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Porphyry-style and epithermal Cu-Mo-Au-Ag mineralization in the northern and southeastern Sulphurets district, B.C.

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ABSTRACT

Four hydrothermal/mineralization events, apparently representing the porphyry-epithermal transition, have been recognized on the flanks of Mitchell Glacier in the northern Sulphurets district in northwestern British Columbia, from earliest to latest: (1) porphyry-style Cu±Au stage coincident with potassic alteration of deep quartz-syenite and surrounding volcanic rocks; Cu-Au-bearing quartz stockworks (e.g., Mitchell deposit; unknown tonnage, about .2% Cu, .025 opt Au) developed at high levels; (2) moderate to high-level quartz-sericite-chlorite-pyrite alteration hosting molybdenite veins and tourmaline; (3) unmineralized advanced-argillic alteration at high levels, and underlying massive pyrite veins and a breccia pipe enriched in Bi-Te-Sn-As; and (4) electrum-bearing, quartz-barite-galena-sphalerite veins within sericite-chlorite-pyrite alteration enriched in Pb-Zn-Ag-Au-Sb-Cd-Hg-Te, akin to adularia-sericite epithermal veins, and best developed at high and peripheral positions with respect to the magmatic-hydrothermal centers; and a high-grade, basalt-hosted disseminated Au zone (Snowfield deposit, 7 million tonnes, .08 opt

Au) with a similar mineral assemblage. This disseminated mineralization, hosted in basaltic andesite, occurs adjacent to a stage-1 quartz stockwork. The West zone vein system (750,000 tonnes, .43 opt Au and 20 opt Ag) in the southeastern part of the district is considered to represent stage-4 mineralization, probably related to a hydrothermal system distinct from those in the northern part of the district.

Host rocks are largely Lower Jurassic Hazelton Group submarine andesitic flows and epiclastic arenites, and calc-alkaline dioritic intrusive rocks. Calc-alkaline quartz-syenite stocks occur at the base of the alteration system in Mitchell Valley, are altered and mineralized by stage 1, and probably drove the hydrothermal activity. Radiometric dating indicates an Early Jurassic mineralization age (about 190-195 Ma). Stable isotope analyses indicate that hydrothermal fluids were a mixture of magmatic fluids and either seawater or meteoric water near sea level.

Introduction

The Sulphurets district (Kirkham and Margolis, this volume) is located in a remote region of northwestern British Columbia, 60 kilometres north of Stewart, B.C., and 20 kilometres west of Bowser Lake. The district, about 80 square kilometres centered at 56°30'N-130°12'W, encompasses widespread hydrothermal alteration and at least 5 areas with significant Cu-Au-Ag-Mo mineralization. The focus of this report is the northern and eastern Sulphurets district - chiefly the Brucejack Lake area and the slopes north and south of Mitchell Glacier (Fig. 1). Significant mineralized areas in this portion of the district and described further below are: the Mitchell Cu-Au quartz-stockwork zone, the Snowfield disseminated Au zone, and the West zone Au-Ag vein system.

The northern and eastern Sulphurets district is largely above tree line in a glaciated terrane with high relief. North and south-facing slopes surrounding Mitchell Glacier rise 700 to 1000 metres above the glacier to elevations of about 2000 metres, and expose glacially-polished outcrops locally covered by moraine. The southeastern part of the district in the Brucejack Lake area lies in a broad plateau at about 1100 metres elevation that is covered by grasses and trees to the west. Access to the area is limited to helicopter.

Since the mid 1980's, a permanent base camp has been established on the west side of Brucejack Lake adjacent to the West zone; no other permanent camp exists in the district.

History of Exploration and Research

Copper mineralization in the western part of the Sulphurets district was recognized in about 1935. In 1959, Granduc Mines Ltd. discovered Au-Ag vein mineralization near Brucejack Lake; and later, R.V. Kirkham recognized porphyry Cu-style mineralization in the district. Granduc continued to conduct intermittent exploration through 1975, including mapping, sampling, magnetometer surveying, and limited drilling (6 holes). By 1975, a widespread 1-3 ppm Au anomaly, now known as the Snowfield gold zone, had been identified. Between 1980 and 1984, Esso Minerals Canada Ltd. continued exploration of the porphyry-Cu mineralization, further explored the Snowfield zone, and began a systematic delineation of the Au-Ag vein mineralization on the west side of Brucejack Lake; in addition, other Au-Ag bearing quartz veins were recognized throughout the area. In 1985, Granduc optioned the property to Newhawk Gold Mines Ltd. and

Helca Mines Ltd. worked in area in mid 1970s

Joe Montgomery recognize Cu porph. 1960 in & Kirkham documented it in 1961 (Kirkham, 1963)

← Au found by Esso Min. Ltd. check w Ron

Lacana Mining (later Corona Corporation, now Homestake Mining Co.), who drilled 5 holes in the Snowfield zone; most holes intersected at least .06 opt Au over 70- to 90-metre widths. From 1985-1990, most work by this joint venture concentrated on drilling and underground exploration of the West zone, leading in 1990 to the announcement of a geological reserve of 826,000 tons grading .45 opt Au and 19 opt Ag, deemed uneconomic. In 1991 and 1992, the district was subdivided into three parcels, with Placer Dome Inc. (Kerr Cu-Au deposit) acquiring the western and northwestern area, including the Main Copper, Sulphurets Gold, and Mitchell Cu-Au stockwork, and Newhawk (partly owned by Homestake Canada Inc.) acquiring 100% interest in the Snowfield zone area. The Brucejack Lake area continues to be explored by a joint venture between Granduc and Newhawk. Between 1991 and 1993, the Mitchell Cu-Au stockwork and Snowfield zone were further drilled, and new Au-Ag vein mineralization was identified in the Brucejack Lake area to the southeast.

Published research, theses, and dissertations on the geology and mineralization of the northern and eastern Sulphurets district include Kirkham (1963), Britton and Alldrick (1988), Alldrick and Britton (1988), Macdonald (1993), Roach and Macdonald (1992), Margolis (1993), and Davies et al. (1994). Much of the information cited in this report is from the recent studies by Margolis (1993) and Davies et al. (1994).

Exploration Techniques

Standard exploration techniques have included rock-chip sampling accompanied by detailed mapping with pace and compass grid control; hand-sawed trenches (about 4cm wide) on smooth, glacially-polished outcrops; dynamite-blasted trenches, typically .5 by 5 metres in size; and non-grid controlled, reconnaissance sampling and mapping. Target areas have been identified largely by pyritic and sericitic alteration, secondary iron-oxide and Cu-carbonate stain, veining, and mineralized float. Recent glacial erosion has resulted in minimal oxidation, exposing sulphides at surface. Little geophysics had been employed until 1991, when the first airborne survey across the district was conducted. Diamond core drilling has followed the identification of mineralization by rock-chip and trench sampling. Exploration holes drilled in the Mitchell Valley and Brucejack Lake areas have been typically 250m deep.

Underground exploration has been restricted to the high-grade Au-Ag veins of the West zone (1985-1990). The decline reached the 1150 level, about 250 metres below surface, with underground drilling augmenting drifting.

Regional Geology

The regional geologic setting has been summarized by Kirkham and Margolis (this volume) and is not repeated here.

Local Geology, Alteration and Mineralization

<u>Host rocks</u>

Rock units in the northern and eastern Sulphurets district are considered to be part of the Lower Jurassic Hazelton Group (Alldrick and Britton, 1988), and include andesitic to basaltic volcanic rocks (flows, flow breccias, pillow lavas, pyroclastic deposits, epiclastic arenites), marine sedimentary rocks (argillite, limestone, chert), and Lower Jurassic (185-195 Ma) plagioclase-K-feldspar-hornblende-quartz phyric to equigranular dioritic to granitic intrusive rocks and hypabyssal flow domes (Macdonald, 1993; Margolis, 1993; Davies et al., 1994). Argillites, arenites, minor limestone, and volcaniclastic conglomerates exposed west of the northerly-trending Brucejack fault (Kirkham and Margolis, this volume) in the southeastern portion of the district near Brucejack Lake are considered by Davies et al. (1994) to be Upper Triassic Stuhini Group.

Rocks west of the Brucejack fault and below the Sulphurets thrust in the Mitchell Valley area (Fig. 1) consist of fine-grained, hydroclastic basaltic-andesite flow breccias with amygdaloidal feeder dikes; andesitic, coarsely phyric (plagioclase, hornblende) massive flows; and well-bedded, volcaniclastic arenite (Margolis, 1993). These units are pre-mineralization and termed Lower Sequence by Margolis (1993). The Lower Sequence is intruded by pre-mineralization plagioclase- and hornblende-phyric diorite (e.g., Iron cap stock, undated, north side of Mitchell Glacier, Figs. 1 and 3) and is host to significant mineralization at the Mitchell Cu-Au and Snowfield Au deposits described below. The Lower Sequence is unconformably overlain by an Upper Sequence of marine sedimentary rocks (carbonaceous argillite, limestone, chert), pillowed basalt flows, and fossiliferous siltstones largely exposed east of the Brucejack fault in the Mitchell Valley area (Fig. 1). Capping the Upper Sequence are two, massive pyroclastic deposits - a lower, andestic pyroclastic flow, and an upper, felsic, welded tuff possibly correlative with the Mount Dilworth formation (Alldrick and Britton, 1988). Margolis (1993) discusses evidence that the lower flow was deposited on the seafloor, resulting in a conspicuous, mottled, red and green alteration consisting of chloritic clasts in a siliceous, hematitic matrix. The Snowfield stock, a K-feldspar-megacrystic diorite (also hornblende and plagioclase phyric) exposed east of the Brucejack fault on the south side of Mitchell Glacier (Fig. 1), is flanked by an apron of comagmatic flow breccias and is considered a syn-volcanic exogenous stock within the Upper Sequence. No mineralization is exposed in the area of the stock. Its U-Pb (zircon) date of 189.6±2.2 Ma indicates a post-mineralization, Pliensbachian age for the Upper Sequence (see below; Margolis, 1993).

In the Brucejack Lake area to the southeast, mapping by Davies et al. (1994) has defined a generally northeast-facing sequence of argillites, feldspathic volcaniclastic arenites, tuffs, andesitic to dacitic pyroclastic and lava flows, and minor chert and limestone. Three intrusive phases recognized by Davies et al. (1994) and Macdonald (1993) in this area are a locally altered and veined (West zone) plagioclase-hornblene diorite (undated), a plagioclase-hornblende porphyry with megacrystic K-feldspar (undated) exposed about 500m west of the West zone, and a dacitic plagioclase-phyric, exogenous flow-dome complex (185 Ma) exposed $\geq$1 km to the east that is not associated with mineralization.

Syn-mineralization intrusive rocks

Leucocratic, equigranular to porphyritic intrusive quartz-syenite and granite that contain no (or very rare) hydrous or ferromagnesian phases are present at the lowest structural levels in the hydrothermal system in the Mitchell Valley area, are locally potassically altered and weakly mineralized (Cu-Au), and are surrounded by potassically-altered country rocks (Margolis, 1993; Kirkham, 1963); fluorite veins are common in potassic alteration within and proximal to the granitoids. This spatial association indicates that the granitoids drove the hydrothermal system, at least in the northern Sulphurets district. A U-Pb (zircon) age of 192.7±5 Ma for the quartz-syenite overlaps with a high-error 200±20 Ma Ar-Ar age of hydrothermal tourmaline and is considered the best estimate of the age of mineralization in the northern Sulphurets district (Margolis, 1993). Davies et al. (1994) propose that the K-feldspar megacrystic porphyry, locally cut by veins apparently related to West zone mineralization and intruding stratigraphy beneath units hosting the majority of West zone veins, drove the West zone hydrothermal system. This intrusion has not been dated.

Composition of volcanic and intrusive rocks

Although largely altered, pre- and syn-mineralization igneous rocks in Mitchell Valley (e.g., basaltic andesite, Iron Cap diorite, quartz-syenite, Snowfield stock), and near Brucejack Lake (dioritic intrusions and flow-domes described by Davies et al., 1994 and Macdonald, 1993) are subalkaline and quartz-bearing. Unlike pre-mineralization igneous rocks in the mineralized areas at Mitchell Valley which contain hornblende, conspicuous accessory apatite, and both plagioclase and potassium feldspar, syn-mineralization quartz-syenite contains no hydrous phases and is dominated by K-feldspar with minor albite microlites, indicative of the release of a magmatic aqueous phase during mineralization (Margolis, 1993). Unidirectional solidification textures in granitoid recognized by Kirkham (1963; personal communication 1990) are also indicative of saturation in an aqueous phase during their emplacement.

Structural geology

The general structural features and history of the district are outlined by Kirkham and Margolis (this volume) and not repeated here. Post-mineralization thrusting and high-angle faulting have resulted in block rotations, folding, and penetrative cleavage which have deformed mineralized veins (Margolis, 1993) and hindered the determination of the nature of syn-mineralization deformation and stresses. Although Roach and Macdonald (1992) propose that the West zone vein system formed within a sinistral shear zone, based on the orientations of cleavage in and around the zone, Davies et al. (1994) suggest that cleavage formation and folding is at least largely post-mineralization. Large stage-3 massive pyrite veins (see below) in both the Iron Cap and western Mitchell areas (Fig. 1) lie within unfoliated potassic alteration (unfoliated due to lack of phyllosilicates) and occur in two orientations separated by about 60°. Margolis (1993) suggests that these veins may have formed as strike-slip fractures resulting from a horizontal principal compression axis. It is possible, then, that the Sulphurets region during lower Jurassic mineralization and volcanism experienced compressional or transpressional deformation.

Alteration and mineralization: temporal and spatial patterns

As shown in Figure 4, four distinctive, cross-cutting alteration/mineralization events have been recognized in the northern Sulphurets district on the flanks of Mitchell Valley (Margolis, 1993). Stage 1 is characterized by pervasive, widespread potassic alteration (fine-grained K-feldspar flooding) accompanied by disseminated, low-grade Cu-Au mineralization; disseminated molybdenite is rare. Cu mineralization occurs as chalcopyrite; no bornite has been identified in the Mitchell Valley area. Closer to quartz-syenite at low levels in the system, potassic alteration is richer in Cu (typically .2 wt.%) and contains hydrothermal biotite, specularite, and magnetite; gold grades are generally <.015 opt in this "proximal" facies at depth. The proximal facies also extends to high levels in and surrounding stage-1 quartz stockwork zones which apparently mark the centers of the hydrothermal systems, but the alteration has largely been overprinted by stage-2 quartz-sericite-pyrite-chlorite (QSPC). Outboard of proximal potassic alteration, Cu and Au contents diminish in potassic flooding without biotite-magnetite-specularite (medial potassic alteration). Distal potassic alteration is transitional to outer stage-1 propylitic alteration and consists of K-feldpsar flooding with epidote and fine-grained albite. Drill hole 16 in the Iron Cap area (Figs. 1 and 3) intersected 300m of .2% Cu, .02% Mo, and .007 opt Au in medial and proximal potassic alteration. Rare quartz-chalcopyrite±magnetite veins occur at deep levels in proximal and medial potassic alteration near quartz-syenite. At shallower levels, extensive zones of quartz veining (quartz-stockworks) were emplaced during stage 1 within proximal potassic alteration, subsequently converted largely to QSPC during stage 2. The white to clear quartz veins are typically 1-3 cm wide, reach densities of 75%, are largely randomly oriented, and contain minor chalcopyrite, pyrite, and electrum, and rare molybdenite; K-feldspar and magnetite are absent in the veins. The veins have been deformed (transposed, folded) by post-mineralization deformation. Both veins and wallrock are enriched in Cu-Au. The Mitchell stockwork (Fig. 5), about 800 by 600 metres, contains a homogenous grade of about 0.2 wt.% Cu and .025 opt Au. The Snowfield quartz-stockwork is not as well mineralized (Figs. 6 and 7) and apparently represents a shallower portion of a stockwork unrelated to that at Mitchell (Margolis, 1993). Unlike the abundant stage-3 advanced-argillic alteration in the area of the Snowfield stockwork, only rare veinlets of pyrophyllite are present in the Mitchell area.

Stage-2, largely developed at high levels and localized in the center of the system (within and surounding quartz stockworks), consists of QSPC alteration, which replaced proximal potassic alteration (chlorite after biotite) in and surrounding quartz stockworks, and outer QSP alteration, which replaced medial and distal potassic alteration (Fig. 5). Stage-2 QSPC alteration with abundant, relict, stage-1 magnetite and chalcopyrite is present on the west side of the Mitchell stockwork (chlorite-magnetite zone in Fig. 5). Tourmaline (black, schorl-dravite, disseminated and veinlets) and molybdenite (disseminated and veins with quartz and pyrite) are common in stage-2 alteration. Tourmaline and most of the molybdenite in the Mitchell Valley area were apparently emplaced during stage 2; no Cu mineralization accompanied stage-2. A K-Ar age of 200±20 Ma for the hydrothermal tourmaline was obtained by Margolis (1993). QSP(C) alteration that replaced chalcopyrite-bearing potassic alteration is characterized by pyrite grains with chalcopyrite inclusions, most of the Cu was leached during the stage-2 overprint. The recognition of these inclusions is important in exploration for unreplaced, chalcopyrite-Au bearing potassic alteration at depth. Molybdenite veins are restricted to QSP alteration, contain no chalcopyrite, and cut quartz-chalcopyrite veins. Unlike the stage-1 chalcopyrite, preserved within overprinting pyrite of QSP alteration, molybdenite grains are intergrown (apparently stable) with chlorite and occur isolated in the QSP matrix outside of pyrite grains. Textures in rare veins of fluorite in deep proximal potassic alteration and quartz-syenite indicate that the fluorite was emplaced after potassic alteration.

Stage 3 is characterized by pervasive, advanced-argillic alteration (pyrophyllite-kaolinite-woodhouseite-svanbergite-quartz-pyrite-barite) at shallow levels at and above the quartz stockwork zones, and veins of massive pyrite within potassic or QSPC alteration beneath the advanced-argillic facies (Figs. 6, 7 and 8; Margolis, 1993). Rare pyrophyllite veins in advanced-argillic alteration cut molybdenite and tourmaline veins. Massive pyrite veins are widest and longest (11m by 800m) at lower levels closer to quartz-syenite (e.g., Iron Cap area, Figs. 1 and 3), and are narrow (typically 3 cm) at shallower levels, concentrated in the area of quartz stockworks. Sericitic alteration haloes are weakly developed marginal to the veins within pervasive potassic alteration. A steeply-plunging breccia pipe (20m diam.) containing angular to rounded, poorly-sorted clasts of potassic alteration cemented by massive pyrite is present west of the Mitchell stockwork in distal potassic alteration (Fig. 5). Pyrite within the massive pyrite veins and breccia pipe contains inclusions of hedleyite (Bi_7Te_3), hessite (Ag_2Te), rare Sn-sulphide (kesterite), galena, Cu-As sulphide, and is locally arsenic rich. Bismuth is restricted to the stage-3 pyrite. The massive pyrite veins, such as those at Iron Cap, contain high-grade, but erratic, gold mineralization (≤.2 opt); however, petrographic study indicates that the gold is introduced with later, stage-4, quartz containing galena, sphalerite, tetrahedrite, barite, and Hg-Au-Ag telluride. No significant mineralization was introduced in advanced-argillic alteration. No cross-cutting relationships were observed between veins of pyrophyllite and massive pyrite (Margolis, 1993).

Quartz-barite veins rich in galena, sphalerite, tetrahedrite-tennantite, lesser pyrite, chalcopyrite, acanthite, and electrum, and rare Hg-Au-Ag telluride and pyrargyrite represent stage-4. This mineralization (Pb-Zn-Ag-Sb-Ba-Au-Hg-Cd-Te-Cu) is well-developed peripheral to quartz stockworks and at high levels within QSP(C) alteration (e.g., Josephine zone, Figs. 6 and 7, veins typically assay >1 opt Au). Stage-4 veins in the northern Sulphurets area are largely <1m wide. The veins do not occur within the central, high-level parts of the system represented by the quartz-stockworks. Locally, the stage-4 assemblage is a matrix surrounding massive pyrite within the stage-3 massive pyrite veins; stage-4 quartz-barite veins cut massive pyrite veins, and commonly follow the same vein structures. Althaugh, stage-3 massive pyrite veins and the breccia pipe are locally gold-rich (.1 to .2 opt), as in the Iron Cap area on the north side of Mitchell Glacier, it appears that the gold was introduced by later stage-4 fluids; i.e., fluids of stage 4 locally followed the same paths as earlier stage-3 fluids.

Gold-silver vein mineralization in the Brucejack Lake area includes the West zone and subparallel but smaller Shore zone about 750m to the northeast (both east of the Brucejack fault), as well as other scattered vein occurrences. The West zone (Fig. 9) consists of a N40W trending zone of veins (≤6m wide) dipping steeply northeast that is at least 50 metres wide (Roach and Macdonald, 1992). Veins have strike lengths of up to 250m, but commonly are longer in the down-dip than the strike direction. Veins consists of quartz with minor K-feldspar, albite, carbonate, and barite in a foliated wallrock matrix of quartz-sericite-pyrite-chlorite-carbonate-K-feldpsar. Metallic phases in decreasing order of abundance are pyrite, sphalerite, chalcopyrite, galena, tetrahedrite, pyrargyrite, polybasite, electrum, stephanite, and acanthite (Roach and Macdonald, 1992). The alteration envelope and the majority of veins are concentrated along the contact between a section of argillite and overlying andesitic volcanic rocks which are exposed along the limbs of a northwest-trending syncline (Davies et al., 1994). The West zone veins have a similar mineral assemblage and a similar Ag:Au ratio (about 45) as stage-4 veins in the Mitchell Valley area, except that the former attain greater widths, sulphosalts are more common, and tellurides are absent. In Mitchell Valley, pyrargyrite is restricted to the Josephine zone, the highest level stage-4 veins in the area (Figs. 6 and 7); its abundnace in the West zone may indicate that the Brucejack Lake veins are similarly at a high and peripheral position with respect to a magmatic-hydrothermal center. Minor disseminated molybdenite in the lower levels of the West zone supports this (B. Way, Newhawk Gold Mines, pers. commun., 1990).

The Snowfield gold zone (at least 7 million tonnes at about .08 opt Au; values as high as .25 opt) is a disseminated style of stage-4 mineralization that was emplaced adjacent to a stage-1 quartz stockwork zone and stage-3 advanced-argillic alteration at relatively shallow levels and probably close to a magmatic center (Snowfield quartz stockwork; Figs. 6 and 7; Margolis, 1993). The mineralization occurs within QSPC-altered basaltic-andesite flow breccias that had previously been altered by stages 1 and 2. Electrum typically occurs as <1mm inclusions in pyrite grains that also contain inclusions of galena and sphalerite; the textures probably reflect recrystallization of pyrite. Galena, sphalerite, tetrahedrite-tennantite, acanthite, and barite also occur disseminated in the matrix or as coatings (<< 1 mm) on pyrite grains. Millimetre-scale clots of pyrite and rutile are common. Spessartine garnet is common in higher-grade areas, occurring as reddish-brown, 5 mm, equant grains. Rocks of the zone are strongly foliated (steep dip) as are rocks throughout the area. Higher grades (> .06 opt Au) occur as a gently-dipping, roughly tabular to wedge-shaped body from 35 to >75m thick surrounded by lower grades (.03-.06 opt Au).

<u>Stable-isotope studies</u>

Oxygen and hydrogen isotopic data for sericite, pyrophyllite, quartz, and magnetite of the four hydrothermal stages reveal that stage 1 contained the greatest component of probable magmatic fluid (estimated $\delta^{18}O$ water = 3.7-9.2), the highest value is a quartz-magnetite pair from a quartz-magnetite-chalcopyrite vein in proximal potassic alteration in quartz-syenite. Fluids for later stages and peripheral areas contained a greater component of a lighter $\delta^{18}O$ water (estimated $\delta^{18}O$ water = 2.9-6.5 for stage 2, 3.3-4.9 for stage 3, and .8-3.9 for stage 4; Margolis, 1993). This lighter water was either seawater or meteoric water near sea level, based on the $\delta^{18}O$-δD data, comparisons with data from active and fossil magmatic-hydrothermal systems, and the rock record at Sulphurets. Isotope geothermometry indicates temperatures of about 520°C for stage-1 (quartz-magnetite-chalcopyrite vein), and about 330°C for stage-2 QSPC alteration (Margolis, 1993).

Gold residence

There are two principle gold environments in the northern and eastern Sulphurets district. In the porphyry-style stage 1, gold accompanies and positively correlates with Cu and occurs as electrum grains within chalcopyrite, in the high-level quartz stockworks (Mitchell deposit) and pervasive proximal and medial potassic alteration. The second setting is in late-stage quartz-barite veins (Josephine zone, West zone) and the Snowfield gold deposit (stage-4); gold occurs as electrum or rarely telluride, accompanied by galena, pyrite, sphalerite, tetrahedrite, pyrargyrite, and only rare chalcopyrite. Stages 2 and 3 in the Mitchell Valley area did not produce significant gold mineralization. In the first case, isotopic evidence for high temperatures and magmatic waters, a strong positive correlation between Cu and Au, and the occurrence of electrum in chalcopyrite, indicate that Au, like Cu, was probably carried as a chloride complex. In the second case, Au was probably sulphidecomplexed in a more reduced fluid, as indicated by its lack of correlation with base metals, the evidence for a sulfidation mechanism for its precipitation in the Snowfield gold deposit (see below), and the abundance of barite at this stage (Margolis, 1993).

Geochemistry of mineralization

Mineralization is enriched in a polymetallic suite distributed among four stages, at least in the northern and eastern part of the district (Fig. 4): widespread Cu-Au with minor Mo in stage 1 potassic alteration and quartz stockworks; Mo-B-F in stage 2; Bi-Te-As-Cu-Pb-Sn in weakly mineralized stage-3 massive pyrite; and Pb-Zn-Ag-Au-Ba-Sb-Cd-Hg-Te-Cu in stage-4 veins and the Snowfield deposit. Elevated Cd in stage 4 occurs in sphalerite. The Snowfield gold deposit is characterized chemically by the following: (1) unlike stage-4 veins, which have Ag-to-gold ratios (Ag:Au) of >15 (typically 20-50), the Snowfield mineralization has a uniquely low Ag:Au ratio of ≤1; (2) Ag, Pb, and Zn are concentrated outside of the high-grade Au wedge; (3) there is a positive, linear correlation between Au and As, but not between Au and other metals; (4) Mn and V show conspicuous decreases in concentration in the center of the high-grade wedge.

<u>Origin of Snowfield gold deposit</u>

Margolis (1993) proposed that sulfidation of the host basaltic-andesite by relatively reducing and alkaline hydrothermal fluids led to gold precipitation in the Snowfield gold deposit. The positive correlation between Au and As is characteristic of mineralization produced by sulfidation of the host rock, a process in which sulphide-sulphur in the hydrothermal fluid reacts with ferrous iron in the wall rock to produce pyrite (or pyrrhotite), thereby removing sulfur from the fluid and causing the precipitation of metals, such as gold and probably arsenic, which are carried as sulphide complexes in the relatively reduced fluid (Phillips et al., 1984; Margolis, 1989). The clots of pyrite and rutile are indicative of the sulfidation of a ferrous-iron mineral in the wall rock; candidates for this phase are hydrothermal biotite and magnetite produced during earlier stage-1 potassic alteration, and stage-2 chlorite formed from them. A sharp depletion in vanadium (from about 50 to 10 ppm) within the center of the high-grade wedge may have resulted from the sulfidation of stage-1 magnetite or specularite, which are known to contain trace V; the V may have been incompatible in the pyrite and removed by the hydrothermal fluid. The contrast in complexing between gold (sulphide) and Ag-Pb-Zn-Cu (chloride) explains their lack of correlation and a low Ag:Au ratio of the mineralization and electrum. Ag, probably carried as chloride, would not have precipitated as a result of sulfidation of the wallrock, but by increasing pH or decreasing temperature (Romberger, 1988).

Calculations using program CHILLER (Reed, 1982) indicate that the gold mineralization could have formed by sulfidation of the basaltic andesite by a relatively alkaline water (pH $\geq$ 4 at 280°C; Margolis, 1993). Furthermore, the calculations show that Mn leaching and mineralization with a higher Au:Ag ratio could have formed under conditions of higher water-to-rock ratio (w/r) compared with the surrounding zones richer in Mn-silicate and Ag-Pb-Zn sulphide, implying that the high-grade wedge was the locus of fluid flow (i.e., a conduit). As hydrothermal fluids migrated outside of the conduit, silver, lead, and zinc sulphides precipitated owing to the breakdown of chloride complexes as pH increased. The high-grade wedge has a notably lower chlorite content than surrounding lower-grade zones; the modelling indicates that this may have resulted from conversion of chlorite to sericite under the relatively lower pH conditions at high w/r within the central conduit.

The model for the Snowfield gold deposit is one in which relatively reducing, alkaline fluids, similar to those which form adularia-sericite epithermal deposits (Heald et al., 1987), sulfidized basaltic andesite, yielding high-grade gold mineralization with a low Ag:Au ratio, local spessartine, and low silver-lead-zinc in a central conduit under high w/r. Lesser gold with higher Ag-Pb-Zn sulphides precipitated in surrounding zones at lower w/r. Hydrothermal fluids may have been focused along a bedding-parallel zone which was relatively more permeable or reactive. The deposit formed during stage 4, superjacent and lateral to the porphyry Cu-Mo center, represented by the quartz-stockwork zone and overlying advanced-argillic facies (Fig. 7). It replaced stage-2 sericite-chlorite alteration which had overprinted the Cu-rich potassic zone surrounding the stockwork. Spessartine garnets occur in late-stage Pb-Zn mineralization which formed about 600m above the porphyry-Mo deposit at Henderson, Colorado (White et al., 1981); and this is the same setting (with respect to porphyry-style mineralization) as the Snowfield deposit.

Economics

None of the mineralized areas discussed here is in production. Although geologic resources are significant, poor infrastructure, locally steep terrane, and a lack of oxidation resulting from recent glaciation, have precluded mining of the zones.

At Snowfield, a resource of about 7 million tonnes at 2.5 gpt Au is evenly distributed, resulting from the disseminated style of mineralization. Preliminary bench-scale metallurgical tests indicate recoveries in the range of 69-79% using conventional flotation and cyanidation techniques on a pyrite concentrate. Given the remote and rugged location of the deposit, the resource is not considered economic at the current ($380) gold price. The West zone's diluted mineable ore reserves are estimated at 500,000 tonnes of 14.4 gpt Au and 617 gpt Ag at a cutoff of 10.3 gpt Au equivalent (Ag/Au = 66) and a minimum mining width of

1.5m. Gold and silver recoveries are estimated at 90 and 89%, respectively, using combined gravity and flotation techniques. A feasibility study completed in 1990 proposed a 350 ton per day operation, direct operating costs of $145 per ton, an operating life of 4.5 years, and capital of about $43,000,000. A discounted cash-flow rate of return of 6.7% was estimated based on $400/oz gold and $5/oz Ag prices.

Discussion and Conclusions

The northern Sulphurets district displays a multi-stage porphyry-epithermal system as depicted in Figure 10. The early, potassic Cu-Au mineralization is a porphyry-style system dominated by high-temperature magmatic fluids of probable high salinity. Tourmaline and the bulk of the molybdenite were apparently introduced with second-stage fluids that produced QSPC alteration; presumably this fluid was at least in part magmatic, as indicated also by the stable-isotope data. The transition from Cu to Mo-B-F is consistent with experimental studies indicating that, with protracted evolution of magmatic aqueous fluids from a silicic melt, Mo, B, and F are partitioned into the magmatic aqueous phase after the bulk of the Cu (Candella, 1986). Unmineralized, pervasive stage-3 advanced-argillic alteration at high levels and the emplacement of massive pyrite veins beneath were followed by stage-4, quartz-barite veins containing base-metal sulphides and high-grade Au-Ag mineralization. These veins (Josephine zone, West zone) and the disseminated variety (Snowfield gold zone) are similar to base-metal adularia-sericite epithermal systems (Heald et al., 1987) which commonly form peripheral to and following associated porphyry Cu and acid-sulfate mineralization (Margolis et al., 1991). At Sulphurets, these veins do not occur in the high-proximal position (Fig. 10). The vertical scale of the system, from the upper portion of the quartz-syenite to the advanced-argillic facies, spans at least 800 metres in the western Snowfield area (Fig. 8). An additional 250 metres in vertical extent is indicated by the position of the stage-4 Josephine vein zone (Fig. 7). Therefore, the vertical extent of the system is at least 1 km.

In the northern Sulphurets district, at least two centers of mineralization are apparent, one centered on the area of the Mitchell stockwork, and a second centered on the area of the Snowfield stockwork about

1.5 km to the southeast. The Mitchell stockwork is truncated by the southeast-vergent Mitchell thrust (Fig. 8), with deeper-level quartz-syenite and potassic alteration in the hangingwall on the north and south sides of the glacier; the amount of displacement along the thrust is not known (Margolis, 1993). Both these stockworks lie in the lower plate of the thrust and, therefore, do not appear to represent a duplication of one system by thrust displacement. The apparent restriction of abundant tourmaline to the Snowfield area is further evidence that it is distinct from that at Mitchell. The centers of hydrothermal systems are apparently marked by the high-level, Cu-Au quartz-stockwork zones, where later QSPC alteration and massive pyrite veins are also concentrated. It is likely that these stockwork zones represent a central plume of magmatic fluids, possibly above volatile-rich cupolas in the large quartz-syenitic intrusive body, which underlies much of the alteration in the northern Sulphurets district. It is possible that the West zone vein mineralization is related to a third magmatic-hydrothermal system underlying the area west of Brucejack Lake. Post-mineralization, right-lateral motion along the Brucejack fault does not appear to be sufficient to place the West zone area adjacent to the Josephine zone and the Snowfield magmatic center 5-6km to the northwest (Davies et al., 1994). The Josephine veins are apparently related to the magmatic-hydrothermal system underlying the Snowfield stockwork on the north side of the Snowfield gold zone.

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FIGURE 1. Generalized geologic map of the study area; data from this study and modified from Britton and Alldrick (1988); drill hole DDH-16 (Iron Cap area) shown with granitoid (quartz-syenite) in subsurface; elevations increase north and south away from Mitchell Glacier; Iron Cap, Mitchell, and Snowfield areas are located on north side of the glacier (west of Brucejack fault), at and west of the mouth of the glacier, and south of the glacier west of the Brucejack fault, respectively.

FIGURE 2. Generalized alteration map of the study area.

FIGURE 3. Cross-section looking northwest across the Iron Cap area north of Mitchell Glacier; the east side of the Brucejack fault has moved toward the viewer as indicated by the dot-filled circle; the quartz-syenite is shown cutting the pre-mineralization diorite stock, although the shape of these bodies at depth is not known; similarly, the trace of the potassic-propylitic boundary at depth is not known; note drill hole 16 (see text and Fig. 1.

FIGURE 4. Diagram summarizing the four stages of hydrothermal alteration and related mineralization in the northern Sulphurets district; QTZ-SER-PY-CHL is abbreviation for quartz-sericite-pyrite-chlorite.

FIGURE 5. Map showing the distribution of hydrothermal alteration in the Mitchell area; abbreviations are: CHL-MT, chlorite-magnetite zone in CHL-SER-PY (chlorite-sericite-pyrite) alteration; QTZ-SER-PY, quartz-sericite-pyrite; Mb, molybdenite; cross-section A-A′ is shown in Figure 8.

FIGURE 6. Map showing the distribution of alteration in the Snowfield area; cross-sections A-A′ and B-B′ are shown in Figures 8 and 7, respectively; note the increasing elevation from the north side of the map (50 metres south of Mitchell Glacier) to the level of the Josephine vein zone; elevations then decrease south toward Hanging Glacier; the Mitchell area is located northwest of the map area (see Fig. 5); for orientation, the quartz-syenite is shown - it is potassically altered as are surrounding country rocks; abbreviations are - QSPC, quartz-sericite-pyrite±chlorite; ADV.-ARG., advanced-argillic.

FIGURE 7. Cross-section looking east-northeast across the Snowfield area; section B-B′ (Fig. 6); note the inferred quartz-syenite and preserved potassic alteration at depth, as indicated by the distribution of alteration and quartz-syenite to the west (Figs. 6 and 8); the high-grade portion of the Snowfield gold deposit is projected beneath the ice to the south; however, the distribution of the mineralization in this area is not known; note the conical shape of the quartz stockwork, the distribution of advanced-argillic alteration, and the high and peripheral Au-rich Josephine vein zone.

FIGURE 8. Cross-section looking northeast across the western part of the study area, including the eastern Mitchell and western Snowfield areas; see Figures 5 and 6 for cross-section location (A-A′); elevations above sea level are in metres; note the location of advanced-argillic alteration at high levels relative to potassic alteration and quartz-syenite, and the truncation of the Mitchell stockwork by the Mitchell thrust.

FIGURE 9. Cross-section looking northwest along the axis of the West zone; modified from Roach and Macdonald (1992); black areas are Au-rich quartz veins, stippled area is silicic alteration envelope (quartz>sericite), squares and rectangle are workings; levels in metres above sea level.

FIGURE 10. Schematic model of the hydrothermal system: a. stage 1, question mark indicates a lack of information concerning the uppermost part of the system; b. stage 2, thick line marks the lower limit of the bulk of stage-2 alteration; c. stage 3, short thick lines (veins) are massive pyrite, thick line near the top of the figure marks the lower limit of advanced-argillic alteration; d. stage 4, shaded veins are stage-3 massive pyrite. abbreviations: qtz, quartz; ser, sericite; py, pyrite; chl, chlorite; mb, molybdenite; tourm, tourmaline. The vertical scale is approximately 1 km, the horizontal scale approximately 2 km.