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Contrasting styles of alkalic porphyry copper-gold deposits in the northern part of the Iron Mask batholith, Kamloops, British Columbia

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ABSTRACT

The Crescent, DM, and Pothook zones are copper-gold porphyry deposits which formed in association with alkalic intrusions of the early Jurassic Iron Mask batholith. The characteristics of the Crescent and DM deposits are nearly identical. Both formed along the contact between the Cherry Creek monzodiorite and Pothook diorite phases of the batholith. Permeable intrusion breccias along the contact concentrated the flow of hydrothermal fluids. Early, pre-ore alteration is represented by pervasive, sulphide-barren potassium metasomatism. The precipitation of copper-gold ore occurred during subsequent fracture-controlled potassic alteration, and is most strongly developed in chlorite-sulphide veins and their alteration envelopes. A central zone of potassic alteration is surrounded by a propylitic, pyritic halo in both deposits. The DM zone is unique among alkalic porphyry deposits in its high abundance of quartz-sulphide veins.

The Pothook deposit formed at the westernmost contact of the Iron Mask batholith with enclosing Nicola Group volcanic rocks. Pervasive potassium metasomatism, similar in style to that at Crescent and DM, is associated with intrusion of the Cherry Creek monzonite. Pervasive and fracture-controlled albitic alteration is associated with intrusion of the Sugarloaf diorite and introduced minor copper-gold mineralization. Most of the copper-gold mineralization was introduced during formation of veins and breccia matrices dominated by magnetite/hematite and sulphide. Late-stage chlorite veining may have remobilized or introduced additional gold mineralization.

Copper and gold assays in the Crescent deposit are well-correlated and have a nearly constant Cu:Au ratio, suggesting that the metals coprecipitated during a single hydrothermal event. In the Pothook deposit, copper and gold do not correlate closely, lack spatial correspondence, and suggest that transport and/or deposition of the two metals were not identically controlled and that they may have been introduced at different times by separate hydrothermal events.

Introduction

At least 10 alkalic suite copper-gold porphyry deposits are present in the Afton mining camp (Fig. 1). Deposits in the district which have been mined include the Afton, Ajax East, Ajax West, Crescent, and Pothook deposits; the Big Onion, DM, and Python-Macaoo zones have published reserves but no production (Kwong, 1987; L. Bond, pers. comm., 1993). These deposits are all hosted by the Iron Mask batholith, a large, composite, alkalic intrusion of earliest Jurassic age (204 ± 3 Ma; Mortensen et al., this volume) that intruded and is hosted by Carnian to Norian, Nicola Group volcanic rocks (Preto, 1977) of the Quesnellia intraoceanic island arc terrane (Souther, 1992). These copper-gold deposits have been classified within the silica-saturated group of alkalic porphyry deposits by Lang et al. (1992).

Descriptions of the Pothook, Crescent, and DM deposits are based on maps of the Crescent (Lang, 1994) and Pothook (Stanley, 1994) open pits prepared at scales of 1:600, an outcrop map at 1:2400 scale of the northern part of the batholith (Stanley et al., 1994), and examination of diamond drill core from the three deposits. The geology of the deposits, the characteristics of hydrothermal alteration and mineralization, and the currently recognized controls on the distribution of mineralization are summarized, and the relationship of the deposits to the evolution of magmatic and hydrothermal events in the northern part of the batholith are considered.

The main orebody in the district is the Afton deposit (Fig. 1; Lat. 50°39′N; Long. 120°31′W; NTS 92I/10E), which is located 360 km northeast of Vancouver, and 10 km west of Kamloops, British Columbia. The Pothook deposit is located on the southwestern edge of the Iron Mask batholith, approximately 750 m southeast of the Afton deposit. The DM and Crescent deposits lie 1.5 km and 3 km east of Afton, respectively.

Road access to each of the deposits is via the main entrance to the Afton mill complex, which turns south off the Trans-Canada highway about 2 km west of its intersection with the Coquihalla highway. The individual deposits are reached via mine haulage roads. The topography around the deposits is gentle and comprises glaciated, gently rolling hills between 650 m and 800 m in elevation. Annual rainfall averages 26 cm. In the immediate area of the deposits, vegetation is dominated by sagebrush with a complete absence of forest cover. Outcrop is less than 5%.

History, Production and Reserves

Between 1986 and 1988, 2.36 Mt of ore were mined from the Pothook open pit at an average grade of 0.35% Cu and 0.77 g/t Au with a strip ratio of 2.4:1 (updated from Stanley, 1994). The Crescent deposit yielded 1.448 Mt of ore with an average grade of 0.44% Cu and 0.18 g/t Au (updated from Lang, 1994) during open pit production in 1989 and 1990. The DM zone has unmined geological open pit reserves of 2.685 Mt at 0.38% Cu and 0.27 g/t Au (L. Bond, pers. comm., 1994).

Historical exploration in the Afton area has been adequately summarized by Carr and Reed (1976), Preto (1972), Kwong (1987), and Ross et al. (this volume) and will not be repeated here. The Pothook, Crescent and DM zones were exposed in outcrop and have been the object of sporadic exploration since the beginning of this century. The startup of the Afton mining and milling complex in 1977 made it feasible to develop these prospects to the production stage.

The Crescent and DM deposits were explored and developed by Afton Operating Corporation (a partnership between Teck Corporation (73%) and an affiliate of Metall Mining Corporation (27%) until 1991 when Teck acquired full ownership) under an option agreement with the Comet-Davenport group of companies. The Pothook deposit is wholly owned by Afton Operating Corporation.

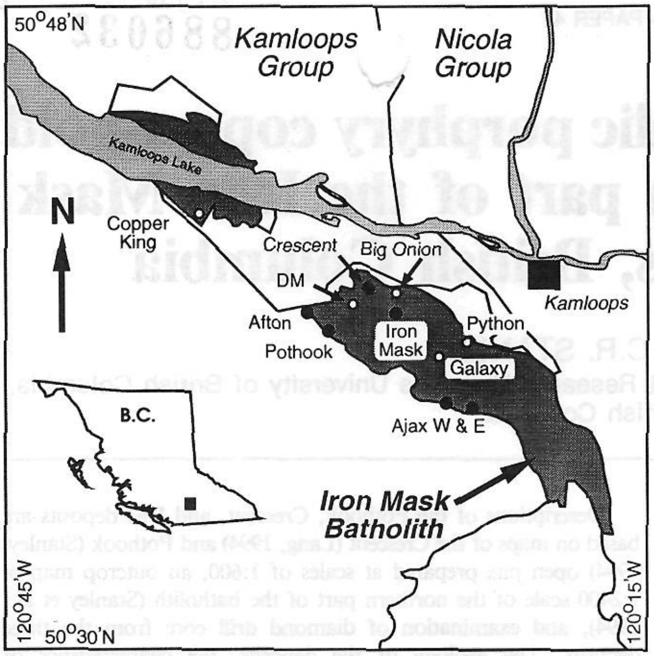

FIGURE 1. Location of the Iron Mask batholith and associated Cu-Au deposits.

Regional Geology

The geology of the Iron Mask batholith is most recently discussed by Snyder and Russell (1993a; this volume) and Stanley et al. (1994). These reports should be consulted for detailed descriptions of the intrusive units which form the batholith, and the volcanic facies which form the Nicola Group host rocks. Snyder and Russell (1993a; this volume) have revised the sequence of magmatic events in the batholith from that presented previously (Northcote, 1977; Kwong, 1987); the old and revised igneous sequences are shown in Figure 2.

The Crescent Deposit

Rock Types

The geology of the Crescent open pit (Fig. 3) is dominated by Pothook diorite and a finer grained, locally porphyritic monzodiorite intrusion of the Cherry Creek phase. Andesite and plagioclase diorite porphyry dikes are minor constituents.

The Pothook diorite is the oldest unit and dominates the south and west portions of the pit (Fig. 3). Least-altered samples of the diorite are greenish grey and equigranular, with a mineral assemblage comprising euhedral to subhedral plagioclase and pyroxene, poikiolitic biotite, anhedral magnetite and K-feldspar, and accessory euhedral apatite and subhedral titanite. Grain size is typically 1.5 mm to 3 mm, but more fine-grained areas have been recognized, particularly near the contact with the Cherry Creek monzodiorite. Throughout the batholith Pothook diorite is notable for a magnetite concentration which locally exceeds 15%, large poikiolitic biotite grains which enclose plagioclase and augite (Snyder and Russell, 1993a), and magnetite-apatite-actinolite ± trace sulphide veins and segregations which may reach several metres in width (Cann, 1979; Stanley et al., 1994). Near its contact with the Cherry Creek monzodiorite, Pothook diorite has been affected by strong potassium metasomatism which has locally given it a pseudoporphyritic texture as a result of conversion of the margins of plagioclase grains to massive, pink K-feldspar. Subangular to rounded xenoliths of an amphibolitized mafic rock, interpreted as a Nicola Group volcanic unit, are only rarely present.

The northern part of the pit (Fig. 3) is dominated by a monzodiorite intrusion of the Cherry Creek phase of the batholith (Stanley et al., 1994). In general, Cherry Creek monzodiorite is more fine grained than Pothook diorite, is variably porphyritic, and is a light pinkish or greenish grey colour. Phenocrysts include euhedral plagioclase laths, less abundant, more equant, subhedral to euhedral pyroxene, and trace to minor, subhedral amphibole. The aphanitic to fine-grained groundmass comprises orthoclase, magnetite, biotite, plagioclase and, in places, apatite. Near intrusive contacts the plagioclase phenocrysts have a trachytic texture. Strong to intense potassium metasomatism has locally obliterated the porphyritic texture and has converted the rock to a nearly aphanitic, maroon-coloured rock.

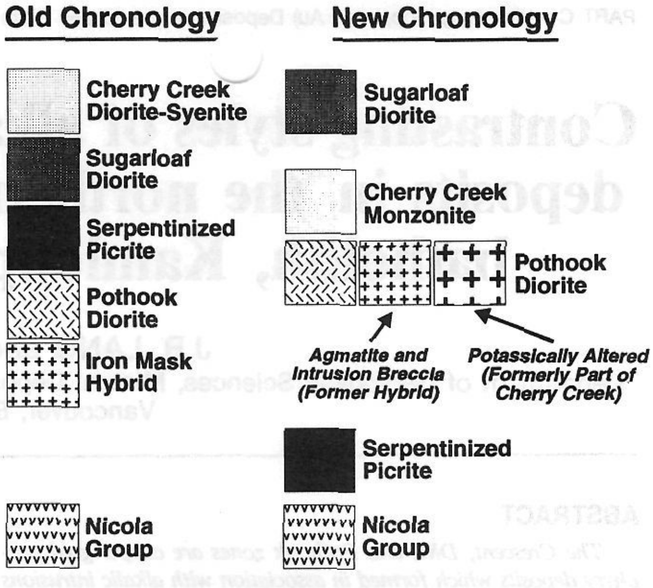

FIGURE 2. Comparison of old and revised stratigraphy of the Iron Mask batholith (after Snyder and Russell, this volume).

Plagioclase diorite porphyry dikes are common throughout the northern end of the batholith but are rare in the Crescent pit. They are dark green in colour and range from 1 m to 5 m in width. Narrow dikes are aphyric or have only very small plagioclase phenocrysts. Wider dikes have cores characterized by subhedral plagioclase and pyroxene phenocrysts in a fine-grained to aphanitic, dark grey-green groundmass, and chilled aphanitic margins up to 1 m in width. In the Crescent pit these dikes intruded during the waning stages of the pervasive potassium metasomatism but are cut by later mineralized veins.

Andesite dikes are rare in the Crescent pit and are typically less than 1 m wide, black to dark green in colour, and aphanitic. Larger dikes in the northern part of the Iron Mask batholith have pyroxene and plagioclase phenocrysts less than 3 mm in size in an aphanitic groundmass. These rocks are not altered and are interpreted to be related to Eocene mafic volcanic rocks of the Kamloops Group.

Structures

Major structures include the North, Centre, South and West Faults (Fig. 3). These faults all have dips steeper than 70°. The North, Centre and South Faults all trend about 070° to 090° but their displacement is unknown. The West Fault has a northwesterly orientation and displacement of plagioclase diorite porphyry dikes between benches 2245 and 2315 suggests a maximum dextral offset of a few metres; on the west side of this fault the intrusive contact between the Cherry Creek and Pothook phases appears to be offset by 50 m to the north but the structure responsible for this movement is not exposed. These fault zones range from 0.5 m to 5 m in width and are dominated by gouge or strongly shattered material with abundant calcite and chlorite; locally they contain calcite-quartz ± pyrite ± trace chalcopyrite.

The Crescent deposit has been intensely fractured along planar

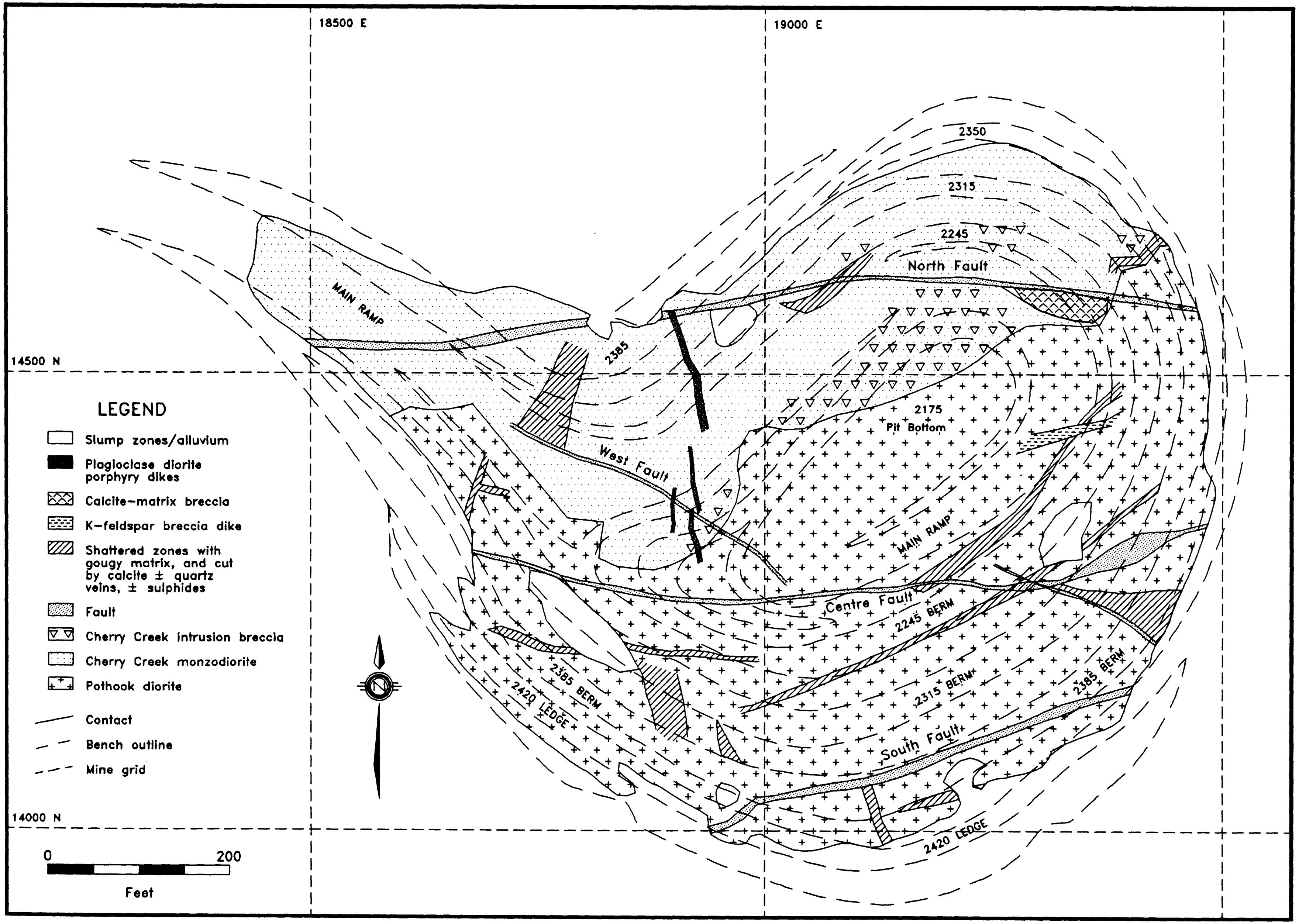

FIGURE 3. Geologic map of the Crescent open pit.

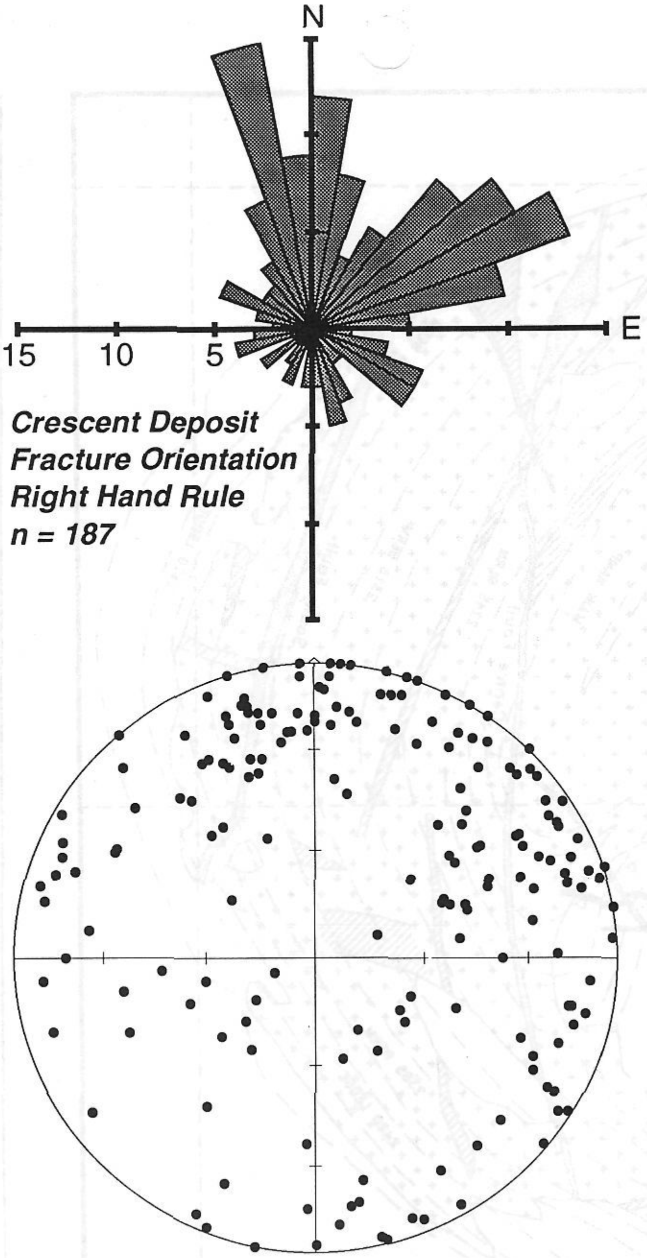

FIGURE 4. Structural orientations of fractures in the Crescent open pit. Upper figure shows preferred orientations of all types of fractures and faults with right-hand rule applied. Lower figure is lower hemisphere projection of same data illustrating the predominantly steep fracture orientations.

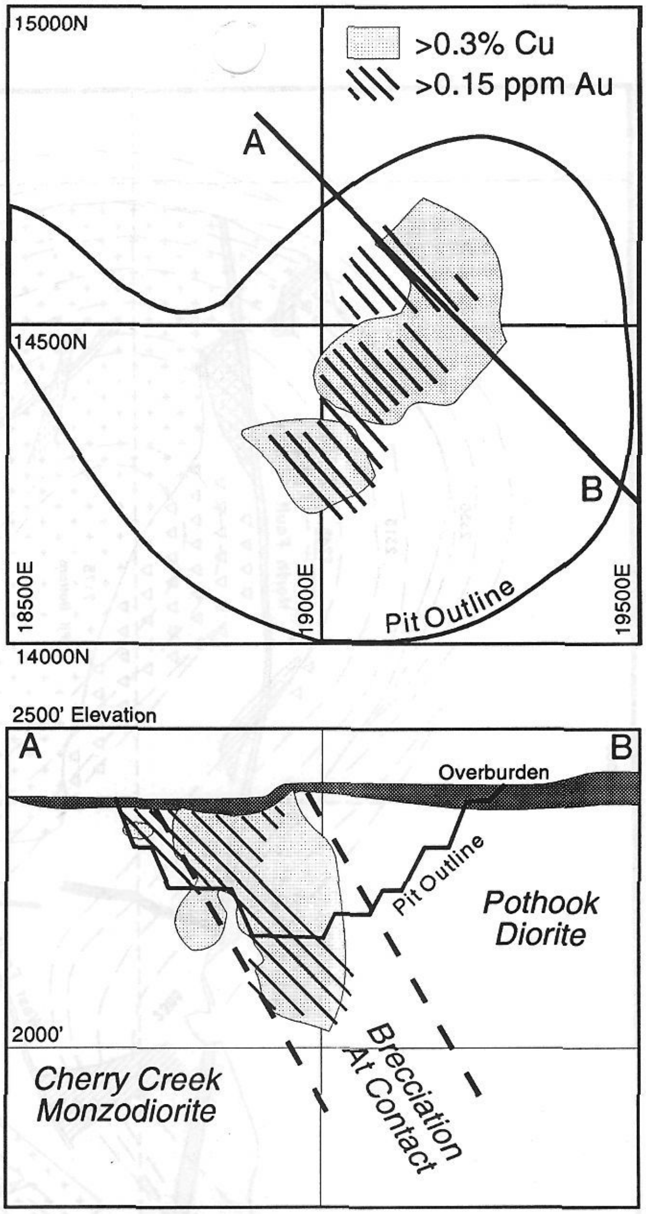

FIGURE 5. Plan and section of Cu-Au mineralization in the Crescent deposit (after Bond and Tsang, 1988).

structures, many of which can be traced over more than one bench. The fractures form zones of shattered rock which are usually less than 10 cm wide but may range up to many metres in width, and are commonly occupied by veins and vein swarms containing calcite-chlorite-quartz ± pyrite ± epidote ± trace chalcopyrite. Hydrothermal veins may be the dominant fill in narrower fractures but are a minor component of larger structures. Most of the fractures dip more steeply than 60° and have orientation modes of roughly 350°, 060° and 120° (Fig. 4). Fractures with relatively shallow dip were also noted. Steeply dipping fractures almost invariably host calcite-quartz veins but these are generally absent in shallow dipping fractures.

Contact Between Pothook and Cherry Creek Intrusions

The contact zone between the two major intrusive phases provided the locus for hydrothermal alteration and mineralization in the Crescent deposit. Vein density and alteration are strongest along and adjacent to the contact. The most important features along this contact are the development of intrusion breccias, pervasive potassium metasomatism, and the formation of fractures that were utilized by hydrothermal fluids.

Toward its margin, the Cherry Creek monzodiorite incorporated an increasing number of dominantly angular inclusions of Pothook diorite displaying various degrees of potassium metasomatism, and minor fragments of amphibolitized Nicola Group volcanic rocks and massive magnetite veins. Even more rarely, fragments macroscopically similar to the Cherry Creek intrusion itself are present; these are either ripped up margins of the Cherry Creek intrusion or strongly metasomatized Pothook diorite which has assumed a pseudoporphyritic texture, as described above. Locally the inclusions are sufficiently abundant to be called intrusion breccia. A dike of diatreme breccia lies south of the main contact (K-feldspar breccia dike in Fig. 3).

The main contact was affected by intense potassium metasomatism. This alteration was contemporaneous with or immediately followed intrusion of the Cherry Creek monzodiorite, and affected both the Pothook and Cherry Creek intrusions. Typically, plagioclase and orthoclase were selectively replaced by pink K-feldspar, and magnetite was destroyed in strongly altered areas. The alteration is centred on the contact a [illegible] rong effects extend an unknown distance into the Cherry Creek intrusion and up to 75 m into the Pothook diorite, at which point the intensity of alteration decreases gradationally but rapidly, although local effects continue beyond the pit boundary to the southeast. In the Crescent deposit, and elsewhere in the northern end of the batholith, the Pothook diorite commonly acquires a 'spotted' texture near its contact with intrusions of Cherry Creek due to the presence of ovoid clots up to 7 mm across which comprise chlorite with lesser calcite. Nearly identical occurrences of pervasive potassium metasomatism are present in many exposures of Pothook diorite in the northern end of the batholith. The widespread nature of this pink K-feldspar alteration has caused altered Pothook diorite to be confused with Cherry Creek monzonite. This alteration is probably related to late-stage crystallization of the Cherry Creek phase, and it preceded the precipitation of sulphides in the Crescent deposit.

Alteration and Mineralization

The ore reserve in the Crescent pit formed a tabular zone oriented about 050° with a southerly dip of 60° (Fig. 5; Bond and Tsang, 1988). Mineralization continues to at least 300 m depth (L. Tsang, pers. comm., 1993). The six vein types which have been recognized in the pit are discussed from early to late in the paragenetic sequence defined by cross-cutting relationships (Table 1).

Magnetite veinlets are the earliest fracture-controlled alteration. They have irregular forms, are most common near the main intrusive contact, are usually less than 1 mm but may exceed 1 cm in width, and have narrow, distinct alteration envelopes of pink K-feldspar. Only very minor chalcopyrite has been observed.

Throughout the deposit, veins of pink K-feldspar with minor biotite and very rare sulphides have the appearance of syenite dikelets. Many of these veins formed as replacements of wall rock along tight fractures but in a few areas of the batholith similar features are clearly intrusive.

Chlorite-sulphide veining is best developed within the tabular ore zone and its hangingwall in the Pothook diorite and gives a mottled colour to the rock in shades of pink, black and green. Individual veinlets are narrow and discontinuous and may impart a brecciated appearance to the rock. The major minerals are chlorite, which is predominantly a replacement of biotite which has been locally preserved, and magnetite which either coprecipitated with or is replaced by hematite. Calcite is common, K-feldspar is trace and epidote was observed in one case. Quartz is minor and sporadically present and pyrite is absent to minor. Several per cent chalcopyrite may be present within these veinlets or in their alteration envelopes. Host rocks between the veinlets are altered by K-feldspar, chlorite, magnetite/hematite and calcite. This alteration type is largely coincident with the ore zone, and the high concentration of chalcopyrite in these veins suggests that they carry most of the copper.

Epidote veins are abundant and widespread but are most common peripheral to the ore zone. They range from planar to irregular, and are up to several centimetres in width. Epidote and calcite are the major minerals but pyrite and chalcopyrite locally constitute up to 10%. Minor K-feldspar and albite were observed, together with rare quartz. Distinct alteration envelopes were not observed, but the veins are often associated with clots of alteration minerals similar to those found in the veins themselves. Chlorite is common and is associated with disseminated chalcopyrite. Beyond the pit boundary these veins carry magnetite, hematite, epidote and minor calcite, in some cases with alteration envelopes of albite and/or epidote.

Calcite-quartz veins are widely distributed through the deposit. They range up to several cm in width, have sharp contacts with their host, and are usually planar. Calcite usually exceeds quartz in abundance. Hematite, pyrite, chalcopyrite and K-feldspar are present, and epidote was observed in one sample. Envelopes of pink K-feldspar are almost always developed, and may contain minor chalcopyrite and magnetite. Commonly, the grain size of calcite and the abundance of quar [illegible] crease toward the core of these veins, whereas the reverse is rare.

Veins characterized by quartz-calcite-chlorite but devoid of sulphide or other minerals also occur within some fractures in the deposit. These veins have no alteration envelopes and cut mafic dikes which are interpreted as Eocene in age; they are therefore unrelated to formation of the copper-gold mineralization.

Veins dominated by calcite, with common but minor chlorite and very rare pyrite, occur throughout the deposit. They range from fracture coatings to dilatant veins many centimetres wide, are continuous and planar, have sharp contacts with their hosts, and lack alteration envelopes. Similar veins have been observed to cut mafic dikes of probable Eocene age throughout the northern end of the batholith.

Fault breccias occur throughout the open pit, but magmatic hydrothermal breccias have not been observed. In fault breccias the fragments are typically angular and have not been milled. The matrix is usually dominated by calcite with lesser quartz and, less commonly, chalcedony, and typically contains little or no sulphide, although rare examples with up to 10% chalcopyrite have been observed. Most sulphide contained within fault breccias is found in the fragments. One sample shows two stages of brecciation. The later stage has an unmineralized calcite matrix. Fragments within this matrix are themselves an earlier hydrothermal breccia with a matrix of calcite and minor hematite, chalcopyrite and pyrite; the fragments in this earlier breccia are altered by K-feldspar and chlorite and contain over 5% sulphide with a high chalcopyrite to pyrite ratio. The sulphides are both disseminated and contained within calcite-quartz veins that are restricted to the fragments.

Zoning of alteration minerals was discussed by Lang (1994) and his observations are summarized here. Calcite and chlorite are very evenly distributed, whereas quartz, hematite and albite are erratically distributed. Magnetite is consistently abundant throughout the deposit, even though the Pothook diorite contains nearly twice as much primary magnetite as the Cherry Creek monzodiorite, and reflects its partial destruction during potassium metasomatism. K-feldspar is most abundant in the Cherry Creek monzodiorite and potassically altered Pothook diorite, but decreases sharply to the south and west sides of the pit away from the main intrusive contact. The abrupt decrease on the west occurs at an atypically sharp contact between the Pothook and Cherry Creek units and may represent a fault contact or a zone in which fluid flow was restricted by an absence of permeable intrusion breccias. Pyrite and epidote are most abundant on the margins of the deposit and reflect a propylitic, pyritic halo.

Vein types also vary spatially (Lang, 1994). Magnetite veins occur in both the Pothook and Cherry Creek intrusions but are most abundant near the contact. K-feldspar veins are more commonly developed in the Pothook diorite, but are most consistently abundant near the contact zone. Chlorite-sulphide veins are more abundant in the hangingwall of the intrusive contact and are roughly coincident with the ore zone. Calcite-quartz veins show no distinct distribution pattern. Epidote veins are most abundant on the margins of the pit. Magnetite-apatite-actinolite-epidote veins occur in many exposures of the Pothook diorite in the northern end of the Iron Mask batholith but are not directly related to formation of the Crescent deposit.

Chalcopyrite was the dominant ore mineral, and trace amounts of bornite and molybdenite have been reported (Preto, 1967; Bond and Tsang, 1988). Supergene effects were limited to near surface, in situ oxidation without enrichment in metal grade. Copper carbonates are the dominant copper minerals formed during weathering.

The DM Deposit

This description of the DM deposit derives from reconnaissance examination of diamond drill core by the authors, and from a report

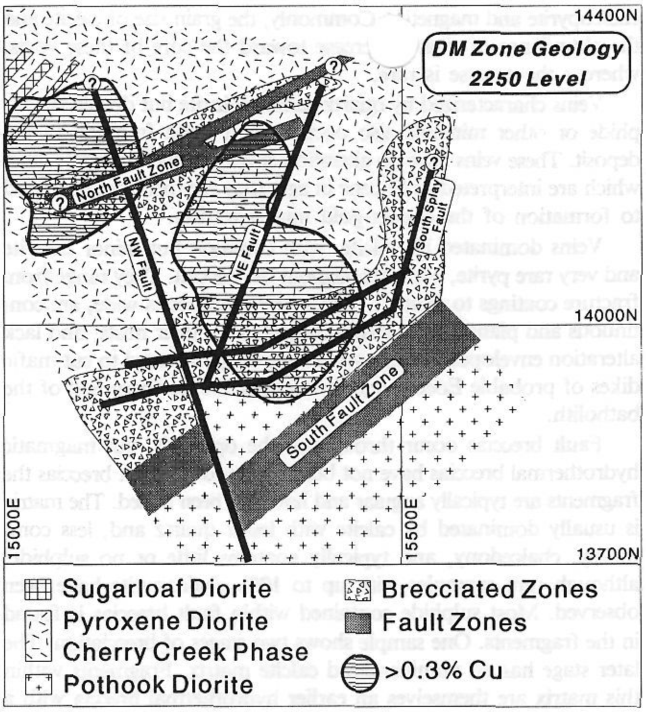

FIGURE 6. Simplified geologic map of the 2250-foot level of the DM deposit (modified from Bond and Tsang, 1988).

on trench and drill core geology by Bond and Tsang (1988). The DM zone shares many similarities with the Crescent deposit, including a location along the contact between the Pothook and Cherry Creek intrusions, early pervasive alteration followed by a similar sequence of vein types, and disruption by faults.

Geology

The geology of the DM zone is shown in Figure 6. Most of the DM zone lies between the South (SFZ) and North (NFZ) Fault zones, which are wide, composite, subparallel zones which strike 050° to 060° and dip about 70° to the southeast. Hydrothermal effects are not evident south of the SFZ, but alteration occurs on both sides of the NFZ. The NW Fault, which strikes about 325° and dips steeply to the west, cuts and displaces the NFZ, SFZ and mineralization. Other major faults include the South Splay Fault, which varies markedly in orientation along its length, and the NE Fault which trends about 020° and dips steeply to the west. Although the relative timing and sense of movement of the faults is not well-constrained, most displacement occurred after Jurassic magmatic and hydrothermal activity. Strongly brecciated rocks lie both along and between the NFZ and SFZ but are predominantly intrusion rather than fault breccias.

The boundaries between the major intrusive rock types in the DM deposit coincide, in part, with the NFZ and SFZ. To the south of the SFZ lies unaltered Pothook diorite. North of the NFZ lies a pyroxene diorite or monzodiorite which is macroscopically similar to the Cherry Creek intrusion exposed in the Crescent deposit. Locally, this pyroxene diorite grades laterally into strongly altered intrusion breccia. Between the main fault zones lies both Cherry Creek and Pothook units which each exhibit various degrees of alteration, and abundant intrusion breccia with fragments of altered Pothook diorite in a matrix of Cherry Creek monzodiorite. The contact between the Cherry Creek and Pothook intrusions lies near the SFZ, but interfingering of the two units and intense potassium metasomatism obscures its exact location. All gradations appear to exist between unaltered pyroxene diorite, Cherry Creek intrusion breccia and unaltered and altered Pothook diorite, and together these rock types form a continuum resulting from various degrees of alteration and intrusion breccia development. In several locations throughout the DM zone, diorite dikes which range in width from one to five metres and [illegible]ch contain prismatic, locally trachytic, euhedral hornblende phenocrysts are interpreted as Sugarloaf diorite. In surface trenches, these dikes trend northeasterly, but it is not yet known if this orientation is consistently developed. Weakly altered plagioclase diorite porphyry dikes and minor, postmineral andesite dikes similar to those in the Crescent deposit are also present.

Alteration and Mineralization

Mineralization occurs in two pipe-like bodies (Fig. 6) which dip steeply to the south and which converge at depth (Bond and Tsang, 1988). Both ore zones occur in rock characterized by intrusion breccias, with lesser mineralization hosted by unbrecciated rock.

Alteration in the DM zone is nearly identical to that observed in the Crescent deposit. Pervasive, locally magnetite destructive potassium metasomatism introduced little or no sulphide and formed preferentially in intrusion breccia along the contact between the Pothook and Cherry Creek intrusions. Pervasive alteration was followed by a sequence of veins similar to that at the Crescent deposit (Table 1) but which includes two additional varieties. In the DM zone most sulphide mineralization was introduced by chlorite-sulphide veins, but quartz-dominated veins with abundant sulphide which formed early in the paragenesis also carry significant copper mineralization. Locally, quartz abundance reaches 15%. Late-stage veins dominated by gypsum are abundant in the northern part of the DM zone. A second, sulphide-bearing variety of gypsum vein is reported by Bond and Tsang (1988) to have formed earlier in the sequence. Quartz veins have a preferred orientation of 290° and dip 60° to 70° to the southwest (Bond and Tsang, 1988) but data are not available for other vein types. Zoning patterns of alteration minerals and vein types remain to be evaluated. Magmatic hydrothermal breccias are minor but fault breccias are common.

The major ore mineral is chalcopyrite. Bornite is locally important as disseminated grains along the footwall of the SFZ (Bond and Tsang, 1988). Pyrite is abundant both in and peripheral to the ore zone, but its distribution is truncated by the SFZ. Pyrite is present with chalcopyrite but not with bornite (Bond and Tsang, 1988). Supergene oxidation has converted copper sulphides to copper carbonates and minor native copper in a shallow zone of weathering, but no enrichment has occurred.

The Pothook Deposit

The Pothook deposit is located at the westernmost contact of the Iron Mask batholith with enclosing Nicola Group volcanic rocks. The geology of the Pothook deposit is shown in Figure 7.

Rock Types

Several different volcanic rock types comprise the Nicola Group in the deposit area. These consist of: (1) dark green to black, aphyric to plagioclase-phyric, massive basalt flows; (2) maroon to dark grey, aphyric to sparsely plagioclase or augite-phyric, poorly bedded, ash to lapilli mafic tuffs and lesser blocky agglomerates; (3) black, crowded, augite-phyric, massive basalt flows; (4) dark grey, crowded, plagioclase-phyric andesite flows and feeder dikes; (5) dark green to black, crowded, augite-phyric picrite flows (Stanley et al., 1994).

The oldest intrusive unit is fine- to medium-grained diorite of the Pothook phase which is petrographically similar to that described at Crescent, although here it incorporated numerous xenoliths of volcanic rocks which in places, especially near the margins of the intrusion, are sufficiently abundant to form an intrusion breccia. Apophyses of Pothook diorite also intruded along faults and steeply dipping depositional contacts in the volcanic host rocks, and these dike-like intrusions have fine-grained chilled margins. Volcanic rocks adjacent to the diorite contact recrystallized to a biotite hornfels containing disseminated magnetite and less than 1% disseminated pyrite cubes.

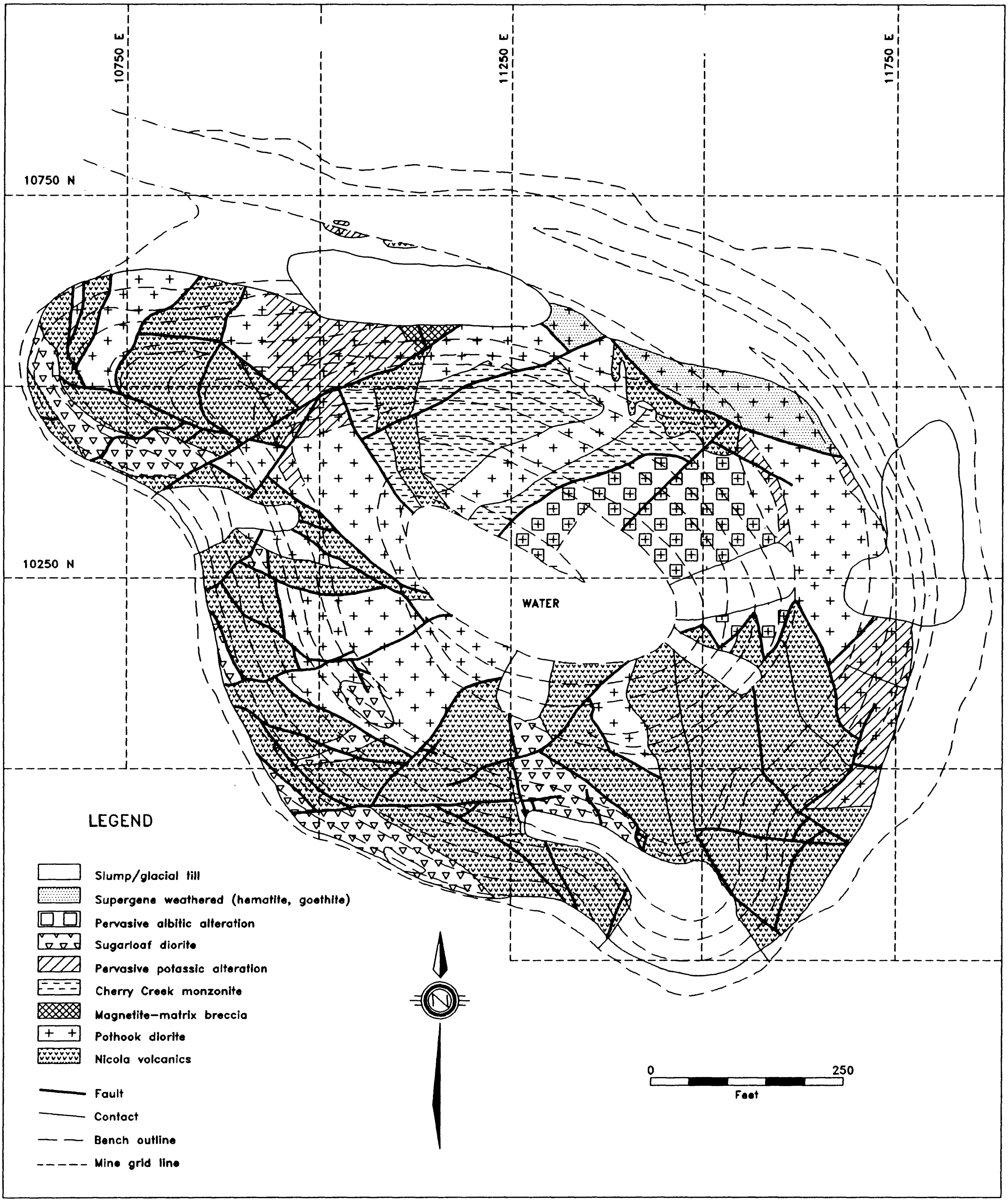

FIGURE 7. Geologic map of the Pothook deposit.

A medium-grained variety of Pothook diorite was intersected at depth in exploration drill holes. This later variety intrudes the fine- to medium-grained variety of Pothook diorite, with which it is petrographically similar. It is not observed to intrude, nor contain xenoliths of, Nicola Group volcanic rocks.

The Cherry Creek monzonite phase was next to intrude. In the deposit area it intruded only Pothook diorite but is structurally juxtaposed against other rock types. This variety of the Cherry Creek phase is generally a very fine-grained, equigranular, orthoclase-plagioclase-biotite-augite monzonite with accessory magnetite and apatite and trace quartz (Snyder and Russell, 1993a). It also contains small miarolitic cavities filled with quartz, and locally exhibits an aplitic texture. Its emplacement was controlled by pre-existing structures within the Pothook diorite (Stanley et al., 1994). No contact metamorphic effects were observed in Pothook diorite adjacent to the Cherry Creek monzonite.

Sugarloaf diorite was next emplaced into the Nicola Group and, less commonly, into Pothook diorite, but was not observed to in-

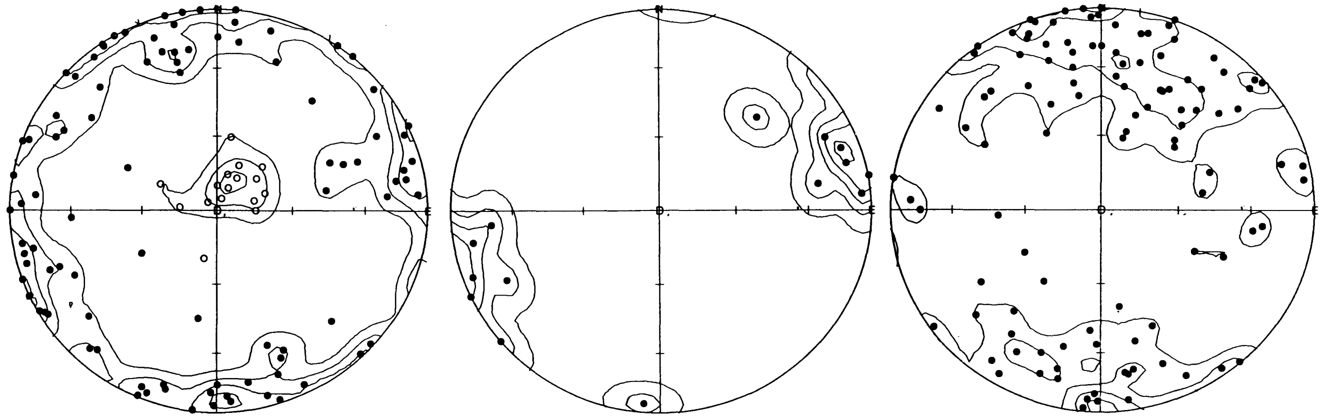

FIGURE 8. Steronets of poles to structural features in the Pothook deposit. A: Poles to steeply dipping faults cutting the Pothook diorite and Nicola Group (closed symbols; n = 97), and to listric faults with southwesterly directed throw (open symbols; n = 16). B: Poles to structurally-controlled K-feldspar epidote veins (n =14). C: Poles to Fe-oxide-sulphide veins (n = 112).

trude the Cherry Creek monzonite. Alteration of the Cherry Creek phase by hydrothermal activity ascribed to the Sugarloaf diorite (see below) establishes the Cherry Creek phase as the older intrusion. Sugarloaf diorite contains large, sparse to crowded, stubby hornblende phenocrysts, generally smaller augite, and plagioclase phenocrysts, and commonly displays a trachytic texture. The phenocrysts are set in an aphanitic groundmass of plagioclase, orthoclase and disseminated magnetite (Snyder and Russell, 1993a). The Sugarloaf diorite was emplaced as a set of northwest-trending, steeply-dipping dikes along the southwestern edge of the batholith. The dikes are widest, most abundant, and may be, in part, radially-oriented around Sugarloaf Hill, which is thought to be a subvolcanic intrusive neck (Snyder and Russell, 1993b). Sugarloaf diorite effected texturally-destructive recrystallization of mafic volcanic wall rocks to an actinolite-plagioclase hornfels with abundant disseminated magnetite. No contact metamorphic effects were observed in Pothook diorite where it is intruded by Sugarloaf diorite dikes.

Late, relatively rare mafic dikes intruded the Pothook area and are petrographically and temporally identical to andesite dikes of probable Eocene age at Crescent.

Structures

Three episodes of steep faulting are recognized in the Pothook deposit. The first faults formed after intrusion of the Pothook diorite, but prior to intrusion of Cherry Creek monzonite, and have dips mostly greater than 70°. This stage of faulting disrupted the contact between Pothook diorite and hornfelsed Nicola Group and juxtaposed volcanic rocks without contact metamorphic effects against Pothook diorite. Displacements along these numerous faults are subvertical and generally less than 100 m. These structures lie preferentially along orientations of north-northwest and east-northeast (Fig. 8) and formed before the pervasive potassic alteration described below. The second episode of steep faulting took place after intrusion of the Cherry Creek monzonite. The third episode of steep faulting dissected many of the Sugarloaf diorite dikes and K-feldspar-epidote veins. Both the second and third faulting events utilized pre-existing structures and further disrupted the margin of the batholith.

Another episode of faulting followed intrusion of the Sugarloaf diorite and the ore-forming event. Unlike earlier episodes, movement along these faults occurred along relatively shallow planes with southeasterly strikes and dips generally less than 30° to the southwest (Fig. 8). Numerous faults with this orientation cut the upper southwest wall of the open pit and display spoon-like, concave-upward (listric) forms. The displacement direction is generally to the southwest, and movements of up to 50 m are indicated on individual fault planes. Given the number of these faults, the overlying Pothook diorite and Sugarloaf diorite dikes may have moved up to or exceeding 250 m from the margin of the batholith onto unmetamorphosed Nicola Group to the southwest. This stage of faulting may reflect unroofing of the Iron Mask batholith, possibly during a period of extensional tectonics that affected the region during the Eocene (Preto, 1972; Souther, 1992).

The youngest faults caused further movement on pre-existing, northwest-striking faults. These structures dropped supergene weathered material into grabens where it was protected from subsequent Pleistocene glacial erosion.

Alteration and Mineralization

The earliest alteration formed after, and possibly concurrent with, the first episode of steep faulting which formed after intrusion of the Pothook diorite. It comprises magnetite-apatite-actinolite veins, blebs, schleiren and breccias formed along dilatant fractures. These fractures also locally contain epidote and chlorite, both within the structures and in alteration envelopes surrounding them. Blebs and schleiren tend to occur in wide envelopes around major magnetite veins. In and adjacent to the Pothook deposit, all of these magnetite-bearing structures are hosted by intrusions of, or intrusion breccias with a matrix of, the fine- to medium-grained phase of the Pothook diorite.

A selectively pervasive potassic alteration occurs within, but near the margins of, the Cherry Creek monzonite, and in Pothook diorite adjacent to exposures of Cherry Creek monzonite in the north wall of the open pit. This alteration involved selective replacement of plagioclase by K-feldspar in both the Pothook and Cherry Creek phases, and the partial destruction of disseminated magnetite in the Pothook diorite. Biotite remained stable, but augite was commonly replaced by epidote. At its margins, this alteration grades outward into fractures with K-feldspar alteration envelopes, indicating that at least the outer parts of these alteration zones formed from coalescing alteration envelopes.

Pervasive albitic alteration formed after emplacement of the Sugarloaf diorite. Development of this alteration ranges from envelopes around isolated fractures to totally pervasive where adjacent envelopes coalesce. Its distribution is limited to the Pothook and Sugarloaf diorites. In the Pothook diorite, albite replaced plagioclase, augite and orthoclase, chlorite replaced biotite, and moderate, subequal amounts of chalcopyrite and pyrite precipitated. On the southeast wall of the open pit the Pothook diorite has been almost entirely converted to albite. Elsewhere, Pothook diorite is more weakly albitized, commonly in fracture envelopes, where plagioclase is selectively replaced by albite but biotite, augite and orthoclase remained stable. In the Sugarloaf diorite, albite selectively replaced plagioclase and orthoclase, but hornblende was stable. Sugarloaf diorite also contains blebs of epidote which may be related to this alteration event.

The pervasive albitic alteration is overprinted by fracture-controlled potassic alteration represented by K-feldspar-biotite-epidote veins. These veins were controlled by steeply dipping, north-northwest-striking fractures (Fig. 8) and are restricted to the Pothook and Cherry Creek intrusions. They are well developed on both the southeast and north walls of the open pit. These veins are not significantly dilatant but are continuous across 20 vertical and 30 horizontal metres, and in many places constitute sheeted vein sets. During this hydrothermal alteration, the assemblages of vein and alteration envelope minerals varied among different host rocks. In unaltered to moderately albitized Pothook diorite and Cherry Creek monzonite the veins are filled primarily by K-feldspar and biotite and have epidote envelopes. In pervasively albitized Pothook diorite the veins are commonly filled by epidote and have K-feldspar and biotite envelopes. In Pothook diorite affected by pervasive potassic alteration the veins are generally filled only by epidote. All of these varieties contain subequal amounts of chalcopyrite and pyrite, along with minor bornite, but they did not contribute substantially to the total metal budget in the deposit.

The main stage of copper ore formation is represented by Fe-oxide-sulphide veins. On the southwest side of the open pit, these veins are characterized by a chlorite-pyrite-chalcopyrite-magnetite-(specular) hematite assemblage, whereas on the northeast side they contain chalcopyrite, bornite and magnetite. These veins, like the K-feldspar-epidote veins which they cut, were not significantly dilatant. They have a preferred orientation approximately perpendicular to that of the K-feldspar-epidote veins, ranging from west-southwest to northwest, with dips generally greater than 45° (Fig. 8). The density of these mineralized veins appears to control ore grade, and produced intervals grading up to 2% Cu and 2 g/t Au in exploration drill core. Where these veins cut Nicola Group volcanic rocks or their metamorphosed equivalents chlorite selvages and envelopes are developed, whereas in intrusive hosts epidote envelopes and selvages predominate. These veins are discontinuous and commonly dissipate into microfractures with epidote or chlorite envelopes. Previously existing fault zones are also at least partially filled by these Fe-oxide-sulphide veins.

In the centre of the open pit, now observable only in drill core, there is a large body of clast-supported, hydrothermal breccia which contains rotated fragments of Pothook, Cherry Creek and Sugarloaf intrusions and Nicola Group volcanic rocks in a matrix of rock flour, chlorite and pyrite, with subordinate magnetite, chalcopyrite and bornite. In places, especially toward the centre of the breccia, the clasts are rounded and range in size from 5 mm to 100 mm. Toward the margins of the breccia the clasts are larger and more angular, and the breccia grades into a crackle zone with unrotated fragments in a stockwork of Fe-oxide-sulphide veins.

The mineralizing episode that produced the sulphide-bearing veins and breccia was followed by, or possibly evolved into, a propylitic assemblage represented by chlorite-minor calcite-trace pyrite veins without significant associated copper or gold mineralization. Chlorite veinlets range from large continuous joints to microfractures, and cut both volcanic and intrusive rocks. Chlorite veins do not occur in Pothook diorite which was depleted of Fe and Mg by pervasive albite alteration, but late microfractures filled with kaolinite-calcite may be temporally equivalent (Bond, 1985; Stanley, 1994).

Calcite veins cross-cut the chlorite veins. In intrusive rocks these veins consist solely of calcite and have no alteration envelopes. In volcanic hosts they are commonly associated with talc and serpentine and have chlorite selvages. Calcite veins are discontinuous and have no preferred orientation. In general, wider calcite veins remain isolated from each other but are commonly truncated and cross-cut by smaller calcite veins. The overall abundance of calcite veins suggests that the rocks have been shattered.

Rare, late quartz (amethystine)-calcite-chlorite veins cut all rock and alteration types in the open pit. They partially fill all faults, including those with shallow dips, open spaces in previously formed veins, and shallow-dipping fractures without displacement which are oriented parallel to the shallow-dipping faults.

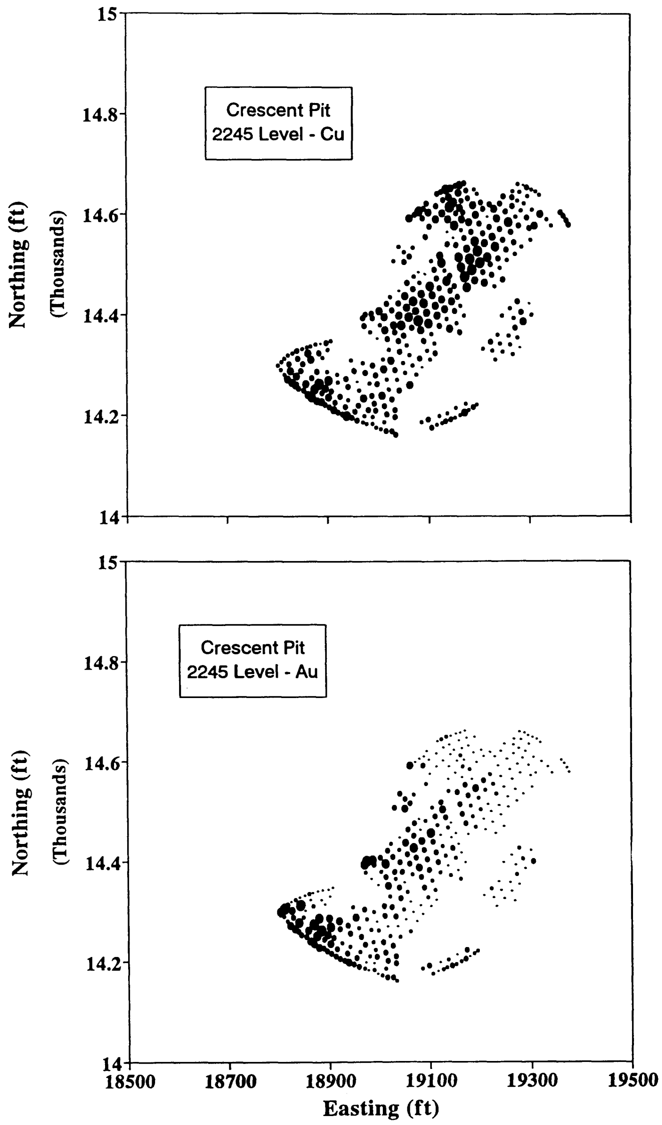

FIGURE 9. **Bubble plots of production blasthole Cu (upper figure) and Au (lower figure) assays from the 2245-foot level in the Crescent deposit. Assays have been transformed and scaled to enhance geochemical contrast.**

During a period of late Tertiary supergene weathering, some of the chalcopyrite and bornite was destroyed and replaced by native copper, chalcocite and earthy hematite, and pyrite was also partially destroyed and replaced by earthy hematite and goethite. The high calcite and low pyrite abundances in the Pothook deposit, as well as in the Crescent and DM deposits, limited acid development such that supergene effects were restricted to oxidation without any notable enrichment in grade (Carr and Reed, 1976; Kwong, 1987). This weathering is predominantly fracture-bound, is typically present in open spaces thought to have formed by dissolution of earlier calcite, and penetrates to depths of up to 50 m below the bedrock surface in unfractured rocks and to greater than 200 m below the bedrock surface along faults.

Discussion and Conclusions

Relationship Between Copper and Gold Grades

Figure 9 shows the distribution of copper and gold as determined from blasthole assays in the Crescent deposit. Higher copper and gold grades were present along the contact zone and its immediate hangingwall, and in the offset of the contact in the western end of the open pit, but sporadic high values were present

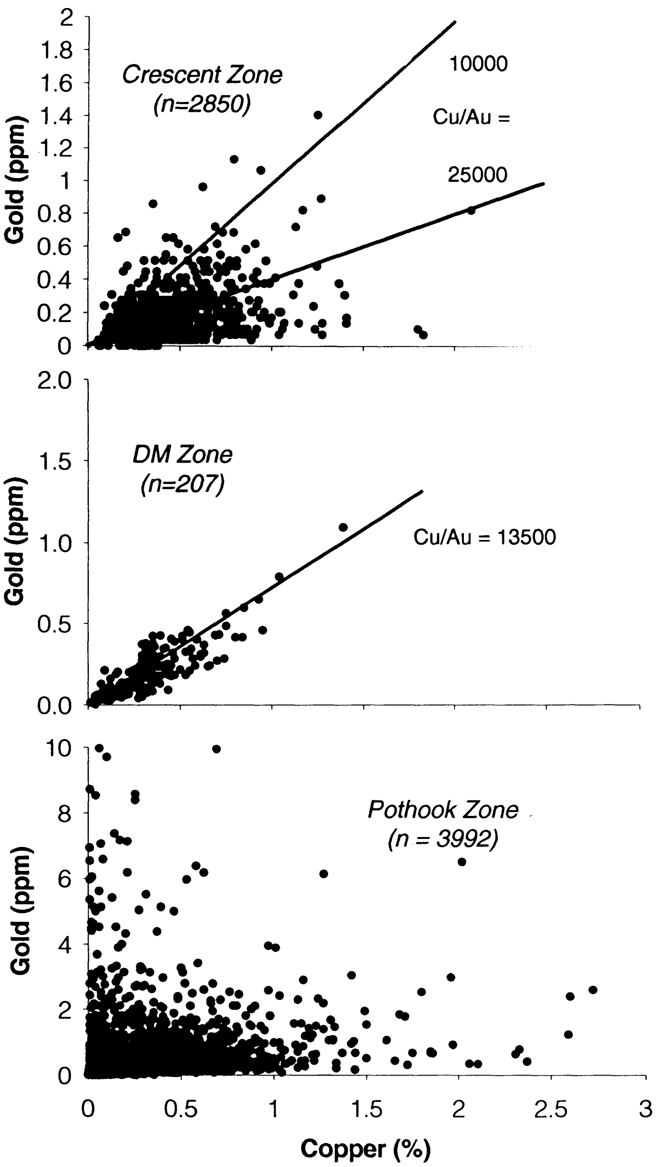

FIGURE 10. Scatterplot of exploration drill hole and production blasthole Cu and Au assays from the Crescent deposit (upper figure, n = 2850), DM zone (middle figure n = 207), and the Pothook deposit (lower figure n = 3992).

throughout the deposit. Copper and gold grades are very well correlated at a nearly constant Cu:Au ratio of around 25 000 with fewer values ranging up to ratios of 10 000 (Fig. 10). The correlation suggests that copper and gold were co-precipitated during a single hydrothermal event, and that later overprints are absent. A strong correlation between copper and gold is also present at the geologically similar DM deposit (Fig. 10).

At Pothook, copper and gold from both exploration drill holes and production blastholes show markedly different behaviour from that observed at Crescent and DM (Figs. 9 and 11). In general, copper and gold concentrations are not well correlated, and high copper concentrations may occur in samples with relatively low gold grades, and vice versa. This behaviour contrasts with both the close correlation between copper and gold and the relatively constant Cu:Au ratios observed at Crescent and DM and within most other individual alkalic porphyry deposits (Stanley, 1993).

The distribution of higher copper grades at Pothook defines a strong structural control along trends with variable strikes (Fig. 11). Many of these trends can be traced directly into steeply-dipping fault zones (cf. Fig. 7) which were active before, during and after mineralization. The spatial pattern of higher gold grades, however, suggests that the controls on gold distribution in the Pothook deposit differed from those [illegible]pper (Fig. 9). The high density of blastholes, the continuity of assay intervals in exploration drill core samples, and sample masses greater than 2 kg, suggest that the lack of correlation between copper and gold is more plausibly related to differences in mineral paragenesis than to either local mobility during supergene weathering or to nugget effects. Copper and gold may, therefore, have been introduced at different times, or by different means, during the hydrothermal history of the Pothook deposit.

Sequence and Evolution of Hydrothermal Fluids

The sequence of magmatic and hydrothermal events in the Crescent, DM and Pothook deposits is summarized and compared in Table 1. The magmatic sequence conforms to that defined by Snyder and Russell (this volume) for the batholith as a whole. Within the magmatic framework of the northern end of the Iron Mask batholith, hydrothermal fluids entered the system at several different times and with markedly different results.

The earliest fluids were associated with the Pothook diorite phase of the batholith. Snyder and Russell (1993b) consider the agmatite phase of the Pothook diorite a modification of the intrusion breccia phase (fragments of Nicola Group volcanic rocks enclosed by a matrix of normal Pothook diorite); they interpret the agmatite as a product of selective volatile assimilation which led to enhanced volatile concentration in the matrix magma which promoted recrystallization of both the volcanic fragments and the Pothook matrix. For the main Pothook diorite intrusion, it is tempting to suggest that the magmatic volatiles responsible for late-stage growth of poikiolitic biotite were incorporated into the magma through operation of the selective assimilation process near the margins of the intrusive mass. The hydrothermal fluids which formed the widespread magnetite-apatite-amphibole veins may have had a similar source, or may represent concentration along joint sets or fractures by orthomagmatic hydrothermal fluids released during late-stage crystallization of other, still molten parts of the Pothook diorite. The role of selective assimilation in concentrating volatiles and producing hydrothermal fluids which formed the later copper-gold ore zones remains to be evaluated.

A second, distinct, and widespread hydrothermal event in the northern end of the batholith resulted in formation of zones of pervasive potassium metasomatism with little or no sulphide. These zones are invariably located along the margins of Cherry Creek intrusions, as noted by Preto (1967), and the spatial and temporal association of these events suggests that hydrothermal fluids evolved at high temperatures during late-stage crystallization of the Cherry Creek phase. The common presence of intrusion breccias at the margin of Cherry Creek intrusions favoured these zones as fluid conduits.

Pervasive albite alteration formed in response to intrusion of dikes and stocks of Sugarloaf diorite and constitutes a third major hydrothermal event. This alteration type is best developed in the Ajax East and Ajax West deposits (Ross et al., this volume), where it is associated with significant sulphide mineralization, and in the Pothook pit, where it introduced only minor sulphide mineralization. The restriction of the albitic alteration to within and adjacent to Sugarloaf dikes suggests that it probably formed as an integral part of the late-stage crystallization of the Sugarloaf diorite.

In all deposits in the northern end of the batholith, as well as in the Ajax deposits, subsequent alteration was more strongly fracture-controlled. Most of the copper-gold mineralization was introduced in this stage although at Ajax a greater relative proportion was introduced with pervasive and fracture-controlled, albite-dominated alteration. The main fracture-controlled alteration comprises core zones of potassic alteration assemblages, and propylitic assemblages which lie either peripheral to the potassic cores or locally overprint them. In the Crescent and DM zones, fracture-controlled potassic alteration introduced most of the copper-gold mineralization, but a relatively smaller proportion in the Pothook deposit. In the Pothook zone, Fe-oxide-sulphid [illegible]ns and breccia matrices are the major carrier of ore.

In the Pothook deposit, ore-stage mineral zoning is spatially consistent with both the predominant orientation of the veins and a hydrothermal fluid source in the Sugarloaf diorite dikes. The zoning of pyrite-chalcopyrite and chalcopyrite-bornite mineral assemblages across the deposit suggests that copper-gold mineralization may have precipitated under variable conditions of temperature and/or fluid sulphidation (Einaudi, 1993) which resulted from fluid migration away from the Sugarloaf diorite dikes. The competency of the host rocks to mineralization was augmented by early alteration events, particularly hornfels development and albitization, which facilitated subsequent development of brittle fractures that served as fluid flow paths and precipitation sites for main-stage mineralization. Sugarloaf diorite is also thought to be the intrusion most closely related to the formation of copper-gold mineralization at the Ajax deposits (Ross et al., this volume). The very porphyritic texture of the Sugarloaf diorite suggests that it possessed a higher volatile fugacity than earlier intrusions in the batholith, and is therefore consistent with its relationship to copper-gold mineralization.

The relationship of Sugarloaf diorite to mineralization in other deposits is not yet known. Preto (1967) reports albitization related to Sugarloaf diorite dikes in the Galaxy prospect, but the mineralization in this zone is spotty and its relationship to the dikes and their related alteration is not well understood. In the DM zone dikes of Sugarloaf diorite are present, but the distribution of alteration and mineralization is not yet sufficiently defined to establish a direct genetic link. Sugarloaf diorite is not exposed in the Crescent deposit or its drill core, and here the mineralizing intrusion is either a phase of the Cherry Creek intrusion, or an intrusive phase which is not exposed. The permeability of the brecciated zones along the contact between the Cherry Creek and Pothook intrusions could have facilitated fluid ascent from considerable depth in both the Crescent and DM deposits.

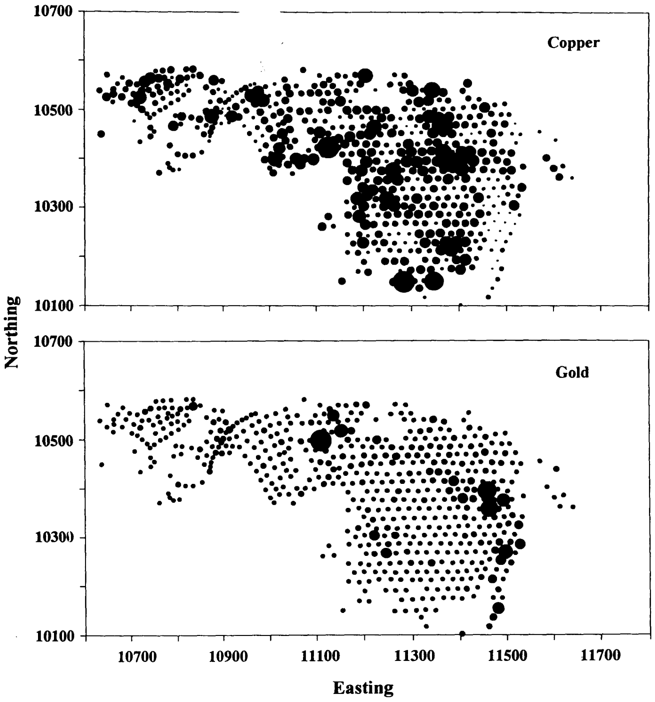

FIGURE 11. Bubble plot of production blasthole Cu (upper figure) and Au (lower figure) assays from the 2340-foot level of the Pothook open pit. Assays have been transformed and scaled to enhance geochemical contrast. The smallest and largest bubbles correspond to Au grades of 0.034 and 28 972 g/t, and Cu grades of 0.01% and 2.60%, respectively. (n = 635).

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