

PORPHYRY DEPOSITS

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Abstract

Porphyry deposits are the world's most important source of Cu and Mo, and are major sources of Au, Ag, and Sn; significant byproduct metals include Re, W, In, Pt, Pd, and Se. They account for about 50 to 60% of world Cu production and more than 95% of world Mo production. In Canada, they account for more than 40% of Cu production, virtually all Mo production, and about 10% of Au production. 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. They are distinguished from other granite-related deposits such as skarns and mantos by their large size and structural control, mainly stockworks, veins, vein sets, fractures, and breccias. Porphyry deposits 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 1%. In porphyry Cu deposits, for example, Cu grades range from 0.2% to more than 1% Cu; in porphyry Mo deposits, Mo grades range from 0.07% to nearly 0.3% Mo. In porphyry Au and Cu-Au deposits, Au grades range from 0.2 to 2 g/t Au. Associated igneous rocks vary in composition from diorite-granodiorite to high-silica granite; they are typically porphyritic epizonal and mesozonal intrusions, commonly subvolcanic. A close temporal and genetic relationship between magmatic activity and hydrothermal mineralization in porphyry deposits is indicated by the presence of inter-mineral intrusions and breccias that were emplaced between or during periods of mineralization. Porphyry deposits range in age from Archean to Recent, although most economic deposits are Jurassic or younger.

Résumé

Les gîtes porphyriques constituent, à l'échelle mondiale, la plus importante source de cuivre et de molybdène, une grande source d'or, d'argent et d'étain, de même qu'une source considérable de métaux récupérés comme sous-produits, dont le rhénium, le tungstène, l'indium, le platine, le palladium et le sélénium. En outre, ils comptent pour 50 à 60 % environ de la production mondiale de cuivre et pour plus de 95 % de celle de molybdène. Au Canada, ces proportions atteignent plus de 40 %, dans le cas du cuivre, presque 100 %, dans celui du molybdène et quelque 10 %, dans celui de l'or. Les gisements porphyriques consistent en vastes accumulations de minerai à teneur faible ou moyenne où la répartition des minéraux métalliques primaires (hypogènes) est régie principalement par des contrôles structuraux et liée, tant sur le plan spatial que génétique, à des intrusions porphyriques de composition felsique à intermédiaire. Ils se distinguent des autres gisements apparentés à des granites, comme les skarns et les mantos, par leur grande taille et leurs contrôles structuraux, la minéralisation se présentant surtout dans des stockwerks, des filons, des réseaux de filons, des fractures et des brèches. Ils renferment généralement des centaines de millions de tonnes de minerai, quoique leur volume peut varier de quelques dizaines de millions de tonnes à des milliards de tonnes. Leurs teneurs en métaux varient considérablement mais se situent habituellement en moyenne à moins de 1 %. Par exemple, la teneur en Cu des gisements porphyriques de cuivre va de 0,2 % à plus de 1 %, celle en Mo des gisements porphyriques de molybdène, de 0,07 % à presque 0,3 % et celle en Au des gisements porphyriques d'or et de cuivre-or, de 0,2 à 2 g/t. Les roches ignées qui leur sont associées montrent une composition variant de la diorite-granodiorite au granite fortement siliceux et se présentent en général sous forme d'intrusions à texture porphyrique épizonales et mésozonales, habituellement subvolcaniques. Dans les gîtes porphyriques, la présence de brèches et d'intrusions mises en place entre les zones minéralisées pendant ou entre les périodes de minéralisation témoigne d'un étroit lien temporel et génétique entre le magmatisme et la minéralisation hydrothermale. L'âge des gîtes porphyriques s'étend de l'Archeen à l'Holocène, quoique la plupart des gisements rentables datent du Jurassique ou d'une époque plus récente.

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 breccias) serve to distinguish porphyry deposits from a variety of deposits that may be peripherally associated, including skarns, high-temperature mantos, 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 metal content of porphyry deposits is diverse. The following subtypes of porphyry deposits were defined by Kirkham and Sinclair (1995) 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 (\pm Au, Mo, Ag, Re, PGE)
- Cu-Mo (\pm Au, Ag)
- Cu-Mo-Au (\pm Ag)
- Cu-Au (\pm Ag, PGE)
- Au (\pm Ag, Cu, Mo)
- Mo (\pm W, Sn)
- W-Mo (\pm Bi, Sn)
- Sn (\pm W, Mo, Ag, Bi, Cu, Zn, In)
- Sn-Ag (\pm W, Cu, Zn, Mo, Bi)
- Ag (\pm Au, Zn, Pb)

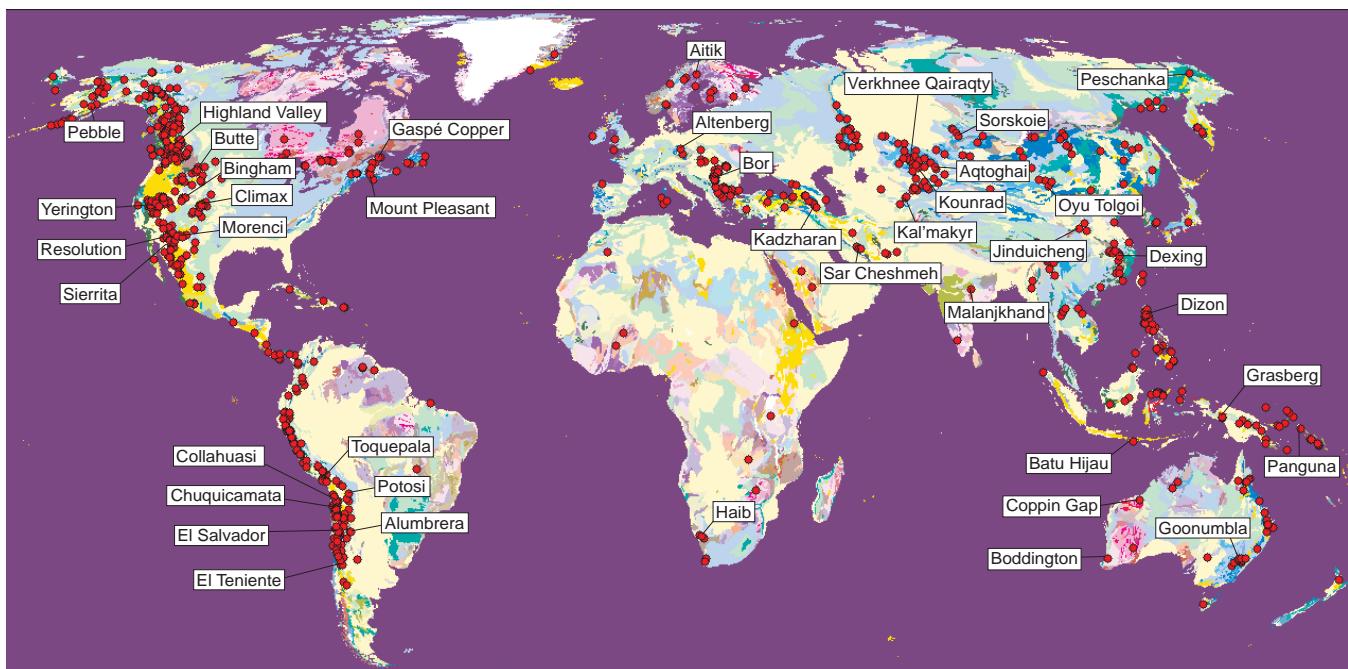


FIGURE 1. Global distribution of porphyry deposits (from Kirkham and Dunne, 2000). World geology is from Chorlton (2004). See Appendix 2 (World) for deposit details.

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, around the western margin of the Pacific Basin, and in the Tethyan orogenic belt in eastern Europe and southern Asia. 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 porphyry deposits in Canada is shown in Figure 2.

Importance

Porphyry deposits are the world's most important source of Cu and Mo; they account for about 60 to 70% of world Cu production and more than 95% of world Mo production. Porphyry deposits are also major sources of Au, Ag, and Sn; significant byproduct metals include Re, W, In, Pt, Pd, and Se.

Historical production of Cu and Au from porphyry deposits in Canada relative to total Canadian production is shown in Figure 3. Canadian production of Cu from porphyry deposits began in the 1920s with the exploitation of high-grade ores in the Copper Mountain district, British Columbia, although the first significant large-scale production from a recognized porphyry deposit did not begin until 1955, from the Copper Mountain deposit at Mines Gaspé, Quebec. Copper production from porphyry deposits increased rapidly in the 1960s and early 1970s with the development of deposits in British Columbia such as

Bethlehem and Lornex in the Highland Valley district, Granisle and Bell Copper in the Babine district, Ingerbelle in the Copper Mountain district, Brenda, Island Copper, and Gibraltar. In 2000, production of Cu from Canadian porphyry deposits amounted to 267,000 t, or about 2% of total world Cu production and approximately 43% of total Canadian Cu production; the major part of Canadian Cu production was from magmatic Cu-Ni deposits at Sudbury and from numerous volcanogenic massive sulphide (VMS) deposits scattered across the country. About 60% of Canadian Cu reserves are in porphyry deposits, largely in the Cordillera, but they include a considerable amount of low-grade Cu resources that are currently subeconomic.

Since 1970, porphyry deposits have become increasingly important sources of Au in Canada (Fig. 3B). In 2000, porphyry Cu-Au deposits (e.g. Kemess and Mount Polley) and porphyry Au deposits (e.g. Troilus) collectively produced about 15 t Au, representing nearly 10% of total Canadian Au production.

Canadian Mo production in 2000 was entirely from porphyry deposits and totalled 6980 t, of which the Endako porphyry Mo deposit produced about 71%, the Highland Valley porphyry Cu deposit 20%, and the Huckleberry porphyry Cu-Mo deposit the remaining 9%.

At present (2006), no porphyry W-Mo or Sn deposits are in production in Canada. From 1983 to 1985, approximately 1120 t W were produced from the porphyry W-Mo deposit at Mount Pleasant in New Brunswick, and significant W resources remain at Mount Pleasant and in the Logtung W-Mo porphyry deposit in Yukon Territory. To date, most Canadian W production has come from smaller, but higher grade, skarn W deposits such as Cantung, Northwest Territories, which has produced more than 50,000 t W. From 1985 to 1992, more than 21,000 t Sn were produced from the granite-related, porphyry-type Sn deposit at East Kemptville,

Porphyry Deposits

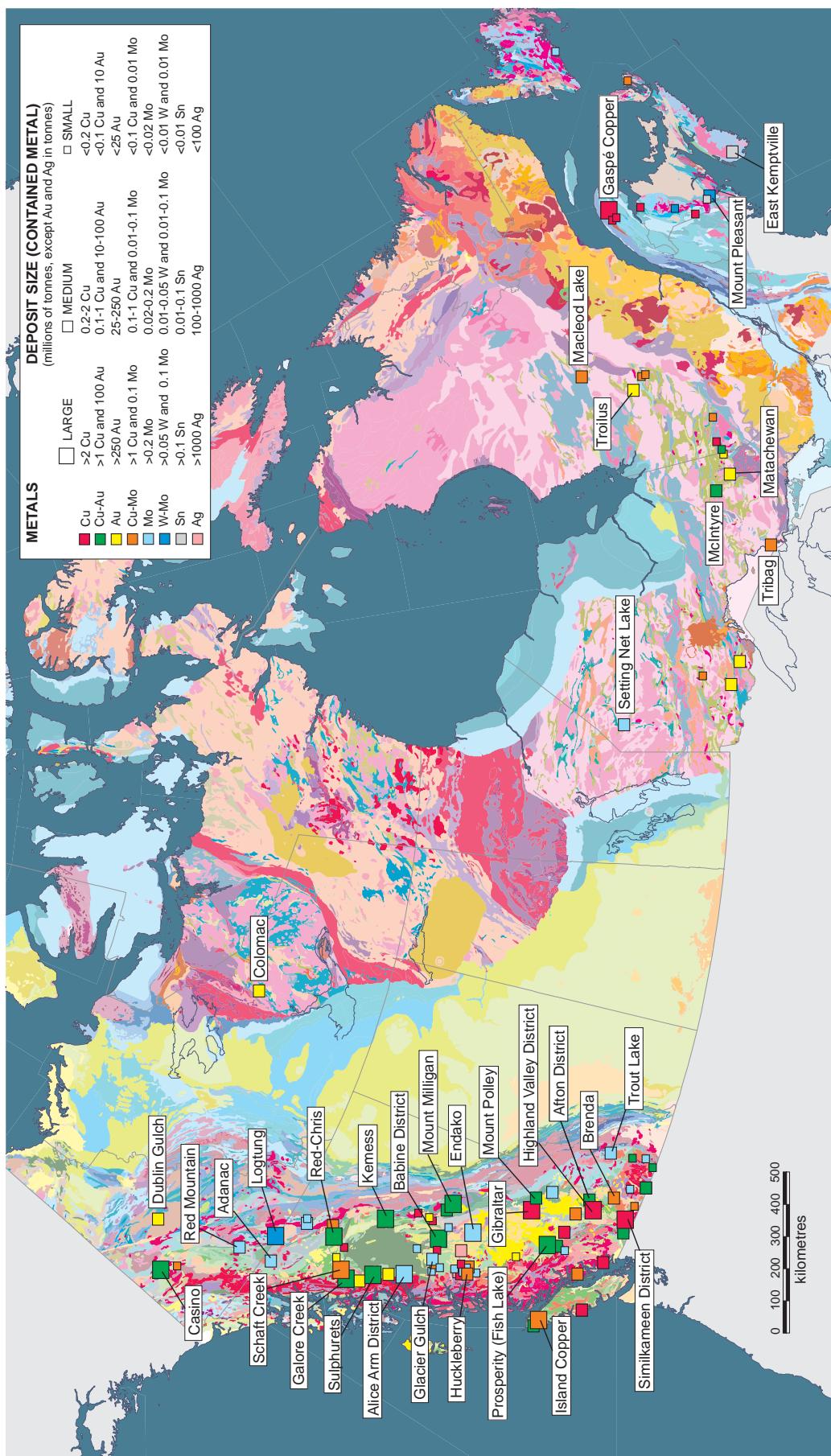


FIGURE 2. Distribution of selected porphyry deposits in Canada (Kirkham and Dunne, 2000). Canadian geology is from Wheeler et al. (1996). See Appendix 1 (Canada) for deposit details.

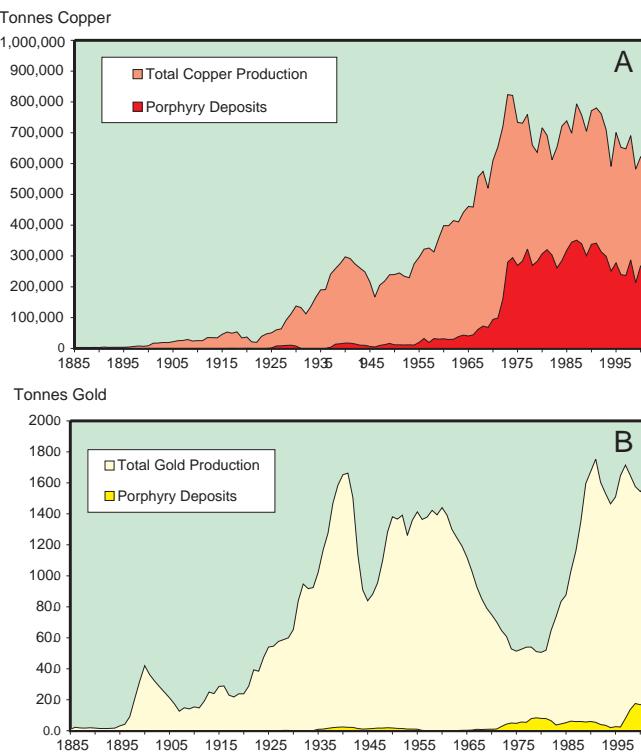


FIGURE 3. Canadian production of copper (A) and gold (B) between 1885 and 2000. Data are from Natural Resources Canada and Statistics Canada.

Nova Scotia. Prior to production from East Kemptville, the only significant production of Sn was from the Sullivan sedimentary exhalative (SEDEX) Pb-Zn-Ag deposit, which produced about 10,000 t Sn from 1941 to 1985 (BC MINFILE: <http://www.em.gov.bc.ca/Mining/Geolsurv/Minfile>).

Minor metals present in significant amounts in some Canadian porphyry deposits include Re, In, and PGE. During its operations from 1971 to 1995, the Island Copper porphyry Cu-Mo deposit produced about 28 t Re (Perelló et al., 1995). The Mount Pleasant porphyry Sn-polymetallic deposits contain more than 600 t In (Sinclair et al., 2006). Some porphyry Cu-Au deposits contain significant amounts of PGE; the Afton deposit, for example, has a measured and indicated resource of 68.7 Mt grading 1.1% Cu, 0.9 g/t Au, 2.6 g/t Ag, and 0.1 g/t Pd (Bradbrook, 2006).

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 1% (Appendix 1 (Canada) and Appendix 2 (World)).

In **porphyry Cu** deposits, Cu grades range from 0.2% to more than 1% (Fig. 4); Mo content ranges from approximately 0.005 to about 0.03% (Fig. 5); and Au contents range from 0.004 to 0.35 g/t (Fig. 6). 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 that contained as much as 1200 ppm Re (unpublished data). Some Au-rich porphyry Cu deposits have relatively high contents of Pt-group elements (PGE) (Mutschler and Mooney, 1993; Tarkian and Stribrny, 1999).

Cu grades in **porphyry Cu-Au** deposits are comparable to those of the porphyry Cu subtype (Fig. 4), but Au contents tend to be consistently higher (0.2-2.0 g/t, Fig. 6). Sillitoe (1993b) suggested that porphyry Cu deposits should contain >0.4 g/t Au to be called Au-rich. However, Au is an important coproduct at grades as low as 0.2 g/t Au (Fig. 7). Kirkham and Sinclair (1995) suggested that a 1:1 ratio (i.e. 1 g/t Au to 1% Cu) could be useful in defining Au-rich porphyry Cu deposits, particularly at higher copper grades; Kesler et al. (2002) suggested a slightly lower ratio of about 0.8:1 should be the division between Au-rich and Au-poor deposits. Although the number of deposits in this class is limited, deposits such as Grasberg in Indonesia, with a resource greater than 2.5 billion tonnes grading 1.1% Cu and 1.04 g/t Au (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 contained a geological resource of about 179 Mt grading 0.23% Cu and 0.67 g/t Au prior to mining (Appendix 1 (Canada)). **Porphyry Au** deposits contain 0.8 to 2.0 g/t Au in deposits that range in size from about 30 to greater than 200 Mt of ore

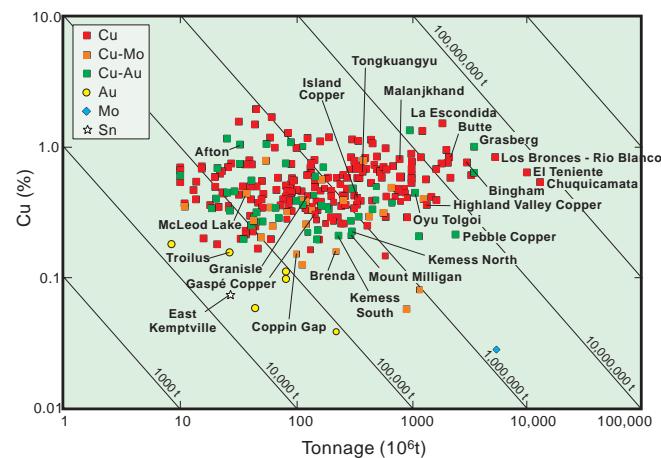


FIGURE 4. Cu grades versus tonnage for Canadian and foreign porphyry deposits (modified from Kirkham and Sinclair, 1995). Diagonal lines indicate tonnes of contained Cu.

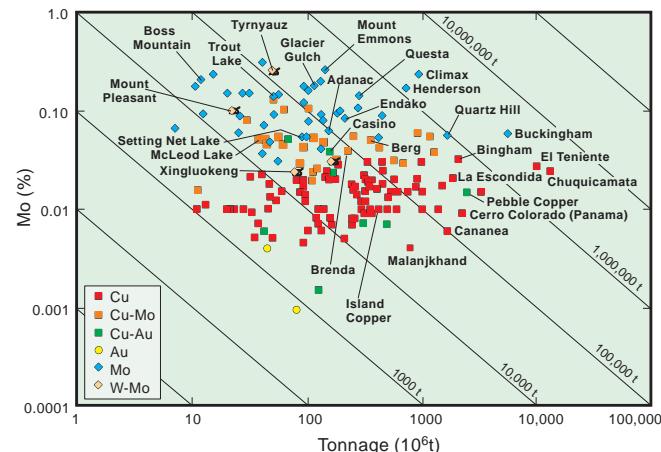


FIGURE 5. Mo grades versus tonnage for Canadian and foreign porphyry deposits (modified from Kirkham and Sinclair, 1995). Diagonal lines indicate tonnes of contained Mo.

Porphyry Deposits

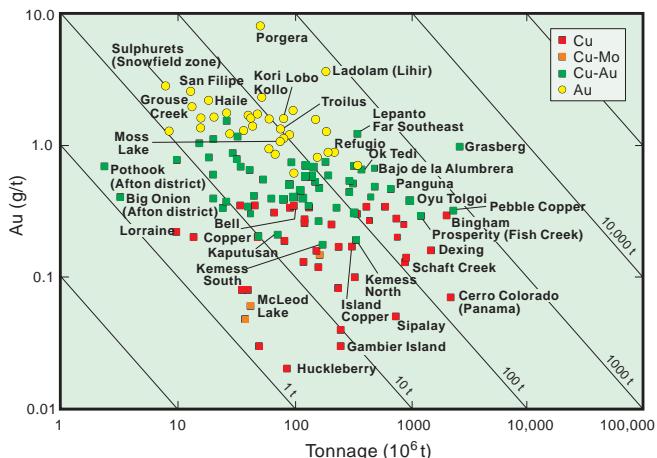


FIGURE 6. Au grades versus tonnage for Canadian and foreign porphyry deposits (modified from Kirkham and Sinclair, 1995). Diagonal lines indicate tonnes of contained Au.

(Fig. 6). At the Troilus deposit, Quebec, production and reserves to the end of 2002 totalled 71 Mt grading 0.93 g/t Au and 0.1% Cu (Appendix 1 (Canada)).

Porphyry Mo deposits are divided herein into two subtypes; Climax-type and Endako-type, which correspond generally to Sillitoe's (1980) classification of rift-related and subduction-related porphyry Mo deposits. Climax-type deposits are large and rich, as exemplified by the Climax and Henderson deposits in Colorado, with resources of 907 Mt grading 0.24% Mo and 727 Mt grading 0.17% Mo respectively. These deposits represent one end of a spectrum of Mo-bearing deposits, many of which have lower Mo grades and/or tonnages (Fig. 5). The opposite end of the spectrum in terms of grade is represented by the Endako deposit, for which combined production and reserves to the end of 2002 totalled 341 Mt with an average grade of 0.066% Mo (Appendix 1 (Canada)). The dividing line between rift-related (Climax-type) and subduction-related (Endako-type) deposits is 0.15% Mo (Sillitoe, 1980), although some Endako-type deposits may contain high-grade zones in excess of 0.15% Mo (e.g. Glacier Gulch and Trout Lake, British Columbia and Red Mountain, Yukon Territory). Limited data are available for W and Sn grades in most porphyry Mo deposits, but some, such as Climax, have produced significant amounts of W and Sn.

Porphyry W and W-Mo deposits contain tens of millions of tonnes to more than 100 Mt at grades of 0.1 to 0.3% W (Sinclair, 1995a); **porphyry Sn** deposits contain tens to hundreds of millions of tonnes grading 0.2 to 0.5% Sn (Sillitoe et al., 1975; Sinclair, 1995b).

Porphyry Ag deposits are not well represented; the large, low-grade, vein-stockwork Real de Angeles deposit in Mexico, with reserves of 85 Mt grading 75 g/t Ag, 1.0% Pb, and 0.92% Zn (Pearson et al., 1988), is a possible example.

Cu and Mo contents indicate that a continuum exists between porphyry Cu and porphyry Mo deposits (Fig. 8). 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 (Westra and Keith, 1981; Kirkham and Sinclair, 1995). A continuum may also exist between porphyry Mo and por-

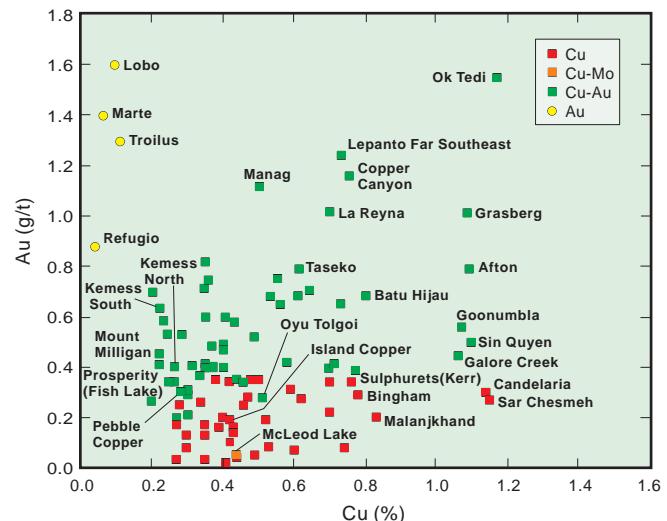


FIGURE 7. Au versus Cu grades in Canadian and foreign porphyry deposits (modified from Kirkham and Sinclair, 1995).

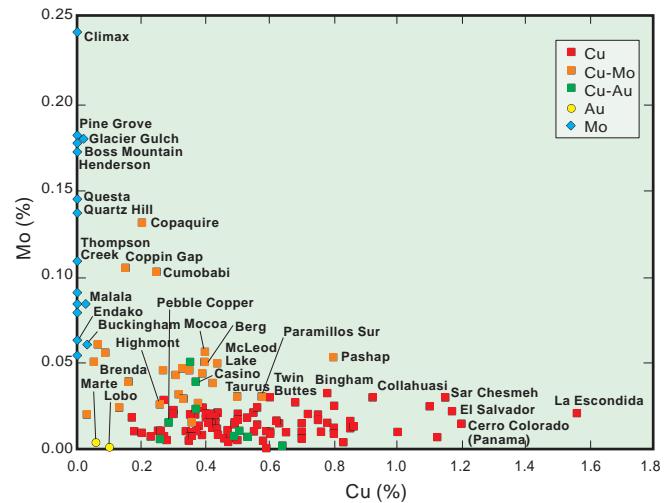


FIGURE 8. Mo versus Cu grades in Canadian and foreign porphyry deposits (modified from Kirkham and Sinclair, 1995).

phyry W-Mo and W deposits, although more data are required to substantiate such a relationship. 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.

Geological Attributes

Temporal Distribution

Porphyry deposits range in age from Archean to Recent, although most are Jurassic or younger (Fig. 9). 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 for Miocene, of which there are no significant deposits in Canada.

Porphyry-type deposits of Precambrian age are not as well represented and, in some cases, their classification is contentious. For example, Goodman et al. (2005) consider Troilus to be an "orogenic" deposit related to metamorphism,

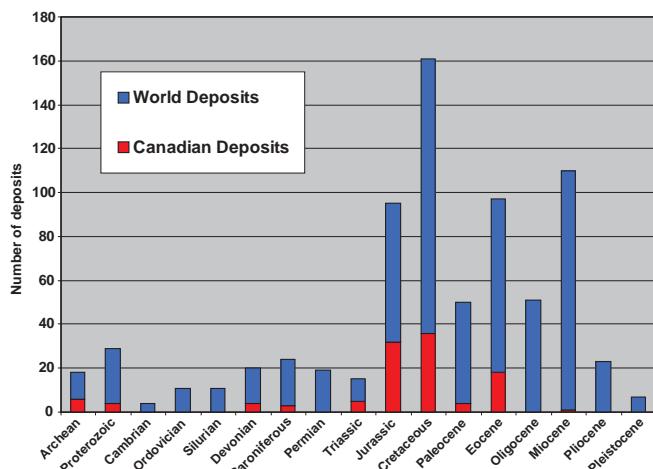


FIGURE 9. Age distribution of porphyry deposits (based on data from Kirkham and Dunne, 2000).

rather than a premetamorphic porphyry deposit as described by Fraser (1993). In the Chibougamau district, Cu-Au vein deposits in strongly foliated rocks have been considered to be shear related (e.g. Archambault et al., 1984) but Pilote et al. (1995) demonstrated that they are premetamorphic in origin and likely related to the Clark Lake porphyry deposit. Other examples of Precambrian porphyry-type deposits include Aitik, Sweden (Wanhainen et al., 2003), Malanjkhand, India (Sikka and Nehru, 1997); Tongkuangyu, China (Weixing and Dazhong, 1987); Boddington, Australia (Roth et al., 1991); Haib, Namibia (Minnitt, 1986); Setting Net Lake, Ontario (Ayres et al., 1982), and McIntyre, Ontario (Mason and Melnyk, 1986). The Coppin Gap Cu-Mo deposit in Australia, dated at approximately 3.3 Ga (de Laeter and Martyn, 1986; Williams and Collins, 1990), is the oldest known porphyry deposit in the world.

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. 10). In southern Arizona, porphyry Cu deposits are associated with granitic rocks emplaced in a continental setting, within or along the margins of calderas that are now largely eroded (Lipman and Sawyer, 1985). 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 (Richards and Kerrich, 1993; MacDonald and Arnold, 1994). Porphyry Cu deposits in the Yulong belt of Tibet are related to pull-apart basins in a large, post-subduction strike-slip fault (Hou et al., 2003). 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; Camus, 2002).

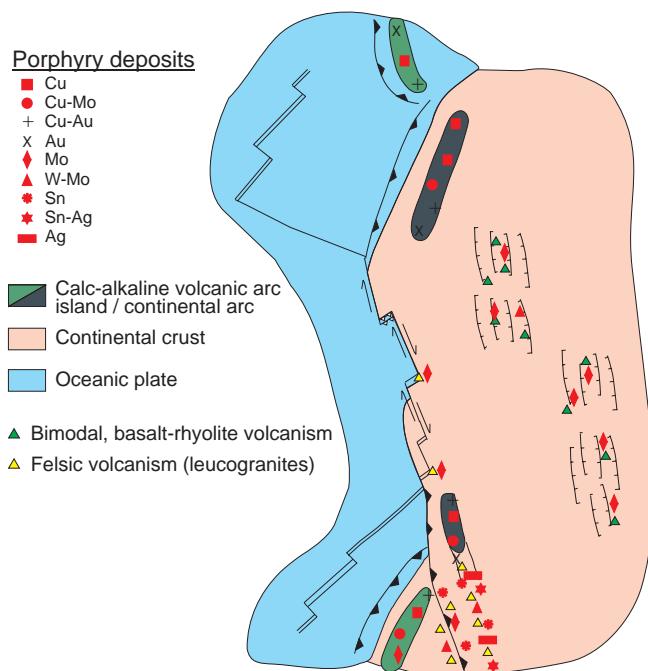


FIGURE 10. Schematic diagram showing the tectonic settings of porphyry deposits (Kirkham and Sinclair, 1995).

Climax-type porphyry Mo deposits are typically associated with anorogenic granites that have been emplaced in continental settings, particularly rift or extensional environments (Fig. 10). The Climax and Henderson deposits, for example, are genetically related to small stocks connected at depth to a regional batholith emplaced during active extension in the Rio Grande rift (Bookstrom, 1981; Carten et al., 1988b, 1993). Endako, on the other hand, is related to a composite batholith that formed in a continental subduction-related environment (Whalen et al., 2001). Some porphyry Mo deposits, such as Kitsault and Glacier Gulch, occur in areas of continental subduction that are underlain by slab gaps or windows (Kirkham, 1998). Others 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. 10). The Mount Pleasant W-Mo deposit in southern New Brunswick is associated with F-rich granitic rocks that have intruded along the Gander-Avalon boundary zone during a period of extension possibly related to crustal delamination (Whalen et al., 1994, 1996). A few deposits, such as Questa, New Mexico, are associated with high-silica rhyolites and granites that formed in continental calderas (Lipman, 1988). 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, for example, are related to subvolcanic intrusions that were emplaced in thick continental crust above a relatively shallow-dipping subduction zone (Sillitoe, 1976; Grant et al., 1980).

Details of each setting and related controls on magma generation, composition, and emplacement conceivably had

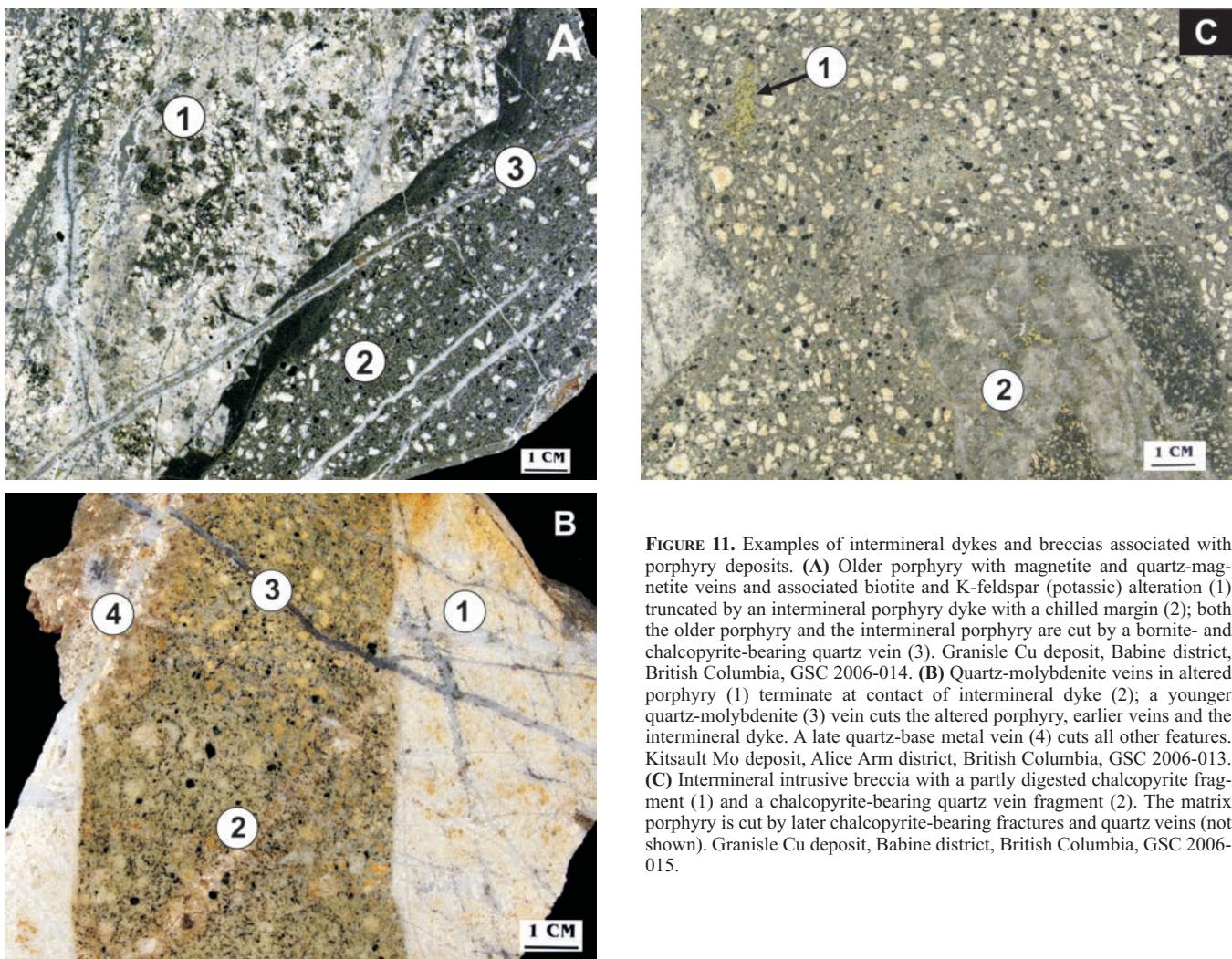


FIGURE 11. Examples of intermineral dykes and breccias associated with porphyry deposits. (A) Older porphyry with magnetite and quartz-magnetite veins and associated biotite and K-feldspar (potassic) alteration (1) truncated by an intermineral porphyry dyke with a chilled margin (2); both the older porphyry and the intermineral porphyry are cut by a bornite- and chalcopyrite-bearing quartz vein (3). Granisle Cu deposit, Babine district, British Columbia, GSC 2006-014. (B) Quartz-molybdenite veins in altered porphyry (1) terminate at contact of intermineral dyke (2); a younger quartz-molybdenite (3) vein cuts the altered porphyry, earlier veins and the intermineral dyke. A late quartz-base metal vein (4) cuts all other features. Kitsault Mo deposit, Alice Arm district, British Columbia, GSC 2006-013. (C) Intermineral intrusive breccia with a partly digested chalcopyrite fragment (1) and a chalcopyrite-bearing quartz vein fragment (2). The matrix porphyry is cut by later chalcopyrite-bearing fractures and quartz veins (not shown). Granisle Cu deposit, Babine district, British Columbia, GSC 2006-015.

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 (Schønwandt, 1988; Brooks et al., 2004), 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 Collahuasi 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, Collahuasi 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. Porphyry Cu and Cu-Au deposits in the Babine district of British Columbia are associated with porphyritic intrusions emplaced within a zone of extension related to the development of pull-apart basins situated between dextral strike-slip faults (McIntyre and Villeneuve, 2001). 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. 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 (e.g. Kirkham, 1971; Fig. 11).

The composition of intrusions associated with porphyry deposits varies widely and appears to exert a fundamental

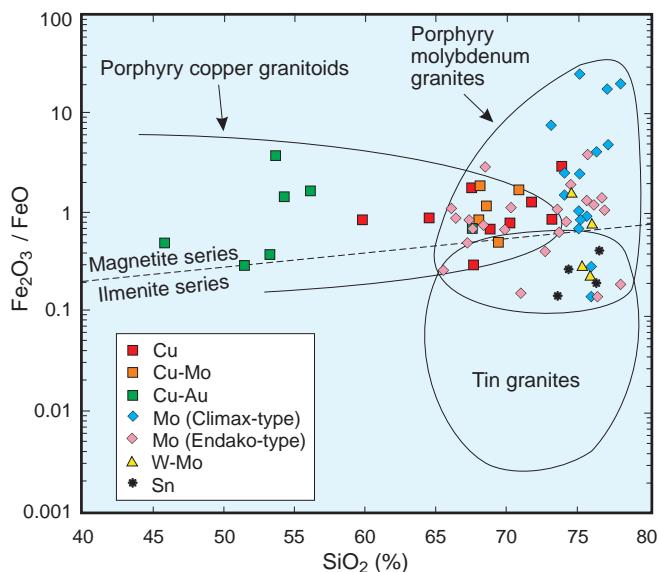


FIGURE 12. SiO_2 - $(\text{Fe}_2\text{O}_3/\text{FeO})$ variation diagram for granitic rocks related to porphyry deposits of Cu, Cu-Mo, Cu-Au, Mo, W-Mo, and Sn (modified from Kirkham and Sinclair, 1995). The dividing line between the magnetite and ilmenite series is from Ishihara (1981) and the field of tin granites is from Lehmann (1990).

control on the metal content of the deposits (Fig. 12). Intrusive rocks associated with porphyry Cu-Au and porphyry Au deposits tend to be low-silica (45–65 wt.% SiO_2), mafic and relatively primitive in composition, ranging from calc-alkaline dioritic and granodioritic plutons to alkalic monzonitic rocks (e.g. Richards, 1990; Ross et al., 1995; Snyder and Russell, 1995; Holliday et al., 2002; Wilson et al., 2003; Cooke et al., 2004). Porphyry Cu and Cu-Mo deposits are associated with intermediate to felsic, calc-alkaline intrusive rocks that range from granodiorite to granite in composition (60–72 wt.% SiO_2) (e.g. Kesler et al., 1975; Titley and Beane, 1981).

Porphyry deposits of Mo (Climax-type), W-Mo, W, and Sn, in comparison, are typically associated with felsic, high-silica (72–77 wt.% SiO_2) and, in many cases, strongly differentiated granitic plutons (Mutschler et al., 1981; White et al., 1981; Kooiman et al., 1986; Guan et al., 1988). Intrusions associated with Endako-type porphyry Mo deposits range more widely in composition, from granodiorite to granite (65–77 wt.% SiO_2 , Fig. 12). They also typically have low fluorine contents (<0.1% F) compared to intrusions associated with Climax-type deposits (Mutschler et al., 1981) and Endako-type deposits are distinguished as being fluorine-deficient or fluorine-poor (Theodore and Menzie, 1984; Linnen et al., 1995; Selby et al., 2000).

Oxidation state of granitic rocks, reflected by accessory minerals such as magnetite, ilmenite, pyrite, pyrrhotite, and anhydrite, also influences metal contents of related deposits (Ishihara, 1981). For example, porphyry deposits of Cu, Cu-Mo, Cu-Au, Au, Mo (mainly Climax-type), and W are generally associated with oxidized, magnetite-series plutons, whereas porphyry Sn and some Endako-type Mo deposits are related to reduced, ilmenite-series plutons (Fig. 12).

Small amounts of alkaline magmatic rocks associated with calc-alkaline intrusions may be significant for the formation of related porphyry deposits. For example, lampro-

phyre dykes are contemporaneous with felsic igneous rocks at Climax, Henderson, and other porphyry Mo deposits and are likely part of a bimodal suite (Bookstrom, 1981; Bookstrom et al., 1988). In addition to melting lower crustal rocks, underplated or injected mafic magmas represented by the lamprophyre dykes may have supplied some volatiles such as CO_2 and SO_2 (Keith et al., 1993). At Bingham, Utah, minette dykes that are coeval with ore-related monzonite represent mafic alkaline magmas that appear to have mixed with the more felsic monzonitic magmas, transferring substantial amounts of sulphur, copper, and other metals to the felsic magma and hydrothermal fluids in the process (Keith et al., 1997). Repeated injections of hot mafic melt into colder felsic magmas also would have triggered periodic eruptions and magmatic degassing resulting in extensive brecciation and mineralization of surrounding rocks (Hattori and Keith, 2001).

Felsic intrusive rocks that are closely associated with some porphyry deposits are characterized by distinct textural features such as comb-quartz layers (Fig. 13) and other unidirectional 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 one millimetre to several centimetres or more in thickness and are separated by interlayers of fine-grained, porphyritic aplite (Fig. 13A,B). Prismatic quartz crystals in the layers are oriented roughly perpendicular to the planes of layering and appear to have grown on a crystallized aplite substrate inward toward the centre of the intrusion (Fig. 13C). Closely related features include vein dykes and parting veins (Fig. 13D; Kirkham and Sinclair, 1988; Seedorf et al., 2005). Comb-quartz layers 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). Small stocks with abundant comb-quartz layers, therefore, represent conduits for large volumes of degassed magmatic-hydrothermal fluids that are capable of producing large porphyry orebodies. For example, at the Henderson Mo deposit, two of the nine associated plutons are characterized by significantly greater textural variation, including well developed comb-quartz layers (termed “brain rock”); these two plutons are responsible for about 80% of the Mo mineralization (Carten et al., 1988a).

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; Lowell and Guilbert, 1970; 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; Titley et al., 1986; 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.

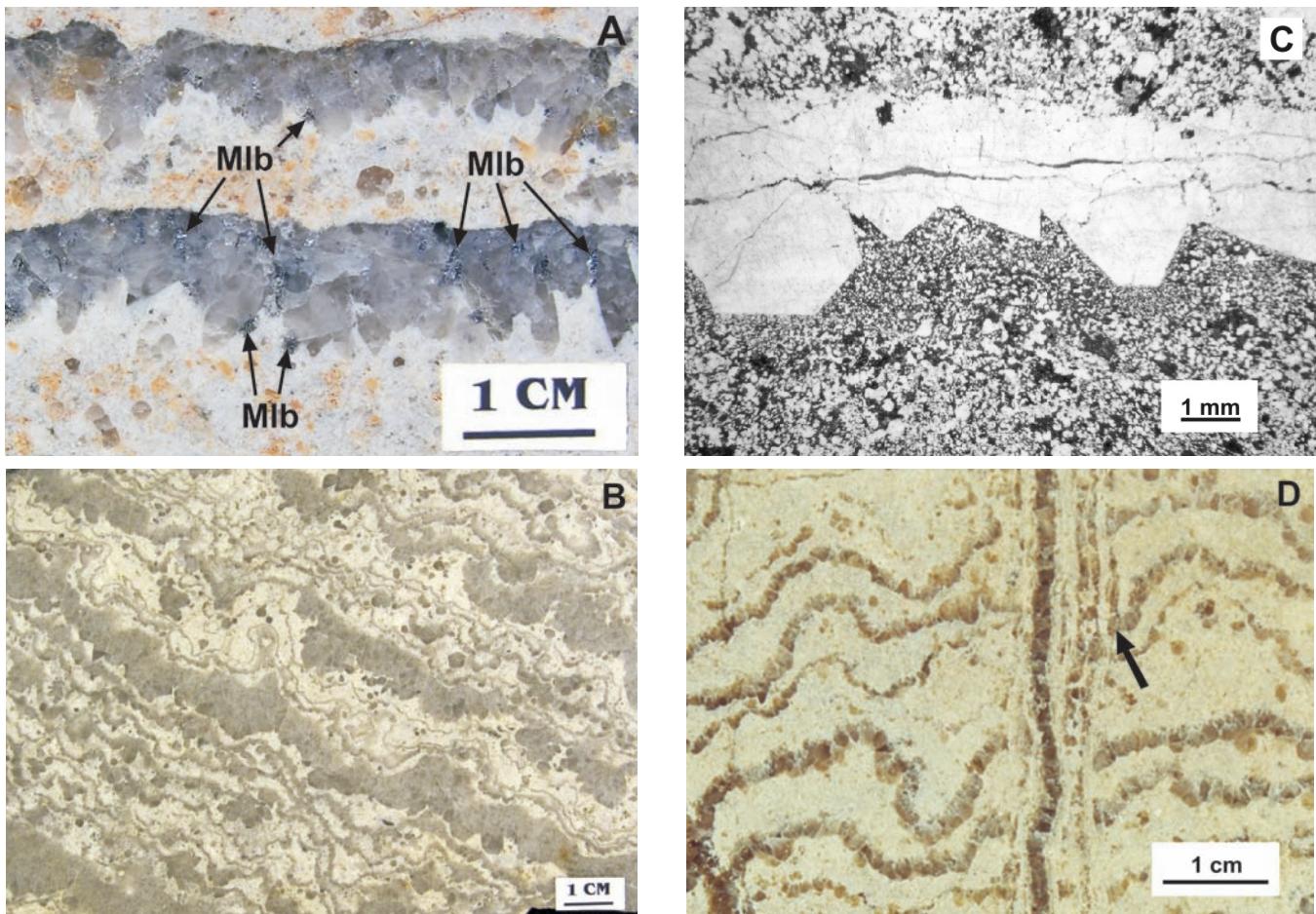


FIGURE 13. Examples of comb-quartz layers in felsic intrusions associated with porphyry deposits. (A) Comb-quartz layers containing molybdenite (Mlb) separated by aplite interlayers; growth direction from the top to the bottom. Anticlimax Mo deposit, British Columbia, GSC 2006-018. (B) Multiple thin to thick comb-quartz layers separated by aplite interlayers; growth direction of the quartz crystals in the layers was from the upper right to the bottom left. Logtung W-Mo deposit, Yukon Territory, GSC 2006-003. (C) Photomicrograph of a comb-quartz layer in aplitic granite showing euhedral termination of quartz crystals approximately perpendicular to the layer; the very fine-grained texture of the granite adjacent to the crystal faces 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 Sn deposit, New Brunswick, GSC 204152-T. (D) Contorted comb-quartz layers (growth direction towards the bottom of the photograph) cut by a parting vein, which consists of quartz veinlets with numerous septa or partings of aplite; one of the quartz veinlets in the parting vein appears to be rooted at the termination of a comb-quartz layer (arrow). Logtung W-Mo deposit, Yukon Territory, GSC 2006-006.

Einaudi, 1982; Sillitoe, 1988a,b; Jones, 1992). 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 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; Linnen and Williams-Jones, 1987; 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 these deposits are huge sulphur anomalies (Hunt, 1991). 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-

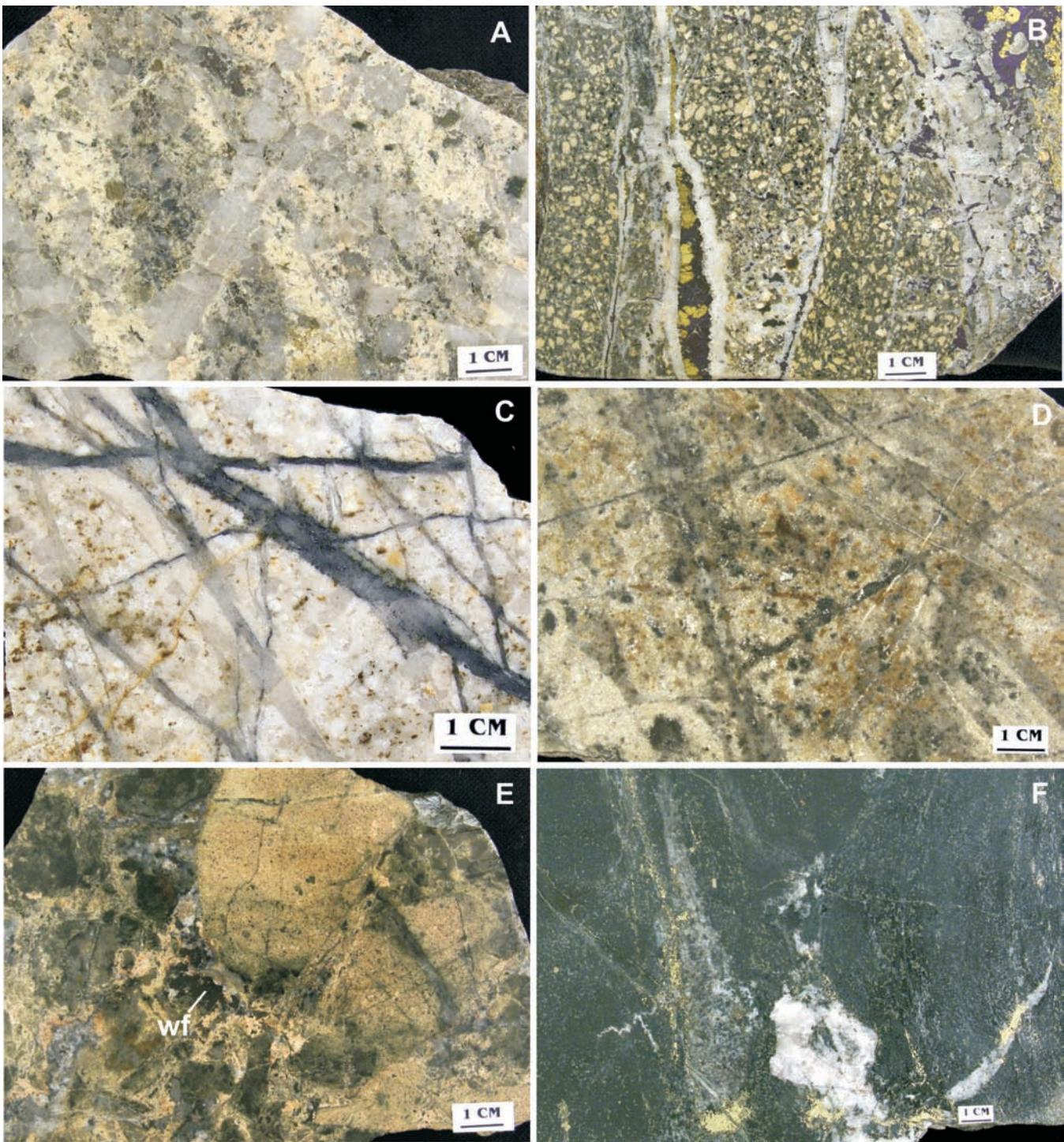


FIGURE 14. Examples of different mineralization styles associated with porphyry deposits. (A) Bornite-bearing quartz veins cutting highly sericitized Bethsaida granodiorite. Valley Cu deposit, Highland Valley district, British Columbia, GSC 2006-012. (B) Chalcopyrite- and bornite-rich quartz-apatite veins and veinlets cutting biotite-feldspar porphyry. High-grade ore, Granisle Cu deposit, Babine district, British Columbia, GSC 2006-016. (C) Quartz-molybdenite stockwork in sericitized granodiorite porphyry; cross-cutting and offset relationships of molybdenite-bearing fractures and quartz veinlets indicate multiple stages of mineralization. Kitsault Mo deposit, Alice Arm district, British Columbia, GSC 2006-007. (D) Stockwork of wolframite-bearing fractures cutting intensely altered breccia. Fire Tower zone, Mount Pleasant W-Mo deposit, New Brunswick, GSC 2006-005. (E) Mineralized breccia containing granite clasts with wolframite-bearing fractures that are truncated at the margins of the clasts, indicating that the granite was mineralized prior to the incorporation of the clasts in the breccia; wolframite (wf) also occurs as disseminated grains in breccia matrix. Fire Tower zone, Mount Pleasant W-Mo deposit, New Brunswick, GSC 2006-004. (F) Chalcopyrite disseminated along foliation planes and in a crosscutting quartz vein in deformed biotite-rich mafic breccia. Troilus Au deposit, Quebec, GSC 2006-010.

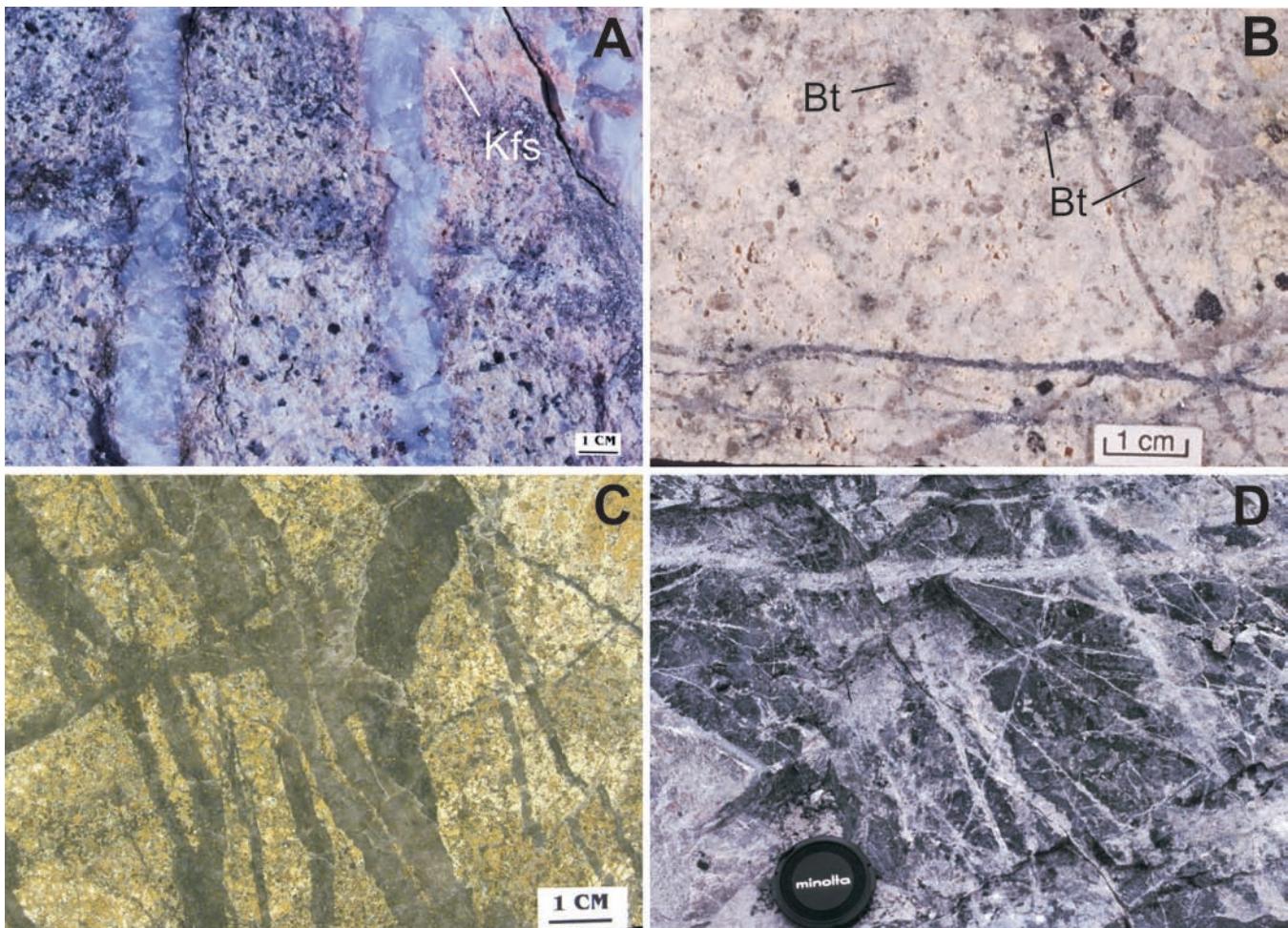


FIGURE 15. Examples of different types of alteration associated with porphyry deposits. (A) Potassic K-feldspar (Kfs) alteration around mineralized quartz veins in Bethsaida granodiorite. Valley Cu deposit, Highland Valley district, British Columbia, GSC 2006-017. (B) Potassic alteration of granodiorite porphyry consisting of pervasive pink K-feldspar and patches of fine-grained hydrothermal biotite (Bt) associated with quartz-molybdenite veinlets. Red Mountain Mo deposit, Yukon Territory, GSC 2006-008. (C) Quartz-pyrite-chalcopyrite vein stockworks in feldspar porphyry heavily overprinted by sericitic (phyllitic) alteration. Bell Cu-Au deposit, Babine district, British Columbia, GSC 2006-011. (D) Stockwork of wolframite- and molybdenite-bearing fractures with white selvages of quartz-topaz-fluorite-sericite alteration cutting chloritized granite. Fire Tower zone, Mount Pleasant W-Mo deposit, New Brunswick, GSC 2006-009.

feldspar, anhydrite, epidote, chlorite, scapolite, albite, calcite, fluorite, and garnet.

Porphyry Au deposits: Principal ore minerals are native Au and electrum; minor amounts of chalcopyrite, bornite, and molybdenite may also be present. 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; minor amounts of chalcopyrite may also be present. Associated minerals include pyrite, magnetite, quartz, K-feldspar, biotite, muscovite, clay minerals, fluorite, and topaz.

Porphyry W-Mo deposits: Principal ore minerals are scheelite, wolframite, molybdenite, cassiterite, stannite, bismuthinite, 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 freibergerite, stephanite, acanthite, sphalerite, and galena; associated minerals include arsenopyrite, pyrrhotite, pyrite, adularia, quartz, fluorite, and calcite.

Alteration

Hydrothermal alteration is extensive and typically zoned on a deposit scale (Lowell and Guilbert, 1970) as well as 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 K-feldspar and/or biotite (\pm amphibole \pm magnetite \pm anhydrite; Fig. 15A,B) and an outer zone of propylitic alteration that consists of quartz, chlorite, epidote, calcite and, locally, albite associated with pyrite. Zones of phyllitic alteration (quartz + sericite + pyrite, Fig. 15C) and argillic alteration (quartz + illite +

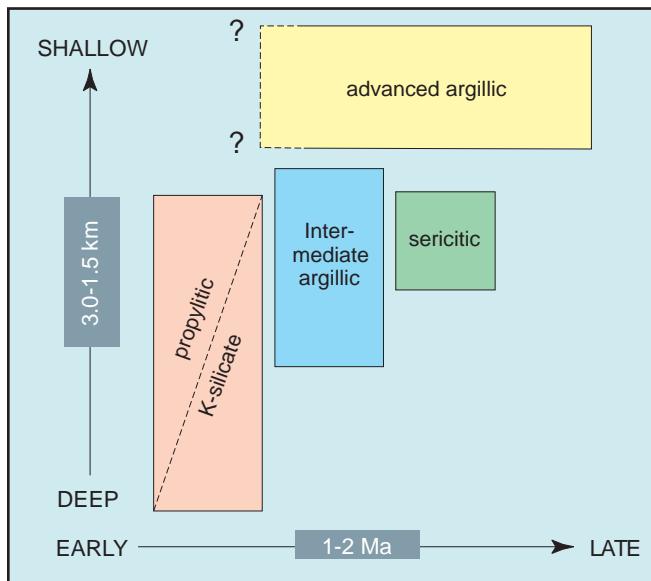


FIGURE 16. Schematic time-depth relations of principal alteration types in Au-rich porphyry Cu systems and other types of porphyry deposits (after Sillitoe, 1993b).

pyrite \pm kaolinite \pm smectite \pm montmorillonite \pm 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. Moyle et al., 1990; Sillitoe, 1993b). 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 phyllitic alteration. Sodic-calcic alteration (oligoclase + quartz + sphene + apatite \pm actinolite \pm 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 composition of the host rocks. In mafic host rocks with significant iron and magnesium, biotite (\pm 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 environ-

ments, minerals such as pyrite, magnetite (\pm hematite), and anhydrite are common, whereas pyrrhotite is present in more reduced environments (Rowins, 2000). Fluorine-rich systems, such as those related to many porphyry Sn and W Mo deposits, and Climax-type 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 (Fig. 15D), which is surrounded by propylitic alteration consisting 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 \pm 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.

Phyllitic alteration zones are not present in all porphyry deposits. In many deposits in which they are present, however, phyllitic alteration is superimposed on earlier potassic alteration assemblages (Carson and Jambor, 1979). At Chuquicamata in Chile, for example, a zone of intense phyllitic alteration with associated pyrite that extends to depth in the core of the deposit is superimposed on earlier potassic alteration and small amounts of associated Cu sulphides with low Cu grades. This phyllitic zone contains higher than average Cu grades and, in the weathered zone, oxidation of the pyrite produced acid leaching that resulted in an extensive deep supergene-enriched Cu zone (Ossandón et al., 2001).

Advanced argillic (high sulphidation) and adularia-type (low sulphidation) epithermal alteration zones with associated precious-metal deposits occur above or near several porphyry Cu and Cu-Mo deposits (e.g. Far Southeast-Lepanto, Hedenquist et al., 1998). These alteration zones, in places, show a marked telescoping of older potassic and younger epithermal alteration (Moyle et al., 1990; Sillitoe, 1990, 1993a,b; Setterfield et al., 1991; Vila and Sillitoe, 1991; Eaton and Setterfield, 1993; Richards and Kerrich, 1993). The advanced argillic assemblages include illite, quartz, alunite, natroalunite, pyrophyllite, diasporite, and 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. Sillitoe (1993a) also 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

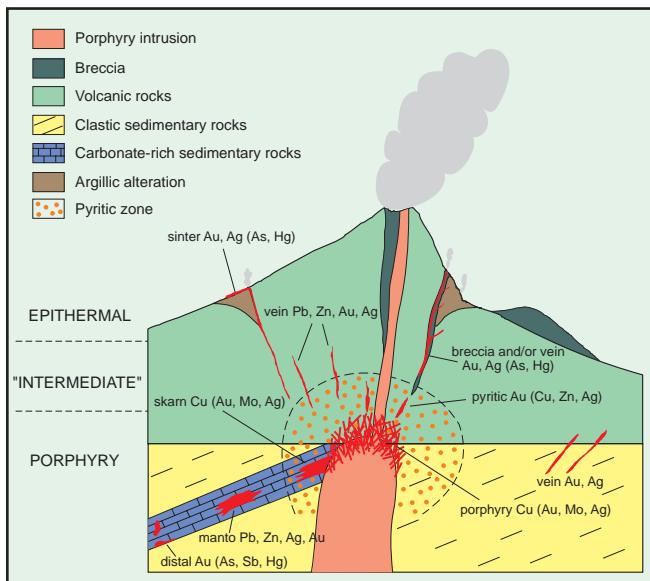


FIGURE 17. Schematic diagram of a porphyry Cu system in the root zone of an andesitic stratovolcano showing mineral zonation and possible relationship to skarn, manto, "mesothermal" or "intermediate" precious-metal and base-metal vein and replacement, and epithermal precious-metal deposits (Kirkham and Sinclair, 1995).

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.

Magmatic-Hydrothermal Model

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. 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 and were replaced by waters of dominantly meteoric origin. Redistribution, and possibly further concentration of metals, occurred in some deposits during these waning stages (Brimhall, 1980; Brimhall and Ghiors, 1983).

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 Bodnar, 1991; 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), Shinohara et al. (1995) and Cloos (2002). These studies indicate that the small porphyritic stocks associated with porphyry deposits were largely liquid until ore formation was essentially complete and were conduits for enormous volumes of ore-forming fluids produced by degassing of large subjacent magma bodies. In the context of porphyry Mo deposits, Shinohara et al. (1995) examined various mechanisms of fluid transport, including gravitational ascent of bubbles in a static magma, and concluded that convection of the magma itself provided the most favourable model for the transport of fluids to the

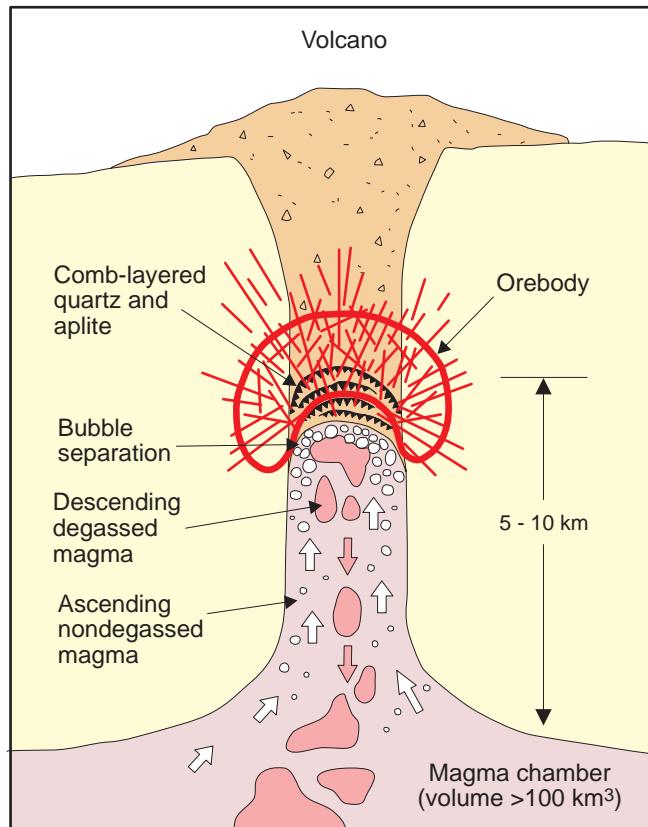


FIGURE 18. Schematic diagram of a convecting magma that is feeding a small subvolcanic intrusion below a porphyry deposit (modified from Shinohara et al., 1995). Fluid separation from the degassing magma occurs near the top of the magma column, forming pockets of magmatic-hydrothermal fluid in which comb-quartz layers grow inward from intrusion margins. Mineralized vein and fracture stockworks form when the fluid pressure exceeds lithostatic pressure and tensile strength of the surrounding rocks.

site of deposit formation. This model is presented schematically in Figure 18. According to this model, fluid-charged, nondegassed magma rises by convection from a deep magma reservoir in a column that is about 300 m in diameter at the top. Fluid separation from the magma occurs at a shallow, subvolcanic depth, focusing volatiles near the top of the magma column and producing degassed magma that descends through the nondegassed magma because of its lower volatile content and consequently greater density. Areas where ore-forming fluids accumulated in cupolas of intrusions associated with porphyry Mo and W-Mo deposits are characterized by abundant comb-quartz layers (Shannon et al., 1982; Carten et al., 1988a; Kirkham and Sinclair, 1988; Lowenstern and Sinclair, 1996). The occurrence of comb-quartz layers in intrusions associated with some porphyry Cu, Cu-Au, and Au deposits, as well as porphyry Mo deposits (Kirkham and Sinclair, 1988; Atkinson and Hunter, 2002; Kirwin, 2005), suggests that the Shinohara et al. (1995) model may be applicable to porphyry deposits in general.

Role of Mafic Magmas

Another modification to the orthomagmatic model involves mixing of mafic magmas with felsic to intermediate, ore-related calc-alkaline magmas prior to the onset of mineralization. Hot mafic melt injected into colder felsic magma can trigger vigorous convection leading to catastrophic magmatic degassing and explosive venting in subvolcanic plutons (Sparks et al., 1977), and extensive brecciation and mineralization of surrounding rocks (Hattori and Keith, 2001). For example, Dietrich et al. (2000) proposed that magma mixing was responsible for the formation of the Bolivian porphyry tin deposits, which are associated with small subvolcanic rhyodacite bodies. They suggested that influx of primitive melt into the lower levels of an upper crustal felsic magma system and subsequent mixing produced hybrid, rhyodacitic melt and triggered volcanic activity. Consequent decompression of the felsic magma system resulted in the release of Sn-W-B-As-bearing magmatic vapour phases from the felsic magma that were focused in subvolcanic vents to form the deposits.

Mafic magmas may also contribute volatiles and metals to the ore-forming fluids. Carten et al. (1993) suggested that, for high-grade porphyry Mo deposits, volatiles (F, Cl, S, CO₂) released from underplated and injected saturated mafic magmas were responsible for stripping metals from the overlying felsic magmas. At Bingham, Utah, mafic alkaline dykes and volcanic rocks that are coeval with ore-related monzonite contain minute magmatic sulphide globules 1 to 500 µm in size and composed chiefly of pyrite, pyrrhotite and chalcopyrite (Keith et al., 1997). Mafic magmas represented by these alkaline rocks appear to have mixed with the more felsic monzonitic magmas prior to mineralization and may have contributed more than half of the S and significant amounts of the Cu, Au, and PGE in the Bingham deposit (Maughan et al., 2002). Halter et al. (2002) further suggested that sulphide melts may control Cu:Au ratios in porphyry deposits by preconcentrating Cu and Au during the evolution of the magmatic system before volatile saturation. Destabilization of the sulphide melts during the later exsolution of chloride-rich volatiles would result in bulk transfer of metals and sulphur to hydrothermal ore-forming fluids.

Source and Evolution of Ore-Forming Fluids

The origin and evolution of metal-bearing fluids responsible for porphyry deposits are complex, depending on their initial compositions and cooling paths. Although some of the metal in the deposits may be derived from upper crustal rocks by meteoric fluids (Sheets et al., 1996), wall rocks of the intrusions and deposits are generally not considered to be viable sources for the metals in porphyry deposits (Kirkham and Sinclair, 1995). The bulk of the metal content of porphyry deposits appears to have been deposited from highly saline fluids (up to 60% NaCl equiv.) of magmatic derivation (Hedenquist and Lowenstern, 1994). In some cases, such hypersaline fluids may have separated directly from felsic magmas (e.g. Cline and Vanko, 1995; Ulrich et al., 1999, 2001; Harris et al., 2003; Webster, 2004). In other cases, the most primitive fluids exsolved from felsic melts are of low to moderate salinity, containing 2 to 12% NaCl equiv. (Redmond et al., 2004; Rusk et al., 2004). On ascending from their igneous source and undergoing decompression and cooling, such fluids commonly separate into a low-density vapour phase and a dense, hypersaline liquid. Although vapour-rich phases can contain significant amounts of metals such as Cu and Au (Rusk et al., 2004), the bulk of the metal content is partitioned into the hypersaline brines (Ulrich et al., 2001; Redmond et al., 2004).

Ore minerals may precipitate from the metalliferous fluids in response to adiabatic expansion (decompression) and fluid cooling, chemical effects of phase separation, interaction with wall rocks, or mixing with meteoric water. In some porphyry copper deposits, such as Bingham and Bajo de la Alumbrera, sulphide deposition was primarily due to cooling of metal-rich, saline brines below 400°C (Ulrich et al., 2001; Redmond et al., 2004). In other porphyry copper deposits, such as Butte and El Salvador, interaction of the magmatic fluid system with meteoric water had a significant impact on metal deposition (Gustafson and Hunt, 1975; Hemley and Hunt, 1992). In tin-rich systems, acid neutralization of the magmatic ore-bearing fluids by feldspar alteration to muscovite-quartz ± topaz ± fluorite (phyllitic alteration) or by mixing with meteoric water are effective mechanisms for cassiterite deposition (Heinrich, 1990).

Exploration Methods

Geological Methods

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. In weathered zones, hypogene sulphide minerals are commonly absent due to oxidation and leaching but associated silicate and other gangue minerals that remain may serve as guides to ore. 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; Perelló et al., 2001).

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 and W-Mo deposits occur mainly in areas of continental crust characterized by extensional tectonic settings with bimodal mafic and felsic magmatism. For Climax-type porphyry Mo deposits in particular, one of the key exploration criteria is a tectonic setting that reflects a changeover from compressional to extensional tectonics (Keith et al., 1993).

Geochemical Methods

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. For deposits that are deeply buried by post-mineralization rocks or sediments, detection of associated geochemical anomalies may require the application of partial extraction techniques (e.g. Kelley et al., 2003). Biogeochemical methods have also been developed for detecting porphyry deposits (Dunn et al., 1996; Dunn, 2000), particularly in arid regions (e.g. Chaffee, 1982).

In most parts of Canada, interpretation of geochemical data must take into account the effects of glaciation, which can be complex. For example, in the Babine district of British Columbia, the use of geochemistry for exploration has been problematic because of the widespread surficial cover, the variable distribution of glacial, glaciolacustrine, and glaciofluvial sediments, and an incomplete understanding of the glacial history of the region (Carter et al., 1995). However, Levson (2001) demonstrated that ice flow and related glacial dispersion were dominantly southeasterly, although they have been influenced locally by topographic control and by late-glacial, westerly ice flow, and that copper anomalies in basal till can be traced northwesterly in the up-ice direction to locate buried mineralization.

Geophysical Methods

The dispersed nature of sulphide distribution in porphyry deposits is particularly amenable for the application of the induced polarization (IP) method, which was originally developed specifically for porphyry Cu exploration (Brant, 1966). Controlled source audio-frequency magnetotelluric (CASMT) surveys have proven to be an extremely effective technique for defining the horizontal limits and depth extent of porphyry systems (Corry et al., 1988). Magnetic surveys can be used to outline porphyry Cu and Cu-Au deposits with abundant hydrothermal magnetite, and pyrrhotite- and/or magnetite-bearing skarn and hornfels zones around porphyry-related intrusive rocks. Conversely, some deposits are characterized by magnetic lows due to the destruction of magnetite in phyllitic 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). Recent developments in remote sensing have included the application of hyperspectral imaging to outline hydrothermal alteration around porphyry deposits (e.g. Cudahy et al., 2001; Berger et al., 2003).

Knowledge Gaps

One of the most fundamental problems in exploration for porphyry deposits is to identify factors that can distinguish the relatively few fertile igneous complexes from the many that are not. Despite the close association of porphyry deposits with intermediate to felsic intrusive rocks and general agreement that their formation involves the separation of metalliferous fluids from ore-related magmas, the processes that form porphyry deposits are diverse and significant knowledge gaps remain.

Role of Tectonic Setting

The view that porphyry Cu (\pm Mo \pm Au) deposits form in subduction-related island arcs associated with converging plates is overly simplistic (Richards, 2003). The large Andean porphyry Cu systems formed during discrete periods of regional uplift, tectonic shortening, and crustal thickening that have been attributed to increased convergence velocity and convergence angle (Camus, 2002). Giant deposits such as Bingham and Grasberg, although ultimately related to plate convergence, are not located in areas of steady-state subduction and arc volcanism. Climax-type porphyry Mo deposits occur in tectonic settings that are transitional between compressional and extensional tectonics (Keith et al., 1993). Changes or variations in tectonic setting such as arc reversals, low-angle subduction, and slab window and slab gap environments are other factors that must also be considered (e.g. Solomon, 1990; Kirkham, 1998).

Sources of Metals and Sulphur in Porphyry Deposits

Ore-related magmas can be generated in various ways, ranging from mantle melting to melting and/or assimilation of lower or upper crustal rocks, or a subducted plate. Consequently, the metals in porphyry deposits may have diverse origins. For example, although Cu, Au, and PGE are likely derived primarily from mafic, mantle-derived magmas (e.g. McInnes et al., 1999; Skewes et al., 2002), other sources for these metals may include subducted plates (Noll et al., 1996) and lower crustal rocks (e.g. Lang and Titley, 1998; Barra et al., 2002). There is general consensus that Mo, W, and Sn are derived from crustal rocks (Candela and Piccoli, 2005; Seedorf et al., 2005); however, it is debated whether the source regions need to be enriched in specific metals such as Sn and W (e.g. Keqin and Jinchu, 1988) or whether magmatic processes such as fractionation are more important than the primary metal content of magmas (e.g. Lehmann, 1982). The source of abundant sulphur in porphyry deposits is problematic because of the relatively low solubility of sulphur in felsic magmas compared to mafic magmas. To account for this "excess sulphur", Hattori and Keith (2001) have emphasized the role of mafic melt in supplying sulphur to felsic magma and magmatic-hydrothermal fluid. Streck and Dilles (1998), on the other hand, have argued that hydrous magmas may contain abundant oxidized sulphur dissolved as sulphate or anhydrite, and that porphyry ore fluids may be enriched in SO₂ gas via the breakdown of anhydrite.

Controls on Metal Ratios in Porphyry Deposits

Although there is a general relationship between magma composition and metal ratios, other factors are likely

involved. For example, preconcentration of Cu and Au in sulphide melts associated with mafic primitive magmas may exert a fundamental control on Cu:Au ratios in porphyry Cu deposits (Keith et al., 1997; Halter et al., 2002). In contrast, porphyry Au deposits in the northern Cordillera are associated with reduced, ilmenite-series granitic rocks in a continental arc setting and have an affiliation toward porphyry W-Mo rather than porphyry Cu systems (McMillan et al., 1995; Hart et al., 2004); the Au in these deposits is likely of crustal origin and may have been concentrated by magmatic fractionation under reducing conditions (Thompson et al., 1999). In porphyry Sn and W deposits, metal ratios are affected by the relative concentrations of Cl and F in the ore-bearing magmatic-hydrothermal fluids, which are in turn controlled by fractional crystallization and the resulting chemistry of the residual melts from which the fluids have exsolved (Audébat et al., 2000).

Relationship between Porphyry Deposits and Other Types of Intrusion-Related Hydrothermal Deposits, such as Epithermal Deposits

It is increasingly clear that high-sulphidation epithermal deposits may be part of porphyry systems (e.g. Hedenquist et al., 1998; Heinrich et al., 2004). Intermediate-sulphidation deposits may be related to porphyry deposits, but do not show such close connections as high-sulphidation deposits, and many low-sulphidation precious metal deposits do not appear to be linked to porphyry deposits (Sillitoe and Hedenquist, 2003).

Critical Factors for the Formation of Giant Porphyry Deposits

Giant-sized porphyry Cu deposits do not appear to have significantly different anatomical characteristics compared to smaller deposits; the primary controls on deposit size are instead likely related to large-scale lithotectonic conditions, the favourable criteria for which are not yet well defined (Clark, 1993). Some evidence suggests that magmas associated with the generation of giant porphyry Cu deposits were highly enriched in Cu, in which case only small amounts of magma would have been required to produce large deposits (e.g. Core et al., 2006). In other cases, intrusions that are not unusually enriched in Cu may have generated porphyry deposits by the efficient collection of Cu from large volumes of magma (Skewes and Stern, 1995; Cloos, 2002). In the latter case, to produce a giant deposit would require significant longevity of the ore-forming process and of the favourable lithotectonic conditions necessary to sustain it.

Areas of High Potential in Canada

Many parts of the Canadian Cordillera are favourable for various types of porphyry deposits. Areas with some of the highest potential for porphyry Cu-Au deposits are those underlain by Late Triassic to Early Jurassic alkaline volcanic and intrusive rocks, 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 the 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 Tatsha 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 (Hart et al., 2004). Areas with potential for porphyry Mo deposits include the Alice Arm district, Smithers area and the Tatsha Ranges, where deposits that are transitional between Climax- and Endako-type deposits, such as Kitsault and Glacier Gulch, are associated with Late Cretaceous to Eocene intrusions. These areas may also have potential for low-grade, Endako-type deposits associated with Oligocene intrusions, comparable to the Quartz Hill deposit in nearby Alaska (Wolfe, 1995), or with Late Jurassic intrusions as at Endako. Porphyry Mo and W-Mo deposits in northern British Columbia and southern Yukon Territory are associated with intrusions that range from mid-Cretaceous to Eocene in age (Sinclair, 1995c).

In the Canadian Appalachians, subduction-related mid-Devonian intrusions in New Brunswick and Quebec (Gaspé) have potential for porphyry Cu and Cu-Mo deposits. Mid to Late Devonian granitic plutons that appear to have been emplaced in an extensional environment along the Gander-Avalon boundary in southern New Brunswick have potential for associated porphyry deposits of W, Mo, and/or Sn, such as at Sisson Brook and Mount Pleasant (Sinclair, 2005).

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 underexplored. Numerous porphyry-type deposits occur in the Abitibi and Opatica greenstone belts, including one that is currently in production (Troilus). These and other 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.

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