→ Snowfields (Sulphurets)

Porphyry-style and epithermal copper-molybdenum-gold-silver mineralization in the northern and southeastern Sulphurets district, northwestern British Columbia

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ABSTRACT

Four hydrothermal/mineralization stages, 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, these events are: (1) a porphyry-style copper ± gold stage coincident with potassic alteration of deep quartz-syenite and surrounding volcanic rocks; copper-gold-bearing quartz stockworks (e.g., Mitchell deposit; unknown tonnage, about 0.2% Cu, 0.86 g/t Au) developed at high levels; (2) a moderate- to high-level quartz-sericite-chlorite-pyrite alteration hosting molybdenite veins and tourmaline but no copper-gold; (3) unmineralized advanced argillic alteration at high levels, and underlying massive pyrite veins and a breccia pipe enriched in Bi-Te-Sn-As; (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 centres; and a high-grade, basaltic andesite-hosted disseminated gold zone (Snowfield gold deposit, ≥ 7 million tonnes grading 2.74 g/t Au) with a similar mineral assemblage. This disseminated mineralization is adjacent to a stage-1 quartz stockwork (Snowfield stockwork). The West zone vein system (750 000 tonnes grading 14.74 g/t Au and 686 g/t 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 at least the early stages of hydrothermal activity. Radiometric dating indicates an Early Jurassic mineralization age (about 190 Ma to 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 km north of Stewart, British Columbia, and 20 km west of Bowser Lake. The district, about 80 km² centred at Latitude 56°30′N and Longitude 130°12′W, encompasses widespread hydrothermal alteration and at least five areas of significant copper-gold-silver-molybdenum mineralization. The focus of this paper is the northern and eastern Sulphurets district — chiefly the north and south slopes of Mitchell Glacier and the area on the west side of Brucejack Lake (Fig. 1). Significant mineralized areas in this portion of the district and described below are: the Mitchell copper-gold quartz stockwork zone, the Snowfield disseminated gold zone, and the West zone gold-silver vein system.

The northern and eastern Sulphurets districts are largely above tree line in rugged glaciated terrane. North- and south-facing slopes surrounding the westerly draining Mitchell Glacier rise 700 m to 1000 m above the glacier to elevations of about 2000 m, 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 1400 m elevation that is covered by grasses and trees at lower elevations to the west. Current access to the district is limited to helicopter. Since the mid-1980s, 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, and barite veins at Brucejack Lake were staked. In 1959, Granduc Mines Ltd. discovered gold-silver vein mineralization near Brucejack Lake, and in 1960, recognized porphyry copper-style mineralization in the district (Kirkham, 1963). Granduc continued to conduct intermittent exploration through 1975, including mapping, sampling, magnetometer surveying, and limited drilling (6 holes). By 1975, a widespread 1 ppm to 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 copper mineralization, further explored the Snowfield zone, and began systematic delineation of the gold-silver vein mineralization on the west side of Brucejack Lake; in addition, other gold-silver bearing quartz veins were recognized throughout the area. In 1985, Granduc optioned the property to Newhawk Gold Mines Ltd. and Lacana Mining (later Corona Corporation, now Homestake Mining Co.), which drilled five holes in the Snowfield zone that year. Most holes intersected at least 2.0 g/t Au over 70 m to 90 m widths. From 1985 to 1990, work by this joint venture concentrated on drilling and underground exploration of the West zone, leading to the announcement of geological reserves of 749 000 tonnes grading 15.4 g/t Au and 650 g/t Ag, deemed uneconomic in 1990. In 1991 and 1992, the district was subdivided into three parcels, with Placer Dome Inc. (Kerr copper-gold deposit) acquiring the western and northwestern areas, including the Main Copper, Sulphurets Gold, and Mitchell copper-gold stockwork, and Newhawk (42% owned by Homestake Canada

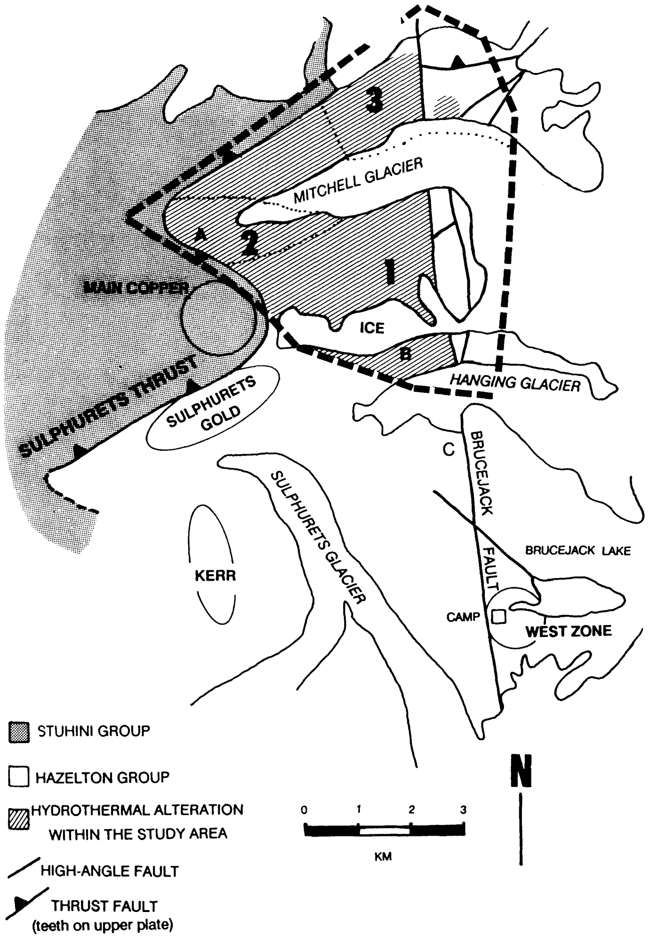

FIGURE 1. Generalized map of the Sulphurets district; geology from Britton and Alldrick (1988); heavy dashed line outlines research area of Margolis (1993), from which the bulk of this report draws its data; dotted lines in that area mark the three subdistricts as discussed in the text: (1) Snowfield (number placed at location of Snowfield gold zone); (2) Mitchell (number placed at Mitchell stockwork zone); and (3) Iron Cap (number placed at pyrite vein area); "A" = Alder zone, "B" = Josephine zone; Main Copper, Sulphurets Gold, Kerr, West zone, and "C" (Goldwedge) are other mineralized zones noted in the text.

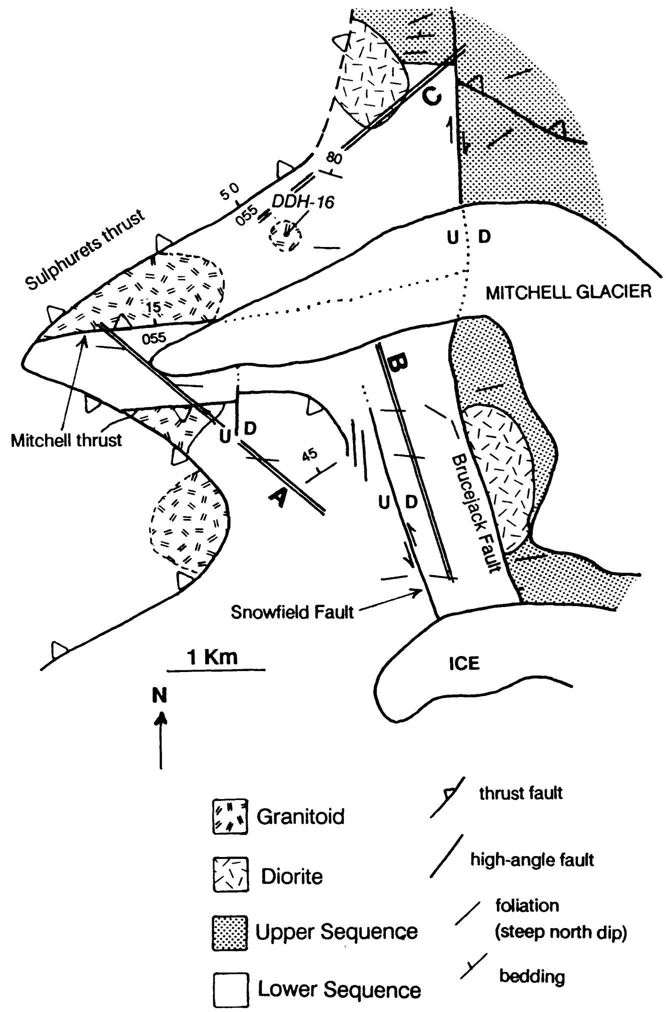

FIGURE 2. Generalized geologic map of the northern Sulphurets district; data from Margolis (1993) and modified from Britton and Alldrick (1988); drill hole DDH-16 (Iron Cap area) shown with granitoid (quartz-syenite) projected to surface; elevations increase north and south away from Mitchell Glacier; double lines are approximate locations of cross-sections A, B and C of Figures 8, 7, and 3, respectively.

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 copper-gold stockwork and Snowfield zone were further drilled, and new gold-silver veins were discovered in the Brucejack Lake area to the southeast.

Published research, and unpublished Master's and Doctoral research 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; diamond-sawed trenches (about 4 cm wide) on smooth, glacially-polished outcrops; dynamite-blasted trenches typically 0.5 m by 5 m in size; and reconnaissance sampling and mapping. Target areas have been identified largely by pyritic and sericitic alteration, secondary iron-oxide and copper-carbonate stain, veining and mineralized float. Recent glacial erosion has exposed sulphides at surface. Identification of mineralization by rock-chip and trench sampling was followed by diamond core drilling. Exploration drill holes tested the Mitchell Valley and Brucejack Lake areas to an average depth of 250 m. Little geophysics had been employed until 1991, when the first airborne survey across the district was conducted.

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

Regional Geology

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

Local Geology, Alteration and Mineralization

Host Rocks

Rock units in the northern and eastern Sulphurets district are 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 Ma to 195 Ma) plagioclase-K-feldspa[illegible]rnb[illegible]-quartz phyric to equigranular dioritic to granitic intrusive rocks and hypabyssal domes (Macdonald, 1993; Margolis, 1993; Davies et al., 1994). Argillites, arenites, minor limestone and volcaniclastic conglomerates exposed west of the northerly-trending Brucejack Fault (Fig. 1) 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 (Figs. 1 and 2) consist of fine-grained, hydroclastic basaltic-andesite flow breccias with amygdaloidal feeder dikes; andesitic, coarse plagioclase-hornblende phyric massive andesite flows; and well-bedded, volcaniclastic arenite (Margolis, 1993). These units are premineralization and termed Lower Sequence by Margolis (1993). The Lower Sequence is intruded by premineralization plagioclase- and hornblende-phyric diorite (e.g., Iron Cap stock, undated, north side of Mitchell Glacier, Figs. 2 and 4) and is host to significant mineralization at the Mitchell copper-gold and Snowfield gold 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. 2). Capping the Upper Sequence are two, massive pyroclastic deposits — a lower, andesitic pyroclastic flow, and an upper, felsic, welded tuff, possibly 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 hornblende-plagioclase diorite exposed east of the Brucejack Fault on the south side of Mitchell Glacier (Figs. 2 and 7), is flanked by an apron of comagmatic flow breccias and is considered a syn-volcanic exogenous dome 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 postmineralization Pliensbachian age for the Upper Sequence (Margolis, 1993).

In the Brucejack Lake area to the southeast (Fig. 1, the area of the West zone vein system), mapping by Davies et al. (1994) has defined a folded but 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-hornblende diorite (undated), a plagioclase-hornblende porphyry with megacrystic K-feldspar (undated) exposed about 500 m west of the West zone, and a dacitic plagioclase-phyric, exogenous flow-dome complex (185 Ma) exposed ≥1 km to the east that is not associated with mineralization.

Synmineralization Intrusive Rocks

Leucocratic, equigranular to porphyritic intrusive quartz syenite and granite (granitoids in Fig. 2) are present at the lowest structural levels in the hydrothermal system in the Mitchell Valley area. These intrusions rarely contain hydrous or ferromagnesian phases and are locally potassically altered, weakly mineralized (copper-gold), and 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) note that a K-feldspar megacrystic porphyry west of the West zone is cut by veins apparently related to the zone and intrudes stratigraphy beneath units hosting the majority of the veins. They propose that the intrusion drove the West zone hydrothermal system. This intrusion has not been dated.

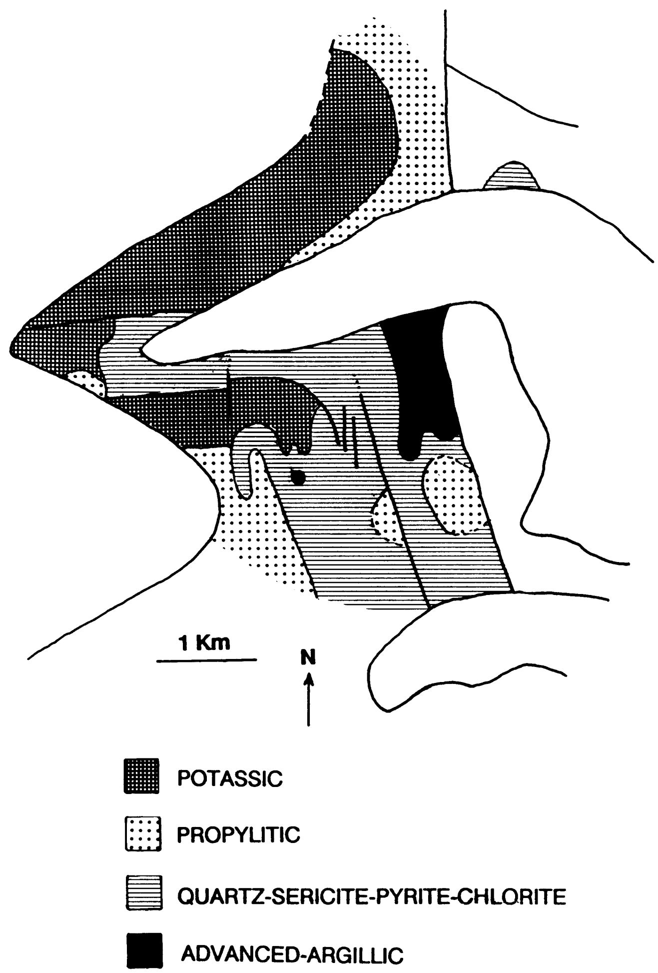

FIGURE 3. Generalized alteration map of the northern Sulphurets district.

Composition of Volcanic and Intrusive Rocks

Predominantly altered, pre- and synmineralization 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 premineralization igneous rocks in the mineralized areas at Mitchell Valley which contain hornblende, conspicuous accessory apatite, and both plagioclase and K-feldspar, synmineralization 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 rocks recognized by Kirkham (1963; pers. comm., 1990) also indicate saturation in an aqueous phase during emplacement.

Structural Geology

The general structural features and history of the district are outlined by Kirkham and Margolis (this volume). Postmineralization 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 synmineralization 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)

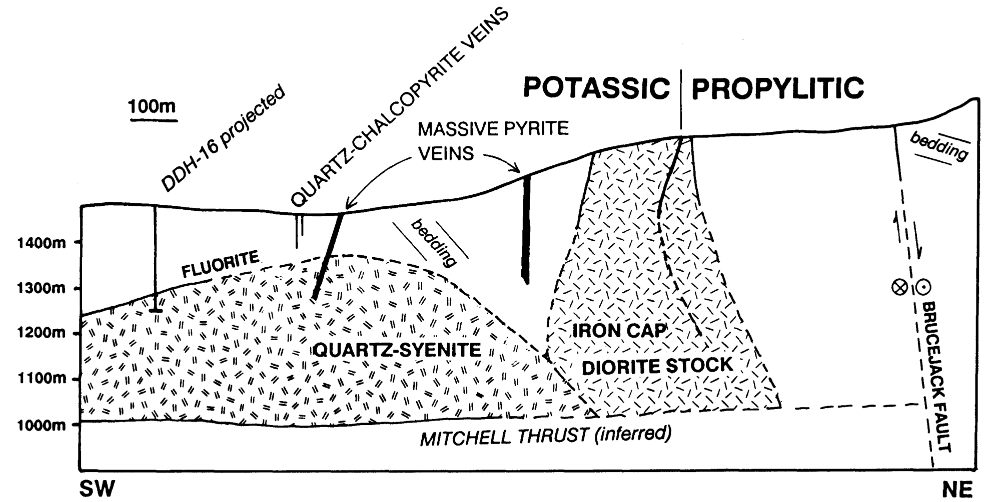

FIGURE 4. Cross-section C of Figure 2 looking northwest across the Iron Cap area north of Mitchell Glacier; the east side of the Brucejack Fault has moved toward the viewer as indicated by the dot-filled circle; the quartz-syenite is shown cutting the pre-mineralization Iron Cap diorite stock, although 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 Figure 2).

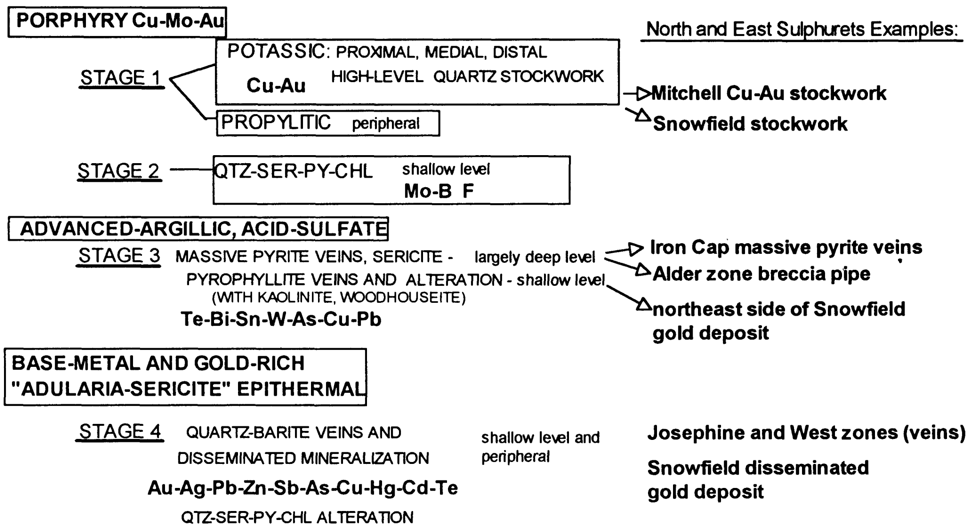

FIGURE 5. Diagram summarizing the four stages of hydrothermal alteration and related mineralization in the northern Sulphurets district; QTZ-SER-PY-CHL abbreviates quartz-sericite-pyrite-chlorite.

suggest that cleavage formation and folding is largely post-mineralization. Large stage-3 massive pyrite veins (see below) in both the Iron Cap and western Mitchell areas 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 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 5, four distinctive, cross-cutting alteration/mineralization events have been recognized in the northern Sulphurets district on the flanks of Mitchell Valley, based on cross-cutting relationships observable at map, outcrop, and thin-section scales (Margolis, 1993). Stage-1 is characterized by pervasive, widespread potassic alteration (fine-grained K-feldspar flooding) accompanied by disseminated low-grade copper-gold mineralization; disseminated molybdenite is rare. Copper 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 copper (typically 0.2 wt.%) and contains hydrothermal biotite, specularite and magnetite; gold grades are generally <0.5 g/t 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 centres of the hydrothermal systems, but the alteration has largely been overprinted by stage-2 quartz-sericite-pyrite-chlorite (QSPC). Outboard of proximal potassic alteration, copper and gold 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-feldspar flooding with epidote and fine-grained albite. Drill hole 16 in the Iron Cap area (Figs. 2 and 4) intersected 300 m of 0.2% Cu, 0.02% Mo, and 0.24 g/t 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 higher levels, extensive quartz stockworks were emplaced during stage 1 within proximal potassic alteration that was subsequently overprinted by QSPC during stage-2. In the Mitchell subdistrict, the QSPC replace-

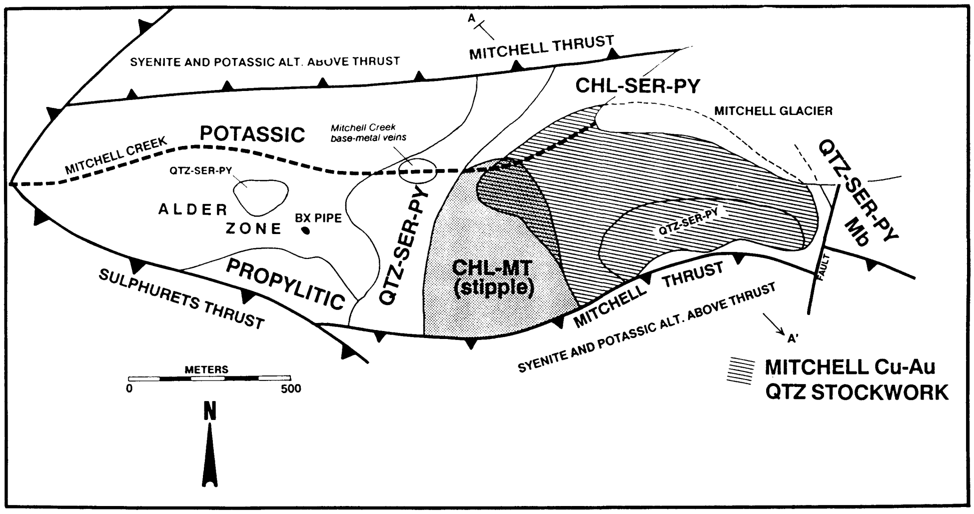

FIGURE 6. Map showing the distribution of hydrothermal alteration in the Mitchell area; abbreviations are: CHL-MT, chlorite-magnetite zone within pervasive CHL-SER-PY (chlorite-sericite-pyrite) alteration; QTZ-SER-PY, quartz-sericite-pyrite; Mb, molybdenite; cross-section A-A' is shown in Figure 9.

ment of proximal potassic is particularly evident in a "chl-mt" zone (Fig. 6), in which chlorite, in thin section, appears to have replaced hydrothermal biotite, there is abundant disseminated magnetite and chalcopyrite, and fine-grained K-feldspar is partially altered to sericite. The white to clear quartz veins are typically 1 cm to 3 cm wide, reach densities of 75%, are largely randomly oriented, and contain minor chalcopyrite, pyrite and gold, and rare molybdenite. K-feldspar and magnetite are absent in the veins. The veins have been deformed (transposed, folded) by postmineralization deformation. Both veins and wallrock are enriched in copper and gold. The Mitchell stockwork (Fig. 6), about 800 m by 600 m, contains a homogenous grade of about 0.2% Cu and 0.86 g/t Au. The Snowfield quartz stockwork contains only weak Au-Mo-Cu (Figs. 7 and 8) and is probably located at a higher position relative to the Mitchell stockwork zone (Margolis, 1993). Unlike the widespread stage-3 advanced argillic alteration cutting and lying above the Snowfield stockwork, only rare veinlets of pyrophyllite are present in the Mitchell area.

Stage-2 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. 6) above the syenite intrusions (Margolis, 1993). 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. 6). Tourmaline (black schorl-dravite, disseminated and veinlets) and molybdenite (disseminated and veins with quartz and pyrite) are common in stage-2 alteration; no tourmaline and only minor disseminated molybdenite occur in potassic alteration. Cross-cutting and textural relations indicate that tourmaline and most of the molybdenite in the Mitchell Valley area were emplaced during stage-2. No copper mineralization accompanied stage-2. A K-Ar age of 200 ± 20 Ma for the hydrothermal tourmaline was obtained by Margolis (1993). QSPC alteration that replaced chalcopyrite-bearing potassic alteration is characterized by a lower chalcopyrite content and pyrite grains containing rare chalcopyrite inclusions. Chemical compositions of potassic and adjacent QSP overprint indicate that most of the copper (chalcopyrite) was leached during stage-2. The recognition of these inclusions is important in exploration for unreplaced, chalcopyrite-gold 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. Rare veins of fluorite in deep proximal potassic alteration and quartz-syenite contain fragments of potassically-altered rock, indicating that the fluorite was emplaced after potassic alteration.

Stage-3 is characterized by a pervasive, advanced argillic, acid-sulphate alteration assemblage consisting of pyrophyllite, kaolinite, woodhouseite-svanbergite $[(Ca,Sr)Al_3(PO_4)(SO_4)(OH)_6]$, quartz, pyrite, and barite at shallow levels at and above the quartz-stockwork zones. Bracketed between stages-2 and -4, and probably coeval with the advanced argillic phase, are veins of massive pyrite and massive-pyrite cemented breccias within potassic or QSPC alteration beneath the advanced argillic zone (Figs. 7, 8 and 9; Margolis, 1993). Rare pyrophyllite veins in advanced argillic alteration cut molybdenite and tourmaline veins. The massive pyrite veins are widest and longest (11 m by 800 m) at deeper levels closer to quartz syenite (e.g., Iron Cap area, Fig. 4), and are narrow (typically 3 cm) at shallower levels, where they are concentrated in the lower parts of quartz stockworks (Mitchell stockwork). Sericitic alteration haloes are weakly developed marginal to the veins within pervasive potassic alteration. A steeply-plunging breccia pipe (20 m diameter) 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 (Alder zone, Fig. 6). 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 (≤ 7 g/t); however, textures in thin-section and outcrop indicate that the gold was introduced during stage-4 (see below). No significant mineralization was introduced with the advanced argillic alteration. No cross-cutting relationships were observed between veins of pyrophyllite and massive pyrite.

Quartz-barite and barite-only veins locally rich in galena, sphalerite, tetrahedrite-tennantite, lesser pyrite, chalcopyrite, acanthite, electrum, and rare Hg-Au-Ag telluride and pyrargyrite represent stage-4 and occur within QSPC alteration. This mineralization (Pb-Zn-Ag-Sb-Ba-Au-Hg-Cd-Te-Cu) is well-developed peripheral to quartz stockworks and large massive pyrite veins and at high levels within QSPC alteration (e.g., Josephine zone, Figs. 7 and 8, veins typically assay >30 g/t Au). Stage-4 veins in the northern Sulphurets area are largely <1 m 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

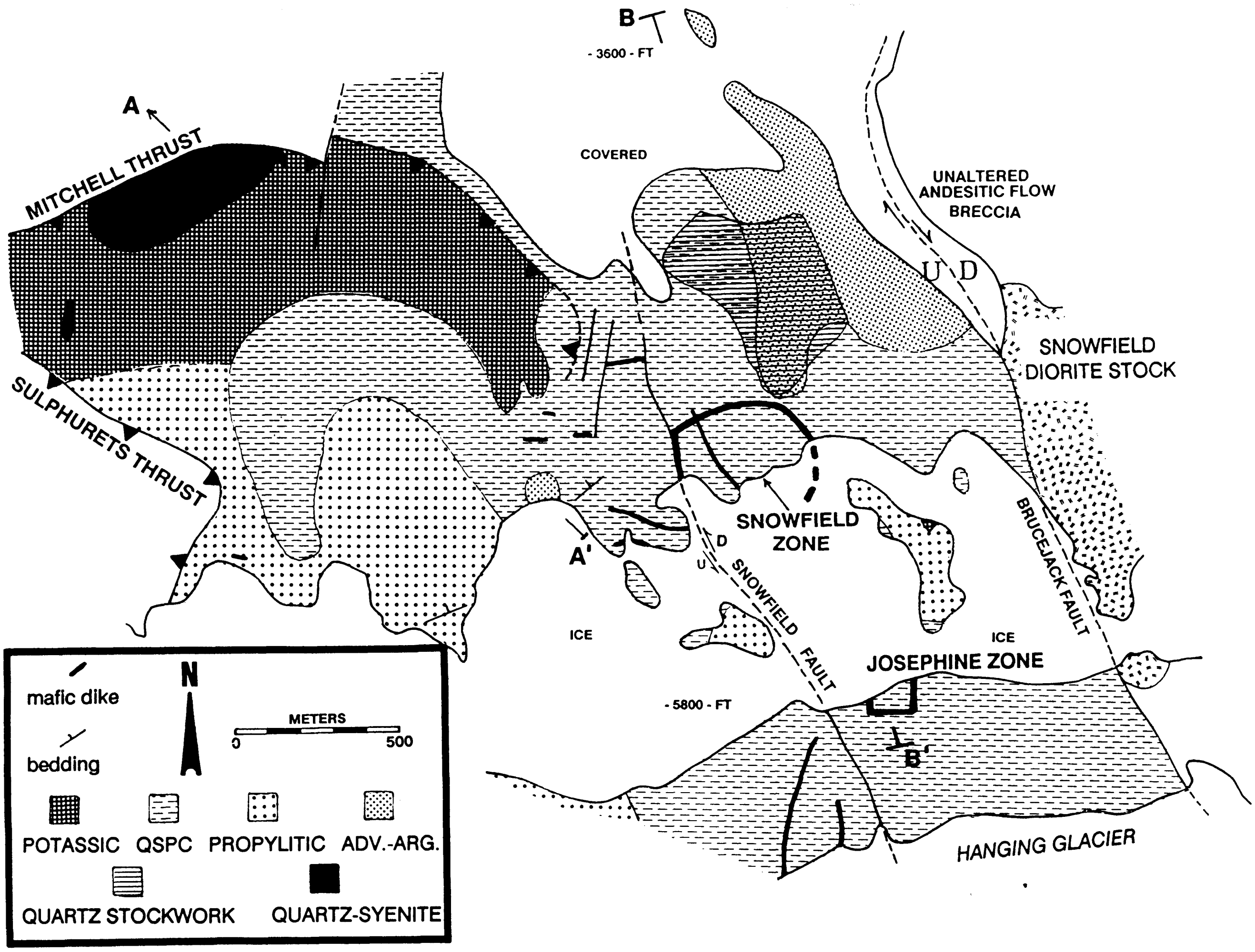

FIGURE 7. Map showing the distribution of alteration in the Snowfield area on the south side of Mitchell Glacier; cross-sections AA' and BB' are shown in Figures 9 and 8, respectively; note that elevation increases from the northern-most outcrop shown (50 m south of Mitchell Glacier) to the level of the Josephine vein zone; elevations then decrease south toward Hanging Glacier; the Mitchell area is located northwest of the map area (Fig. 6); for orientation, the quartz-syenite is shown for reference — and both it and surrounding country rocks are potassically altered; "Snowfield zone" is Snowfield gold deposit; abbreviations are — QSPC, quartz-sericite-pyrite ± chlorite; ADV-ARG, advanced-argillic.

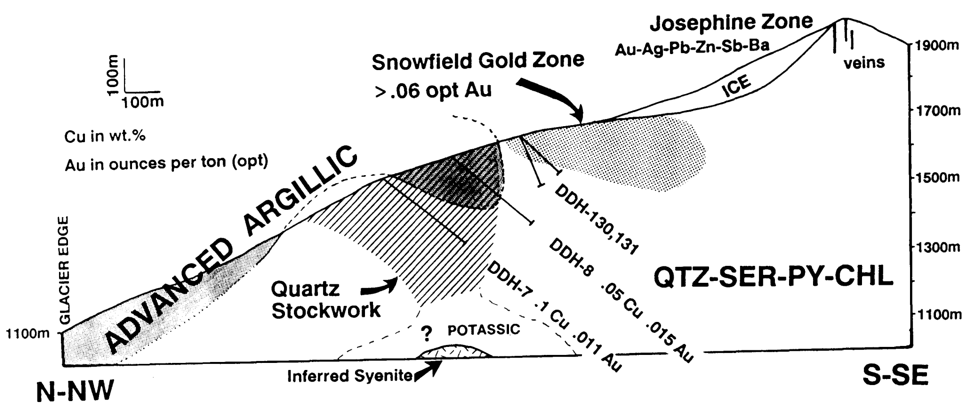

FIGURE 8. Cross-section BB' of Figure 7 looking east-northeast across the Snowfield area; note the inferred quartz-syenite and potassic alteration at depth, projected from similar known alteration and quartz-syenite elsewhere (Figs. 7 and 9); the high-grade portion of the Snowfield gold deposit is projected 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 gold-rich veins of the Josephine zone.

follow the same vein structures. Although stage-3 massive pyrite veins and the breccia pipe are locally gold-rich (3 g/t to 7 g/t), 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 750 m to the northeast, both east of the Brucejack Fault, as well as other scattered vein occurrences, such as the Goldwedge veins (Fig. 1). The West zone (Fig. 10) consists of a 140°-trending system of veins (≤6 m wide) dipping steep[illegible]rth The zone of veins is at least 50 m wide (Roach and Macdonald, 1992). Veins have roughly equal strike and dip dimensions of up to 250 m. Veins consist of quartz with minor K-feldspar, albite, carbonate, and barite in a foliated quartz-sericite-pyrite-chlorite-carbonate-K-feldspar-altered wallrock. 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 occur above a contact between 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 silver:gold ratio (about 45) as stage-4 veins in the Mitchell Valley area. However, 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. 7 and 8). Its abundance 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 centre. Minor disseminated molybdenite in the lower levels of the West zone supports this hypothesis (B. Way, pers. comm., 1990).

The Snowfield zone (at least 7 million tonnes grading 2.75 g/t Au; values as high as 8.6 g/t) 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 centre (Snowfield quartz stockwork; Figs. 7 and 8; Margolis, 1993). The mineralization occurs within QSPC-altered basaltic-andesite flow breccias that had previously been altered by stages-1 and -2. Gold typically occurs as <1 mm inclusions in pyrite grains that also contain inclusions of galena and sphalerite. It is uncertain if the texture reflects a primary habit or the 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 equant grains (≤5 mm). Rocks of the zone are strongly foliated (steep dip) as are rocks throughout the area. Higher grade mineralization (>2 g/t Au) occur as a gently-dipping, roughly tabular to wedge-shaped body from 35 m to >75 m thick, surrounded by lower grades (1 g/t to 2 g/t Au).

Stable Isotope Studies

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 0.8-3.9 for stage-4). This lighter water was either seawater or meteoric water near sea level based on the $\delta^{18}O$-δD data and comparisons with data from active and fossil magmatic-hydrothermal systems, and the marine 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 principal gold environments in the northern and eastern Sulphurets district. In the porphyry-style stage-1 potassic alteration and quartz stockworks, gold accompanies and positively correlates with copper; it occurs as grains within chalcopyrite at the high-level quartz stockworks of the Mitchell deposit. The second setting is in late stage-4 quartz-barite veins (Josephine zone, West zone) and the Snowfield deposit; gold occurs in the native form or rarely in 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 minerali-

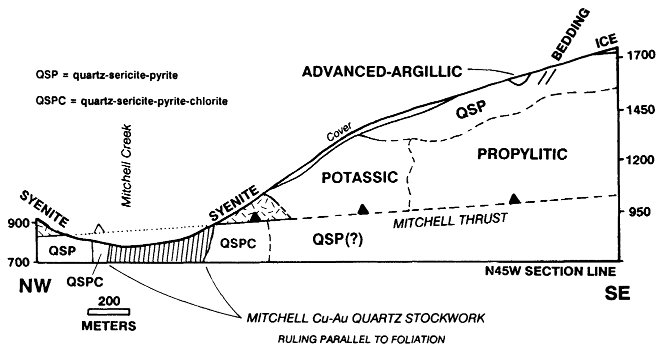

FIGURE 9. Cross-section AA' of Figures 6 and 7 looking northeast across the western part of the Mitchell Glacier and including the eastern Mitchell and western Snowfield areas; elevations above sea level are in metres; note the location of advanced-argillic alteration at high levels relative to potassic alteration and quartz-syenite, and the truncation of the Mitchell stockwork by the Mitchell thrust.

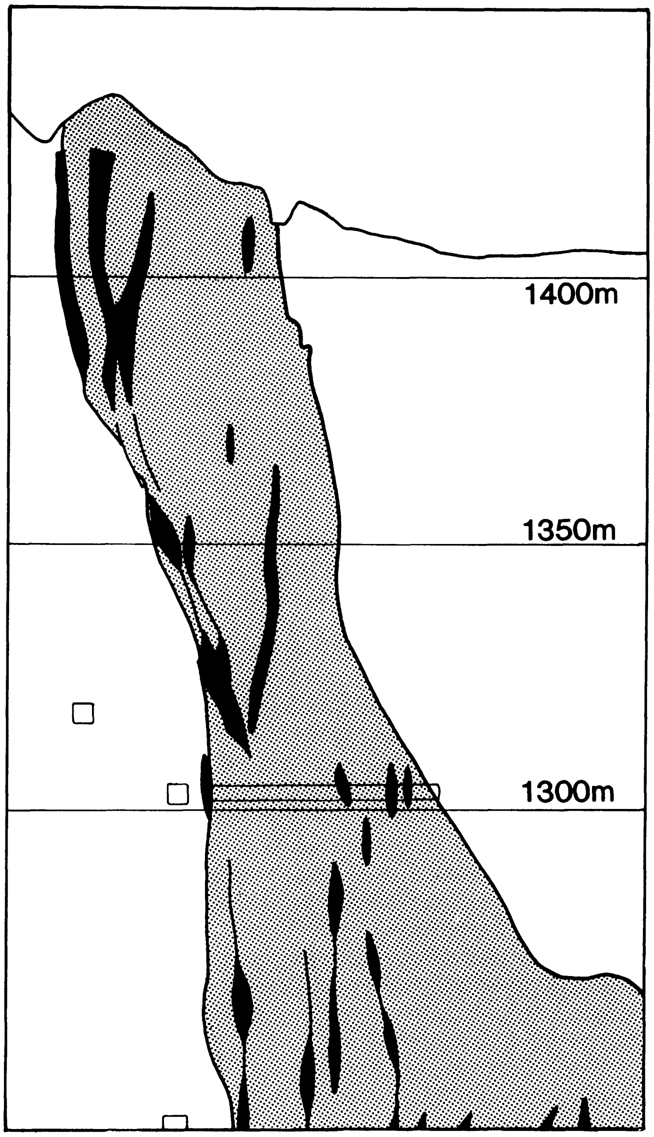

FIGURE 10. Cross-section looking northwest along the axis of the West zone; modified from Roach and Macdonald (1992); black areas are gold-rich quartz veins, stippled area is silicic alteration envelope (quartz>sericite), squares and rectangle are workings; mine levels in metres above sea level.

zation. In the first case, isotopic evidence for high temperatures and magmatic waters, a strong positive correlation between copper and gold, and the occurrence of electrum in chalcopyrite, indicate that gold, like copper, was probably carried as a chloride complex. In the second case, gold was probably sulphide-complexed in a more reduced fluid. At the Snowfield deposit, this sulphide complexing is indicated by the lack of correlation between gold and silver, lead, and zinc, and the evidence for a sulphidation mechanism for gold's precipitation (see below).

Geochemistry of Mineralization

Mineralization is enriched in a polymetallic suite distributed among four stages (Fig. 5): 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 cadmium in stage-4 occurs in sphalerite. In addition to cross-cutting relations, the Sn-Te-Bi-As in the massive pyrite supports a genetic link between the advanced argillic alteration and pyrite veins (cf. Ashley and Alpers, 1975).

The Snowfield deposit is characterized chemically by the following: (1) unlike stage-4, gold-rich, quartz-barite, base-metal veins, which have Ag:Au ratios of >15 (typically 20 to 50), the Snowfield mineralization has a uniquely low silver:gold ratio of ≤ 1; (2) Ag, Pb, and Zn are concentrated where gold grades are generally <2 g/t outside of the high-grade gold wedge; (3) there is a positive linear correlation between gold and arsenic, but not between gold and other metals; (4) manganese and vanadium show conspicuous decreases in concentration in the centre of the high-grade wedge.

Origin of Snowfield Gold Deposit

Margolis (1993) proposed that sulphidation of the host basaltic andesite by relatively reduced hydrothermal fluids caused gold precipitation in the Snowfield deposit. The positive correlation between gold and arsenic is characteristic of mineralization produced by sulphidation, 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 sulphur 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 sulphidation of an iron-bearing 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 ppm to 10 ppm) within the centre of the high-grade wedge may have resulted from the sulphidation of stage-1 magnetite or specularite, which are known to contain trace vanadium (microprobe analyses); the vanadium 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 silver:gold ratio of the mineralization and electrum. Silver, probably carried as chloride, would not have precipitated as a result of sulphidation 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 sulphidation of the basaltic andesite by a relatively alkaline water (pH ≥ 4 at 280°C; Margolis, 1993). Furthermore, the calculations show that manganese leaching and mineralization with a lower silver:gold ratio could have formed under conditions of higher water-to-rock ratio (w/r) compared with 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 beyond 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; modelling indicates that this may have resulted from conversion of chlorite to sericite under the relatively lower pH and higher w/r conditions within the central conduit.

The model for the Snowfield deposit is one in which a reduced and alkaline fluid, similar to that which forms adularia-sericite epithermal deposits (Heald et al., 1987), sulphidized basaltic andesite, yielding high-grade (2 g/t to 7 g/t) gold mineralization with a low silver:gold ratio, local spessartine, and low silver-lead-zinc in a central conduit under high w/r. Lesser gold with greater amounts of Ag-Pb-Zn sulphides precipitated in surrounding zones at lower w/r. The gold-bearing hydrothermal fluids may have been focussed along a bedding-parallel zone which was relatively more permeable or reactive. The deposit formed during stage-4, adjacent to a quartz-stockwork zone (stage-1) and overlying advanced argillic facies (stage-3), which probably developed superjacent to and at the centre of a porphyry copper-molybdenum system (Fig. 8). The gold mineralization occurred within an area of stage-2 sericite-chlorite-pyrite alteration which overprinted a copper-rich potassic zone in and surrounding the stockwork (rare copper-rich potassic alteration is preserved several hundred metres southeast of the gold zone; Fig. 7). Spessartine garnets occur in late-stage lead-zinc mineralization which formed about 600 m above the porphyry-molybdenum 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 are in production. Although geologic resources are significant, poor infrastructure, locally steep terrane, and erosion of oxidized horizons by recent glaciation, have precluded mining.

At the Snowfield zone, a resource of about 7 million tonnes grading 2.9 g/t Au is very evenly distributed, a reflection of the disseminated style of mineralization and the sulphidation process. Preliminary bench-scale metallurgical tests indicate recoveries in the range of 69% to 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 1994 gold price of about US$380 per ounce.

The West zone's diluted mineable ore reserves are estimated at 543 540 tonnes of 14.4 g/t Au and 593 g/t Ag at a cutoff of 10.3 g/t Au equivalent (silver/gold = 66) and a minimum mining width of 1.5 metres. 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 tonne per day operation, direct operating costs of $145 per tonne, 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 US$400/oz gold, US$5/oz silver prices, and an exchange rate of CDN$100 = US$85.

Discussion and Conclusions

The northern Sulphurets district displays a multi-stage porphyry-epithermal system as depicted in Figure 11. The early potassic copper-gold mineralization is a porphyry-style system dominated by high-temperature magmatic fluids of probable high salinity. Tourmaline and the bulk of the molybdenite were introduced with second-stage fluids that produced QSPC alteration; stable isotope data indicate that at least part of this fluid was of magmatic origin (Margolis, 1993). Experimental studies show that during protracted evolution of magmatic aqueous fluids from a silicic melt, Mo, B and F will partition into the magmatic aqueous phase after the bulk of the copper (Candella, 1986). This is consistent with the observed transition from early Cu to later Mo-B-F at Sulphurets. Unmineralized, pervasive stage-3 advanced argillic alteration at high levels and the emplacement of massive pyrite veins beneath were followed

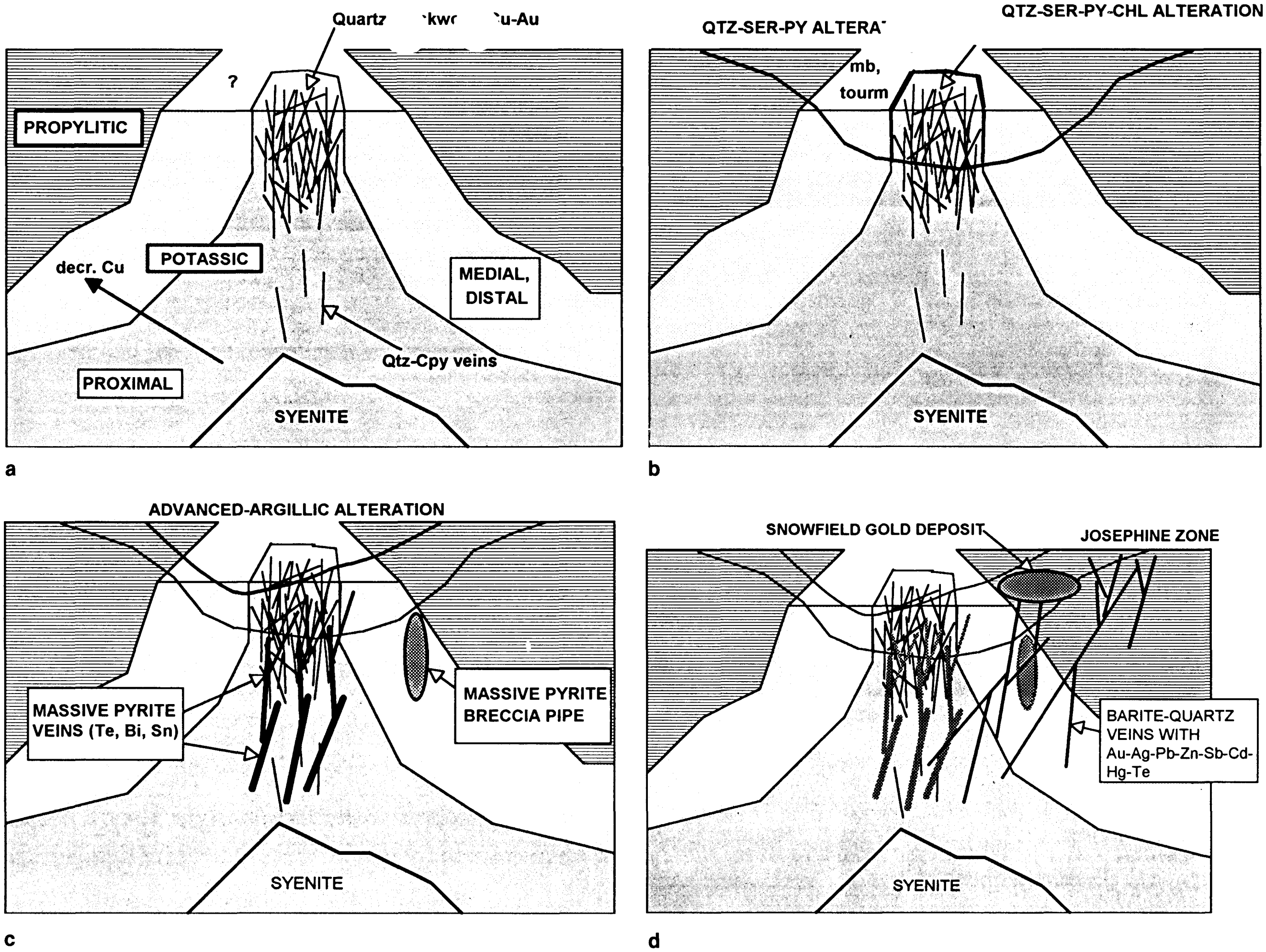

FIGURE 11. Schematic model of the hydrothermal system: a. Stage 1, horizontal line at top is highest exposed level, potassic zone is all shaded patterns, propylitic is horizontal ruling; b. Stage 2, thick line marks the lower limit of the bulk of stage-2 alteration, chloritic alteration overprints the biotite-rich proximal potassic facies of the quartz stockwork; c. Stage 3, thick lines are massive pyrite veins, thick line across the top of the figure marks the lower limit of advanced-argillic alteration; d. Stage 4, shaded veins are stage-3 massive pyrite, medium thickness straight lines are stage-4 veins, note the absence of the veins in the centre of the system. Abbreviations: qtz, quartz; cpy, chalcopyrite; ser, sericite; py, pyrite; chl, chlorite; mb, molybdenite; tourm, tourmaline. The vertical scale is approximately 1 km, the horizontal scale approximately 2 km.

by stage-4 quartz-barite veins containing base metal sulphides and high-grade gold-silver mineralization. These veins (Josephine zone, West zone) and the disseminated variety (Snowfield zone) are similar to base metal adularia-sericite epithermal systems (Heald et al., 1987) which commonly form above and adjacent to and following associated porphyry copper and acid-sulphate alteration (Margolis et al., 1991). At Sulphurets, these veins do not occur in the high-proximal position (Fig. 11d). Mixing of oxidized, cooler, meteoric water or seawater with the hypogene hydrothermal fluids may have led to the widespread precipitation of barite (cf. Hayba et al., 1985) marginal to quartz-stockwork zones and large massive pyrite veins, apparently marking the centres of the hydrothermal systems. The vertical scale of the system, from the upper portion of the quartz-syenite to the advanced argillic facies, spans at least 800 m in the western Snowfield area (Fig. 9).

In the northern Sulphurets district at least two centres of mineralization are apparent, one centred on the area of the Mitchell stockwork and a second centred 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. 9), 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 stockworks lie in the lower plate of the thrust and, therefore, are distinct stockwork systems. Restriction of abundant tourmaline to the Snowfield area is further evidence that it is distinct from the Mitchell area alteration and mineralization. The centres of the two hydrothermal systems are marked by the high-level, copper-gold quartz-stockwork zones, where later QSPC alteration and massive pyrite veins are also concentrated. Relict proximal potassic alteration at high levels in and surrounding the Mitchell quartz stockwork indicates that the stockworks mark a central plume of magmatic fluids, possibly above volatile-rich cupolas of extensive quartz syenitic intrusions, which underlie much of the alteration in the northern Sulphurets district. The West zone vein mineralization may be related to a third magmatic hydrothermal system underlying the area west of Brucejack Lake. Postmineralization right-lateral motion along the Brucejack Fault is not sufficient to place the West zone area adjacent to the Josephine zone and the Snowfield magmatic centre 5 km to 6 km 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 zone.

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