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PORPHYRY Cu-Mo DEPOSITS OF THE HIGHLAND VALLEY DISTRICT, GUICHON CREEK BATHOLITH, BRITISH COLUMBIA, CANADA

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Abstract - Copper-molybdenum and copper-gold porphyry deposits in the Quesnel terrane occur in association with either calc-alkalic or alkalic intrusive suites respectively, emplaced within a succession of island arc volcanic rocks that are of Late Triassic to Middle Jurassic or Late Cretaceous to Eocene age. The Highland Valley porphyry district, in southern British Columbia, consists of five major copper-molybdenum deposits, Valley, Lornex, Bethlehem, Highmont and JA, located within a fifteen square kilometre area in the centre of the Guichon Creek batholith. The batholith is a Late Triassic calc-alkalic intrusion that REE data suggest was derived from either subducted oceanic crust or depleted mantle. The crystallisation age of the batholith, based on U-Pb zircon analyses, is 210 Ma. Mineralisation occurred in late magmatic and early post magmatic time. Oxide analyses suggest a single source magma but younger phases were locally injected into older due to tectonic forces. The earliest deposits occurred after separation of a fluid phase that is marked by a sharp discontinuity in the evolution path of the alkali oxides.

The batholith is elongated northward and segmented by major northerly and northwest-striking faults that are intimately related to mineralisation. Most of the sulphide mineralisation is in fractures, veins, faults or breccia bodies, and all the deposits are hosted entirely within the rocks of the granodiorite batholith. In general, early potassic and propylitic alteration are overprinted by later phyllic and argillic alteration. In more detail, complications in cross-cutting alteration and vein relationships suggest local influxes of hotter aqueous solutions. Phyllic alteration is characterised by the formation of both microscopic sericite and medium grained 'flaky sericite' (muscovite). Principal hypogene metallic minerals in the deposits are bornite, chalcopyrite, molybdenite and pyrite. Only the Lornex and Valley deposits remain in production in 2004. For these two deposits, the total ore milled to the end of 2002 has exceeded a billion tonnes. As of December 31, 2002, remaining reserves in the Lornex and Valley mine deposits are 296 million tonnes grading 0.42% copper and 0.008% molybdenum.

The area is veneered by glacial deposits. Induced polarisation surveys have proven to be the most useful exploration tool for Highland Valley deposits, but silt, soil and lithogeochemical surveys, and alteration mapping can be effective. A regional lithogeochemical study showed generally high copper values (120 to 100 ppm) in the older rocks of the batholith and less than 50 ppm in the younger rocks. A zone in which copper abundance is less that 10 ppm lies several kilometres south of the large, younger deposits, offers a potential source for much of the copper in them.

Introduction

The Highland Valley porphyry copper district is 40 kilometres southeast of Cache Creek and 54 kilometres southwest of Kamloops in south central British Columbia, Canada. The setting and major deposits in the district, Bethlehem, JA, Highmont, Lornex and Valley mine were described in a series of papers in Canadian Institute of Mining and Metallurgy (CIM) Special Volume 15 and updated information on the Valley mine was presented in a paper in CIM Special Volume 46 (Casselman *et al.*, 1995). At present, production continues only from the Valley and Lornex mines, which are operated by Highland Valley Copper, a partnership between Teck Cominco Limited (63.9%), BHP Billiton Limited (33.6%) and others. Production at Bethlehem and Highmont has ended, and JA remains undeveloped. Getty Copper Corp. is investigating the potential of the Getty North (formerly Krain) and other deposits north of Highland Valley. Highland Valley Copper is now the largest mining operation in the province. In 2002, daily mill throughput averaged 136 600 tonnes of ore grading 0.410% copper and 0.011% molybdenum. Total tonnages of ore milled to the end of 2002 are 404.7 million tonnes from Lornex with grades of 0.409% copper and 0.014% molybdenum and 623.9 million tonnes from Valley with grades of 0.428% copper and 0.007% molybdenum. As of December 31, 2002, proven plus probable reserves in the Lornex and Valley mine deposits are 86.2 million tonnes grading 0.356% copper and 0.011% molybdenum, and 209.6 million tonnes grading 0.445% copper and 0.006% molybdenum respectively.

This report presents a general overview of the camp, then more detail on the Valley mine deposit. Reports prepared and thesis studies carried out prior to publication of CIM Special Volume 15 are referenced in McMillan (1976); studies concluded between 1976 and 1984 are discussed in Geological Association of Canada, Mineral Deposits Division Field Guide and Reference Manual Series Number 1 (McMillan, 1985), and updated material can be found in CIM Special Volume 46 (Casselman *et al.*, 1995).

General Geological Setting

Introduction

The Highland Valley porphyry deposits are within the Guichon Creek batholith, one of a series of plutons that are associated and likely comagmatic with the Nicola Group, a succession of Late Triassic island arc volcanic rocks within the southern portion of the Quesnel Trough in the Intermontane belt. The Nicola Group volcanic rocks form part of a 30 to 60 km wide, north northwest-trending belt that extends from southern B.C. into the southern Yukon. This belt is enclosed by older rocks and invaded by

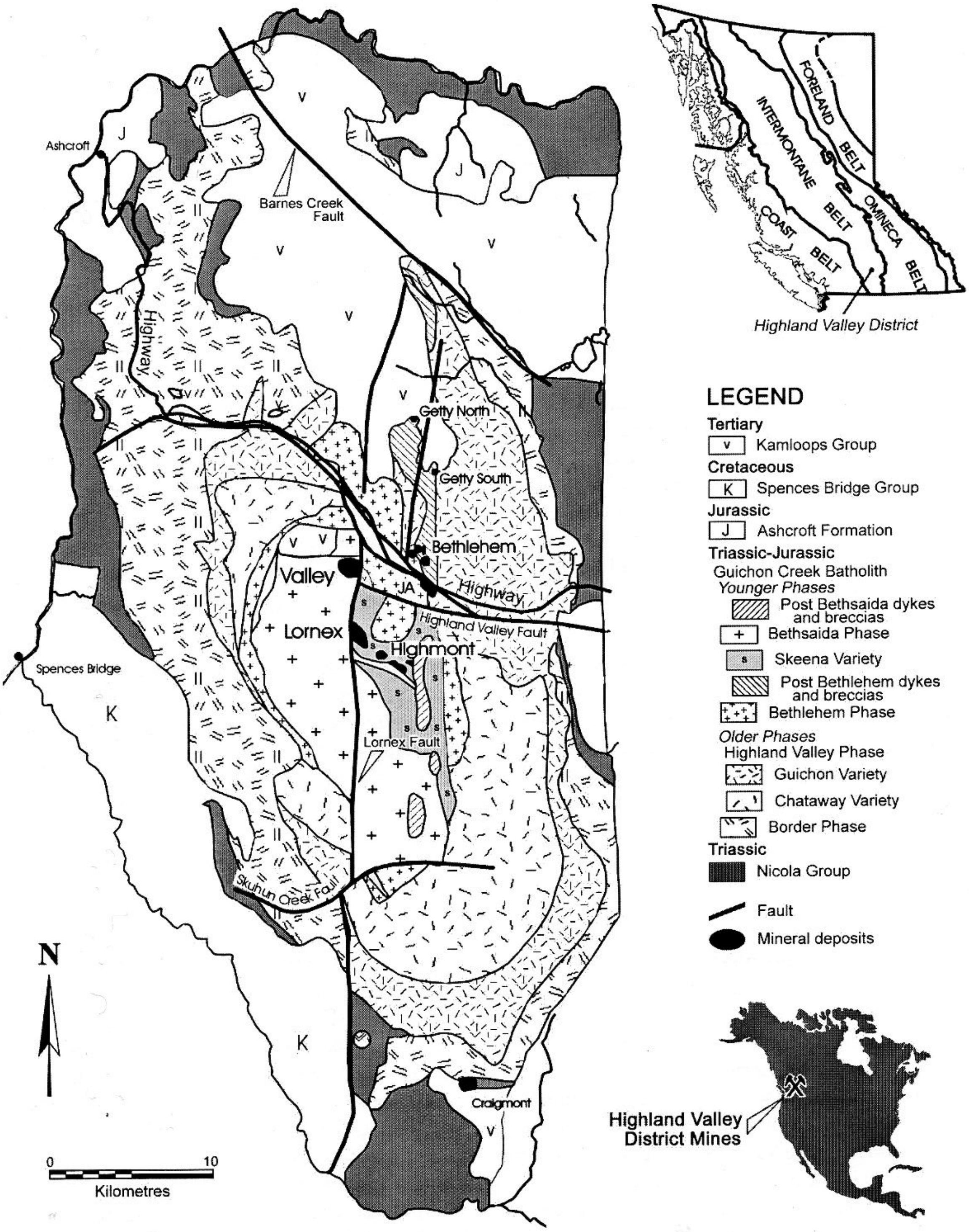

Figure 1: ***Location and general geology of the Guichon Creek batholith*** showing important Highland Valley porphyry copper-molybdenum deposits (modified after McMillan, 1976, CIM Special Volume 15).

batholiths and smaller intrusives. Parts of the belt are obscured by subsequent depositional basins which contain Jurassic and Cretaceous volcanic and sedimentary rocks and Eocene, Miocene and Pliocene volcanic and associated sedimentary rocks.

Tectonic Setting

The island arc host rocks of the Guichon Creek batholith are components of the Quesnel terrane, which is part of the Intermontane Super-terrane. The Super-terrane, which consists of the oceanic Slide Mountain and Cache Creek terranes and the island-arc Quesnel and Stikine terranes, originated offshore. Closure of the Slide Mountain ocean began in late Paleozoic time, and Stikinia, the Cache Creek Terrane and Quesnellia may have been linked (amalgamated) by latest Triassic time. Destruction of this ocean basin may in part be responsible for formation of the island-arcs. Worldwide, many porphyry deposits are closely related to consuming-margin, island-arc processes (Sawkins, 1990), and alkalic and calc-alkalic plutonic rocks generated along the Quesnel and Stikine arcs have associated porphyry copper-gold and copper-molybdenum deposits respectively. The calc-alkalic Guichon Creek batholith, which was emplaced into the Quesnel arc at about 210 Ma (Mortimer *et al.*, 1990), hosts the Highland Valley porphyry copper-molybdenum deposits. The deposits are interpreted to be of late-magmatic and early post-magmatic age.

The Intermontane Super-terrane began to impinge on the North American craton in mid-Jurassic time, circa 184 Ma (Nixon *et al.*, 1993) . Apparently, complete closure of the Slide Mountain ocean resulted in mid to late Jurassic thrusting of Cache Creek rocks over Quesnellia (Mortimer, 1986) and mid-Jurassic to early Cretaceous thrusting of the Slide Mountain and to a lesser extent Quesnellia allochthons onto the miogeocline. Researchers using Lithoprobe vibroseismic (Cook *et al.*, 1992) and refraction seismic (Zelt *et al.*, 1992) survey data for the Intermontane belt identified strong, west-dipping reflectors. One of these, perhaps an extension of the Coldwater fault, apparently decouples the Guichon Creek batholith from its basement. The reflector is about 10 to 15 km deep, well below the gravity-indicated depth of all but the root zone of the batholith (Ager *et al.*, 1973). It is likely that movement on this decoupling fault or faults post-dates mineralisation. The faults probably originated during Mesozoic to early Tertiary compression that occurred when Quesnellia docked with north America, and became reactivated during Eocene extension.

Geology

The Guichon Creek batholith is a large, composite intrusion with a surface area of about 1000 square kilometres (Fig. 1). A cluster of 5 major porphyry copper deposits lie within a 15 square kilometre zone in the centre of the batholith. The detailed geology and setting of the batholith are described by Northcote (1969), McMillan (1976, 1983, 1985) and Monger and McMillan (1989).

The batholith is a semi-concordant composite intrusive that is elliptical and elongated slightly west of north. Its average width is 20 km and its average length 65 km. This elongation is interpreted to reflect the influence of deep-seated structures and emplacement during tectonic activity. McMillan (1976) interpreted weakly developed foliation in the granitic rocks as a magmatic feature. Ned Brown (Pers. Comm., 2000) reviewed the field data and also concluded that the foliation was largely magmatic, but was locally controlled by tectonism. For example, under the roof of the batholith the magmatic fabric in the underlying pluton parallels the schistose fabric in the roof rocks. In other parts of the pluton the fabric more closely follows phase boundaries and may not be tectonically controlled. A geological and gravity model (Ager, McMillan and Ulrych, 1973) indicates that the batholith has steep eastern and western edges, but is relatively shallow and flat-bottomed north and south of Highland Valley. A central, steeply plunging root or feeder zone is inferred under Highland Valley (Fig. 2). The steep plunge implies that there has been post-emplacement tilting of the batholith. All the known major deposits lie around the projection of the root zone to surface.

The batholith intrudes and metamorphoses Late Triassic Carnian to Norian-aged island arc volcanic and associated sedimentary rocks of the Nicola Group. Adjacent to the contact, a metamorphic halo up to 500 metres wide developed. Close to the granite contact, assemblages are typical of the hornblende hornfels facies, further out, albite-epidote facies are typical (Northcote, 1969).

Rocks at the border of the batholith are older and more mafic; successive phases moving inward toward the core are younger and more felsic. Thus, rocks of the batholith range from relatively melanocratic, medium grained diorite and quartz diorite (tonalite) at the border through to relatively leucocratic, coarser grained granodiorite in the core. The phases are nearly concentric in plan view. Although contacts can be sharp, they are generally gradational; chilled contacts are unusual. Some phases clearly intrude others and illustrate their relative ages through dykes, contact brecciation, xenoliths and local finer grained contacts. Other units are completely gradational. A phase may show intrusive contacts with another phase in one area but grade into the same unit elsewhere. Northcote (1969) and McMillan (1976) concluded that generally successive pulses of magma were injected before the preceding phase was completely solidified.

Chemically, the Guichon Creek batholith is a calc-alkaline (Fig. 3), I-type intrusion (McMillan, 1976). Variations in the major and minor element geochemistry indicate that there are local areas of assimilated country rock in the border zone of the intrusion. In outcrop, these areas have inclusions of amphibolite and granitised sedimentary and volcanic rocks, and also show compositional variations, for example much lower or higher than average silica. Total rare earth element (TREE) values in the batholith are low and phases show only slightly positive or no europium anomalies. Hornblende is the main carrier of Rare Earth Elements (REE), so as hornblende was removed by fractional crystallisation REE, other than Eu, became depleted in the remaining magma; all hornblendes analysed

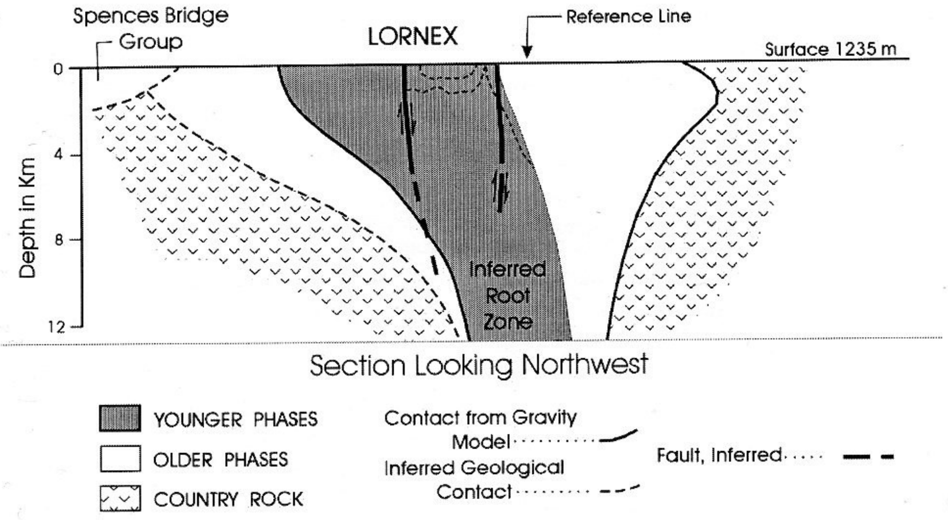

Figure 2: ***Northeast-southwest section across the Guichon Creek batholith*** based on interpretation of the gravity profile and surface geology looking northwest. (After Ager *et al.*, 1973)

had pronounced negative Eu anomalies (Fig. 4). In the Guichon Creek batholith, TREE abundances in hornblendes increase in successively younger phases and heavy to light REE ratios increase (Nie-Fengjun *et al.*, 1989). However, because mafic abundances are much lower in the younger phases, TREE values are lower in these phases. Source rocks that are likely to produce magmas with these kinds of REE signatures are either depleted mantle or subducted oceanic crust.

The REE data indicate that evolution of the Guichon Creek batholith took place through fractional crystallisation involving hornblende, sphene and apatite (Nie-Fengjun *et al.*, 1989). Based on major and minor element analyses, Johan and McMillan (1980) interpreted evolution to be due to fractional crystallisation with early cumulates containing abundant plagioclase with pyroxene, amphibole and magnetite, later joined by biotite during crystallisation of the "younger phases" (see legend, Fig. 1). Local pyroxene cores preserved in amphiboles in Border phase diorites add credence to this interpretation. For the younger phases, the REE patterns also suggest either that new melt was injected or that crystallised rocks remelted and became incorporated into the magma (Nie-Fengjun *et al.*, 1989).

McMillan (1976), McMillan and Johan (1981), McMillan (1982) and Tombale (1984) concluded that the phases of the batholith were derived from a single source magma. Oxides other than the alkalis have smooth evolutionary curves. During crystallisation of the older (Border and Highland Valley) phases, the trend was toward both potassium and sodium enrichment. However, between the older and younger phases there is a discontinuity in evolutionary trends. In the earliest of the younger phases

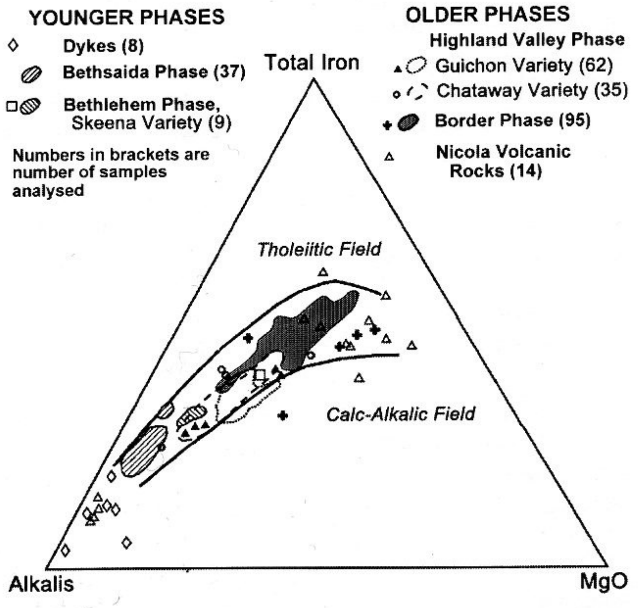

Figure 3: ***Ternary plot of alkalis, total iron and magnesium for rocks of the Guichon Creek batholith.*** Alkalic and tholeiitic trend lines are plotted for reference; the analyses show a clear calc-alkalic trend (modified after McMillan and Johan, 1981).

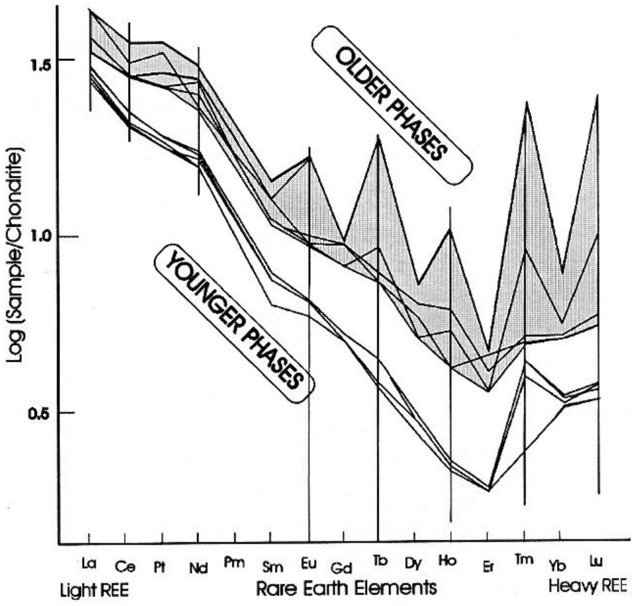

Figure 4: ***Rare earth element abundances normalised against chondrites*** for 10 samples of major phases of the Guichon Creek batholith (after Casselman *et al.*, 1995, CIM Special Volume 46).

(Bethlehem phase), potassium is sharply lower relative to sodium and the trend looks trondhjemitic (Fig. 5), although if dykes are considered, subsequent evolution was again toward both sodium and potassium enrichment (Olade, 1976; Briskey *et al.*, 1981). McMillan and Johan (1981) interpreted this discontinuity to mark separation of a fluid phase within the crystallising magma.

Ages of Intrusion and Mineralisation

Isotopic dating in the batholith yielded potassium-argon ages averaging 202±8 million years, rubidium-strontium ages of 205±10 million years (Preto *et al.*, 1979), and a uranium-lead zircon age of 210±3 million years (Mortimer *et al.*, 1990). Initial strontium ratios are primitive, 0.7025 to 0.7046 (Preto, *et al.*, 1979), also suggesting that the magma was derived from the mantle or subducted oceanic crustal material. Potassium-argon ages of hydrothermal muscovite range from 202±4 Ma (Jones, 1975) to 192±8 Ma (Blanchflower, 1971). Considering the lower closing temperature of the K-Ar system, these results suggest that the age of the hydrothermal alteration and mineralisation are slightly younger, but not significantly different than the age of crystallisation of the batholith.

Younger Rock Packages

Rapid uplift and erosion followed intrusion of the Guichon Creek batholith. By Early Jurassic time the batholith was locally unroofed and shedding debris into sedimentary basins now preserved along its north and northwest flanks as the Ashcroft Formation. Where exposed, the contact between the Ashcroft Formation sediments and the Nicola Group volcanic country rock is an angular unconformity (McMillan, 1974), and locally Ashcroft Formation conglomerates unconformably overlie rocks of the batholith.

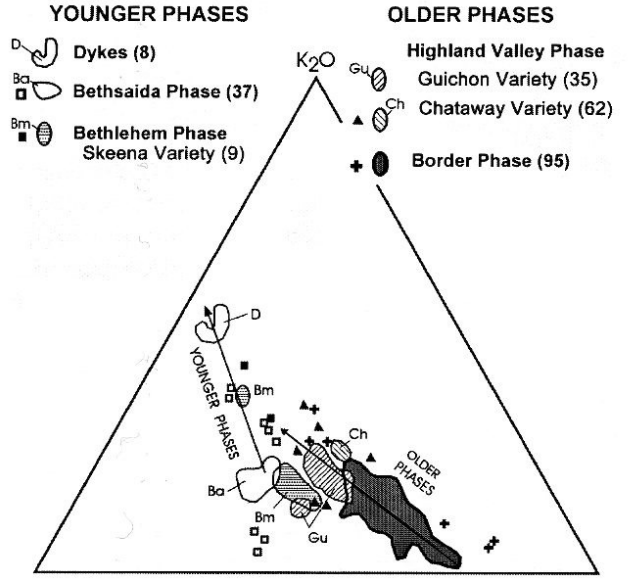

Figure 5: ***Ternary plot of alkalis versus lime for major phases of the Guichon Creek batholith.*** There is a 'discontinuity in the evolution path between the 'older' and 'younger' phases (see legend Fig. 1 for explanation of terms). After McMillan and Johan (1981).

Two younger volcanic-dominated successions are important in the area. A northwest trending belt of Late Albian (Irving and Thorkelson, 1990) continental volcanic and sedimentary rocks unconformably overlie both the Nicola Group country rock and intrusive rocks along the southwest flank of the batholith. The distribution of Spences Bridge Group rocks was locally controlled by reactivation of older faults, like the Lornex fault, that were important controls for Cu-Mo mineralisation in the batholith. As well, Tertiary continental volcanic and sediments cover extensive areas of the batholith, overlie Triassic and Jurassic rocks from north of Highland Valley to the Thompson River, form isolated outliers, fill fault-bounded valleys, and form local intrusive centres within the batholith.

A thin layer of glacial deposits covers much of the batholith. In the Highland Valley, Pleistocene stratigraphy is complex; the area was influenced by three or possibly four major glaciations. In general, near the Valley mine, Bobrowsky *et al.* (1992) reported that the Highland Valley is infilled by a thin basal unit of weathered bedrock covered by fluvial fan deposits overlain by a thick sequence of thin-bedded glacio-lacustrine rhythmites that are progressively coarser and thicker up section. This is in turn overlain by a moderately thick, well to poorly bedded sand and sandy gravel foreset bed complex formed by a series of prograding, coalescing delta fronts. Poorly sorted sand and gravel beds interbedded with clast-supported diamicton that represent outwash deposits in proglacial and subglacial environments followed. Subsequent intercalated subglacial outwash sands and gravels are overlain by basal till deposited as ice overrode the valley. Above the till are sands, gravels and diamictons deposited in a superglacial environment that ended with braided stream deposition during in situ ice decay. Local stratified sand and marl with interbeds of peat represent Holocene deposits formed in depressions formerly occupied by stagnating ice blocks.

General Structure of the Guichon Creek Batholith

The batholith is internally subdivided into segments by northerly and north-westerly to westerly striking faults. The major northerly structures are the central Lornex fault, the bounding Guichon Creek fault to the east and the Bonaparte disturbed zone to the west (Fig. 1). The major north-westerly structures occupy, from south to north, Skuhun Creek, Highland Valley and Barnes Creek. Dykes fill large-scale tension fractures that have orientations similar to those of the major faults. The most important are the north-westerly striking Gnawed Mountain dyke, and the northerly striking dyke swarms that extend from the Skuhun Creek fault through the Highland Valley to the Barnes Creek fault (McMillan, 1976).

The major faults may reflect reactivation of older regional structures. Those that cut the batholith originated in the Mesozoic, prior to mineralisation, and have been periodically reactivated at least until the Tertiary. During formation of the deposits they apparently channelled hydrothermal fluids into faulted, fractured and brecciated sites where conditions led to deposition of metallic minerals.

Later movement on the faults may have influenced the distribution of Jurassic sediments, and they locally influenced the distribution of Cretaceous and Tertiary strata. Early movement on the Lornex fault was dextral and perhaps reverse, but block faulting occurred during the Cretaceous and Tertiary events.

Regional Alteration Assemblages and Patterns

Away from the mineral deposits, virtually every thin section reviewed during mapping of the Guichon Creek batholith displayed weak deuteric alteration. Further, alteration and veining on mineralised joints was widespread.

Reconnaissance alteration mapping in the batholith by Casselman from 1980 until 1983 defined distal, regionally significant green sericite vein and chlorite (epidote) vein alteration types (Casselman *et al.*, 1995). Rocks with distal alteration assemblages are weakly to strongly fractured, and the intensity of alteration is commonly directly proportional to the spacing of fractures. In areas mapped as moderately to strongly altered, alteration occurs along more than 20% of the fractures developed in 50% of the outcrops present. In areas of weak alteration, between 5 and 20% of the fractures in 50% of the outcrops are affected.

Distal green sericite alteration ranges from thin coatings on fractures to pervasive replacement of whole feldspar grains adjacent to the fractures. In thin section the green altered feldspar consists dominantly of sericite with lesser and variable amounts of chlorite, kaolinite and carbonate. The chlorite (epidote) vein-type alteration coats fracture planes, forms veinlets and replaces mafic minerals. Epidote and, less commonly, quartz or carbonate may accompany the chlorite, and occur locally as separate veinlets. Most mafic minerals in the batholith are chloritised to some degree, so chlorite alteration was only considered to represent distal hydrothermal alteration if it was accompanied by fracture fillings or veinlets.

The type of vein alteration developed depends strongly on the composition of the host rock; mainly green sericite veins characterise the more felsic Skeena and Bethsaida phases, but chlorite (epidote) veins predominate in the earlier, more mafic phases of the batholith. However, close to the five main deposits and other significant copper-molybdenum or copper-iron (hematite) showings, both vein types commonly develop regardless of the composition of the host rock.

The composite zone defined by these distal, vein-controlled alteration-types encloses the proximal alteration assemblages associated with the major ore deposits. Proximal alteration and veining types include potassic (potassic feldspar and hydrothermal biotite), phyllic, argillic and propylitic. If the distribution of the distal alteration zones had been determined during the early stages of exploration in the district, it would have focused attention on the productive core area of the batholith.

Individually, the areas of sericite and chlorite alteration respectively form ovoid, north to north-westerly trending zones. Taken together they form a crudely oval area approximately 20 by 30 kilometres in size. About half the outcrops within this area have been effected to some degree by one or the other of the distal alteration-types (Casselman *et al.*, 1995). Smaller zones of similar alteration that occur outside this area are structurally controlled and often associated with small Cu-Mo and Cu-hematite showings. Overall, Casselman found that moderately to strongly developed distal alteration zones enclosed each of the five main deposits and formed extensions outward from these deposits along the Lornex and Highland Valley faults.

General Geology of the Highland Valley Ore Deposits

Ore Deposits: General Formation Model

Significant porphyry deposits in the Guichon Creek batholith (Table 1) are confined to the central part of the intrusion (Fig. 1). McMillan (1976, 1982) and others (Westerman, 1970; Olade 1974; Johan and McMillan, 1980) present evidence to relate mineralisation to separation of a fluid phase due to water saturation in the evolving, crystallising magma. Metals and other mobile elements were scavenged into this fluid. Significantly, the first mineralising event, which closely follows emplacement of the Bethlehem phase, also corresponds with the first major episode of dyking and formation of breccia bodies in the batholith. The Bethlehem deposits, Getty North (formerly Krain), Getty South (formerly South Seas or Trojan) and other mineralised zones resulted. The second, and most significant mineralising event, which formed the Valley, Lornex, Highmont, JA and several smaller deposits, followed emplacement of the Bethsaida phase, the youngest major phase of the batholith. Dyke emplacement and breccia formation also occurred during this event. Most of the mineralisation is structurally controlled, although sulphides replacing mafic minerals are important in more mafic host rocks, such as those at Getty North. Grades in the deposits are best in areas where a number of closely spaced fracture swarms intersect.

Geological Settings of the Deposits

Highland Valley porphyry deposits occur either in younger phase rocks, or in dyke swarms and intrusive breccias associated with younger phase rocks. The various Bethlehem Copper deposits occur close to contacts along which Bethlehem phase granodiorites intrude more mafic Guichon granodiorites. Mineralisation occurs along fractures and veins in the granodiorites, in intrusive breccias, and in dacite porphyry dykes, although not all the dykes are mineralised (Briskey and Bellamy, 1976). North of Bethlehem, many showings and two moderate-sized deposits are known. Getty South (formerly South Seas) mineralisation is in a breccia pipe cutting Guichon granodiorite. It has associated porphyry dykes similar to those at Bethlehem. Getty North (formerly Krain) mineralisation is also in Guichon granodiorite and is associated with porphyry dykes and a sheet-like body of Bethlehem granodiorite (Christie, 1976).

The Highmont deposits are largely in Skeena granodiorite adjacent to the large, composite Gnawed Mountain dyke.

The dyke is largely pre-ore and is weakly to moderately well mineralised in the ore zones. Breccia bodies occur at Highmont but do not host significant reserves (Reed and Jambor, 1976). Lornex has a thick quartz porphyry dyke at its south end but mineralisation is mainly in Skeena granodiorite close to the contact with the Bethsaida granodiorite, the youngest major phase of the batholith (Waldner *et al.*, 1976). Valley mine mineralisation is almost entirely within the Bethsaida granodiorite; porphyry dykes are present but volumetrically insignificant, and no breccia bodies are known (Casselman *et al.*, 1995).

Structural Characteristics of the Deposits

Most copper and molybdenum mineralisation in Highland Valley deposits is fracture controlled. As a generalisation, better grades occur where fracture density is high or where several sets of fracture swarms overlap. Except where mafic minerals are relatively abundant, little truly disseminated mineralisation is present, although sulphides do occur in alteration zones that fringe veins and fractures in all the deposits.

The Lornex fault is well defined between Skuhun Creek and Highland Valley, where it truncates the Lornex deposit on the west and the Valley mine on the east. Geologic contacts along this segment of the fault show 5 to 6 km of cumulative right-lateral offset. The dip of the fault near Lornex varies from moderate to steep toward the west (Waldner *et al.*, 1976) but drilling at Valley mine indicates that the fault is nearly vertical there. Drill results also suggest that the fault splits into several strands south and perhaps east of Valley mine. Lineaments suggest that strands of the fault continue north of Highland Valley, but this is uncertain because outcrop is sparse and Tertiary volcanic cover extensive. The Lornex fault can be traced southward to beyond the Nicola River as lineaments on satellite images, topographic maps and airborne magnetic maps. Evidence indicates that movement on the Lornex fault occurred over a long span of time, beginning in the Mesozoic and continuing periodically into Tertiary time (McMillan, 1976). The elongated shape of the batholith suggests that a precursor to the fault controlled the emplacement and shape of the batholith (Carr, 1969). If, as Carr (1969) and Allen and Richardson (1970) speculated, the Valley mine and Lornex deposits were once joined, then dextral offset on the Lornex fault post-dates ore emplacement. It should be emphasised that the relationship between the fault and the ore bodies at Lornex and the Valley mine is not simple. Simply removing lateral offset between the two deposits does not produce matching geology, Cu-Mo grade patterns, alteration zones or sulphide zonation patterns. McMillan (1976) argued that the Valley mine formed at a deeper level under higher temperature conditions than the Lornex deposit but the amount of vertical offset on the Lornex fault is not closely constrained.

The Tertiary block faulting created a pattern of horsts and grabens. For example, the area between the Highland Valley and Skuhun Creek faults is a horst and areas to the north and south are grabens (McMillan, 1976). A series of Tertiary basins occur along the Highland Valley and underlie Guichon Creek valley. This structural pattern influenced the depth of erosion and consequently the level of exposure of the ore deposits. Depth of emplacement of the deposits was inferred based on the host rocks, variations in the intensity of alteration, and the presence of porphyry dyke swarms and intrusive to explosion breccias. From deepest to closest to surface the deposits apparently sort as follows: Valley mine, Lornex, Highmont and JA, the Bethlehem deposits and South Seas, then Krain (Fig. 6).

General Characteristics of Alteration in the Deposits

As with most other calc-alkaline porphyry deposits, the Lowell and Guilbert (1970) alteration model applies in a general way to Highland Valley deposits. However, as Guilbert pointed out during the 1992 Northwest Mining Association Porphyry Deposit short course, this model is a composite made from observations at several deposits. Thus not all the components occur in all the deposits. In general, the five main Highland Valley deposits have central potassic alteration, fringing propylitic alteration and central overlapping, partly overprinted phyllic and argillic alteration, similar to the distribution described by Gustafson and Hunt (1975) for the El Salvador deposit in Chile. Two deposits, Lornex and Valley, have central silicic zones.

The silicic alteration consists both of quartz veining and of pervasive silica flooding. The zone at Lornex plunges northward, is moderately developed, and is relatively well mineralised. That at Valley mine plunges northwest and is more intensely developed. Except at its fringe, it is generally poorly mineralised.

Potassic alteration in Highland Valley deposits is defined by the distribution of hydrothermal potassic feldspar or biotite. Valley mine has a moderately to strongly developed vein-controlled potassic feldspar alteration in the central, deeper parts of the deposit. Anhydrite is locally preserved in this zone, and magnetite-rich zones in the Salt and Pepper granodiorite are interpreted to be part of the potassic alteration assemblage. At JA, the carapace of the JA stock is flooded and veined with potassic feldspar. However, where grades of mineralisation are higher, the potassic mineral is secondary biotite. Perhaps the zone with potassic feldspar is related to emplacement of the stock rather than mineralisation. Remnant patches of weakly to moderately developed secondary biotite in the argillic alteration zone near the centre of the Lornex deposit suggest that a larger, coherent zone may have existed but is now largely overprinted. Bethlehem has a coherent, moderately developed, central biotite alteration zone. At JA and Highmont, hydrothermal biotite is widespread but the distribution is patchy; it is largely overprinted by younger chlorite alteration. At Highmont, Reed and Jambor (1976) found that the distribution of weak and sporadic remnants of pervasive hydrothermal biotite alteration more or less correspond to the mineralised zones.

Phyllic alteration is well developed in Highland Valley deposits and grades out into argillic alteration. It consists of sericite and "flaky sericite" (muscovite) veinlets and fracture-controlled alteration zones as well as quartz veinlets with sericite and flaky sericite (muscovite) selvages. This vein-related alteration generally occurs outboard of the potassic alteration zones, if present, and is widespread and moderately to strongly developed. It is an important copper ore host at the Valley mine and is widespread and moderately developed and mineralised at Lornex. A moderately developed zone of this kind flanks the potassic core zone in the Jersey zone at Bethlehem Copper. Phyllic alteration is only weakly developed in the other major deposits.

The term argillic alteration, as used here, consists of pervasive kaolinite and sericite development, with lesser montmorillonite. It is widely developed in Highland Valley deposits, but the intensity varies considerably between deposits. It is widespread and moderately to strongly developed at the Valley mine and at Lornex. It is stronger adjacent to vein-type phyllic alteration zones and also extends out to, or just beyond, the 0.1 percent copper isopleth in these deposits. It is moderately well developed at Bethlehem, and extends out to the 0.1 percent copper isopleth (Briskey and Bellamy, 1976). Argillic alteration is generally weakly developed at Highmont and in the JA deposit. Argillic alteration affects feldspars and, to a lesser extent, mafic minerals. Fracture-controlled argillic alteration also occurs. Kaolinite dominates in these moderately to intensely developed zones that occur mainly with late-stage faults and clearly overprint main stage alteration types.

Propylitic alteration zones are generally outboard of and gradational with the argillic zones. All Highland Valley deposits have propylitic alteration halos, but the intensity varies with the original mafic mineral content of the altered rock. The halo in leucocratic rocks, as at the Valley mine, is weakly developed and sporadic, whereas in more mafic rocks, such as at the Bethlehem mine, it is moderately to strongly developed. Propylitic alteration is weakly to locally moderately developed in the Lornex, JA and Highmont deposits. Except at Bethlehem, the propylitic zones typically contain much less than 1 percent pyrite; at Bethlehem the abundance approaches 1 percent. The distinguishing minerals of the propylitic assemblage are epidote, chlorite and pyrite. Microscopically, feldspars are altered to sericite, carbonate and clay minerals, and mafics to chlorite, carbonate and epidote.

Late stage alteration minerals include carbonate, gypsum and zeolite. Typically these are in post-ore veins.

Metal Zoning Patterns

Metallic mineral zoning is generally well developed in Highland Valley deposits. The typical pattern is from bornite through chalcopyrite to a pyrite-dominated zone, albeit the pyrite content generally is 1 percent or less. The pattern may be nearly concentric, as at Bethlehem and Valley, or it may be elongated, as at JA, where the trends follow the contact of the stock, Highmont, where zoning is parallel to the contact of the Gnawed Mountain dyke, or Lornex, where zones follow the structure that controlled emplacement of the large quartz porphyry dyke. However, because grades are mainly controlled by structure, sulphide zoning does not consistently correlate closely with grade. Thus, although the bornite-dominant zones at Bethlehem, Lornex and Valley have better than average grades, the higher grade zones at Highmont and JA are in the chalcopyrite-dominant zone.

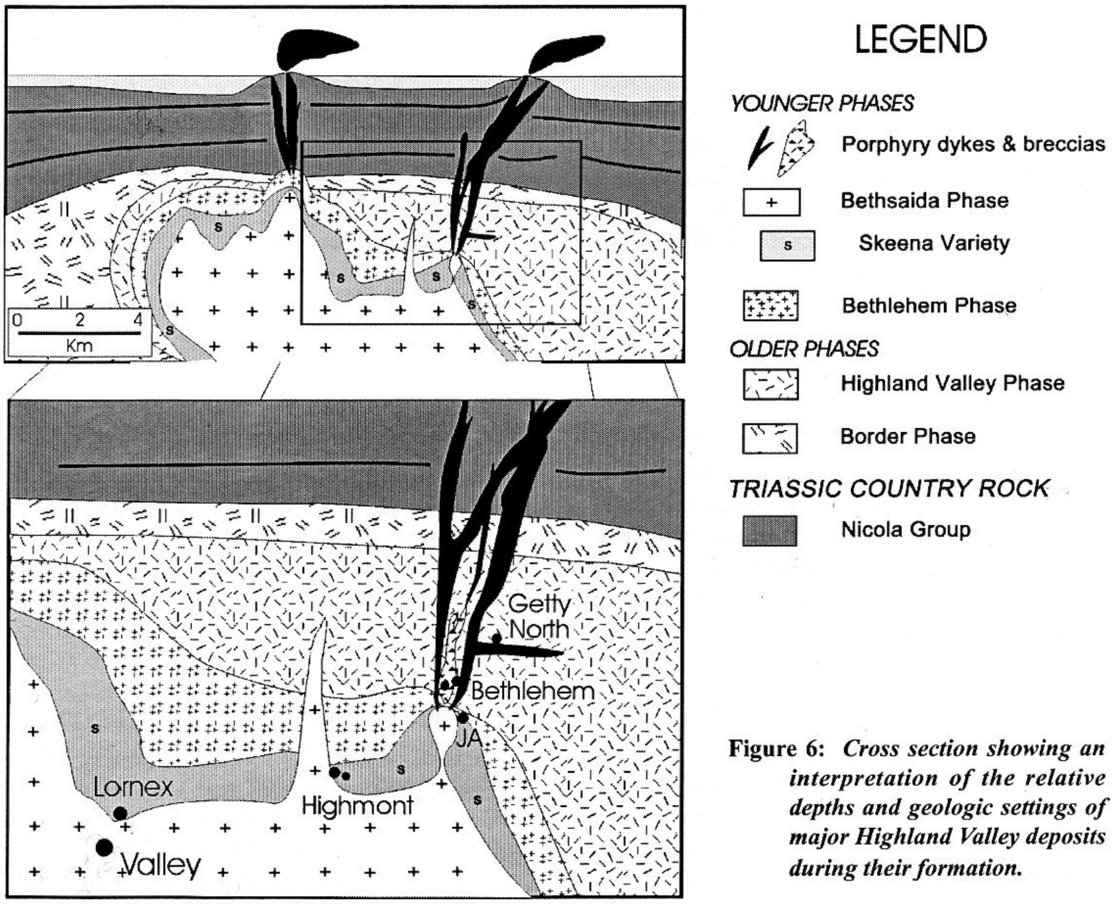

Figure 6: ***Cross section showing an interpretation of the relative depths and geologic settings of major Highland Valley deposits during their formation.***

Molybdenite abundance and distribution patterns change from deposit to deposit. Grades can be economically significant, as at Highmont, Lornex and JA, or barely recoverable, as at Bethlehem and the Valley mine. The distribution of molybdenum coincides in a general way with the distribution of copper, but the two are not identical. For example, at Highmont, Reed and Jambor (1976) report that the top of the molybdenite zone is below that of the copper zone and its base extends deeper. At the Valley mine and Lornex, the best molybdenum grades developed at the margins of the deposits. At JA the zone of most continuous molybdenite occurrences corresponds with the copper zone to the north, but extends beyond it in the south. At Bethlehem, molybdenum is erratically distributed.

Geochemical Zoning Patterns

Major and trace elements are zoned across the batholith as well as around Highland Valley deposits. Most major elements in the batholith show a smooth differentiation trend, but alkalis display a sudden decrease in the relative amount of potassium (Fig. 5), between the younger and older phases (McMillan and Johan, 1981; McMillan, 1982, 1985). Tombale *et al.* (1985) report a decrease in K/Rb ratios during differentiation; they interpret this to represent fractional crystallisation involving both biotite and hornblende, and the effects of an aqueous phase. Minor elements fall into three groups; some have smooth differentiation trends, controlled by ferromagnesian minerals; some are influenced by Na, K and Ca abundances; and some, most notably Rb, Cu, U, Th, La and Zr, show a discontinuity between the older and younger phases (Brabec, 1971; McMillan, 1982). In the case of copper, this change is dramatic. In the older phases, average copper abundances range from more than 120 to about 100 parts per million; in the younger phases, the averages are from about 50 to less than 10 parts per million (Fig. 7). This dramatic change may mark the time of separation of a fluid phase from the water-saturated melt and partitioning of the more mobile elements into that fluid (McMillan and Johan, 1981).

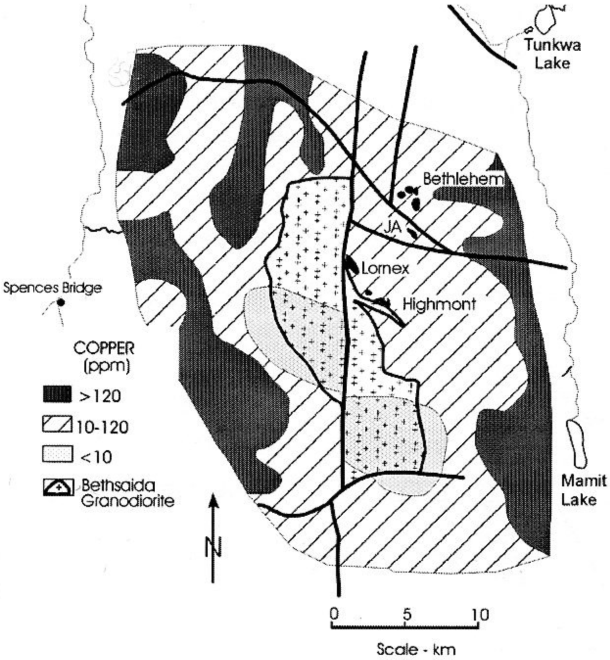

Figure 7: ***Copper abundances for lithogeochemical samples of the major phases of the Guichon Creek batholith*** showing the outline of the youngest (Bethsaida) phase for reference.(after McMillan, 1985).

Near the deposits, Olade (1974, 1976) and Osatenko and Jones (1976) documented the changes related to mineralisation. The lithophile elements Ca, Na, Mg, Sr, Ba and Mn, decrease from the borders of the deposits to their cores. For example, at the Valley mine, Osatenko and Jones report increasing intensity of leaching from the propylitic through the argillic into the phyllic zone. Other elements at the Valley mine tend to be enriched in the ore zone, notably Si, K, Rb, Fe and Ti. Olade reported similar patterns for the JA and Lornex deposits but documented Fe depletion in the core zones. He noted that potassic alteration zones gained Rb, Ba, Si, K and S, but lost Ca, Mg, Fe, Na and Al. Lithophile element depletion zones in the deposits more or less coincide with the various alteration zones, whereas femic elements, Zn, Mn, Ti, V, Ni, Co, Fe and Mg, are less mobile and tend to reflect host rock type. Anomalous sulphur and copper concentrations form halos up to 500 metres wide around the deposits.

Applied Exploration Techniques

Geochemical and geophysical techniques tried during exploration of the Guichon Creek batholith include silt and soil surveys, auger sampling at the bedrock contact, and induced polarisation, magnetometer, HLEM, and VLF-EM surveys. In the 1960's, silt and soil geochemical surveys were conducted over several of the five main deposits, but results were inconsistent due to the veneer of glacial overburden. Auger sampling near the bedrock surface was successful but too costly to be widely applied. Of the various geophysical methods tried, induced polarisation was the only tool found to be consistently useful in locating and defining significant copper-molybdenum mineralisation. Casselman *et al.* (1995) discussed induced polarisation surveys conducted over the Valley, Bethsaida and Lornex deposits. These surveys outlined two anomalies enclosed within a broad, roughly circular, weakly anomalous area of 6-8 msec, 4.5 km in diameter. Background for the area is generally 3-5 msec.

The Valley deposit was outlined by a roughly oval 10 msec chargeability contour 1750 m north-easterly by 950 m north-westerly in size. The 10 msec contour was, in part, roughly coincident with the 0.3% Cu contour defined by diamond drilling. The Bethsaida zone was outlined by a roughly oval 10 msec chargeability contour with axes 1400 m east-west and 1000 m north-south. It is 1000 m southwest of the Valley mine and connected to it by the drill-defined 0.1% bedrock copper contour. Enclosed within the 10 msec contour was an oval, strongly anomalous area outlined by the 15 msec contour that is roughly 500 m east-west by 750 m north-south. Diamond and percussion drilling within the Bethsaida zone chargeability anomaly located a large area of 0.1 to 0.2% Cu enclosing smaller, poorly defined higher grade zones. At Lornex, the survey outlined a weakly anomalous northerly trending, hourglass-shaped anomaly 750 m by 2000 m in size. Chargeability was more than 5.0 msec, about twice background.

Valley Mine

During the 1970's attempts to develop the Valley mine were frustrated by rapidly escalating capital and operating costs, a four year copper price slump, and problems associated with joint ownership of the orebody. In 1981 Cominco purchased 100% ownership of both Valley Copper Mines and Bethlehem Copper Corporation, and formed the Highland Valley Copper Division of Cominco. In 1982, production at the Bethlehem Copper deposit ceased and pre-production development of the Valley mine orebody commenced. In January 1983 the company began milling Valley ore in the Bethlehem Copper concentrator.

In 1985, discussions, precipitated by low metal prices, led Cominco and Lornex to bring together the two operations. The position of the Lornex mill, about an equal distance from the Lornex and Valley mines, made using the larger, higher grade Valley deposit to feed the modern, highly-efficient Lornex mill, attractive. The Highland Valley Copper partnership came into being on July 1, 1986; Cominco owned 55% and Lornex 45%; the two companies shared control and management equally (Hansen, 1987).

In 1988, to take advantage of higher copper prices, the Partnership decided to increase daily production by merging with Teck's Highmont operation, which closed in 1984 due to low molybdenite prices. To attain increased throughput, the Highmont mill was dismantled and relocated beside the Lornex mill. Ownership of the Highland Valley Copper operation now consisted of Cominco 50%, Rio Algom 33.6%, Teck 13.9% and Highmont Mining 2.5%. The Company ranks second in the world on the basis of tonnes milled and ninth for copper production because of its relatively low grade ore. During 2002, approximately 208 000 t were mined each day, of which 136 000 t were ore. Mill feed is dominantly from the Valley mine with the remainder from the Lornex mine. The mill processed 49.8 Mt for the year that produced 447 000 dry tonnes of concentrate containing 176 090 t (386.7 million pounds) of copper and minor precious metals. Molybdenum concentrate production for the year was 4600 dry tonnes containing 2459 tonnes (5.4 million pounds) of molybdenum (Highland Valley Copper General Fact Sheet, May 2003).

Ore Production and Reserves

Ttable 1 below lists ore produced to December 31, 2002, and remaining proven plus probable reserves.

Host Rocks

The main host to the Valley mine mineralisation is porphyritic granodiorite of the Bethsaida phase of the Guichon Creek batholith. Rocks of the Bethsaida phase are medium to coarse grained with coarse phenocrysts of quartz and biotite. A typical modal composition (volume percent) is plagioclase 56%, potassic feldspar 10%, quartz 29% and biotite 4%. Accessory minerals are hornblende, magnetite, hematite, sphene, apatite and zircon, which make up the remaining 1% (Osatenko and Jones, 1976).

Bethsaida "Salt and Pepper" granodiorite in the southeastern part of the deposit hosts the eastern part of the "Silicic Re-entrant", a term applied to the siliceous core zone of the deposit. The granodiorite is only slightly

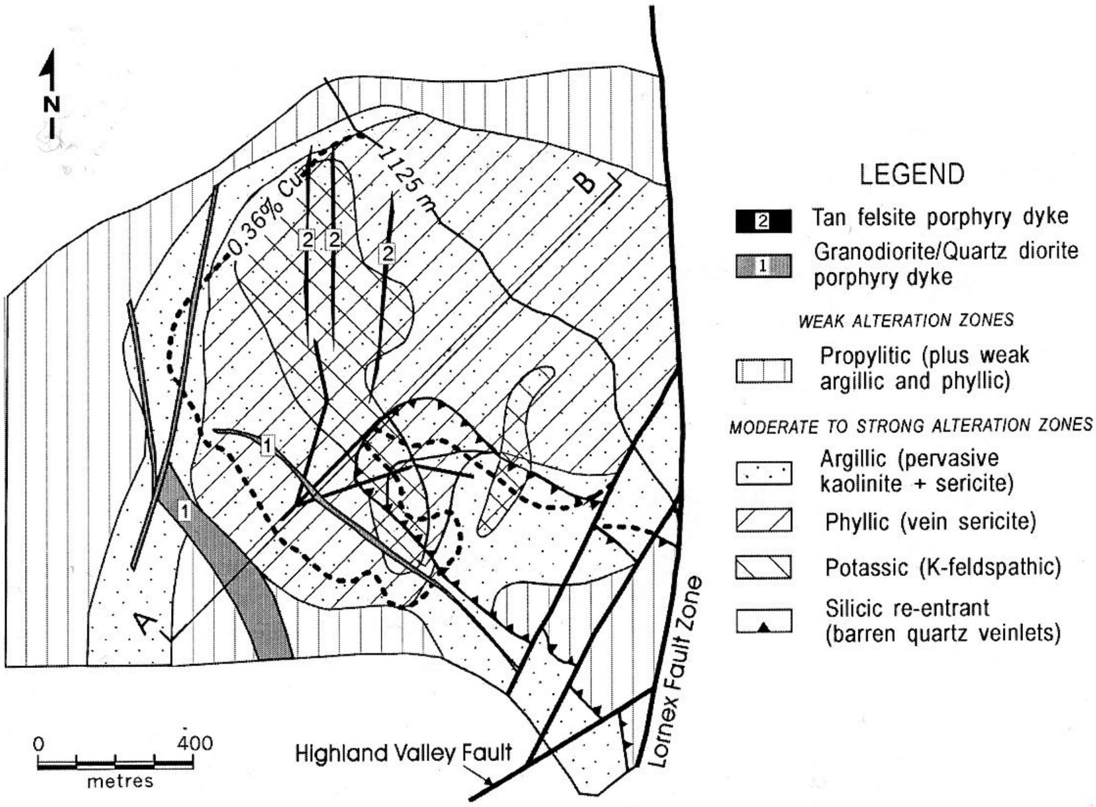

Figure 8: ***Plan view showing the distribution of major alteration types in the Valley deposit projected to the 1125 m level*** (after Casselman *et al.*, 1995, CIM Special Volume 46).

porphyritic. It is medium grained and consists of quartz (20%), feldspar (60%), with plagioclase greatly in excess of potassic feldspar, biotite (5-10%), and magnetite, sphene, apatite and zircon. Quartz consists of anhedral aggregates of interstitial grains and orthoclase is interstitial and perthitic. Biotite is subhedral to euhedral. The Salt and Pepper granodiorite is cut by mineralised and later barren quartz veinlets. Chalcopyrite and bornite occur in quartz-potassic feldspar and quartz-flaky sericite veinlets and alteration zones. Based on composition, textures and contact relationships, Casselman *et al.* (1995) interpret the Salt and Pepper granodiorite as a younger variety of the Bethsaida granodiorite.

Volumetrically, dykes are a minor component in the Valley deposit but several kinds occur. Granodioritic feldspar porphyry and quartz diorite porphyry dykes occur in the western, central and southern parts of the deposit. They vary in width from about 0.6 to 35 metres. Granodiorite feldspar porphyry consists of approximately 60% medium to coarse-grained plagioclase phenocrysts and a small number of quartz phenocrysts in a fine-grained matrix consisting of quartz, potassic feldspar and minor plagioclase with trace amounts of magnetite, hematite and biotite. Quartz diorite porphyry, which ranges from fine to coarse grained, contains up to 50% plagioclase and 8% quartz phenocrysts in a fine-grained matrix of quartz and plagioclase that contains minor amounts of potassic feldspar, magnetite and hematite (Osatenko and Jones, 1976). These dykes are variably cut by mineralised fractures and quartz veinlets. A single potassium-argon determination on biotite from a porphyry dyke gave an apparent age of 204 ± 4 Ma (Osatenko and Jones, 1976).

Aplite dykes up to 0.3 m in width occur throughout the deposit. An average modal composition (volume percent) is potassic feldspar 45%, quartz 44%, plagioclase 10% and biotite 1%. The aplite dykes are of pre-mineralisation age because they are invariably cut by mineralised fractures.

A swarm of tan-coloured felsite porphyry dykes intrude the Bethsaida granodiorite in the northwestern part of the deposit. These dykes, which are up to 4.5 metres in width, are characterised by a higher proportion of matrix (about 80%) than the other porphyry dykes. Their matrix is light tan in colour and consists primarily of potassic feldspar and quartz. Phenocrysts make up 20% of the rock and include quartz, plagioclase, potassic feldspar and biotite. These dykes were intruded during the waning stages of mineralisation. Some contain inclusions of sericite-veined Bethsaida granodiorite, others contain disseminated chalcopyrite and bornite and a scattering of mineralised quartz veins (Casselman *et al.*, 1995).

Three types of lamprophyre dykes, spessartite, hornblende-vogesite and vogesite cut both the alteration and the mineralisation. A vogesite lamprophyre returned a potassium-argon age of 132 ± 3 Ma (Jones, 1975).

Alteration

Alteration types recognised at Valley mine are silicic, potassic, phyllic, argillic, propylitic, biotitic and post-mineral veining. These alteration types are often intimately associated, even at the hand specimen scale. Except where otherwise acknowledged, data in this section are mainly after Osatenko and Jones (1976). A generalised plan view through the deposit showing the distribution of the major alteration types is depicted on Fig. 8.

Silicic Alteration and Veining

Stockworks of quartz veinlets are common at Valley mine. Most are 1 to 2 cm in width, but can be up to 25 cm thick. Type 1 veins are usually vuggy, and commonly have selvages of either medium-grained sericite, intergrown sericite and potassic feldspar, or potassic feldspar alone. They contain minor amounts of sericite, sericitised plagioclase, potassic feldspar, calcite, hematite, bornite, chalcopyrite, pyrite, molybdenite, digenite and covellite (Casselman *et al.*, 1995). Type 2 veins are most abundant in the Silicic Re-entrant in the southeastern part of the deposit. Most are 2 to 5 mm in width, have no alteration envelopes, and carry essentially no sulphides. Both fine-grained and medium-grained varieties occur. Type 2 veins have sharp contacts with both weakly altered and pervasively altered country rocks; most contain minor amounts of potassic feldspar. Muscovite is notably absent.

Potassic Alteration

Jambor and McMillan (1976) and Bond and McMillan (1998) note that potassic feldspar alteration is especially common at deeper levels in the deposit. Secondary potassic feldspar is most common as disseminations in quartz veinlets, or replacing adjacent country rock. It also occurs as thin, fracture controlled replacement zones. In the phyllic alteration zone, potassic feldspar typically forms thin, discontinuous selvages at the edges of the sericite-quartz veins where it apparently replaces sericitised plagioclase or vein sericite. Microscopic grains of anhydrite are commonly associated with potassic feldspar and sericite alteration (Jambor and McMillan, 1976).

Table 1: ***Ore produced to December 31, 2002, and remaining proven plus probable reserves***

Valley Mine	**Mt**	**Copper (%)**	**Molybdenum (%)**
Production (Million tonnes)	623.9	0.428	0.007
Reserves (at Dec. 31, 2002)	209.6	0.445	0.006

Lornex Mine	**Mt**	**Copper (%)**	**Molybdenum (%)**
Production (Million tonnes)	404.7	0.409	0.014
Reserves (at Dec. 31, 2002)	86.2	0.356	0.011

Cut-off is at an equivalent grade of 0.25% copper with a 2.0 times molybdenum factor.

Copper mineralisation is typically weak in the potassic feldspar alteration zones, and consists of chalcopyrite with trace amounts of bornite and molybdenite. Hydrothermal biotite (brown to green) is seen as overgrowths on primary biotite, replaces plagioclase and forms thin veinlets and replacement patches.

A major zone of potassic feldspar alteration in the west-central part of the deposit is intimately associated with, and enveloped by an extensive zone of moderate to strong phyllic and argillic (pervasive kaolinite and sericite) alteration. These grade outward into a zone dominated by weak to moderate argillic alteration that is fringed by a mixed zone of weak to moderate propylitic alteration and areas with no hydrothermal alteration. Well developed barren quartz-veinlet stockworks occur in the Silicic Re-entrant in the southeastern part of the deposit. Although the core area of the Re-entrant is poorly mineralised; its outer contact nearly coincides with the 0.36% copper isopleth. Aside from the Silicic-Re-entrant, quartz veinlets are only moderately developed within the ore zone but most of those present are mineralised.

Phyllic Alteration

Phyllic alteration is the most common alteration type associated with copper mineralisation at Valley mine (Bond and McMillan, 1998). It consists mainly of so-called flaky sericite, which is actually muscovite, and quartz. These occur both as replacement zones and as selvages on quartz veinlets. Sericite replacement zones follow fractures and range up to 3 cm in width. Most zones are vuggy, and their contacts are generally irregular and diffuse. Locally they contain narrow, discontinuous quartz veinlets and grade into the veinlet selvage type. Sericite borders on quartz veinlets range to 25 millimetres in width, but these widths do not correlate closely with the thickness of associated quartz veinlets.

Flaky sericite replacement zones and veinlet envelopes consist predominantly of fine-grained quartz and medium-grained muscovite (Osatenko and Jones, 1976). Other components are calcite, brick-red hematite, altered feldspar, sericitised biotite, bornite, chalcopyrite, and trace amounts of pyrite and molybdenite.

The mineralogy and contact relationships of vein sericite replacement zones and sericitic selvages on quartz veinlets are very similar and transitional types occur. Perhaps in some cases the original fractures that channelled the altering fluids were sealed by late stage quartz or earlier fractures were reopened and filled by quartz veinlets.

Moderate to strong phyllic alteration occurs in areas of moderate to strong argillic alteration and fracturing. Although the zones closely follow the 0.3% Cu isopleth, the alteration may extend up to 100 m beyond it into lower grade zones. Areas of stronger phyllic alteration (greater than 15%) correlate closely with areas of greater than 0.5% copper. Areas of moderate to strong phyllic alteration generally correlate well with areas of moderate to strong fracturing and moderate to strong argillic alteration (Casselman *et al.*, 1995).

Areas of moderate to strong secondary potassic feldspar alteration are also characterised by areas of moderate to strong fracturing, but they are spatially separated from phyllic and argillic alteration zones. Generally potassic alteration zones have less than 0.3% Cu content. Areas with propylitic alteration are characterised by weak fracturing and less than 0.15% Cu content (Casselman *et al.*, 1995).

Argillic Alteration

Argillic alteration, which is characterised by pervasive alteration of feldspar, is gradational into both pervasive phyllic and propylitic alteration. The intensity of argillic alteration development is directly related to fracture intensity. X-ray and thermo-gravimetric analysis show kaolinite to be the dominant clay mineral species in the deposit, although some montmorillonite occurs on its west side (Jones, 1975). Where pervasive argillic alteration is most intense, plagioclase is completely altered to a soft, green or white mixture of sericite, kaolinite, quartz and calcite. In these areas biotite is replaced by sericite, siderite, kaolinite and quartz; primary potassic feldspar is weakly altered to sericite and kaolinite; and magnetite is oxidised to hematite. Chalcopyrite, pyrite and sphalerite are present in trace amounts.

Plagioclase grains in areas of moderate pervasive argillic alteration are from 15 to 40% altered. Moderate argillic alteration extends an average of 100 m beyond the 0.3% Cu isopleth. Those with strong argillic alteration, where plagioclase is more than 40% altered, closely coincide with areas of greater than 0.5% Cu content (Casselman *et al.*, 1995).

Propylitic Alteration

Propylitic alteration is mainly peripheral to the deposit in areas of little or no fracturing. It also forms small areas within the deposit and, to some extent, below the 853 m level on its west side. Propylitic alteration is characterised by weak to moderate alteration of plagioclase to clay, some sericite, epidote, clinozoisite, and calcite, and alteration of biotite to chlorite and epidote. Thermo-gravimetric analyses of composite samples suggests that a calcite-rich zone, with calcite contents up to 4.2%, surrounds the deposit; values within the deposit are about 1% (Osatenko and Jones, 1976). Despite these data, defining the propylitic alteration zone associated with the Valley mine is difficult because deuteric alteration produced a similar suite of minerals in the country rocks on a regional scale. Propylitic alteration zones within the deposit have low copper contents, and the peripheral propylitic alteration zone lies outside the 0.15% Cu isopleth (Bond and McMillan, 1998).

Post-mineralisation Veining

Late-stage gypsum, anhydrite (some is syn-ore), kaolinite and fluorite veinlets occur at Valley mine. Gypsum veinlets are the most common type and most are less than 2 mm in width. They form white to orange, fibrous crystal aggregates that are oriented perpendicular to wallrock contacts. Gypsum is most common in areas with potassic feldspar alteration; it is rare above the 1036 m level.

Perhaps significant hydrothermal alteration only occurred below this level (Jambor and McMillan, 1976) or perhaps gypsum deposited above this level dissolved once the zone was above the ground water table.

Age Relationships

Interpretations of the relative ages of phyllic (vein sericite) and adjacent argillic (pervasive kaolinite and sericite) alteration zones vary. Contacts between them are sharp to gradational and it has been argued that the argillic alteration zones adjacent to phyllic zones might constitute transitions toward unaltered rock (McMillan, 1976). Locally, however, flaky sericite replacement zones and veinlet envelopes with sharp contacts apparently crosscut and post-date the pervasive argillic alteration zones. In contrast, Reed and Jambor (1976) concluded that sericite in the argillic zones is residual, and the kaolinite is actually younger. They interpret the same alteration sequence for all the Highland Valley deposits with early potassic and propylitic alteration overprinted by phyllic then argillic alteration.

Casselman *et al.* (1995) concluded that the main alteration types at the Valley mine have overlapping periods of formation. Based on crosscutting relationships they interpret the timing of alteration at the Valley mine as follows:

i). Early potassic alteration developed in the core of the deposit and was fringed by a zone of weak propylitic alteration. Zones enriched in disseminated magnetite in the Silicic Re-entrant within the Bethsaida Salt and Pepper granodiorite may be remnants of the original potassic zone; Froese (1981) showed that magnetite, biotite and potassic feldspar can coexist in equilibrium in the potassic alteration zone. Subsequent alteration partially overprinted these original zones;

ii). Argillic alteration may have overlapped and followed next;

iii). Fracture-controlled phyllic (vein sericitic) alteration can either be gradational with or cut the argillic (pervasive kaolinite-sericite) alteration, and quartz veinlets with phyllic envelopes consistently cut argillic alteration zones;

iv). Casselman noted that quartz veinlets with disseminated or bordering secondary potassic feldspar cut both argillic and phyllic alteration zones;

v). Barren quartz veinlets found in the Silicic Re-entranthave no evident alteration halos. Generally they cut both phyllic and potassic alteration zones. However, in some cases they are cut by veins with phyllic alteration. Casselman *et al.* (1995) argue that the lack of alteration rims on the barren veins indicates that they formed in equilibrium with the country rock, and may represent periods of influx of hotter magmatic fluids.

The overlapping and apparently contradictory alteration interrelationships led Casselman *et al.* (1995) to conclude that the hydrothermal system of the mineralising event was long-lived and cyclical. A factor that made interpretation difficult is that refracturing occurred along existing veins allowed new veins to be deposited along them. Overall, they felt that potassic alteration occurred during two or more events, mineralised quartz veinlets formed mainly during the phyllic alteration event, but flaky sericite-quartz alteration zones and quartz veinlets with muscovite-sericite selvages continued to form through to the time when potassic feldspar-bearing barren quartz veins were being deposited. The barren quartz veinlets developed late in the mineralising process, near the waning stages of both the phyllic and the second potassic alteration events. Obviously interpretation of the relative ages of alteration sequences in the Highland Valley deposits continue to be a source of controversy.

Grade and Metal Zoning

Casselman *et al.* (1995) note that the copper grade zones at Valley mine are elongated northwest-southeast and drape around the lower grade silicic re-entrant. The outer limit of the silicic re-entrant more or less conforms with the 0.36% copper isopleth. The increase in copper grade in both vertical and lateral directions away from the silicic re-entrant reflects an increase in the frequency of mineralised fractures. The barren quartz vein stockwork in the Silicic Re-entrant sealed many fractures and diluted copper grades.

Molybdenite mineralisation occurs as disseminations in crystalline sericite veins, fills fracture and shear zones, and occurs in late phase quartz veins. The quartz veins range from a few centimetres to 1.5 m in width and are usually mineralised with pyrite and chalcopyrite. Often, the molybdenum is distributed along multiple shears that parallel the borders of the veins resulting in a ribbon-like texture.

Casselman *et al.* (1995) noted that the highest molybdenum grades, 0.011% and greater, generally occur outside the 0.36% Cu isopleth in the western and northwestern parts of the deposit. Inside the 0.36% Cu isopleth, molybdenum grades are generally less than 0.006% in the western part, and 0.006 to 0.011% in the central and eastern parts of the deposit. Two molybdenum-enriched areas in the upper central part of the deposit suggest that prior to erosion there, a more extensive zone of greater than 0.011% molybdenum may have capped the deposit.

Relative Bornite Abundances

Casselman *et al.* (1995) note that a large zone of 40% and higher bornite relative to bornite + chalcopyrite occupies the central part of the deposit. The outer margin of the bornite dominant zone partially coincides with, but in places extends up to about 200 m beyond the 0.36% Cu isopleth. Within the zone, two areas of greater than 70% bornite generally exceed 0.36% copper content. Bornite to bornite + chalcopyrite ratios decrease progressively away from the centre of the deposit and the outer margin of the 40 to 70 % zone closely follows the 0.16% Cu isopleth, although it extends about 100 m beyond it on the western side of the deposit. Outside the zone bornite is uncommon (Casselman *et al.*, 1995). Although the total sulphide content within the Silicic Re-entrant is low, the bornite to bornite + chalcopyrite ratio is relatively high.

Relative bornite percentages were based mainly on visual estimations of bornite to bornite + chalcopyrite ratios in diamond drill core. However, point count studies of a number of sulphide concentrates prepared from reject assay material corroborated the visual estimates.

Arsenic Zoning

GT Metallurgical Services (1973) and Jones (1974) reported a minor amount of enargite associated with the primary copper sulphides. Arsenic values are variable but are on average below the penalty level imposed by smelters. Arsenic values in the copper concentrate indicate that enargite is generally more abundant in the bornite dominant zones (Casselman *et al.,* 1995).

Discussion

The Highland Valley porphyry district within the Guichon Creek batholith is one of a number of copper-molybdenum and copper-gold porphyry deposits that occur in the Quesnel terrane in association with either calc-alkalic or alkalic intrusive suites respectively. The intrusions were emplaced into a succession of island arc volcanic and associated rocks that are of Late Triassic to Middle Jurassic or Late Cretaceous to Eocene age. The Guichon Creek batholith is a Late Triassic calc-alkalic intrusion that REE data suggest was derived from either subducted oceanic crust or depleted mantle. The crystallisation age of the batholith, based on the U-Pb zircon analyses, is 210 Ma. Mineralisation occurred in late magmatic and early post magmatic time. The porphyry deposits were formed in an island arc setting before what is now the Quesnel terrane was accreted to North America.

The Guichon Creek batholith was derived from a single source magma but younger phases were locally injected into older due to tectonic forces. Cumulate crystallisation drove the differentiation and oxide analyses of less mobile major and trace elements have simple evolutionary curves. However, more mobile elements show a discontinuity between the older and younger phases of the batholith that is interpreted to mark partitioning of these elements into a fluid phase that separated when the crystallising magma became water saturated. The earliest porphyry deposits, which are accompanied by porphyry dyke swarms and breccia bodies, occurred after separation of this fluid phase.

The batholith is elongated northward and segmented by major northerly and northwest-striking faults that are intimately related to mineralisation. Most of the sulphide mineralisation is in fractures, veins, faults or breccia bodies, and all the deposits are hosted entirely within the rocks of the granodiorite batholith.

Alteration patterns are similar to those for other porphyry deposits but the intensity and mineralogy are influenced by the setting and the composition of the host rocks. In general, early potassic and propylitic alteration are overprinted by later phyllic and argillic alteration. In more detail, complications in cross-cutting alteration and vein relationships suggest local influxes of hotter aqueous solutions. Phyllic alteration is characterised by formation of both microscopic sericite and medium grained 'flaky sericite' (muscovite). Where host rocks are leucocratic, propylitic alteration halos are poorly developed. Principal hypogene metallic minerals in the deposits are bornite, chalcopyrite, molybdenite and pyrite. Pyrite abundances in the pyrite halos are 1% or less.

Lithogeochemistry indicates a generally high copper background (120 to 100 ppm) in the older rocks of the batholith and less than 50 ppm in the younger rocks. A central zone with less that 10 ppm copper that lies several kilometres south of the deposits may have provided the copper in the younger deposits. From an exploration perspective, other granitic bodies with similar 'negative geochemistry', that is generally high lithogeochemical background levels of copper in the less differentiated phases, combined with a strongly depleted zone or zones within one of the more evolved phases may indicate potential for formation of major porphyry deposits in the body.

Induced polarisation surveys have proven to be the most useful exploration tool in this glaciated area, but alteration mapping, silt, soil and deposit-oriented lithogeochemical surveys can be effective.

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References

Ager, C.A., McMillan, W.J. and Ulrych, T.J., 1973 - Gravity, magnetics and geology of the Guichon Creek batholith, *B.C. Ministry of Energy, Mines and Petroleum Resources Bulletin* 62, 18p.

Allan, J. and Richardson, J., 1970 - The geological setting of the Valley Copper orebody, *Canadian Institute of Mining and Metallurgy,* Annual Meeting, Toronto, preprint.

Blanchflower, J.D., 1971 - Isotopic dating of copper mineralization at Alwin and Valley properties, Highland Valley, British Columbia. *Unpublished BSc thesis, The University of British Columbia,* Vancouver.

Bobrowsky, P.T., Kerr, D.E. and Sibbick, S.J., 1993 - Drift exploration studies, Valley Copper pit, Highland Valley Copper mine, British Columbia: Stratigraphy and sedimentology (92I/6,7,10,11); *in Geological Fieldwork 1992: British Columbia Ministry of Energy, Mines and Petroleum Resources Paper* 1993-1, pp. 427-437.

Bond, L. and McMillan, W.J., 1998 - Porphyry copper deposits of the Canadian Cordillera with Emphasis on plutonic types and the Highland Valley camp of South-central British Columbia, *Annual Meeting 1998, Montreal, Canadian Institute of Mining,* compact disc for Technical Program.

Brabec, D., 1971 - A geochemical study of the Guichon Creek batholith, British Columbia; *Unpublished PhD Thesis, The University of British Columbia,* Vancouver.

Briskey, J.A. and Bellamy, J.R., 1976 - Bethlehem Copper's Jersey, East Jersey, Huestis and Iona deposits; *in* Sutherland Brown, A., (Ed.), Porphyry deposits of the Canadian Cordillera: *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 105-119.

Briskey, JA., Field, C.W. and Bellamy, J.R., 1981 - Geology, petrology and geochemistry of the Jersey, East Jersey, Huestis and Iona porphyry copper-molybdenum deposits, Highland Valley, B.C.; *in* M. Silberman, C. Field and A. Berry (Eds.), Proceedings of the Symposium on Mineral Deposits of the Pacific Northwest, 1980: *United States Geological Survey,* Open File Report 81-355, pp. 106-126.

Carr, J.M., 1969 - Valley; in Annual Report, 1968: *British Columbia Department of Mines and Petroleum Resources,* 181p.

Casselman, M.J., McMillan, W.J. and Newman, K.M., 1995 - Highland Valley porphyry copper deposits near Kamloops, British Columbia. A review and update with emphasis on the Valley deposit; *in* T.G. Schroeter (Ed.), Porphyry Deposits of the Northwestern Cordillera of North America: *Canadian Institute of Mining and Metallurgy,* Special Volume 46, pp. 161-191.

Christie, J.S., 1976 – Krain; in Sutherland Brown, A. (Ed.), Porphyry deposits of the Canadian Cordillera: *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 182-185.

Cook F.A., Varsek, J.L., Clowes, R.M. Kanasewich, E.R., Spenser, E.S., Parrish, R.R., Brown, R.L., Carr, S.D., Johnson, B.J. and Price, R.A., 1992 - Lithoprobe crustal reflection cross section of the southern Canadian Cordillera 1: Foreland thrust and fold belt to Fraser River fault, *Tectonics,* v. 11, pp. 12-35.

Froese, E., 1981 - Applications of thermodynamics in the study of mineral deposits, *Geological Survey Canada,* Paper 80-28, 38p.

GT Metallurgical Services, 1993 - Distribution of arsenic in the Valley deposit, *GT Metallurgical Services,* Kamloops, B.C., Unpublished internal report, Cominco Ltd.

Gustafson, L.B. and Hunt, J.P., 1975 - The Porphyry Copper Deposit at El Salvador, Chile, *Economic Geology,* v. 70, pp. 857-912.

Hansen, P., 1987 - Highland Valley Copper: A strategy for increased productivity, *Canadian Institute of Mining and Metallurgy* Bulletin, 80, No. 904, pp. 42-45.

Irving, E. and Thorkelson, D.J., 1990 - Determining paleohorizontal and latitudinal shifts: Paleomagnetism of Spences Bridge Group, British Columbia, *Journal of Geophysical Research,* v. 95, pp. 19 213-19 234.

Jambor, J.L. and McMillan, W.J., 1976 - Distribution and origin of the "Gypsum Line" in the Valley Copper porphyry deposit, Highland Valley, British Columbia; in Report of activities, *Geological Survey of Canada,* Paper 76-1B, pp. 335-341.

Johan, Z. and McMillan, W.J., 1980 - Possibilities d'Individualisation d'une Phase Fluide a partir d'un Bain silicate: Consequences geochimiques. Exemple du Batholith de Guichon Creek; in Johan, Z. (Coordinateur), *Bureau de Récherches Géologiques et Minières,* Memoire 99, pp. 85-94.

Jones, M.B., 1975 - Hydrothermal alteration and mineralization of the Valley Copper deposit, Highland Valley, B.C., Unpublished PhD Thesis, *Oregon State University.*

Lowell, J.D. and Guilbert, J.M., 1970 - Lateral and vertical alteration - Mineral zoning in porphyry ore deposits, *Economic Geology, v.* 65, pp. 373-408.

McMillan, W.J., 1974 - Stratigraphic sections from the Jurassic Ashcroft Formation and the Triassic Nicola Group contiguous to the Guichon Creek batholith; *in* Geological Fieldwork, *Ministry of Energy, Mines and Petroleum Resources,* Paper 1974-1, pp. 27-34.

McMillan, W.J., 1976 - Geology and genesis of the Highland Valley ore deposits and the Guichon Creek batholith; *in* Sutherland Brown, A. (Ed.), Porphyry Deposits of the Canadian Cordillera, *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 85-104.

McMillan, W.J., 1982 - The Behavior of U, Th and other trace elements during evolution of the Guichon Creek batholith, British Columbia; *in* Maurice, Y.T. (Ed.), Uranium in Granites, *Geological Survey of Canada,* Paper 81-23, pp. 49-54.

McMillan, W.J., 1985 - Geology and ore deposits of the Highland Valley camp; *in* Sinclair, A.J. (Ed.), Mineral Deposits Division Field Guide and Reference Manual Series, Number 1, *Geological Association of Canada,* 121p.

McMillan, W.J. and Johan, Z., 1981 - Rock geochemistry, geology and genesis of the Guichon Creek batholith in British Columbia, Canada, as it relates to Highland Valley ore deposits. *in* Silberman, M.L., Field, C.W. and Berry, A.L. (Eds.),.Proceedings of the Symposium on Mineral Deposits of the Pacific Northwest, 1980, *United States Geological Survey,* Open File report 81-355, pp. 84-105.

Monger, J.W.H. and McMillan, W.J., 1989 - Geology, Ashcroft, British Columbia, *Geological Survey of Canada,* Map 49-1989, 1:250 000 scale.

Mortimer, N., 1986 - Two belts of Late Triassic, arc-related, potassic igneous rocks in the North American Cordillera, *Geology*, v. 14, pp. 1035-1038.

Mortimer, N., Van der Heyden, P., Armstrong, R.L. and Harakal, J. (1990): U-Pb and K-Ar dates related to the timing of magmatism and deformation in the Cache Creek Terrane and Quesnellia, southern British Columbia; *Canadian Journal of Earth Sciences,* v. 27, pp. 117-123

Nie-Fengjun, McMillan, W.J. and Panteleyev, A., 1989 -

Translated title: Petrological characteristics and rock-forming mechanism of the Guichon Creek batholith, *Institute of Mineral Deposits, Chinese Academy of Geological Sciences* Bulletin, 93-106.

Nixon, G.T., Archibald, D.A. and Heaman, L.M., 1993 - ^{40}Ar-^{39}Ar and U-Pb geochronometry of the Polaris Alaskan-type complex, British Columbia; Precise timing of Quesnellia-North America interaction [abs.], *Geological Association Mineralogical Association Canada,* Abstracts with Program, 18, A-76.

Northcote, K.E., 1969 - Geology and geochronology of the Guichon Creek batholith, *British Columbia Department of Mines and Petroleum Resources,* Bulletin 56.

Olade, M.A.D., 1974 - Bedrock geochemistry of porphyry copper deposits, Highland Valley, Unpublished PhD Thesis, *The University of British Columbia.*

Olade, M.A.D., 1976 - Geochemical evolution of copper-bearing granitic rocks of the Guichon Creek batholith, British Columbia, Canada, *Canadian Journal of Earth Sciences,* v. 13, pp. 199-209.

Osatenko, M.J. and Jones, M.B., 1976 - Valley Copper; *in* Sutherland Brown, A. (Ed.), Porphyry Deposits of the Canadian Cordillera, *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 130-143.

Preto, V.A., Osatenko, M.J., McMillan, W.J. and Armstrong, R.L., 1979 - Isotopic dates and strontium isotopic ratios for plutonic and volcanic rocks in the Quesnel Trough and Nicola Belt, South Central B.C., *Canadian Journal of Earth Sciences,* v. 16, pp. 1658-1672.

Reed, A.L. and Jambor, J.L., 1976 - Highmont: Linearly zoned copper-molybdenum porphyry deposits and their significance in the genesis of the Highland Valley ores; *in* Sutherland Brown, A. (Ed.), Porphyry Deposits of the Canadian Cordillera, *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 163-181.

Sawkins, F.J., 1990 - Metal deposits in relation to plate tectonics, *Springer-Verlag,* Second Edition, 461p.

Sutherland Brown, A. (1976): Morphology and Classification; *in* Sutherland Brown, A. (Ed.), Porphyry Deposits of the Canadian Cordillera, *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 44-51.

Tombale, A.R., 1984 - An Interpretation of lithogeochemical data of the Guichon Creek batholith, Unpublished MSc thesis, *The University of British Columbia,* 141p.

Tombale, A.R., Sinclair, A.J. and McMillan, W.J., 1985 - Variation of K/Rb ratio in the major units of the Guichon Creek batholith (92I). *in* Geological Fieldwork 1984, *British Columbia Ministry of Energy, Mines and Petroleum Resources,* Paper 1985-1, pp. 419-425.

Waldner, M.W., Smith, G.D. and Willis, R.O., 1976 – Lornex; *in* Sutherland Brown, A. (Ed.), Porphyry Deposits of the Canadian Cordillera, *Canadian Institute of Mining and Metallurgy,* Special Volume 15, pp. 120-129.

Westerman, C.J., 1970 - A petrogenic study of the Guichon Creek batholith, British Columbia, Unpublished MSc Thesis, *The University of British Columbia.*

Zelt, B.C., Ellis, R.M., Clowes, R.M. Kanasewich, E.R., Asudeh, I., Luetgard, Z., Ikami, A., Spence, G.D. and Hyndman, R.D., 1992. Crust and upper mantle velocity structure of the Intermontane Belt, southern Canadian Cordillera, *Canadian Journal of Earth Sciences,* v. 29, pp. 1530-1548.