PORPHYRY DEPOSITS

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Definition

Porphyry deposits are large, low- to medium-grade deposits in which primary (hypogene) ore minerals are dominantly structurally controlled and which are spatially and genetically related to felsic to intermediate porphyritic intrusions (Kirkham, 1972). The large size and structural control (e.g., veins, vein sets, stockworks, fractures, 'crackled zones' and breccia pipes) serve to distinguish porphyry deposits from a variety of deposits that may be peripherally associated, including skarns, high-temperature mantos, breccia pipes, peripheral mesothermal veins, and epithermal precious-metal deposits. Secondary minerals may be developed in supergene-enriched zones in porphyry Cu deposits by weathering of primary sulphides. Such zones typically have significantly higher Cu grades, thereby enhancing the potential for economic exploitation.

The following subtypes of porphyry deposits are defined according to the metals that are essential to the economics of the deposit (metals that are byproducts or potential byproducts are listed in brackets):

Cu (±Au, Mo, Ag, Re, PGE)
Cu-Mo (±Au, Ag)
Cu-Mo-Au (±Ag)
Cu-Au (±Ag, PGE)
Au (±Ag, Cu, Mo)
Mo (±W, Sn)
W-Mo (±Bi, Sn)
Sn (±W, Mo, Ag, Bi, Cu, Zn, In)
Sn-Ag (±W, Cu, Zn, Mo, Bi)
Ag (±Au, Zn, Pb)

For deposits with currently subeconomic grades and tonnages, subtypes are based on probable coproduct and byproduct metals, assuming that the deposits were economic.

Geographical Distribution

Porphyry deposits occur throughout the world in a series of extensive, relatively narrow, linear metallogenic provinces (Fig. 1). They are predominantly associated with Mesozoic to Cenozoic orogenic belts in western North and South America and around the western margin of the Pacific Basin, particularly within the South East Asian Archipelago. However, major deposits also occur within Paleozoic orogens in Central Asia and eastern North America and, to a lesser extent, within Precambrian terranes. The distribution of selected porphyry deposits in Canada is shown in Figure 2.
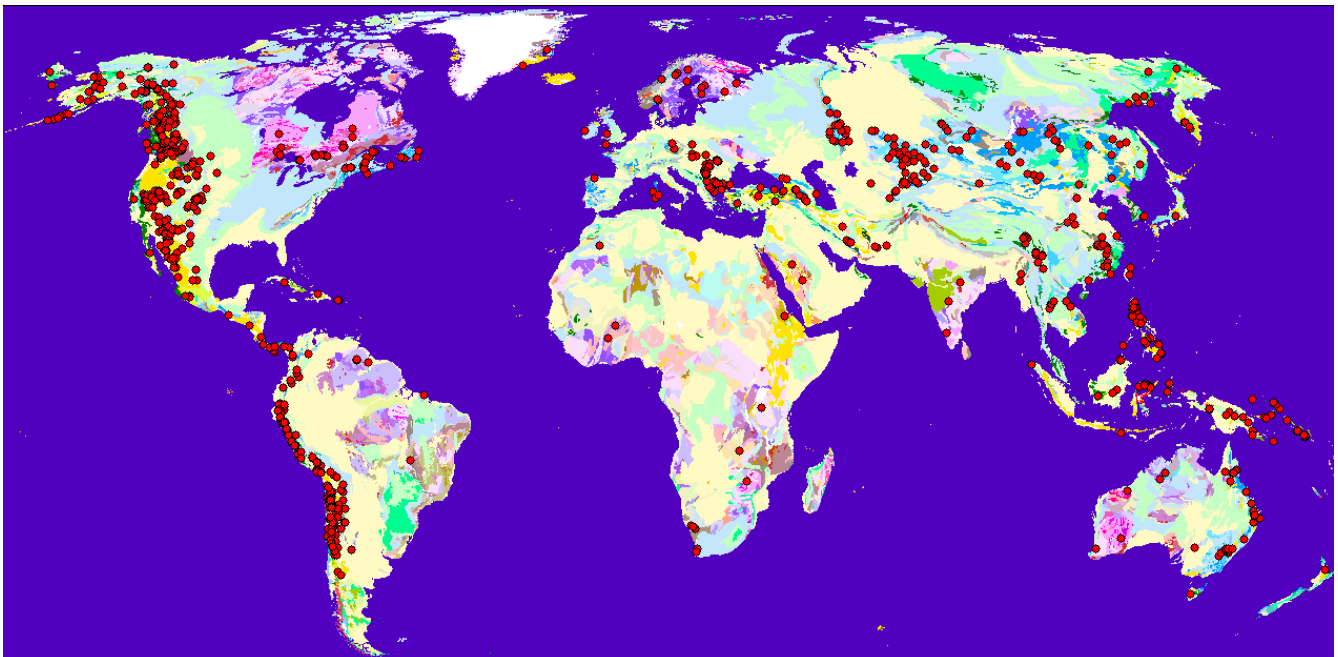

Figure. 1. Global distribution of porphyry deposits.

Importance

Porphyry deposits are the world's most important source of Cu, Mo and Re, and are major sources of Au, Ag and Sn; significant byproduct metals include W, In, Pt, Pd and Se. They account for about 50 to 60 per cent of world Cu production, although less than 50 per cent of Canadian Cu production is from porphyry deposits. This is primarily because of important Canadian Cu production from Cu-Ni ores at Sudbury and from numerous volcanogenic massive sulphide deposits scattered across the country. About 60 per cent of Canadian Cu reserves are in porphyry deposits, largely in the Cordillera (Fig. 2), but they include a considerable amount of low-grade Cu resources that are currently subeconomic. Porphyry deposits account for more than 99 per cent of both Canadian and world Mo production and reserves. In the past few years, porphyry Cu-Au (e.g., Kemess, B.C.) and porphyry Au (e.g., Troilus, Quebec) deposits have become increasingly important sources of Au. At present (2004), no porphyry W-Mo or Sn deposits are in production in Canada.

Grade and Tonnage

Porphyry deposits are large and typically contain hundreds of millions of tonnes of ore, although they range in size from tens of millions to billions of tonnes; grades for the different metals vary considerably but generally average less than one per cent (Appendix 1).

In **porphyry Cu** deposits, Cu grades range from 0.2% to more than 1% Cu (Fig. 3); Mo content ranges from approximately 0.005 to about 0.03% Mo (Fig. 4); and Au contents range from 0.004 to 0.35 g/t (Fig. 5). Ag content ranges from 0.2 to 5 g/t. Re is also a significant byproduct from some porphyry Cu deposits; at Island Copper, for example, Re was extracted from molybdenite concentrates
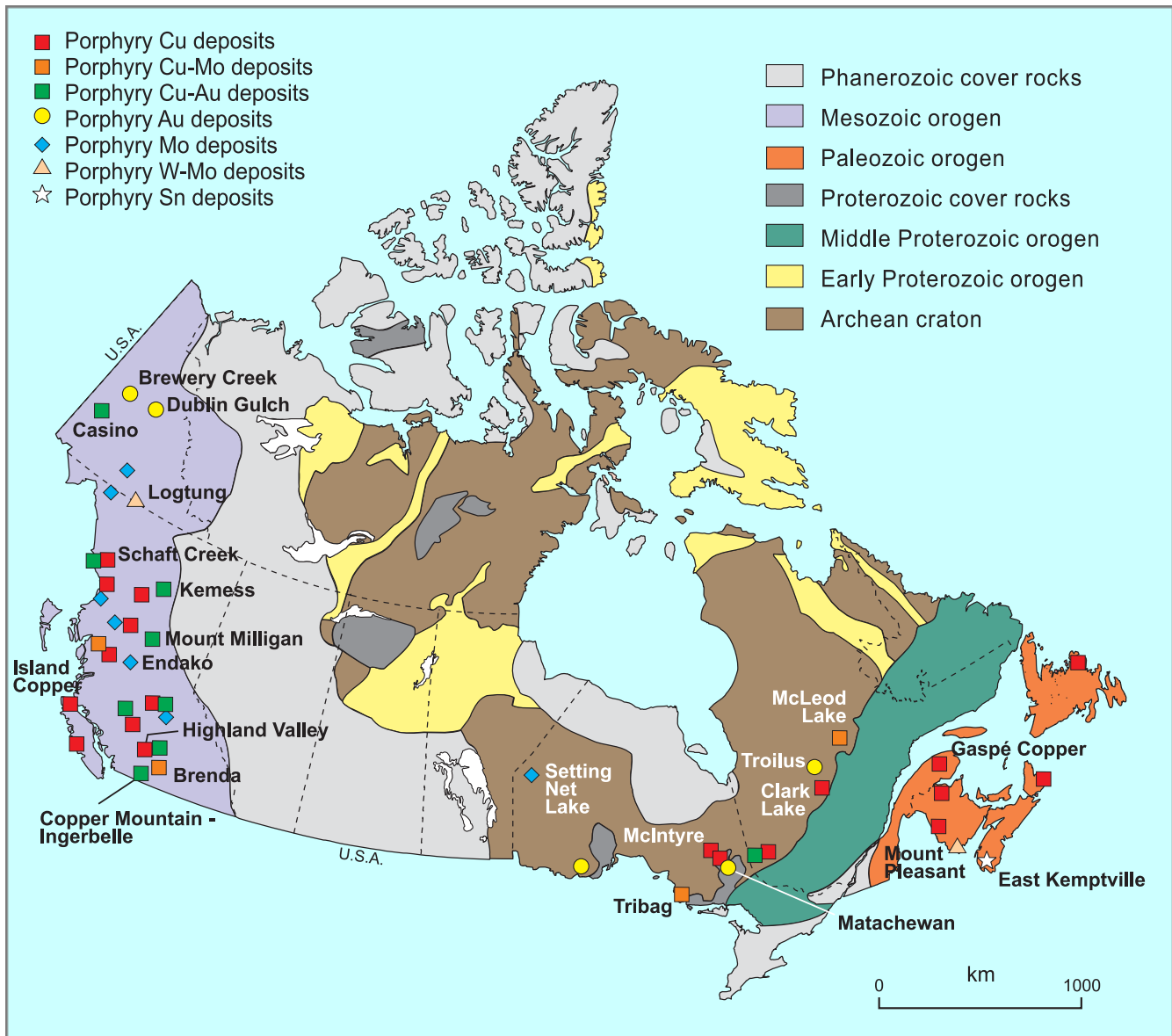

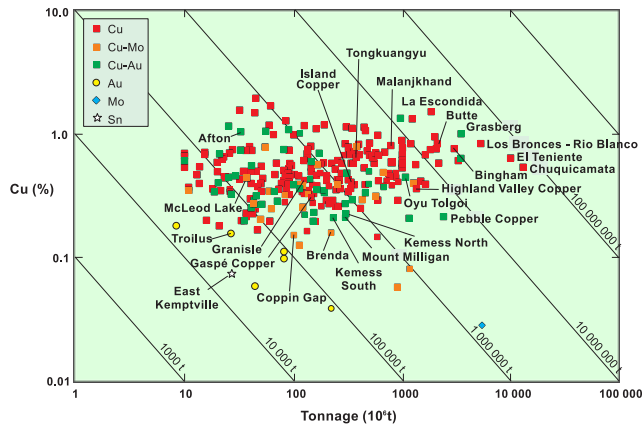Figure 2. Distribution of selected porphyry deposits in Canada.

Figure 3. Cu grades versus tonnage for Canadian and foreign porphyry deposits.

that typically contained more than 1000 ppm Re. Some Au-rich porphyry Cu deposits have relatively high contents of Pt-group elements (PGE)(Mutschler and Mooney, 1995; Tarkian and Stribrny, 1999).

Cu grades in **porphyry Cu-Au** deposits are comparable to those of the porphyry Cu subtype (Fig. 3), but Au contents tend to be consistently higher (0.2 to 2.0 g/t)(Fig. 5). Sillitoe (1993b) suggested that porphyry Cu deposits should contain >0.4 g Au/t to be called Au rich. However, Au is an important coproduct at grades as low as 0.2 g/t Au (Fig. 6). Although the number of deposits in this class is limited,
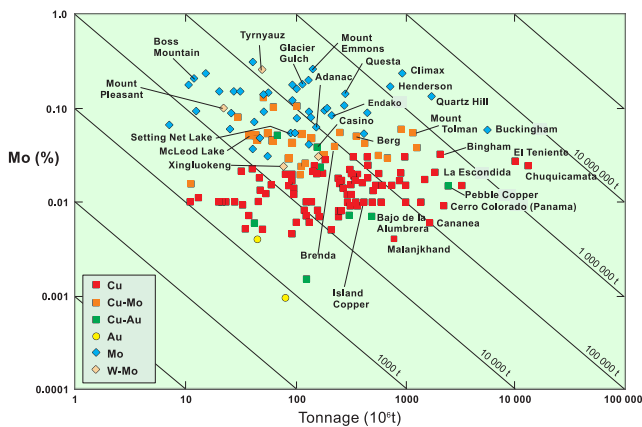

Figure 4. Mo grades versus tonnage for Canadian and foreign porphyry deposits.

deposits such as Grasberg in Indonesia, with a resource greater than 2.5 billion tonnes grading 1.1% Cu and 1.04 g Au/t (Freeport-McMoRan Copper and Gold Inc., Annual Report 2000), indicate that porphyry Cu-Au deposits can contain major Au as well as Cu resources. In comparison, the Kemess South deposit in British Columbia contains about 212 Mt grading 0.63% Cu and 0.215 g/t Au. Some porphyry Cu-Au deposits also contain significant amounts of PGE (e.g, Afton; Appendix 1).

Porphyry Au deposits contain 0.8 to 2.0 g Au/t in deposits that range in size from about 30 to greater than 200 Mt of ore (Fig. 5). The Troilus deposit, Quebec, which is

probably an intensely deformed porphyry deposit (Fraser, 1993), contains about 71 Mt of material grading 0.93 g Au/t and 0.1% Cu.

Grade-tonnage relationships for **porphyry Mo** deposits show that the very large and rich Climax and Henderson deposits in Colorado, with resources of 907 Mt grading 0.24% Mo and 727 Mt grading 0.17% Mo respectively, are end members of a spectrum of Mo-bearing deposits, most of which have lower Mo grades and/or tonnages (Fig. 4). The geological resources of the Endako deposit, for example, are about 336 Mt with an average grade of 0.07% Mo. Limited data are available for W and Sn grades in most porphyry Mo deposits, but some deposits, such as Climax, have produced
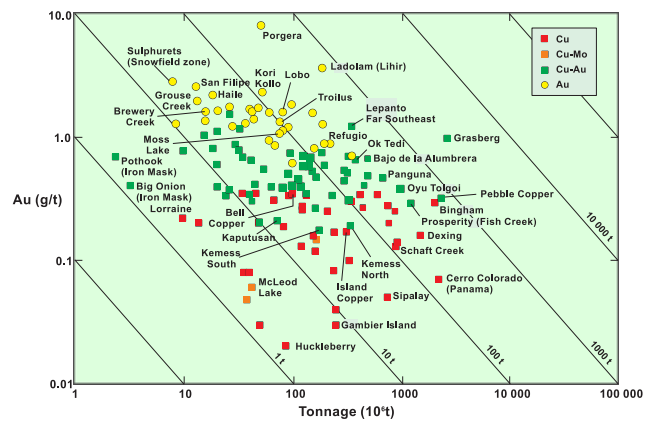

Figure 5. Au grades versus tonnage for Canadian and foreign porphyry deposits.

significant amounts of W and Sn.

Cu and Mo contents indicate that a continuum exists between porphyry Cu and porphyry Mo deposits (Fig. 7). End member deposits are abundant and important economically but deposits with intermediate Cu and Mo contents indicate that porphyry Cu deposits, with minor or no Mo, grade to porphyry Mo deposits with negligible Cu contents (e.g., Westra and Keith, 1981). A continuum may also exist between porphyry Mo and porphyry W-Mo and W deposits, although more data are required to substantiate such a rela-
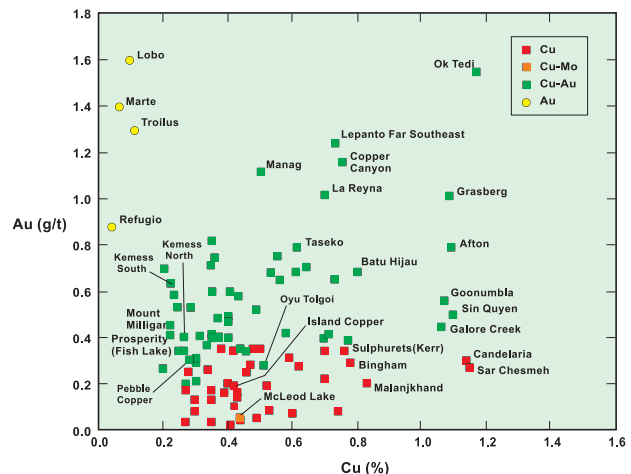

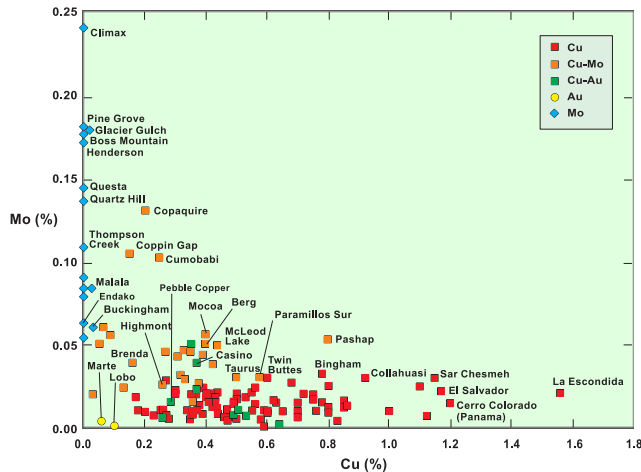Figure 6. Au versus Cu grades in Canadian and foreign porphyry deposits.

Figure 7. Mo versus Cu grades in Canadian and foreign porphyry deposits.

tionship. These examples illustrate some of the difficulties in making sharp distinctions between different porphyry deposit subtypes and one reason for viewing porphyry deposits as a single large class of deposits characterized by diverse metal contents with gradational boundaries between metal subtypes.
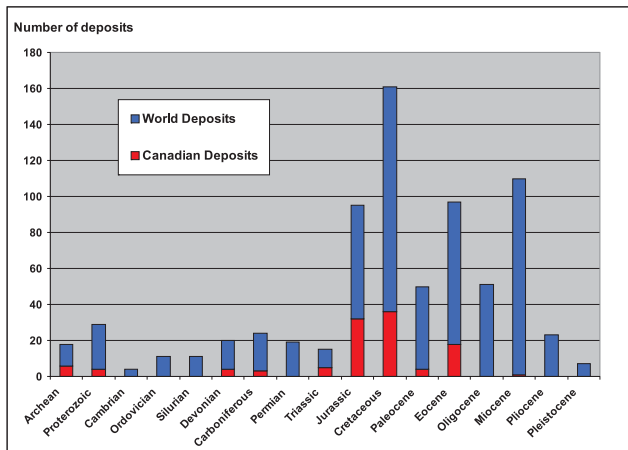

Figure 8. Age distribution of porphyry deposits.

Geological Attributes

Temporal Distribution

Porphyry deposits range in age from Archean to Recent, although most are Jurassic or younger (Fig. 8). On a global basis, the peak periods for development of porphyry deposits are Jurassic, Cretaceous, Eocene and Miocene in age. These ages also correspond to peak periods of porphyry mineralization in Canada, except Miocene, of which age there are few deposits in Canada.

Although porphyry-type deposits of Precambrian age are not as well represented, important examples include Malanjkhand, India (Sikka and Nehru, 1997), Tongkuangyu, China (Weixing and Dazhong, 1987), Boddington, Australia (Roth et al., 1991), Haib, Namibia (Minnitt, 1986) and

Troilus, Quebec (Fraser, 1993). Other examples of Precambrian porphyry deposits include McIntyre and Setting Net Lake, Ontario; Clark Lake and McLeod Lake, Quebec; and Coppin Gap, Australia. Dated at approximately 3.3 Ga (Williams and Collins, 1990), the Coppin Gap Cu-Mo deposit is the oldest known porphyry deposit in the world.
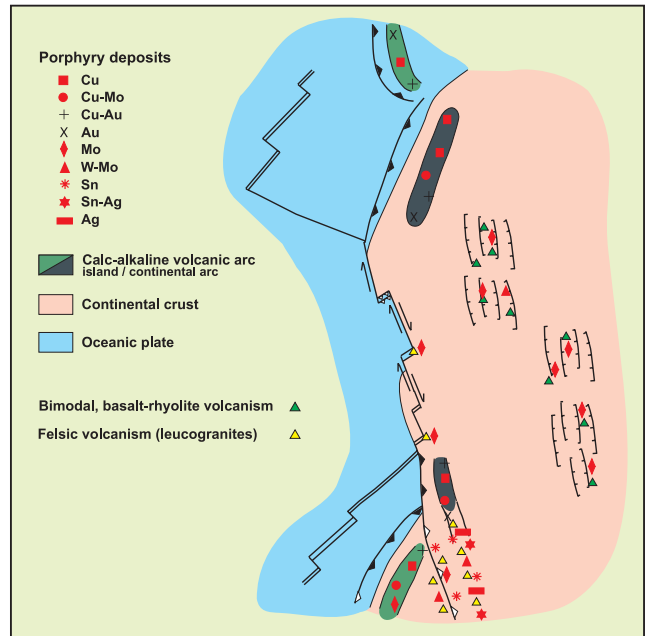

Figure 9. Schematic diagram showing the tectonic settings of porphyry deposits.

Continental Scale (Geotectonic Environment)

Tectonic Setting

Porphyry deposits occur in a variety of tectonic settings. Porphyry Cu deposits typically occur in the root zones of andesitic stratovolcanoes in subduction-related, continental- and island-arc settings (Mitchell and Garson, 1972; Sillitoe, 1973, 1988a; Sillitoe and Bonham, 1984)(Fig. 9). Porphyry Cu-Au deposits, such as those associated with Triassic and Lower Jurassic silica-saturated, alkaline intrusions in British Columbia, formed in an island-arc setting, although possibly during periods of extension. Grasberg and Porgera formed in a continental-island-arc collisional zone during or immediately following subduction (MacDonald and Arnold, 1994; Richards and Kerrich, 1993). Porphyry Au deposits of Tertiary age in the Maricunga belt in Chile appear to have formed in a continental-arc setting along strike to the north from major porphyry Cu deposits of the same general age (Sillitoe, 1992, 1993b).

Porphyry Mo deposits are typically associated with anorogenic or A-type granites that have been emplaced in continental settings, particularly rift or extensional environments (Fig. 9). The Climax and Henderson deposits, for example, are genetically related to small cupolas (small plugs and stocks) on the upper surface of a regional batholith emplaced during active extension in the Rio Grande rift (Bookstrom, 1981; Carten et al., 1988b, 1993). Other por-

phyry Mo deposits appear to have formed during extension in areas adjacent to strike-slip faults (e.g., northern Cordillera - Quartz Hill, Adanac, Casmo and Mount Haskins)(Fig. 9). A few deposits, such as Mount Pleasant, New Brunswick and Questa, New Mexico, are associated with high-silica rhyolites and granites that formed in continental calderas (Lipman, 1988; McCutcheon, 1990; McCutcheon et al., 1997). For most porphyry deposits, however, the depth of erosion is such that caldera settings are conjectural (e.g., Lipman, 1984).

Some porphyry Mo deposits, along with porphyry W-Mo and porphyry Sn deposits, formed in areas of great continental thickness related to collisional tectonic settings, although the deposits generally postdate the collision event. Porphyry Sn deposits in Bolivia, in particular, are related to S-type peraluminous intrusions that were emplaced above deep levels of a Benioff Zone (Ishihara, 1981; Kontak and Clark, 1988; Lehmann, 1990).

Details of each setting and related controls on magma generation, composition and emplacement conceivably had a major influence on the size, metal contents and nature of individual deposits. However, exceptions to typical settings, such as the Tribag and Jogran porphyry Cu-Mo deposits in Ontario that apparently are related to a continental rift environment (Kirkham, 1973; Norman and Sawkins, 1985), and the Malmbjerg porphyry Mo deposit in East Greenland, which is related to the Iceland mantle plume, indicate that individual porphyry deposits can occur in diverse and unique settings.

Regional Structures

In some cases, the distribution of porphyry deposits can be related to regional structures. The Rio Grande rift system in the western United States, for example, is the locus for porphyry Mo deposits (Bookstrom, 1981). The West Fissure zone along strike of the Eocene porphyry Cu belt in northern Chile, from El Salvador in the south to past Collahausi in the north, was active both during and following porphyry emplacement and hydrothermal activity (Baker and Guilbert, 1987). Also within this belt, cross structures apparently controlled the distribution of individual deposits such as Quebrada Blanca, Collahausi and Escondida (Sillitoe, 1992; Richards et al., 2001). The major Philippine strike-slip fault system in the northern part of the island arc system, similar to the West Fissure zone in northern Chile, was probably also a control on the location of major magmatic and hydrothermal centres, which might be localized in areas that are pull-apart structures at dilational bends. In many districts, however, perhaps because of intense alteration and multiple intrusions, regional structural control is obscure.

Deposit Scale

Geological Setting and Related Magmatic Rocks

Porphyry deposits occur in close association with porphyritic epizonal and mesozonal intrusions, typically in the root zones of andesitic stratovolcanoes. Possible exceptions are some porphyry Au deposits such as Porgera, Papua New Guinea and QR, British Columbia that show a close associ-
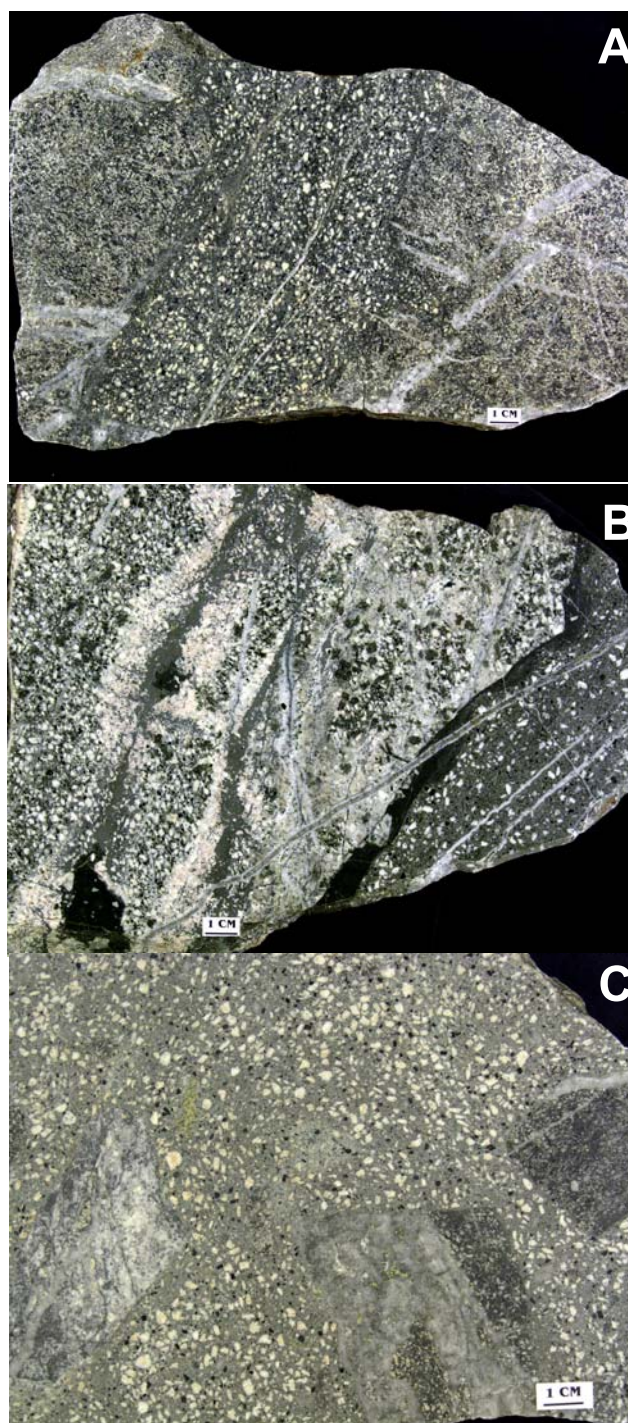
Figure 10. Examples of intermineral dykes and breccias associated with porphyry deposits. A) Intermineral porphyry dyke truncates magnetite- and chalcopyrite-bearing quartz veins in altered porphyry and is, in turn, cut by chalcopyrite-bearing quartz veins. Granisle deposit, Babine district, British Columbia (KQ-70-53B); B) Intermineral porphyry dyke with chilled margin cuts older porphyry with magnetite and quartz-magnetite veins and associated potassic alteration; both the older porphry and the intermineral porphyry are cut by bornite- and chalcopyrite-bearing quartz veins. Granisle deposit, Babine district, British Columbia (KQ-70-57A); C) Intermineral intrusive breccia consisting of matrix porphyry with a partially digested chalcopyrite fragment and highly altered porphyry fragments with chalcopyrite-bearing quartz veins. Granisle deposit, Babine district, British Columbia (KQ-70-55).

ation with small alkaline mafic intrusions emplaced at very shallow depths (Richards and Kerrich, 1993; A. Panteleyev, personal communication, 1994). A close temporal relationship between magmatic activity and hydrothermal mineralization in porphyry deposits is indicated by the presence of intermineral intrusions and breccias that were emplaced between or during periods of mineralization (Kirkham, 1971)(Fig. 10).

Felsic intrusive rocks that are closely associated with some porphyry deposits are characterized by distinct textural features such as comb-quartz layers (Fig. 11) and other undirectional solidification textures (Shannon et al., 1982; Kirkham and Sinclair, 1988). Comb-quartz layers occur in places along the margins and in the upper parts of small intrusions or cupolas. They generally range from less than 1 mm to several cm or more in thickness and are separated by interlayers of fine-grained, aplitic granite. Prismatic quartz crystals in the layers are oriented roughly perpendicular to the planes of layering and appear to have grown on a crystallized aplitic substrate inward toward the center of the intrusion. They are significant because individual layers likely crystallized from pockets of exsolved magmatic-hydrothermal fluid and the development of multiple layers reflects a continuous supply of magmatic fluid from subjacent magma (Lowenstern and Sinclair, 1996).

Magma composition and petrogenesis of related intrusions exert a fundamental control on the metal contents of porphyry deposits. Intrusive rocks associated with porphyry Cu, porphyry Cu-Mo, porphyry Cu-Au and porphyry Au

tend to be low-silica, relatively primitive dioritic to granodioritic plutons, whereas porphyry deposits of Mo, W-Mo, W and Sn typically are associated with high-silica, strongly differentiated granitic plutons. Oxidation state of granitic rocks, reflected by accessory opaque minerals such as magnetite, ilmenite, pyrite and pyrrhotite, also influences metal contents of related deposits (Ishihara, 1981). For example, porphyry deposits of Cu, Cu-Mo, Cu-Au, Au, Mo and W are generally associated with more oxidized, magnetite-series plutons in contrast to porphyry Sn deposits, which are typically related to reduced, ilmenite-series plutons (Fig. 12).
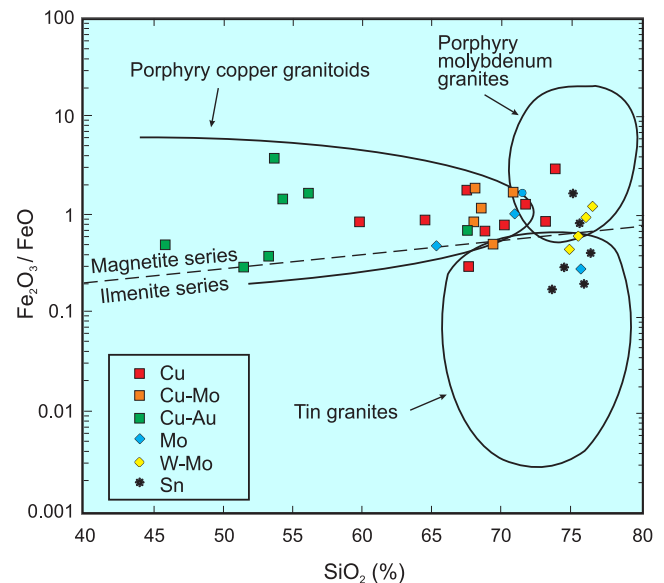

Figure 12. SiO_2-(Fe_2O_3/FeO) variation diagram for granitic rocks related to porphyry deposits of Cu, Cu-Mo, Cu-Au, Mo, W-Mo and Sn (modified from Lehmann, 1990).

Morphology and Architecture

The overall form of individual porphyry deposits is highly varied and includes irregular, oval, solid or "hollow" cylindrical and inverted cup shapes (e.g., Sutherland Brown, 1969; James, 1971; McMillan and Panteleyev, 1980). Orebodies may occur separately or overlap and, in some cases, are stacked one on top of the other (Wallace et al., 1968; White et al., 1981; Carten et al., 1988a). Individual orebodies measure hundreds to thousands of metres in three dimensions. Orebodies are characteristically zoned, with barren cores and crudely concentric metal zones that are surrounded by barren pyritic halos with or without peripheral veins, skarns, replacement manto zones and epithermal precious-metal deposits (e.g., Einaudi, 1982; Sillitoe 1988 a,b; Jones, 1992) (Fig. 13). Complex, irregular ore and alteration patterns are due, in part, to the superposition and spatial separation of mineral and alteration zones of different ages.

Associated Structures and Mineralization Styles

At the scale of ore deposits, associated structures can result in a variety of mineralization styles, including veins, vein sets, stockworks, fractures, 'crackled zones' and breccia pipes (Fig. 14). In large, complex, economic porphyry
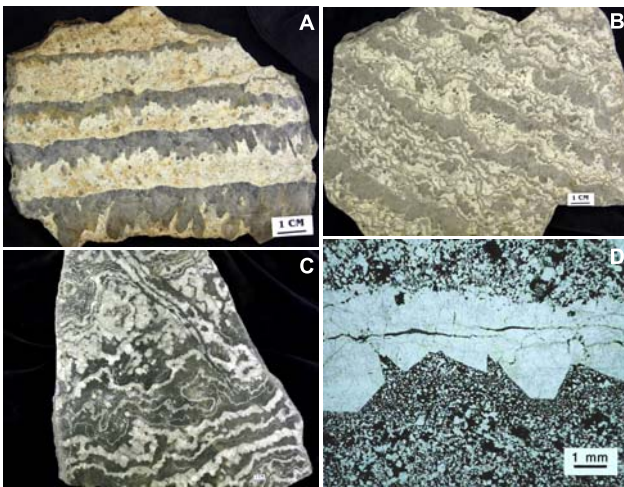

Figure 11. Examples of comb-quartz layers in felsic intrusions assciated with porphyry deposits. A) Comb quartz layers containing molybdenite separated by aplite interlayers; growth direction from top to bottom. Anticlimax deposit, British Columbia (SYA-Anticlimax); B) Multiple thin to thick comb quartz layers separated by aplite interlayers; growth direction of the quartz crystals in the comb layers was from the upper right to the bottom left. Logtung deposit, Yukon Territory (SYA85-15B). C) Multiple thin to thick comb quartz layers, highly contorted in places, and separated by interlayers of chloritized aplite; growth direction of the quartz crystals in the comb layers was from top to bottom. North zone, Mount Pleasant, New Brunswick (SYA86-28); D) Photomicrograph of a comb quartz layer in granite porphyry showing euhedral termination of quartz crystals approximately perpendicular to the layer; the very fine grained texture of the granite adjacent to the crystal faces is thought to have resulted from pressure quenching and consequent rapid cooling related to sudden (catastrophic) release of the fluid phase in which the quartz crystals were growing. North zone, Mount Pleasant, New Brunswick.
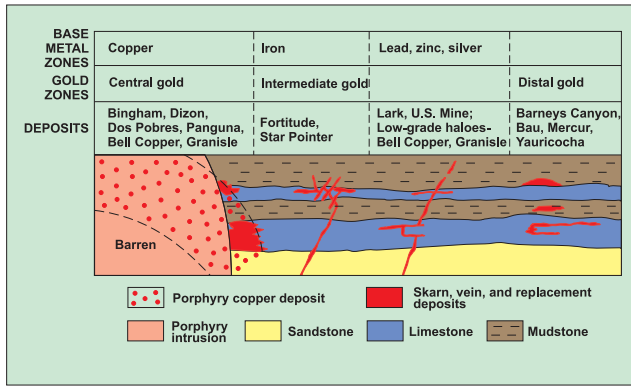
Figure 13. Generalized zoning model for Au-enriched porphyry Cu systems (after Jones, 1992).

deposits, mineralized veins and fractures typically have a very high density. Orientations of mineralized structures can be related to local stress environments around the tops of plutons or can reflect regional stress conditions (Rehrig and Heidrick, 1972; Heidrick and Titley, 1982; Carten et al., 1988a). Where they are superimposed on each other in a large volume of rock, the combination of individual mineralized structures results in higher-grade zones and the characteristic large size of porphyry deposits.

Mineralogy

The mineralogy of porphyry deposits is highly varied, although pyrite is typically the dominant sulphide mineral in porphyry Cu, Cu Mo, Cu Au, Au and Ag deposits, reflecting the fact that large amounts of sulphur were added to the deposits. In porphyry deposits of the more lithophile elements, i.e., Sn, W and Mo, the overall sulphur and sulphide mineral contents are lower. Principal ore and associated minerals of the different porphyry deposit subtypes are as follows:

Porphyry Cu, Cu-Mo and Cu-Mo-Au deposits: Principal ore minerals are chalcopyrite, bornite, chalcocite, tennantite, enargite, other Cu sulphides and sulphosalts, molybdenite and electrum; associated minerals include pyrite, magnetite, quartz, biotite, K-feldspar, anhydrite, muscovite, clay minerals, epidote and chlorite.

Porphyry Cu-Au deposits: Principal ore minerals are chalcopyrite, bornite, chalcocite, tennantite, other Cu minerals, native Au, electrum and tellurides; associated minerals include pyrite, arsenopyrite, magnetite, quartz, biotite, K-feldspar, anhydrite, epidote, chlorite, scapolite, albite, calcite, fluorite and garnet.

Porphyry Au deposits: Principal ore minerals are native Au, electrum, chalcopyrite, bornite and molybdenite; associated minerals include pyrite, magnetite, quartz, biotite, K-feldspar, muscovite, clay minerals, epidote and chlorite.

Porphyry Mo deposits: Principal ore minerals are molybdenite, scheelite, wolframite, cassiterite, bismuthinite and native bismuth; associated minerals include magnetite, quartz, K-feldspar, biotite, muscovite, clay minerals, fluorite and topaz.

Porphyry W-Mo deposits: Principal ore minerals are scheelite, wolframite, molybdenite, cassiterite, stannite, bis-

muthinite and native bismuth; other minerals include pyrite, arsenopyrite, loellingite, quartz, K-feldspar, biotite, muscovite, clay minerals, fluorite and topaz.

Porphyry Sn and Sn-Ag deposits: Principal ore minerals are cassiterite, tetrahedrite, argentite, stannite, wolframite, chalcopyrite, sphalerite, franckeite, cylindrite, teallite, molybdenite, bismuthinite, other sulphides and sulphosalts, native Ag and native Bi; associated minerals include pyrite, arsenopyrite, loellingite, quartz, K-feldspar, biotite, muscovite, clay minerals, fluorite and topaz.

Porphyry Ag deposits: Principal ore minerals are freibergite, stephanite, acanthite, sphalerite and galena; associated minerals include arsenopyrite, pyrrhotite, pyrite, adularia, quartz, fluorite and calcite.

Alteration

Hydrothermal alteration is extensive and typically zoned both on a deposit scale and around individual veins and fractures (Fig. 15). In many porphyry deposits, alteration zones on a deposit scale consist of an inner potassic zone characterized by biotite and/or K-feldspar ($\pm$ amphibole $\pm$ magnetite $\pm$ anhydrite) and an outer zone of propylitic alteration that consists of quartz, chlorite, epidote, calcite and,
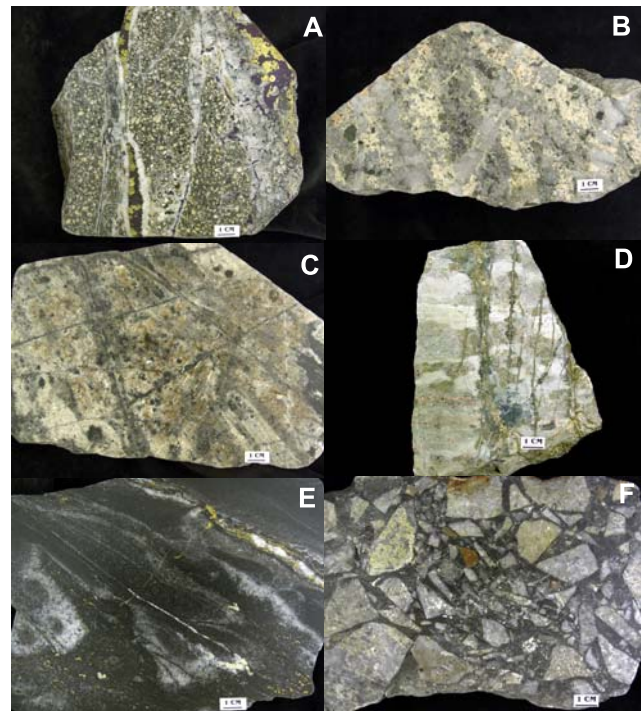

Figure 14. Examples of different mineralization styles associated with porphyry deposits. A) Chalcopyrite- and bornite-rich quartz-apatite veins and veinlets cutting biotite-feldspar porphyry. High-grade ore, Granisle deposit, Babine district, British Columbia (KQ-70-48); B) Bornite- and chalcopyrite-bearing quartz veins cutting highly sericitized Bethsaida granodiorite. Valley deposit, Highland Valley district, British Columbia (KQ-82-49); C) Stockwork of wolframite-bearing fractures and quartz veinlets in altered breccia. Fire Tower zone, Mount Pleasant, New Brunswick (SYA81-26B); D) Quartz-pyrite-chalcopyrite veinlets cutting fine-grained diopside-garnet skarn. Typical veinlet stockwork ore, Copper Mountain deposit, Mines Gaspé, Quebec (KQ-70-386); E) Pyrite and chalcopyrite disseminated, along fractures, and in deformed quartz vein in foliated breccia consisting of felsic fragments in biotite-rich matrix. Troilus deposit, Quebec (SYA91-1B); F) Breccia consisting of fragments of silicified granite in a dark matrix of sphalerite and cassiterite. Fire Tower zone, Mount Pleasant, New Brunswick (SYA95-32A).
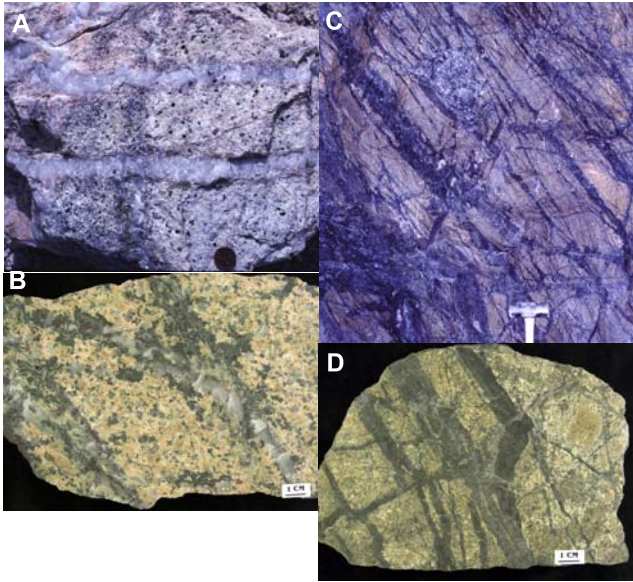
Figure 15. Examples of different types of alteration associated with porphyry deposits. A) Potassic (K-feldspar) alteration around chalcopyrite- and bornite-bearing quartz veins. Valley deposit, Highland Valley district, British Columbia; B) Bornite-bearing quartz veins cutting Bethsaida granodiorite that is pervasively and potassically altered to K-feldspar. Valley deposit, Highland Valley district, British Columbia (KQ-82-50B); C) Fine-grained granite cut by wolframite- and molybdenite-bearing fracture stockwork with biotitic alteration selvages; D) Quartz-pyrite-chalcopyrite vein stockworks in feldspar porphyry heavily overprinted by sericitic (phyllic) alteration. Bell deposit, Babine district, British Columbia (KQ-82-71).

locally, albite associated with pyrite. Zones of phyllic alteration (quartz + sericite + pyrite) and argillic alteration (quartz + illite + pyrite ± kaolinite ± smectite ± montmorillonite ± calcite) may be part of the zonal pattern between the potassic and propylitic zones, or can be irregular or tabular, younger zones superimposed on older alteration and sulphide assemblages (e.g., Ladolam; Moyle et al., 1990). The spatial and temporal relationships between different types of alteration are shown schematically in Figure 16.

Economic sulphide zones are most closely associated with potassic alteration, as demonstrated by Carson and Jambor (1974) for several porphyry Cu and Cu Mo deposits. Sodic alteration (mainly as secondary albite) is associated with potassic alteration in some porphyry Cu-Au deposits, such as Copper Mountain and Ajax, British Columbia (Preto, 1972; Barr et al., 1976; Ross et al., 1995). Albitic alteration partly overlaps potassic alteration and Cu on the north side of the Ingerbelle deposit at Copper Mountain; at the Ajax deposit, highest Cu grades occur near, but not in, the most intensely altered albitic rocks. Eaton and Setterfield (1993) indicated that the subeconomic Nasivi 3 porphyry Cu deposit in the centre of the shoshonitic Tavua caldera, adjacent to the epithermal Emperor Au mine in Fiji, contains an albitic, Cu bearing core surrounded by peripheral propylitic alteration and overprinted by younger phyllic alteration. Sodic-calcic alteration (oligoclase + quartz + sphene + apatite ± actinolite ± epidote) has been documented in the deep root zones beneath potassically-altered porphyry Cu deposits at Yerington and Ann-Mason, Nevada (Carten, 1986; Dilles and Einaudi, 1992).

Alteration mineralogy is controlled in part by the com-

position of the host rocks. In mafic host rocks with significant iron and magnesium, biotite (± minor hornblende) is the dominant alteration mineral in the potassic alteration zone, whereas K-feldspar dominates in more felsic rocks. In carbonate-bearing host rocks, calc-silicate minerals such as garnet and diopside are abundant.

Alteration mineralogy is also controlled by the composition of the mineralizing system. In more oxidized environments, minerals such as pyrite, magnetite (± hematite) and anhydrite are common, whereas pyrrhotite is present in more reduced environments. Fluorine-rich systems, such as those related to many porphyry Sn and W Mo deposits, and some porphyry Mo deposits, commonly contain fluorine-bearing minerals as part of the alteration assemblages. At Mount Pleasant, for example, potassic alteration is rare and the principal alteration associated with the W-Mo deposit consists of quartz, topaz, fluorite and sericite, and the surrounding propylitic alteration consists of chlorite + sericite (Kooiman et al., 1986). Similarly, alteration in some low grade Sn deposits in Australia (e.g., Ardlethan) grades out from a central zone of quartz + topaz to zones of sericite and chlorite ± carbonate (Scott, 1981). Siems (1989) suggested that lithium silicate alteration (e.g., lithium-rich mica and tourmaline), which accompanies Sn, W and Mo in some granite-related deposits, is analogous to potassic alteration in porphyry Cu and Mo deposits.

Phyllic alteration zones are not present in all porphyry deposits. In many deposits in which they are present, however, phyllic alteration is superimposed on earlier potassic alteration assemblages (Carson and Jambor, 1979). At Chuquicamata in Chile, for example, a zone of intense phyllic alteration extends to depth in the core of the deposit and is superimposed on earlier potassic alteration and small amounts of associated Cu sulphides with low Cu grades. This phyllic zone contains higher than average Cu grades and associated arsenic-bearing Cu minerals and molybdenite.

Advanced argillic (high sulphidation) and adularia-type (low sulphidation) epithermal alteration zones with associat-
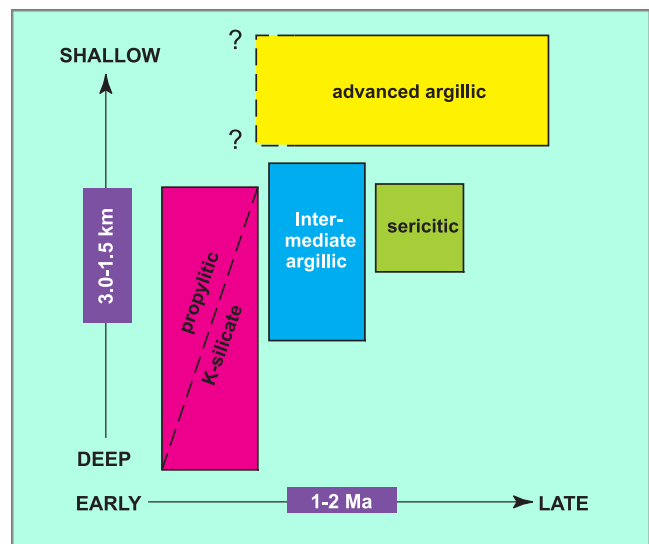

Figure 16. Schematic time-depth relations of principal alteration types in Au-rich porphyry Cu systems and other types of porphyry deposits (after Sillitoe, 1993b).

ed precious-metal deposits occur above or near several porphyry Cu and Cu-Mo deposits. These alteration zones, in places, show a marked telescoping of older potassic and younger epithermal alteration (Fig. 13, 16; Sillitoe, 1990; 1993a,b; Moyle et al., 1990; Vila and Sillitoe, 1991; Setterfield et al., 1991; Eaton and Setterfield, 1993; Richards and Kerrich, 1993). The advanced argillic assemblages include illite, quartz, alunite, natroalunite, pyrophyllite, diaspore and a high pyrite content. Adularia assemblages, with quartz, sericite and clay minerals, have lower pyrite contents. Sillitoe (1993a) suggested that advanced argillic or high-sulphidation-type epithermal systems can occur in spatial association with porphyry Cu, Cu-Mo, Cu-Au and Au deposits, but not with porphyry Mo deposits. Adularia- or low-sulphidation-type epithermal systems probably form from more dilute ore fluids and may or may not occur on the peripheries of porphyry systems. Furthermore, Sillitoe (1993a) suggested that base-metal-rich epithermal deposits form from more concentrated NaCl brines and, similar to porphyry deposits, are parts of magmatic-hydrothermal systems.

Genetic and Exploration Models

A generalized empirical model for porphyry deposits is illustrated schematically in Figure 17, which shows a porphyry Cu deposit associated with a small subvolcanic porphyritic intrusion and surrounded by a more extensive pyritic zone. The larger scale of the hydrothermal system is reflected by related, peripheral types of deposits, including skarn Cu, replacement (manto) Zn, Pb, Ag, Au and various types of base- and precious-metal veins and breccia-hosted deposits.

The most applicable genetic model for porphyry deposits is a magmatic-hydrothermal one, or variations thereupon, in which the ore metals were derived from temporally and genetically related intrusions (Fig. 17). Large polyphase hydrothermal systems developed within and above genetically-related intrusions and commonly interacted with meteoric fluids (and possibly seawater) on their tops and peripheries. During the waning stages of hydrothermal activity, the magmatic-hydrothermal systems collapsed inward upon themselves and were replaced by waters of dominantly meteoric origin. Redistribution, and possibly further concentration of metals, occurred in some deposits during these waning stages.

Variations of the magmatic-hydrothermal model for porphyry deposits, commonly referred to as the "orthomagmatic" model, have been presented by such authors as Burnham (1967, 1979), Phillips (1973) and Whitney (1975, 1984). These authors envisaged that felsic and intermediate magmas were emplaced at high levels in the crust and underwent border zone crystallization along the walls and roof of the magma chamber. As a consequence of this crystallization, supersaturation of volatile phases occurred within the magma, resulting in separation of volatiles due to resurgent, or second, boiling. Ore metals and many other components were strongly partitioned into these volatile phases, which became concentrated in the carapace of the magma chamber (Christiansen et al., 1983; Candela and Holland, 1986; Manning and Pichavant, 1988; Candela, 1989; Cline and
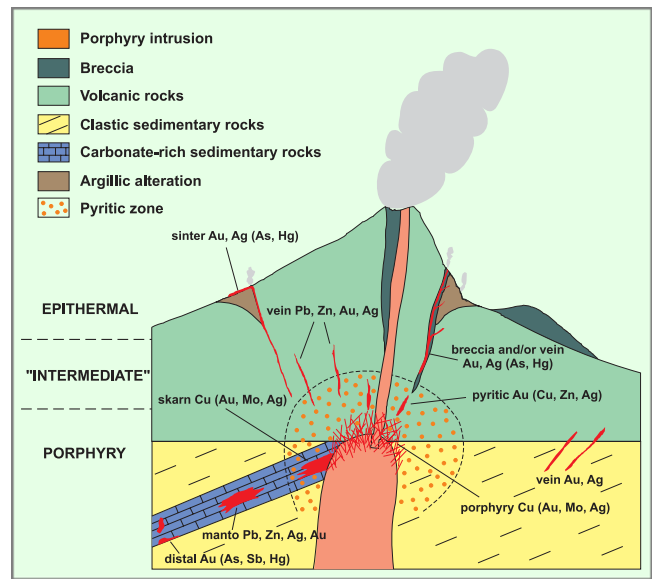

Figure 17. Schematic diagram of a porphyry Cu system in the root zone of an andesitic stratovolcano showing mineral zonation and possible relationship to skarn, manto, "mesothermal" or "intermediate" precious-metal and base-metal vein and replacement, and epithermal precious-metal deposits.

Bodnar, 1992; Heinrich et al., 1992). When increasing fluid pressures exceeded lithostatic pressures and the tensile strength of the overlying rocks, fracturing of these rocks occurred, permitting rapid escape of hydrothermal fluids into newly-created open space. A fundamental control on ore deposition was the pronounced adiabatic cooling of the ore fluids due to their sudden expansion into the fracture and/or breccia systems, thus the importance of structural control on ore deposition in porphyry deposits. Aplitic and micrographic textures in granitic rocks associated with porphyry deposits are the result of pressure-quench crystallization related to the rapid escape of the ore fluids (Shannon et al., 1982; Kirkham and Sinclair, 1988).

Modification of the above orthomagmatic model is required for at least some, if not most, porphyry deposits, in view of studies by Shannon et al. (1982), Carten et al. (1988a) Kirkham and Sinclair (1988) and Shinohara et al. (1995). These authors concluded that, in many porphyry deposits, the underlying genetically-related intrusions were largely liquid in their carapaces until ore formation was essentially complete. Kirkham and Sinclair (1988) suggested that crystallization deep within a batholithic magma chamber could have been the cause of resurgent boiling, rather than local border zone crystallization as envisaged by Burnham (1967, 1979), Whitney (1975, 1984) and Carten et al. (1988b). According to this model, volatiles streamed through large volumes of magma, stripping it of its metal content, and accumulated in small cupolas at the top of the magma chambers (Fig. 18). These volatile-rich, ore-forming fluids would have lowered the liquidus temperature of the magma in the cupolas, keeping them largely liquid during the ore-forming process. Areas where these ore-forming fluids accumulated in cupolas of siliceous intrusions associated with some porphyry Mo, Cu-Mo and W-Mo deposits are indicated by abundant comb quartz layers (Shannon et al., 1982; Carten et al., 1988a; Kirkham and Sinclair, 1988).

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Such a model is consistent with the sequence of erupted products from large-volume ash-flow tuff eruptions - that is, early high-silica eruptive products with few crystals followed by more mafic eruptive products rich in crystals (Hildreth, 1979, 1981; Smith, 1979; Keith et al., 1986; Keith and Shanks, 1988). Similarities in chemical characteristics of siliceous intrusions associated with the Quartz Hill porphyry Mo deposit in Alaska and the Bishop Tuff in California (Hudson et al., 1981) indicate that the magmas responsible for the Quartz Hill deposit could have been similar to those that produced the Bishop Tuff.
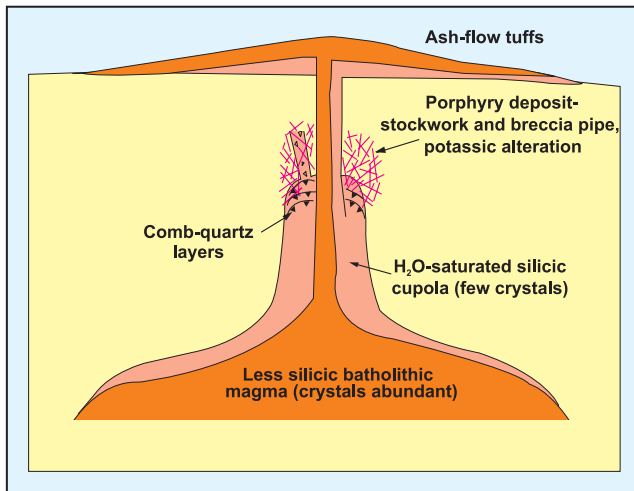

Figure 18. Schematic diagram of a crystallizing batholithic mass with an overlying volatile-saturated cupola and related ash-flow tuffs illustrating the environment of formation of porphyry deposits (modified from Kirkham and Sinclair, 1988).

Another possible modification to the orthomagmatic model involves mixing of mafic magmas with the felsic to intermediate, ore-related calc-alkaline magmas prior to the onset of mineralization. Carten et al. (1993) suggested that, for high-grade porphyry Mo deposits, volatiles (F, Cl, S, CO_2) released from underlying saturated mafic magmas were responsible for stripping metals from the overlying felsic magmas. Maughan et al. (2002) concluded that ore-related porphyries at Bingham, Utah mixed with mafic alkaline magmas prior to mineralization and that the mafic magmas may have contributed more than half of the S and significant amounts of the Cu, Au and PGE in the Bingham deposit.

Wallrocks of the intrusions and deposits are not considered to be viable sources for the metals in porphyry deposits. Perhaps the most convincing argument against a wallrock source for metals is the strong, universal petrogenetic and temporal association of deposits of specific metals with intrusions of specific compositions and petrogenesis. With the exception of some Au deposits, such as Porgera in Papua New Guinea, no known significant porphyry-type deposits are related to gabbros or more mafic rocks, suggesting that heat engine models for genesis of porphyry deposits have little or no relevance. Furthermore, the metal content of most porphyry deposits is related to one or more specific phase(s) of intrusion, as at Henderson, Colorado, where two of the eleven identified phases, the Seriate and the Henderson stocks, together provided an estimated 62% of the Mo in the deposit (Carten et al., 1988a). At Bingham, Utah the early Last Chance augite monzonite intrusion has no known significant associated mineralization, although it was emplaced at a time when a scavenging heat engine should have been most effective; on the other hand, the subsequent quartz monzonite phases of the Bingham stock and the related small, but not insignificant, latite porphyry phases (Wilson, 1978) have huge amounts of associated metals. Another example is the Battle Mountain district in Nevada where, at essentially the same place in the earth's crust at different times, a porphyry Mo deposit, and a porphyry Cu deposit with related Au-rich skarn zones, were formed (Kirkham, 1985; Theodore et al., 1982, 1992). Such evidence indicates strongly that input of metal-rich magmatic-hydrothermal fluids was essential for the formation of these deposits.

Key Exploration Criteria

Several features of porphyry deposits conducive to exploration are related to their large size. Metal, mineral and alteration patterns tend to be large, concentric and zoned, thus yielding useful clues to areas with exploration potential. Large pyritic halos, for example, may be used to delineate the extent of the deposits, and also the intensity and complexity of the hydrothermal system.

On a regional scale, the presence of epizonal to mesozonal felsic to intermediate porphyritic intrusions, especially if accompanied by large pyritic alteration zones, indicate that the area could be prospective for porphyry deposits. Porphyry Cu and Cu-Mo deposits are relatively abundant in island- and continental-arc volcanic terranes; porphyry Mo deposits are relatively abundant in subaerial areas of crustal extension with bimodal mafic and felsic magmatism. The tectonic settings of other subtypes of porphyry deposits are less well understood.

Porphyry deposits tend to have large geochemical dispersion halos and reconnaissance stream sediment and soil geochemical surveys have been effective exploration tools in many parts of the world. Careful study and interpretation of leached cappings have also been used to differentiate between barren and mineralized deposits, some with major supergene enriched ores (Blanchard, 1968; Anderson, 1982).

Induced polarization surveys have been useful in outlining sulphide distribution in porphyry deposits, and magnetic surveys have been used to outline porphyry Cu and Cu-Au deposits with abundant hydrothermal magnetite, and pyrrhotite- and/or magnetite-bearing hornfels zones around porphyry-related intrusive rocks. Conversely, some deposits are characterized by magnetic lows due to the destruction of magnetite in phyllic alteration zones. Gamma ray spectrometry surveys have been used to outline potassic alteration zones closely related to mineralized zones in the Mount Milligan deposit in central British Columbia and the Casino deposit in west-central Yukon Territory (Shives et al., 2000).

Knowledge Gaps

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, significant knowledge gaps remain and may be summarized as follows:

• What are the sources of metals in porphyry deposits? Ore-related magmas can be generated in various ways, ranging from mantle melting to melting and/or assimilation of crustal rocks. Do the source regions need to be enriched in specific metals, or are magmatic processes such as fractionation more important than the primary metal content of magmas? Can ore components be added during magma ascent through the crust?

• What is the role of tectonic setting? The view that porphyry Cu (±Mo±Au) deposits form in subduction-related island arcs associated with converging plates is overly simplistic (Richards, 2003). What are the effects of changes or variations in tectonic setting such as arc reversals or low angle subduction of aseismic ridges or seamount chains? Why are some magmatic arcs more productive than others?

• What controls metal ratios in porphyry deposits? Although there is a general relationship between magma composition and metal ratios, other factors are likely involved. For example, Au-rich porphyry Cu deposits commonly are associated with more primitive magmas in island arc settings, whereas porphyry Au deposits in the northern Cordillera occur in a continental arc setting and have an affiliation toward porphyry W-Mo rather than porphyry Cu systems (McMillan et al., 1995).

• What controls fluid separation from magmas? Porphyry mineralization is typically episodic and related to one or more intrusions in a complex of multiple intrusions. What are the dynamics of fluid (volatile) degassing of magmas and how is it triggered?

• What controls fluid composition? How are metals scavenged from magmas and concentrated in hydrothermal ore-bearing fluids?

• What is the relationship between porphyry deposits and other types of intrusion-related hydrothermal deposits, such as epithermal deposits? Is there a geochemical transition between them?

• What are the critical factors for the formation of giant porphyry deposits?

Areas of High Potential in Canada

Many parts of the Canadian Cordillera are favourable for various types of porphyry deposits, although exploration is currently focused primarily on deposits with gold potential. Areas with some of the highest potential for porphyry Cu-Au deposits are those underlain by Late Triassic to Early Jurassic alkaline intrusions, which occur mainly in the Quesnel and Stikine terranes. Some of the more favourable areas include the Afton and Cariboo districts, the Mt. Milligan area and the Galore Creek area. In the Toodoggone region, calc-alkaline intrusions of Late Triassic to Early Jurassic age are associated with the Kemess North and South porphyry Cu-Au deposits and potential for additional deposits is high. Eocene calc-alkaline intrusions in the Babine district, Stikine terrane, have high potential for porphyry Cu-Au deposits and Late Cretaceous to Eocene calc-alkaline intrusions in the Tatsa Ranges, Stikine Terrane are favourable for porphyry Cu-Mo deposits. Mid-Cretaceous calc-alkaline intrusions of the Mayo plutonic suite in the North American terrane have potential for porphyry Au deposits.

Although exploration for porphyry deposits in Precambrian terranes has been limited, large, low-grade, porphyry-type deposits of Cu, Au and Mo associated with Archean and Proterozoic intrusions have been recognized and the potential for porphyry deposits in Precambrian terranes is likely underappreciated. Numerous porphyry-type deposits occur in the Abitibi and Opatica greenstone belts, including one that is currently in production (Troilus), and these areas have high potential. Areas where felsic to intermediate, subvolcanic plutons have intruded shallow marine or subaerial volcanic and sedimentary rocks should be the most favourable areas for exploration.

Acknowledgements

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