Geoscience Canada

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Volume 7, numéro 2, june 1980

URI : https://id.erudit.org/iderudit/geocan7_2art02

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Éditeur(s)

The Geological Association of Canada

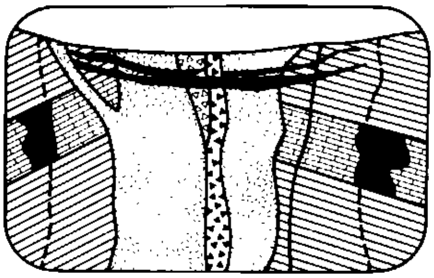
ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

McMillan, W. J. & Panteleyev, A. (1980). Ore Deposit Models – 1. Porphyry Copper Deposits. *Geoscience Canada*, *7*(2), 52–63.



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 coppers, 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 geological 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/alteration 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 coppers have 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 equip-

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

			(Grade Approximate)	
Country	Name	Reserves *(Million Tonnes)*	Copper *per cent*	Molybdenite *per cent*
United States	(1) Bingham Canyon	1 400	0.71	0.05
	(2) Butte*	large	?	?
	(3) San Manuel	1 000	0.75	0.015
	(4) Twin Buttes	800	0.74	0.017
	(5) Safford	2 000	0.40	–
Mexico	(6) La Caridad	600	0.75	0.016
	(7) Cananea	1 700	0.79	–
Panama	(8) Cerro Colorado	3 000	0.8	present
Chile	(9) Chuquicamata	>2 000	1.3	0.04
	(10) El Teniente	3 250	0.87	0.03
	(11) El Abra	1 500	0.80	–
New Guinea	(12) Bougainville	750	0.47	–
Philippines	(13) Biga	700	0.5	–
Iran	(14) Sar Cheshmeh	450	1.13	.03
Canada	(15) Valley Copper	> 750	0.48	–
	(16) Lornex	400	0.41	0.014

*No reserve or grade figures available; from 1880-1964, 326 million tonnes with 2.45 per cent copper mined.

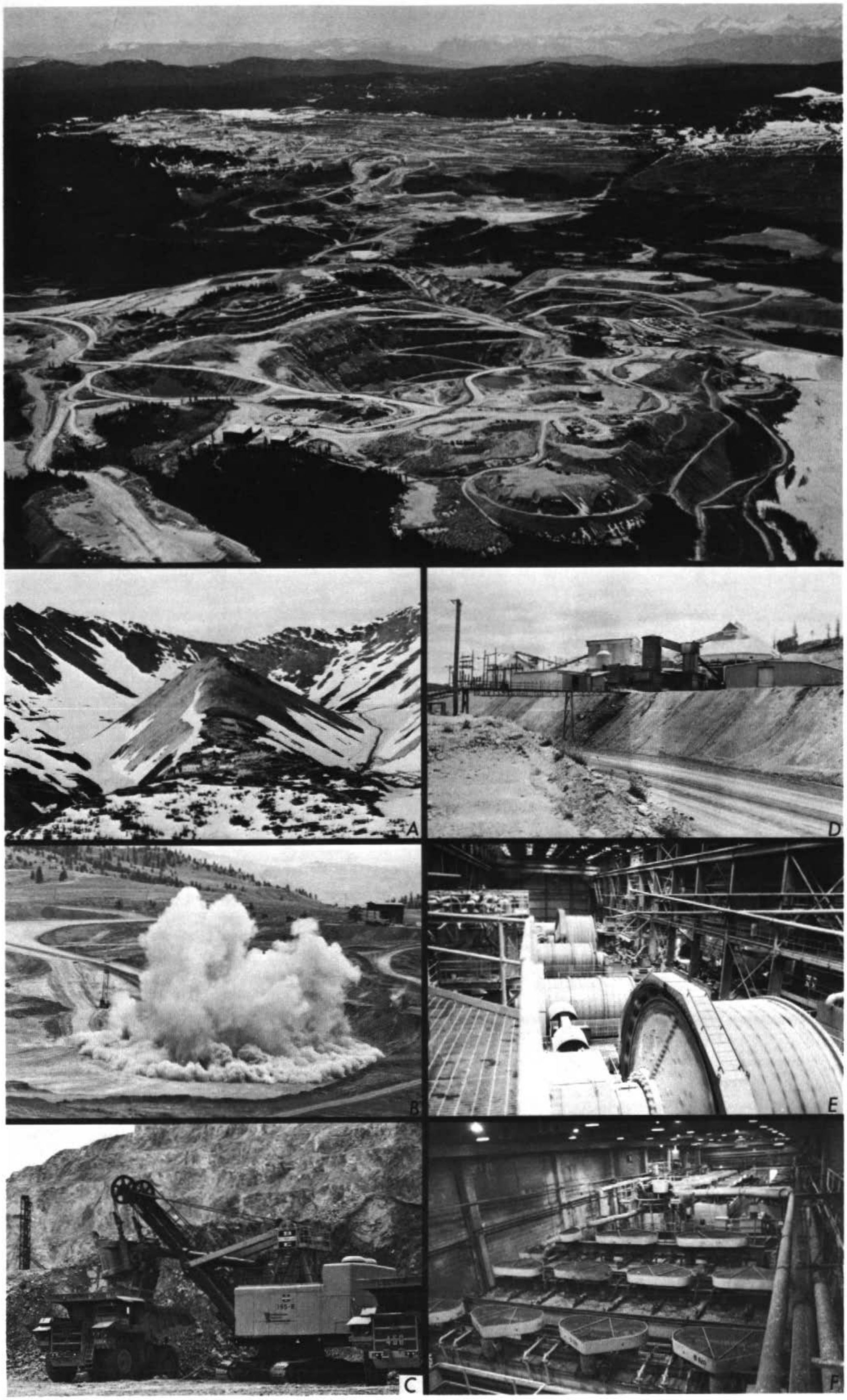

Figure 1
Highland Valley, south-central British Columbia in June 1976. Viewed southwesterly; Bethlehem Copper (foreground) and Lornex open pits. 1A to F show aspects of development and mining from: A—exploration (Berg deposit); B—preparation for production (Afton); C to F—mining, milling, grinding, flotation (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 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; Gaál and Isohanni, 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 (Titley and Hicks, 1966; Lowell

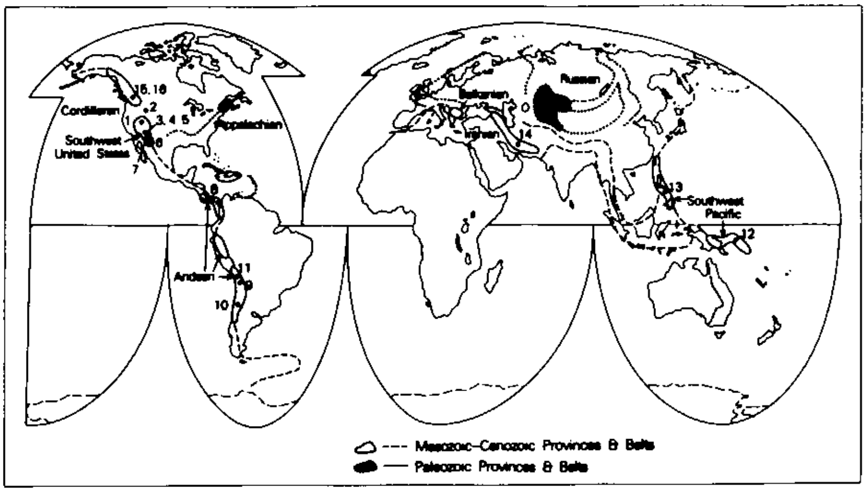

Figure 2
World wide distribution of porphyry provinces. Numbers refer to deposits described in Table 1.

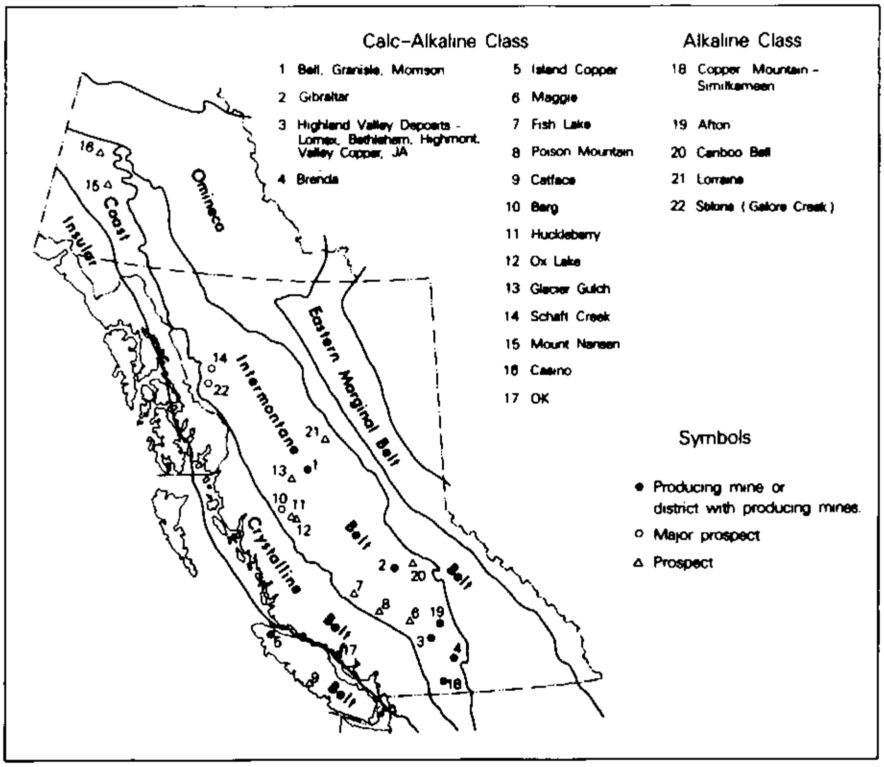

Figure 3
Cordilleran porphyry mines and prospects and their tectonic settings.

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

	Classic (Stock-related)	Volcanic	Plutonic
Setting	Associated with post-orogenic stocks intruding unrelated host rocks; co-magmatic volcanic piles rarely preserved Cordilleran deposits are of Late Mesozoic to Tertiary age.	In basic to intermediate volcanic piles intruded by comagmatic calc-alkalic or alkalic (dioritic or shoshonitic suite) plutons, magmatism produces consanguineous and intimately associated intrusive/extrusive assemblages. Cordilleran deposits are of Mesozoic age.	In large calc alkalic plutons emplaced in or near comagmatic volcanic rocks, plutons typically have mafic borders and are moderately to strongly differentiated Cordilleran deposits are of Mesozoic age.
Plutons	Multiple phases emplaced as successive, small (0.5 to 2 km^2), cylindrical porphyritic intrusions, numerous pre-, intra-, and post-mineral porphyry dykes emplaced at shallow depth	Calc-alkalic – very small to small sheets, dykes and plugs (0.2 to 10 km^2), with much textural variety, subvolcanic emplacement. Alkalic – high level sheets, dykes, plugs associated with underlying differentiated mesozonal pluton or small batholith.	Batholithic rocks (>100 km^2) immobilized at relatively deep levels (2 to 4 km) Phaneritic coarse-grained to porphyritic rocks with local swarms of pre- to post-ore porphyritic dykes.
Structural Control of Intrusions	Passive, structure need not be significant; many stocks localized by intersections of regional faults.	Calc alkalic – emplacement in volcanic vents, fault zones, radial fractures. Alkalic – intrusive centres localized by regional structures. High level intrusive rocks invade volcanic vents and fault zones.	Diapiric emplacement; magmatic pulses and differentiation cause sharp to gradational internal phase boundaries.
Breccias	Abundant and characteristic, post-ore argillic diatremes are common Other types present include collapse breccias, intrusive breccias, and carapace or stoping breccias. Early breccias can be mineralized.	Calc alkalic – common and diverse, include primary pyroclastic tephra, alteration pseudo-breccia, vent agglomerate, shatter and igneous breccias Mineralized breccias are characteristic; some contain magnetite or tourmaline. Alkalic – intrusive and volcanic breccias common and generally mineralized, as in calc-alkalic types.	Common in association with late-stage porphyry dyke swarms. Breccias pre, intra, and post-ore, some contain specularite or tourmaline.
Alteration	Potassic, phyllic, and propylitic universally developed as annular shells around intrusions, argillic of varying importance. Early developed biotite (EDB) can be part of an isochemical hornfels and has often been misidentified as part of the potassic zone	Calc-alkalic – propylitic is widespread, potassic is more restricted but can be intense; alteration centred on zones of high permeability. Similar to classic-type deposits with small core zones of potassic and local phyllic and/or argillic shells. Alkalic – local intense to pneumatolytic potassic alteration; early hydrothermal biotite overprinted by propylitic, then by sodic and/or potassic (albite-K-feldspar) and rarely scapolite alteration.	Phyllic, phyllic-argillic, and propylitic types are best developed, local potassic alteration. Fracture controlled to pervasive, commonly as alteration envelopes on multistage fractures and veins. Centred on orebodies but patterns of zoning complicated by overprinting
Orebodies	In margins and adjacent to porphyry intrusion(s) as annular ore shells, or as domal cappings, pronounced lateral zoning Pyrite is found throughout, the weakly mineralized core is surrounded by zones dominated by molybdenite, then chalcopyrite, and, finally, a pyritic halo.	Calc-alkalic – generally Cu-Mo deposits intimately associated with breccias and intensely altered rocks, orebodies lensoid and irregular, with some preferential bedding control Most ore contains chalcopyrite with rare bornite or molybdenite as 'dry' fracture fillings. Alkalic – generally Cu-Au deposits in intrusive breccia or in highly fractured country rock; some replace porous country rock. Locally magnetite-apatite of magmatic origin present as vein or breccia infillings; zoning is from chalcopyrite ±magnetite and bornite outward to a pyrite halo.	Large and diffuse vein stockworks; some breccia control, some faults mineralized, sulphides relatively sparse. Zoning is evident with iron content increasing outward from bornite to chalcopyrite to pyrite rich zones; Mo distribution is variable. Some deposits have low-grade quartz-rich core zones.

and Guilbert, 1970). The term "classic" has been applied to them because of their historical significance, because of the role they played in development of genetic models, and because no term currently in the literature adequately describes them. Deposits of this type have variously been labelled simple, cylindrical, phallic (Sutherland Brown, 1976) and hypabyssal.

In the Canadian Cordillera, Mesozoic deposits are of the volcanic or plutonic types (Figs. 6 and 7) and are associated with calc-alkalic or alkalic plutons which commonly intrude and mineralize comagmatic volcanic piles. Cenozoic deposits are generally of the classic type (Fig. 5). To date, the majority of Canadian Cordillera porphyry deposits occur in the Intermontane Belt, although a few have been discovered in the Insular and Coast Crystalline Belts (Fig. 3).

Intrusions Associated with Porphyry Copper Deposits

Intrusions associated with porphyry copper deposits are diverse but generally felsic and differentiated. Those in island arc settings have primitive strontium isotopic ratios (Sr^{87}/Sr^{86} of 0.705 to 0.702) and, therefore, are derived either 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-alkalic 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

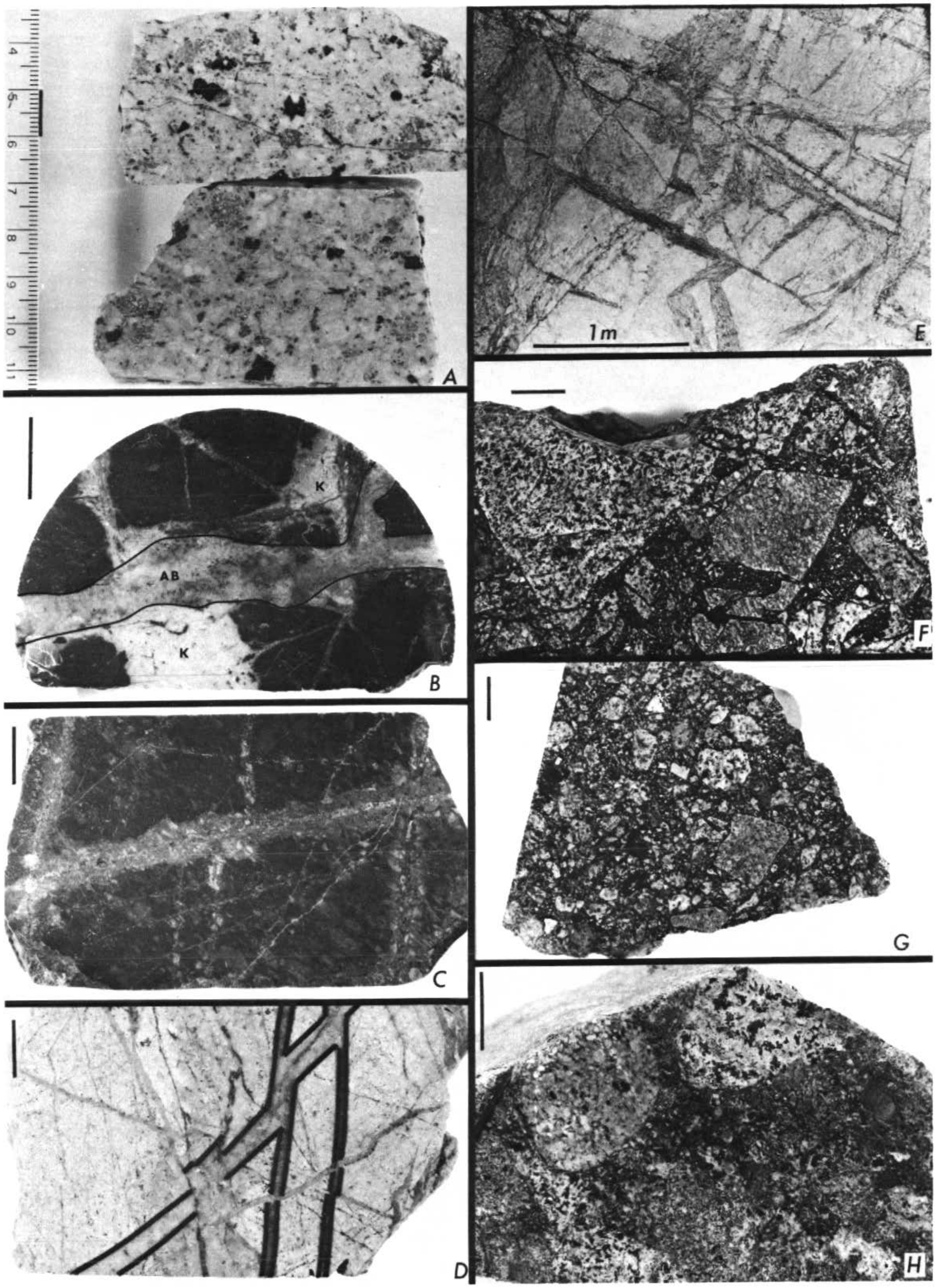

Figure 4

Lithologic and alteration types in porphyry deposits. Except where noted scale bar is 1 cm long. A—biotite quartz feldspar 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—breccias 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.

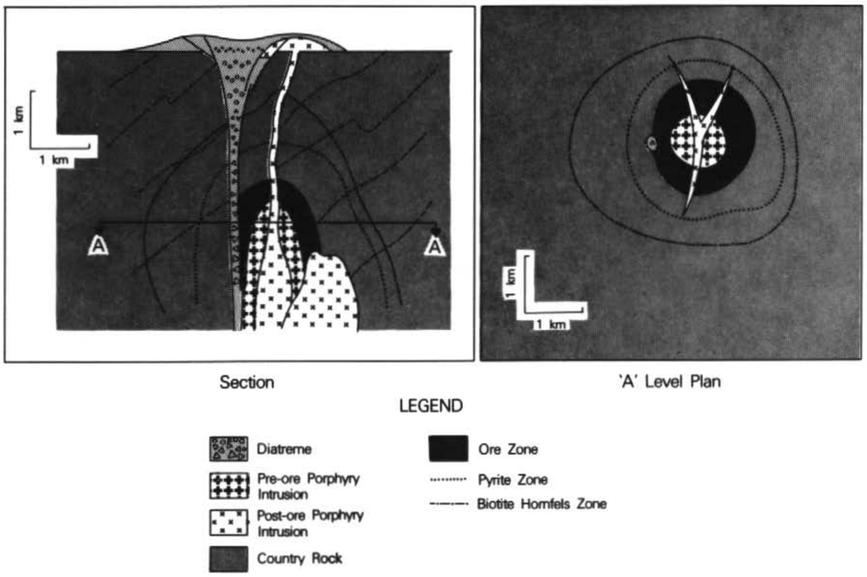

Figure 5
Model of classic-type porphyry copper deposits (after Sutherland Brown, 1976).

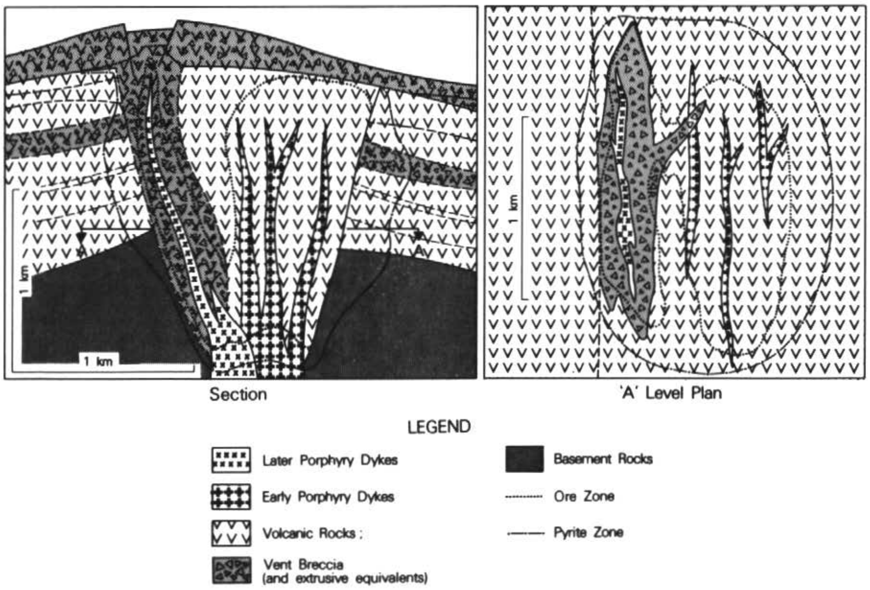

Figure 6
Model of volcanic-type porphyry copper deposits (after Sutherland Brown, 1976).

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

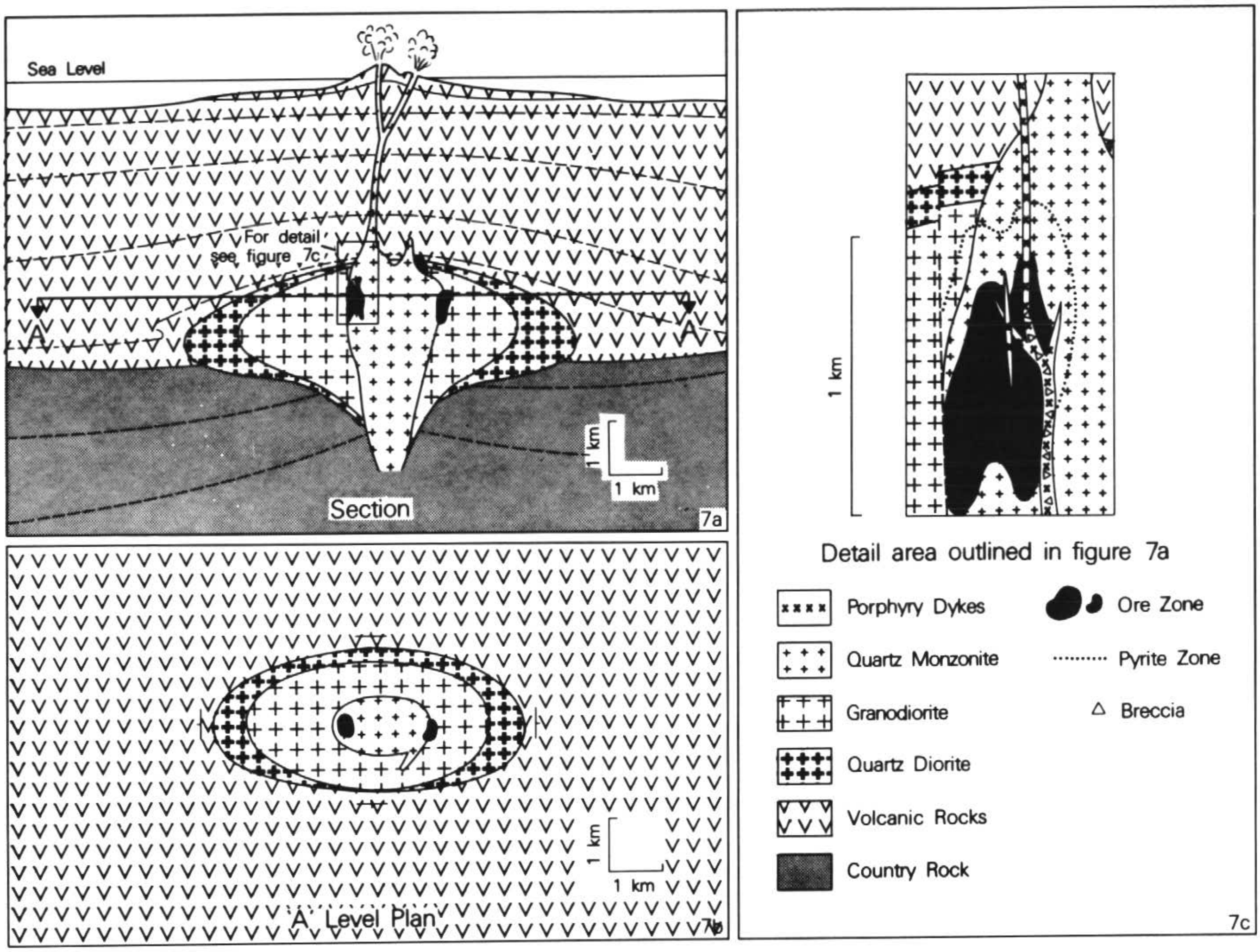

Figure 7
Model of plutonic-type porphyry copper deposits.

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 behaviour 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 albitized 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 (Guilbert 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 both 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.

Hypogene Mineralization and Zoning

Hypogene mineralization consists of disseminations, fracture fillings, and quartz veinlets containing varying amounts of pyrite, chalcopyrite, bornite, and molybdenite. Zoning in porphyry coppers differs, not only between classes of deposits (Table II), but also between individual deposits. In deposits of the classic 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° to over 750° Celsius. At Cerro Verde, Peru (Le Bel, 1979a, 1979b), for example, fluid inclusions homogenized at between 380° and 410° Celsius. Temperatures derived from study of sulphur isotopes, sulphide-sulphate ratios, C^{13}, 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 of 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 (Sillitoe, 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 liason 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. Aluminum silicates 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 Afton, 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 stated or implied and is generally accepted (Sillitoe, 1972; Creasey, 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; Sillitoe, 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, ore-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 convection 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,

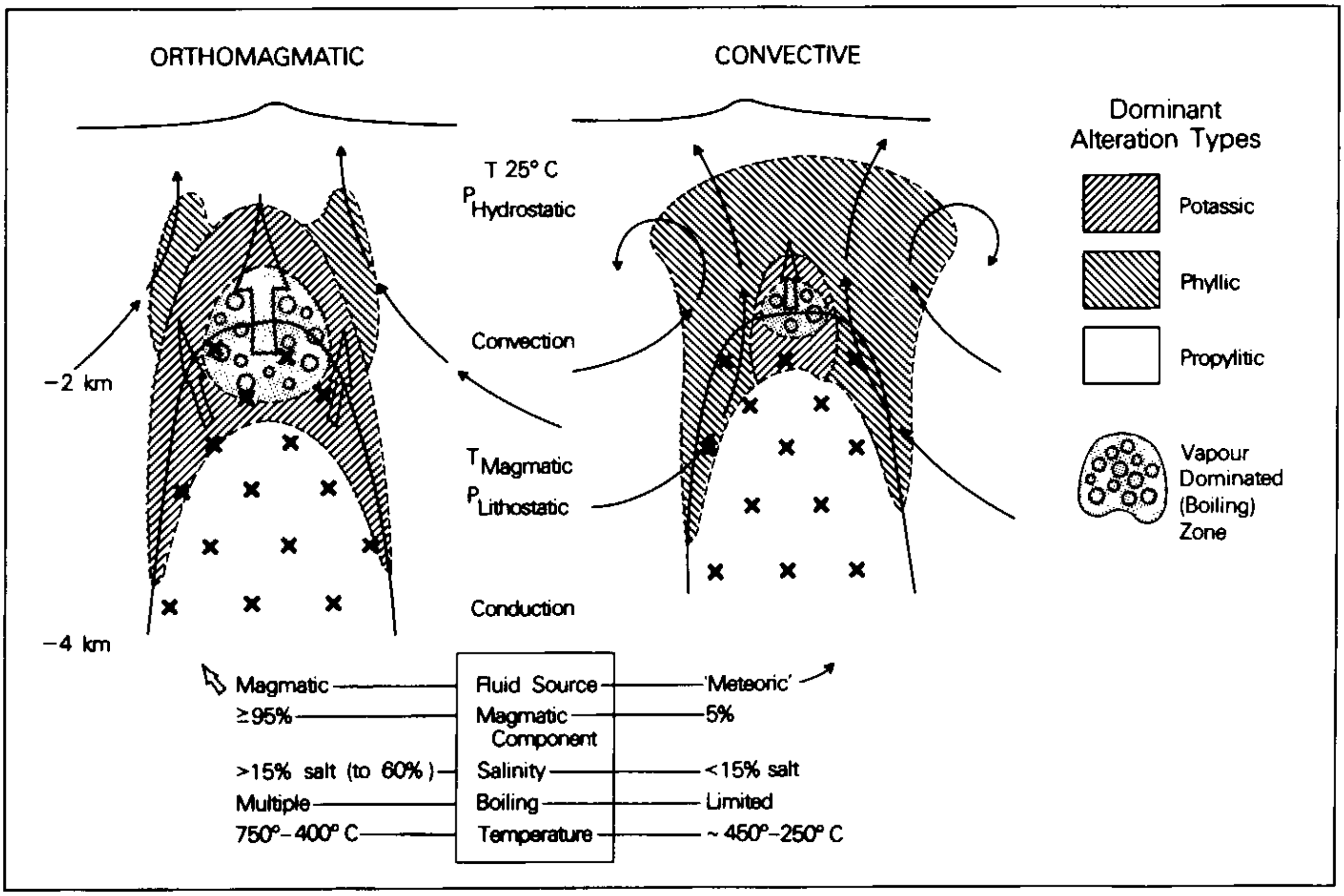

Figure 8
Model of hydrothermal systems with contrasting orthomagmatic and convective fluid flow patterns. For explanation, see text.

1975; Henley and McNabb, 1978). Further crackling results from magmatic pressures, boiling, and hydrofracturing (Phillips, 1973). In the convective end member, the fluid is mostly groundwater whose source is meteoric, connate, or seawater (Cathles, 1977; Norton and Knapp, 1977; Norton, 1978). In this model, thermally driven convective cells are initiated by emplacement of the magma. The permeability of the country rock, enhanced by the intrusive events, is sufficient to allow convective circulation to begin. Convection thoroughly redistributes fluids and concentrates ore and gangue constituents in and near the intrusion.

In the evolving dynamic systems that produce porphyry copper deposits, proportions of magmatic and meteoric fluids can be expected to fluctuate, both in time and space. Application of fluid inclusion studies, stable isotope, and fluid dynamic simulation studies to the end-member models yields the following observations:

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 refracturing of the rocks. In the convective systems, boiling appears to have been local and of limited duration.

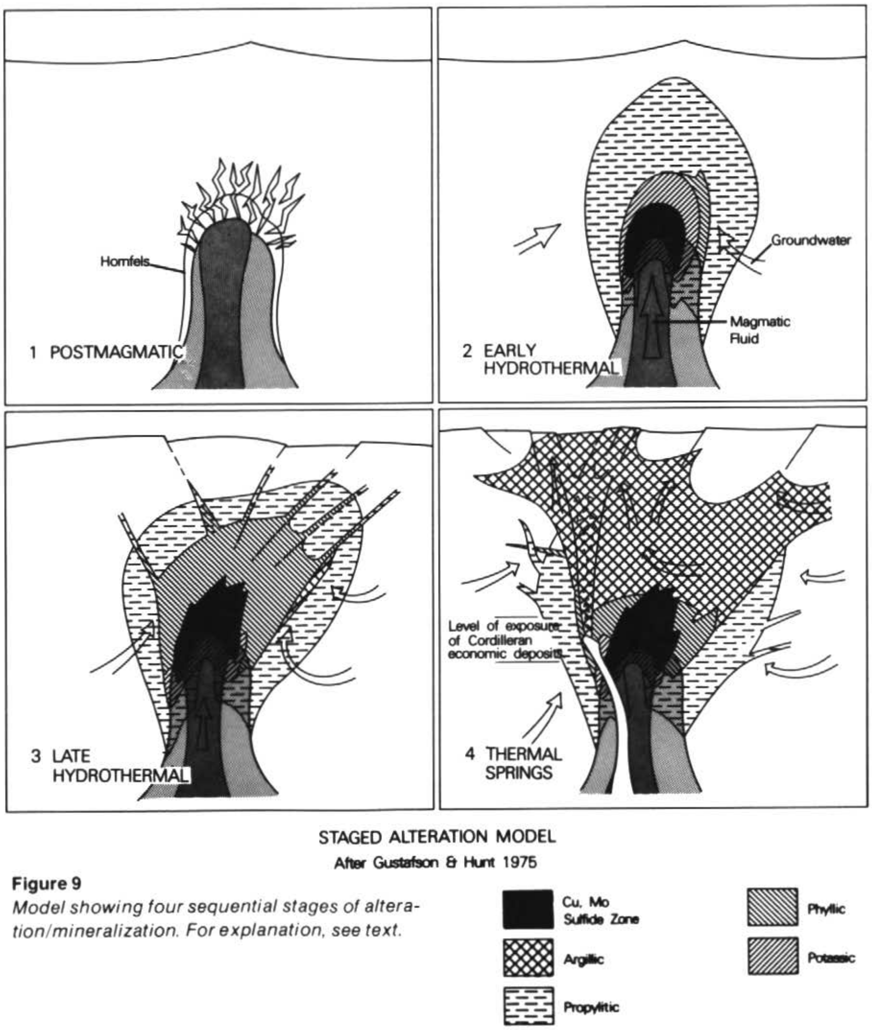

Figure 9
Model showing four sequential stages of alteration/mineralization. For explanation, see text.

5) In orthomagmatic systems, fluid temperatures range from magmatic down to 400º Celsius; seemingly, high temperatures persisted for a protracted period of time. In convective systems, heat transfer efficiency is greater, and, although temperatures briefly reach 450° Celsius or more, they quickly drop to about 250°. 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 transfer (Fig. 9, stage 2). Heating during stage 1, abetted by the heat and mass transfer of stage 2, leads to initial mineralization and produces a potassic core, peripheral propylitic alteration zones, and possibly minor phyllic zones. Stages 1 and 2 constitute the orthomagmatic end-member model outlined above. At least in the potassic zone, stage 2 hydrothermal processes take place at high temperature and lithostatic pressure. For brief periods, however, fluid pressures may exceed lithostatic pressure and become an important control in fracture and breccia propagation. Alteration reactions in this stage trend toward pervasive prograde chemical equilibrium in the altered rocks. Alteration and mineralizaiton processed may terminate at the end of stage 2, but generally continue and evolve.

All three types of porphyry copper deposits in the Canadian Cordilleran display elements of stages 1 and 2. In some, such as the classic-type Granisle deposit (Wilson *et al.*, 1980) and several volcanic-type deposits, such as Copper Mountain, Stikine Copper and Schaft Creek, much of the ore was deposited during these orthomagmatic stages. In plutonic deposits, because the country rock is granitic, thermal metamorphic effects (stage 1) are difficult to recognize. Stage 2 potassic alteration is erratically distributed; either it was not originally widespread or it has been overprinted by later alteration. In the plutonic deposits main-stage mineralization has a predominent orthomagmatic component.

Later alteration and mineralization are controlled by convective hydrothermal circulation involving both magmatic and meteoric fluids, but dominated by the latter (Fig. 9, stage 3). Groundwater flows toward and through the crackled intrusion, resulting in widespread phyllic overprinting of earlier alteration types. So long as permeability is maintained, pressure is hydrostatic and heat loss is rapid. This cooler, more acidic, hydrothermal regime produces K-feldspar and biotite-destructive alteration. Pervasive alteration may result, or retrograde margins or envelopes develop on veins and fractures as is common in the plutonic deposits of Highland Valley, British Columbia. Extensive remobilization and enrichment of early formed copper sulphides by means of hypogene leaching can take place at this stage (Gustafson and Hunt, 1975; Brimhall, 1979).

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 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.

Acknowledgements

This paper was solicited by J. M. Allen on behalf of the Mineral Deposits Section of the Geological Association of Canada. We thank our colleagues in the Geological Division, A. Sutherland Brown, N. C. Carter, T. Höy, and V. A. Preto for their discussion and comments on the manuscript and are grateful for the editorial scrutiny of Richard Butler. We thank R. W. Hodder and T. J. Bottrill for their thoughtful reviews of the manuscript.

Draughting was done by J. P. St. Gelais and the manuscripts typed by D. Bulinckx and J. Patenaude. Permission to publish was granted by the Chief Geologist, Mineral Resources Branch, British Columbia Ministry of Energy, Mines and Petroleum Resources.

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MS received February 8, 1980;
Revised March 17, 1980