Ore deposits related to intermediate to felsic intrusions – Formation of Porphyry Cu-Mo Deposits

- GLY 361 - Lecture 8
The Host Intrusions related to Porphyry Cu-Mo Deposits
Nature of the Intrusions

- Epizonal (shallow).
- Between depths of 1 to 6 km, with most emplaced at a depth between 1 and 2 km (1-2 kbar; 750-850°C)
- Generally felsic, differentiated and range in composition from quartz diorite to **quartz monzonite**.
- The granitic varieties belong to the I-type granitoids.
Figure 1.11 Generalized scheme that links granite compositions and magmatic oxidation state to metal associations and intrusion-related ore deposit types (modified after Barton, 1996). Ore deposit types referred to are "alkalic," "porphyry," and "lithophile" and are discussed in more detail in Chapter 2. Metals shown in bold reflect the more important associations.
• Typical intrusion is a small (~1 to 3 km diameter) pluton.

• Intrusions emplaced as crystal-liquid mixtures.

• No evidence to indicate that the wall rocks affected the overall magmatic composition of the intrusion.

• Porphyritic texture \(\rightarrow\) relatively sudden crystallisation due to chilling and the concentration and subsequent release of a significant volatile phase.

• Porphyrty dykes are nearly ubiquitouos.
Fluid separation from the degassing magma occurs near the top of the magma column, forming pockets of magmatic-hydrothermal fluid in which comb-quartz layers grow inward from intrusion margins.

Mineralized vein and fracture stockworks form when the fluid pressure exceeds lithostatic pressure and tensile strength of the surrounding rocks.

Shinohara et al., 1995
Breccias

- Indicate explosive escape of volatiles - formed before, during and after mineralization.
- Those that formed at the same time are important hosts of mineralization.
Although porphyry copper deposits are spatially and temporally associated with these intrusions it is not possible to relate the main mineralizing event to any one of the intrusive phases.
Ore formation not only related to the intrusions.

We also have to consider the **hydrothermal alteration process** and its products *(because the deposits formed in a relatively shallow environment).*
Alteration Shell due to hydrothermal circulation
Hydrothermal alteration

Alteration of rocks by traversing fluids is marked by the development of a new mineral assemblage.

Such assemblage can be of the same chemical composition as the original rock, when the alteration is *isochemical*, or be of a new chemical composition when the alteration is *allochemical*. In both cases the new mineral assemblage reflects the

i) original rock composition,
ii) the properties and the amount of the fluid that passed through the rock and
iii) the fluid-rock reaction.

The simplest fluid passing through a rock is water with dissociated components of $H^+$ and $OH^-$, and the dissolved cation and anion components in aqueous solution. The simplest alteration is the isochemical *hydrolysis* in which $H^+$ ions substitute for a metal ion (“$H^+$ - *metasomatism*”), like in the hydrolysis of K-feldspar with water to muscovite or sericite and quartz:

$$ \frac{3}{2} KAlSi_3O_8 + H^+ \leftrightarrow \frac{1}{2} KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 + K^+ $$

= isochemical substitution of $K^+$ ions with $H^+$, requires only the presence of $H^+$
Hydrothermal alteration

\[ \frac{3}{2} \text{KAlSi}_3\text{O}_8 + \text{H}^+ \rightarrow \frac{1}{2} \text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + 3\text{SiO}_2 + \text{K}^+ \]

In this reaction \(\text{H}^+\) ions are consumed from the solution, which becomes more basic until the K-feldspar is used up. The new mineral assemblage is muscovite and quartz.

A continuing reaction upon the products of the above K-feldspar hydrolysis will produce kaolinite:

\[ \text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + \text{H}^+ + 1.5\text{H}_2\text{O} \rightleftharpoons 1.5 \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + \text{K}^+ \]

In the presence of plagioclase in the same rock, simultaneously pyrophyllite will be formed:

\[ 2\text{NaAlSi}_3\text{O}_8 + 2\text{H}^+ \rightleftharpoons \text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_2 + 2\text{SiO}_2 + \text{Na}^+ \]

In the above reactions, further \(\text{H}^+\) ions are used up and the fluid becomes more basic and K and Na- rich. The above reactions thus inevitably result in \(\text{H}^+\) consumption (\(\rightarrow\)) and in a progressively more alkaline fluid.

The reaction of a simple mineral assemblage with water can thus result in a multicomponent reaction with new mineral assemblage, even if the system remains isochemical.
Hydrothermal alteration

Allochemical reaction:

The alteration products will be more complex in an open chemical system, in which the dissolved chemical components in the fluid, other than H\(^+\), also take part in the reactions:

The accumulation of base cations in the fluid by H\(^+\) consumption will effect the alteration downstream of the fluid flow direction, where the base cations can react with the wall rock ("cation metasomatism") e.g.:

\[
\text{(plagioclase)} \\
2\text{NaAlSi}_3\text{O}_8 + 4\text{(Mg,Fe)}^{2+} + 2\text{(Fe,Al)}^{3+} + 10\text{H}_2\text{O} \rightarrow \text{(Mg,Fe)}_4\text{(Fe,Al)}_2\text{Si}_2\text{O}_{10}\text{(OH)}_8 + 4\text{SiO}_2 + 2\text{Na}^+ + 12 \text{H}^+ \\
\text{(chlorite)}
\]

or

\[
3\text{CaMg(CO}_3\text{)}_2 + 4\text{SiO}_2 + 6\text{H}^+ + 4\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_4\text{O}_{10}\text{(OH)}_2 + 6\text{H}_2\text{CO}_3 + 3\text{Ca}^{2+} \\
\text{(talc)}
\]

By addition of e.g. Fe, Mg and Al from the fluid, plagioclase will be chloritised and a significant amount of H\(^+\) will be produced, consequently the acidity of the fluid will be increased.
Any fluid in the same rock can thus become more basic on its pathway, and subsequently more acidic, when reacting with the same or with another rock, and produce different mineral assemblages.

The reaction,

\[
3\text{CaMg(CO}_3\text{)}_2 + 4\text{SiO}_2 + 6\text{H}^+ + 4\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 + 6\text{H}_2\text{CO}_3 + 3\text{Ca}^{2+},
\]

is important for processes where fertile granites intrude carbonate rocks and produce skarn deposits (e.g. W - Sn deposits).

The above considerations are, however, too static and too simple to reflect the reality. In the real world, the fluids change with each meter of flow and in time (~ 0.1-10m/a), while they react with rocks.

It is therefore important to consider the amount of fluid reacting with the rock and the time the rock was exposed to the constantly compositionally changing fluid.
Fluid kinetics are more important than steady state equilibria. (Reed, 1997)

Mineral assemblages that form through alteration vary as a function of 5 factors:

- Temperature
- Pressure
- Host rock composition
- Fluid composition
- The ratio of fluid to rock in the alteration process

The “Fluid/Rock Ratio” is considered to be the most important factor, as it dictates the extent of the alteration process.

Temperature and pressure dictate the stability of mineral assemblages.

The host rock composition dictates to some extent the availability of components for formation of new mineral assemblages.

Fluid composition influences the extent to which the host rock is dissolved and the amount and composition of the new elements brought into the system.
The fluid/rock ratio (f/r)

Reed, 1997, has shown that because hydrothermal fluids migrate along pathways that represent evolving chemical gradients, alteration should be viewed as a dynamic function of the fluid/rock ratio.

At any instant time the degree of alteration pinches out towards the alteration front, downstream of the fluid movement, because of the constantly diminishing ability of the progressively “used up” fluid, to alter the newly trespassed rock.

Thus, the sequence of alteration minerals outwards and downwards of the fracture or vein serving as a conduit, reflects the sequence of reactions that relate to a decreasing fluid/rock ratio (distal regime). Upstream of the conduit the fluid/rock ratio increases as the rock has experienced stronger alteration by more fluids (proximal regime).
Alteration mineral assemblage changes in, e.g. a rock of andesitic composition, subjected to reaction with hydrothermal solution. The alteration halo weakens outwards and stream-downwards from the conduit. As the fluid changes its composition on its way downstream, the f/r decreases and the strength of effects of alteration decreases. The acidity of the fluid decreases in the same directions in this example.
Hydrothermal Alteration Zones, Minerals, and Ores in a Porphyry Copper Deposit

**Explanation:**
- Chl - Chlorite
- Epi - Epidote
- Carb - Carbonate
- Q - Quartz
- Ser - Sericite
- K-feld - Potassium Feldspar
- Bi - Biotite
- Anh - Anhydrite
- py - Pyrite
- Kaol - Kaolinite
- Alun - Alunite
- cp - Copper
- gal - Galena
- sl - Sulfide
- Au - Gold
- Ag - Silver
- mb - Molybdenite
- mag - Magnetite

**A** Chl-Ser-Epi-mag

**B** (Modified from Lowell and Guilbert, 1970)
Hydrothermal Alteration

• Extensive, zoned on a deposit scale as well as around individual veins and fractures.
  – Ore can be found in 3 situations
    1) Totally within the host stock (veins)
    2) Partially in stock and partially in country rock
    3) Totally within the country rock

• Economic hypogene Cu and Cu-Fe sulphide zones most closely associated with potassic (and phyllic/sericitic) alteration.

• Orebodies are usually surrounded by a pyrite-rich shell, which occur in concentric zones.
  - usually a central barren core passing outwards firstly to Mo-rich mineralisation, then Cu-rich mineralisation as the main ore shell is encountered. Pyrite gradually increases to form a pyrite-rich halo (10-15%) but with minor chalcopy and Mo.
  - highest Cu values often occur at the boundary between the potassic and phyllic zones with weak minzn in the propolyitic zones
Hydrothermal Alteration

- Four alteration zones associated with porphyries:
  1) Potassic zone
  2) Phyllic zone
  3) Argillic zone
  4) Propylitic zone
1.) **K-silicate/ Potassic alteration**

- High alteration T at 500-600°C
  - high temperature requires close relationship to intrusions.

- Results from the introduction of varying amounts of additional K, introduced by metasomatic processes and associated leaching of Ca and Na from alumino-silicate minerals.
1.) K-silicate/ Potassic alteration

- development of secondary orthoclase-biotite-chlorite and minor sericite, which replace primary orthoclase, plagioclase and mafic minerals.
1.) K-silicate/ Potassic alteration

quartz - k-feldspar - biotite

- **Opaque minerals**: magnetite, cpy, bn, and py.
- Py always present as a minor phase
• (A) Potassic K-feldspar (Kfs) alteration around mineralized quartz veins in granodiorite.

• (B) Potassic alteration of granodiorite porphyry consisting of pink K-feldspar and patches of fine-grained hydrothermal biotite (Bt) associated with quartz-molybdenite veinlets.
2.) Phyllic/ sericitic alteration

- forming over a wide temperature range by hydrolysis (H+ metasomatism)

- leaching of Na, Ca and Mg from the alumino-silicate-bearing rocks, K either introduced or provided from original K-feldspar in the rock.

- complete replacement of the original rock-forming silicates by sericite (or other muscovite-like minerals) and quartz (note that K-feldspar is no longer present).
  - complete destruction of the original rock textures.
2.) Phyllic/ sericitic alteration

quartz - sericite - pyrite

- Fe derived from the destruction of the mafic minerals and newly introduced Fe is present in pyrite that may represent as much as 10 % (volume) of the rock.

- cpy generally present but rarely exceeds 0.5 Vol.%.
Quartz-py-cpy vein stockworks in feldspar porphyry heavily overprinted by sericitic (phylllic) alteration.
3.) Propylitic alteration

- most widespread alteration type
  - corresponding to greenschist facies metamorphism
- Intermediate T at 200-350°C and low f/r ratio
- alteration is typically isochemical and of H+ metasomatism type.
- characterized by the neo-mineralization of Ca and Mn-bearing minerals.
3.) Propylitic alteration

chlorite - epidote - carbonate

- Chlorite, epidote, clinozoisite and zoisite, calcite and albite replace the common mafic minerals and the anorthite component of plagioclase associated with the introduction of H\(^+\) and CO\(_2\).

- Apatite, anhydrite, ankerite, and hm are accessory minerals.

- None/minor amounts of sulphides and economic concentrations of cpy present in rare occasions.
4.) Argillic alteration

- T below ~250°C by H+ metasomatism
- strong alkali leaching by extremely acidic fluids in high f/r environments (proximal regime).
- Where limited amounts of K, Ca and Mg remain (as indicated by the presence of montmorillonite, illite, hydro-micas and chlorite + or - kaolinite), it is referred to as intermediate argillic alteration.
4.) Argillic alteration

quartz - kaolinite - chlorite

- Assemblage characterized by clay minerals
  - kaolinite, pyrophyllite, dickite and alunite, with some quartz, topaz and tourmaline.

- Advanced argillic alteration: diaspore, quartz and amorphous silica, andalusite, rarely corundum.

- Py is the principal sulphide present but lesser amounts of cpy and even less commonly, bn may be present.
Silication alteration:
Alteration of carbonate rocks and minerals into silicates by introduction of new components to the system (allochemical; cation metasomatism). It represents the main process in formation of polymetallic skarn deposits developed when acidic magmatic fluid infiltrates carbonate rocks. f/r rations are usually high and temperature range is wide. Rich polymetallic ores are build through neutralisation of acidic fluids.

Skarn: calc-silicate rock formed by metasomatism between carbonates and silicate-rich rocks or fluids at contact between carbonate country rocks and a hot, hydrous fluid from silicate intrusion, such as a granite

Silicification alteration:
Formation of new quartz or amorphous silica during alteration, usually as a by-product of isochemical $\text{H}^+$ metasomatic alteration of feldspars. Usually expressed as quartz veins and silicified fractures. Where strong silicification occurs, it may be due to addition of $\text{Si}^{4+}$ from the fluid into the rock (cation metasomatism), that can be associated with epithermal gold mineralisation and Si- sinter deposits.
**Carbonatization alteration:**
Formation of a carbonate-rich assemblage of calcite, dolomite, magnesite, siderite, etc. by CO$_2$-rich fluids of neutral to alkaline pH (otherwise dissolution of carbonates) and low salinity (otherwise transport of metal cations). It applies to e.g. some Archean greenstone belt Au deposits accompanied by quartz, muscovite, biotite, albite and chlorite alteration and amphibolite. (Compare to greenschist and amphibolite facies metamorphism)

**Greisenitization alteration:**
Mineral assemblage typical for Sn, W - greisen in S-type granites with high concentrations of incompatible elements like F, Li, B. Occurring in the upper zones (cupolas) of granitic intrusions, with quartz, muscovite, topaz, tourmaline and fluorite, adjacent to quartz, cassiterite-wolframite veins. (Compare skarn deposits)

**Hematitisation alteration:**
Formation of hematite and minerals with high Fe$^{3+}$/Fe$^{2+}$ ratio, with associated K-feldspar, sericite, chlorite and epidote, by saline, oxidising fluids in magmatic-hydrothermal environments (e.g. granitoid Olympic Dam complex Cu-Au-Fe-U deposit in S Australia).
Hypogene Mineralization

2 types of fluids involved:

1. **Ortho-magmatic fluid**: dominated by water of magmatic origin, predominantly responsible for alteration at the apex of the crystallising porphyritic intrusion.

2. **Meteoric water**: becomes involved in a convective circulation cell, driven by the heat of the intrusion, in the adjacent wall rocks.
Figure 8 Model of hydrothermal systems with contrasting orthomagmatic and convective fluid flow patterns. For explanation, see text.
Sources of ore fluids, S and economic metals

i) **Magmatic source**: A hydrothermal fluid, enriched in metals, forms as result of magmatic crystallization.

ii) **Country rock source**: the metals are scavenged and transported in convecting cells driven by the heat of the magma.

iii) **Independent hydrothermal fluids**: generated in the same source area as the magma. This was proposed because the magma itself may be incapable of transporting the metals. The coincidence of the intrusion and the mineralization happens because both followed the same access route.
Metal zoning and paragenetic sequence:

Zonation of hydrothermal ore deposits is a very characteristic feature that can be observed at regional, provincial, and outcrop to hand specimen scale. Regional metallogenic zones are distributed e.g. parallel to subduction complexes, like along the western margin of South America. Provincial mineralization usually is confined to batholiths as alteration halo from high f/r ratio close to the intrusion, and progressively lower f/r ratios distal to the intrusion (e.g. Sn-W-Cu-Pb-Zn-Ag-Sb-U). Outcrop and hand specimen zonations are confined to single vein systems (e.g. sphalerite - galenite).

Such zonation implies sequential precipitation of a paragenetic (common origin) ore sequence following similar sequence of precipitation conditions (compare lateral changes in f/r ratio along a conduit and proximal and distal alteration regime!)

From such considerations, the idea of a “reconstructed vein” was born (Emmons, 1936; Guilbert & Park, 1986).

A “reconstructed vein” is an idealised composite vein, extending from the deep crust (hypothermal) to the surface, and containing typical paragenetic components, starting with W and Sn and followed by Cu, Zn, Pb, Mn, Ag... into the mesothermal, and Au, Sb, Hg in the epithermal.

The composition of a paragenetic sequence depends, however, on many factors, not only on the temperature.
### Table 3.3 The “Emmons Reconstructed Vein” concept showing empirical observations that relate to typical patterns of zonation and paragenetic sequences in many hydrothermal ore deposits

<table>
<thead>
<tr>
<th>Vein</th>
<th>Metal</th>
<th>Ore mineralogy (in bold), and related alteration assemblages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface (epithermal)</td>
<td>Hg</td>
<td>Chalcedony, quartz, barite, fluorite, and carbonate minerals</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td><strong>Cinnabar</strong>: chalcedony, quartz, barite, fluorite, and carbonate minerals</td>
</tr>
<tr>
<td></td>
<td>Au</td>
<td><strong>Stibnite</strong>: quartz</td>
</tr>
<tr>
<td></td>
<td>Ag</td>
<td><strong>Gold, electrum, acanthite</strong>: quartz, chalcedony, adularia, alunite, carbonate minerals, silicification, some potassic, phyllic, and propylitic alteration</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>Quartz and carbonate minerals</td>
</tr>
<tr>
<td></td>
<td>Zn</td>
<td><strong>Acanthite, rhodochrosite</strong>: quartz and carbonate minerals, some phyllic, argillic, propylitic alteration</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td><strong>Galena</strong>: quartz with minor carbonate minerals</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Sphalerite</strong>: quartz with occasional carbonate minerals, advanced argillic alteration</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Chalcopyrite, tennantite-tetrahedrite</strong>: quartz, phyllic, propyllic, argillic alteration</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Chalcopyrite</strong>: quartz, phyllic alteration</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Molybdenite, huebnerite, scheelite, cassiterite</strong>: quartz, potassic alteration</td>
</tr>
<tr>
<td></td>
<td>Ni</td>
<td>Potassic alteration, anhydrite, carbonate minerals</td>
</tr>
<tr>
<td>Intermediate (mesothermal)</td>
<td>Pb</td>
<td><strong>Low T minerals</strong></td>
</tr>
<tr>
<td></td>
<td>Sn</td>
<td><strong>Possible sequence for metal-chlorides:</strong></td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td><strong>Possible sequence for metal-chlorides:</strong></td>
</tr>
<tr>
<td>Deep (hypothermal)</td>
<td>Fe</td>
<td>Barren</td>
</tr>
</tbody>
</table>

**Source**: after Guilbert and Park (1986).

Possible paragenetic sequence of metal sulphide precipitation

The reconstructed vein does not correspond to proximal and distal regime of f/r ratios!
The paragenetic sequence of Fe-Ni-Sn-Cu-Pb-Ag-Au-Sb-Hg is a metal-sulphide precipitation reaction. If the metals are transported as chlorides a paragenetic sequence of Cu-Ag-Pb-Zn is more likely.

Paragenetic sequences are controlled by more than one variable and reproducible zonation patterns are likely to apply only to hydrothermal ore forming processes within the same zoning class.

Variables like valence state of aqueous metal species, Gibbs free energy values for a specific temperature, stoichiometry, etc..... result in different paragenetic sequences.

The sequence of Mn-Zn-Cd-Pb-Hg would not precipitate under the same Temp. conditions within a different zoning class.
Replacement processes:

In deeper levels of the crust, where pore space is not readily available, mineralisation alteration and precipitation occurs through replacement. Replacement occurs when the original minerals in a rock are dissolved and almost simultaneously (successively) replaced by others, secondary minerals. The fluid transport depends on interconnected micro-fractures and remnant pore space. Thus, porosity needs to be maintained during replacement processes.

Replacement will be blocked if the molar volume of the secondary mineral is higher than that of original mineral. Reduction in molar volume supports mineral replacement.

Comparison of molar volumes shows that calcite can be replaced by most calc-silicate and sulphide minerals (e.g. skarn deposits). Oxide minerals, however, like magnetite or ilmenite can not be completely sulphidized because of the increased molar volume of sulphides.
In this sequence minerals will only comprehensively replace those to their left because of lower molar volume.
Formation of a Porphyry Cu deposit

Initial formation of a porphyry copper deposit associated with a magma chamber beneath a stratovolcano. Hot water circulating near the magma forms low-grade copper mineralization next to the solidifying magma. High-grade mineralization forms over the top of the magma and in chemically reactive wall rocks, like limestone.
Formation of a Porphyry Cu deposit

Erosion removes the stratovolcano and top of the original copper deposit. Rainwater and weathering cause copper to be leached from the top of the deposit and re-deposited as the downward-moving groundwater reaches the water table. The resulting enriched zone is commonly high grade and fairly flat.
Formation of a Porphyry Cu deposit

After erosion and enrichment, the deposit is covered by younger rocks, in this case volcanic rocks. The high-grade enriched zone is protected from further erosion, but now is buried and hidden. The volcanic landscape at the surface may contain few clues to the geological riches that lie at depth. Finding the deposit may require special methods (e.g., geochemical or electrical surveys), a number of risky drill holes, persistence, or luck.
Exploration Guide

GEOCHEMICAL SIGNATURE:

• Calcalkaline systems can be zoned with a cupriferous (*Mo) ore zone having a ‘barren’, low-grade pyritic core and surrounded by pyritic halo with peripheral base and precious metal-bearing veins.

• Central zones with Cu commonly have coincident Mo, Au and Ag with possibly Bi, W, B and Sr.

• Peripheral enrichment in Pb, Zn, Mn, V, Sb, As, Se, Te, Co, Ba, Rb and possibly Hg.

• Deposits are large-scale repositories of sulphur, mainly in the form of metal sulphides, chiefly py.

• Large geochemical dispersion halos - reconnaissance stream sediment and soil geochemical surveys.

• Deeply buried deposits by post-mineralization rocks or sediments - partial extraction techniques.

• Biogeochemical methods, particularly in arid regions.
GEOPHYSICAL SIGNATURE:

• Ore zones can be associated with magnetite-rich rocks → magnetic surveys.
• More intensely hydrothermally altered rocks → magnetic and resistivity lows.
• Dispersed nature of sulphide distribution → I.P. method (originally developed specifically for porphyry Cu exploration).
• Pyritic halos surrounding cupriferous rocks → I.P. surveys.
• Defining the horizontal limits and depth extent of porphyry systems → CASMT surveys.
• Outline hydrothermal alteration around porphyry deposits → remote sensing - hyperspectral imaging.
OTHER EXPLORATION GUIDES:

• Large-scale, zoned metal and alteration assemblages. Ore zones can form within certain intrusive phases and breccias or are present as vertical 'shells' or mineralized cupolas around particular intrusive bodies.

• Weathering can produce a pronounced **vertical zonation** with an oxidized, limonitic leached zone at surface (leached capping), an underlying zone with copper enrichment (supergene zone with secondary copper minerals) and at depth a zone of primary mineralization (the hypogene zone).
Exploration Guide

Problems:

- Identifying factors that can distinguish the relatively few fertile igneous complexes from the many that are not.

- Despite the close association of porphyry deposits with intermediate to felsic intrusive rocks and general agreement that their formation involves the separation of metalliferous fluids from ore-related magmas, the processes that form porphyry deposits are diverse and significant *knowledge gaps* remain.