly silicates, but as you might imagine, mafic rocks are a bit more prone to form metal ores under the right circumstances. However, the crust and mantle also contain large amounts of **volatiles** like water (H_2O), CO_2, methane (CH_4), H_2S, HF, or HCl. As the name suggests, these tend to be a bit more chemically active and can break down silicates to form a number of different minerals. This can form useful ores from both mafic and felsic magmas, but felsic magmas are usually richer in volatiles (because they usually form due to mixing of volatiles into previously mafic magmas), which somewhat offsets their initial deficit of metals. The result is a variety of different mineral types that are often richer in metals than silicates and much easier to break down:

- **Native metal**: a natural mineral that contains a single metal element, with no more than minor impurities of other elements ("native" is sometimes also used for pure nonmetal elements). Convenient for extraction, but generally pretty rare.
- **Alloy**: a combination of multiple metal elements with few nonmetal impurities. Again, fairly rare in nature.
- **Sulfide**: a mineral containing metals bonded to sulfur (S). Commonly formed directly from magma, and tends to gradually break down when exposed to water or oxygen at the surface. Tends to make good ore, and sometimes brightly colored too.
- **Oxide**: a mineral containing metals bonded to oxygen (O). Can also form from magma, but also often forms by alteration of sulfides or other minerals at the high temperatures and pressures formed underground by continent collisions or other metamorphic processes. Also often good ore, and more stable on the surface.
- **Hydroxide**: a mineral containing metals bonded to hydroxide (OH^-). Often formed at or near the surface by chemical reactions between water and other minerals, and usually breaks down if buried or heated. There aren't many notable hydroxide ores, but a couple I'll mention.
- **Carbonate**: a mineral containing metals bonded to carbonate ions (CO_3^{2-}). Like hydroxides, usually formed at or near the surface by reactions between CO_2 and other minerals. Common in marine

sediments and often extracted for other purposes than metal production, but a few rarer types are mined as metal ores.

You may recall the **siderophile** (iron-loving), **chalcophile** (sulfur-loving), and **lithophile** (silica-loving) (and also nonmetal volatiles/atmophiles) categories for elements I used a long time back; these matter less here than they did for planet formation (gas and dust coalescing into a planet are a lot more free to move around and find their preferred mix than minerals moving through the crust) but *broadly* speaking, mafic rocks will contain more siderophiles and chalcophiles and felsic rocks more lithophiles. Chalcophiles are also more likely to form sulfide ores, but there are exceptions and it doesn't help that the categorization of some elements varies between sources.

There are also a couple groups of metals with very similar chemical behavior such that they can be mostly expected to occur together: the **Platinum Group Elements (PGEs)** including platinum (Pt) and palladium (Pd); and the **Rare Earth Elements (REEs)** including the lanthanides along with scandium (Sc) and yttrium (Y).

Finally, a quick stoichiometry note: often minerals are described as a regular mix of elements in an exact ratio (e.g. chalcopyrite is $CuFeS_2$, a 1:1:2 mix of copper, iron, and sulfur atoms), but many minerals actually exist as a **solid solution**, wherein one element can substitute for another within the crystal structure without changing the overall properties much, and the actual ratio of elements varies throughout a single crystal. Olivine, for example, has a crystal structure that can accommodate either magnesium (Mg_2SiO_4, forsterite) or iron (Fe_2SiO_4, fayalite), and a single olivine crystal often contains a mix of magnesium and iron. This is why you'll sometimes see chemical formulas with optional elements (for olivine, $(Mg,Fe)_2SiO_4$, indicating that the first element can be either Mg or Fe) or non-integer ratios (e.g. a specific olivine crystal could be $(Mg_{0.7}Fe_{0.3})_2SiO_4$, indicating a 70:30 mix of Mg and Fe, and pyrrhotite is $Fe_{0.8\text{-}1}S$, indicating it can contain anywhere between an 80:100 and 1:1 mix of Fe and S). In some cases a mineral may predominantly have one composition, with only a small amount of **impurities** substituting into its structure; this may make it harder to refine a pure metal from the ore, though it can also make it easier to produce certain alloys, and some ores are mined primarily to extract the impurities, which may include some particularly rare metals.

There are various classification schemes for ores, based on the metals they include, the grade and size, the depth and temperature of formation, and so on. For my purposes I'll break them down by the dominant method of formation, which informs the geological environments they appear in—i.e. where they might appear on the map we made earlier (and because of that I may gloss over various subtleties in slightly different deposit types with different formation histories that don't impact their distribution or ore type). By way of demonstration, I'll mark out the rough areas where we might expect such ores to occur on Teacup Ae. But actual formation of ore deposits depends on a lot of subtleties that we can't reasonably interpret from such a broad view of tectonic history (variations in surface rock, requirements for particular sequences of events, variations in magma composition over time). Some apparently ideal areas for a type of deposit may lack them, and some misfit deposits will appear in odd locations. So don't take these recommendations as absolute law.

Magmatic

Ores formed from magma as it rises through the crust. Often this magma comes from the crust itself, where it has reached greater depth due to subduction or the weight of mountain formation on the surface. The increased temperature (and other factors like the introduction of water at subduction zones) causes the rock to partially melt. Metals tend to melt before silicates do, so the magma already starts out metal-enriched compared to the source rock.

The great pressure in the mantle will then squeeze this magma upwards through cracks in the crust, and as it rises it will cool. As it does so, some of the elements in the magma start to crystallize. This removes these elements from the melt, changing its composition and thus chemical behavior, so as the magma continues to rise, cool, and solidify, different minerals will crystallize out, and some of these will be particularly rich in certain metals.

Layered Complexes

These form primarily from mafic volcanic activity: magma gathers in a chamber or pushes into the surrounding rock to form long igneous intrusions, and then gradually cools. They may also be occasionally formed by large meteorite impacts that form pockets of magma underneath the impact, buried in ejecta (but there's only one good example of this on Earth). The first minerals formed are generally silicates, leaving the remaining magma relatively silica-poor, allowing ores to form a couple different ways:

- **Cumulates**: Crystals of ore form within the magma that then sink to the bottom of the chamber, forming an ore-rich layer. This will deplete the magma of metals, causing silicates to form again, so often the resulting deposit alternates between layers of silicates and ores.
- **Immiscible melts**: Later and at shallower depth, ongoing formation of minerals out of the magma and leaching of sulfur from the surrounding rock may shift the composition of the remaining magma such that it separates out into two liquids too chemically

dissimilar to mix with each other, like oil and water. The more metal-rich liquid—usually iron sulfide—will generally be denser and sink below the other, eventually cooling to form a thick ore layer.

In either case, the result is a deeply buried ore deposit—often 10s of km deep—that must then be uplifted to the surface by later tectonic activity and exposed by erosion. The exposed deposit may be as small as a single vein formed by an intrusion, but many are large layers of ore across a vast region, and these larger deposits are often higher-grade, as the large chambers allow for more gradual cooling. Today, a few large layered complexes dominate the world's supply of PGEs and vanadium.

Layered complexes (mostly small cumulates) may also form in ocean crust as it forms along mid-ocean ridges; these remain buried under the seafloor and usually will eventually subduct, but during island arc collisions sections of ocean crust called **ophiolites** can be lifted onto the continental crust and remain there long afterwards.

Occurrence: Mostly in **cratons** or **old crust**, as the remnants of billions of years of rifting and hotspot volcanism, and then subsequent uplift. Some may also appear in younger **igneous provinces**, but these have often had less time for exposure by uplift and erosion, and the less mafic nature of the modern crust disfavors their formation. Some large **craters** may form immiscible melt ores, but again, the time needed for exposure often means exposed deposits of these type are on older crust and don't much resemble impact craters anymore. Small but significant deposits in ophiolites may appear in and around **orogenies** with a history of island arc collisions.

Cumulates and immiscible melt deposits form under similar conditions but at different depths and stages, so are found in the same regions but usually not together in the same deposit.

Ores: Cumulates tend to form more oxides, particularly ores of **chromium** (chromite, $FeCr_2O_4$) with significant impurities of **PGEs** as well as sometimes ores of **titanium** (ilmenite, $FeTiO_3$) and **vanadium** (V, as impurities in magnetite, Fe_3O_4); the **iron** in these ores may also be extracted as a byproduct.

Immiscible melt deposits contain more sulfides, mostly ores of **iron** (pyrite, FeS_2; pyrrhotite, $Fe_{0.8\text{-}1}S$;), but more importantly **copper** (chalcopyrite, $CuFeS_2$) and **nickel** (pentlandite, $(Fe,Ni)_9S_8$). They can also occasionally have significant ores of **PGEs** (cooperite, (Pt,Pd,Ni)S; sperrylite, $PtAs_2$) and **cobalt** (cobaltite, CoAsS).

Occasionally, the silicate layers of the complex are pure enough to be worth mining for their **silica** or silicate **gems** (labradorite, $(Ca,Na)(Al,Si)_4O_8$).

Pegmatites

Ores formed from more felsic magma with some amount of water mixed in. These typically form from gradual cooling of magma chambers or intrusions deep underground, like layered complexes; as silica-rich minerals crystallize out, the remaining magma is increasingly enriched in water and some rare metals. The final part of the magma to crystallize will still be predominantly silicates, but may also contain large crystals of rare minerals and oxide ores.

Occurrence: The largest are found in the greenstone belts of the **cratons** and **old crust**, but they can also be found in **old orogenies** and sometimes older and more eroded parts of **active orogenies**.

Ores: These are mostly mined for their rare **gems** (emerald, beryl, garnet, tourmaline, topaz), but they may also contain a variety of ores including those of **tin** (cassiterite, SnO_2), **lithium** (spodumene, $LiAl(SiO_3)_2$), **beryllium**, **boron**, **bismuth**, **tantalum**, **niobium**, **cesium**, **uranium**, **molybdenum** (molybdenite, MoS_2), **tungsten** (wolframite, $(Fe,Mn)WO_4$), and **REEs** (monazite, $(Ce,La,Th)PO_4$).

Carbonatites

Odd carbon-rich volcanic rocks that form in the earliest stages of rifting, with a somewhat unusual mineral mix rich in REE ores. They erode away fairly quickly on the surface so must either be fairly young or buried and later exposed.

Occurrence: **Hotspots** and young **rifts** within continents.

Ores: A major source of **REEs** (monazite, $(Ce,La,Th)PO_4$; bastnaesite, $(La,Ce,Y)CO_3F$), as well as **niobium** (pyrochlore), **zirconium**, **barium** (barite, $BaSO_4$), and sometimes **phosphorus** (apatite, $Ca_5(PO_4)_3(F,Cl,OH)$), **fluorine** (fluorite, CaF_2), or **uranium**.

Kimberlites

Highly mafic volcanic rock deposited in funnel-shaped “pipes” in the early stages of hotspot or rifting activity by magmas rising from the mantle. Along the way they sometimes pick up diamonds, which form mostly in the mantle and then collect at the base of cratons.

Occurrence: Diamond-bearing deposits form exclusively within **cratons** where there has been some history of hotspot or rifting, though this may predate your tectonic history; deposits can be buried and then exposed billions of years later.

Similar **lamproite** deposits are not restricted to cratons and may occasionally carry diamonds, but only rarely and in small deposits with low-quality gems, to the point that only one such deposit is mined on Earth.

Ores: Mined essentially only for **diamonds** (crystalline C).

Hydrothermal

Ores formed by the movement of water and other volatiles (CO_2, H_2S) through the crust at high temperatures and pressures. These hydrothermal fluids can come from multiple sources; they can descend from the surface through cracks and pores in the crust, they can be trapped in buried aquifers and then heated by volcanic intrusions, they can be released from rising magma, and they can be released from rocks containing volatiles due to increasing heat and pressure. Many geologists distinguish between **hydrothermal-magmatic** ores produced by fluids released from magma and other hydrothermal ores, but for a few of these deposit types the source of the fluids isn't clear and for a couple it's likely a mix of sources, so I'll just lump them all together here, other than parceling out the family of felsic hydrothermal-magmatic ores that all form similarly.

Fluids released from magma may already have some dissolved metals, but as this fluid passes through the crust, it may also dissolve some of the surrounding rock, or—if the fluid is very hot, which it often is—it may chemically alter the rock such that it releases some of its component elements. As with the formation of magma, metals and metal-containing compounds tend to enter the fluid more readily than silicates, so the fluid becomes relatively metal-enriched. It then enters a **trap zone**, where decreasing temperature, decreasing pressure, or different chemical conditions cause the dissolved compounds to crystallize—as with magma, forming a series of different minerals as the conditions and composition of the fluid changes, some of which will be particularly rich in metals.

Felsic Hydrothermal-Magmatic

This is a subgroup of deposits that all form in very similar circumstances: porphyries, skarns, manto ore, and epithermals. All form around magma chambers or intrusions of felsic magma in orogenies with ongoing subduction and volcanism due to movement of hydrothermal fluids released from the magma. The main distinction between them is the distance from the magma chamber at which they form, but this is generally only a difference of a few kilometers at most; on the scale of continents, you can expect them all to be mixed in together in the same area. They can and in many cases do form together, but just as often are each found alone; each type of deposit requires its own specific conditions to form, and even if they do form together, one may be much more deeply buried.

All are more common in areas affected by flat-slab subduction (https://www.sciencedirect.com/science/article/pii/S0012821X0500525X). Most deposits include sulfide ores of **copper**, **gold**, **silver**, **lead**, and **zinc** but there are a lot of variations, particular between deposits that form on continents and those in island arcs (or continents that recently collided with island arcs), but no ore is totally exclusive to either type of orogeny.

Porphyries

Ore deposits formed in felsic magma chambers or intrusions. As the magma cools, silicates crystallize around the edges, leaving the remaining magma volatile-enriched and compressed (as the silicate feldspars expand when they solidify). Eventually the pressure is high enough that the silicates shatter and metal-rich fluids released from the magma rush into the fractures. They then cool and deposit thin veins of quartz with small amounts of ores mixed in. The resulting deposit is low-grade, but the deposits are often so large as to make mining worth the effort.

Porphyries are also often subject to a process of **secondary enrichment**: rainwater seeping through the rock dissolves some of the sulfide minerals, producing sulfuric acid which further dissolves the ores. These are carried to the water table, where the acidic water is diluted and reacts with some of the other minerals present, depositing out the dissolved metals as oxide, hydroxide, or carbonate ores. The effect is to concentrate the ores into a more compact, higher-grade deposit.

Occurrence: As will be the default for felsic hydrothermal-magmatic deposits: mostly in **active orogenies** with ongoing subduction and volcanism, especially with flat-slab subduction, and older deposits occasionally in **collisional** and **old orogenies** as well.

Ores: Predominantly sulfide ores of **copper** (chalcopyrite, $CuFeS_2$; bornite, Cu_5FeS_4, occasionally native Cu), and occasionally **lead** (galena, PbS) and **zinc** (sphalerite, (Zn,Fe)S) or **silver** (acanthite, Ag_2S, galena impurity). Sometimes **molybdenum** (molybdenite, MoS_2), moreso on continents—sometimes in deposits with little copper and some **tungsten** (scheelite, $CaWO_4$)—or **gold** (native Au), moreso in island arcs. Secondary enrichment produces higher-grade ores of primarily copper (chalcocite, CuS_2; azurite, $Cu_3(CO_3)_2(OH)_2$; cuprite, Cu_2O).

Skarns

Ore deposits formed by felsic volcanism in a similar manner to porphyries, but formed not within the magma chamber but rather in the surrounding rocks, most often in carbonate-rich sedimentary rocks like limestone that strongly react with the acidic hydrothermal fluids. Fluids released from the magma are injected into the surrounding rock and dissolve or react with it, then cool and deposit new minerals—mostly carbonates and silicates, but sometimes also high-grade ores of metals extracted from the rock or magma.

Occurrence: Similarly to porphyries. Some carbonate sediment is required (though many form in intermixed felsic volcanic and sedimentary rocks), but marine sediments of this sort are commonly pushed up into mountains during **orogenies**.

Ores: Commonly ores of **copper** (chalcopyrite, $CuFeS_{2;}$ bornite, Cu_5FeS_4, occasionally native Cu), and **gold**, sometimes **silver**, **tin** (cassiterite), or **zinc** (sphalerite) and **lead** (galena), and occasionally small amounts of **boron**, **uranium**, **fluorine**, and **REEs**. Sometimes **tungsten** (scheelite, $CaWO_4$) and **molybdenum** (molybdenite, MoS_2), moreso on continents, or rich ores of **iron** (magnetite, pyrite), moreso on island arcs.

Manto

Formed by felsic volcanism near carbonate-rich sedimentary rocks, similar to skarns, but formed further from the magma and at lower temperatures—often associated with smaller intrusions rather than magma chambers. The deposits tend to appear in horizontal layers near preexisting faults in the sediment.

Occurrence: Pretty similar to skarns, though more specifically restricted to limestone and similar carbonate-rich sediments and so more often occurring on the **edges of an orogeny**, often in the **forearc region**.

Ores: Sulfide ores, often in distinct zones further from the fluid source: First **copper** (chalcopyrite, $CuFeS_{2;}$ bornite, Cu_5FeS_4, occasionally native Cu) and **gold**; then **lead** (galena) and **silver** (argentite); finally **zinc** (sphalerite) and **manganese**.

Epithermal

These form above or to the side of magma chambers, close to the surface; usually just below hot springs. This time, there's no specific requirement for the type of surrounding rock. There are a few major subtypes:

- **High-sulfidation** deposits form above the magma chamber, on the flanks of volcanoes, from fluids that haven't much mixed with groundwater and so remained hot and acidic. The acidic fluids leach metals out of the surrounding silicate rock to form large, low-grade deposits of ore in clay.

- **Low-sulfidation** deposits form around the volcano from fluids that have travelled further and mixed more with groundwater and so become diluted and cooler. As they approach the surface, the pressure eventually drops enough to allow them to boil, leaving ores behind. The resulting deposit may be small, high-grade veins or lower-grade ore distributed in porous rock—or a mix of both.
- **Intermediate-sulfidation** deposits form between the two, often forming long, high-grade veins.

Though these can all form in the same overall conditions, actual ore formation comes down to subtleties in the type of surrounding rock and timing of events and so these deposits don't usually form together.

Occurrence: Because they form so shallowly and so erode away quickly, these are particularly associated with **active orogenies**, but a few can still be found in **old orogenies**.

Ores: Mostly **gold** (native Au) or sometimes **silver** (acanthite, Ag_2S), usually predominantly one or the other, with some ores of **copper** in high-sulfidation deposits; **mercury** (cinnabar, HgS) in low-sulfidation deposits; and **lead** (galena) and **zinc** (sphalerite) in intermediate-sulfidation deposits.

Volcanogenic Massive Sulfide (VMS)

Moving on to other types of hydrothermal deposits, these deposits are formed on the ocean floor by hydrothermal vents at rifts and hotspots: Fluids released from magma rise through faults in the crust and, upon bursting through the seafloor, the fluid rapidly cools and deposits out a variety of ores (as the name implies, predominantly sulfides), often in concentric rings of different ores formed at different temperatures.

Some form on continental crust in shallow seas around local rifts or hotspots, but most form on oceanic crust. Most of those will eventually be subducted, but when a continent collides with an island arc or another continent, some ocean floor sediments will be scooped up between them—often including fresh VMS deposits formed by the subduction zone that caused the collision—and remain among and around the resulting collisional mountain zone.

The resulting deposits are usually (though not always) small but very high grade, such that they're almost always worth mining. Mining of fresh deposits on the ocean floor has also been proposed in recent years, though there are significant ecological concerns associated with the idea.

Occurrence: Common in **old orogenies**, **active orogenies** with some history of slab rollback or island arc collisions (though generally not young continent-continent collisions, perhaps because of burial under sediments), and occasionally found in the greenstone belts around **cratons** from orogenies in the distant past. Young deposits are present on the **ocean floor** at mid-ocean ridges, hotspots, and rifting areas associated with slab rollback.

Ores: Predominantly sulfide ores of **iron** (pyrite, Fe_2S), **copper** (chalcopyrite, $CuFeS_2$, occasionally native Cu), and **zinc** (sphalerite, (Zn,Fe)S), often but unusually not always with **lead** (galena, PbS), and often also small amounts of **silver** and **gold** and a variety of other metals, including **cobalt** (cobaltite, CoAsS), **tin**, **selenium**, **manganese**, **cadmium**, **bismuth**, **gallium**, **vanadium** (patronite, VS_4) or **germanium**. Different ores are often separated into different regions of the deposit, making them easier to sort.

Sedimentary Exhalitive (SedEx)

Similar to VMS deposits but formed not by fluids produced by volcanism but by fluids trapped under deep beds of sediment, typically brines that have leached metals from the surrounding rock. Burial and tectonic motion compresses and heats the fluid and it rises through faults until reaching the surface, cooling in seawater, and depositing out ores.

The resulting deposits are less common and lower-grade than VMS but generally far larger. But there is a bit of a spectrum between the two, with varying mixes of volcanic and surface-derived fluids.

On Earth they seem to have stopped forming about 250 million years ago, perhaps due to shifts in seafloor chemistry.

Occurrence: Old, deep **sedimentary basins** that formed below shallow seas and have since been uplifted or exposed by sea-level fall, often on the inland side of **orogenies** that have formed by island arc collisions.

Ores: Predominantly ores of **lead** (galena) and **zinc** (sphalerite), commonly with **iron** (pyrite, FeS_2) that may be mined as well, and sometimes with **silver**, **copper**, or **manganese** (rhodochrosite, $MnCO_3$).

Greisen

Deposits sometimes found in granite, a common felsic rock. As the magma cools and solidifies, it releases fluorine-rich fluids that run through fissures in the rock and react with surrounding minerals, depositing thin ore veins. Large masses of granite called **plutons** are commonly formed underground in orogenies, so these must be exposed by significant later erosion.

Occurrence: Mostly **old orogenies**, occasionally in the inland foothills of **active orogenies**.

Ores: Mostly oxide ores of **tin** (cassiterite), **tungsten** (wolframite), and **molybdenum**.

Intrusion-Related Veins

Many ores form as veins, but this refers specifically to thick veins formed by fluids released by bodies of magma into faults in bedrock formed by tectonic stress, depositing out mostly quartz mixed with various ores, though past that the details vary. The best veins tend to form in hard igneous or metamorphic rock, which will form large faults under stress rather than many small cracks (though the latter may form small veins rich enough to make it worth extracting the whole rock for later refinement). The deposits are small but high-grade and easy to mine by just following the line of the vein (and often the upper end of a vein will branch out into many veinlets, making discovery easier), and so were commonly mined in the past but have become less popular today in favor of larger deposits.

Occurrence: Mostly around **rifts**, but occasionally around **old orogenies** due to stretching and faulting of rock after compression.

Ores: Mostly **gold** (), **silver**, **tin**, and **tungsten** (wolframite, $(Fe,Mn)WO_4$), occasionally **copper**, **nickel** (nickeline, NiAs) **cobalt** (cobaltite, CoAsS; smaltite, $CoAs_3$), and **uranium**

Iron Oxide Copper Gold (IOCG)

A variety of large, old, somewhat high-grade deposits. Many of the details of how they form are still debated: they're generally associated with rising felsic magma around orogenies, often where it encounters sediment, and ore formation probably happens when fluids released from the magma shatter the above rock, much like porphyries and skarns. But how much minerals or water in the surrounding rock plays a role is unclear, and it and this is a bit of a grab-bag category so it may vary between deposits: uranium-rich deposits likely derive their ores from surrounding granite while more exclusively iron-rich **Kiruna-type** deposits may get theirs mostly from magma (and so are sometimes considered a wholly different category).

In any case, the deposit generally forms as a funnel-shaped “pipe” with oxides near the surface and sulfides below them, and often several large deposits form in the same area. These deposits have all formed after the appearance of oxygen in the atmosphere (roughly 2 billion years ago on Earth), though they seem to have become rarer recently (after ~800 million years ago on Earth), perhaps due to shifts in tectonic activity or crustal chemistry.

Occurrence: Predominantly **old crust**, with a few younger deposits near the inland edges of **old** and **active orogenies**.

Ore: As one might expect, ores of **iron** (magnetite, hematite), **copper** (chalcocite, bornite, chalcopyrite), and **gold** (native Au or alloys), though grade of each can greatly vary (with Kiruna-type deposits containing more exclusively iron), and also sometimes rich ores of **silver** (argentite), **uranium** (uraninite), **thorium**, and **REEs**. Impurities are generally rare, making refinement easier.

Mesothermal Gold

This is another group of diverse and poorly understood deposits that goes by a variety of names (lode gold, orogenic gold, shear zone gold). The deposits commonly appear in association with island arc collisions: the subduction and subsequent collision likely pushes down the base of the crust, causing partial melting of the gold-rich rock there. The gold mixes into hydrothermal fluids also released during subduction and collision, and then rises through large faults in the crust created by the collision. As the fluid rises, it mixes with groundwater and eventually its chemistry shifts such that it deposits out silicate or carbonate veins rich in gold ore.

Because these follow shallow-angled faults from the deep crust, they generally appear not in the center of orogenies but in their compressed and folded foothills. There may be some association with cratons—the roots of cratons may be better sources of gold or large, ancient faults around their edges may be ideal for vein formation–but there are numerous exceptions. But because these ores form relatively deep (~1-5 km), they're more often found near older orogenies with more time to erode.

However they form, the result is large numbers of small but high-grade ore veins.

I'll also mention **Carlin type** deposits here, as the only unambiguous examples on Earth are in one area (northeast Nevada) and appear to have formed similarly to mesothermal deposits, with the one major distinction that they appear in faults formed by tectonic *extension* rather than collision and compression.

Occurrence: Some may be found around **new orogenies**, but most are found near **old orogenies** or in the greenstone belts in and around the edge of **cratons**.

Carlin types are only known from one **basin-and-range area**, but are expected to also be possible in areas affected by slab rollback (e.g. trailing-edge active margins).

Ores: This may surprise you, but primarily **gold** (native Au, though the grains are sometimes mixed into iron sulfides; Carlin types in particular have only microscopic gold grains) and small amounts of **silver** (as Au impurity)

Mississippi Valley Type (MVT)

These form in basins of marine limestone deposited on continents by shallow seas (such as the eponymous region of North America). How these form is still debated: Some geologists propose that volcanic activity below the limestone beds produces hydrothermal fluids that then travel along the bottom of the beds until reaching a trap along their edges, react with the limestone there, and then cool and deposit out a range of carbonate minerals and ores. Others propose that the fluids are primarily groundwater that has seeped through nearby mountains, leaching away their minerals on the way, and then similarly moves under the beds to traps at their edges. There are also a number of other Pb-Zn-Ag deposits sometimes not included as MVTs because they are believed to form differently (possibly linked to buried salt) but that form in the same places with the same ores, so I won’t go over them separately.

Regardless, the resulting deposits are generally fairly large but grade can vary.

Occurrence: At the edges of a large **sedimentary basin** or around formations of volcanic rock that protrude through them, especially old basins.

Ores: Predominantly suflide ores of **lead** (galena, PbS) and **zinc** (sphalerite, ZnS), sometimes with **silver** and **barium** (barite).

Sediment-Hosted Stratiform Copper (SSC)

Widespread but poorly understood deposits that consistently appear in marine sediments on continents. As best as we can tell, at some point after sedimentation, perhaps prompted by rifting activity, sulfur-rich fluids from either seawater, deposited minerals, or organic material circulates through the sediment and dissolves metals already present. Once these encounter chemically reducing material (carbonates, hydrocarbons, mafic bedrock), they deposit out into flat layers. Most deposits are too low-grade to be worth mining, but a few large deposits provide much of the world’s copper.

Occurrence: **Marine sediments** on continents, ideally deposited by warm shallow seas rich in life that would have deposited carbon-rich material and with some later rifting activity, including old sediments that may be on **old crust**.

Ores: Sulfide ores of predominantly **copper** (chalcopyrite, $FeCuS_2$; bornite, Cu_5FeS_4; chalcocite Cu_2S; occasionally native Cu), and sometimes also low-grade ores of **lead**, **zinc**, and either **cobalt** (carrollite, $Cu(Co,Ni)_3S_4$) or **silver**, though almost never both together.

Surficial

Ores formed by weathering, erosion, and other non-volcanic processes occurring on the surface. Because these occur at the surface, many may be exposed shortly after forming, unlike most of the deposits we've discussed so far. But some may still be buried and then not exposed for millions or even billions of years. Geologists will sometimes distinguish between **sedimentary** ores formed in the process of sediment deposition and other surficial processes (usually involving groundwater flow), but I'll just put them together here.

On the other hand, I'm mostly skipping cases of **secondary enrichment** where surface processes increase the grade of a preexisting ore deposit, usually by movement of groundwater concentrating ores at the water table or removal of non-ore materials by weathering and erosion; for our purposes this is basically just altering a deposit rather than forming a new one, and I'm mentioning the most relevant cases in the sections for each deposit type.

Placers

These are simply parts of other ore deposits (which I'll call **primary** deposits) that have been broken down into small pieces ("clasts") and transported by erosional processes with little or no chemical alteration. Clasts of ore will generally be denser than those of silicates, and so will tend to deposit first when rivers slow or will otherwise separate out during gravity-sensitive depositional processes. A river network may thus take low-grade ore spread out across its drainage basin and concentrate it into a richer deposit. Grade varies, but even if it's fairly low in strict terms, sifting through river sediment may be far easier than mining through hard rock. The lowland deposits may also be easier to access than those in high mountains and more easily identified by early societies living along rivers. Thus, many metals were first extracted from placers.

Beach placers can also sometimes be formed on coasts by wave action, and wind and glacial action can also form placers but these are rarely worth mining.

If more ore continues to erode upstream, placer deposits may replenish over time, allowing a low rate of continuous extraction.

Occurence: Any ore deposits (of appropriate chemistry) in eroding terrain can have corresponding placer deposits downstream as much as 100s of km away. But placers need not always be associated with any single source deposit, as they can concentrate low-grade ores from a large area or may have formed from a deposit that has now totally eroded away; I'll talk in later sections about the source deposits for placers of certain ores but this is just to give you an idea of the areas they might form.

Particularly rich placer deposits will tend to form around the base of **active orogenies** or perhaps fairly young **old orogenies**, which are likely to have quickly-eroding exposed ores, often where mountain rivers pass onto flatter ground such that they slow down and heavier ore clasts deposit out. The richest and most accessible deposits may be within the bed or banks of a current river, but placer deposits may also remain after river migration or be buried after formation and then exposed by later uplift and erosion as much as billions of years later; some particularly rich gold paleo-placers on Earth are found in ancient sediment on **cratons**.

Beach placers may occasionally form on coasts near young orogenies, or former coasts at a time with higher sea levels.

Ores: To form a placer deposit, an ore has to be able to survive transport in a river and often regular exposure to water thereafter without dissolving. Thus, sulfide ores rarely form placers, but many oxides and hydroxides do, including ores of **iron** (hematite, Fe_2O_3), **tin** (cassiterite, SnO_2), and **uranium**. A few stable and dense native metals also form particularly good placers, in particular **gold** (Au) and **PGEs**, as well as some gems like **diamonds** (C), ruby and sapphire (Al_2O_3), and garnet ($(Ca,Mg,Fe,Mn)_3(Al,Fe,Cr)_2(SiO_4)_3$). Beach placers tend to include ores of **titanium** (ilmenite; rutile), **zirconium** (zircon), and **REEs** and **thorium** (monazite, $(Ce,La,Th)PO_4$),

Laterites

These form primarily in sediments over metal-rich bedrock in tropical climates with distinct wet and dry seasons. Heat and heavy rain cause intense chemical weathering that dissolves silica, carbonates, and alkali metals. In the dry season evaporation pulls the water to the surface, depositing these minerals there, and then they're washed away in the next wet season. The remaining sediment below the surface is largely composed of iron and aluminum oxides that better resist the weathering (though some amount of silica usually remains as quartz).

A similar process can also occur in karst regions in cooler climates, though not as frequently or productively.

Occurrence: Widespread in **tropical sediments** where there are strong wet and dry seasons and occasionally present in colder climates in **karst regions** or **exposed sediments** deposited in warmer times. Nickel-rich laterites in particular require shallow, highly mafic bedrock (generally well-exposed **cratons** or ophiolites in **orogenies** with a history of island arc collisions), while REE-rich laterites generally require felsic bedrock (found in **old orogenies**). Colder regions may sometimes have buried laterites formed in a warmer period in the past.

Ores: Depends on the source rock. Most common are oxide and hydroxide ores of **iron** (hematite, Fe_2O_3; goethite, FeO(OH)) and **aluminum** (bauxite rock containing gibbsite, $Al(OH)_3$, and boehmite/diaspore, AlO(OH)), occasionally with **manganese**; highly mafic bedrock can produce rich ores of **nickel** (as impurities in goethite or a variety of silicates), sometimes with **cobalt** () and **chromium**; felsic volcanic bedrock can produce **titanium** or **REEs**.

Bog Iron

Small but high-grade iron ore deposits formed in peat bogs and lakes. Oxygen-poor groundwater will dissolve iron as it passes through the rock, then emerges onto the surface in a spring. The dissolved iron then either reacts with oxygen produced by plants in the water or, more commonly, is oxidized by microbes in the water, in either case depositing as solid nodules. The water must be fairly oxygen-poor (to allow the iron to reach and deposit on the surface rather than more promptly underground), hence the requirement for bogs that are fed primarily by rain or springs rather than river water.

Though small, the resulting deposits are easy to find and mine, and the ore easy to refine. They are also renewable; once the ore is extracted, new ore will gradually deposit over a few decades.

Occurrence: Wetlands primarily in cool, temperate climates, in places with at least some nearby iron-rich bedrock (which is common essentially anywhere except in the middle of deep sedimentary basins). In addition to those in the bogs, these regions may contain buried ores formed in the recent past.

Ores: Hydroxide and oxide ores of **iron** (goethite, FeO(OH); magnetite, Fe_3O_4; hematite, Fe_2O_3).

Banded Iron Formations (BIF)

These formed during the gradual oxygenation of the oceans, billions of years ago. The early oceans were rich in dissolved iron, and oxygen produced by early photosynthetic microbes reacted with this iron to form solid oxides that deposited on the seafloor, forming alternating bands of iron-rich ore and iron-poor silicates (the exact reason for the banding is unclear, but it's likely related to variations in activity by the microbes). Deposits in the oceans have long since subducted, but those deposited in shallow seas on the early continents remain today.

Most BIF deposits formed after oxygen levels started rising but had not yet risen high enough to remove dissolved iron from the oceans completely (around 2.8-1.8 billion years ago on Earth). The deep seas remained oxygen-poor for some time thereafter, so some deposits formed on the seafloor from iron emitted by submarine volcanic activity and were, like VMS deposits, then scooped up onto the continents by tectonic collisions. But even these stopped forming after the final increase to near-modern oxygen levels when complex animal and plant life appeared (around 500 million years ago on Earth).

Later movement of groundwater through BIFs can cause **secondary enrichment**, concentrating the iron into a more compact deposit with about twice the usual grade, and these are generally mined first before moving on to the lower-grade deposits around them.

Occurrence: Primarily on **cratons**, occasionally on **old crust** as well, in either case requiring the ancient marine sediment to be exposed.

Ore: Predominantly oxide ores of **iron** (magnetite, Fe_3O_4; hematite, Fe_2O_3; occasionally siderite, $FeCO_3$), sometimes with **manganese** (hausmannite, Mn_3O_4, braunite, $Mn^{2+}Mn^{3+}_6(SiO_4)O_8$) or **gold** (native Au).

Oolitic

Formed by deposition of dissolved metals in marine sediment similar to BIFs, but younger, still forming today where iron-rich tropical rivers flow into the sea. The iron mineralizes around small particles, forming small spherical **ooids** that then join together into ore deposits (non-ooilitic iron ores can also sometimes form in similar locations but I won't go through every type). If the sea is more enclosed, oxygen-poor conditions on the seafloor may instead encourage formation of manganese ores.

Formerly a major iron source, these have mostly been abandoned in favor of richer, purer BIFs, but they remain a major manganese source. Similarly, large amounts of **manganese nodules** are deposited on much of the deep ocean floor, but so far there's been little interest in mining there.

Occurrence: **Marine sediment** deposited by warm shallow seas with sources of metal-rich water flowing off of orogenies. Seafloor manganese nodules are widespread but most common near hydrothermal vents at **plate boundaries** and **hotspots**.

Ore: **Iron** (goethite/limonite, FeO(OH); hematite, Fe_2O_3; siderite, $FeCO_3$) and **manganese** (pyrolusite, MnO_2).

Uranium Infiltration

Though uranium ores may appear in a variety of deposits, their richest deposits form due to a quirk of uranium's chemistry: when **oxidized** (stripped of some of its electrons) it dissolves easily in water, but when **reduced** (given electrons) it will deposit as solid ores. Water is a good oxidizer, and so will dissolve out uranium as it flows over mountains and volcanic rock; if uranium-laden groundwater seeping into sedimentary rock then encounters reducing material, a sharp boundary can form between the reduced region and the sediment oxidized by water, and uranium carried in the groundwater will deposit out as it encounters this boundary. This mostly forms two kinds of deposits:

- **Unconformity-related** deposits form at the boundary between the highly mafic bedrock of cratons and younger (almost always Proterozoic) sediment over it. These tend to be the largest and highest-grade uranium deposits.
- **Roll-front** deposits occur in sandstone where the groundwater encounters organic material, like the fossil fuels we've been discussing; the ore forms at the sharp boundary between rock oxidized by the groundwater and the remaining reduced material. Microbes can play a role here as well, reducing uranium for energy. These can form basically anywhere fossil fuels are found, but grade varies; in some cases the uranium is almost fully absorbed into the fuel and difficult to separate, which is why many coal power plants release more radioactive material than nuclear power plants.

Occurrence: Unconformity-related deposits form over **cratons** where the old bedrock encounters

Ores: **Uranium** and sometimes **vanadium** in roll-front deposits.

Evaporites

Formed by evaporation and eventual complete drying out of a body of water. Minerals dissolved in the water deposit out as it dries, often in distinct layers as different minerals deposit at different concentrations.

Aside from acting as a deposit themselves, evaporites buried under sediment may also play a role in the formation of other deposits, such as SedEx deposits (they can provide a source of water when compacted and heated) and oil and gas reservoirs as we'll discuss in the next post.

Occurrence: Regions where bodies of water might once have existed but have since dried up, recently or in the far past. This may include dry lakebeds in endorheic basins (https://worldbuildingpasta.blogspot.com/2022/02/an-apple-pie-from-scratch-part-viib.html#endorheicbasin) as we've discussed in the past, which have a particular tendency to form evaporates in **rifts**, but many evaporites form along shorelines, particularly in arid climates; they commonly form in **sabkhas**, ephemerally flooded coastal basins, or coastal lagoons, and during periods of sea level fall this can gradually distribute deposits over large areas. Even enclosed seas that don't entirely dry up can begin depositing out evaporates if an arid climate and high evaporation helps increase the salinity; **marine sediments** formed in warm climates thus often contain evaporites, and later tectonic stress may squeeze them into more concentrated **salt domes**, sometimes even bursting through the above layers of sediment to reach closer to the surface.

Ores: Evaporites derived from seawater deposit a predictable sequence of **calcite** ($CaCO_3$), **gypsum**($CaSO_4$), **halite** (NaCl), and **sylvite** (KCl); lake evaporites are more variable possibly including **niter** (KNO_3).

Phosphorites

Large phosphate-rich deposits formed in shallow water along coastlines in shallow water along coastlines or in estuaries from the burial of phosphorus-rich sea life.

Occurrence: Coastlines with some history of uplift or sea level-fall (which has happened everywhere to some extent in the current ice age cycle), especially in regions with strong upwelling (bringing up a steady supply of phosphorus from the deep ocean). Older deposits can sometimes be found among **orogenies** from former seas closed in collisions.

Ores: Predominantly **phosphates**, sometimes with **REEs**.

Brine

Rather than waiting for minerals to deposit out of fluids, we can sometimes extract minerals directly from those fluids ourselves. This is generally done in dry endorheic basins fed by either hot springs or water flowing over young volcanic rock; the water gathers in a lake and then most of it evaporates, leaving the minerals behind concentrated in a rich brine. Some brines can also be extracted directly from hot springs, and they may be occasionally found in underground aquifers alongside oil fields.

Occurrence: Mostly dry endorheic basins within **active orogenies**, with minor sources at hot springs within volcanically active orogenies or at **rifts**.

Ores: Mostly **lithium**, sometimes with some **boron**, **potassium**, and **bromine**.

Resources

Now that we have a general sense of where ores *can* appear, let's run through each of the major mineral resources in turn and pick specific spots where they *will* appear on our world. Within the general restrictions we've established, the placement and type of deposits is largely an artistic choice; I'm not going to get too caught up trying to account for every subtle step of formation processes across billions of years of geology (it's not as if nature is particularly cautious to ensure every deposit on Earth fits the same patterns anyway).

We'll take the element of technology into account here as well, noting which ores become available in what general sequence as technology for extraction and refinement advances—though for now I won't dig too much into how the technology actually works. The details of this will vary between metals, but we can roughly split the history of metal extraction into four broad eras:

- **Early** (before ~1000 BCE): Basic mining of surface deposits with simple methods and hand tools. There is some shift over this era from extraction of unrefined minerals and native metals to the development of smelting for various ores.

- **Preindustrial** (1000 BCE – 1750 CE): With the advent of the iron age, the development of better tools, and the formation of larger, more urbanized societies, more intensive mining of ores sets in. The development of hand-powered pumps to remove water from mines also allows for underground mining of rich deposits. There is some gradual improvement in tools and methods over this time, and shifting demand as urbanization increases and transportation infrastructure improves.
- **Industrial** (1750 – 1950): The development of steam engines allows for much easier pumping of water out of mines and thus deeper and more intensive mining, as well as later providing energy for smelting and transportation. Industrialization increases the demands for metals (and fuels) in turn. Improvements in chemistry also allow for both better refinement of metals and identification of new metals which are soon mined as well.

- **Modern** (after ~1950): Modern machinery allows for mines reaching up to km underground and economic mining of low-grade ores. Developments in metallurgy and electronics create demand for a variety of new metals and mineral resources, some only recently identified. The development of modern geology also allows for identification of many new ore deposits not previously recognized.

Note that I'll be using the history of extraction on Earth as a guide and there may be an element of historical accident here; for example, many of the largest layered complex, IOCG, and SSC deposits are in fairly remote regions, and this isn't necessarily an inherent consequence of their geology, so it may be conceivable that they would have been mined earlier if more conveniently placed, but I'm not familiar enough with the particulars of mining technology to be sure.

Metals

To start off we'll tackle all the metals, all of which share some chemical character even if they become more distinct in the details. For some context here are some *rough* values of current production (https://nora.nerc.ac.uk/id/eprint/534316/1/WMP_2017_2021_FINAL.pdf), prices (https://en.wikipedia.org/wiki/Prices_of_chemical_elements#cite_ref-src-imar-ree_66-0), and (where I could find good numbers) minimum ore grades as of around 2020, though these can vary significantly year-to-year.

Metal	Global Production of Refined Metal (tonnes/year)	Typical Market Price ($USD/kg)	Minimum Exploited Ore Grade (% metal)
Iron	1,400,000,000 iron, 1,900,000,000 steel	0.5 iron, 1 steel	30
Aluminum	67,000,000 (and substantial recycling)	2	35
Manganese	50,000,000	2	40 directly, 10 byproduct
Potassium	45,000,000 potash, ~200 K metal	0.4 potash, 12 K metal	
Chromium	35,000,000	10	20

Copper	20,000,000	6	0.3 large deposits, 3 small deposits
Zinc	13,000,000	2	6 Zn+Pb
Silicon	8,500,000 Si+alloys, ~3,000,000 Si metal	2	98 SiO_2
Barium	6,900,000 barite, ~5 Ba metal	0.5 barite, 600 Ba metal	
Titanium	6,500,000 TiO_2, ~300,000 Ti metal	3 TiO_2, 10 Ti metal	1 primary 0.1 placer
Nickel	2,800,000	10	2
Lead	2,600,000	2	6 Zn+Pb
Zirconium	1,100,000 zircon, ~10,000 Zr metal	2 zircon, 40 Zr metal	1 zircon+Ti
Strontium	500,000	6	
Rare Earth Elements	400,000 together	ranges from 5 La/Ce to 3,000 Sc/Tm	5 light REEs, 0.01 heavy REEs
Molybdenum	300,000	40	0.1
Tin	260,000	20	0.3 primary, 0.01 placers
Cobalt	170,000	30	0.3
Vanadium	110,000	400	1 directly, 0.01 byproduct
Antimony	100,000	6	3
Lithium	100,000	80	1
Magnesium	100,000	2	25
Sodium	100,000	3	
Tungsten	100,000	40	0.1
Niobium	90,000	70	0.3
Arsenic	50,000	1	not targeted
Uranium	50,000	100	0.2
Cadmium	25,000	3	0.3
Calcium	25,000	2	
Silver	25,000	500	0.04 directly, 0.005 byproduct

Bismuth	5,000	6	
Selenium	3,500	20	
Gold	3,000	40,000	0.00002
Mercury	2,500 (down from 10,000 at peak)	30	0.6
Tantalum	1,500	300	0.03
Indium	800	200	
Tellurium	500	60	
Platinum Group Elements	200 Pt, 200 Pd, 60 Ru+Rh+Os+Ir	10,000 Ru/Os, 30,000 Pt, 60,000 Pd/Ir,100,000 Rh	0.0005 primary, 0.0001 byproduct, 0.00001 placer
Gallium	400	150	0.003
Beryllium	200	800	0.1
Germanium	100	1,000	0.01
Hafnium	100	900	
Thorium	70	300	
Cesium	50	60,000	
Rhenium	50	3,000	
Thallium	10	4,000	
Rubidium	3	15,000	

Iron (Fe)

Iron is by far the most commonly extracted metal, accounting for over 90% of modern ore extraction. First used for tools, weapons, and jewelry, it is now mostly used as a structural material in buildings and vehicles but has a variety of other uses and can generally be regarded as the default metal of the modern world. It is often alloyed with carbon to make **steel** (~1% C) or **cast iron** (>2% C), chromium to make **stainless steel** (>11% Cr), and various other metals for specialty alloys.

As you might have picked up, iron ores form in a variety of ways and are generally pretty common (most sulfide ores contain some pyrite and most oxide ores some magnetite, but I only mentioned them where they're rich and pure enough to be worth large-scale mining). We can generally assume that pretty much everywhere has some access to iron, but I will go over the main deposit types mined through history and which deposits might be richest.

Unrefined iron oxide (ochre) found in many sediments has been used as a pigment since prehistory. The earliest iron metal was extracted as early as 3500 BCE from **meteorites**, where it can often be found as an alloy with nickel and shaped with simple tools; these may appear anywhere meteorites fall, though may be easier to find in deserts or tundra, but are small deposits. Small amounts of native iron may also rarely form in mafic volcanic rock.

Iron’s high melting temperature made smelting difficult until techniques using charcoal were developed; this was likely first practiced before 2500 BCE but was not widespread until after 1200 BCE (steel production started soon after but ore quality, refinement difficulty, and fuel requirements limited it until the industrial period). This then allowed for iron to be produced from its numerous ores, mostly starting with higher-grade hematite, goethite, and limonite deposits but also including magnetite and siderite. **Bog iron** and **placer** deposits were often the first exploited, but could only ever provide a small supply—suitable for a local village but not large cities—and were largely abandoned after industrialization. **Laterites** and **oolitic** deposits were also widely mined throughout the preindustrial period and into the industrial period, along with other types of **ironstone** found widely in small quantities in sediment as a result of various surface processes. The largest preindustrial mines were typically at **skarn** deposits, though placement of major mining operations was often more restricted by availability of fuel for smelting (first charcoal derived from wood and later coal when coking methods were developed) rather than ores. Mining of usually underground **IOCG** (and similar **Kiruna-type**) deposits began in the late 19th century and soon came to dominate production.

Large-scale mining of **BIF** deposits only began in the modern period, but they now provide the majority of the world’s iron, with current mining mostly concentrated on the highest-grade deposits formed by secondary enrichment. Rich **IOCG/Kiruna-type** and **skarn** deposits are still commonly mined, while mining of **layered complex**, **VMS**, **SedEx**, and **laterite** deposits may produce iron as a byproduct of more valuable metal extraction; mining of small-scale and **oolitic** deposits has largely stopped.

The only regions likely to be particularly iron-poor are those covered in volcanic ash or deep layers of young sediment, though even then there’s likely to be some iron in outcrops, placers, or bogs; it may just be difficult to transport in the preindustrial period.

Copper (Cu)

Copper is one of the oldest and most enduring metals worked by humans, thanks largely to its easy refinement. It was likely the first metal used for tools and weapons, first as a pure metal and then alloyed with arsenic or tin to form **bronze**. Iron and steel have largely replaced it in those original uses, but it has remained in use in art, coinage, plumbing, and architecture. More recently copper’s high conductivity (and lower cost than more conductive silver) has favored its use major component of electronics and wiring thanks to its, which has become the primary source of demand. Though surpassed in production by other structural metals, it is still the fifth-most produced metal.

Though not quite as ubiquitous as iron, copper appears in a wide variety of ore deposits associated with essentially all types of tectonic environment, and particularly tends to appear in large numbers of individual deposits along convergent boundaries. The uncommon native form has been gathered since around 8700 BCE, likely from **placers** sourced from and later large veins of **SSC**, **felsic hydrothermal-magmatic**, or **VMS** deposits. Smelting may have developed as early as 7500 BCE (likely as an accidental byproduct of pottery firing), allowing for extraction from ores, mostly starting with brightly colored green malachite and blue azurite produced by secondary enrichment and often found on the surface. Production of the stronger metal bronze by alloying with arsenic (often present in some copper ores) from about 5000 BCE and tin (usually mined separately) from 3000 BCE prompted increased extraction and more complete mining of deposits including chalcopyrite and bornite ores. Early and preindustrial sources were mostly **VMS** deposits along with some **skarns**, **SedEx** deposits, **intrusion-related veins**, and **porphyries** with significant secondary enrichment.

Improved refinement and exploration methods in the industrial period allowed mining of non-native Cu from lower-grade **porphyry** and **SSC** deposits; these now dominate the global supply, but there are also some particularly large **IOCG** and **immiscible melt** deposits; smaller **VMS**, Cu-rich **SedEx**, and **felsic hydrothermal-magmatic** deposits other than porphyries are also still mined if sufficiently high-grade.

Gold (Au)

The archetypal precious metal, much-desired despite having few practical applications before the modern period due to its softness and rarity and so devoted mostly to jewelry, coinage, and financial use. Its desirability as a storage of value may be attributed both to its distinctive appearance and very low chemical volatility, which makes it easier to store and also means it usually occurs in its native form (though usually with some amount of alloyed Ag), making it easier to recognize and extract even in the early period. It also helps that it’s rare in terms of total abundance but occurs in small amounts in a wide variety of deposits, such that most regions will have some nearby supply. The lack of practical uses may actually be favorable; better to have a currency that stays in circulation at a (relatively) stable value rather than one with fluctuating supply due to the consumption of one or another industry. Today, aesthetic and financial uses still consume about 90% of production, but it has found a secondary use in electronics thanks to its decent conductivity and high corrosion resistance.

Some native gold may have been collected since prehistory, but the earliest clear evidence of extraction dates to about 4500 BCE. **Placers**, usually along rivers, have been a major source throughout history, sourced in turn from a variety of primary deposits, with active orogenies usually providing the richest supply but good placers sometimes also forming from **mesothermal** deposits. But mining of primary deposits also began in the early period, with **epithermal** deposits tending to be the richest sources but mining of **intrusion-related vein**, **skarn**, and possibly **VMS** deposits as well.

This pattern largely held until the industrial period when mining of lower-grade **mesothermal** (and **Carlin-type**) deposits started as well. Cu extraction at **porphyry** and **IOCG** deposits starting around the same time also often produces Au as a byproduct. **Epithermal**, **VMS**, and **skarn** deposits are still mined as well, but the dominant source remains **placers**; recent placers are mostly mined at small scale but have a large cumulative output, and a few large **paleo-placer** deposits found on cratons in the 19th century are now a major source.

Silver (Ag)

Another precious metal but with a more complex history. It is still fairly rare and chemically stable but substantially more common than gold, and is about as soft as gold in its pure form but can be alloyed with a small amount of copper to make a more durable material that's still too soft for tool use but more suitable for ornamentation or utensils. It is thus ideal for more widespread use in currency and art when gold is too rare and expensive, and can also be more widely applied to secondary uses such as in mirrors. Its antibacterial properties make it particular useful for cutlery and in small amounts in medicine. More recently, its high conductivity and low reactivity has given it widespread use in electronics, including in screens, batteries, and solar panels, and it also has secondary uses in film photography and various catalysts.

Like Cu and Au it was likely first gathered in its native form (or alloyed with Au) in **placers**, but it's not as ubiquitous as native Au and so for a time it was the more precious metal. Extraction from mostly galena by cupellation was developed by 3000 BCE. Because of its common association with other ores the details of its early extraction are somewhat obscure, but it appears likely it was mined in the early period either as native Ag, argentite, or a galena impurity from **skarn**, **manto**, **epithermal**, and **VMS** deposits. The biggest preindustrial mines were typically **epithermal** deposits (often in the same regions as Au-rich epithermals but usually not the same deposits) mining at all the above-mentioned deposits continued as well along with **SedEx**, **intrusion-related vein**, and some **MVT** deposits as well.

As the demand for other metals increased in the industrial period, the emphasis of many mining operations shifted and silver is now predominantly produced as a byproduct of Cu and Pb/Zn extraction from **felsic hydrothermal-magmatic**, **VMS**, and **SedEx** deposits and Au extraction in its various deposits, which essentially always have at least some Ag impurity.

Tin (Sn)

A fairly rare but not quite precious metal. Tin metal has some uses, mostly for decorative purposes as it is soft but fairly easy to cast and shape, but tin is mostly notable for its use in various alloys, particularly with copper to make **bronze** (~10% Sn). Compared to earlier arsenical bronze, tin bronze is easier to smelt and cast and less prone to release toxic gas in the process. But rich Cu and Sn ores don't often occur in the same deposit so the tin must often be transported long distances; demand for bronze likely drove the development of many early trade networks. Since ~1500 BCE tin has also been alloyed with small amounts of Cu, Sb, or Pb to make **pewter** (~90% Sn), which is somewhat harder than pure Sn and was widely used for tableware prior to the modern period; and with larger amounts of Pb to make **solder** (~60% Sn), which has a very low melting temperature and so can be easily used to join other metals together (by placing liquid solder between them and then letting it harden). Today soldering in electronics is the dominant use (more frequently with Pb substitutes), with secondary uses as a corrosion-resistant plating for steel, an additive in polymers, and in continued production of bronze and various other alloys.

Tin deposits are known for being fairly geographically limited compared to other ancient metals, though small deposits are more widespread. The earliest production of a Cu–Sn alloy at around 4600 BCE was likely from accidental smelting of Cu ore with Sn impurities, but intentional extraction of cassiterite began by about 3000 BCE, likely beginning at **placer** deposits, which are fairly common in rivers downstream of primary deposits due to cassiterite's density and chemical stability. It is notoriously unclear where exactly many ancient societies sourced their tin and when they might have started mining primary deposits, but it was likely at some point in the early or earliest preindustrial period. **Pegmatite** and **greisen** deposits are generally richest, but **intrusion-related veins** and some **skarn** and **VMS** deposits can have significant Sn as well; the last two can be particularly important as they often have Cu ores as well, sometimes mixed together with Sn ores, allowing for on-site bronze smelting, intentionally or not.

The pattern of deposit types mined hasn't changed too much over time, but individual tin deposits, even quite rich ones, have often gone unnoticed for long periods because cassiterite has a fairly unremarkable appearance and in many cases appears as unremarkable fragments; so extraction patterns may shift as much by accident as technology. Today, Sn-rich **skarns** are perhaps more often exploited and **intrusion-related vein** and **VMS** deposits less often, though the latter may still produce tin as a byproduct of other metals. **Placers** have also become less important though are still commonly mined to very low grades, as are **paleo-placers**. Some **porphyries** contain large amounts of tin but at grades as yet too low to be worth mining.

Zinc (Zn)

A common metal that is rarely used on its own. Refinement as a pure metal is difficult because zinc boils at a lower temperature than its ores must be smelted at, so an airtight container is required to contain the Zn gas; this may have been managed as early as 1000 BCE, but it was not practiced at scale until the 12th century and even then was not widespread until the industrial period. Far easier is alloying zinc with copper to make **brass** (~10-40% Zn), which is corrosion-resistant and easy to cast like bronze but softer, making it less suitable for tools and weapons but easier to work and so better for sculpture, utensils, and furniture. More recently, its low surface friction has also favored its use in machinery, plumbing, electronics, and ammunition. Since the late 19th century galvanizing of steel (covering it in a thin zinc layer that slows corrosion) has surpassed brass as the dominant use, with secondary uses in various other alloys, batteries, catalysts, and as an additive in rubber and plastic for UV protection.

Production of brass began around 3000 BCE, but thereafter patterns of early and preindustrial zinc extraction vary as much by culture as by overall technological development. In India, extraction from sphalerite in **SedEx** deposits was practiced at low levels through the preindustrial period; whereas in the Mediterranean and Europe, zinc was not understood as a distinct metal until the 18th century and brass was produced by heating mixed copper and smithsonite, produced by secondary enrichment of **SedEx**, **MVT**, **VMS**, and **skarn** deposits, while Ag/Pb mines often left rich Zn sulfide ores untouched.

After development of galvanizing in the later 19th century, demand for zinc greatly increased, with extraction primarily from sphalerite in **SedEx** and **MVT** deposits but also **VMS**, **skarn**, **manto**, and **intrustion-related vein** deposits.

Lead (Pb)

Though it has a poor reputation today, lead has a long history as a metal with diverse uses thanks to the generally low cost of refinement and casting. After some early use in art, cosmetics, and, bizarrely, medicine, it was mostly used in the preindustrial period for plumbing, coinage, and roofing, and later for paints, as a glass additive, and finally as a fuel additive. After discovery of its toxicity late 19th and 20th century it was phased out of many of these uses and it is now mostly used for inexpensive lead-acid batteries, with secondary uses in ammunition, construction, and electronics.

Lead may have been one of the first metals smelted, by around 7000 BCE, thanks to its low melting temperature. But for much of its history (perhaps even initially) lead has been produced largely as a byproduct of extraction of silver, which is a common impurity in galena—thus lead's low cost, as Ag mining produced large amounts of byproduct lead despite its lower demand. Still, the extent to which any ancient mine was targeting one or another metal can be unclear; it may be that the easy availability of lead caused widespread use that eventually drove enough demand to justify more targeted lead extraction in the preindustrial period. Regardless, early and preindustrial Ag/Pb mining occurred at **SedEx**, **intrusion-related vein**, **skarn**, **manto**, and some **MVT** and **VMS** deposits (Ag-rich epithermal deposits contain some Pb (and Zn) ore but not as much and not as directly associated with the Ag ore).

After the late 19th century lead (and Ag) became predominantly a byproduct of growing Zn extraction, often at the same deposits but including some Ag-poor deposits as well; Pb and Zn ore almost always occur together, excepting some Zn-rich, Pb-poor VMS deposits. A high Pb grade can help justify mining of deposits with lower Zn grades, but it is rarely a primary target of extraction.

Nickel (Ni)

Well-regarded for its tendency to form strong alloys and resist corrosion by forming a thick oxide layer, but a somewhat enigmatic metal throughout much of history: Nickel ore is easily confused with copper and so it was not identified as a distinct metal until the 18th century, but it was known since at least ~1500 BCE that certain nickel-rich copper ores could be used to make strong and corrosion-resistant **cupronickel** (a.k.a. "white copper" or "paktong", ~20% Ni) used for weapons and coinage. Once identified, nickel and cupronickel were widely used for coinage, then nickel was found to be a good additive to stainless steel in the late 19th century and this has been its dominant use since. In the modern period it has been used in various "superalloys" like **Inconel** (~60% Ni) used in aerospace vehicles for their strength, corrosion resistance, and high melting temperatures. Secondary uses include as a plating material, in batteries and other electronics, and in magnets.

Early and preindustrial nickel ores for cupronickel production likely came from small **immiscible melt** deposits and **intrusion-related veins**, likely as nickeline. In the industrial period Ni-rich **laterites** were the dominant source for a time, and then identification and mining of larger **immiscible melt** deposits began in the late 19th century; pentlandite in **immiscible melts** and various ores in l**aterites** remain the dominant sources today, particularly a few giant immiscible melt deposits.

Aluminum (Al)

A ubiquitous metal today despite being unknown for much of history. Though common in silicate rock, it doesn't produce many ores and refinement is difficult and very energy-intensive. The Al sulfate salt **alum** has been mined since at least 700 BCE for use in dyeing and as a fire retardant. The presence of a metal in alum was long suspected but it wasn't isolated until the 19th century. Industrial production began in the later part of the century once refinement techniques were developed and affordable energy became available. Though not as strong as steel, aluminum is much lighter and more corrosion-resistant, favoring its use in vehicles (particularly aerospace), packaging, and light construction, almost always alloyed with a small amount of various other metals. Al sulfate salts are also still used for dyeing and tanning. Aluminum is now second only to iron in total production (even before counting the substantial portion of Al produced by recycling, which requires much less energy).

Preindustrial alum was extracted on its own or refined from alunite, both found commonly around **orogenies**, with production limited as much by knowledge of the refinement process as ore availability. Since aluminum metal production started in the preindustrial period, it has been produced essentially only from bauxite in **laterite** deposits. But smelters are often placed based on availability of cheap energy, even if far from any deposits.

Chromium (Cr)

Another major medal today with a short and fairly straightforward history. Isolated in the late 18th century, it was first used in small amounts for pigments and leather tanning. Cr-containing steel alloys were then produced in mid-19th century, eventually leading up to the discovery of the highly corrosion-resistant **stainless steel** (>11% Cr) in the early 20th century, which has been its dominant use ever since. It's also been used for various "superalloys", often alongside nickel, with good performance at high temperature that make them ideal for engines, which has given chromium some strategic importance. Secondary uses include chrome-plating for corrosion resistance or aesthetic purposes and continued use in pigments and tanning. It is now the fourth-most produced metal, after Fe, Al, and Mn.

For a short period it was extracted in small amounts from crocoite ores sometimes produced by secondary enrichment of lead ores, but from the early 19th century it has been mined almost exclusively as chromite from

cumulate deposits; in the industrial period this was mostly small deposits around orogenies with a history of island arc collisions, but larger buried deposits have been found in the modern period and a handful now dominate the global supply.

Manganese (Mn)

Yet another fairly straightforward metal with huge current production. MnO_2 has been used since prehistory as a pigment and in the preindustrial period for coloring glass. Some Mn-rich iron ores may also have been inadvertently used to create harder alloys in the preindustrial period, but it's unclear if this was ever done intentionally. Mn metal was only isolated in the late 18th century but was soon discovered to be useful for removing sulfur and oxygen from iron ore during refinement, which has been its dominant use since. It was also the first non-Fe metal commonly alloyed into steel, making an impact- and abrasion-resistant alloy useful for helmets and heavy machinery. It also has secondary uses in aluminum alloys and batteries. Though somewhat displaced in several of these roles by other metals, it is still the third-most produced metal today, after Fe and Al.

Industrial-period Mn and earlier MnO_2 came mostly from pyrolusite in **oolitic** deposits or as a common impurity or secondary ore in iron ore deposits; the largest modern sources are a few Mn-rich **BIF** deposits, but unlike iron **oolitic** deposits are still mined as well as some large **SedEx** deposits, and it's a common byproduct of Fe extraction. Large amounts of **Mn nodules** exist on the ocean floor but are not yet worth mining.

Molybdenum (Mo) and Tungsten (W)

Two hard, dense metals with similar chemistry and history. Both were first isolated in the 18th century and found to make hard alloys in the 19th century, but due to issues with refinement and working of the metal they weren't widely used until the 20th century. They can both be used to make hard, dense alloys like high-speed steel that retain their strength at high temperature, ideal for cutting and drilling, though tungsten is generally preferable, and is also used to make **tungsten carbide**, a particularly hard, dense material. They are particularly useful for military purposes, as armor, armor-piercing ammunition, and barrels for large artillery pieces, and so acquired strategic significance in the world wars (moreso Molybdenum in WWI when tungsten supplies were more limited and then tungsten in WWII), with the Allies often attempting to restrict their supply to Germany.

Because of their chemical similarity, their ores can often be found in the same deposits, but not always: Mo is mostly extracted as molybdenite from continental **porphyries**, which tend to have Mo with either Cu or W but not both (or Cu with neither Mo or W); W comes mostly from scheelite in

skarns, which more regularly have a mix of Mo and W; **greisens** are a secondary source of both Mo and W; and smaller amounts of both Mo and W come from **pegmatites** and exclusively W from **intrusion-related veins**.

Titanium (Ti)

A high-performance metal with fairly common ore but hampered by difficult refinement. It was identified as a metal in the late 18th century but not isolated until the 20th. 95% of extracted ores are refined to TiO_2 for use predominantly as white pigment in paints, paper, plastic, etc., largely replacing Pb paints after the early 20th century. Industrial production of Ti metal began only in the modern period, but its high strength-to-weight ratio quickly made it desirable for aircraft, which has remained its main use, with secondary uses in other vehicles and various consumer products, but despite fairly abundant ores the expensive refining process has limited its widespread adoption. Its use in military aircraft and submarines in particular has given it some strategic importance.

Historically it has been mined mostly from **beach placers**, but **cumulate** deposits and nearby **laterites** are an increasing source (and also typically the ultimate source of placers). Purer but rarer rutile ore is most desirable, but ilmenite is also mined at about 10 times the minimum grade (the numbers I gave in the table are for rutile), ultimately accounting for most production. Some Ti is now also produced as a byproduct of oil sands extraction, not because the mined material is particularly Ti-rich but simply because they must process so much of it.

Platinum Group Elements (PGEs)

A chemically similar group of rare transition metals that are often found together in the same minerals or as alloys. **Platinum** (Pt) and **palladium** (Pd) are the most economically important, but **ruthenium** (Ru), **rhodium** (Rh), **osmium** (Os), and **iridium** (Ir) are all mined and used in smaller quantities as well.

Alloys of platinum and gold (often with other PGEs) have been used in jewelry and art since around 1200 BCE, though how intentionally is not always clear and platinum was not clearly understood as a distinct metal until the 18th century; the other PGEs were all isolated within the next century. Today they are mostly used as catalysts, mostly in engines and organic chemistry, with secondary uses in electronics and specialist alloys. Platinum and to a lesser extent palladium are also still used in jewelry and finance.

Like gold, platinum is often found as a native metal alloyed with various amounts of the other PGEs and commonly forms **placers**, which account for essentially all preindustrial extraction and are still mined to very low grades. Primary PGE ore has been mined since the 19th century almost exclusively from **layered complexes**; the richest are generally chromite impurities in **cumulate** deposits, while pentlandite and pyrrhotite impurities in **immiscible melt** deposits are usually produced only as byproducts of Ni extraction. 80% of Earth's Pt comes from a single cumulate deposit in South Africa, though the other PGEs are more broadly distributed. **SSC** and Ni-rich **laterite** deposits may contain some PGEs but as yet they are too low-grade to be worth extraction.

Rare Earth Elements (REEs)

Another chemically similar group of metals, including **scandium** (Sc) and **yttrium** (Y) along with the **lanthanides**: **lanthanum** (La), **cerium** (Ce), **praseodymium** (Pr), **neodymium** (Nd), **samarium** (Sm), **europium** (Eu), **gadolinium** (Gd), **terbium** (Tb), **dysprosium** (Dy), **holmium** (Ho), **erbium** (Er), **thulium** (Tm), **ytterbium** (Yb), and **lutetium** (Lu). (Technically **promethium** (Pm) is also a lanthanide and has some industrial uses, but it's unstable and vanishingly rare in nature so produced exclusively in nuclear reactors through neutron bombardment of U or Nd). In terms of average concentration they're not actually all that rare on Earth, they just tend not to form high-grade ores and are difficult to separate into the individual elements.

REEs were unknown before the industrial period, the individual elements were not all identified until the start of the 20th century. The unseparated alloy **mischmetal** (~50% Ce, 25% La, etc.) produced directly from mixed ore has seen some use since the early 20th century in lamps, lighters, and batteries, but reliable separation of the individual elements and significant extraction began only in the modern period. The elements have various unique properties, such that small but critical amounts are used in a variety of modern technologies (usually alloyed with a more common metal):

- Pr, Sm, Dy, Ho, and especially Nd produce powerful permanent magnets that retain their magnetism at high temperatures, useful for motors, generators, speakers, and various other electronics.
- All REEs to varying extents but especially Y and Eu have optical properties useful for lights, screens, lasers, and fiber optics.
- La, Ce, and Lu are used as catalysts in oil production and Sm as other catalysts.
- Specialist alloys of Al with Sc or Ce, Mg with Pr, Fe/Cr with Gd or Yb, and V with Er have various uses, particularly in aerospace vehicles.
- Tb–Dy–Fe alloy can respond strongly to magnetic fields in a way useful for various sensors.
- Sm, Gd, and Ho are good at absorbing neutrons and so are used for shielding or control in nuclear reactors.

- Y, La, Ce, Sm, Gd, and Tm can be used in superconductors at various temperatures, though all still cold enough to make their widespread use difficult.

Their widespread use in modern electronics and smart weaponry and their often geographically restricted deposits gives them some potential strategic importance.

There is some tendency for the more common lighter lanthanides (La to Sm) to separate into different ores from the heavier elements (Eu to Lu), with the latter generally being more desirable and mined to much lower grades. The earliest significant extraction of mostly lighter REEs was from **beach placers**, but modern extraction is predominantly from **carbonatite** deposits. In the 21st century a few **laterite** deposits around old orogenies have become a major source, particularly of heavy REEs. Some **IOCG**, **pegmatite**, **skarn**, and Ti-rich **beach placer** deposits produce small amounts of byproduct REEs.

Lithium (Li)

A metal with a short but complex history: first isolated in the early 19th century but not much produced until the 20th, Li compounds were at first mostly used for lubricating grease in aircraft engines and soaps. Demand increased after the mid-20th century for use in producing tritium or lithium deuteride fusion fuel in thermonuclear weapons, and it might see similar use in the future for fusion reactors or engines. In the modern period it has also entered use in glass and Al production, lightweight Al alloys for aerospace, and medicine. In the 21st century demand has greatly increased for use in rechargeable Li-ion batteries.

For most of that period it has been extracted primarily from spodumene in **pegmatites**, often alongside Sn, REEs, Ta, or Be. Since the late 20th century **brines** have been increasingly preferred for production of Li metal, as refinement is much easier. Increasing demand and few current regions of production has led to some concerns about its geopolitical impact, but there are still significant potential Li sources not yet exploited.

Notes

Many of the sources I used here were very broad, and I frequently mixed their information in a way that made citing them in each case a bit inconvenient, so here’s my main ones:

- Andy Jackson’s Ore Deposits 101 video series is a good introductory overview https://www.youtube.com/channel/UCvTUbe96QQfPkMhjIF5yu9w/videos
- “Economic Geology: Principles and Practices” by Walter L. Pohl is very comprehensive if fairly technical and ultimately provided most of my particular information on things like deposit locations and ore types, especially for the more obscure metals.
- “Archaeometallurgy—Materials Science Aspects” by Andreas Hauptmann is a good source for historical extraction patterns of several key metals. https://link.springer.com/content/pdf/10.1007/978-3-030-50367-3.pdf