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Porphyry Deposits of the Canadian Cordillera

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See table of contents

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Article abstract

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Deposits of the early Mesozoic period occur in at least three different arc terranes (Wrangellia, Stikinia and Quesnellia) with a single deposit occurring in the oceanic assemblage of the Cache Creek terrane. These terranes were located outboard from continental North America during formation of most of their contained early Mesozoic porphyry deposits. Some of the deposits of this early period may have been emplaced during terrane collisions. Metal assemblages in deposits of the calc-alkalic suite include Mo-Cu (Brenda), Cu-Mo (Highland Val-ley, Gibraltar), Cu-Mc-Au-Ag (Island Cop-per, Schaft Creek) and Cu-Au (Kemess, Kerr). The alkalic suite deposits are characterized by a Cu-Au assemblage (Copper Mountain, Afton-Ajax, Mt. Milligan, Mount Polley, Galore Creek). Although silver is recovered from calc-alkalic and alkalic porphyry copper mining operations, silver data are seldom included in the published reserve figures. Those available are in the range of 1-2 grams per tonne (g-t-1). Alkalic suite deposits are restricted to the early Mesozoic and display distinctive petrology, alteration and mineralization that suggest a similar tectonic setting for both Quesnellia and Stikinia in Early Jurassic time.

The younger deposits, late Mesozoicto Cenozoic in age, formed in an intra-continental setting, after the outboard host arc and related terranes accreted to the western margin of North America. These deposits are interpreted to occur n continental arc settings, and individual deposits are hosted by a variety of older country rocks. These younger deposits also snow a spectrum of metal associations: Cu-Mo (Huckleberry, Berg), Cu-Au (-Mo) (Bell, Granisle, Fish Lake, Casino),Mo (Endako, Boss Mountain, Kit-sault,Quartz Hill), Mo-W (Logtung), Au-W (Dub-lin Gulch) and Au (Ft. Knox). There maybe a continuum between Mo, Mo-W, Au-Mo-W and Au deposits. The distribution and timing of these post-accretion deposits likely reflect major crustal structures and subduction geometry.

Cordilleran porphyry metallic deposits show the full range of morphological and depth relationships found in porphyrydeposits worldwide. In addition, the Cordillera contains numerous alkalic suite deposits, which are rare worldwide: the unusual, possibly syntectonic Gibraltar deposit; and end-member gold-richgranite-hosted deposits, such as Ft. Knox (Alaska).

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ABSTRACT

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Cordilleran porphyry metallic deposits show the full range of morphological and depth relationships found in porphyry deposits worldwide. In addition, the Cordillera contains numerous alkalic suite deposits, which are rare worldwide: the unusual, possibly syntectonic Gibraltar deposit; and end-member gold-rich granite-hosted deposits, such as Ft. Knox (Alaska).

RÉSUMÉ

Les gisements de porphyres métallogéniques sont de grands gisements à basses teneurs, qui sont associés à des phénomènes intrusifs et dont l'assemblage métallique peut contenir du cuivre, du molybdène, de l'or et de l'argent.

La genèse de ces gisements est reliée à la mise en place de plutons hypabyssaux, généralement porphyriques et de composition intermédiaire à felsique qui sont générés à la zone de contact de plaques convergentes.

Les gisements de porphyres métallogéniques des cordillères canadiennes sont associés à deux suites intrusives distinctes : une suite calco-alcaline et une suite alcaline. Ces gisements des cordillères canadiennes se sont formés au cours de deux périodes séparées : une première, du Triassique supérieur au Jurassique moyen (Mésozoïque inférieur) et, l'autre, du Crétacé supérieur à l'Éocène (Mésozoïque/Cénozoïque).

Des gisements du Mésozoïque inférieur existent dans au moins trois terranes de milieux en arc différents (Wrangellia, Stikinia et Quesnellia), alors que le terrane de milieu océanique de Cache Creek ne renferme qu'un seul gisement de ce type. Lors de la genèse de la plupart des gisements de porphyres métallogéniqes du Mésozoïque inférieur, ces terranes se trouvaient en dehors de la plaque continentale de l'Amérique du Nord. Il est possible que certains des gisements de cette première période se soient constitués lors de collisions de terranes. Parmi les assemblages métalliques des gisements de la suite calco-alcaline, on retrouve ceux de Brenda (Mo-cu), de Highland Valley et de Gibraltar (Cu-Mo), de Island Copper et de Schaft Creek (Cu-Mo-Au-Ag) et, de Kemess et de Kerr (Cu-Au). Les gisements de la suite alcaline, tels ceux de Copper Mountain, de Afton-Ajax, de Mt. Milligan, de Mount Polley et de Galore Creek, sont caractérisés par un assemblage métallique Cu-Au. Bien que de l'argent soit extrait des gisements de porphyres cuprifères des suites calco-alcalines et alcalines, il est rare qu'il en soit fait mention dans les données publiées sur les calculs de réserve, et les teneurs publiées font mention de teneurs de l'ordre de 1à 2 grammes par tonne. Les gisements de la suite alcaline sont exclusivement d'âge mésozoïque inférieur, et leur parenté pétrologique, d'altérations et de minéralisations permet

de penser que les terranes de Quesnellia et de Stikinia ont tous deux subi les effets d'environnements tectoniques semblables au Jurassique inférieur.

Les gisements plus jeunes, d'âge mésozoïque supérieur à cénozoïque, se sont formés dans un milieu intracontinental, après que les milieux en arc d'origine et leurs terranes associés aient été soudés à la bordure ouest de la plaque de l'Amérique du Nord. Ces gisements se sont constitués en milieux d'arcs continentaux, pense-t-on, mais on les retrouve aujourd'hui au sein de roches encaissantes variées plus anciennes. On retrouve tout un éventail d'associations métalliques au sein de ces gisements plus jeunes : de Huckleberry et de Berg (Cu-Mo), de Bell, de Granisle, de Fish Lake, et de Casino (Cu-Au- Mo'), de Endako, de Boss Mountain, de Kitsaut, et de Quartz Hill (Mo), de Logtung (Mo-W), de Dublin Gulch (Au-W) et, de Ft. Knox (Au). Il se pourrait qu'il existe une suite compositionnelle continue entre les gisements de Mo, de Mo-W, de Au-Mo- W et d'Au. La distribution et la chronologie de ces gisements post-acrétionnairess sont probablement le reflet de l'influence de grandes structures crustales et des paramètres géométriques de la subduction.

Les gisements de porphyres métallogéniques des cordillères présentent tous les caractéristiques morphologiques et les relations de profondeur des autres gisements de porphyres métallogéniques de ce type dans le monde. Cependant, les cordillères renferment en plus de nombreux gisements d'une suite alcaline, fait plutôt rare ailleurs dans le monde. C'est le cas du gisement peu courant, possiblement syntectonique, de Gibraltar et du gisement de fin de suite granitique riche en or, tel Ft. Knox en Alaska.

INTRODUCTION

This short paper places porphyry deposits of the Canadian Cordillera in a broad tectonic context. It is derived largely from the paper "Regional Geological and Tectonic Setting of Porphyry Deposits in British Columbia and Yukon Territory," in CIM Special Volume 46 (Schroeter, 1995). It draws extensively from the work and ideas of many explorationists and researchers, and the improved understanding of the tectonic framework of the Cordillera. The metallogeny of the region, with respect to the formation of porphyry deposits, is discussed with reference to this tectonic framework.

Titley and Beane (1981) defined porphyry deposits as intrusion-related, large-tonnage, low-grade mineral deposits with metal assemblages that may include all or some of copper, molybdenum, gold and silver. The genesis of porphyry deposits is related to the emplacement of intermediate to felsic, hypabyssal, generally porphyritic intrusions that are commonly formed at convergent plate margins (Sawkins, 1990).

EXPLORATION FOR PORPHYRY DEPOSITS IN THE CANADIAN CORDILLERA

Economic Importance

During most of the 20th century, copper has been the most important metal produced in British Columbia, and since the 1960s, it has come largely from porphyry deposits. Many of the porphyry copper deposits also produced significant amounts of molybdenum, gold and silver. In 1992, statistics compiled by the Ministry of Energy, Mines and Petroleum Resources indicated that porphyry copper mines accounted for 88% of the copper, 17% of the gold, 26% of the silver, and 28% of the molybdenum produced in British Columbia, for a gross value of $844 million (Brueckl, written comm., 1994). The Endako porphyry molybdenum deposit accounted for the remainder of the molybdenum production. In addition, reserve statistics for 1991 indicated that more than 80% of British Columbia's copper reserves and half the province's gold reserves are located in porphyry copper deposits (Schroeter and Lane, 1991).

Although there has been no significant production from porphyry deposits in Yukon, a significant percentage of its proven base and precious metal reserves occurs in porphyry deposits. Several of these have undergone recent exploration and re-evaluation, and intrusion-related gold, peripheral vein and derived placer deposits are important exploration targets in Yukon. Metallogenic models for these gold deposits are in the early stages of development.

Canadian Cordilleran porphyry deposits contain all the major commodities and metal associations found in porphyry deposits worldwide. These include relatively rare deposit types such as those enriched in both molybdenum and gold, tungsten-rich deposits, and gold-only deposits.

During the 1980s, porphyry Cu-Au deposits throughout the world became highly profitable, and active exploration for these deposits continued in areas that were recognized as prospective: for example, Papua-New Guinea, the Philippines, and Indonesia. In addition to economic factors, the discovery of the Mt. Milligan alkalic suite Cu-Au deposit in 1987 created new activity in porphyry exploration in the Canadian Cordillera. It had been recognized for a number of years that alkalic porphyry deposits are enriched in gold. Discovery of the particularly gold-rich 66 Zone at Mt. Milligan confirmed this association, and fuelled exploration interest. Numerous deposits were re-evaluated, and new occurrences discovered. Much of the activity was focussed in the Mt. Milligan area within the Quesnellia terrane, partly due to the discovery, partly due to the concentration of similar alkaline intrusions in that area, and partly because thick glacial overburden had limited past exploration.

In 1990, porphyry deposits of calc-alkalic affinity again became exploration targets in the Cordillera. On a worldwide basis, many deposits associated with diorite to quartz monzonite, calc-alkalic to quartz alkaline intrusions are enriched in gold at levels at least as high as those in the alkaline suite in British Columbia (Cox and Singer, 1988; Sillitoe, 1993). The discovery of deposits at Kemess in northern British Columbia and Pebble Copper in Alaska, and re-evaluation of Fish Lake in southern British Columbia and Casino in Yukon emphasized the potential importance of gold-rich calc-alkalic porphyry deposits in the northwestern Cordillera. Exploration continued in several prospective areas during the early 1990s: for example, the Hushamu (Expo) deposit on northern Vancouver Island, the Sulphurets Gold and Kerr deposits in northwestern British Columbia, and the Huckleberry deposit in west-central British Columbia. Finally, recognition of the porphyry association for intrusion-hosted gold mineralization at the Fort Knox deposit near Fairbanks, Alaska generated new interest and led to further exploration in Alaska and Yukon.

TECTONIC FRAMEWORK

Although the importance of plate tectonic processes in the formation of porphyry deposits was noted in CIM Special Volume 15 (Sutherland Brown, 1976) detailed tectonic models for the evolution of the Cordillera were only beginning to emerge at that time. In 1976, there was growing awareness that the five morphological belts that define the Cordillera reflect regions with very different geological histories. It was also recognized that within these regions there are distinct geological provinces, and that some of these provinces might have originated outboard from North America, subsequently being added or accreted to the ancient western margin of the continent. In particular, Monger *et al.* (1972) argued that the eastern Canadian Cordillera consists of rocks with ties to North America, while the western Cordillera consists largely of island arc and oceanic assemblages that are generally allochthonous with respect to the continent. These ideas led to the development of tectonic models based on the accretion of numerous disparate crustal fragments known as terranes. Acceptance of these tectonic models provides a new framework in which the origin and timing of porphyry deposits may be examined.

The Canadian Cordillera comprises the ancient North American continental margin and miogeocline with marginal pericratonic terranes with similarities to North America in the east, and allochthonous terranes to the west (Fig. 1). From east to west the allochthonous terranes are Quesnellia, Cache Creek, Stikinia and Wrangellia. Stikinia and Wrangellia are separated by the Coast Plutonic-metamorphic complex, which incorporates roof pendants of the bordering terranes (Monger *et al.*, 1991). Most of the early Mesozoic porphyry deposits occur in Quesnellia and Stikinia with the exception of a few deposits in the Cache Creek terrane and Wrangellia. The younger Mesozoic to Tertiary deposits are less terrane specific but are also most common east of the Coast Plutonic complex. A few deposits, typically porphyry molybdenum and/or tungsten, occur in the ancient continental margin. An exception is the Quartz Hill molybdenum deposit in Alaska, which is hosted by Miocene granites of the Coast Plutonic Complex.

The timing and importance of amalgamation (the joining together of terranes to form a large compound terrane or superterrane) and accretion (the addition of terranes or superterranes to the ancient continental margin of North America) are the sources of many debates about the tectonic evolution of the Cordillera. The Intermontane superterrane contains the most important terranes with regard to porphyry deposits.

Although uncertainties in terrane accretion models remain, much of the debate involves the timing of collisional events and the extent of post-accretion but pre- Early Cretaceous northward translation of terranes. However, porphyry deposits in the Cordillera formed mainly before or after this period, hence deposits may be divided into pre- to syn- and post-accretion groups. The early and middle Mesozoic porphyry deposits appear to have formed in complex island arc settings and are related to processes that took place before accretion of their volcano-sedimentary host terranes to the North American continent. These deposits occur in Quesnellia, Stikinia and Wrangellia with a single example in the Cache Creek terrane (Fig. 1). The Late Cretaceous and Tertiary porphyry deposits formed in post-accretion continental magmatic arcs built across older terranes and overlap assemblages, and in intracontinental settings.

CLASSIFICATION OF PORPHYRY DEPOSITS

World-wide Classification

A variety of criteria have been used to classify porphyry deposits. The simplest breakdown is based on the principal commodities, copper *versus* molybdenum, as was used in CIM Special Volume 15 (Sutherland Brown, 1976). The importance of gold to the economics of porphyry deposits allows for further subdivisions which are used in CIM Special Volume 46 (Schroeter, 1995).

Porphyry copper deposits have been subdivided on the basis of the correlation between their tectonic environments of formation or crustal association, and enrichment in molybdenum *versus* gold (Sillitoe, 1972; Kesler, 1973). Titley and Beane (1981) and Barr *et al.* (1976) used the petrology of related intrusions to subdivide porphyry copper deposits. In general, petrological associations correlate well with tectonic settings and metal abundances. Cox and Singer (1988) demonstrated a number of general relationships among metal abundances, tectonic setting, crustal environment, petrological association, mineralogy, and depth of emplacement. Unfortunately, none of these characteristics provides an unambiguous classification of porphyry Cu±Mo±Au deposits, and there are exceptions to the generalizations. Sillitoe (1993) described various features that are common to gold-rich porphyry copper deposits, but again noted that no single feature provides a clear discriminant for the classification or explanation of gold-rich deposits.

Similarly, different classification schemes for porphyry molybdenum deposits have been proposed, based on the character of related intrusions, into granodiorite or granite types (Mutschler *et al.*, 1981), or into calc-alkaline, alkali-calcic and alkalic types (Westra and Keith, 1981). The deposits have also been grouped into fluorine-rich and -poor varieties (Theodore and Menzie, 1984), which correspond roughly to the granite and granodiorite classes, respectively. White *et al.* (1981) proposed a widely accepted separation, based on petrology, into deposits related to either granite porphyry or alkali rhyolite, and those related to quartz monzonite. The former are commonly referred to as Climax-type deposits after the Climax mine. Carten *et al.* (1993) modified this scheme to define three groups of deposits: a high-silica rhyolite-alkaline suite, a differentiated monzogranite suite, and a granite-related Mo-Cu suite with Mo>0.05%. Known porphyry molybdenum deposits in the Canadian Cordillera fall in the differentiated monzogranite suite.

Sillitoe (1979) predicted the existence of porphyry deposits in which gold would be the principal or sole economic commodity. Several discoveries have been made since then that can be classified as porphyry gold deposits. The Marte and Lobo gold deposits in Chile (Vila and Sillitoe, 1991) exhibit many features typical of porphyry deposits associated with calc-alkaline diorite intrusions, but contain only minor amounts of copper and molybdenum. Like Marte and Lobo, the Sulphurets Gold (Fowler and Wells, 1995) and Snowfield mineralized zones (Margolis and Britten, 1995) in northwest British Columbia have some characteristics of porphyry gold deposits. The recent Fort Knox (Bakke, 1995) and Dublin Gulch (Hitchins and Orssich, 1995) discoveries in Alaska and Yukon respectively, are zones of gold mineralization hosted by granitic intrusions. These discoveries have tungsten-bismuth geochemical signatures similar to those of many porphyry molybdenum deposits (Soregaroli and Sutherland Brown, 1976). These data suggest the existence of a new sub-class of porphyry deposits.

The compositions of major porphyry

deposits throughout the world are plotted by principal commodities in Figure 2 (after Cox and Singer, 1988; and Sillitoe, 1993). Some of the general tectonic and petrological associations and correlations are depicted, but there are many examples of deposits whose relative metal abundances differ from these typical associations. Classification of deposits by features other than relative metal abundances is possible for porphyry molybdenum deposits, and may be possible in the future for some porphyry gold deposits.

Canadian Cordilleran Classification
Classification of porphyry deposits in the Canadian Cordillera (McMillan, 1991)

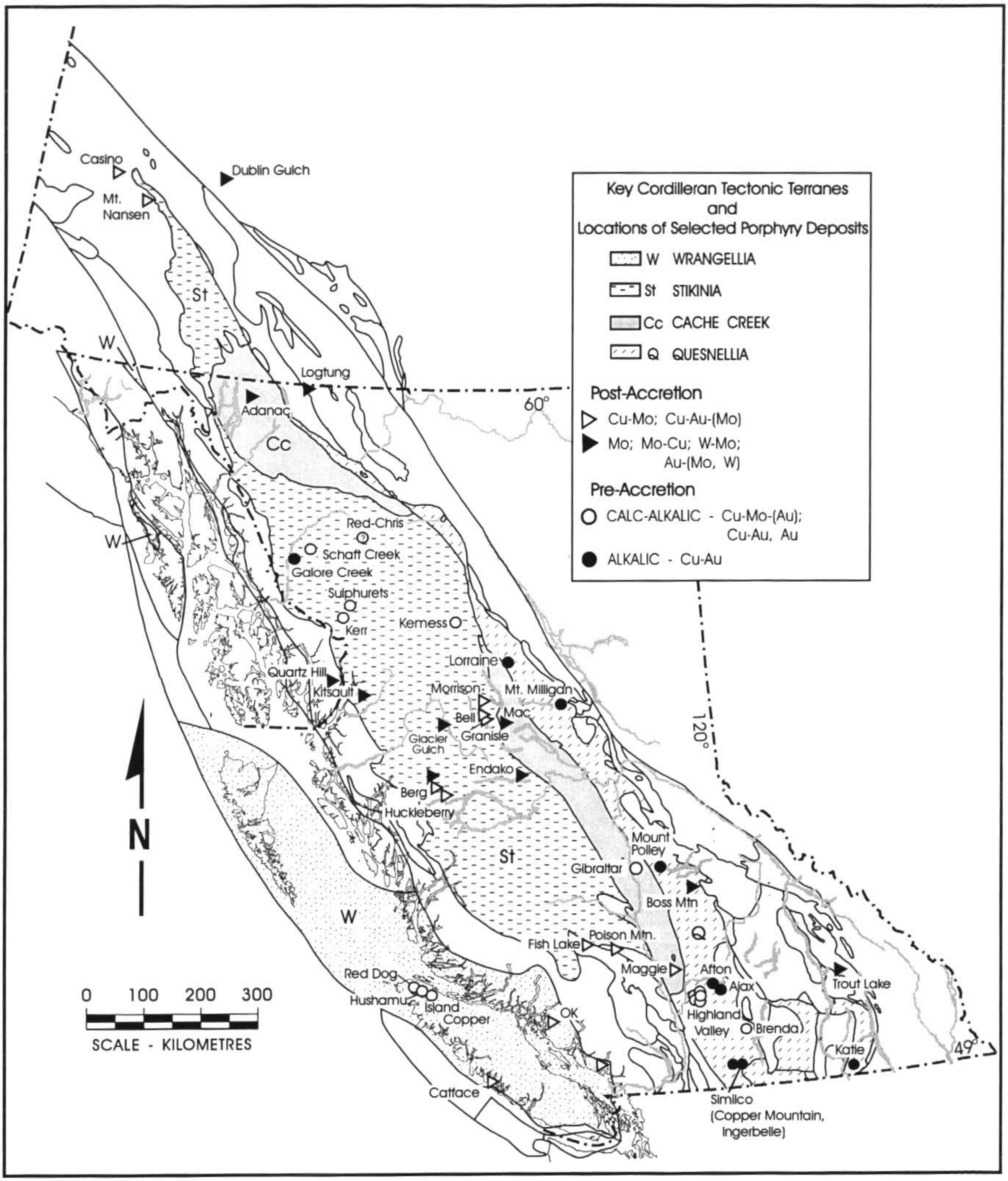

Figure 1 *Locations of selected Cordilleran porphyry deposits in their tectonic settings. Key terranes are highlighted. Pre- and post-accretion deposits and their characteristic metal associations are distinguished.*

can be based on relative metal abundances using the same subdivisions as for world-wide deposits (Fig. 3). Precise tectonic reconstruction for deposits that were emplaced in the early Mesozoic is difficult, and in many cases the composition of the associated crust or basement is uncertain. Rather than show arbitrary affiliations, we divide deposits only into pre- to syn-accretion and post-accretion groups; that is, they formed before or during, or after addition of the composite terranes to North America. The pre-accretion porphyry deposits are probably genetically linked to subduction-related tectonic processes in discrete island arcs, although there is evidence that at least some of these arcs had older continental basements. Some mid-Jurassic deposits, like Mt. Milligan, may have formed during accretion of the Intermontane superterrane. The post-accretion deposits were emplaced during Cretaceous and Tertiary time and are hosted by several of the older terranes. Consequently, the composition of their basement rocks varies considerably. The relative metal abundances of porphyry copper deposits — Mo:Au and Cu:Au ratios (Fig. 3) — do not correlate with terrane or timing of emplacement (pre- or syn- *versus* post-accretion) but several generalizations can be made:

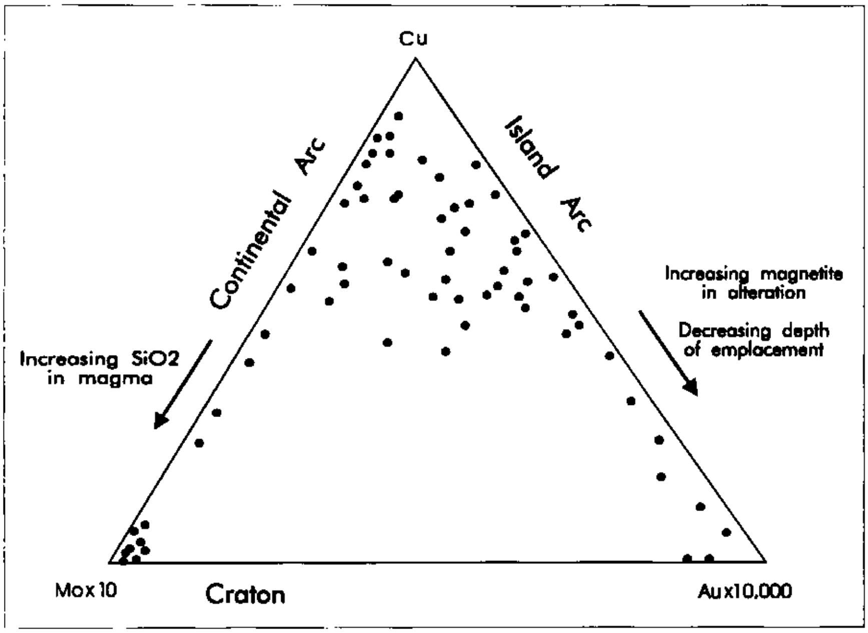

Figure 2 *Plot of relative abundances of copper (in percent), molybdenum (percent x 10) and gold (in grams per tonne) for various porphyry deposits from around the world (after Cox and Singer (1988) and Sillitoe (1993).*

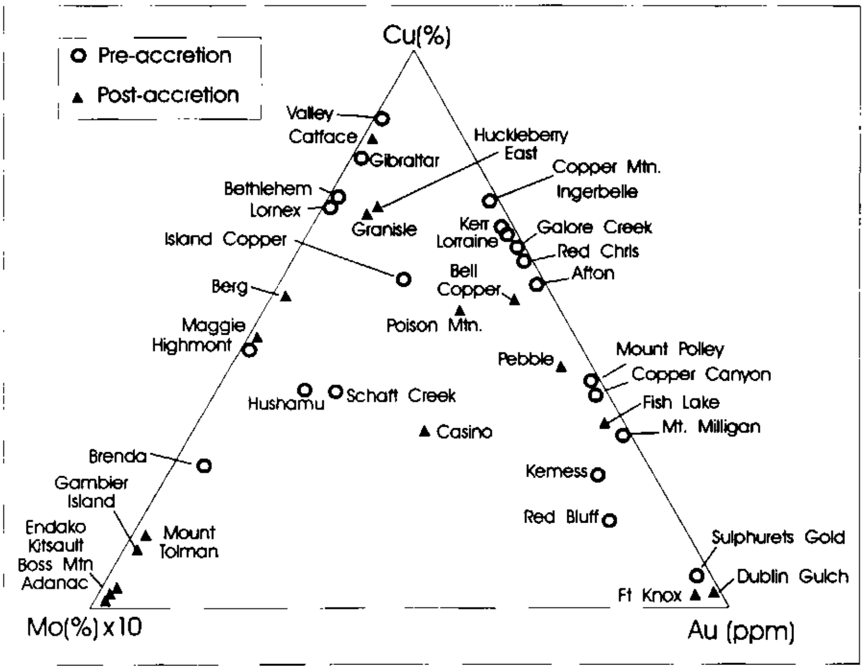

Figure 3 *Plot of relative abundances of copper (in percent), molybdenum (percent x 10) and gold (in grams per tonne) for selected Cordilleran porphyry deposits. Pre- to syn- and post-accretion deposits are distinguished by open circles and filled triangles respectively. Data are plotted based on reported reserves, thus some non-economic quantities of copper, molybdenum or gold may have been omitted. Some data points would shift if data were complete.*

- Porphyry copper-gold deposits of the unusual alkalic suite (Barr *et al.*, 1976) were emplaced in two different terranes prior to or during accretion (Mt. Milligan) in mid-Jurassic time.
- Porphyry molybdenum deposits are restricted to the post-accretion setting.
- Porphyry gold deposits related to granites (Fort Knox and Dublin Gulch) are restricted to post-accretion time. Porphyry gold deposits related to more conventional porphyry environments (*e.g.*, Sulphurets Gold and Snowfield) can also predate accretion.

The breakdown of deposits into pre- to syn-accretion and post-accretion ages is used as the major division in the classification. Deposits are further subdivided on the basis of petrology into the calc-alkalic and the distinctive alkalic suites, and by principal commodities. The alkalic suite is well defined in terms of metal content, petrology and alteration (Lang *et al.*, 1994). The calc-alkalic suite is not as well defined and includes a range of petrological associations and deposit types which may be subdivided into Cu-Mo, Cu-Mo-Au, Cu-Au or Au-only deposits. Possible examples of pre-accretion porphyry gold deposits, Sulphurets Gold and Snowfield, are not separated into a distinct category because they occur within a complex porphyry Cu-Mo-Au system (Kirkham and Margolis, 1995). Post-accretion deposits are divided by principal commodity into Cu-Mo, Cu-Au±Mo, Mo, Mo-Cu, W-Mo, and Au±Mo±W types. The petrology and characteristics of the post-accretion deposits are variable but no distinct type equivalent to the alkalic suite is defined.

DISTRIBUTION OF PORPHYRY DEPOSITS

The distribution of selected porphyry deposits within the major terranes of the Cordillera is shown in Figure 1. Pre-accretion deposits are divided into the alkalic and calc-alkalic suites, whereas post-accretion deposits are all calc-alkalic. The ages of deposits discussed in this section are based largely on recent U-Pb zircon and Pb-Pb titanite-potassium feldspar isochron methods carried out at the University of British Columbia (Mortensen *et al.*, 1995). These geochronological studies have refined the timing of formation of porphyry mineralization in the Cordillera and influenced resultant metallogenic models.

Pre-accretion to Syn-accretion

Pre-accretion deposits are concentrated in the Quesnel and Stikine terranes but also occur in Wrangellia and the Cache Creek and Yukon-Tanana terranes (Fig. 1). Deposits in the Quesnel terrane range in age from 216 Ma to 183 Ma with the majority of major deposits having formed between 205 Ma and 195 Ma (Mortensen *et al.*, 1995). Deposits of both alkalic and calc-alkalic association formed in this period.

The largest cluster of porphyry deposits in British Columbia occurs in the southern part of Quesnellia in the Highland Valley area within the calc-alkaline Guichon Creek Batholith (McMillan, 1985; Casselman *et al.*, 1995). The Guichon Creek Batholith was emplaced at about 210 Ma (Mortimer *et al.*, 1990), which is approximately contemporaneous with the intrusion of the alkaline Iron Mask batholith now located about 50 km to the east. The Iron Mask batholith hosts several porphyry Cu-Au deposits including Afton and Ajax. Alkalic porphyry Cu-Au deposits were also emplaced at this time both to the south (Copper Mountain) (Figs. 4, 5) and to the north (Mount Polley) in Quesnellia. The two contrasting types of intrusions are now only a few tens of kilometres apart, which suggests that the simple model of east-dipping subduction below Quesnellia proposed by Monger (1984) requires modification (Lang *et al.*, 1995).

Syn-collisional deposits in Quesnellia developed in Late Triassic and Early-to-Middle Jurassic time. The structural style and setting of the 217 Ma Gibraltar deposit suggests that it is syn-collisional, and formed during subduction of the Cache Creek ocean beneath Quesnellia (Bysouth *et al.*, 1995). Similarly, the youngest pre-accretion porphyry deposits recognized, which occur in the Mt. Milligan area of central Quesnellia and the Rossland area of southeastern Quesnellia, may have formed during accretion. The *circa* 184 Ma age of emplacement of these deposits is close to the interpreted age of accretion of Quesnellia onto the ancient continental margin of North America (Nixon *et al.*, 1993; Ghosh, 1990), suggesting that a complex tectonic environment may have existed during this period of porphyry emplacement in this terrane.

Pre-accretionary porphyry deposits of Stikinia are concentrated in northern British Columbia and range in age from approximately 220 Ma to 185 Ma, similar to the range of ages of deposits in Quesnellia (Mortensen *et al.*, 1995). Stikinia deposit ages fall into two distinct clusters and correlate with two volcanic groups: the late Triassic Stuhini Group, and the Early-to-Middle Jurassic Hazelton Group, including the informal Toodoggone formation, which hosts the Kemess deposit in northeast Stikinia (Diakow *et al.*, 1991). Schaft Creek represents the largest pre-accretionary porphyry prospect related to calc-alkaline magmatism. This deposit is hosted mainly in Late Triassic volcanic rocks. The deposit is adjacent, and appears to be related to, the calc-alkaline Hickman

Figure 4 *Copper Mountain deposit, a pre-accretion alkalic copper deposit, southern British Columbia. A composite photograph of pit 3 looking southeast. The light grey coloured dike in the west background (right side of photograph) is one of a swarm of post-ore dikes. The contact of the dioritic border phase of the Copper Mountain stock crosses the photograph just west (to the right) of the dike. A zone of white albitized Nicola volcanic rocks that occurs in the east middle ground (right side of photograph) is related to a cross fracture.*

Figure 5 *A view looking southwest into the East Ingerbelle pit, Copper Mountain area, southern British Columbia.*

batholith that was emplaced at about 220 Ma (Spilsbury, 1995). In the younger group of deposits, the Sulphurets camp and the adjacent Kerr deposit were emplaced at 190 Ma to 195 Ma (Ditson *et al.*, 1995). In addition, the camp contains the Sulphurets Gold and Snowfield deposits with disseminated and fracture-controlled zones of gold-only mineralization (Fowler and Wells, 1995).

Unlike those in Quesnellia, alkalic deposits in northern Stikinia are restricted to a narrow age range and are related to a suite of undersaturated alkaline intrusions (Mortensen *et al.*, 1995; Lang *et al.*, 1995). The age of the alkaline intrusions may coincide with the termination of Stuhini volcanism and perhaps the initiation of Hazelton volcanism. It is possible, therefore, that alkaline magmatism represents an end-of-arc event in this part of British Columbia. Galore Creek (Figs. 1, 3), which is the only significant deposit in this group of alkaline intrusions, is also distinctive among the alkaline porphyry deposits of the Cordillera because it intrudes its own alkaline volcanic carapace (Enns *et al.*, 1995).

There are two important groups of pre-accretion deposits that occur in the Cache Creek terrane and Wrangellia, and two enigmatic, possibly porphyry, deposits, Minto and Williams Creek, in the Yukon-Tanana terrane (Johnson and Mortensen, 1994). The Late Triassic Gibraltar porphyry copper-molybdenum-gold deposits were emplaced into the oceanic Cache Creek terrane at 217 Ma (Bysouth *et al.*, 1995). Most current tectonic models (see for example Monger *et al.*, 1991) assume that amalgamation and accretion in the Intermontane superterrane occurred in response to subduction of the oceanic Cache Creek terrane. However, Bysouth *et al.* (1995) assume a fore-arc setting for the terrane, a model that may better explain porphyry mineralization, as well as some of the unusual petrological and structural features of the Gibraltar deposit.

In Wrangellia, uranium-lead dating of the Rupert stock near the Island Copper mine (Perello *et al.*, 1995), on northern Vancouver Island, which is apparently genetically associated with mineralization, yielded an age of approximately 167 Ma (Friedman and Nixon, 1995). Further, U-Pb analyses of intrusions related to mineralization at Island Copper dated by Ross *et al.* (1996) bracket the mineralization at between 169 Ma and 166 Ma. By analogy, the Hushamu deposit (Dasler *et al.*, 1995) was likely also emplaced at approximately this time. These deposits are interpreted to be related to volcanic strata of the Middle Jurassic Bonanza volcanic arc and the coeval suite of Island intrusions. The character and pattern of alteration at Island Copper differs from other British Columbia calc-alkalic deposits, but is similar to deposits in the Philippines (Perello *et al.*, 1995).

Post-accretion

Post-accretion deposits were emplaced into most of the previously amalgamated terranes and the autochthonous platformal margin of continental North America (Fig. 1). Porphyry copper deposits formed between 110 Ma and 45 Ma, and porphyry molybdenum deposits from about 140 Ma to 8 Ma. Different plutonic suites and related metallogenic signatures are recognized during these periods, and porphyry deposits related to these suites cluster in time and space throughout the Cordillera. The clusters appear to be spatially related to major crustal structures, such as the transverse Stikine and Skeena arches, but the tectonic settings for the individual events are uncertain.

Porphyry Copper (Gold, Molybdenum) Deposits

The most significant post-accretion porphyry Cu±Au±Mo deposits include the Late Cretaceous Fish Lake deposit in the south, Huckleberry and the Eocene Babine Lake deposits (Bell, Granisle and Morrison) in the Skeena arch area in central British Columbia, and the Dawson Range belt that includes Casino in Yukon and possibly Taurus in Alaska (Leriche, 1995). Some but not all of these deposits are gold enriched.

Porphyry Molybdenum, Tungsten and Gold Deposits

Porphyry molybdenum deposits are exclusively post accretion. These deposits are widely distributed in the Cordillera and partly overlap in time and space with porphyry Cu-Mo-Au deposits. Metallogenic episodes are recognized at about 140 Ma, 110 Ma to 100 Ma, 80 Ma to 60 Ma, and 50 Ma (related to the Alice Arm intrusions), with local events occurring at 54 Ma to 48 Ma and 8 Ma (Christopher and Carter, 1976). The oldest deposit, Endako, is dated at 138 Ma; the youngest, Salal Creek, at 8 Ma. Endako has been the major molybdenum-producing mine in the province, operating since 1965. The other significant producer was Boss Mountain, dated at about 100 Ma. It also opened in 1965, and produced intermittently until 1983 (Macdonald *et al.*, 1995).

Porphyry molybdenum deposits are typically related to complex, multiple intrusive events. Many individual deposits are hosted by cylindrical stocks that are 500 m or less in diameter (Mac prospect; Cope and Spence, 1995). Others are related to larger epizonal plutons (Quartz Hill, Alaska; Wolfe, 1995), swarms of porphyritic sills (Louise Lake; Hansen and Klassen, 1995) or dike swarms (Salal Creek; Soregaroli and Sutherland Brown, 1976). Some, like Endako (Bysouth and Wong, 1995) and Adanac (Pinsent and Christopher, 1995), are genetically related to relatively young phases of batholiths or, like Mount Tolman (Lasmanis and Utterback, 1995), large stocks. Mineralization at Endako and Adanac is genetically linked to epizonal quartz monzonites and related rocks that are young phases of the Topley and Surprise Lake batholiths, respectively. In contrast, the 102 Ma quartz monzonite that hosts the Boss Mountain deposit cuts an unrelated 187 Ma granodiorite batholith. Deposits, like Kitsault, that are genetically associated with the 54 Ma to 48 Ma Alice Arm and related intrusive suites, generally occur in small quartz monzonite stocks with histories of multiple intrusion (Woodcock and Carter, 1976).

In Yukon and northern British Columbia, the Cassiar suite, a distinctive suite of intrusions (Panteleyev, 1980) with associated molybdenum and tungsten mineralization (principally skarn-type) was emplaced at approximately 110 Ma to 100 Ma (Mortensen *et al.*, 1994). The plutons that are spatially associated with porphyry deposits and skarns intrude miogeoclinal strata and associated pericratonic terranes, and were derived, at least in part, from crustal material (Sinclair, 1995). The largest of these deposits, and the only one with reported tonnage, is Logtung with 162 million tonnes grading 0.13% WO_3 and 0.03% MoS_2 (Noble and Spooner, 1987).

Porphyry Gold Deposits

The slightly younger Tombstone Suite (94 Ma to 87 Ma; Mortensen *et al.*, 1994) that occurs in western-central Yukon also has a W-Mo association, but more importantly, this suite includes granites that contain significant gold mineralization in central Yukon (Dublin Gulch) and central Alaska (Fort Knox). Both are characterized by distinctive Mo-W-Bi-As-Sb geochemical signatures. Although the origin of these deposits is uncertain, existing data suggest an intrusion-related (porphyry) model with an affiliation toward porphyry Mo-W rather than Cu porphyry systems.

Post-emplacement Effects — Weathering

Weathering and the formation of supergene-enriched mineralization is not an important factor in most Canadian Cordilleran porphyry deposits. There are, however, notable exceptions, particularly in central British Columbia and Yukon. Much of the central Yukon Territory and Alaska were not glaciated during the Quaternary. Porphyry deposits in these unglaciated regions have extensive supergene zones and leached caps that have remained intact. The most prominent of these are in the Dawson Range and include the Casino and Taurus properties. At Casino, a leached cap between 30 m and 170 m thick overlies a supergene zone that averages 80 m in thickness (Bower *et al.*, 1995). At the Williams Creek copper deposit at the east end of the Dawson Range, weathering has oxidized the deposit to a depth of 240 m. The preserved weathering profile, locally including a thick regolith and leached caps, has hampered exploration for porphyry deposits in Yukon. The permafrost and modern-day semi-arid climate of the Dawson Range inhibits continued supergene processes. However, the climate in the Early Tertiary was probably suitable for the formation of deep weathering and associated leached caps and enrichment zones above porphyry deposits (Godwin, 1976; Bower *et al.*, 1995).

DISCUSSION AND CONCLUSIONS

Porphyry mineralization is genetically related to plate tectonic processes, but may not result from continuous processes active during subduction (Thompson, 1995). The latest Triassic alkalic porphyry deposits of Stikinia illustrate this concept. Alkaline intrusions appear to be coeval with the cessation of Triassic Stuhini Group volcanism, and at least local deformation of the Stuhini arc. Subsequent reactivation of subduction caused renewed volcanism that produced the Jurassic Hazelton arc. This tectonic hiatus may have resulted from collision of part of the Yukon-Tanana terrane with Stikinia that caused a lull in subduction (Johnston and Erdmer, 1995; Johnston, 1995). Several other porphyry deposits may have formed during collisional events. The Minto and Williams Creek deposits in Yukon Territory are controlled by brittle-ductile shear zones that formed during imbrication of the Yukon-Tanana terrane with oceanic strata of the Slide Mountain terrane along regional thrust faults (Mortensen, 1992). The Gibraltar deposits show similar structural features, but the origin of these structures is uncertain. Finally, the Mt. Milligan and Rossland area deposits may also be syn-collisional in timing.

Porphyry deposits in the Canadian Cordillera formed in temporally restricted clusters, some of which may be controlled by collision or other tectonic events. Although the precise tectonic environment is uncertain in many cases, porphyry mineralization appears to have been directly associated with specific phases of distinctive intrusive suites that may have been emplaced during brief time intervals. More work and precise dating is needed to verify this hypothesis.

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