ORE PETROLOGY

Lecture I

ORE-FORMING PROCESSES AND FLUIDS

- **Ore deposits form in a great variety of ways and all of these geologically different processes work toward taking diffuse elements and minerals and concentrating them 10-1000 or more times thus turning them into valuable mineral deposits.**

Some of the geological processes for forming ore deposits are:

- Evaporation of Sea water, Salt, Potash k_2CO_3, Borax $Na_2B_4O_7.10H_2O$.
- Melting glaciers: Sand and Gravel.
- Alluvial: Concentration of dense, durable minerals like gold, tin, platinum and diamonds.
- Weathering: Nickel laterites and Bauxites.
- Sedimentary precipitation: Iron ores

- Diagenesis and extraction of connate brines: MTV deposits and sedimentary exhalative deposits.
- Metamorphism: Sapphires & Ruby. Metamorphic fluids: Orogenic gold
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- Magmatic differentiation and magma mixing: e.g., Chromium, magnetite, Lithium, REEs.
- Liquid immiscibility: Nickel, Copper, Platinum.
- Hydrothermal: Copper, Zinc, Lead, Mercury, Arsenic, Gold, Silver, Bismuth, and Antimony

- We will concentrate on:

the most common processes

particularly those that form the most kinds of deposits.

These are:

the hydrothermal processes, magmalic processes along with precipitation from seawater.

Ore forming fluids can be subdivided into:

- 1) Magmatic
  2) Magmatic-hydrothermal
  3) Seawater, meteoric water and connate water
  4) Mixing of 2 and 3
- 5) Metamorphic fluids.

MAGMATIC FLUIDS AND PROCESSES

- Magmatic ore deposits (also known as orthomagmatic deposits) comprise the following common types:
- 1) Chromite deposits,
- 2) PGEs, deposits.
- 3) Copper-iron-Nickel sulfides,
- 4) Iron-titanium-vanadum deposits
- These deposits are selectively crystallized and concentrated by the following processes:
- **a) Fractional crystallization, b) Liquid Immiscibility**

a) Fractional crystallization:

- Takes place by **gravitational settling** or rising such as formation of layered chromite and or magnetite deposits and supported by:
- 1) mixing of a new magma with the cooling and crystallizing intrusion,
- 2) change (increase) in the partial pressure of oxygen, and in part the total pressure in the magma chamber

b) Liquid Immiscibility

- It is the separation an originally homogeneous magma into two coexisting liquid fractions.
- We have two types of immiscibility lead to formation of ore deposits:
- 1- Oxygen immiscibility:
- Formation of magnetite-apatite or ilmenite-rutile-apatite (with anorthosites and alkaline rocks).
- 2- Sulfide Immiscibility :
  Formation of sulfide deposits (pentlandite-pyrrhotite-calcopyrite).

HYDROTHERMAL FLUIDS AND PROCESSES

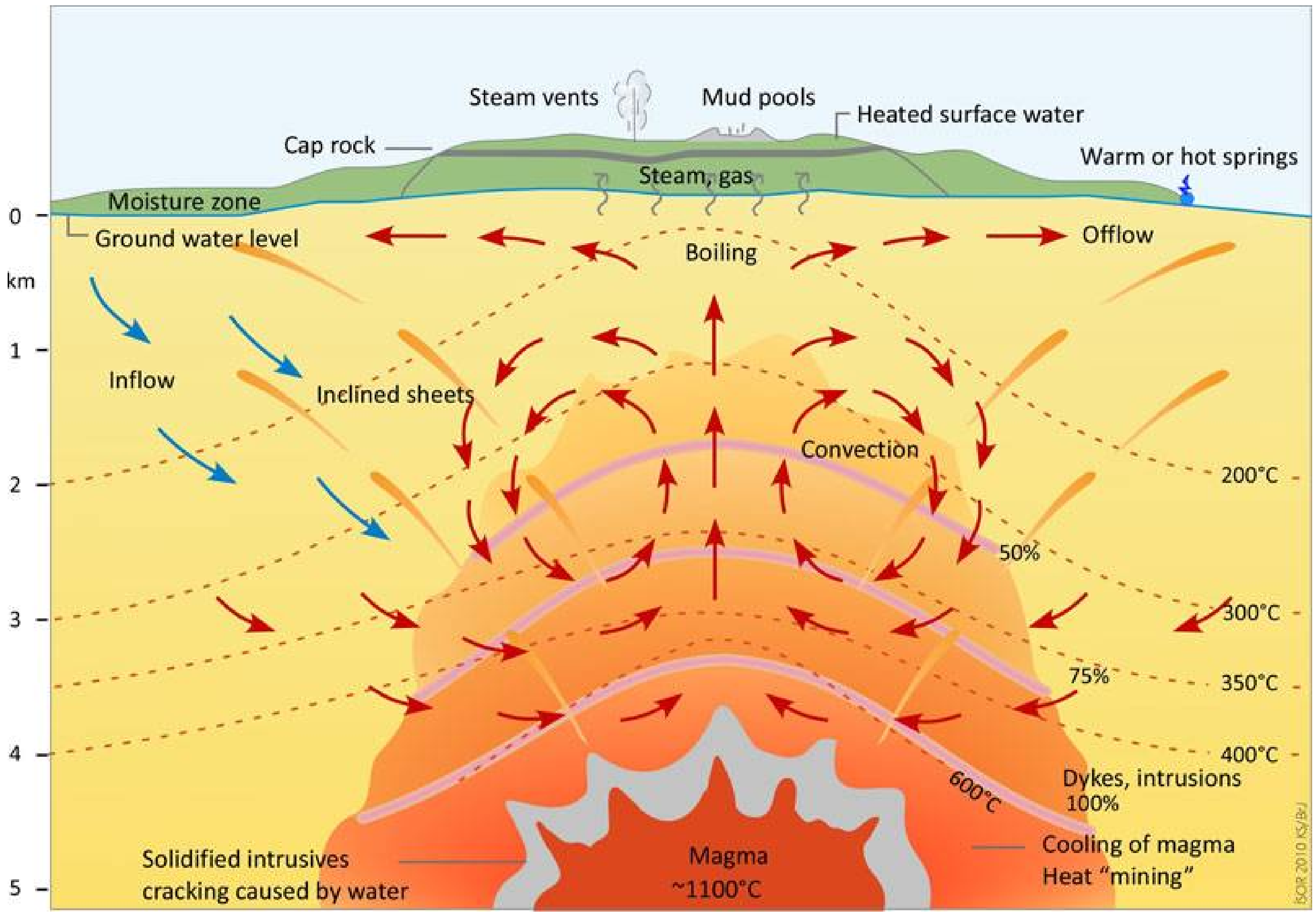
Hydrothermal mineral deposits form when a hot, aqueous solution (dominantly composed of hot water) flows through permeable units in a restricted portion of the earth’s crust and precipitate a localized mass of minerals from its dissolved load.

- Hydrothermal fluids are common in active or recently active volcanic terrains. This conclusion comes from presence of geothermal systems in these active volcanic terranes.

What is a geothermal system??

- A geothermal system is one in which hot fluids circulate and these form where a combination of favorable structures and rocks occur together in areas of high heat flow. In general the favorable conditions include:
- 1) An aquifer zone to contain the heated water
  (permeable unit(s) or fracture zone).
- 2) A cap-rock
  (a unit of low permeability overlying the aquifer)
- 3) Recharge channels 4) Discharge channels
- 5) Heat source

Geothermal system



Aquifer zone:

- Aquifers may be:
- A naturally permeable unit,
- A group of permeable units,
- Or a zone of fracture-fault permeability or both i.e., permeable fractured unit.

Cap Rock:

- The cap rock is a unit of lower permeability overlying the aquifer which insulates the system. It keeps the water hot and prevents leakage.
- The cap rocks may be naturally impermeable or become impermeable by a process called self sealing, This is the result of the precipitation of minerals (silica, carbonates) within permeable units due to temperature decrease, pressure decrease, and/or oversaturation.
- Warm water is buoyant and will rise thus cooling slightly and this, coupled with a slight pressure decrease, causes some precipitation, particularly of quartz and carbonate.

Recharge:

- Recharge channels represent areas where water enters an aquifer from 4 propabe sources:
- 1) Seawater
- 2) Connate water (water trapped in sediments and breccias at time of formation)
- 3) Metamorphic water-especially common at transition from greenschist to amphibolite
- grade due to dehydration reactions
- 4) Magmatic

Source of metals in hydrothermal fluids have 3 origins:

- 1- Rocks or sediments through which fluids pass and interact
- 2- Magmas
- 3-Combination of 2-mixing in geothermal systems

- Open hydrothermal system:
  A hydrothermal system with both recharge and discharge channels.

- Closed hydrothermal system:
  A hydrothermal system with only discharge channels.

- **Water to rock ratio** in hydrothermal systems vary from very low (0.1) to very high (150/1).
- Rock-dominated hydrothermal system:
  In which water-rock ratio <40/1
- Water-dominated hydrothermal system:
  In which water-rock ratio >40/1

MAGMATIC HYDROTHERMAL FLUIDS:

- Magmatic hydrothermal fluids are aqueous fluids result from exsolution from a water-saturated magma in any stage of its crystallization history.

- The exsolved fluid may be in liquid or vapor phase, so the process comes from “water saturation” or from “vapor-saturation”, the latter also called “boiling”.

- Water is the major constituent of this exsolved fluid although it may contain significant amounts of CO_2, SO_2, H_2S, NaCl, KCl, FeCl, CaCl, HCl, HF, …..

  and a wide variety of metals such as Pb, Zn, Hg, As, Bi, Sb, Au, Ag, Cu, Bi, Mo, Sn, W, …etc.
- The process can be achieved in two ways:
  1-By decreasing pressure of the system "First boiling" 2-Progressive crystallization of the magma or "Second boiling"

- Immiscibility in these systems can occur at low pressures where the aqueous fluid actually separates into two phases-1) a dense, very saline brine and 2) a low salinity aqueous solution.

- The exsolved water rise very rapidly to collect in the highest parts of the magma chamber.
- Observation strongly supports this:
- 1) Ores commonly occur around cupolas within or adjacent to intrusive bodies
- 2) Initial volcanic eruptions are dominantly gas rich and explosive.
- 3) Analysis of lava lakes shows that gas content decreases with depth.
- 4) Hydrous minerals in felsic intrusions (biotite, hornblende) tells us something about
- water exsolution-ie to crystallize these minerals the magma needs to have 2-5% water
- Yet analysis of such intrusions finds only 0.5-1% water in the crystallized rock-so a lot has been lost.

- Volume (per unit mass) of water-saturated magma is much < the equivalent volume (per unit mass) of silicate melt + low density aqueous fluid (volume change may be as much as 30 % particularly at shallow levels,).
- So exsolution of an aqueous fluid within a magma is accompanied by release of great mechanical energy, This over pressuring of the chamber interior can lead to brittle fracturing. This hydro-fracturing leads to the formation of cracks with steep dips. These fractures will then propagate into the country rocks and become conduits for the exsolving fluid phase.

- Magmatic-hydrothermal fluids, when move into the near surface environment with little interaction with geothermal waters, fluids remain saline and acidic, but if they mixed thoroughly with geothermal waters, they will add their dissolved component to the circulating waters and lose their characteristics.

- These two different paths lead to different ore deposits with different geological characteristics.

Seawater

Seawater is extensively circulated through the oceanic crust as part of large scale geothermal systems. It is responsible for widespread alteration and metal redistribution with seawater losing Mg and Ca and gaining Fe and metals.

The drawdown of seawater into faults and fractures in the oceanic crust, particularly along mid-ocean ridges, its heating up, and chemical interaction with basalts, gabbros, and diabase as it moves downward and then its subsequent re-emergence from exhalative vents was a major oceanographic discovery that helped, and in some ways hindered, our understanding of VMS deposits.

- Concentration and transportation of metals in seawater depends on: 1) temperature 2) the degree of mixing with magmatic hydrothermal fluids.
- This will determines deposition of Fe oxide or sulfide or deposition of Zn, Cu, Pb, Ag, and/or Au,

- **Meteoric Water:**
- This is rain, river, and/or lake water (groundwater) that has been able to penetrate to relatively deep levels in the crust and to become involved in widespread circulation through the crustal regime. Meteoric water is responsible for hydrothermal ore deposits, especially those with low temperatures of transport and precipitation (uranium ores, native copper).

Connate water

- This is water included within interstitial pore spaces of sediment as it is deposited, or within breccia deposits (debris flows). Originally this water is either meteoric or seawater.
- It undergoes substantial modification as the sediment or breccia is buried, compacted, and lithified.
- The stage of formation from water-rich sediment to lithified rock produces aqueous solutions that evolve with time and depth. Such fluids move upwards through the stratigraphic sequence and can be involved in the formation of ore deposits.

- **Metamorphic water:**
- When temperatures exceed 3000 C the process of digenesis evolves into metamorphism. When hydrous silicate and carbonate minerals break down to form anhydrous minerals exsolving water as they do so; this is at the transition from greenscist to amphipolite grade. This begins at about 3000 C
- Examples (kaolinite to phyropyllite).

$$\mathbf{Al_2Si_2O_5(OH)_4 \rightarrow AlSi_2O_5(OH)}$$

kaolinite phyropyllite

- Chlorite to biotite at 4000 C:

$$\mathbf{(Mg,\ Al,\ Fe)_{12}(Si,\ Al)_8O_{20}(OH)_{16} \rightarrow K_2(Mg,\ Fe)_6Si_5A_{l2}O_20(OH,\ F)_4}$$

Chlorite biotite

- at even higher grades hornblende to pyroxene.
- Carbonates also breakdown and it is not unusually for heated metamorphic waters to be rich in CO_2. Metamorphic reactions and waters are important in orogenic gold deposits.
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