Ore Deposit Models - 1. Porphyry Copper Deposits

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Introduction
In this review we discuss porphyry copper deposits in which the products are copper, copper and molybdenum, or copper and gold. In the first descriptive part, we outline the definition, history, distribution, and geologic characteristics of porphyry copper deposits; in the second part, a model is presented that incorporates known characteristics with genetic concepts. Most references cited are recent summary papers, which can be used as sources for more extensive research. Our discussion reflects most directly on the Canadian Cordillera, although we anticipate that it may be applicable elsewhere. Porphyry molybdenum deposits, though similar to porphyry copper, are sufficiently different to warrant a separate paper and are not discussed here.

Originally, the term porphyry copper was applied to mineral deposits with widely dispersed copper mineralization in acid porphyritic rocks. Now the term combines engineering considerations with geologic features and refers to large, relatively low-grade, epigenetic, intrusion-related copper deposits that can be mined using mass mining techniques. The generalized geologic characteristics of porphyry copper deposits are as follows: they are spatially and genetically related to igneous intrusions; the intrusions are generally felsic but range widely in composition; intrusions are epizonal and invariably porphyritic; multiple intrusions, dyke swarms, intrusive breccias, and pebble dykes are characteristic; hosts for intrusions can be any rock type and range from unrelated country rocks to comagmatic extrusive equivalents; the intrusions and surrounding rocks are intensely fractured; mineralization is widespread and exhibits lateral zoning; later supergene alteration can produce vertical zoning resulting in leached cappings and zones of secondary mineralization that can be critical to the economics of mining.

The large size of the intrusive-related porphyry copper hydrothermal systems is possibly their most impressive feature. Lowell (1974) suggests that a deposit should have at least 20 million tonnes containing a minimum of 0.1% copper to be called a porphyry copper. The world’s largest porphyry copper has reserves of 1.5 to 3 billion tonnes of 0.8 to 2% copper (Table I). A typical giant - say, 2 billion tonnes at 1.5% - might eventually produce 30 million tonnes of copper metal. Based on 1978 figures, such a mine could supply Canadian consumption for 130 years or world consumption for more than three years. The largest porphyry copper of the Canadian Cordillera is approximately one billion tonnes with grades just under 0.5% copper; most are much smaller. At the present time, approximately half the world’s copper reserves, 60% of Canadian copper resources, and 90% of British Columbia’s reserves are contained in porphyry deposits.

History
Large, low-grade supergene copper deposits were discovered during the 19th century in the southwestern United States, Chile, and Peru. The grade of these deposits, enriched by secondary processes, was about 2% copper but they remained uneconomic until the development of a method of mass mining, at Bingham Canyon, Utah, in 1906. The concomitant development of froth flotation techniques, which allowed selective separation of copper sulphides, was a key factor in making the enterprise profitable. Soon after, similar deposits were brought into production at Ely in Nevada. Santa Rita in New Mexico, Globe-Miami in Arizona, and El Teniente and Chuquicamata in Chile. In all these deposits, mining began in secondarily enriched (supergene) ore. Consequently, it took several decades for the relationship between the supergene deposits and unweathered, generally uneconomic, primary mineralization (protore) to be understood. Similarly, the significance of porphyry intrusions was slow to be recognized (Emmons, 1927). The genesis of these deposits became evident only when improved mining techniques and advances in equipment were applied. The development of new mining methods was critical; the earliest methods were limited to the extraction of copper from the supergene enrichment of primary ore bodies. The technology was slow to catch up with the growing potential of the new deposits.

Table I
Some Giants of The Porphyry Copper World (Modified After Sutulov, 1974 and Other Sources): For Locations see Figure 2.

<table>
<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Reserves (Million Tonnes)</th>
<th>Copper per cent</th>
<th>Molybdenite per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>(1) Bingham Canyon</td>
<td>1400</td>
<td>0.71</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>(2) Butte*</td>
<td>large</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>(3) San Manuel</td>
<td>1000</td>
<td>0.75</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>(4) Twin Buttes</td>
<td>800</td>
<td>0.74</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>(5) Safford</td>
<td>2000</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>(6) La Caridad</td>
<td>600</td>
<td>0.75</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>(7) Cananea</td>
<td>1700</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Panama</td>
<td>(8) Cerro Colorado</td>
<td>3000</td>
<td>0.8</td>
<td>present</td>
</tr>
<tr>
<td>Chile</td>
<td>(9) Chuquicamata</td>
<td>&gt;2000</td>
<td>1.3</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>(10) El Teniente</td>
<td>3250</td>
<td>0.87</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>(11) El Abra</td>
<td>1500</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>New Guinea</td>
<td>(12) Bougainville</td>
<td>750</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Philippines</td>
<td>(13) Biga</td>
<td>700</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Iran</td>
<td>(14) Sar Cheshmeh</td>
<td>450</td>
<td>1.13</td>
<td>0.03</td>
</tr>
<tr>
<td>Canada</td>
<td>(15) Valley Copper</td>
<td>&gt;750</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(16) Lornex</td>
<td>400</td>
<td>0.41</td>
<td>0.014</td>
</tr>
</tbody>
</table>

*No reserve or grade figures available; from 1880-1964, 326 million tonnes with 2.45 per cent copper mined.
Figure 1
Highland Valley, south-central British Columbia in June 1976. Viewed southwesterly, Bethlehem Copper (foreground) and Lornex open pits. 1A to F show aspects of development and mining from: A—exploration (Berg deposit); B—preparation for production (Afton); C to F—mining, milling, grinding, flotation (Highland Valley).
ment design lowered cutoff grades and enabled mining of the protore at depth.

During World Wars I and II copper demand and production increased dramatically; after the wars, the market for copper softened and there was little reason to prospect for new porphyry deposits. Later, because of the Korean War, demand for copper renewed and revived interest in porphyry copper exploration in the southwest United States. In the mid-1950s, exploration was extended into the Canadian Cordillera, South America, the southwest Pacific, and other regions. Development of these large, low-grade deposits depended and still depends on advances in engineering and ore dressing techniques, on world price and demand, and on taxation policies.

Distribution and Age
Porphyry copper provinces seem to coincide, worldwide, with orogenic belts (Figs. 2 and 3). This remarkable association is clearest in Circum-Pacific Mesozoic to Cenozoic deposits but is also apparent in North American, Australian, and Soviet Paleozoic deposits. In the orogenic belts, porphyry deposits occur in two main settings, in island arcs and at continental margins. Deposits of Cenozoic age, and, to a lesser extent, Mesozoic age predominate. Those of Paleozoic age are less common and only a few Precambrian deposits with characteristics similar to porphyry coppers have been described (Kirkham, 1972; Gail and Ioshani, 1979). Deformation and metamorphism of the older deposits has commonly obscured primary features; hence they are difficult to classify (Griffis, 1979).

Porphyry Copper Classification
Porphyry copper deposits comprise three broad types: plutonic, volcanic and those we will call "classic." The general characteristics of each are presented in Table II and illustrated on Figure 4. Plutonic porphyry copper deposits occur in batholithic settings with mineralization principally occurring in one or more phases of the igneous host rock. Volcanic types occur in the roots of volcanoes, with mineralization both in the volcanic rocks and in associated comagmatic plutons. Classic types occur with high-level, post- orogenic stocks that intrude unrelated host rocks; mineralization may occur entirely within the stock, entirely in the country rock, or in both. The earliest mined deposits as well as the majority of Cenozoic porphyry copper deposits are of the classic type. Their characteristics, particularly for deposits in the southwest United States, have been extensively described (Tittley and Hicks, 1966; Lowell

Figure 2
Worldwide distribution of porphyry provinces. Numbers refer to deposits described in Table 1.

Figure 3
Cordilleran porphyry mines and prospects and their tectonic settings.
<table>
<thead>
<tr>
<th>Setting</th>
<th>Volcanic</th>
<th>Plutonic</th>
</tr>
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<tbody>
<tr>
<td>In basic to intermediate volcanic rocks introd. by magmatic calc-alkaline or alkalic (boninite or shoshonitic suite) plutons. Magnesium produces discontinuities in immobile elements. Mantle xenoliths, megacrysts, and spherules. Cordilleran deposits are of Mesozoic age.</td>
<td>In large calc-alkaline plutons emplaced in or near magmatic volcanic rocks, plutons typically have mafic borders and are modulated to strongly differentiated. Cordilleran deposits are of Mesozoic age.</td>
<td></td>
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Phlogopite
- Multiple phases invaded at succession, small (0.5 to 2 km²), dyke-like porphyritic intrusions, numerous pegmatites, post-mineral porphyry dikes, emplaced at shallow depth
- Diapirs, emplacement in volcanic vents, fault zones, radial fractures.
- Alkaline, intrusive centres localized by regional structures, high-level intrusive rocks invade volcanic vents and fault zones.

Brecia
- Abundant and characteristic, present in all rock types.
- Calc-alkaline, common and diverse; include pyroxene, plagioclase, amphibole, quartz, and minor biotite, tourmaline.

Alteration
- Potassic, phyllic, and propilite universally developed as annular shells around intrusions, alteration of varying intensity. Early developed breccia (EDB) can be part of an aschitic hornfels and has been mineralized as part of the potassic zone.
- Calc-alkaline, propylitic alteration early, hydrothermal alteration pervasive, phyllic, and propylitic alteration.

Orebodies
- In margins and adjacent to porphyry intrusions as annular ore shells, as stratified cappings, pronounced lateral zoning. Pyrite is found throughout, the weakly mineralized core is surrounded by zones dominated by molybdenite, then chalcocite, and, finally, a pyritic halo.
- Calc-alkaline - generally Cu-Mo deposits intimately associated with breccias and intrusively altered rocks, mineralized breccias and lenses, with some preferential bedding control. Most ore is contained in shoshonitic with rare boninite or molybdenite as ore fracture fillings.
- Calc-alkaline - generally Cu-Au deposits in intrusive breccias or in highly altered country rock. Some gegen-bearing country rock. Locally magnetite-spotted, molybdenite present, with vein breccia fyllings, zoning a from chalcopyrite to pyrite rich zones. Mo distribution is variable. Some deposits have low-grade quartz-rich ore zones.

Table II
Characteristics of the Three Types of Porphyry Copper Deposits.

<table>
<thead>
<tr>
<th>Characteristics of the Three Types of Porphyry Copper Deposits.</th>
</tr>
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<tbody>
<tr>
<td>Inclusions associated with porphyry copper deposits are diverse but generally felsic and differentiated. Those in island arc settings have primitive stromium isotope ratios (Sr²⁷/Sr²⁶ of 0.705 to 0.702) and, therefore, are derived from upper mantle material or recycled oceanic crust. In contrast, ratios from intrusions associated with deposits in continental settings are generally higher indicating either derivation from or, more likely, contamination by crustal material. Compositions generally range from quartz diorite to quartz monzonite or granite in calc-alkaline suites, and from diorite to syenomonzonite or syenite in alkalic to shoshonitic (sometimes called dioritic) suites. Multiple intrusive events are characteristic of porphyry districts and many deposits are related to intrusions that are among the most differentiated of those present. In some deposits, however, mineralizing and nonmineralizing intrusions look practically identical. Differentiation alone does not result in the formation of porphyry copper deposits. Magma composition might influence the behaviour of ore constituents. For example, copper is partitioned into octahedral sites in a residual melt, and the ratio of octahedral to tetrahedral sites is high when aluminum is abundant relative to total alkalis (Feiss, 1978). Therefore potassium-poor island arc suites, which usually have high aluminum-alkali ratios, are likely to produce copper-rich hydrothermal fluids. On the other hand, copper enrichment in potassium-rich continental suites may be accounted for by high</td>
</tr>
</tbody>
</table>
Figure 4
Lithologic and alteration types in porphyry deposits. Except where noted scale bar is 1 cm long. A—biotite quartzfeldspar porphyry (QFP); B—biotite hornfels cut by K-feldspar veins (K) which are cut by an anhydrite-biotite vein (AB); the hydrothermal fluids were in equilibrium with country rock; C—biotite hornfels with pale lapilli cut by quartz-pyrite veins with alteration envelopes; hydrothermal fluids were not in equilibrium with the country rock; D—multistage veins in phyllic tuff; E—quartz-chalcopyrite veins with flakey sericite-quartz envelopes in shattered quartz monzonite porphyry; F to H—tectoclas showing a progression from incipient, to angular transported, to rounded transported fragments.
oxygen fugacity and high water pressure in the magma (Mason and Feiss, 1979). Thus, conditions leading to residual metal and volatile concentration, not just chemistry, determine whether a magma will have associated mineralization.

Porphyry copper deposits with associated volcanism generally form during an intrusive phase late in the volcanic cycle and mineralization usually follows one or more pulses of magma emplacement. At Ray, Arizona, for example, early quartz diorite was intruded at 70 Ma, a porphyritic phase at 63 Ma, and a mineralized porphyry at 61 Ma (Cornwall and Banks, 1977). Similarly, at El Salvador and at OK Tedi, the onset of mineralization occurred 1 to 3 million years after initial magma emplacement (Gustafson and Hunt, 1975; Page, 1975, respectively).

Intrusions associated with porphyry copper deposits were generally emplaced as crystal-liquid mixtures at less than four kilometres depth; most were emplaced at only one to two kilometres. Almost invariably they are porphyritic, reflecting "sudden" crystallization due to rapid chilling or to concentration and subsequent release of a volatile phase. Porphyry dykes are nearly ubiquitous and the many breccia bodies associated with porphyry copper systems reflect the sometimes explosive escape of volatiles. Many breccias comprise post-ore diatremes but those that predate or form during mineralization can be important hosts for ore. Several periods of brecciation commonly occur and many mechanisms operate to cause brecciation. These include: explosive release of volatiles, fluidization of fault breccia, solution along fractures, chemical brecciation, roof collapse, shrinkage during crystallization, and others (Kents, 1961; Bryner, 1961). The breccias are typified by transported fragments that range from large angular rotated blocks to rounded, milled fragments in a finely comminuted matrix. Like the breccias, porphyry dykes can be pre-, intra-, or post-ore in age (Kirkham, 1971). Commonly, intense hydrothermal alteration accompanies and affects the breccias and dykes. In such cases, it can be difficult to distinguish porphyry dykes from similar host rocks and, on occasion, even to recognize breccia bodies.

**Figure 5**
Model of classic-type porphyry copper deposits (after Sutherland Brown, 1976).

**Figure 6**
Model of volcanic-type porphyry copper deposits (after Sutherland Brown, 1976).

**Structural Features**
Faults localized magma emplacement in many porphyry copper districts. Fault intersections and strongly fractured zones are particularly important controls. In some areas, plutons seem to be localized by regional basement structures (Schmitt, 1966; Seraphim and Hollister, 1976; and many others) or large scale, circular, cauldron subsidence (?) structures (Eggers, 1979).

Ground preparation in the deposits themselves is generally complex. The intrusions are often fractured by rejuvenation of regional faults along which they were emplaced. Furthermore, dyke emplacement, formation of breccias and hydrofracturing in response to hydrothermal activity also enhance permeability and help create the "plumbing systems" followed by later ore-bearing hydrothermal fluids. Multiple episodes of healing and refracturing typically occur as is shown by crosscutting relationships in veins, and mineralized fractures and faults.

**Alteration**
In general, strong alteration zones develop in and around intrusions associated with porphyry copper deposits. Hydrothermal fluids derived from both the magma and heated groundwaters cause the alteration reactions and lead to formation of stable mineral assemblages analogous to metamorphic facies. Alteration is typically a base leaching process that is controlled by the metal cation to hydrogen ion ratio in the altering solution (Hemley and Jones, 1964). If the alkali to hydrogen...
ratio is low, feldspars, micas, and other silicates are unstable and hydrolysis occurs releasing cations and driving the hydrothermal system toward equilibrium. Reactions are controlled for the most part by temperature and pressure but also by the abundance, composition, and dynamic behavior of fluids, and the amount of wall-rock interaction.

Four alteration types are common: propylitic, argillic, phyllic, and potassic. Under conditions of weak hydrolysis, quartz and alkali feldspar are stable but plagioclase and mafic minerals react with fluid to form the propylitic assemblage of albite, plagioclase, chlorite, epidote, carbonate, and montmorillonite (with or without hydromica) or, less commonly, tremolite/actinolite. More intense hydrolysis produces argillic or phyllic alteration. Argillic assemblages, which are characterized by quartz, kaolinite, and chlorite, with lesser montmorillonite, appear to be transitional into phyllic alteration assemblages. Phyllic assemblages are characterized by quartz and sericite, commonly accompanied by pyrite. Intense hydrolysis at elevated temperature, produces advanced argillic assemblages consisting of quartz, pyrophyllite, kaolinite or dickite, and, in some cases, andalusite. Under conditions of very intense hydrolysis, the end product of alteration could be a porous mass of quartz. Potassic alteration takes place at high temperature in the presence of concentrated hydrothermal fluids. Conditions are equivalent to those in a late magmatic environment and, except where the country rock is granite or quartz monzonite, all constituents of the rock are unstable. Alteration assemblages consist typically of quartz (commonly as resorbed grains), K-feldspar, biotite, intermediate plagioclase (oligoclase to andesine), and rare anhydrite.

In a generalized model, alteration assemblages are strongly zoned around the mineralized intrusion. They form shells with a core of potassic alteration grading outward through phyllic, argillic, and propylitic alteration zones into unaltered country rock (Lowell and Guilbert, 1970). In fact, the complete alteration sequence is rarely developed or preserved, and assemblages are strongly influenced by the composition of the host rocks (Guibert and Lowell, 1974). For example, potassic alteration might produce secondary K-feldspar and sericite in rhyolite, but biotite in andesite. Furthermore, pressure, temperature, and permeability, conditions that determine lateral and vertical alteration zoning, change during the course of mineralization. These changes, with time, result in superimposed and crosscutting stages of pervasive and vein-related alteration. In strongly fractured or otherwise permeable rocks, alteration tends to be pervasive and younger assemblages may completely mask older ones. In less permeable rocks, alteration is fracture and vein controlled and changes in temperature, pressure, and fluid composition can be inferred from various suites of alteration minerals.
and from fluid inclusion data. Commonly a variety of alteration types exist between adjacent fractures or veins.

Invariably stockworks of veins with many cross-cutting relationships are present in porphyry copper deposits. These veins demonstrate that multiple episodes of fracturing and healing occur and that each stage may have hydrothermal fluids of different character. In general, the age sequence of alteration types is similar but not identical to the lateral zoning sequence from oldest to youngest. Vein alteration types are commonly potassic and propylitic, then phyllic, and finally argillic.

**Hyogene Mineralization and Zoning**

Hyogene mineralization consists of disseminations, fracture fillings, and quartz veinlets containing varying amounts of pyrite, chalcopyrite, bornite, and molybdenite. Zoning in porphyry copperers differs, not only between classes of deposits (Table II), but also between individual deposits. In deposits of a classical type, a typical pattern would be as follows: a weakly mineralized or barren core zone centred on the intrusion has minor chalcopyrite and molybdenite and rare bornite; pyrite is generally less than 2%. Surrounding ore shells have enrichment in first molybdenite, then chalcopyrite; pyrite abundance increases outward in the ore shells. A peripheral pyrite-rich halo with 10 to 15% pyrite but only minor amounts of chalcopyrite and molybdenite encloses the ore shells. Base metal veins with gold and silver are usually found in radial fracture zones peripheral to the pyrite halo. Overall, pyrite is the most abundant and widespread sulphide mineral in porphyry copper deposits.

The zoning discussed above adequately describes classic-type deposits in the southwestern United States and Tertiary deposits in the Canadian Cordillera. However, Mesozoic deposits in the Cordillera are of volcanic and plutonic type and differ from classic types (Table II). Volcanic types usually have poorly defined metal zoning, in which central, weakly pyritized ore zones containing chalcopyrite, bornite, and magnetite are flanked by barren pyritic zones. Mineral zoning in plutonic types generally proceeds from bornite in the core through chalcopyrite into poorly developed pyritic halos; some have a low-grade siliceous core zone; molybdenite zones are irregularly distributed.

**Ore Fluids and Sulphur Sources**

A knowledge of the compositions and variations in composition of hydrothermal fluids and of temperature and pressure conditions are of critical importance in understanding porphyry copper systems. Both fluid inclusion and isotopic studies have provided the basis for evaluating the nature of ore forming fluids (Nash, 1976; Sheppard, 1977). The fluids involved in alteration and ore formation are metal and salt-rich brines containing both magmatic and meteoric components. Proportions of each may change at any stage in the hydrothermal process and may vary from place to place in the porphyry system.

Homogenization temperatures from various deposits range from 250°C to over 750°C Celsius. At Cerro Verde, Peru (Le Bel, 1979a, 1979b), for example, fluid inclusions homogenized at between 380°C and 410°C Celsius. Temperatures derived from study of sulphur isotopes, sulphide-sulphate ratios, C13, and the composition of sericite (actually phengitic muscovite) concur with the homogenization temperatures.

Sulphur, hydrogen and oxygen isotope studies shed light on the sources of sulphur and water in the ore deposits. At Cerro Verde, sulphur isotopes from pyrite and chalcopyrite display magmatic or mantle values, whereas sulphate minerals have meteoric values. Detailed study revealed that sulphates and carbonates began crystallizing under magmatic conditions but were subsequently modified by meteoric waters. Similarly, in the United States, studies of hydrogen and oxygen isotopes (Sheppard et al., 1971) and fluid inclusions from Bingham Canyon and Butte (Roedder, 1971) indicate that heated meteoric water is involved in porphyry copper formation. At Valley Copper, in British Columbia, as at Cerro Verde, the ore fluid was apparently a mixture (Jones, 1975). Magmatic water comprised roughly 75% of the ore fluid during main-stage mineralization; later the system was quenched by an influx of meteoric or sea water.

Geological and geochemical evidence in porphyry deposits invariably suggest formation depths of less than four kilometres and indicates that most formed at one to two kilometres depth (Silitoee, 1973). At Cerro Verde and Valley Copper, for example, Le Bel and Jones, respectively, inferred pressures of 200 to 300 bars, equivalent to a depth of one to two kilometres.

**Sources of Metals in Porphyry Copper Deposits**

The close liaison between porphyry belts and orogenic belts suggests that the fundamental control of porphyry belts is tectonic. Isotopic evidence indicates that sulphur in the deposits is largely of upper mantle or remelted oceanic crust origin, although meteoric waters play an important role in alteration and metal deposition in the porphyry environment.

The origin of the metals in the deposits is more speculative. Metals and sulphur in hydrothermal fluids may be concentrated as by-products of magmatic crystallization. However, Noble (1970) and more recently Banks and Page (1977) argued that magmas are incapable of transporting sufficient quantities of metals and sulphur to produce porphyry copper deposits. They concluded that hydrothermal fluids originate independently from magmas but in the same source area. In this theory, porphyry intrusions are associated with the deposits only because magma and later hydrothermal solutions followed the same access routes. Another possibility is that metals and/or sulphur are derived from the country rock. In this theory, metal is scavenged from the country rock by convecting fluids driven by the heat of the associated magma.

**Post-Depositional Effects**

Metamorphism and deformation are rarely significant in Cordilleran porphyry copper deposits. One exception is Gibraltar, a plutonic porphyry deposit in central British Columbia, in which contemporaneous mineralization and deformation has been described (Drummond et al., 1976). In older terranes, metamorphism and deformation may mask original alteration types and zoning through retrograde reactions and fabric readjustments. Alteration assemblages most resistant to change in low-grade metamorphic terranes will be propylitic, phyllic, and argillic, whereas only phyllic alteration will survive in higher grade terranes. Aluminosilicates derived from argillic (aluminous) assemblages may signal earlier hydrothermal activity, particularly in granitoid rocks.

Supergene effects have received little attention in this review because only a few porphyry deposits in the Canadian Cordillera contain significant supergene mineralization. Some of these deposits show grade enrichment, but often the supergene zones present metallurgical problems which result in poor recovery and low-grade concentrates. At Atcon, however, the supergene zone is not enriched, rather, the natural beneficiation converted sulphide ore into native copper and oxide ore, thus simplifying milling and smelting. Nevertheless, an understanding of supergene effects and processes in the porphyry environment is necessary, especially at the exploration stage, to interpret the weathered outcrops and leached cappings that constitute many of the surface showings in the Canadian Cordillera. For a thorough account of supergene effects, see Ney et al. (1976).
**Relationship with Plate Tectonics**

Porphyry copper deposits are found mainly in island arcs and near continental margins, both of which represent destructive boundaries of lithospheric plates (Mitchell and Garson, 1972). In this setting a genetic relationship between subduction, magmatism, and related porphyry deposits is generally accepted (Silviose, 1977). Beyond this generalization, the relationship is often difficult to substantiate, even in the youngest Cenozoic orogenic belts (Gustafson, 1978), let alone in older terranes (Sangster, 1979). For example, at OK Tedi, the youngest known porphyry copper deposit, mineralization is 1.1 to 1.2 Ma old (Page and McDougall, 1972) but subduction apparently took place some 30 million years earlier. Furthermore, some porphyry deposits lie in continental settings. Mesozoic to Cenozoic porphyry deposits in the southwestern United States, for example, are hundreds of kilometres from the continental margin and 200 kilometres inland from the western edge of the Precambrian craton (Rogers et al., 1974). This is much too far inland to be related to a typical subduction zone and debate continues whether there is any relationship between this mineralization and subduction (Lowell, 1974; Silviose, 1975).

**Models for Porphyry Copper Deposits**

No single model can adequately portray alteration and mineralization processes that have produced the wide variety of porphyry copper deposits. However, over- forming regimes that are the products of volatile-enriched magmas emplaced in highly permeable terranes, can be described in a series of models that represent successive stages in an evolving process. End-member models of hydrothermal regimes (Fig. 8) attempt to show contrasting conditions for systems dominated by magmatic and meteoric waters, respectively. In both, enough time has lapsed after magmatic emplacement for convective cells to become established in the country rock in response to the magmatic heat source. The convecting fluids transfer mass and heat from the magma into the country rock and redistribute elements in the convective system. In intrusive settings, where these hydrothermal regimes operate, temperatures range from magmatic at depth, to ambient at the surface (greater than 800° to 20° Celsius). At depth, fluid pressure is lithostatic and probably equivalent to a maximum load of four to five kilometres, near the surface, it approaches hydrostatic. At depth, the main cooling is accomplished through conduction; near the surface, cooling results from convective fluid movement. The fundamental difference between these two models is the source and flowpath of the hydrothermal fluids.

The two models shown on Figure 8 represent end members of a continuum. In the traditional orthomagmatic end member, volatiles and metals are concentrated during crystallization of the magma then break through the crystallized carapace, as hydrothermal fluids, in the post-magmatic stage. The initial wave of escaping fluids fractures the country rock, creating crackle zones and a primeval plumbing system that controls the travel paths of subsequent hydrothermal fluids and localizes alteration and mineralization (Burnham, 1967; Holland, 1972; Whitney,
1) In the orthomagmatic model, the cooling stock generates an ascending hydrothermal plume. There is some peripheral entrainment of meteoric water. In the convective model, permeable country rocks are the primary source of fluids. Groundwater flows into the convective cells from as much as 2 km above and 5 km lateral to the stock.

2) The magmatic component constitutes up to 95% of the hydrothermal fluid in the orthomagmatic system and as little as 5% in the convective system.

3) Usually, salinity is relatively high in ore zones. In orthomagmatic systems, saline fluids with greater than 15% and ranging as high as 70% weight-equivalent sodium chloride can be found. In convective systems, overall salinity is low to moderate, generally less than 15% weight-equivalent sodium chloride, though boiling might cause local areas of higher salinity.

4) Highly saline fluid inclusions, with co-existing gas and fluid-rich inclusions, provide the best evidence that boiling occurred. In orthomagmatic systems, there is widespread evidence of boiling or high-temperature entrapment of supercritical fluid. Often, second or multiple episodes of boiling occurred as fluid pressures fluctuated between lithostatic and hydrostatic. These rapid changes in hydraulic pressure seem to have been caused by throttling and repeated self-sealing and refactoring of the rocks. In the convective systems, boiling appears to have been local and of limited duration.

5) In orthomagmatic systems, fluid temperatures range from magmatic down to 400°C; seemingly, high temperatures persisted for a protracted period of time. In convective systems, heat transfer efficiency is greater, and, although temperatures briefly reach 450°C Celsius or more, they quickly drop to about 250°C. These lower temperatures are evidently maintained for a considerable length of time.

6) The following alteration patterns emerge. Orthomagmatic systems are dominated by potassic and propylitic alteration, with narrow zones of phyllic alteration in the area of interaction between magmatic and meteoric fluids. As a consequence, pervasive alteration and mineralization form a series of shells around the core of the intrusion. Convective systems are dominated by phyllic alteration, with peripheral propylitic alteration around restricted, locally obliterated potassic core zones. Alteration and mineralization are both pervasive and fracture controlled.

7) Sulphide distribution patterns can be identical in the two settings, however, there is a fundamental difference in the sources of ore constituents. In the orthomagmatic system, metals and sulphur are derived from the magma and are concentrated in residual fluids. In the convective system, metals and sulphur are scavenged from the enclosing rocks by convecting, heated groundwaters.

A few porphyry copper deposits, for example Granisle and Bell in British Columbia (Wilson et al., 1980), closely resemble one or the other end-member model. Most deposits combine elements of both models, commonly with evidence for early orthomagmatic and later convective alteration/mineralization. Problems in identifying all the events and their sequence arise because younger, superimposed episodes can mask older ones completely. These complications make static, end-member models, such as are shown on Figure 8, inadequate to describe actual porphyry systems; staged models which incorporate changes with time are more realistic. On Figure 9, the four main stages of mineralization/alteration that typically occur in porphyry copper systems are illustrated. The Figure is patterned after Gustafson and Hunt's (1975) description of the El Salvador deposit in Chile.

Intrusion of the magma causes thermal metamorphism due to conductive heat flow (Fig. 9, stage 1). This produces biotite hornfels, often referred to as early developed biotite (EDB). Later, upward and outward flow of fluids increases the rate of cooling of the pluton, and causes additional fracturing and attendant mass

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**STAGED ALTERATION MODEL**

Model showing four sequential stages of alteration/mineralization. For explanation, see text.
porphyry intrusions with the cool groundwater may propagate pebble breccia pipes or diatremes. This stage is rare in classic-type Cordilleran deposits but is well developed in at least one volcanic-type deposit. Island Copper, and several plutonic-type deposits (Highland Valley).

Conclusion
The spectrum of characteristics of a porphyry copper deposit reflects the various influences of each of the four main and many transient stages in the evolution of the porphyry hydrothermal system. Not all stages develop fully, nor are all the stages of equal importance. Various factors, such as magma type, volatile content, the number, size, timing and depth of emplacement of mineralizing porphyry plutons, variations in country rock composition and fracturing, all combine to ensure a wide variety of detail. As well, the rate of fluid mixing, density contrasts in the fluids, and pressure and temperature gradients influence the end result. Different depths of erosion alone can produce a wide range in appearances even in the same deposit. The search for porphyry copper deposits, especially buried ones, must be founded on detailed knowledge of their tectonic setting, geology, alteration patterns, and geochemistry. Sophisticated genetic models incorporating these features will be used to design and control future exploration programs.

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As the system cools, hydrothermal activity wanes, and the convective cell begins to collapse inward and downward (stage 4). The result is a relatively low-temperature, dilute-acid hot spring environment that causes argillic overprinting. At the same time, interaction of post-ore


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