**Magmatic Ore Deposits**

Magmatic ore deposits are those which are formed during crystallization of a magma, deep underground. The host rock for the mineralization can range from ultramafic to felsic. The deposit can consist of massive ores in some cases, and disseminations of rare minerals in others. In the case of more massive ores, there are three primary means of concentrating minerals of value during the formation of these deposits:

- gravitational settling
- differentiation
- immiscible separations

The process of gravitational settling causes early-formed minerals to sink to the bottom of a magma chamber. This process is best exemplified in magmas with ultramafic and mafic compositions, and the best examples are chromite deposits. Chromite is a very high temperature mineral which is also quite heavy. As a result, in some situations it will tend to sink and form layers of massive ore in the bottom of a magma chamber. The intrusion itself tends to be layered, with rocks like dunite (massive olivine) forming the lowest layers, overlain by gabbro layers, overlain by norite (plagioclase-rich rock).

These intrusions are often funnel-shaped, with the neck forming a feeder system. Large magmatic deposits of this type are located at Stillwater, Montana, in south Africa, and in Manitoba.

Differentiation causes a concentrating effect resulting in a concentration of selected elements in the residual magma. These elements are the ones which did not fit well inside of common rock forming minerals. Instead, they become included in the final liquid present, which forms “pegmatite”. Pegmatites are very coarse grained rocks and form at the very last stage of crystallization. The final fluids tend to have a very high water content, which also contributes to forming large crystals. Pegmatites also contain accessory minerals of special interest because they trap the rare elements in their crystal structure. Because of the rarity of some of these elements, the accessory minerals in the pegmatite can be be quite valuable and constitute an ore deposit.

Immiscibility is a physical separation of a portion of a magma. Immiscible melts form irregular shaped segregations or may be injected as a dike into previously crystallized material. Where the immiscible melt material consists of massive chromite or sulfide ore which will probably migrate downward with gravity, due to the abnormally high specific gravity. The famous nickel, platinum and sulfide ores of Sudbury, Ontario are prime examples.

Another important deposit type which is classified as magmatic “diamond-bearing kimberlite”. Kimberlites are rocks of ultramafic composition which are generally fine-grained. Diamonds occur as accessory minerals in the kimberlite, which is frequently highly altered. Kimberlites are thought to represent mantle rocks emplace near the surface by forceful, possibly explosive, intrusion. The shapes are often like a vertical pipe, and some occur as apophyses connected to larger dike structures at depth. The
world’s most famous diamond-bearing kimberlite deposits occur in South Africa; many also occur in central and eastern Canada.

**Porphyry Copper Deposits**

Porphyry copper (pCu) deposits are large, low grade copper deposits, which sometimes contain minor Mo, Ag, and Au. Ore grade is generally around 0.5 % Cu. Almost all known porphyry copper deposits are Tertiary in age. They are thought to have formed in island or continental igneous arc settings associated with a subduction zone. Their composition ranges from tonalite to monzonite. pCu deposits usually form in relatively fine-grained intrusions of felsic composition. Where formed in differentiated intrusive sequences, they tend to be formed in the finest-grained and most felsic end members of the suite.

There are two main compositional groupings in the western U.S.: 1) Continental Margin type, and 2) Island Arc type. Continental margin types are granite-hosted, and typically contain significant Mo values. Island arc types are quartz diorite or monzonite-hosted, and may contain significant Au values.

Ore minerals present in pCu deposits include chalcopyrite, bornite, chalcocite, covellite, cuprite and tenorite. The ores consist of concentrated swarms of quartz-sulfide stockworks and sometimes as sulfide disseminations. Some deposits have a zone of secondary enrichment at the surface caused by groundwater leaching and redepositing the Cu at a lower elevation. Characteristic alteration includes potassic (Biot. + K-feldspar), sericitic (Py + Sericite), and propylitic (Chlorite, Epidote) (more on this in Class 8).

**Porphyry Molybdenum Deposits**

Porphyry molybdenum pMo deposits are large, low grade molybdenum deposits and the exclusive source of Mo. As with the pCu deposits, pMo deposits tend to form in the most differentiated members of an intrusive suite. Unlike pCu deposits, in pMo deposits there is usually only one ore mineral containing Mo, which is the mineral molybdenite. Many pMo deposits contain some tin and tungsten minerals which are recovered from the ores for additional credits. There is often a great deal of faulting associated with these types of deposits. Multiple, overlapping mineralizing events are not uncommon. Typically ore grades are in the range of 0.1 – 0.5 percent MoS₂.

**Tin Greisen Deposits**

Tin greisen deposits tend to form in near the top of granite intrusions, an area referred to as a cupola. The mineralization occurs primarily as big quartz veins containing variable amounts of tin oxide or sulfide minerals. These deposits tend to form in intrusions which lack accessory magnetite. This is because tin substitutes for iron in the mineral magnetite, and becomes unavailable to concentrate in the late stage fluids. Fluid conditions required to form tin oxide (cassiterite) are relatively reducing. These deposits may have distinct metal zoning associated. Tin and Tungsten are dominant lower and
closer (or “proximal”) to the causitive intrusion. Base metals (Cu + Pb + Zn) are distinctly elevated in the outer reaches of the intrusion or area (called “distal”).

**Skarn Deposits**

Web Site:  
[http://www.wsu.edu:8080/~meinert/skarnHP.html](http://www.wsu.edu:8080/~meinert/skarnHP.html)

Skarn deposits are replacement deposits. They form by the replacement of limestone, calcareous rocks (marl or calc-schist), or dolomite. A wide variety of minerals can form in skarn deposits, but the most common include oxide minerals such as magnetite, sulfide minerals such as chalcopyrite, silicate minerals such as epidote, or the tungstate mineral Scheelite. Gold is also mined from skarn deposits. Skarn deposits are a result of the invasion of the country rock by hydrothermal fluids carrying the high metal concentrations outward from the intrusion. The fluid composition steadily changes as the plutonic source goes through the cooling stages. Some skarn mineralization is formed by earlier, higher temperature waters (called “prograde” minerals), and some skarn mineralization is formed later at lower fluid temperatures (called “retrograde” minerals). The waters contain high concentrations of metals, and may even be the same fluids which concurrently formed pCu deposits. There are many ways to classify skarns, but a simple scheme based on composition is:

1. **Tungsten**
2. **Copper +/- Molybdenum**
3. **Iron + Gold**
4. **Tin**
5. **Lead-Zinc - Silver**

Skarns can be either massive and discordant, or stratiform and concordant (with respect to bedding of the host rock). Sometimes the bedding contacts are favorable places for skarns to form. Ore minerals in skarns may be associated with “calc-silicate” minerals such as epidote, tremolite, zoisite, wollastonite. Silica, iron and magnesium are supplied by hydrothermal fluids that evolve from the magma late in the cooling history. The minerals form at the expense of calcite or dolomite in limestone or limey sediments. More abundant impurities in the calcareous sediments appears to enhance the formation of skarn deposits in some examples.

**Volcanic-Related Ore Deposits**

Volcanic-related ore deposits are those which form as a result of volcanic activity, either in an oceanic, submarine environment or in a continental, subaerial environment. Examples of submarine environment types of volcanic-related deposits include copper and other base metal deposits which locally contain anomalous gold and silver. Seawater circulation through fractures in the ocean floor crust is probably a factor in the precipitation of metals from hydrothermal solutions. This occurs either along a rift or around the flanks of a submarine volcano. The three major types of volcanic-related deposits are 1) volcanogenic massive sulfide deposits (or “VMS” deposits), and 2) stratabound shale-hosted deposits (“SS” deposits), and 3) epithermal deposits.
**Volcanogenic Massive Sulfide Deposits (VMS)**

VMS deposits are sulfide-rich deposits hosted in submarine volcanic and sedimentary rocks. VMS deposits are polymetallic, but are chiefly recognized for their rich copper, lead and zinc values. The classic example of a VMS deposit is “Kuroko” type deposits, named after a locality in northeast Japan. At this locality, there were explosive eruptions which laid down pyroclastic rocks, which were interspersed with layers of sediments such as sands and muds. At the vent locations there is typically a plug or dome shaped intrusion of rhyolite or dacite composition. The ore itself is occurs in the form of massive sulfides or dense concentrations of disseminated sulfide minerals of various types.

Kuroko ore which occurs as abundant massive pyrite hosted in siliceous tuffaceous rocks is referred to as “yellow ore”. It tends to occur near the vent site and therefore tend to be hosted in brecciated rocks intruded by fine-grained intrusive rocks. “Black ore” is another type of Kuroko ore which is characterized by concentrations of sphalerite and galena, which are typically much finer grained than the minerals of yellow ores. The circulation of waters, both seawater and “juvenile” (from the magma itself) is thought to play a major role in distribution of the metals. As a result, there is a zonation of metals from a proximal zone of copper-rich mineralization to a distal zone of lead- and zinc-rich mineralization. Barium in the form of the mineral barite forms the most distal portions of the zonation.

**Alaskan Examples:**

**Prince William Sound**: Contains some of the youngest (Eocene) VMS deposits known in the state. Only area to have VMS hosted in ophiolitic rocks. Deposits can consist of either conformable lenses of massive to semi-massive sulfides or crosscutting veins and stockworks. Formed in island arc system, during subduction event. Hosted in either tuffaceous and sedimentary rocks (Midas, Beatson), or ophiolitic rocks, such as mafic flows (Rua Cove).

**Brooks Range**: Hosted in bimodal volcanic and volcanoclastic rock, primarily metarhyolites, interlayered with black phyllite and minor marble of Devonian age (Ambler sequence). Formed in rift setting, in banded flows and tuffaceous rocks. Metamorphosed during Cretaceous.

**Greens Creek**: Hosted in quartz-mica-carbonate phyllite and black, graphitic argillite (Figure 6-3). Very highly deformed (4 folding events) but generally low metamorphic grade. Abundant carbonate alteration (dolomite and ankerite). Silver-rich and anomalous gold zones containing ruby silver or electrum. Black ore (in graphitic schist); white ore (in massive barite, quartz and carbonate).
Stratabound, Sediment-hosted Deposits (SS)

Stratabound, sediment-hosted deposits (SS) have few or no volcanic rocks associated with them, but they are included because it is assumed that some process involving magma is involved. They typically form on the ocean floor, typically around the edges of large, deep sedimentary basins. SS deposits are characterized by having very high zinc, lead, silver and barium values. Zinc and lead occur mainly as sphalerite and galena, and silver occurs primarily as argentiferous galena. The SS deposits in Alaska carry base metal sulfides or barite or both, and they are located in the Brooks Range, with other localities in southwestern, southeastern and east-central Alaska.

They are typically hosted in sequences of dark, fine-grained clastic sedimentary rocks, particularly in black shales or mudstones (in the upper sections) and in turbites (or layered, deep-water siltstones and mudstones, in lower sections). Less commonly the deposits are hosted in limestone units forming a shelf-like layers near the edges of the basins. Deep water varieties contain extremely high zinc values as well as abundant lead, silver and barium. Limestone-hosted varieties are characterized by their higher copper and cobalt values.

Shale-hosted varieties tend to be laminated, and consist of zones of fine-grained, disseminated sulfides. Limestone hosted deposits tend to occur more as veins and be associated with breccias. Banded or layered deposits, semi-concordant to the stratigraphic layering, are generally rich in zinc. The sphalerite occurs as dense accumulations of fine-grained sulfides in parallel layers or bands. This banding is generally parallel to layering in the overall stratigraphy.
Although the origin of the metals is uncertain, but the origin of the is fairly well agreed to be involved with dewatering of the basinal sediments resulting from compaction by the thick overlying column of water. During transport the fluids are heated by the geothermal gradient or by coming into close contact with some type of magma body. High angle fault structures, near the edges of the basin, appear to have channeled metal rich, hot water brines. As the fluids migrated away from the feeder zone, chemical and physical changes of the brines resulted in precipitation of the metals. The hydrothermal fluids precipitated ore in several ways. Sometimes ore is formed by replacement of wall rocks adjacent to a deep fissure. Ore can also be deposited near the top of the fracture where it will typically be in the form of a breccia. Lastly, the metal-rich waters migrate away from the fracture or vent and travel for some distance. The brines accumulate in the deeps, and precipitate metals. Evidence suggests some of these deposits formed under anoxic (lack of oxygen) conditions.

General zoning sequence:

<table>
<thead>
<tr>
<th>Proximal</th>
<th>&gt;</th>
<th>&gt;</th>
<th>Distal</th>
<th>&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Copper</td>
<td>Lead-Zinc</td>
<td>Barite</td>
<td></td>
</tr>
<tr>
<td>Vent/Rift</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Alaskan Examples:**

Red Dog, Brooks Range, Alaska: Hosted in Mississippian shale. Barite lens caps the deposit (Figure 6-4).

Abundant replacement textures. Highly deformed and metamorphosed during the Cretaceous.
Epithermal Deposits

Epithermal deposits are those which form at relatively low temperatures typically in the 100–300 deg. C range, and at very shallow depths or even at the surface. They are most well known for occurrences of gold and silver, but also have very high mercury, lead, zinc, copper, antimony, uranium and vanadium values. The vast majority of known deposits are known to be related to Tertiary or recent volcanic rocks, although a few appear to be caused by heating deeper plutonic sources.

They are almost always localized near volcanic centers, such as calderas, stratovolcanoes, volcanic necks, breccia pipes and shallow intrusions (a “caldera” is a large circular region which is downdropped along a circular fault system). They also tend to be associated with regional doming. The deposits may occur in the volcanic rocks themselves, or the rocks the are extruded onto. The extrusions can be in any form of extruded volcanic rock, and also as shallow intrusions of various types (dikes, sills, pipes), or pyroclastic rocks. In certain cases they are hosted in sedimentary rocks (Carlin). Epithermal deposits occur in a wide range of geometries, ranging from tabular veins to pipe- or funnel-shaped.
Ore minerals include native gold and silver, and telluride and sulfosalts containing variable proportions of gold, silver, lead and antimony. The ore minerals occur in a gangue of quartz, chalcedony, carbonate minerals, fluorite, barite, sericite, adularia and clay minerals (Figure 6-5). Banding of the ore and gangue minerals is common. Other textures include drusy, comby, crusty, vuggy and colloform. There is widespread alteration of rocks around the deposits, especially to the minerals chlorite, sericite, quartz, pyrite, and locally to carbonates and feldspar minerals.

A common metal zoning pattern seen in many examples shows high base metal values in the lower portion of veins and high precious metal values in the upper portions. The ratio of gold to silver typically decreases outward or upward in the deposits. The decreasing temperatures of the hydrothermal waters away from the igneous rock sources is the biggest influence on how the metals are precipitated. Meteoric water influence, during later stages of the volcanism, appears to be common in many examples.

Figure 6-5. General cross sectional model through epithermal vein deposit showing composition and geomgetry of various alteration envelopes. (from SME Mining & Engineering Handbook)

**Examples:**

Creede, Colorado: Rhyolite and latite flows, tuffs and sediments. Well-developed circular, caldera complex. Green quartz good indicator of proximity to mineralization.
Repeated faulting and breccia formation. Native gold and silver, and abundant silver bearing minerals.

**Central China**: Antimony, arsenic and mercury rich. Occur as stibnite-quartz veins and stibnite-galena-arsenopyrite replacement bodies. Controlled by faults and hosted in breccias.

**Delamar, Idaho**: Hosted in silicified rhyolite tuff of Tertiary (Miocene) age caldera complex. Bulk-mineable ore. Characterized by low grade gold and high silver values.