Distribution of Alteration in an Alkalic Porphyry Copper-Gold Deposit at Mount Milligan, Central British Columbia (NTS 094N/01)

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Introduction

The Mount Milligan alkalic porphyry Cu-Au deposit provides an excellent example of sulphide and alteration-mineral zonation for alkalic porphyry systems in British Columbia (BC), as it is moderately tilted ~30–50º, based on the geometry of the intrusive stock and the interpreted dip of the host supracrustal rocks (Rebagliatti 1988; Delong et al., 1991; Sketchley et al., 1995; Delong, 1996; Jago et al., 2007; Jago, 2008). This geometry makes the magmatic-hydrothermal system amenable to the study of vertical and lateral changes over a range of paleodepths, based on examination of a fence of vertical drillholes that crosses the deposit. Moreover, an important fault, the Rainbow fault, separates a lower Cu-Au–rich core zone from the upper Au-rich, Cu-poor zone that is inferred to be the shallower Au-enriched segment of the deposit, thereby increasing the total vertical exposure.

The Mount Milligan site is located 155 km northwest of Prince George (Figure 1). It is the youngest dated (183–182 Ma) of the known major mineralized alkalic porphyry systems in BC (Afton-Ajax, Copper Mountain–Ingerbelle, Galore Creek, Lorraine, Mount Polley and Red Chris; Barr et al., 1976; Mortensen et al., 1995), and represents one of the silica-saturated deposits (Lang et al., 1995). The deposit is located in central Quesnellia, at the terminus of an ~45 km east-southeast structural trend that extends from the southern edge of the Hogem batholith along Chuchi Lake. The deposit (including the Main and Southern Star monzonitic stocks, and hydrothermally affected hostrock) is hosted in mildly shoshonitic volcanic rocks of the Triassic and Early Jurassic Takla Group. It has a measured and indicated resource of 417.1 million tonnes at 0.41 g/t Au and 0.21% Cu (Terrane Metals Corp., 2007), containing 5.5 million ounces Au and 1.9 billion pounds Cu. Mount Milligan is Au enriched compared to other porphyry Cu deposits in BC.

Keywords: *alkalic porphyry Cu-Au, alteration assemblages, zonation*

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Geological Setting

Alkalic intrusions of the Paleozoic–Mesozoic Stikinia and Quesnellia terranes are associated with regionally extensive successions of calcalkaline to mildly alkaline rocks of shoshonitic affinity (K-enriched mafic to intermediate composition) that were produced by complex subduction processes during amalgamation of the late oceanic-arc superterrane to ancestral North America (Mortimer, 1987; Nelson and Bellefontaine, 1996). The rocks in the vicinity of Mount Milligan were emplaced onto and intruded into the Mississippian volcano-sedimentary Lay Range arc and the Pennsylvanian–Permian Slide Mountain marginal basin, a likely back-arc basin between Quesnellia and ancestral North America.

Quesnellia had a two-phase development. The Upper Triassic Nicola and Takla groups (Carnian to Norian, ~227–210 Ma) in southwestern and northeastern BC, respectively, record the evolution of the first phase. These groups consist of basal sedimentary rocks overlain by volcanic and volcaniclastic successions dominated by marine augite-phyric basalt and andesite of calcalkaline to shoshonitic affinity. Coeval intrusions are also present. The high-K and mildly shoshonitic rocks crop out intermittently over a 1000 km strike length in northern Quesnellia (Mortimer, 1987; Nelson et al., 1992). These rocks host and are genetically associated with Late Triassic alkalic porphyry Cu-Au deposits (Barr et al., 1976; Lang et al., 1995). The second stage consists of Early Jurassic carbonate and clastic sedimentary sequences unconformably overlying the Triassic volcanic rocks. In the Mount Milligan area, however, volcanism continued after a Late Triassic to Early Jurassic hiatus, resulting in the paraconformably overlying Early Jurassic Chuchi Lake and Twin Creek successions (Pliensbachian to Toarcian, ~196–180 Ma). These rocks exhibit greater compositional heterogeneity than the Upper Triassic sequence and are composed mainly of plagioclase-augite–phyric, subalkaline to shoshonitic igneous rocks (Nelson and Bellefontaine, 1996). The Mount Milligan Cu-

Au porphyry and related plutons are part of the second stage, and hosted by the Witch Lake succession. Igneous rocks in the Mount Milligan deposit area have U-Pb ages (zircon, titanite, rutile) ranging from 186.9 ±3.3 to 182.5 ±4 Ma (Mortensen et al., 1995; Nelson and Bellefontaine, 1996; R. Friedman, pers. comm., 2008). Regionally, subduction had ceased by ~186–181 Ma with the accretion of Quesnellia to ancestral North America (Mihalynuk et al., 1994). The Mount Milligan porphyry stocks thus formed during the final plutonic activity of the Quesnellia

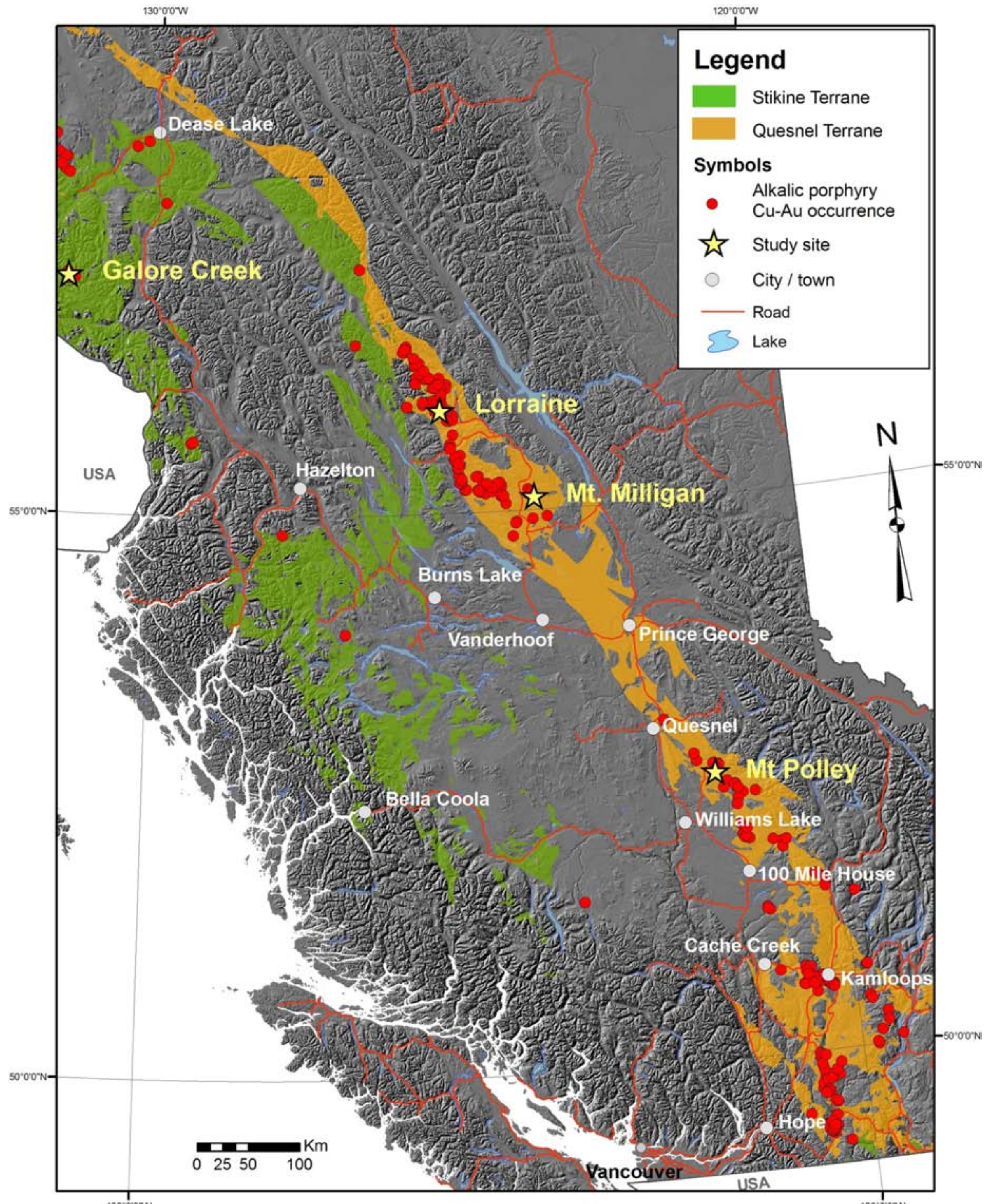


Figure 1: Location of alkalic porphyry Cu deposits in British Columbia, showing location of Mount Milligan with respect to the other deposits and to the Triassic and Early Jurassic Quesnel and Stikine terranes. The Hogem batholith underlies the area around Lorraine and extends southward on the eastern margin of the Pinchi fault toward Mount Milligan.

magmatic-arc system, and were broadly contemporaneous with amalgamation of the marine arc to the margin of North America.

The Hogem batholith has a linear northwesterly trend parallel to the Pinchi fault system, separating the Quesnellia and Cache Creek terranes and suggesting a structural control over batholith emplacement (Nelson and Bellefontaine, 1996). A break in the regional structural trend beneath Chuchi Lake, suggesting a pre-Triassic fault, extends east-southeast from the southern edge of the batholith, transverse to the arc. The inferred fault lies along trend with an east-southeast shift in the Hogem regional magnetic high, indicating deflection by this basement structure. The magnetic anomaly continues ~25 km eastward to the Mount Milligan intrusive suite, a monzonite-diorite-granite pluton located ~7 km north of the porphyry deposit (Nelson and Bellefontaine, 1996). Compositions and textures suggest the pluton is an extension of the Hogem batholith, which implies that the monzonitic porphyry stocks of the Mount Milligan deposit to the south also emanate from a buried extension of the Hogem batholith.

Supracrustal Rocks

The Witch Lake succession, the host supracrustal sequence at Mount Milligan (Figures 2, 3), consists of a moderately northeast-dipping, alternating coherent and clastic sequence that includes porphyritic clinopyroxene basaltic trachyandesite (Lang, 1992; Barrie, 1993; Sketchley et al., 1995). Coherent rocks are lavas and (or) shallow intrusions (Figure 4). Outside the area of intense alteration toward the 66 zone, beyond ~250 m from the MBX stock, the hostrocks contain ~25% clinopyroxene (lesser hornblende) and 3–5% subhedral plagioclase phenocrysts. Plagioclase constitutes 25–50% of the trachytic-textured feldspar groundmass, and cryptocrystalline K-feldspar forms the remainder. Plagioclase is oligoclase-andesine, which is slightly more calcic than the oligoclase in the basaltic trachyandesite and in the Rainbow dike of the MBX zone but comparable to the plagioclase in the MBX stock and Lower monzonite dike in the 66 zone. Apparent- and/or pseudobreccia textures, composed of rounded gravel- to cobble-sized clasts of basaltic trachyandesite in a compositionally similar matrix, are common throughout the hostrocks; some of these textures result from alteration processes, but others are primary volcaniclastic rocks.

Three rock units are critical to the structural interpretation of the hostrock sequence (Figure 3). The Lower Trachyte is an ~70 m thick conformable unit of intensely altered rock situated ~180 m below the Rainbow dike. At depth in drillhole 90-652, the rock has thin mafic laminations that resemble shear bands but could also represent bedding planes in fine epiclastic material (Nelson and Bellefontaine, 1996). These laminations, oriented at ~30º to the horizontal axis of the vertical drillcore, in conjunction with the interpreted orientations of the MBX stock and Rainbow dike, provide the basis for concluding a moderate tilt to the deposit (Sketchley et al., 1995). Compositionally, the Lower Trachyte unit is more silica deficient than is implied in the term ‘trachyte’, and would be more accurately described as tephriphonolite (*after* Lang, 1992; Barrie, 1993). The use of ‘trachyte’ in the name of this unit refers to trachytic microtexture rather than composition. The very fine grained trachytic-textured rocks are characterized by abundant acicular feldspar microlites. Ghosts of former augite phenocrysts are composed of biotite-chlor-

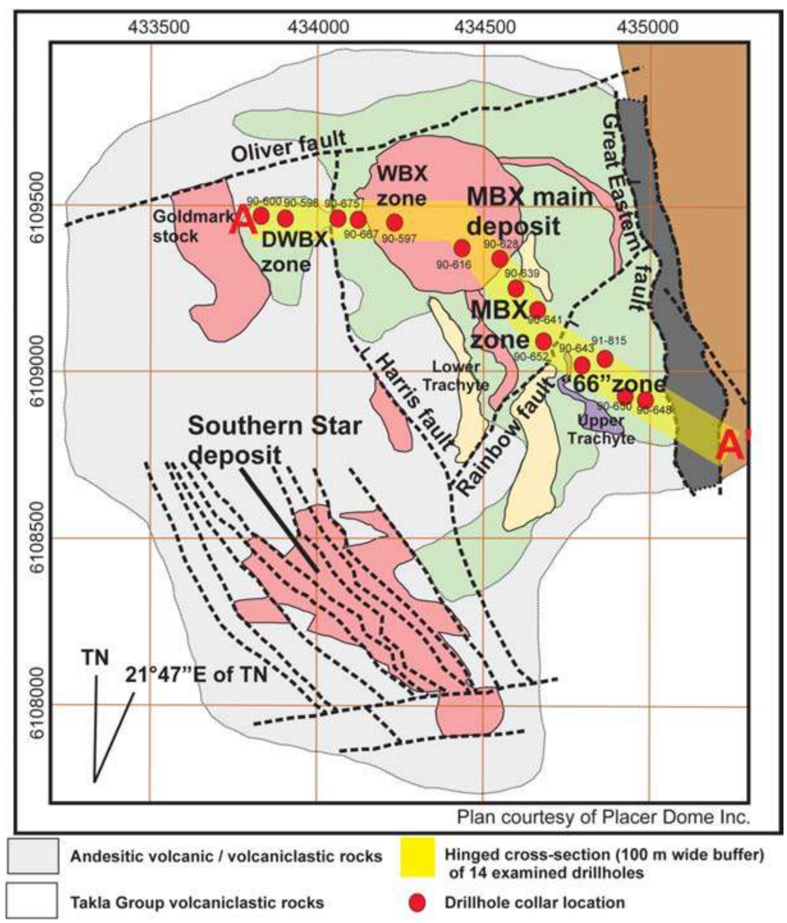


Figure 2: Plan view of the Mount Milligan alkalic porphyry Cu-Au deposit, showing interpreted geology (including the MBX Main deposit, Southern Star deposit and Goldmark stock), major faults, four ore-zone divisions within the MBX Main deposit (DWBX, WBX, MBX and 66), orientation of the hinged cross-section, and locations of the drillholes investigated. Original lithology provided by Placer Dome Inc.

ite±actinolite. Pyrite has replaced some augite phenocrysts and has precipitated in partings, where it is typically mantled by chlorite.

In the 66 zone, the Upper Trachyte unit is an ~20 m thick sequence of weakly vesicular, trachytic-textured rock that forms recrystallized fine granular lenses, and gravel-sized clasts in faults. Compositionally, the unit plots as tephriphonolite (Lang, 1992; Barrie, 1993), but it may be potassically altered trachyandesite, based on the presence of relict mafic phenocrysts. As with the Lower Trachyte unit, hairline fractures filled with sulphide resemble shear bands dipping at 35º to the horizontal axis of drillcore. Similarly oriented layering is defined by granular lenses of K-feldspar (~0.1 mm grains), quartz (5–10 modal %) and minor fragmental plagioclase. These lenses may also reflect relict bedding.

In contrast to the rest of the deposit, the hangingwall of the DWBX zone comprises faulted, polymict fragmental units, which are possibly resedimented hyaloclastite. Juvenile clasts with nondeformed cuspate and tabular shards, and vesicles filled by hydrous microminerals constitute the western fringe of the system in drillhole 90-600.

Intrusive Rocks

The MBX stock is a northwest-striking, elliptical intrusive body with a principal axis ratio of ~2:1 and a diameter of ~400 m. It has a circular near-surface expression due to tilting (Figure 2). The composite stock has at least three plagioclase-phyric phases. Compositions range from normative quartz monzonite to monzodiorite and plot within the alkaline and shoshonitic fields (Lang, 1992; Barrie, 1993). Textural variations include (Figure 5) 1) plagioclase phyric, 2) crowded plagioclase phyric, 3) flow-aligned plagioclase, 4) medium-grained equigranular, 5) xenolithic monzonite containing monzonitic and biotite-magnetite hornfels xenoliths, 6) magmatic-hydrothermal breccia with pink K-feldspar cement, and 7) apparent-breccia resulting from pervasive K-feldspar alteration. Separate intrusive phases have been identified using textural changes and the ratio of modal plagioclase to mafic minerals. Contacts between the phases are typically gradational or obscured by pervasive K-feldspar alteration.

In the WBX zone (drillhole 90-667), the intrusive sequence includes an early monzonite phase with crowded, sericitized plagioclase phenocrysts in a K-feldspar–rich

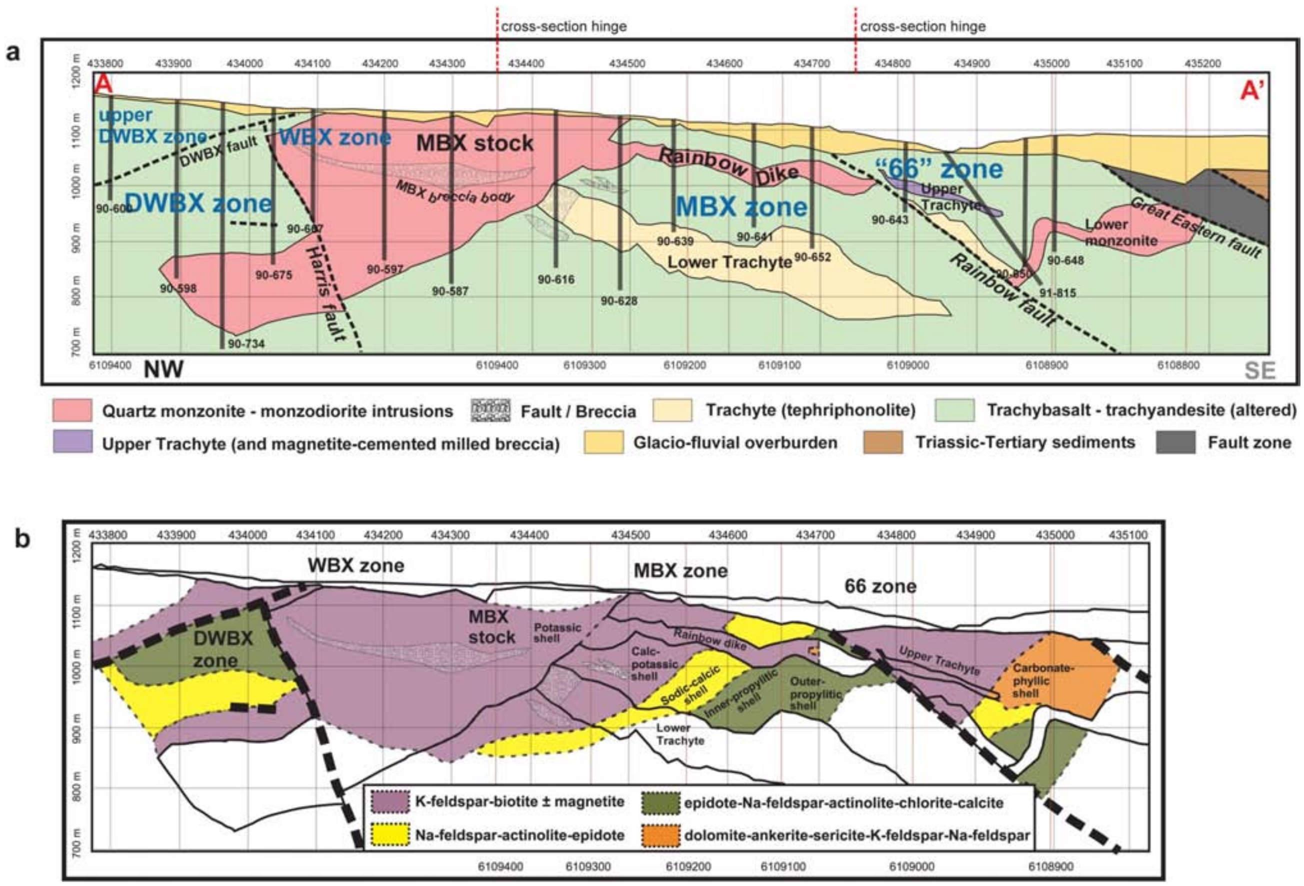


Figure 3: Profile view of the Mount Milligan alkalic porphyry Cu-Au deposit along the hinged cross-section showing **a)** interpreted geology, major structures, four ore-zone divisions of the MBX Main deposit (DWBX, WBX, MBX, and 66), and locations of the drillholes investigated (original lithology provided by Placer Dome Inc.); **b)** distribution of alteration assemblages superposed on the geology.

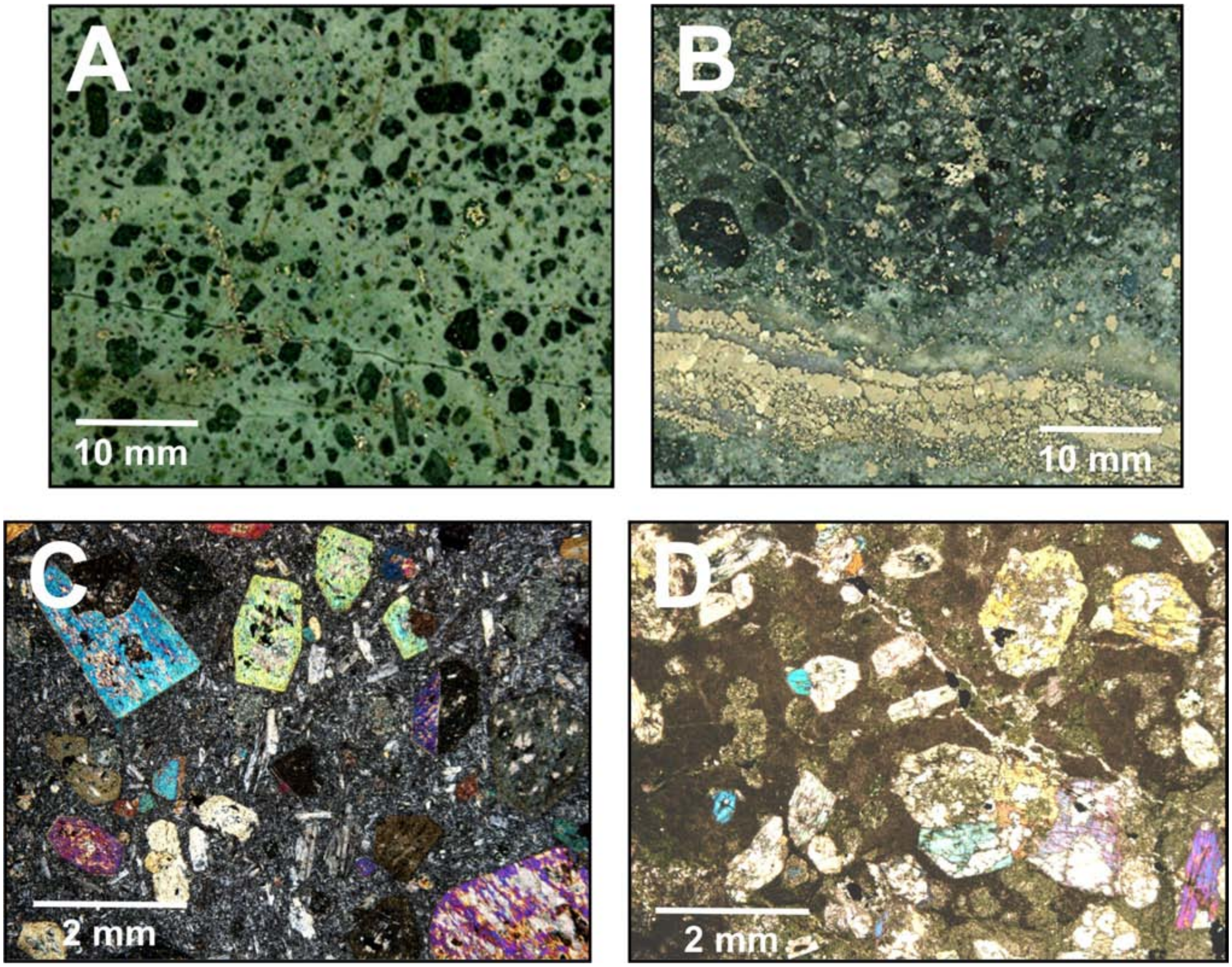


Figure 4: Examples of hostrocks of the Witch Creek succession: **A)** hornblende-augite–phyric trachyandesite altered to K-feldspar–Na-feldspar–actinolite (drillhole 90-598 at 123.3 m); **B)** coarse augite phenocrysts (4–15 mm) in chlorite-altered basaltic trachyandesite with ribboned pyrite-carbonate L3 vein and Na-feldspar–epidote halo (drillhole 90-675 at 174.2 m); **C)** photomicrograph of weakly chloritized trachyandesite with oligoclase-andesine fragments (1 mm) and augite phenocrysts (drillhole 90-648 at 176.5 m); **D)** photomicrograph of basaltic trachyandesite with chlorite-altered devitrified groundmass and glomeroporphyritic augite (drillhole 90-641 at 118 m).

groundmass. This phase forms the outer ~40 m rim of the stock. Inside the stock, the early phase is cut by crowded plagioclase-phyric monzodiorite with a more biotitic groundmass. Both phases are locally mineralized. Weakly sericitized plagioclase-phyric diorite is the youngest phase. In general, the rocks are composed of >60% crowded plagioclase (oligoclase-andesine) with thin albite rims. Primary K-feldspar phenocrysts (~2.5 mm) are also present. Plagioclase is commonly zoned and replaced by a fine-grained sericite. The monzonite groundmass is composed of K-feldspar (~80%) with minor Na-plagioclase (10%), hydrothermal biotite (5%) after primary biotite, and magnetite (1–5%).

A variably jigsaw-brecciated to clast-rotated breccia body extends the length of the MBX stock. It ranges in thickness from 2 m in the WBX zone to 50 m beneath the poorly mineralized centre of the stock, and to 5 m near the MBX zone. The overall geometry is poorly constrained. Where observed in drillcore, it varies from a hematitic, pink, K-feldspar–cemented crackle-breccia to a milled breccia with rounded monzonite pebbles in a magnetite-altered matrix. Chalcopyrite veinlets cut clasts and cement.

The monzodioritic Rainbow dike extends outward from the southeastern to southern margin of the MBX stock. It is an ~50 m thick, east-dipping conformable body for ~250 m, and would be better described as a sill. Approximately 200 m due east of the stock, it has a bowl shape where the sill-like body changes to a vertical, curviplanar dike-like body. Geochemical data (Barrie, 1992) suggest that the Rainbow dike is more silica undersaturated than the MBX stock.

Where least altered, the Rainbow dike is a crowded plagioclase-phyric monzodiorite (Lang, 1992; Barrie,

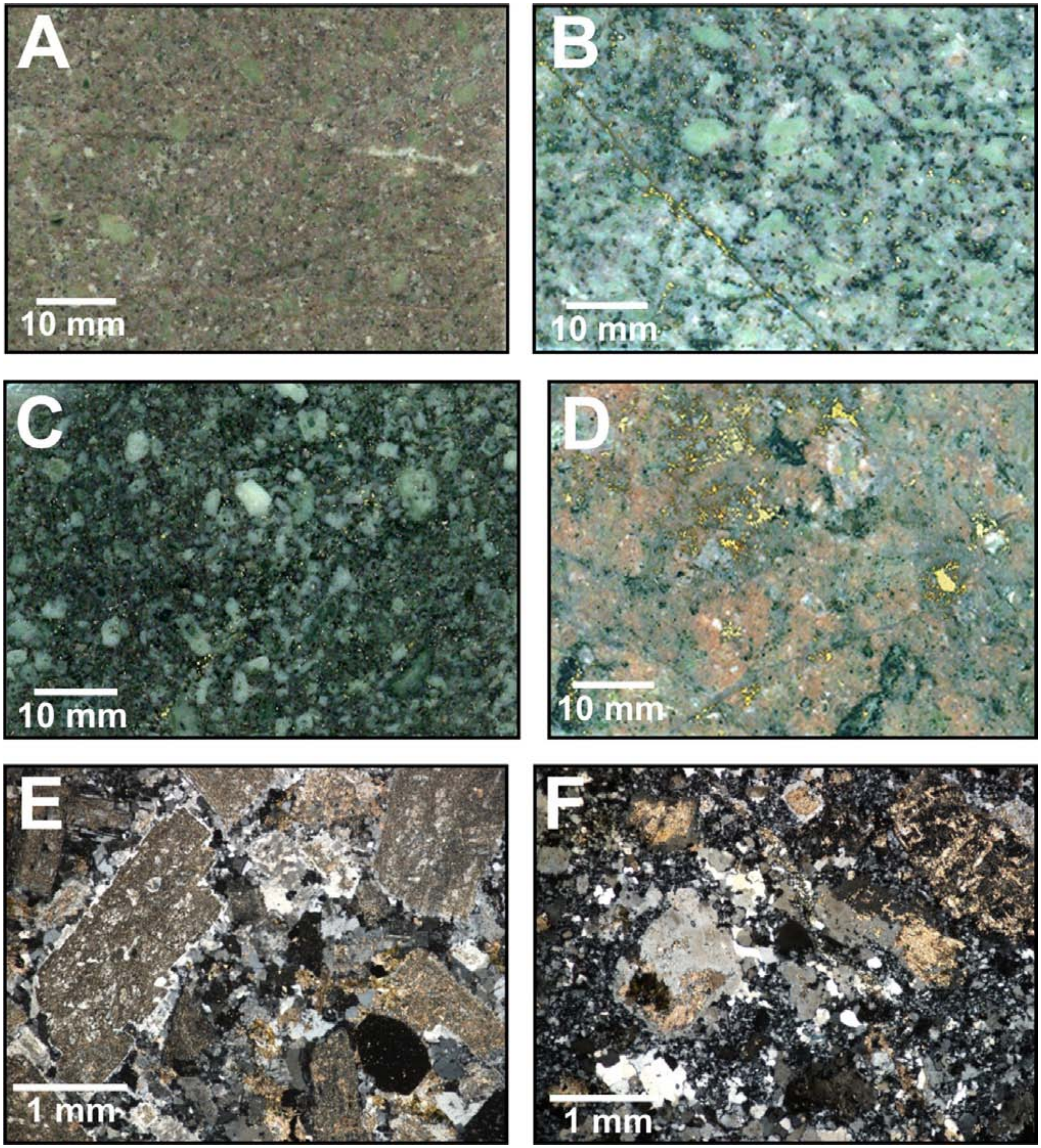


Figure 5: Drillcore sections showing the variety of composition, texture, alteration and sulphide mineralization of monzonitic to monzodioritic rocks in the MBX stock: **A)** sericitized plagioclase-phyric monzonite with K-feldspar–rich matrix, and minor disseminated magnetite (drillhole 90-616 at 126.0 m); **B)** weakly sericitized, crowded plagioclase-phyric monzonite with K-feldspar–altered rims, and interstitial biotite; disseminated sulphide replaces biotite surrounding chalcopyrite veinlet (drillhole 90-597 at 223 m); **C)** plagioclase-phyric monzodiorite with ~10% magnetite-bearing matrix (drillhole 90-667 at 133.0 m); **D)** intense K-feldspar–quartz alteration with clotted biotite replaced by sulphide (drillhole 90-597 at 223 m); **E)** photomicrograph of weakly altered monzonite; sericitized phenocrysts have Na-plagioclase rims; apatite (opaque) at lower right (drillhole 90-597 at 123 m); **F)** photomicrograph of strong potassic alteration converting monzonite to a granular K-feldspar–quartz assemblage; K-feldspar replaces sericitized plagioclase laths (drillhole 90-597 at 223 m).

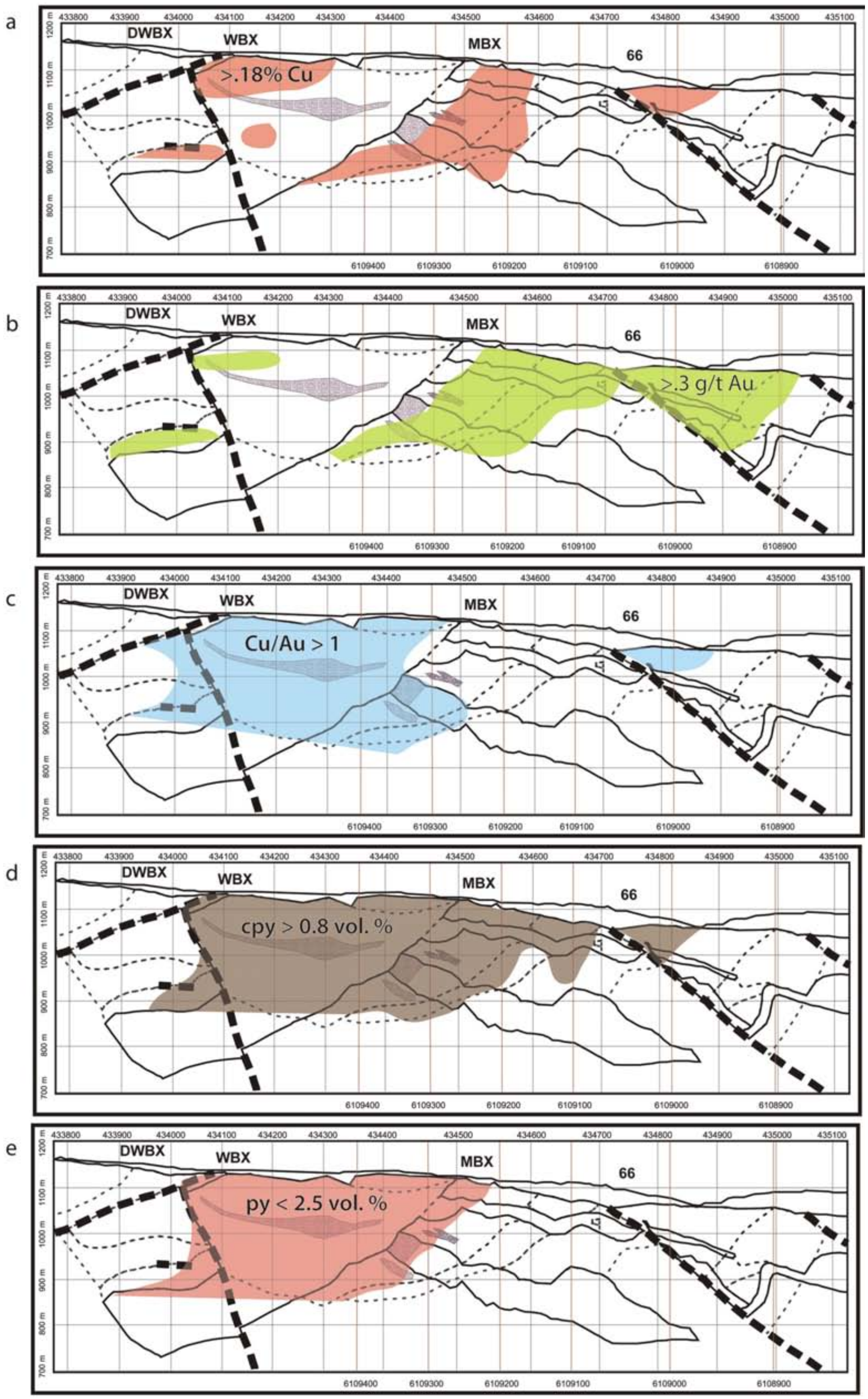


Figure 6: a) Copper grade, **b)** Au grade, **c)** Cu/Au ratio, **d)** chalcopyrite mode estimated in the field, and **e)** pyrite mode estimated in the field, superposed on alteration shells (dotted lines on cross-sections) along the hinged cross-section through the Mount Milligan alkalic porphyry Cu-Au deposit (*see* Figure 3b). Data are binned into five ranges using the Jenks Natural Breaks classing method, which is based on identifying groupings that exist naturally in the data (Jenks and Caspall, 1971). Fire-assay data were provided by Placer Dome Inc. (now part of Barrick Gold Corp.).

1993) with smaller phenocrysts (~2 mm) than those common to the MBX stock. Plagioclase is albite-oligoclase. The groundmass is pale grey K-feldspar with disseminated biotite, trace carbonate and sericite. Within 25 m of the stock (drillhole 90-628), the dike contains gravel-sized monzonitic xenoliths that are probably derived from the stock. The dike is typically in fault contact with host supracrustal rock. Dike contacts, particularly within ~50 m of the stock, are locally obscured due to intense alteration (Sketchley et al., 1995).

Late-mineral dikes in the MBX Main deposit include northeast-trending, moderately northwest-dipping trachyte and monzonite dikes. Northwest-trending, steeply northeast-dipping porphyritic hornblende-plagioclase diorite dikes are the youngest intrusive rock to occur (Sketchley et al., 1995).

Alteration and Mineralization

The deposit is divided into four zones based on location of ore and interpreted structural architecture (Rebagliati, 1988; Sketchley et al., 1995). These are, from west to east (Figures 2, 3)

- the DWBX zone (downdropped WBX), which lies west of the stock and west of the steeply east-dipping Harris fault that separates the DWBX on the west from the WBX zone to the east;
- the WBX zone, which includes the western portion of the MBX stock, the deepest continuous portion, plus an ~40 m wide, biotite-altered envelope of MBX monzonite and hostrock that is cut by the DWBX fault;
- the MBX (magnetite breccia) zone, which represents the main Cu-Au orebody and is located immediately southeast of the MBX stock along strike from the Rainbow dike and Lower Trachyte unit; and
- the downthrown 66 zone, which lies in the hangingwall of the Rainbow fault, an east-northeast-trending, moderately southeast-dipping crossfault that truncates the Rainbow dike and MBX zone to the south.

The north-striking, shallowly east-dipping Great Eastern fault has truncated the hydrothermal features immediately east of the bowl-like portion of the Rainbow dike. The fault separates the Mount Milligan system from early Tertiary volcanic and sedimentary rocks. A second crossfault, the east-northeast trending subvertical Oliver fault, lies immediately north of the MBX stock.

MBX Zone

In the MBX zone (Figure 3), chalcopyrite and minor bornite are associated with potassic (biotite–K-feldspar) alteration and magnetite (Figure 6) within the biotite alteration shell along the brecciated margin of the MBX stock and in the stratiform Lower Trachyte unit and Rainbow dike. Sulphide-bearing quartz veins (Figure 7) are also concentrated at the margins of the MBX stock within monzonite and biotite hornfels. Sodic-calcic alteration (Na-feldspar–actinolite–epidote; (Figure 8) overprints the outer margin of the potassic shell and passes outward to inner- (Figure 9) and outer-propylitic alteration (epidote–Na-feldspar–calcite–actinolite–chlorite), and regional chloritic alteration (Figure 3). The grades of Cu and Au are maximized where albitization of the potassic zone is strongest (Figure 6a–b). Moderate Au grade continues outward within the pyrite halo associated with the peripheral assemblages. A carbonate-phyllic (dolomite-ankerite-sericite-pyrite) vein within the distal Rainbow dike has elevated Au and Cu grades (Figure 10D). Late-stage epidote-chlorite-pyrite has exploited permeable stratigraphic horizons within the biotite shell (Figure 3).

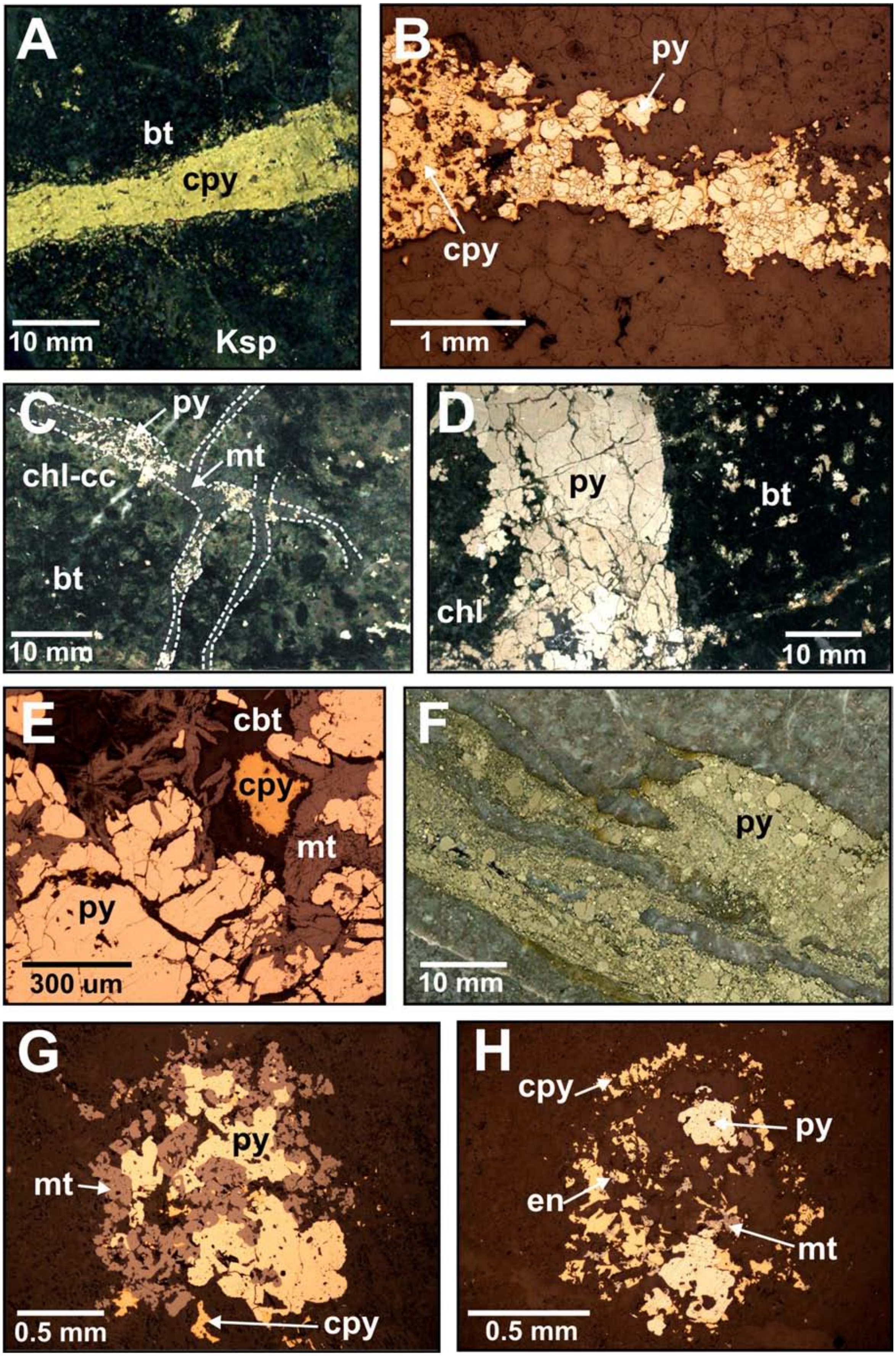
66 Zone

In the 66 zone (Figure 3) above the Rainbow fault, the potassic assemblage reappears and is marked by pervasive K-feldspar alteration and Cu-Fe sulphides in the Upper Trachyte unit, and biotite alteration of surrounding trachyandesite (Figures 3b, 11). Sheeted magnetite veins are concentrated at the lower contact of the Upper Trachyte. The unit terminates in a magnetite breccia, which transitions into a zone of intense carbonate-phyllic alteration. Elevated Au grade is present within minor faults and along late-mineral dike contacts within the carbonate-phyllic assemblage, but decreases with distance from the Upper Trachyte. Gold grade sharply decreases in the outer-propylitic and chloritic alteration zones that surround the carbonate-phyllic–altered shell (Figure 6a–c).

DWBX Zone

In the lower DWBX zone (Figure 3), an ~30 m envelope of Cu-Au associated with potassic alteration and magnetite is nested along the upper contact of a monzonite, potentially the down-dropped MBX stock, where it is cut off by the Harris fault (Figure 6a–c). Pervasive outer-propylitic alteration of volcaniclastic conglomerate bordering the biotite

Figure 7: Early- to transitional-stage veins and replacement sulphide minerals, Mount Milligan alkalic porphyry Cu-Au deposit: **A)** chalcopyrite vein with biotite halo (drillhole 90-675 at 254 m); **B)** photomicrograph of chalcopyrite-pyrite vein with pyrite grains entrained in chalcopyrite (drillhole 90-628 at 38 m); **C)** magnetite-chalcopyrite±pyrite veins in dendritic array with carbonate-chamosite halos (drillhole 90-639 at 116.2 m); **D)** pyrite-magnetite±chalcopyrite veins (drillhole 90-639 at 50.6 m); **E)** photomicrograph of vein, showing magnetite surrounding coarse pyrite and interstitial carbonate replacing trace chalcopyrite (drillhole 90-639 at 50.6 m); **F)** vein cutting monzonite in fault zone between the MBX stock and biotite hornfels (drillhole 90-616 at 194.5 m). **G)** and **H)** photomicrographs of chalcopyrite-pyrite-magnetite±enargite replacement of clinopyroxene phenocrysts (drillhole 90-639 at 34.5 and 50.6 m). Abbreviations: py, pyrite; cpy, chalcopyrite; en, enargite; mt, magnetite; bt, biotite; chl, chlorite; cbt, carbonate; cc, calcite.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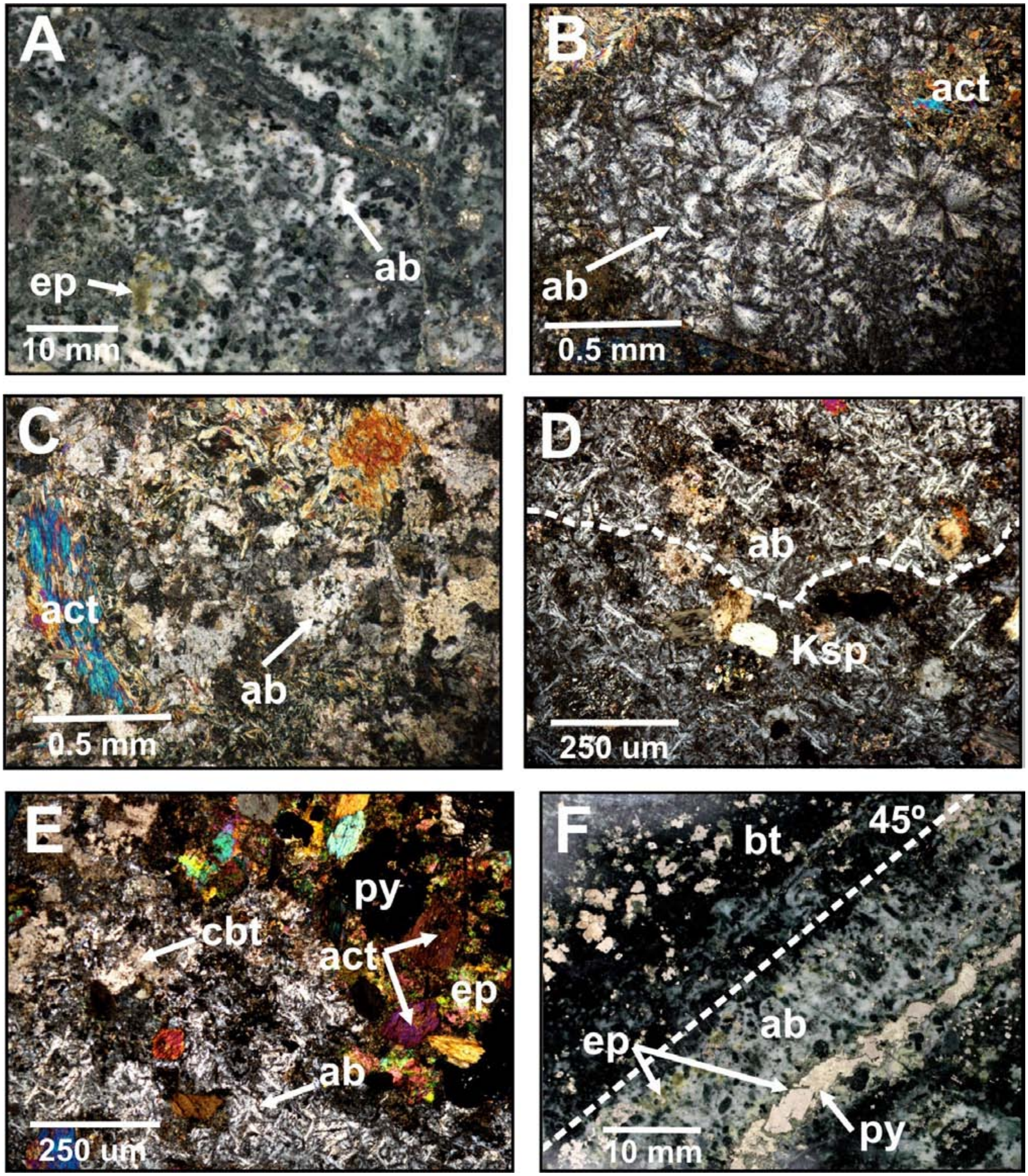

Figure 8: Sodic-calcic (outer-calcpotassic) alteration, Mount Milligan alkalic porphyry Cu-Au deposit: **A)** selective-pervasive albitization of basaltic trachyandesite and weak epidote after Na-plagioclase (drillhole 90-639 at 135 m); **B)** photomicrograph of bow-tie texture of Na-plagioclase groundmass with scattered actinolite needles (drillhole 90-639 at 166 m); **C)** photomicrograph of disintegration of actinolitized phenocrysts within albitized groundmass (drillhole 90-639 at 127.6 m); **D)** photomicrograph of reaction front between Na-plagioclase and K-feldspar alteration (drillhole 90-639 at 193.8 m); **E)** photomicrograph of pyrite-epidote-carbonate replacing Na-plagioclase groundmass (drillhole 90-639 at 193.8 m); **F)** pyrite-chalcopyrite vein with epidote selvage and Na-plagioclase halo overprinting biotite along coarse layering (flow-banding?) at 45º to the horizontal axis of the drillcore (drillhole 90-639 at 182 m). Abbreviations: Ksp, K-feldspar; bt, biotite; ab, Na-plagioclase; act, actinolite; ep, epidote; cbt, carbonate; py, pyrite.

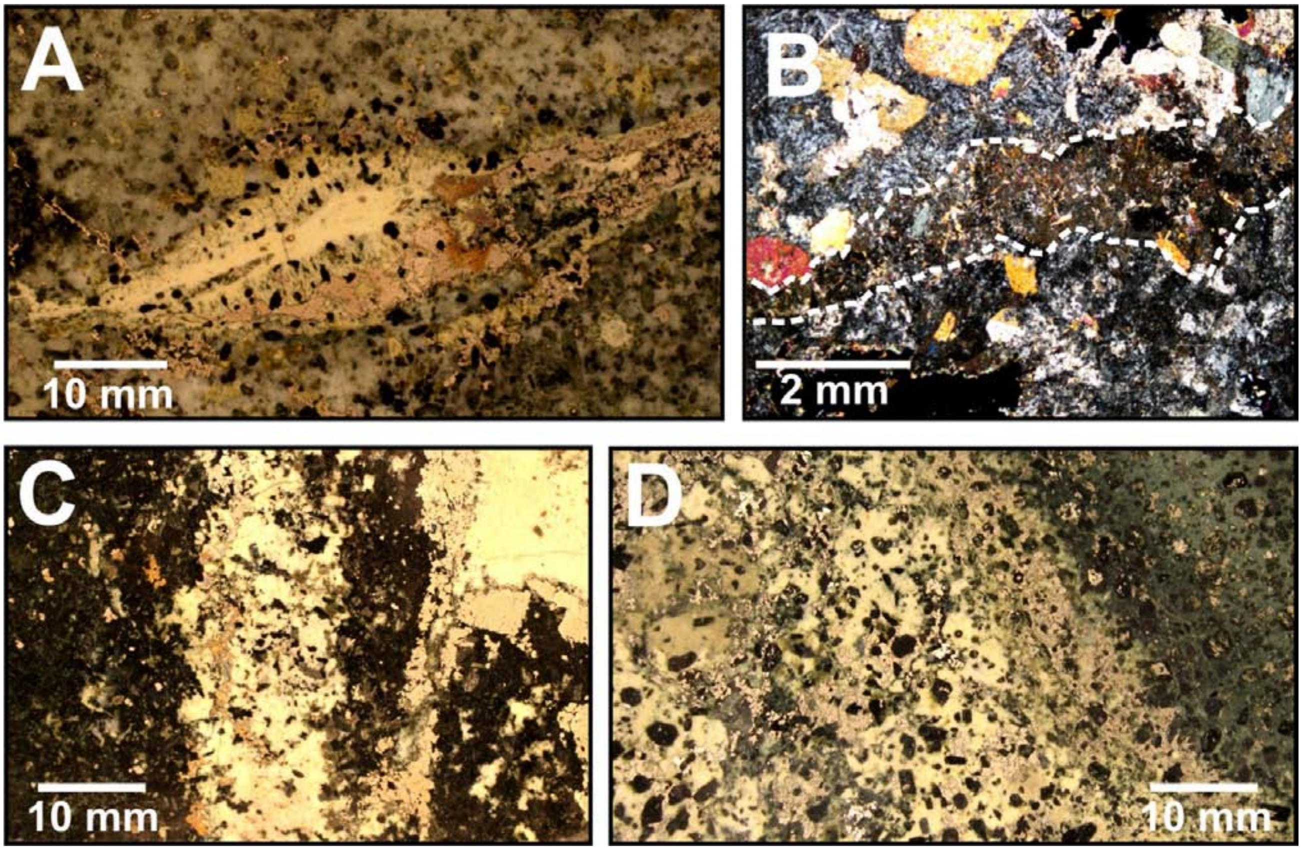

Figure 9: Inner-propylitic alteration, Mount Milligan alkalic porphyry Cu-Au deposit: **A)** Microcrystalline epidote–Na-plagioclase–actinolite–calcite vein with associated pyrite, and cloudy K-feldspar halo (drillhole 90-641 at 112.2 m). **B)** in thin section, the vein is composed of actinolite needles, fine-grained epidote and Na-plagioclase after K-feldspar; scanning electron microscope analysis indicates the prismatic blue mineral in the upper right corner is epidote, although it resembles zoisite (drillhole 90-641 at 112.2 m); **C)** very fine grained epidote–Na-feldspar alteration with coarse pyrite and chlorite halo after biotite (drillhole 90-641 at 132.1 m); **D)** pyrite-rich P1-stage alteration band overprinting chloritized trachyandesite (drillhole 90-815 at 127 m).

hornfels becomes more chloritic towards the Harris fault. Late pyrite veins that cut the potassic zone may be genetically linked with the outer-propylitic assemblage.

Paragenesis

The alteration and metal zoning at the Mount Milligan deposit is divided into vertical and lateral components (Figure 3). Laterally, alteration progresses from potassic and local calcpotassic to sodic-calcic to inner- and outer-propylitic assemblages, spanning ~350 m in the MBX zone. Vertically, alteration progresses from potassic to carbonate-phyllic assemblages, spanning ~300 m in the MBX and 66 zones. The intimate association of metal and alteration zonation with ore grade at the Mount Milligan MBX Main deposit is discernible when comparing alteration shells to fire-assay data (Figure 6a, b).

The potassic and calcpotassic shell is most extensive in the MBX zone, extending ~260 m from the MBX stock, but is largely overprinted by younger alteration stages beyond ~130 m. Copper and Au have a greater than 1:1 relationship (wt %/[g/t]) in the deepest levels (lower DWBX zone, WBX zone), a subequal relationship at intermediate levels (deep MBX zone, Lower Trachyte unit), and less than unity surrounding the Rainbow dike (Figure 6c). The Cu/Au ratio generally decreases upward and outward with increasing Cu and Au grade, although an ~75 m wide interval of highest grade occurs within the Lower Trachyte unit in drillhole 90-628.

Potassic alteration is present in the down-dropped 66 zone (Figure 3), where it is centred on the fault-bounded Upper Trachyte unit. Copper and Au grades are slightly lower than in the upper MBX zone (Figure 6a–c). However, Au grade increases by 100% where the potassic assemblage terminates in a magnetite-altered milled breccia (drillhole 91-815; Figure 11C), and carbonate-phyllic alteration intensifies.

Sodic-calcic alteration defines an intermediate zone between calcpotassic- and propylitic-stage assemblages (Figure 3). It is strongest along the upper margin of the Lower Trachyte unit, but extends below the Lower Trachyte as close as ~50 m to the MBX stock. From the deepest known extent upward to the footwall of the Rainbow dike

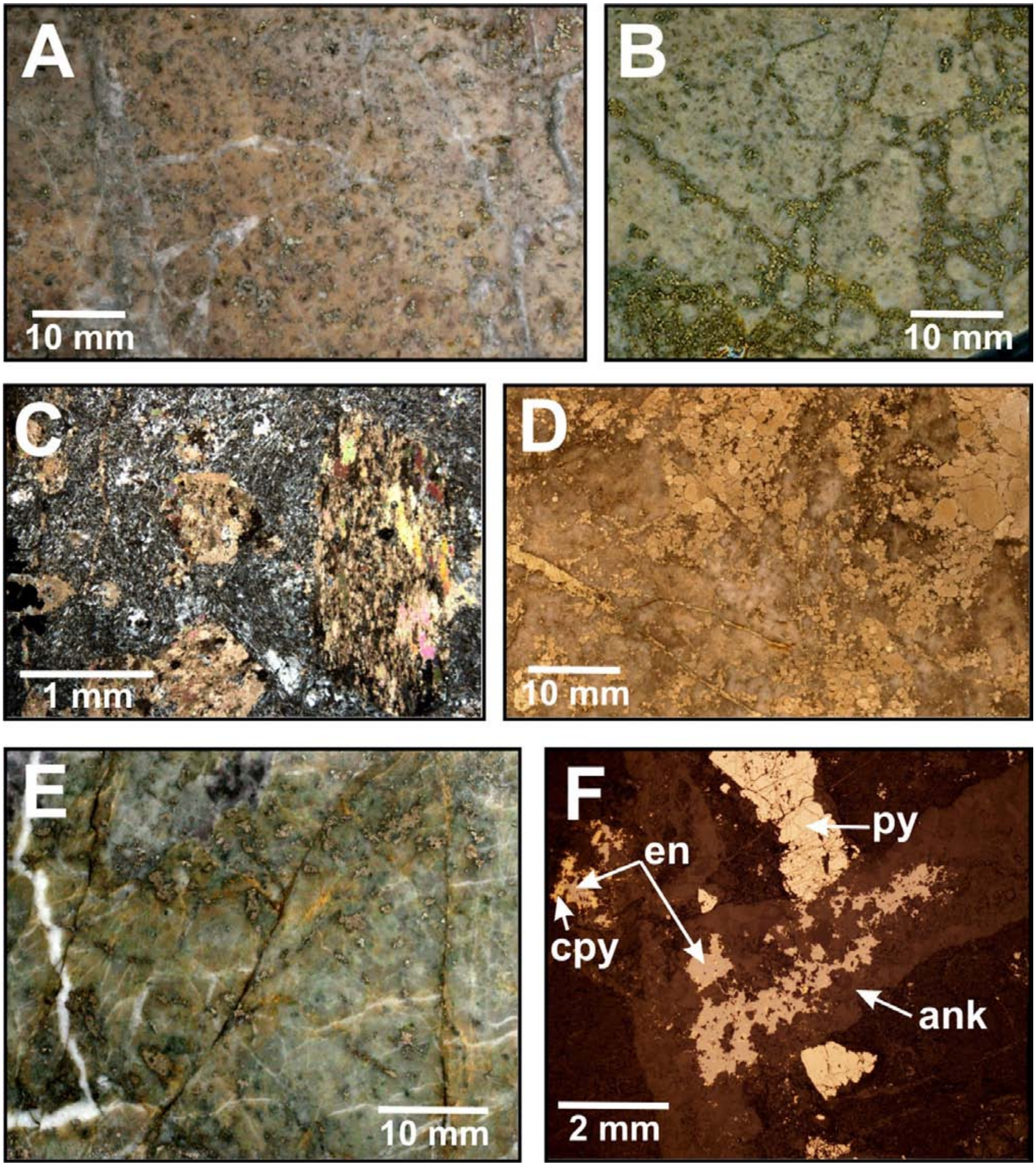

Figure 10: Carbonate-phyllic alteration, Mount Milligan alkalic porphyry Cu-Au deposit: **A)** salmon pink phengite-dolomite-illite±brucite-arfvedsonite alteration with pyrite pseudomorphs and dolomite veinlet stockwork (drillhole 90-650 at 60.5 m); **B)** stockwork of pyrite veinlets in carbonate-phyllic alteration (drillhole 90-648 at 123 m); **C)** photomicrograph of dolomite pseudomorphs in trachytic-textured groundmass; alteration is muscovite-illite-chlorite-biotite; pyrite also replaces phenocrysts and is finely disseminated in the groundmass (drillhole 90-648 at 59.9 m); **D)** carbonate-phyllic vein in distal Rainbow dike with Au-bearing sulphide (5.11 g/t Au); alteration is dolomite-ankerite-sericite-illite (drillhole 90-652 at 81.1 m); **E)** carbonate-phyllic alteration at the upper margin of the Rainbow dike, ~15 m from the MBX stock; alteration is quartz–ankerite–adularia–muscovite–biotite–Na-feldspar–pyrite (90-628 at 31 m); **F)** photomicrograph of ankerite veinlet cutting pyrite veinlet in Lower Trachyte unit; remobilized chalcopyrite is replaced by Cu-sulphosalt; alteration is muscovite-ankerite-brucite-illite (drillhole 90-628 at 201.1 m). Abbreviations: ank, ankerite; cp, chalcopyrite; py, pyrite; en, enargite (Cu-sulphosalt).

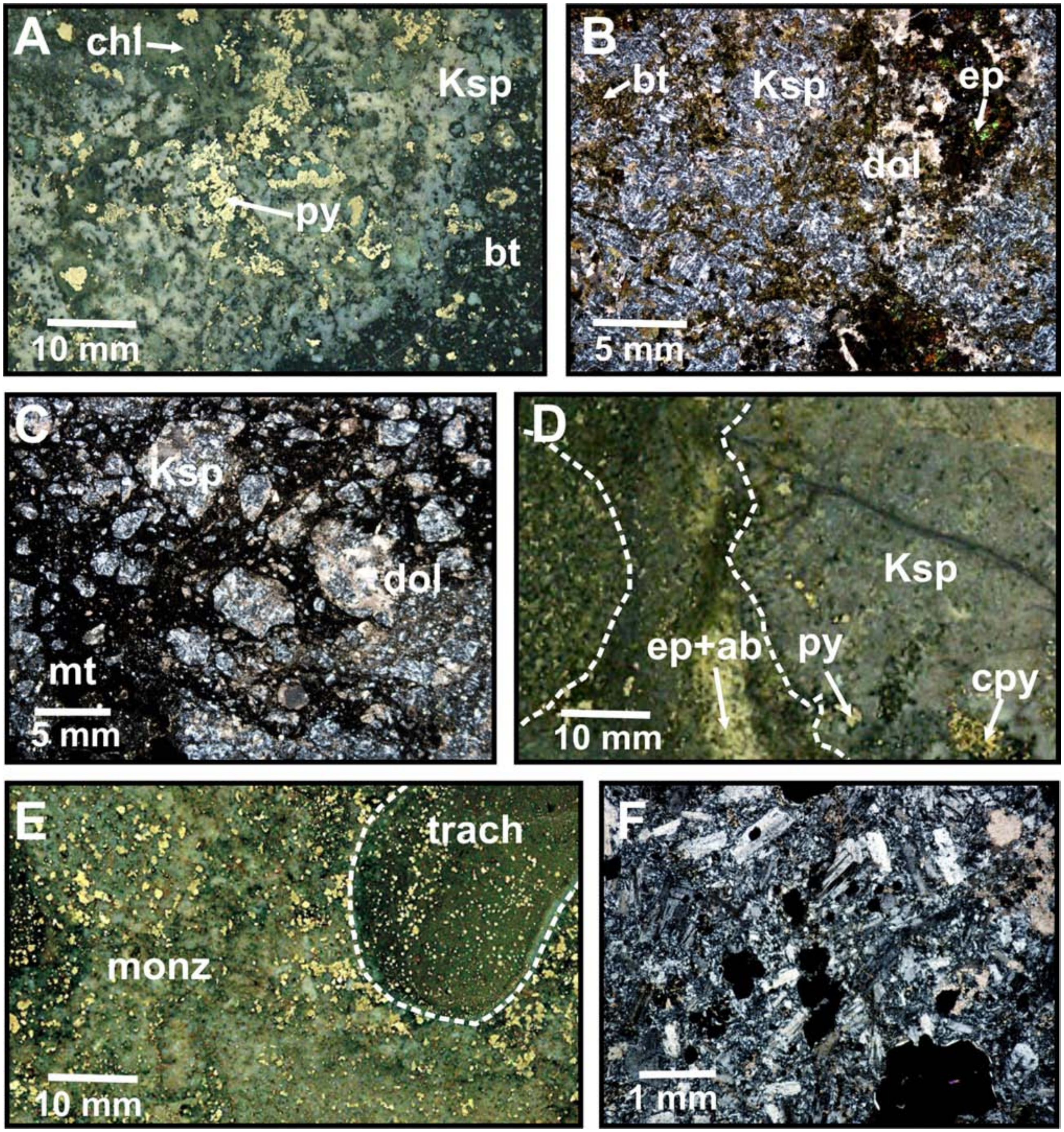

Figure 11: Intermediate-stage potassic alteration in the 66 zone, Mount Milligan alkalic porphyry Cu-Au deposit: **A)** auriferous K-feldspar–pyrite overprinting biotite-altered trachyandesite, footwall of the Upper Trachyte (drillhole 91-815 at 103 m); **B)** photomicrograph of the Upper Trachyte unit, with biotite-filled microfracture network overprinted by pyrite-epidote-dolomite clots (drillhole 91-815 at 86 m); **C)** photomicrograph of magnetite-cemented milled breccia with trachytic clasts altered to K-feldspar–dolomite, southeastern terminus of Upper Trachyte (drillhole 91-815 at 81.1 m); **D)** intensely K-feldspar–altered clasts in breccia at the upper contact of the Rainbow fault (bedded trachyte unit, Placer Dome Inc.), with clotted biotite replaced by sulphide; epidote-albite-chlorite alteration is present between clasts (drillhole 90-643 at 102.5 m); **E)** xenolithic monzonite with trachyte xenolith (drillhole 91-815 at 183 m); **F)** photomicrograph of xenolithic monzonite, with oligoclase-andesine phenocrysts in K-feldspar groundmass; mafic minerals are replaced by pyrite and minor carbonate. Abbreviations: Ksp, K-feldspar; bt, biotite; chl, chlorite; dol, dolomite; ep, epidote; ab, albite; cpy, chalcopyrite; py, pyrite; trach, trachyte; monz, monzonite.

(drillhole 90-639), the Au grade of the sodic-calcic shell increases by ~70%. This represents the best Cu-Au grade of the deposit apart from that within the Lower Trachyte (drillhole 90-628), which may be a deeper portion of the same assemblage.

Inner-propylitic alteration (Na-feldspar–epidote–pyrite) lies outboard of the sodic-calcic shell in the MBX zone at ~150 m from the MBX stock, and also overprints the calcpotassic assemblage (Figure 3). Chalcopyrite-magnetite is destroyed where overprinted by epidote, which is reflected in the low Cu grade, whereas Au grade can remain moderately high.

Late-stage carbonate-phyllic alteration (Figure 3) in the 66 zone develops outward from potassic alteration centred on the Upper Trachyte, and also occurs in a 1.7 m wide vein at the lower margin of the Rainbow dike (drillhole 90-652). Gold grade reaches peak values where the carbonate-phyllic assemblage commences (~4–5 g/t; Figure 6b). It decreases outward to modest levels (0.1–0.6 g/t) except along minor faults and dike contacts, which remain at elevated grade (~1–3 g/t). Chalcopyrite is present in trace amounts within the dominant pyrite, where it hosts gold. In the MBX zone, carbonate-phyllic alteration overprints the upper margin of the Rainbow dike beyond ~230 m from the stock. It follows the Lower Trachyte for at least 90 m, where Cu-sulphosalt replacement of chalcopyrite is observed in ankerite veins.

Outer-propylitic alteration (epidote-chlorite-pyrite) is peripheral to all other alteration stages in the MBX and 66 zones (Figure 3b) but also cuts across the earlier assemblages along permeable horizons. Much of the lower DWBX zone is overprinted by the outer-propylitic stage, reflecting an abundance of permeable volcanic-conglomerate as hostrock. Gold grade is moderate to weak and Cu is insignificant (Figure 6a–c).

A deposit-wide pyrite halo (Sketchley et al., 1995; Oldenberg et al., 1997) is associated with peripheral sodic-calcic, inner- and outer-propylitic, and carbonate-phyllic assemblages where pyrite abundance is typically 1–5 modal % (Figure 6d, e).

Lateral and Vertical Zonation

The Cu-Au ore zone coincides with chalcopyrite-pyrite–and magnetite-bearing potassic alteration in the MBX stock and basaltic trachyandesite hostrock. The magnetite-associated inner calcpotassic shell extends ~130 m outward from the stock margin and abruptly terminates within the sodic-calcic zone. Biotite alteration continues another ~150 m into the hostrock but is overprinted by the sodic-calcic (~100–150 m from the stock margin), inner-propylitic (~150–220 m) and outer-propylitic assemblages (>220 m). Biotite also shows little compositional variation within the deposit (Delong, 1996).

In the 66 zone, the Upper Trachyte hosts a magnetite-bearing Cu-mineralized calcpotassic assemblage, which is surrounded by sodic-calcic and inner- and outer-propylitic assemblages with increasing depth (Figure 2b). Dolomite-ankerite replacement of mafic phases characterizes the Upper Trachyte but increases in intensity to the southeast, forming a funnel-shaped body of carbonate-phyllic alteration in the hostrock.

Conclusions

The highly faulted, Early Jurassic Mount Milligan alkalic porphyry Cu-Au deposit is tilted, providing an oblique cross-section through an alkalic porphyry system. Potassic alteration defines the core and appears to pass upward into a carbonate-phyllic alteration assemblage. Laterally, the magmatic plume marked by the potassic and calcpotassic alteration is fringed by sodic-calcic and finally the inner- and outer-propylitic assemblages. The critical element enabling the reconstruction of the vertical alteration was the recognition of the repetition of potassic alteration immediately above the Rainbow fault in the lower levels of the 66 zone.

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Mineral Deposit Research Unit (MDRU) contribution 229.

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