Porphyry Deposits of the Canadian Cordillera

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ABSTRACT

Porphyry deposits are 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 these deposits is related to the emplacement of intermediate to felsic, hypabyssal, generally porphyritic intrusions that are commonly formed at convergent plate margins.

Porphyry deposits of the Canadian Cordillera occur in association with two distinctive intrusive suites: calc-alkaline and alkalic. In the Canadian Cordillera, these deposits formed during two separate time periods: Late Triassic to Middle Jurassic (early Mesozoic), and Late Cretaceous to Eocene (Mesozoic-Cenozoic).

Deposits of the early Mesozoic period occur in at least three different arc terranes (Wrangellia, Stikinia and Quesnelia) 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-alkaline suite include Mo-Cu (Brenda), Cu-Mo (Highland Valley, Gibraltar), Cu-Mo-Au-Ag (Island Copper, 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-alkaline and alkalic porphyry copper mining operations, silver data are seldom included in the published reserve figures. These available are in the range of 1-2 grams per tonne (g/t). Alkaline suite deposits are restricted to the early Mesozoic and display distinctive petrology, alteration and mineralization that suggest a similar tectonic setting for both Quesnelia and Stikinia in Early Jurassic time.

The younger deposits, late Mesozoic to Cenozoic in age, formed in an intracontinental setting, after the outboard host arc and related terranes accreted to the western margin of North America. These deposits are interpreted to occur in continental arc settings, and individual deposits are hosted by a variety of older country rocks. These younger deposits also show 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 (Dublin Gulch) and Au (Pt. Knox). There may be a continuum between Mo-Mo, Mo-W, Au-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 porphyry deposits worldwide. In addition, the Cordillera contains numerous alkalic suite deposits, which are rare worldwide: the unusual, possibly syntectonic Gibralter deposit; and end-member gold-rich granite-hosted deposits, such as Pt. 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.


Des gisements du Mésozoïque inférieur existent dans au moins trois terranes de milieux en arc différents (Wrangellia, Stikinia et Quesnelia), 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 plus part des gisements de porphyres métallogéniques 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-alcaldine, 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 alcaldine, 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-alcaldines et alcaldines, 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 1 à 2 grammes par tonne. Les gisements de la suite alcaldine sont exclusivement d’âge mésozoïque inférieur, et leur parenté pétrologique, d’altérations et de minéralisations permet...
de penser que les terranes de Quesnella 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'arc continentaux, pense-t-on, mais on les retrouve aujourd'hui au seuil de roches encaissantes variées plus anciennes. On retrouve tout un événail d'associations métalliques au sein de ces gisements plus jeunes : de Huckleberry et de Berg (Cu-Mo), de Bel, de Granisle, de Fish Lake, et de Casino (Cu-Au-Mo), de Endako, de Boss Mountain, de Kitsault, 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 composée contenant trois gisements de Mo, de Mo-W, de Au-Mo-W et d' Au. La distribution et la chronologie de ces gisements post-acréniaux seraient probablement le reflet de l'effet 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 de 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 of 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 alkaline 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 alkaline porphyry deposits are enriched in gold. Discovery of the particularly gold-rich 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 Quesnella 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-alkaline affinity again became exploration targets in the Cordillera. On a worldwide basis, many deposits associated with dorate to quartz monzonite, calc-alkaline 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-alkaline porphyry deposits in the northwestern Cordillera. Exploration continued in several prospective areas during the early 1990s: for example, the Husham (Exp) deposit on northern Vancouver Island, the Suipheerts 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 miogeoclinal 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 Wrangelia. Stikinia and Wrangelia 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 Wrangelia. 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 superterranne) 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 superter-

rane 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 Wrangelia 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 (Schoeter, 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 (Silfitoe, 1972; Kesler, 1973). Tittley 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.

Silfitoe (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, alkaline-calcic and alkaline types (Westra and Keith, 1981). The deposits have also been grouped into fluorine-rich and -poor varieties (Theodore and Menzie, 1994), 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. Caten et al. (1993) modified this scheme to define three groups of deposits: a high-silica rhyolite-alkali 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.

Silfitoe (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 Silfitoe, 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 Dubil 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)

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**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-accrretion and post-accrетion groups; that is, they formed before or during, or after addition of the composite terranes to North America. The pre-accrretion 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-accrretion 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:Cu and Cu:Au ratios (Fig. 3) — do not correlate with terrane or timing of emplacement (pre- or syn-versus post-accrretion) but several generalizations can be made:

- 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-accrretion 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-accrretion and post-accrretion ages is used as the major division in the classification. Deposits are further subdivided on the basis of petrology into the calc-alkaline 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-alkaline 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-accrretion 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-accrretion deposits are divided by principal commodity into Cu-Mo, Cu-Au±Mo, Mo-Cu, W-Mo, and Au±Mo±W types. The petrology and characteristics of the post-accrretion deposits are variable but no distinct type equivalent to the alkalic suite is defined.

**DISTRIBUTION OF PORPHYRY DEPOSITS**

The distribution of selected porphyry de-
Deposits within the major terranes of the Cordillera is shown in Figure 1. Pre-accretion deposits are divided into the alkaline and calc-alkaline suites, whereas post-accretion deposits are all calc-alkaline. 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 (Montgomerie 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 Quesnellia and Stikinia terranes but also occur in Wrangellia and the Cache Creek and Yukon-Tanana terranes (Fig. 1). Deposits in the Quesnellia terrane range in age from 216 Ma to 183 Ma with the majority of major deposits having formed between 205 Ma and 195 Ma (Montgomerie et al., 1995). Deposits of both alkaline and calc-alkaline 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 (Montgomerie 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. Alkaline 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 Mungor (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 oceanic crust beneath Quesnellia (Byers et al., 1996). Similarly, the youngest pre-accretion porphyry deposits recognized, which occur in the Mt.

Figure 4 Copper Mountain deposit, a pre-accretion alkaline copper deposit, southern British Columbia. A composite photograph of pit 3 looking southeast. The light grey colored dike in the west background (right side of photograph) is one of a swarm of post-ore dikes. The contact of the diorite border phase of the Copper Mountain stock crosses the photograph just west (to the right) of the dike. A zone of white altered 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 Quesnella, alkaline 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. Gaiore 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 Wrangelia, and two enigmatic, possibly porphyry, deposits, Minto and Williams Creek, in the Yukon-Tanana terrane (Johnson and Mortensen, 1994). The Late Triassic Gibraltor porphyry copper-molybdenum 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 Gibraltor deposit.

In Wrangelia, 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-alkaline 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, Grasile 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 or 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 migmatic 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% WO₃ and 0.03% MoS₂ (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 affi liation 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 alkaline 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 Hazeltin arc. This tectonic hiatus may have resulted from collision of part of the Yukon-Tanana terrane with Stikinia that caused a lull in subduction (Johnson 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 Gibralter 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.

ACKNOWLEDGEMENTS

In addition to the papers referenced, many people have contributed to the ideas presented in this paper. The following are particularly acknowledged for their suggestions and comments: Mitch Mihalyuk, JoAnne Nelson, Andre Pan- teleyev, Tom Schroeter, Jim Lang, Grant Abbott and Jim Mortensen.

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Accepted, as revised, 31 July 1996.