# Geology, alteration and zoning patterns of the Mt. Milligan copper-gold deposits

D.A. SKETCHLEY
Placer Dome Canada Limited, Kamloops, British Columbia

C.M. REBAGLIATI
Rebagliati Geological Consulting Ltd., Vancouver, British Columbia

C. DeLONG
The University of British Columbia, Vancouver, British Columbia

## ABSTRACT

*The Mt. Milligan porphyry copper-gold deposits are in central British Columbia, 155 km northwest of Prince George. Mineralized outcrops and float were discovered in the Mount Milligan area by prospecting. The most recent discoveries, which utilized lithogeochemistry, were in 1983. Areas containing the outcrops and float then were investigated by geological mapping, soil and lithogeochemical sampling, ground and airborne geophysical surveys, trenching and diamond drilling. This work led to the discovery of the Mt. Milligan Main deposit in 1987 and the Southern Star deposit in 1989. Extensive diamond drilling continued until 1991 and delineated a measured and indicated resource of 299 million tonnes grading 0.45 g/t Au and 0.22 % Cu from the combined deposits.*

*The Mt. Milligan deposits lie within the Early Mesozoic Quesnel Terrane and are hosted by porphyritic monzonite stocks and adjacent volcanic rocks of the Takla Group. The Mt. Milligan Main deposit is centred around the MBX stock and Rainbow dike, and the Southern Star deposit around the Southern Star stock.*

*Potassic alteration is extensive within the stocks and in volcanic rocks adjacent to the MBX stock and Rainbow dike. Propylitic alteration surrounds the potassic alteration and decreases in intensity away from the stocks. Mineralization consists mostly of pyrite, chalcopyrite, lesser magnetite, and minor bornite, molybdenite and gold.*

*Mineralogical zoning is well-developed within the deposits. A biotite-rich subzone forms the core of the potassic alteration zone and hosts most of the copper and gold. Numerous polymetallic veins lie within the propylitic alteration zone just beyond the limit of porphyry-style copper-gold mineralization.*

## Introduction

The Mt. Milligan deposits are large, low-grade, porphyry copper-gold deposits of the alkalic suite. This paper describes the history, exploration, geology, and metal zoning of the deposits. The measured and indicated resource for the combined deposits is 299 million tonnes of 0.45 g/t Au and 0.22 % Cu (Placer Dome Inc., 1992).

The Mt. Milligan deposits are in central British Columbia at 55° 08′ North latitude and 124° 04′ West longitude in NTS mapsheets 92N/1 and 920/4 (Fig. 1). Prince George is 155 km to the southeast; Vanderhoof, 155 km to the southwest; Fort St. James, 86 km to the southwest; and MacKenzie, 95 km to the northeast. The deposits lie near the northern boundary of the Southern Plateau and Mountain Region of the Canadian Cordilleran Interior System. More specifically, the property is within the Nechako Plateau near the southern limits of the Swannell Range of the Omineca Mountains (Holland, 1976).

The area surrounding the deposits is dominated by a north-south ridge (Fig. 2). Mount Milligan (1508 m), which is 8.5 km northwest of the Mt. Milligan deposits, is the highest peak on this ridge and is rounded and symmetrical in shape. The Mt. Milligan Main and Southern Star deposits are on the eastern slopes of the south-central part of the ridge, in an area of gentle relief, at an elevation of 1100 m.

During the Pleistocene, the Nechako Plateau was covered by the Cordilleran ice cap. The ice had moved eastward and northward from the Coast Ranges and over the Rocky Mountains near McLeod Lake, and had coated the surface with a blanket of glacial drift, and altered the preglacial drainage patterns. Drumlins, fluting, eskers and melt-water channels of various dimensions are noticeable features of the plateau surface. The Mount Milligan area is well drained except for depressions where natural vegetation has filled in ponds to form bog-like fens. Drainage from the area is to the northeast via Nation River into Williston Lake, which forms part of the Peace-MacKenzie River basin.

## History

The earliest record of exploration activity in the area is by prospector G. Snell, who found gold-bearing float 2 km west of Mitzi Lake on the southwestern flank of Mount Milligan in 1937 (Fig. 3). In 1945, Snell returned to the area and staked mineral claims. Five samples of pyritic andesite float returned assays ranging from trace amounts to 148.8 g/t Au. However, no gold-bearing material was found in place.

In 1972, Pechiney Development Ltd. (Pechiney) staked mineral claims to cover an area just north of Heidi Lake. Subsequent exploration work identified induced polarization and copper-in-soil geochemical anomalies. Pechiney drilled five diamond drill holes that did not intersect significant copper mineralization. The claims were allowed to lapse.

The Mount Milligan region remained inactive until 1983 when Selco Inc. (Selco), on the recommendation of C.M. Rebagliati, initiated a regional lithogeochemical survey to explore for auriferous porphyry copper deposits. During this work Selco staked claims to cover a regionally significant gold-arsenic lithogeochemical anomaly located east of Heidi Lake. Follow-up on this anomaly resulted in the discovery of mineralized talus and outcrops (Rebagliati, 1983). In early 1984, Selco amalgamated with BP Resources Canada Limited (BP).

In early 1984, prospector R. Haslinger staked mineral claims adjacent to those of Selco. BP optioned these claims from Haslinger in mid-1984, and in late 1984 and early 1985 staked more claims in the area. The Haslinger claims cover part of the Mt. Milligan Main and Southern Star deposits.

During 1984 and 1985, BP completed geological, soil and nature of the Central Copper zone, and lack of drilling on the other known zones on the property.

Detailed environmental studies have not been initiated, but limited petrographic work and field observations suggest that the waste rock may be acid consuming due to the carbonate mineral content.

## Discussion and Conclusions

The Copper Canyon deposit is similar in most respects to the nearby Galore Creek deposits (Allen et al., 1976; Enns et al., this volume). Distinctive features are the high gold content and spatial association with pseudoleucite-bearing volcanic rocks. The latter are unusual for the Stuhini Group, and their association with a distinctive suite of high level alkaline intrusions suggests a possible co-magmatic link.

Emplacement of the alkaline intrusive complex, block faulting and mineralization show a close spatial and temporal relationship. Mineralization occurs both within the alkaline intrusions and in the volcanic rocks, but the higher grade areas found to date are volcanic-hosted. Some late syenite dike phases are weakly mineralized and altered, and cut earlier more intense alteration and mineralization, indicating that the main period of emplacement of the copper-gold mineralization took place during the period of alkaline intrusive activity. These intrusions are assigned to the mid-Jurassic by Logan and Koyanagi, 1989, but recent U-Pb dating of the Galore Creek syenites (Mortenson et al., this volume) suggests an Upper Triassic to Lower Jurassic age (197 Ma to 210 Ma).

While currently uneconomic, the Copper Canyon deposit represents a significant high-grade copper-gold resource. Future development of a large-scale mining operation is dependent on the provision of transportation infrastructure into the region, and development of the Galore Creek deposits. On a smaller scale, the potential for Snip-type gold-bearing shear systems peripheral to the porphyry mineralization has received little attention, and warrants further exploration.


## Acknowledgments

The authors wish to acknowledge the permission of the managements of Consolidated Rhodes Resources Ltd. (more recently Fairhaven Resources Ltd.), Prime Equities International Corporation, Canamax Resources Inc. (more recently Canada Tungsten Inc.) and Silver Standard Resources Inc. to publish this paper.


## REFERENCES


ALLEN, D.G., PANTELEYEV, A. and ARMSTRONG, A.T., 1976. Galore Creek. *In* Porphyry deposits of the Canadian Cordillera. *Edited by* A. Sutherland Brown. Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 402-414.

BOTTOMER, L.R. and CAULFIELD, D.A., 1991. Mineral deposits and exploration trends in the Galore Creek area, northwestern British Columbia. *In* Abstracts, Canadian Institute of Mining and Metallurgy Annual General Meeting, Vancouver, British Columbia, Bulletin, 84, No. 947, p. 81-82.

ENNS, S.G., THOMPSON, J.F.H., STANLEY, C.R. and YARROW, E.W., 1995. The Galore Creek porphyry copper-gold deposits, northwestern British Columbia. *In* Porphyry Deposits of the Northwestern Cordillera of North America. *Edited by* T.G. Schroeter. Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46.

LOGAN, J.M. and KOYANAGI, V.M., 1989. Geology and mineral deposits of the Galore Creek area, northwestern B.C. *In* Geological Fieldwork 1988, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1989-1, p. 269-284.

MORTENSEN, J.K., GHOSH, D. and FERRI, F., 1995. U-Pb geochronometry of intrusive rocks associated with copper-gold deposits in the Canadian cordillera. *In* Porphyry Deposits of the Northwestern Cordillera of North America. *Edited by* T.G.Schroeter. Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46.

RHYS, D.A., 1993. Jurassic porphyry-related shear zone and vein gold deposits in the Johnny Mountain area, northwestern British Columbia. *In* Abstracts, Northwest Mining Association 99th Annual Convention, Spokane, Washington.

lithogeochemical, magnetic and induced polarization surveys, and a trenching program. This work identified two polymetallic-auriferous vein systems and two areas of weak porphyry copper-gold mineralization.

In 1986, when BP discontinued exploration for auriferous porphyry deposits, Lincoln Resources Inc. (Lincoln) optioned the property and continued exploration work. In September 1987, Lincoln undertook a diamond drilling program, and its hole 12 intersected significant copper-gold mineralization (Mt. Milligan Main deposit). This hole was drilled to test a small magnetic anomaly within an area of high chargeability flanking a resistivity high. Following the discovery, ground geophysical grids were expanded and a property wide aeromagnetic survey was conducted.

In 1988, Lincoln reorganized to become United Lincoln Resources Inc. (United Lincoln) and, in 1989, the company amalgamated with Continental Gold Corp. (Continental Gold). In 1989, additional diamond drilling was conducted and hole 199 intersected a new zone of copper-gold mineralization, now known as the Mt. Milligan Southern Star deposit. This drilling also identified low-grade porphyry gold and copper-gold mineralization associated with the Goldmark and North Slope intrusions.

In mid-1990, Placer Dome Inc. (Placer Dome) purchased BP's interest in the mineral claims. Placer Dome then acquired Continental Gold and resumed diamond drilling on the property in late 1990. This work consisted of in-fill and step-out drilling on the Southern Star deposit (Sketchley, 1992).

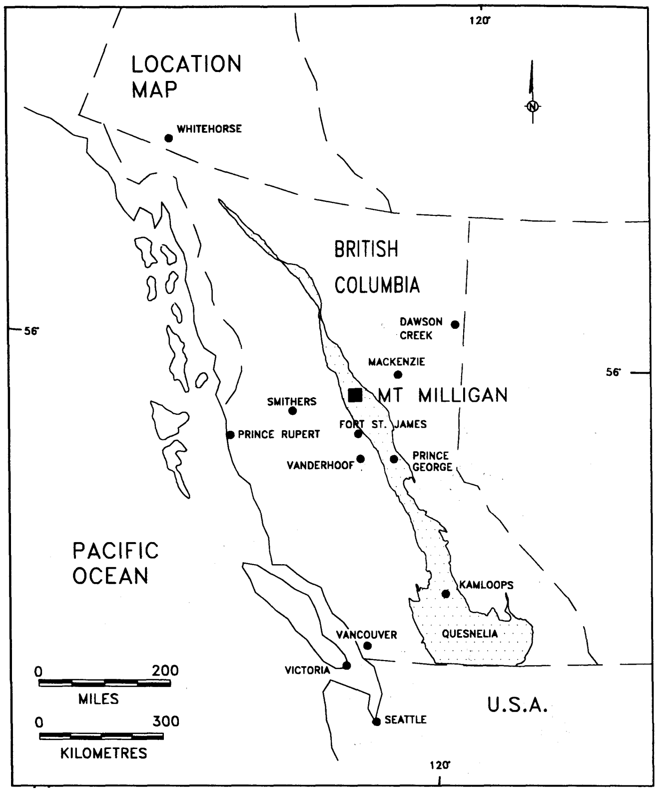


**FIGURE 1. Location map.**

## Soil Geochemical Surveys

Approximately 2100 soil samples were collected from an area of 6 km by 7 km over and surrounding the Mt. Milligan deposits. Most soil samples were taken from the B-horizon, which is developed in till or fluvial material. Samples were collected mainly at 100 m intervals on lines 200 m apart. In an area of 2.5 km by 4 km, which partly overlaps and lies to the west of the Mt. Milligan deposits, in-fill samples were collected at intervals of 50 m along lines 50 m or 100 m apart.

All soil samples were analyzed for 31 elements by Inductively Coupled Plasma Spectrometry (ICP) and for gold by Atomic Absorption (AA) after digestion with aqua regia. Analytical results outlined numerous copper and gold anomalies within the 2.5 km by 4 km area of detailed sampling (Figs. 4 and 5). This area encompasses the Creek, Esker and South Boundary polymetallic vein systems and the Mt. Milligan Main and Southern Star porphyry deposits. The extensive cover of glacial-fluvial and morainal material partially masked and dispersed the bedrock geochemical response. In the North Slope area west of the deposits, geochemical values from the colluvium samples are much higher. Outcrop in this area is close to or at surface and downslope dispersion is prevalent.

## Geophysical Surveys

Ground magnetic, induced polarization and VLF-EM surveys were completed over a 5 km by 5 km area that encompasses the Mt. Milligan deposits and the vicinity of Heidi Lake. An airborne magnetic survey was conducted over an area 10 km by 15 km in size that covers the deposits and Mount Milligan.

The airborne magnetic surveys confirmed the presence of a large regional magnetic high centred over Mount Milligan, which was previously documented on the Geological Survey of Canada Regional Aeromagnetic Map 1584G - Wittsichica Lake (Fig. 6). This magnetic high is related to the Mount Milligan Intrusive Complex and indicates that the complex is more extensive than its area of exposure. The deposit area is characterized by a cluster of weak magnetic highs that are related to small intrusions on the southern side of the Mount Milligan intrusive complex (Fig. 7).

The induced polarization surveys outlined a large, arcuate chargeability anomaly with its centre west of the Mt. Milligan deposits (Fig. 8). The strongest portion of the chargeability anomaly coincides with the pyrite-rich halo of the deposits. An exception is the localized chargeability high on the southeastern side of the MBX stock which coincides with the core of the MBX zone (Fig. 9).

In 1991, after the discovery of the deposits, the Geological Survey of Canada completed an airborne multi-parameter geophysical survey of the Mount Milligan area (Geological Survey of Canada, 1992). This survey recorded gamma-ray spectrometric and total magnetic field data. The potassium data reveal anomalous concentrations centred over Mount Milligan, which coincides with the best exposure of the Mount Milligan Intrusive Complex. A smaller anomaly coincides with the Mt. Milligan deposits and the surrounding alteration halo.

## Trenching

Extensive trenching was conducted on the Mt. Milligan property prior to the discovery of the Mt. Milligan Main and Southern Star deposits. It targeted copper and/or gold soil geochemical anomalies adjacent to the North Slope intrusion and localized highly anomalous concentrations of gold, silver, arsenic and antimony directly overlying the buried Creek, Esker and South Boundary polymetallic multiple vein zones. The trenching exposed mineralized bedrock, which was the cause of the geochemical anomalies investigated.

## Diamond Drilling

Diamond drilling was used to explore the geochemical, magnetic and induced polarization anomalies and to delineate mineralized zones. A total of 194 467 m of exploration and geotechnical diamond drilling in 919 holes was completed by Lincoln, United Lincoln, Continental Gold and Placer Dome between February, 1987 and April, 1991.

## Regional Geology

The Mt. Milligan deposits lie within a belt of Triassic-Jurassic rocks of the Early Mesozoic Quesnel Terrane. This terrane comprises a north-northwesterly trending belt of rocks that extends approximately 1200 km through British Columbia between the

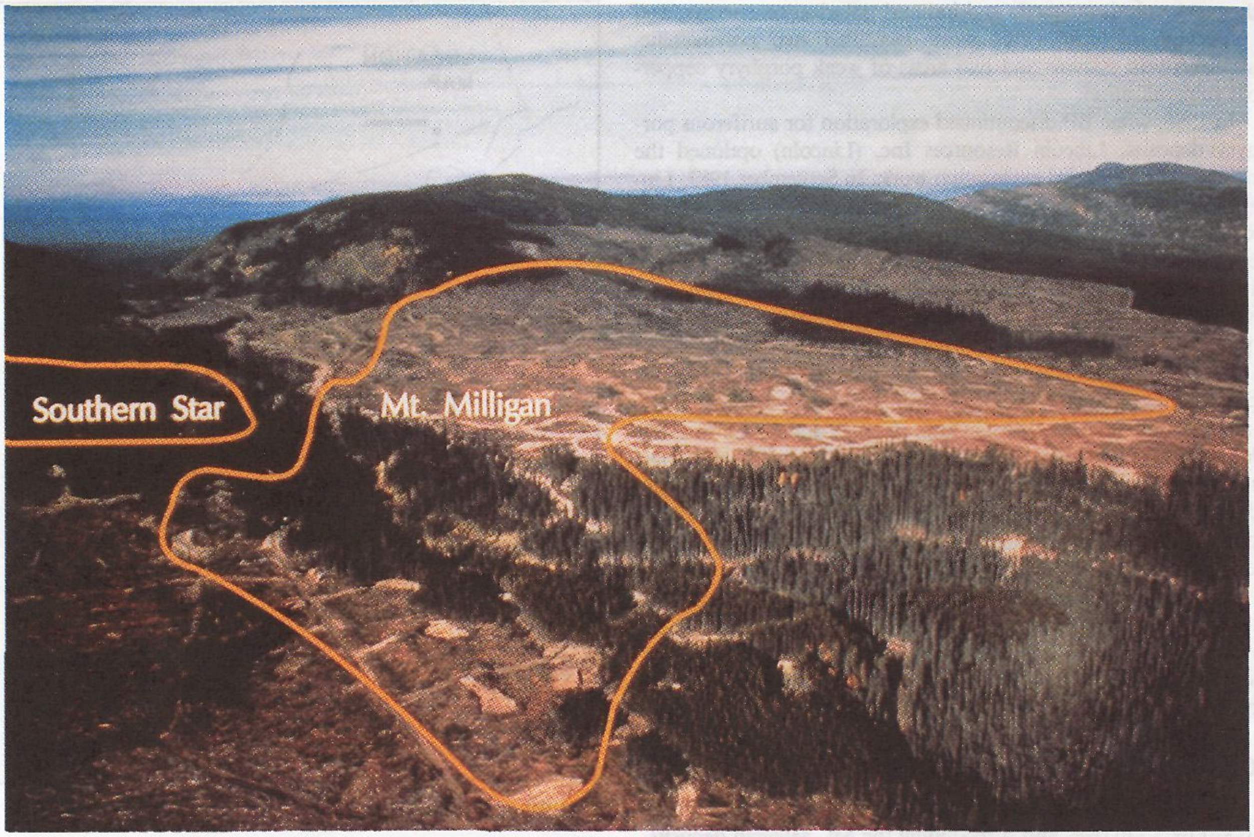


**FIGURE 2. Mt. Milligan Main and Southern Star deposits. Early fall 1989, looking west toward Heidi Lake. Mount Milligan is at far right.**

United States and Yukon borders. The Mt. Milligan deposits are midway along the belt. The Quesnel Terrane is interpreted to be an island arc assemblage (Mortimer, 1987; Monger et al., 1991).

Quesnel Terrane includes rocks of the Late Triassic to Early Jurassic Takla and Nicola Groups. In the Mount Milligan area, the Quesnel Terrane comprises volcanic and sedimentary rocks of the Takla Group, and coeval plutons (Nelson et al., 1991). Two U-Pb zircon ages, 182 Ma for the North Slope stock and 183 Ma for the Southern Star stock (Ghosh, 1992), indicate an Early to Middle Jurassic age for these intrusions. In the northern part of the area, the Hogem Batholith occurs along the western margin of the terrane. A subaqueous to subaerial volcanic complex is present between Mount Milligan and Chuchi Lake (Nelson et al., 1992), in the central portion of the area. In the southeastern part of the area, the Mount Milligan intrusive complex is present to the southeast of the Hogem Batholith. This shift in the location of the major intrusions from the west to the east suggests the presence of a major cross-arc structure.

In the Mount Milligan area, Takla Group rocks comprise the informal Rainbow Creek, Inzana Lake, Witch Lake and Chuchi Lake Formations (Nelson et al., 1991). Volcanic rocks of the Witch Lake and Chuchi Lake Formations form the core of the volcanic complex and are flanked and underlain by sedimentary rocks of the Inzana Lake and Rainbow Creek Formations (Nelson et al., 1992). Slate, and lesser siltstone and epiclastic sedimentary rocks of the Rainbow Creek Formation comprise the lowermost unit. They are overlain by epiclastic sedimentary rocks of the Inzana Formation, which are overlain by, and interfingered with, augite porphyritic volcanic rocks and pyroclastic rocks of the Witch Lake Formation. These rocks grade upward into polymictic laharic breccias and subaerial flows of the Chuchi Lake Formation.

The local distribution of the volcanic rocks coincides with a composite regional magnetic high that is believed to be due to several small intrusive complexes. These intrusive complexes are composed of small intrusions and stocks ranging in composition from gabbro to syenite. They occur at Mount Milligan, and southwest and northeast of Chuchi Lake. Other single and composite plutons are present between these areas.

Crowded feldspar-porphyritic monzonite stocks and dikes that are associated with porphyry-style copper-gold mineralization are related to the intrusive complexes and occur within and around the volcanic complex. These stocks have small magnetic highs on the flanks of the large composite regional magnetic high. Examples of these monzonite stocks in the Mount Milligan area are the MBX, Southern Star, North Slope and Goldmark stocks (Fig. 3).

## Property Geology

The Mt. Milligan property is covered by a continuous layer of till and fluvial material in the area of the deposits and the lowland areas to the east and south. Elsewhere till and colluvial deposits are discontinuous. In the area of the deposits, diamond drilling indicates that the overburden is up to 100 m thick and is composed of a mixture of clay, silt, sand, coarse gravels and several interbedded till sheets. A northeasterly trending esker, in part overlying the Mt. Milligan Main deposit, was found to contain pebbles and boulders of biotite and K-feldspar-altered andesitic volcanic rocks hosting porphyry-type copper-gold mineralization. The up-ice end of the esker coincides with the localized magnetic anomaly investigated by discovery drill hole 12.

The Mt. Milligan property is underlain mostly by volcanic rocks of the Witch Lake Formation of the Takla Group (Nelson et al., 1991). Minor sedimentary rocks of the Rainbow Creek Formation, and Early Tertiary volcanic and sedimentary rocks are present also. Andesitic rocks of the Witch Lake Formation generally trend north-northwesterly and dip moderately to steeply to the east (Fig. 9). However, locally, north of the Mt. Milligan Main deposit, this strata dips steeply to the west.

The Witch Lake Formation is intruded by intrusions that are coeval with the Takla Group and post-Takla Group in age. Coeval

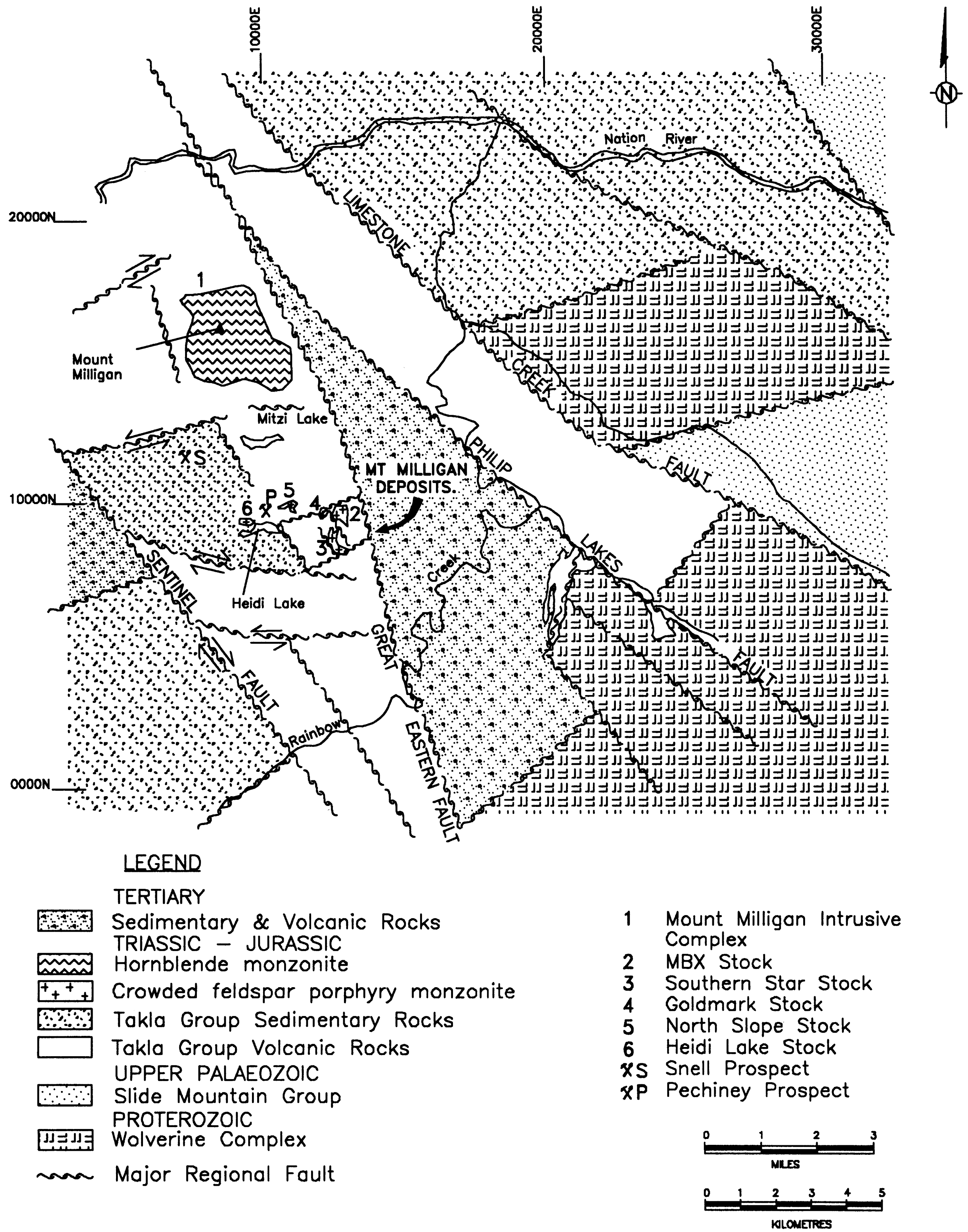


**FIGURE 3. Regional geology: The Mt. Milligan deposits are associated with crowded feldspar porphyry monzonite in Takla Group volcanic rocks.**

intrusions comprise most of the Mount Milligan intrusive complex, which consists dominantly of monzonite with minor diorite/monzodiorite and gabbro/monzogabbro. The MBX, Southern Star, Goldmark and North Slope stocks, which host the mineralization, comprise monzonite. Post-Takla Group intrusions comprise granitic rocks, which constitute a minor portion of the Mount Milligan intrusive complex. Trachyte, monzonite and diorite postmineral dikes are common. K-Ar ages of 96 Ma and 108 Ma from hydrothermal biotite from the Mt. Milligan Main deposit suggest a Cretaceous age for at least one set of these dikes.

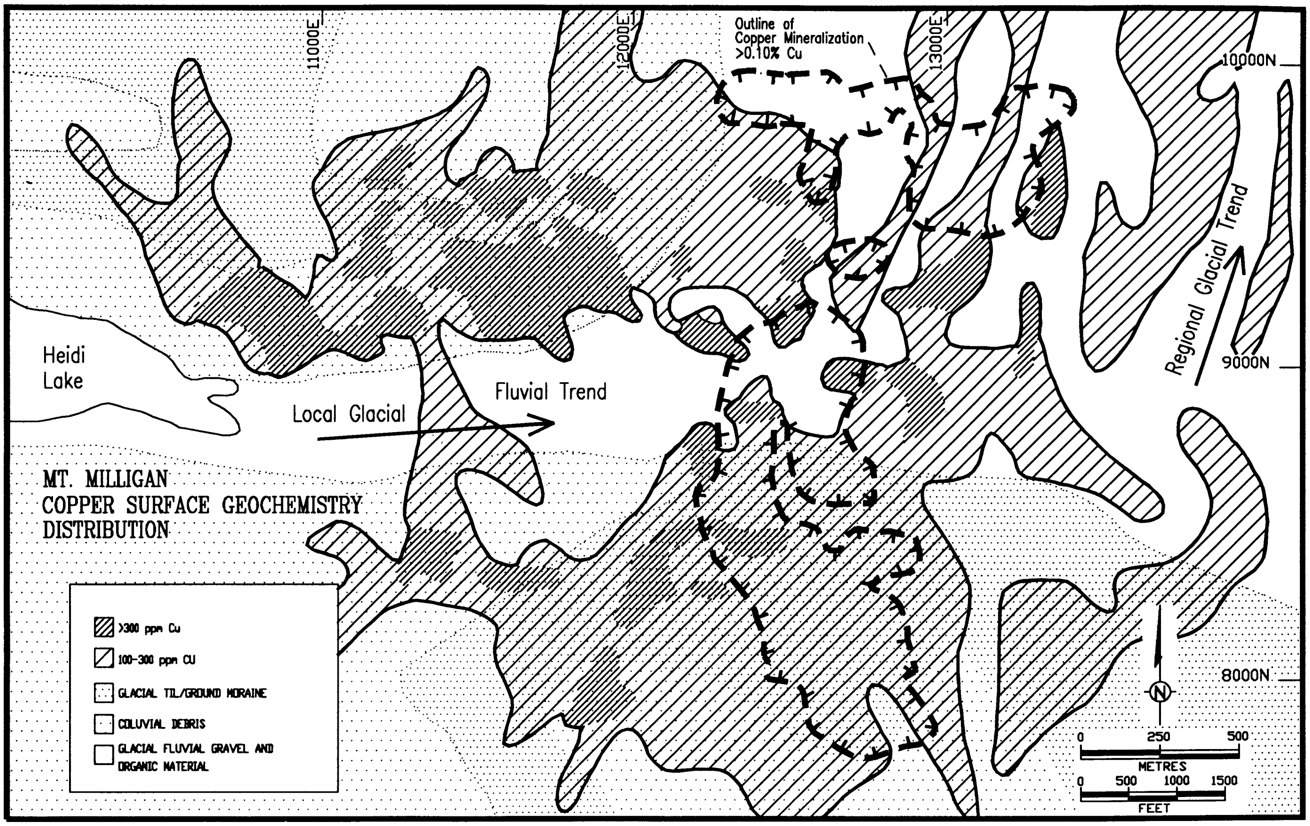


**FIGURE 4. Copper-soil geochemistry: The continuity of the copper anomalies northeast of Heidi Lake reflects the in situ colluvium, in contrast to the elongate anomalous trends further to the east that illustrate glacial dispersion.**

## Deposit Geology

The Mt. Milligan deposits include the Mt. Milligan Main and Southern Star deposits (Figs. 9, 10 and 11). The Mt. Milligan Main deposit occurs within the MBX stock and adjacent latitic, andesitic to high-potassium basaltic, and trachytic volcanic rocks of the Witch Lake Formation. It comprises the Magnetite Breccia (MBX) zone, the 66 zone, the West Breccia (WBX) zone, and the Deep West Breccia (DWBX) zone. The Southern Star deposit occurs within the Southern Star stock and adjacent andesitic to high-potassium basaltic volcanic rocks of the Witch Lake Formation.

Rocks of the Witch Lake Formation generally trend north-northwesterly and dip moderately to steeply east (Fig. 9). However, locally, north of the Mt. Milligan Main deposit, these strata dip steeply west. In the southeastern portion of the Mt. Milligan deposits, the stratigraphy trends northerly to northeasterly. Graded bedding and cross-bedding in tuffaceous rocks indicate that the stratigraphy faces east.

At least four episodes of faulting affected the area containing the Mt. Milligan deposits. The earliest gave rise to the northerly trending, shallowly easterly-dipping, bedding-parallel Rainbow Fault (Fig. 9).

Prominent east-northeasterly trending cross-faults cut the Mt. Milligan deposits. These structures include the Oliver Fault, the Caira Fault and some of the Southern Star cross-faults (Fig. 9). The Caira Fault is intruded by monzonite dikes and may belong to an early episode of faulting, which was reactivated during development of the Oliver Fault.

Northwesterly trending, steeply easterly-dipping faults, manifested by the Divide and seven others (Nos. 5, 7, 8, 9, 10, 12 and 13), occur in the Southern Star deposit and in the western portion of the Mt. Milligan Main deposit (Fig. 9).

The northerly- to northwesterly-striking, moderately easterly-dipping Great Eastern Fault is a major regional structure, which truncates the extreme southeastern portion (66 zone) of the Mt. Milligan Main deposit. This fault juxtaposes Takla Group rocks with Early Tertiary rocks lying to the east (Fig. 9).

Other northerly trending faults are manifested by the steep easterly-dipping Harris Fault (Fig. 9), which separates the WBX and DWBX zones.

## Andesitic Rocks

Rocks mapped in the field as andesitic volcanic rocks are andesite to basalt in composition. These rocks underlie most of the area around the Southern Star and MBX stocks (Figs. 9, 10, and 11). Monolithologic, fragmental varieties constitute most of the unit, and are characterized by actinolite-altered augite porphyritic lapilli tuff and minor augite crystal and lithic tuff (Rebagliati et al., 1990). Minor augite porphyritic flows and heterolithic debris flows (Fig. 12A) are interbedded with the fragmental rocks. Plagioclase and/or hornblende phenocrysts are locally present in the flows, individual lapilli or crystal tuffs. In places, subordinate, discontinuous, heterolithic, coarse fragmental units have finer-grained upper parts, which could be turbiditic caps to submarine debris flows.

Augite porphyry andesite flows are characterized by 10% to 30% euhedral to subhedral phenocrysts of dark green, augite-shaped actinolite pseudomorphs. The actinolite-altered phenocrysts occur singly or are glomeroporphyritic. The phenocrysts generally range in size from 0.5 mm to 3 mm, but some units have crystals up to 8 mm. In some of the coarser-grained flows, plagioclase is a microphenocryst phase in addition to being present in the groundmass. In these flows, the plagioclase comprises up to 40% of the rock. Plagioclase crystals are pale cream, lath-like to stubby, and range from 0.5 mm to 1 mm in length. The groundmass of flows consists of varying amounts of microgranular K-feldspar, anhedral mosaics of plagioclase, coarse anhedral epidote, finer-grained intergrowths of albite and epidote, micron-sized sphene, chloritic material and carbonate. Minor fine-grained felted green biotite and intergrowths of biotite and K-feldspar are present locally. The

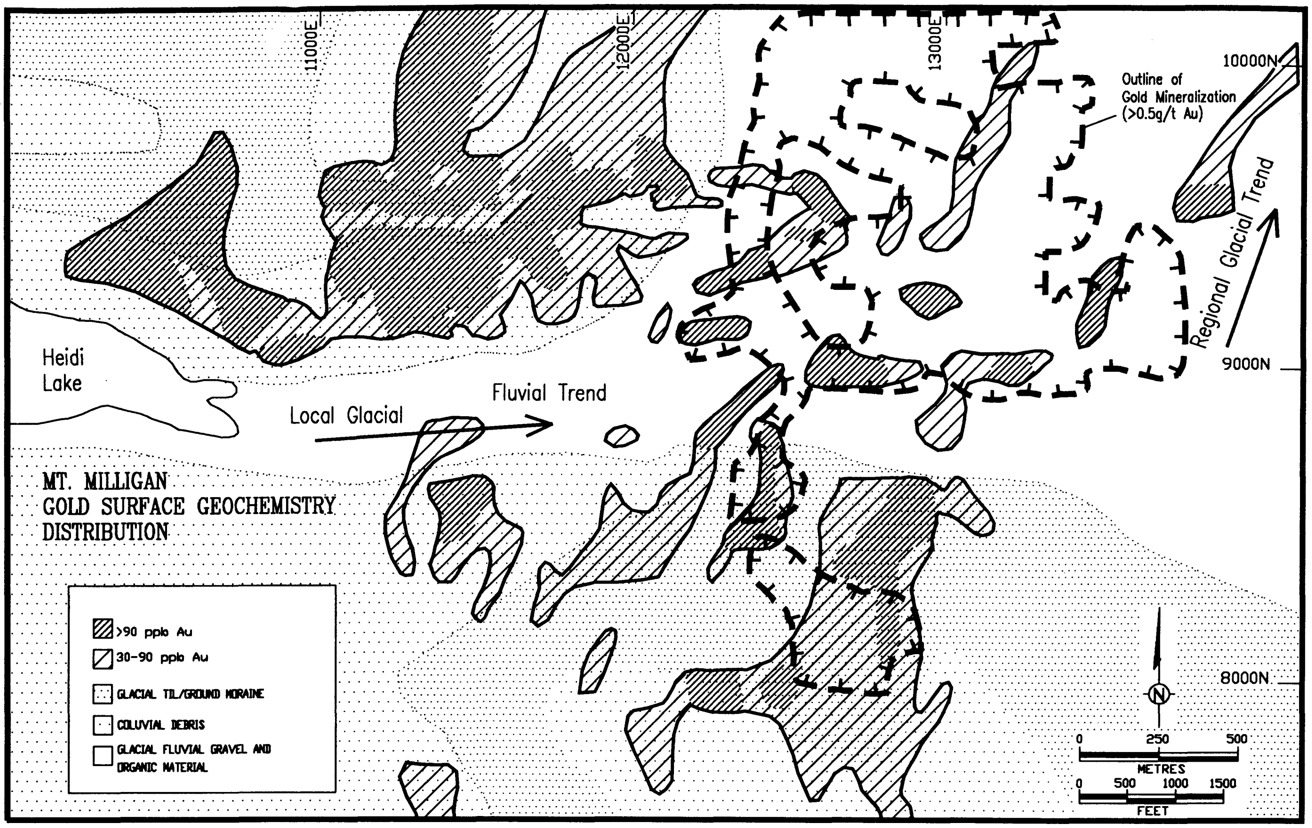


**FIGURE 5. Gold-soil geochemistry: The continuity of the gold anomalies northeast of Heidi Lake reflects the in situ colluvium, in contrast to the elongate anomalous trends further to the east that illustrate glacial dispersion.**

microgranular K-feldspar of the groundmass could be magmatic and/or hydrothermal.

Crystal tuffs and lapilli tuffs, which can resemble flows, are dark green and contain 5% to 40% actinolite pseudomorphs after augite. A fragmental texture is recognizable in thin section. The groundmass consists of irregularly shaped fragments, generally 0.2 mm to 0.5 mm across, fibrous grains of actinolite and a few broken grains of plagioclase. Some larger actinolite crystals, up to 8 mm long, have euhedral faces preserved. Other groundmass components, which are mostly hydrothermal, are felted green biotite, sphene, rutile, sericite, carbonate and epidote.

## Latitic Rocks

Rocks mapped as latitic volcanic rocks are texturally similar to the andesitic volcanic rocks and are characterized by 15% to 40% actinolite-altered augite phenocrysts. These rocks are probably potassically-altered alkali basalts. They underlie most of the area around the MBX stock and less commonly the areas adjacent to the Southern Star stock (Figs. 9, 10 and 11). The latitic volcanic rocks are distinguished from the andesitic volcanic rocks by their: (1) darker colour, (2) general absence of megascopic hornblende, (3) presence of biotite, and (4) greater than one-third K-feldspar content, based on staining. The darker colour is due to the presence of biotite, which is related to potassic alteration. The general absence of hornblende could be a result of destruction during potassic alteration.

## Trachytic Rocks

Rocks mapped as trachytic volcanic rocks are interbedded with the latitic volcanic rocks in the eastern portion of the Mt. Milligan Main deposit (Figs. 9 and 10). They are the only marker units in the area of the deposits (Rebagliati, 1990). The trachytic rocks are characterized by a high K-feldspar content and a lack of mafic minerals. Minor fine-grained plagioclase is present also.

Massive and bedded varieties of trachytic rocks occur on the property. Massive varieties contain curvilinear pyrite-chlorite partings and clots of chlorite, calcite and scarce epidote around pyrite cores (Rebagliati et al., 1990). K-feldspar occurs as microlites. Bedded varieties locally exhibit cross-bedding and graded bedding. They are generally discontinuous, occurring above and below the massive trachytic volcanic rocks and extending laterally from them. Pyrite and chlorite are common along bedding planes and are disseminated throughout the unit (Fig. 12H). Trachytic volcanic rocks are either porous tuffaceous rocks of andesitic composition that underwent intense potassic alteration, or true trachyte flows and tuffs.

## Intrusive Rocks — Pre and Intersulphide Mineralization

The MBX stock is a moderately westerly-dipping monzonite body approximately 400 m in diameter (Figs. 9 and 10). In the southeastern portion of the Mt. Milligan Main deposit, the Rainbow dike, which is up to 50 m thick, protrudes from the footwall of the MBX stock as an elongate bowl-shaped body with gently-dipping sides open to the southeast. The western side of the dike is subparallel to stratigraphy as defined by interbedded trachytic volcanic rocks, and occupies the plane of the Rainbow Fault. The northeastern side steeply cross-cuts stratigraphy (Fig. 9).

The Southern Star stock is a moderately westerly-dipping, north-northwesterly-striking, tabular body of monzonite, which forks at its northern end (Figs. 9 and 11). In plan view, its margins are more irregular and undulose than those of the MBX stock. The stock is approximately 800 m long by 300 m wide.

The MBX and Southern Star stocks are typically crowded plagioclase porphyries containing up to 70% phenocrysts from 1 mm to 10 mm long. These phenocrysts occur in a fine-grained to aphanitic greyish-pink to dark grey groundmass composed mostly of K-feldspar with lesser plagioclase, and minor quartz, hornblende

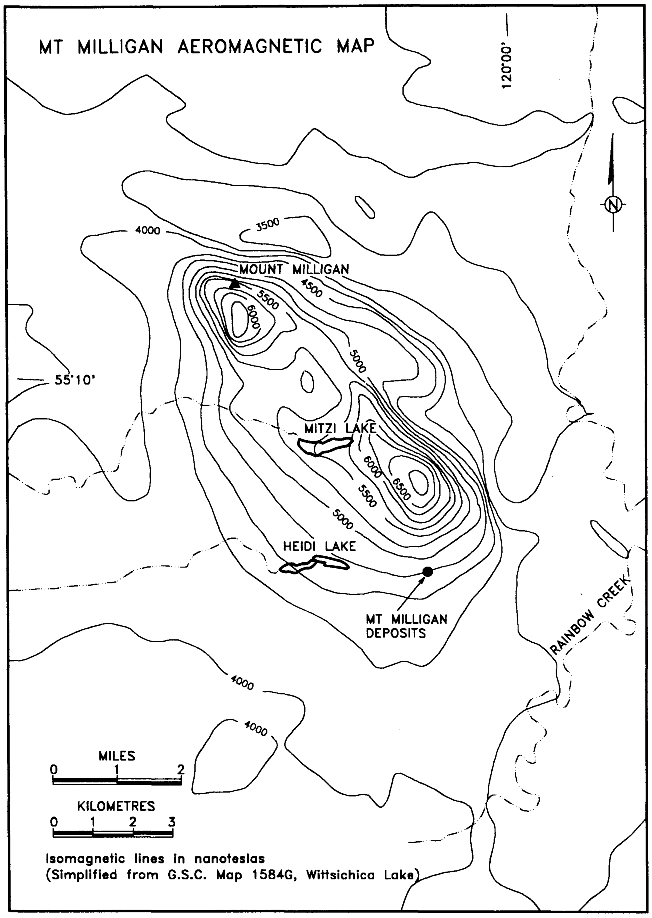


**FIGURE 6. Regional aeromagnetics: A 100 km² magnetic anomaly encompasses the Mount Milligan intrusive complex. At this scale anomalies associated with the MBX and Southern Star stocks are not distinguishable.**

and biotite. Accessory minerals include apatite, chlorite, rutile and sphene.

Some stock margins, particularly those of the Southern Star stock, are characterized by a plagioclase-hornblende porphyritic monzonite border phase. Rafts of volcanic rocks are most common in the Southern Star stock. Localized areas of monzonite intrusion breccia comprise xenoliths of volcanic rock and/or earlier monzonite (Fig. 12B).

Along the contact of the stocks, particularly the MBX stock, a hybrid monzonite-volcanic rock is present. This rock has gradational boundaries and textures that vary between those of monzonite and volcanic rocks. The hybrid contains ghosts of plagioclase phenocrysts and remnants of augite phenocrysts, and could be an intrusion breccia in which the primary textures are obscured by intense pervasive hydrothermal alteration and magmatic assimilation.

Hydrothermal breccia occurs extensively throughout the Southern Star stock, and less commonly in adjacent volcanic rocks and along the margins of the MBX stock. The breccia is characterized by K-feldspar flooding and veinlets that vary in thickness and intensity. There appears to be a gradation from massive relatively unaltered monzonite through to a crackle breccia to well-developed breccia with a K-feldspar-rich matrix (Fig. 12C). In areas of well-developed brecciation and intense K-feldspar alteration, the matrix is aplitic. In areas of abundant veining, brecciation and K-feldspar flooding, clasts of brecciated volcanic rocks appear rotated. The breccia clasts are generally of the same composition as the host rock, although less commonly exotic lithologies are present. Veinlets are composed dominantly of K-feldspar with subordinate to minor quartz, magnetite, pyrite, chalcopyrite, molybdenite and bornite.

Locally, along the eastern margins of the MBX stock, magnetite comprises over 50% of the breccia matrix. Discovery drill hole 12 intersected one of these magnetite-rich breccias in the area now referred to as the MBX (magnetite breccia) zone.

Non-mineralized, late-intermineral plagioclase-hornblende porphyritic monzonite dikes are common throughout the Southern Star stock.

## Intrusive Rocks — Post Sulphide Mineralization

Three suites of postmineral dikes cut the Mt. Milligan Main and Southern Star deposits and consist of trachyte, monzonite, and diorite varieties. These dikes are generally unaltered and lack sulphide mineralization.

The trachyte dikes are the earliest and are most common in the south-southwestern portion of the Mt. Milligan Main deposit and the adjacent northern portion of the Southern Star deposit. They are 1 m to 15 m wide, strike northeasterly and dip moderately northwesterly. Trachyte dikes are grey, massive, fine-grained and non-porphyritic. K-feldspar is the dominant constituent. Most trachyte dikes contain accessory magnetite and some contain traces of chalcopyrite.

The monzonite dikes intruded after the trachyte dikes and occur throughout the Mt. Milligan Main and Southern Star deposits. Monzonite dikes are up to 10 m wide, strike northeasterly and dip moderately northwesterly. They are characterized by abundant plagioclase phenocrysts, up to 2 mm in size, and may contain augite and hornblende phenocrysts, up to 5 mm. The phenocrysts occur in a fine-grained K-feldspar-rich matrix. Accessory magnetite is always present. Some monzonite dikes are weakly propylitized.

The diorite dikes, which are compositionally dacitic (Lang, 1992), are youngest. Although present in both deposits, they are most common in the northeastern portion of the Main deposit. These dikes are up to 5 m wide, strike northwesterly and dip steeply northeasterly. Diorite dikes are characterized by scattered, commonly glomeroporphyritic plagioclase phenocrysts, up to 10 mm long, in a fine-grained matrix. Subsidiary hornblende phenocrysts, up to 2 mm long, and minor quartz eyes, up to 1 mm across, are present also. Some dioritic dikes are weakly carbonate-altered.

## Alteration

Potassic and propylitic alteration are present throughout the Mt. Milligan Main and Southern Star deposits (DeLong et al., 1991). Copper and gold mineralization is associated mainly with the potassic alteration (Figs. 9, 10 and 11), except in the 66 zone where gold-rich, copper-poor mineralization is associated with propylitic alteration. Sericitic alteration, affecting plagioclase phenocrysts in the stocks and related dikes, overprinted the potassic alteration. Early in the alteration history, most augite is replaced by pseudomorphic actinolite. Minor postmineral carbonate alteration is present.

Potassic alteration is most abundant around the contacts of the MBX and Southern Star stocks (Figs. 9, 10 and 11). It decreases in intensity toward their cores and outward into the country rocks (Rebagliati et al., 1990). Potassic alteration is less widespread around the Southern Star stock than the MBX stock. Where faults and fractures are abundant, potassic alteration extends farther beyond the stock contacts. Propylitic alteration is best developed away from the stocks, beyond the potassic zone (Figs. 9, 10 and 11). The propylitic assemblage locally overprinted the potassic alteration; less commonly potassic overprinted propylitic. These relationships can be interpreted to mean the two alteration types are contemporaneous and were locally interrupted by intrusion of monzonite dikes into the propylitic alteration, as seen in the 66 zone. Diagram A in Figure 15 illustrates the separation of the potassic and propylitic alteration assemblages. The trace element geochemistry associations are shown in diagram B of Figure 15.

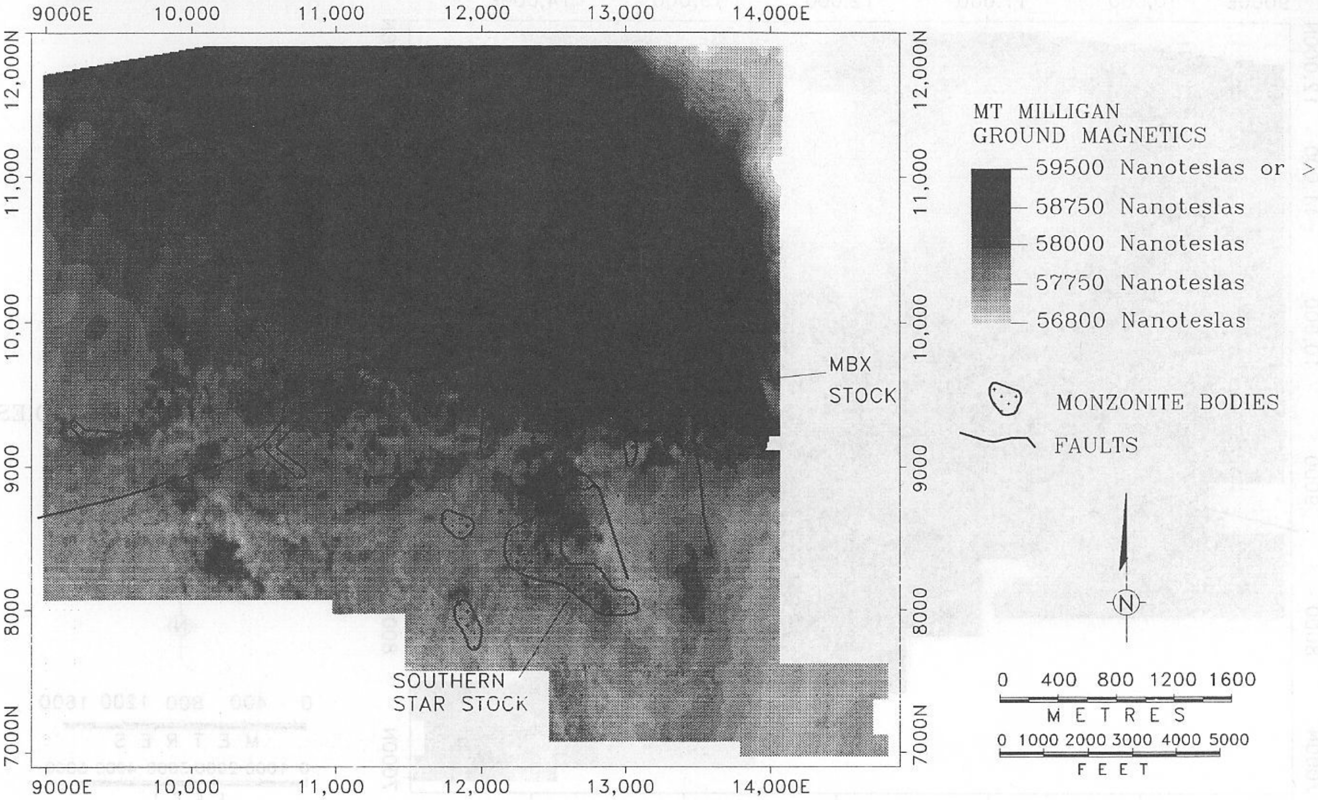


**FIGURE 7. Ground magnetics: Anomalies associated with the MBX and Southern Star stocks are distinguishable as satellitic features to the large magnetic anomaly associated with the Mount Milligan intrusive complex.**

## Potassic Alteration

Potassic alteration is characterized by hydrothermal K-feldspar, which is present throughout the potassic zone. In areas of more intense potassic alteration, hydrothermal biotite, chalcopyrite, lesser magnetite and minor bornite occur in addition to K-feldspar. This is the biotite subzone (Figs. 9 and 10).

Hydrothermal biotite is developed best in latitic volcanic rocks in the biotite subzone. It occurs as fine-grained felted patches that comprise up to 60% or more of the volcanic rocks adjacent to monzonite intrusions, and decreases away from them (Fig. 12D). Pervasive biotite alteration is usually restricted to the groundmass, and leaves distinct, commonly euhedral, pyroxene-shaped pseudomorphs of actinolite and calcite after augite phenocrysts. Locally, the alteration is intense enough to be texturally destructive, and the rock appears as fine-grained, patchy to swirled aggregates of biotite and K-feldspar, usually with magnetite and microscopic acicular actinolite. This type of intense alteration often hosts the highest grade copper and gold mineralization and forms the core of the MBX zone.

Biotite also occurs along the margins of K-feldspar veinlets in latitic and trachytic volcanic rocks. In andesitic rocks, which host the Southern Star stock, hydrothermal biotite occurs only adjacent to K-feldspar veinlets. Actinolite-augite is sometimes partially to completely replaced by calcite or calcite and pyrite.

Monzonite contains hydrothermal biotite near its contacts with volcanic rocks, but generally is much less abundant than in the mafic volcanic rocks.

The highest copper and gold concentrations are related spatially to the biotite subzone. Biotite occurs also as igneous microphenocrysts in monzonite as well as a fine-grained hydrothermal product in the host volcanic rocks. The igneous biotite is not everywhere preserved. It comprises only a small portion of the monzonite, and is texturally distinct from hydrothermal biotite. Microphenocrysts of igneous biotite are coarser-grained and up to 3 mm long, in contrast with the fine-grained felted hydrothermal

**TABLE 1.** Composition of hydrothermal and igneous biotite using the electron microprobe. Data are the average of 141 hydrothermal biotite and 68 igneous biotite analyses, and are the atoms per formula unit based on 22 oxygens

| Anion/Cation | Hydrothermal | Igneous |
|---|---|---|
| Fe +2 | 2.07 | 2.23 |
| Mn +2 | 0.01 | 0.01 |
| Si +4 | 5.75 | 5.54 |
| Al +3 | 2.61 | 2.47 |
| Mg +2 | 3.08 | 2.87 |
| K +1 | 1.94 | 1.93 |
| Ti +4 | 0.18 | 0.51 |
| Ca +2 | 0.02 | 0.00 |
| Na +2 | 0.03 | 0.03 |
| F −1 | 0.22 | 0.32 |
| Cl −1 | 0.03 | 0.04 |

biotite. Furthermore, igneous biotite is a deep pleochroic brown, whereas hydrothermal biotite is paler brown to olive green.

The compositional nature of biotite was investigated using the electron microprobe (Stanley and DeLong, 1993; Table 1). Igneous and hydrothermal biotite also are compositionally distinct. More titanium is present in igneous than in hydrothermal biotite. Two populations of fluorine are present in igneous biotite. Higher-fluorine biotite is present in less altered monzonite near the core of the MBX stock, whereas lower-fluorine biotite is present in altered and mineralized monzonite. In hydrothermal biotite, higher-fluorine concentrations are present where the precursor mineral was hornblende.

The composition of the biotite varies with an increase in the chlorite component in the gold-rich, copper-poor 66 zone. The Fe/(Fe + Mg) ratio of biotite is related to the chlorite component and corresponds roughly to the gold content; high and low Fe/(Fe + Mg) ratios correspond to high and low gold assays.

Pervasive hydrothermal K-feldspar alteration is responsible for

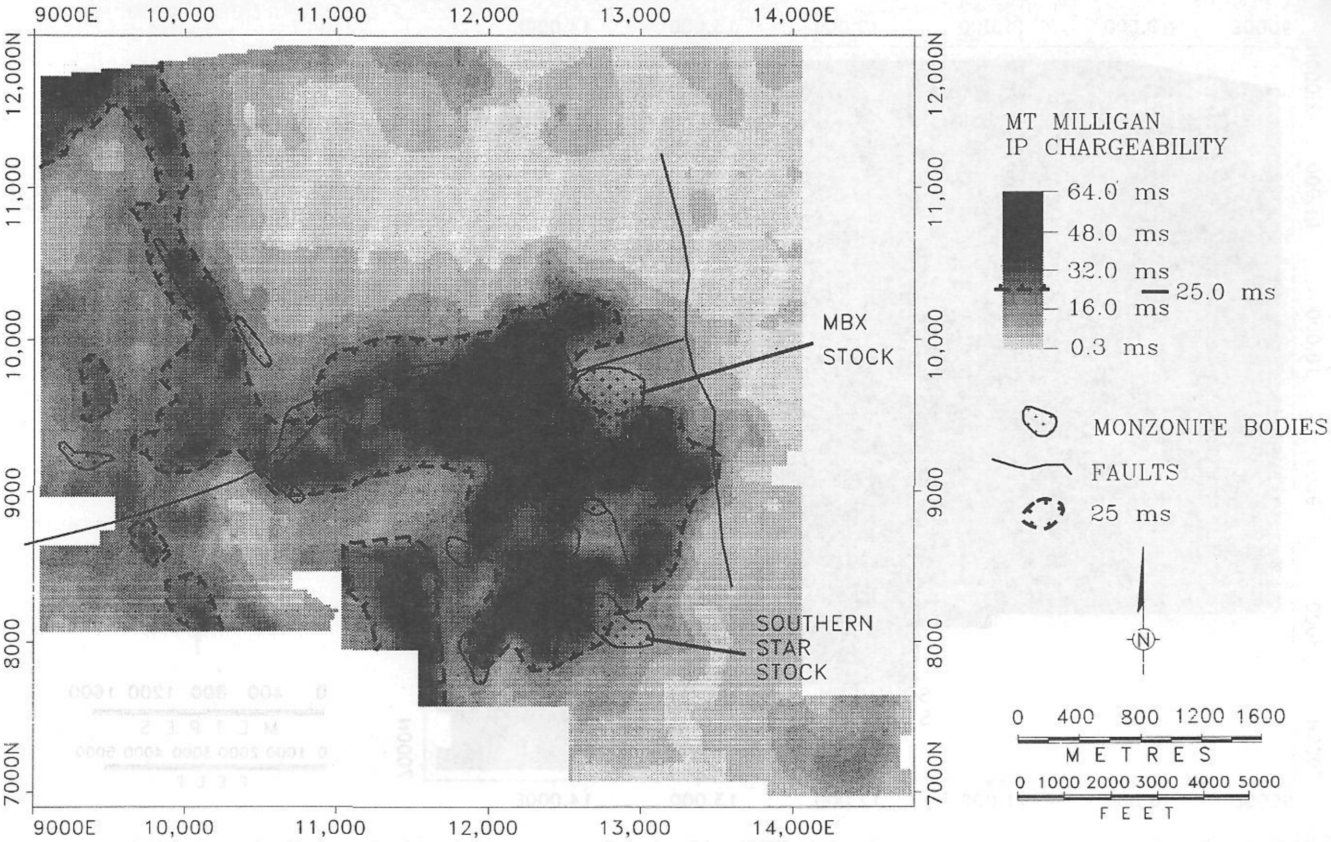


**FIGURE 8. IP chargeability: An extensive sulphide halo is associated with the Main and Southern Star deposits around the MBX and Southern Star stocks, and mineralization around the Goldmark and North Slope stocks. Mineralization on the northeast side of the MBX stock is masked by thick overburden. Northwesterly-trending anomalies are related to sulphide-rich sedimentary rocks.**

the field classification of volcanic andesite to basalt as latitic and trachytic volcanic rocks in the Mt. Milligan Main deposit area. K-feldspar, although more widespread than biotite, is developed erratically. It is associated with copper and gold, but less clearly than biotite. In latitic rocks, K-feldspar occurs as veinlets and envelops along fractures, and as a patchy to pervasive fine-grained greyish to pinkish aphanitic groundmass that obliterates magmatic textures (Fig. 12E). Veinlets commonly contain accessory quartz and minor calcite. Relict augite phenocrysts, replaced by actinolite and calcite, are present locally. In trachytic rocks, intense pervasive K-feldspar alteration occurs in the more permeable tuff beds. In andesitic rocks, which host the Southern Star stock, K-feldspar alteration is mostly fracture-controlled. It occurs around fractures and in veinlets that are generally close to intrusive contacts. Pervasive K-feldspar replacement of the groundmass is uncommon.

K-feldspar alteration is restricted generally to the outer margins of the monzonitic rocks and is similar to that in the volcanic rocks except for its greyish-pink colour. The most intense areas of alteration occur in the Mt. Milligan Main deposit, particularly at the contact of the Rainbow dike with the MBX stock.

## Sericitic Alteration

In the MBX and Southern Star stocks and the Rainbow dike, plagioclase phenocrysts are pale green and are replaced by saussserite, aggregates of sericite, epidote, chlorite and calcite. Minor sericite occurs in K-feldspar and quartz veinlet selvages in the Esker zone. This plagioclase-specific alteration appears to be pervasive and is not related obviously to fracture permeability.

## Propylitic Alteration

Propylitic alteration occurs as a widespread zone that is peripheral to, but locally cross-cuts, and sometimes overlaps potassically-altered rocks. It is characterized by epidote, albite, calcite, chlorite, and pyrite (Figs. 9, 10, 11 and 12D) and is developed best in andesitic and latitic volcanic rocks. Most areas that did not undergo potassic alteration are characterized by minerals of the propylitic assemblage. Propylitization extends up to 2 km from the monzonite stocks.

Epidote, the most common and widespread propylitic mineral, is generally associated with pyrite. It occurs in narrow alteration envelopes around fractures and pyrite-calcite veins, or as veinlets with chlorite and calcite. Epidote also is present as irregular aggregates in the groundmass and medium-grained clots that nucleate commonly on mafic phenocrysts. The clots are roughly circular and are zoned concentrically with pyrite and minor chalcopyrite, epidote and epidote intergrown with albite and calcite. Magnetite is present in the cores of some clots. Where epidote occurs with potassic alteration, it generally overprints and cross-cuts the potassic minerals.

Chlorite, although most common in the propylitic zone, also occurs sporadically in the potassic zone. It occurs on the edges of pyrite grains, replacing mafic grains after primary biotite and hornblende in the groundmass of monzonite, and in tectonically disrupted zones.

Albite forms fine-grained, creamy white irregular patches in the groundmass of volcanic rocks. It is present in the 66 zone with potassic and propylitic alteration, and in the MBX zone with potassic alteration. Albite is sometimes intergrown with minor epidote, although generally the two do not occur together in trachytic volcanic rocks.

Calcite occurs mainly as a replacement of the groundmass in volcanic rocks or as replacement of actinolite, which is a pseudomorph of augite. It also occurs in clots and veinlets with epidote, chlorite and pyrite in latitic and andesitic volcanic rocks. In trachytic volcanic rocks, calcite occurs in clots with chlorite and pyrite.

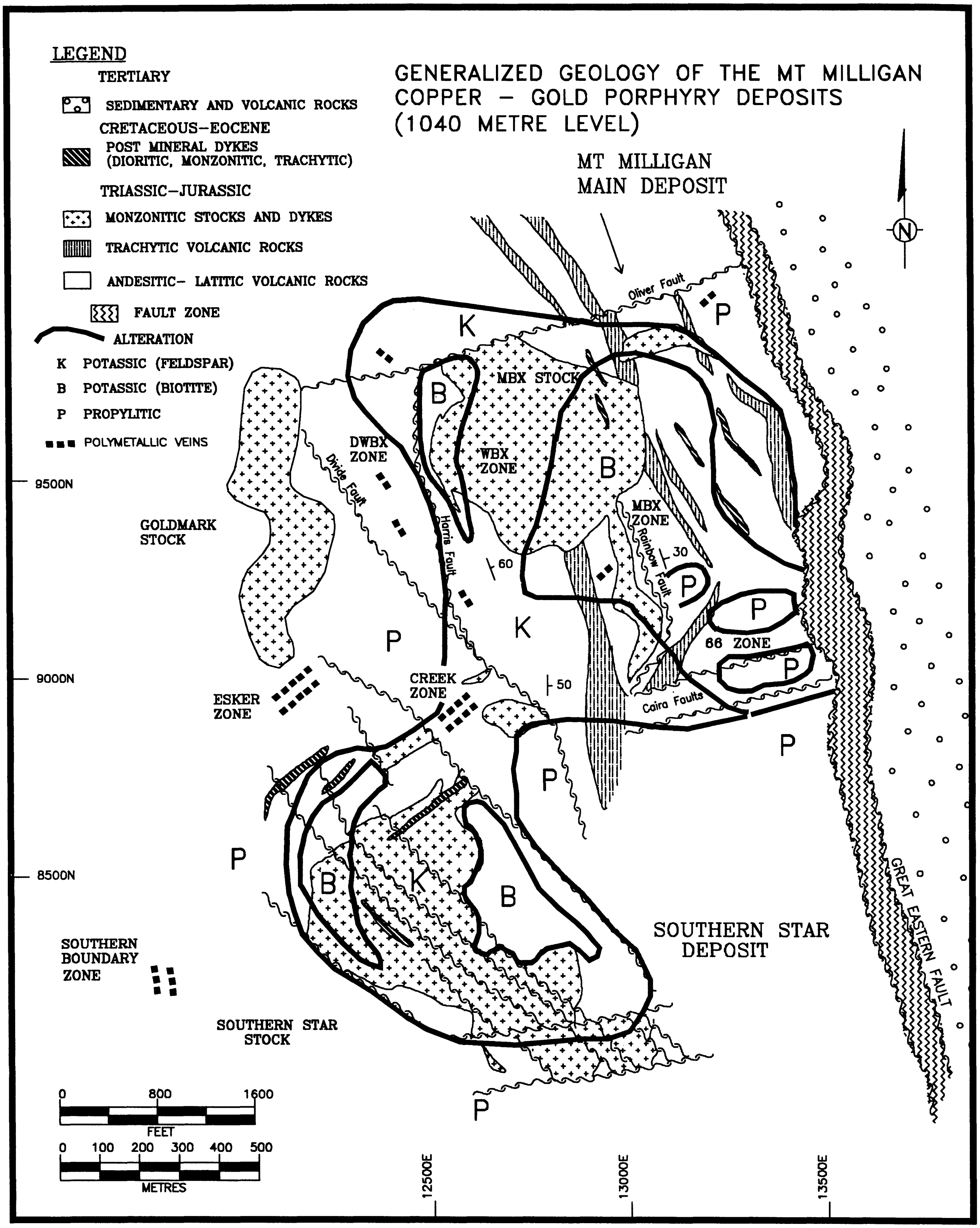


FIGURE 9. Generalized geology of the Mt. Milligan copper-gold porphyry deposits (1040 metre level): The Main and Southern Star deposits are associated with the MBX and Southern Star stocks. In the central portions of the deposits, subzones of biotite alteration occur in potassic alteration, which are surrounded by propylitic alteration in the outer portions of the deposits. Polymetallic veins are developed at the boundary of the potassic alteration and in the propylitic alteration around the periphery of the deposits.

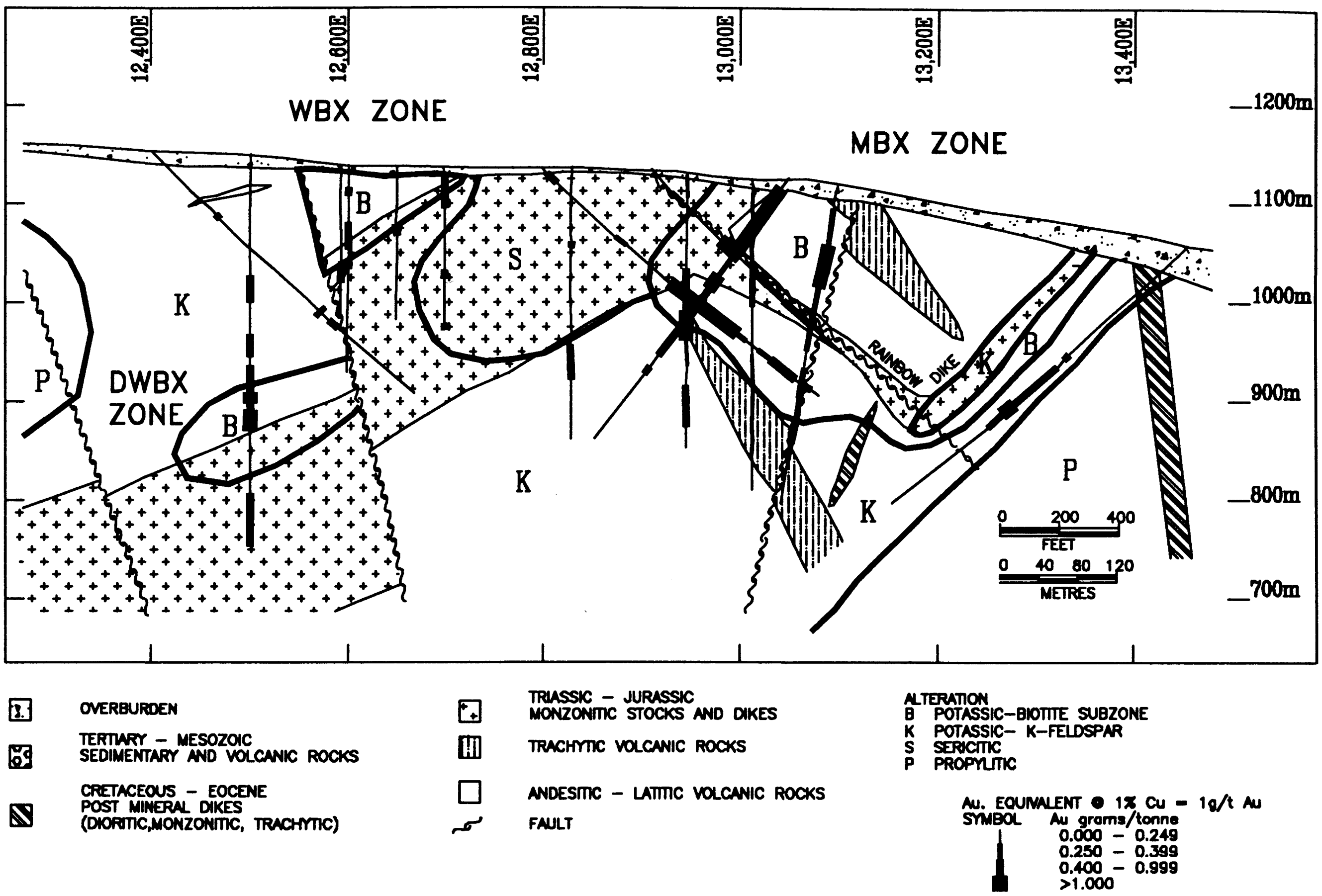


**FIGURE 10. Generalized geology Mt. Milligan Main deposit (Section 9500N): Higher grade copper-gold mineralization is associated with biotite alteration in the MBX zone adjacent to the footwall contact of the MBX stock at the Rainbow dike, and in the WBX zone at the hangingwall contact of the MBX stock.**

### Carbonate Alteration

Calcite and ankerite veinlets cut all rock types and alteration assemblages. The ankerite veins are commonly associated with major structures that locally contain tectonic breccias with a carbonate matrix.

### Albite Alteration Pipes

In the core of the MBX and 66 zones, albite forms pipe-like bodies with gold contents an order of magnitude higher than the average for these zones. These pipes cross-cut potassic and propylitic assemblages (Fig. 12F) and are, therefore, later than the main mineralizing event.

## Hypogene Mineralization

Mineralization in the Mt. Milligan Main deposit comprises four coalescing zones: MBX, 66, WBX and DWBX (Figs. 9 and 10). The MBX zone is in the central part of the deposit, where the Rainbow dike protrudes from the footwall of the MBX stock. The MBX zone contains gold and copper mineralization that grades laterally southeastward into the gold-rich, copper-poor 66 zone, which surrounds the southern half of the Rainbow dike. The WBX zone and its down-faulted extension, the DWBX zone, are located in the northwestern portion of the deposit. Both occur along the hangingwall of the MBX stock, and contain copper and gold associated with quartz veinlets. The WBX and DWBX zones contain high concentrations of quartz veins and much less disseminated chalcopyrite relative to other zones of the deposit.

The copper and gold mineralization in the Southern Star deposit occurs in the hangingwall and footwall of the Southern Star stock and in the adjacent volcanic rocks (Figs. 9 and 11). Sulphides, in particular pyrite, are less abundant in the Southern Star than in the Main deposit.

Mineralization in both deposits consists mostly of pyrite, chalcopyrite, lesser magnetite, minor bornite and traces of molybdenite in potassic alteration, and pyrite in propylitic alteration. In potassic alteration, the best mineralization is developed in monzonite and volcanic rocks adjacent to the footwall and, to a lesser extent, the hangingwall contacts of the stocks. The Rainbow dike and the enclosing volcanic rocks are mineralized also. Copper and gold grades generally decrease with distance from the intrusions, closely paralleling the relative intensity of potassic alteration. In areas of propylitic alteration, pyrite concentrations are highest adjacent to the potassic zone and generally decrease outward from the stocks.

### Chalcopyrite

Chalcopyrite is an integral component of potassic alteration and is most abundant in the biotite subzone where it is present with pyrite, bornite and gold in K-feldspar and quartz veinlets. A decrease in chalcopyrite content occurs with increasing distance from intrusive contacts.

Chalcopyrite occurs mostly as fine disseminated grains and fracture fillings (Fig. 12G), and less commonly as veinlets and other veinlets of calcite, pyrite and lesser quartz and K-feldspar with chalcopyrite selvages. Disseminated grains commonly are present in biotite-rich envelopes around veins. Adjacent to the MBX stock, chalcopyrite is accompanied locally by pyrite, forming coarse sulphide aggregates. Chalcopyrite-bearing veins contain pyrite and magnetite in a gangue of K-feldspar, quartz and calcite. In massive trachytic volcanic rocks, chalcopyrite accompanies pyrite along curvilinear partings and as disseminated grains.

Chalcopyrite also occurs in gold-rich quartz veinlets in the WBX and DWBX zones and Southern Star deposit. Minor K-feldspar

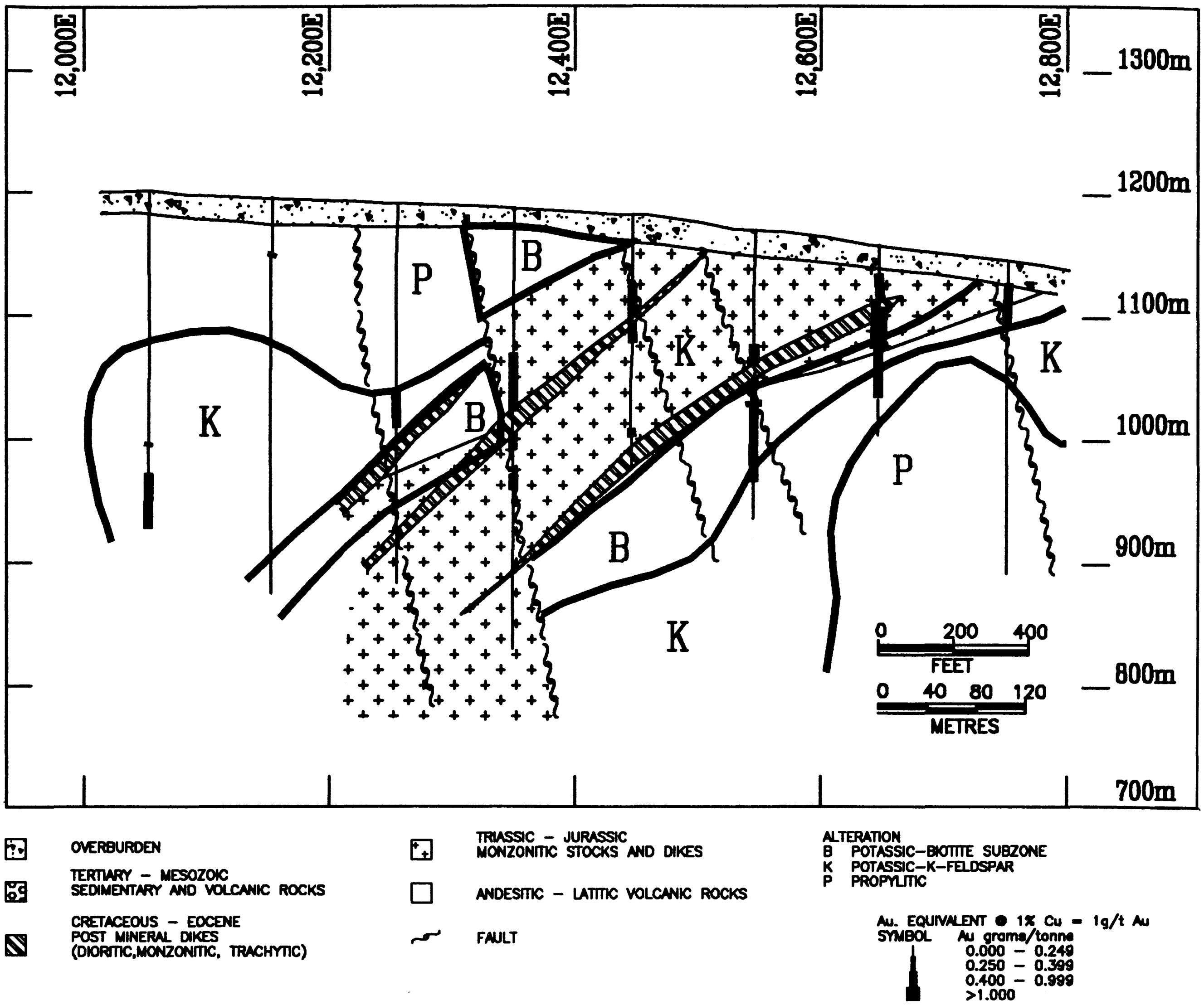


**FIGURE 11. Generalized geology Mt. Milligan Southern Star deposit (Section 8650N): Higher grade copper-gold mineralization is associated with biotite alteration adjacent to the footwall and hangingwall contacts of the Southern Star stock.**

envelopes are associated with these veins, which contain more quartz than other veins on the property. In the Southern Star deposit fracture-controlled mineralization is more important than at the Mt. Milligan Main deposit.

## Magnetite

Magnetite is present throughout the potassic alteration zone and is less common in propylitic alteration. It occurs as disseminated grains, patches, and in veinlets and hydrothermal breccia matrix. A magnetite breccia that occurs in the MBX zone comprises 50% massive magnetite as stockwork veins along the footwall contact of the MBX stock. Disseminated magnetite is most common in biotite-rich rocks. Veinlets with magnetite contain subordinate pyrite, chalcopyrite, K-feldspar, calcite and native gold. In the core of the MBX zone, some of the massive magnetite veins carry gold contents up to 237 g/t. Trachytic rocks contain magnetite-rich laminae. In all but the 66 zone, relative magnetite abundance is related crudely to gold and copper content.

## Bornite

Bornite is present exclusively in potassically-altered volcanic rocks as blebs and disseminated grains in lens-shaped zones close to the footwall contacts of the MBX and Southern Star stocks. K-feldspar veinlets are common in these areas. Bornite is associated with higher gold concentrations (Fig. 15). In contrast, pyrite is rarely associated with bornite.

## Pyrite

Pyrite is the most widespread sulphide in and around the deposits. Pyrite content increases sharply from potassic to propylitic alteration, where it is most abundant and forms a crude halo adjoining the potassic zone (DeLong, 1993). Pyrite occurs as disseminated grains, veinlets, vein selvages, large clots, patches, blebby aggregates and as a partial to complete replacement of mafic minerals such as actinolite and/or augite. It is commonly found with calcite. In the 66 zone, gold is associated with 5% to 20% coarse pyrite. Several generations of pyrite veinlets are indicated by cross-cutting relationships. Pyrite occurs also as a minor constituent of veins in potassically-altered rocks. In trachytic rocks, pyrite occurs with chalcopyrite in curvilinear partings.

## Gold

Gold is present as grains ranging in size from less than 5 microns up to 100 microns. The grains fill microfractures in sulphides, adhere to imperfections on chalcopyrite and pyrite grains, and occur as inclusions in pyrite, chalcopyrite and magnetite. Gold that is visible in hand samples is associated with bornite and less commonly massive magnetite.

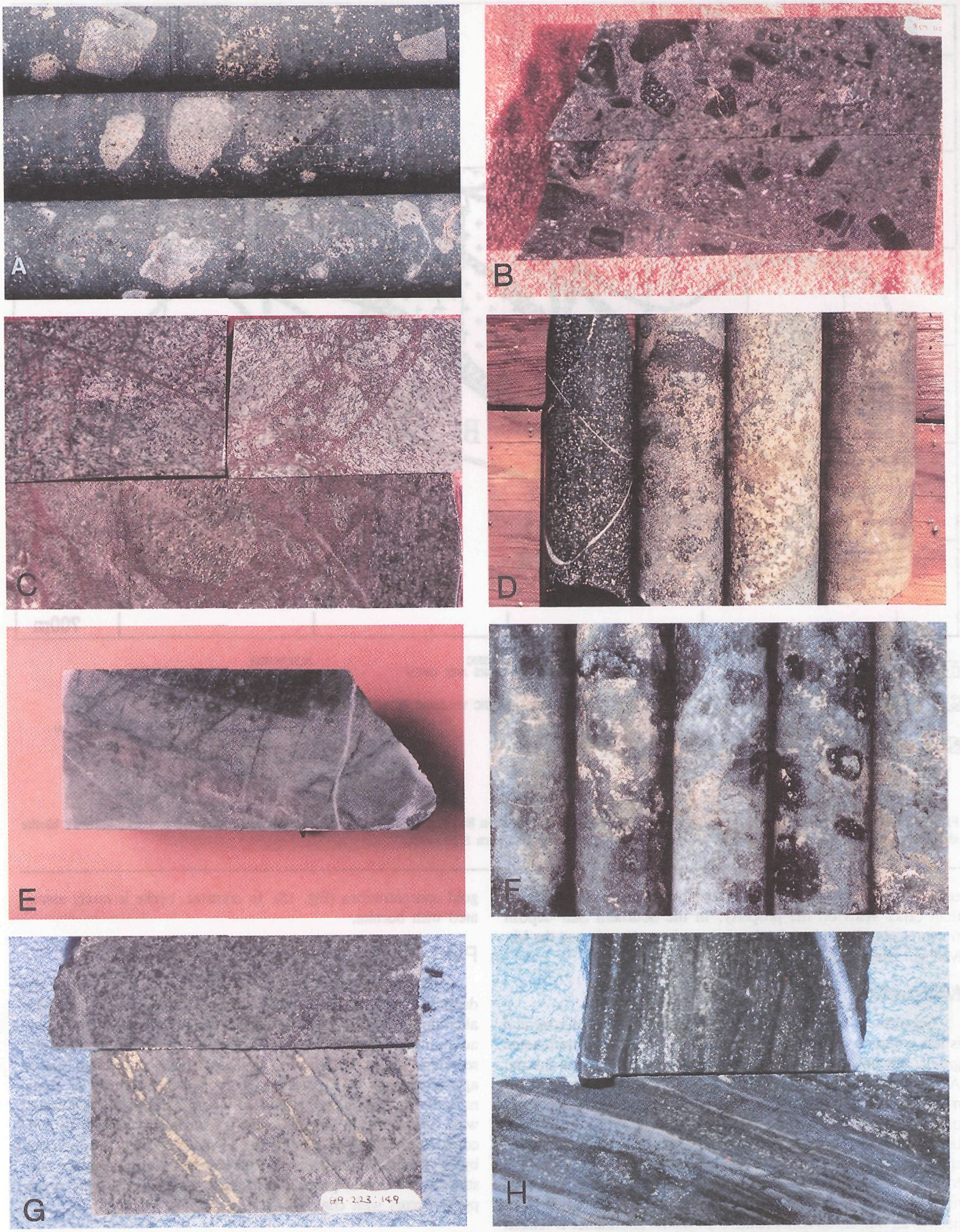


**FIGURE 12. (A) Heterolithic debris flow in the Witch Lake Formation of the Takla Group; (B) MBX stock - monzonite intrusion breccia containing clasts of an earlier monzonite and volcanic rock; (C) Southern Star stock - monzonite intrusion breccias; (D) Alteration types - from left to right are biotite-rich subzone, K-feldspar and biotite potassic alteration, propylitic alteration, and epidote-rich propylitic alteration; (E) K-feldspar envelope around a K-feldspar veinlet that overprints hydrothermal biotite alteration in latitic volcanic rocks adjacent to the MBX stock; (F) Albite and epidote alteration pipe overprinting hydrothermal biotite-altered latitic volcanic rocks in the core of the MBX zone (drill hole 84); (G) MBX stock - (upper) disseminated chalcopyrite in weakly altered core of stock; (lower) fracture-hosted chalcopyrite in K-feldspar-altered periphery of stock; (H) Bedded trachytic volcanic rocks with disseminated pyrite.**

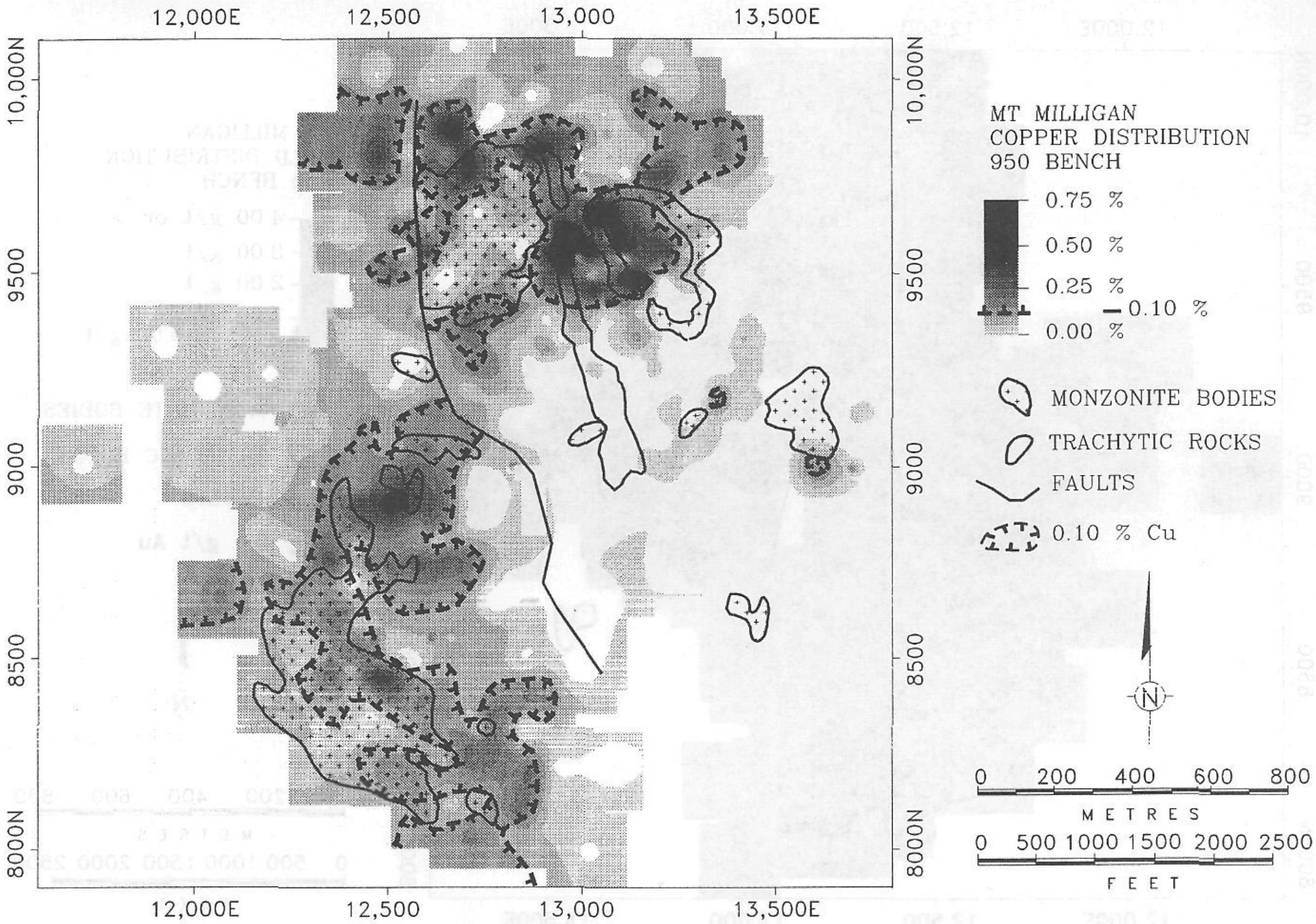


**FIGURE 13. Copper distribution (950 m bench): Elevated copper contents occur around the MBX stock and the western portion of the Rainbow dike adjacent to their contacts, and adjacent to the footwall of the Southern Star stock.**

## Supergene Alteration

Supergene alteration, comprising clay and limonite, is recognized in the MBX and WBX zones, and Southern Star deposit. Glaciation has eroded most of the supergene-altered material, leaving only remnants. These remnants are deeper and more extensive in the MBX and WBX zones than in the Southern Star deposit. In the MBX and WBX zones, weak supergene alteration is approximately 20 m thick over some of the area, and locally is up to 60 m thick. Supergene copper mineralization is developed sporadically *and does not constitute a well-defined zone. There is no copper* enrichment.

Supergene minerals consist of sulphides (covellite, chalcocite and djurleite), oxides (cuprite and tenorite), carbonates (malachite and azurite) and native copper. The sulphides occur as rims around chalcopyrite. Oxides, in particular cuprite, occur as surface coatings on native copper.

Supergene copper sulphide minerals occur commonly with iron oxides (limonite, magnetite and hematite) and iron carbonate (siderite), particularly where malachite and azurite are present. Limonite either completely replaces sulphide minerals or occurs as coatings on surfaces of fractures and hairline cracks.

## Polymetallic Veins

Gold-silver-bearing veins occur in volcanic rocks adjacent to the MBX and Southern Star stocks and cross-cut previously developed propylitic alteration. These polymetallic veins are developed at the boundary of the potassic alteration zone and within the propylitic alteration zone. Most of the veins occur in the Creek and Esker zones, but they are widely distributed around the entire periphery of the Mt. Milligan deposits. The veins comprise sulphide-rich and carbonate-quartz-rich types; most are structurally controlled and generally strike east-northeast.

The sulphide-rich veins are hosted by andesitic volcanic rocks. They contain mostly pyrite with lesser chalcopyrite, sphalerite, galena, molybdenite, arsenopyrite, tetrahedrite-tennantite and gold, and minor amounts of quartz, K-feldspar and carbonate gangue. K-feldspar alteration envelopes are well-developed around some of the polymetallic veins that in turn are enclosed by intense propylitization.

The carbonate-quartz-rich veins occur in propylitized latitic volcanic rocks northwest and northeast of the MBX stock. They contain pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, tetrahedrite, magnetite, ilmenite and hematite in a gangue of quartz, carbonate, chlorite and K-feldspar. Scanning electron microscope work with an analyzer (McIntosh, 1990) showed that the tetrahedrite is silver-bearing.

## Metal Zoning

### Copper and Gold Distribution

Higher copper grades are related to chalcopyrite abundance, which generally is greatest near the margins of the MBX and Southern Star stocks. Highest copper concentrations occur as a halo to the MBX stock and along the footwall of the Southern Star-stock (Fig. 13).

The distribution of gold generally corresponds to that of copper, with several important differences (Fig. 14). Gold concentrations are highest near the margins of the MBX and Southern Star stocks where concentrations of chalcopyrite are greater or bornite is present. However, in the 66 zone, which has the highest gold

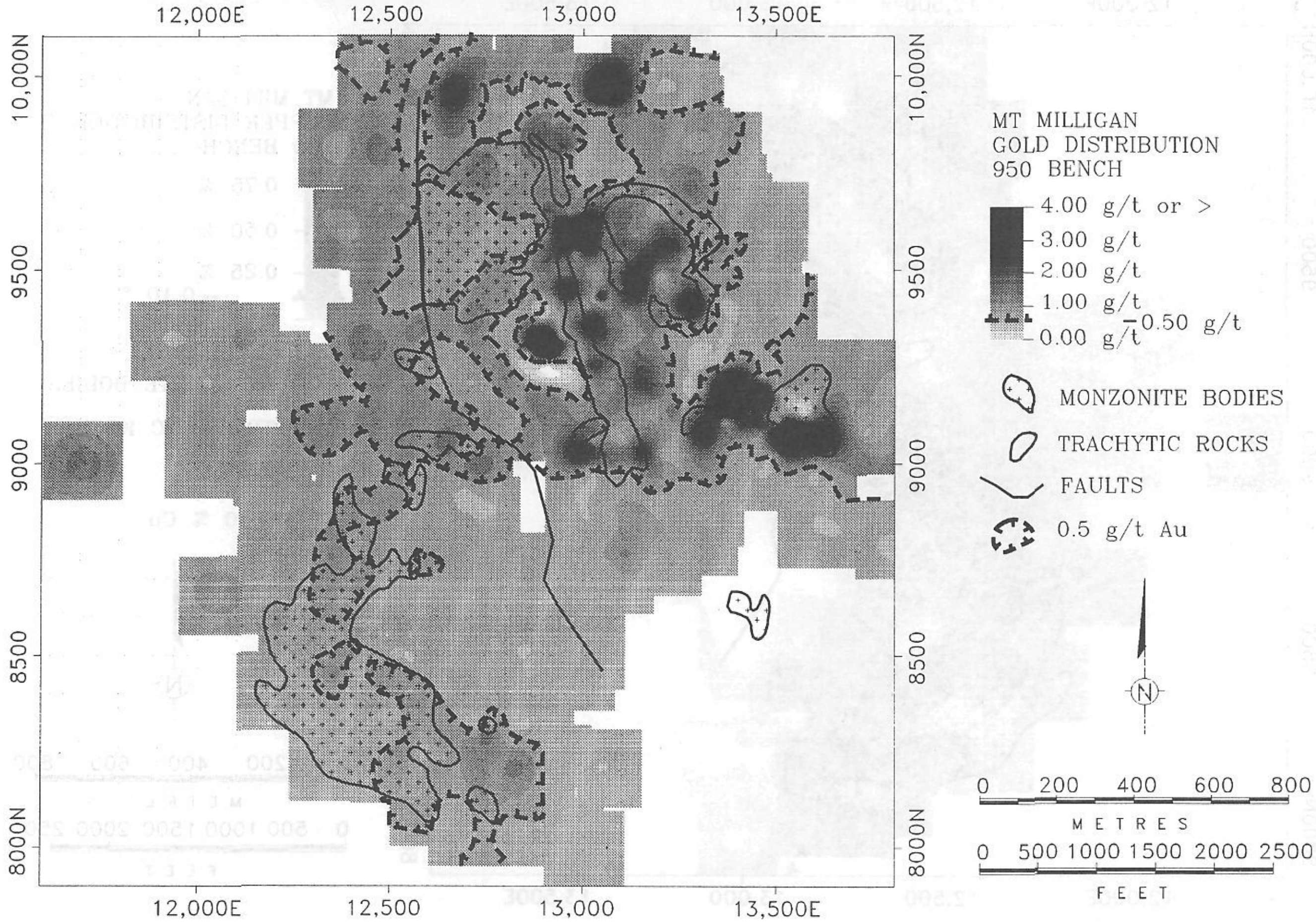


**FIGURE 14. Gold distribution (950 m bench): Strongly elevated gold contents occur around the Rainbow dike and trachytic rocks distal to the MBX stock. Weakly elevated gold contents occur around, but away from, the MBX stock and adjacent to the footwall of the Southern Star stock.**

grades, chalcopyrite is sparse and pyrite is abundant. There, higher gold grades coincide with zones containing clots of pyrite, carbonate and chlorite. Generally, gold concentrations around the Southern Star stock are lower than around the MBX stock where they have a much broader distribution extending to the gold-rich 66 zone.

Generally low Au:Cu ratios (g/t:%) in the order of 1:1, occur in the Southern Star deposit. Higher ratios in the order of 2:1 occur away from the MBX stock. The high Au:Cu ratios in the 66 zone are due to the higher gold concentrations and much lower copper grades.

In summary, copper-gold mineralization forms a central core around the MBX and Southern Star stocks, whereas gold-only, or copper-poor, mineralization characterizes the outer portion of the Mt. Milligan system. Anomalously high lead, zinc, and silver contents are present in a discontinuous zone outside the copper-gold mineralization of the MBX, WBX, and DWBX zones, but within the 66 zone (DeLong, 1993).

## Gold Fineness

The fineness of gold {(Au/(Au+Ag))x1000} was determined for samples selected throughout the Mt. Milligan system. Results indicate that two populations are present: higher fineness gold (850-950) in the porphyry deposits, and lower fineness gold (700-800) in peripheral silver-bearing veins (D. Harris, pers. comm., 1990).

## Discussion

The Mt. Milligan intrusions, which include the MBX and Southern Star stocks, are aligned along a north-northwesterly trending belt. This suggests that their emplacement may have been controlled by an undefined regional structure. A rotation of the easterly-dipping trachytic rocks in the MBX and 66 zones to a subhorizontal position indicates that the stocks were probably nearly vertical when they were emplaced. This rotation would place the Southern Star stock at a lower elevation than the MBX stock. The hydrothermal system that formed the Mt. Milligan deposits is believed to have developed contemporaneously with or soon after emplacement of the stocks and the Rainbow dike as manifested by the presence of hydrothermal breccias.

In the Southern Star deposit the intrusions and hydrothermal system are laterally constrained, which is interpreted as being dominated by structural control. These structures are manifested by: the tabular shape of the Southern Star and Goldmark stocks; the restricted occurrence of potassic alteration in and immediately adjacent to the stock; and the dominance of vein and fracture filling over disseminated sulphides.

The intrusions and hydrothermal system spread laterally in the Mt. Milligan Main deposit area and are interpreted to have been controlled by stratigraphy. This is shown by: the alignment of the Rainbow dike subparallel to bedding; the intense potassic alteration along permeable volcanic beds (trachytic units); the large lateral extent of potassic alteration; and the predominance of copper and gold in the volcanic units adjacent to the MBX stock, which grades laterally to gold well away from the stock.

## Conclusions

The key feature that allowed the Mt. Milligan Main deposit to attain its larger size is the intersection of the MBX stock and the protruding Rainbow dike with a permeable stratigraphic interval, which permitted hydrothermal fluids to move laterally. This resulted in the development of the large proximal copper-gold-rich MBX zone and the more distal gold-rich 66 zone.

Mineralogical zoning is well-developed within the deposits. A biotite-rich subzone of the potassic alteration zone forms the core of the deposit and is surrounded by a propylitic alteration zone. Most of the copper and gold occurs in the biotite-rich subzone. The composition of biotite in the biotite subzone varies and the proportion of the chlorite component in biotite is higher in the gold-rich, copper-poor 66 zone peripheral to the Mt. Milligan Main deposit. Iron-rich biotite, which is due to the chlorite component, is associated with elevated gold values.

## Acknowledgments

The authors acknowledge the contributions of R. Haslinger, B. Bower, N. Caira, R. Farmer, M. Harris, J. Oliver, E. Titley, C. Godwin and the many other geologists affiliated with Pechiney Development Ltd., Selco Inc., BP Resources Canada Limited, Lincoln Resources Inc., United Lincoln Resources Inc., Continental Gold Corp., Placer Dome Inc., the Geological Survey of Canada, the Geological Survey Branch of the British Columbia Ministry of Energy, Mines and Petroleum Resources, and the Mineral Deposit Research Unit at The University of British Columbia who contributed to the exploration and understanding of the Mt. Milligan deposits.

A second group, who so often are overlooked, are those who raised the financial resources that allowed the geological group to continue their work through the discovery and delineation stages. These include D. Copeland, R. Dickinson, D. Forster, J. Franzen and R. Hunter.

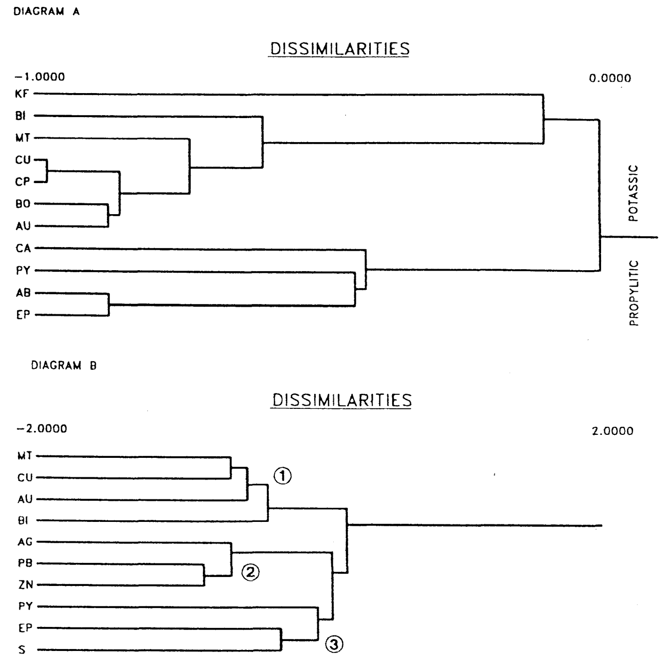


**FIGURE 15. Tree diagram (dendrogram) with mineral and element associations: Length of horizontal line joining pairs or groups of minerals and elements is inversely proportional to the similarity with which the relative abundances vary. Dendrogram A illustrates the separation of the alteration into potassic and propylitic alteration assemblages. Dendrogram B illustrates trace element geochemistry associations. Increased amounts of magnetite and biotite are strongly associated with elevated copper and gold concentrations; silver, lead, and zinc are strongly associated; and increased amounts of pyrite and epidote are strongly associated with sulphur concentrations. The first association reflects copper-gold mineralization and potassic alteration; the second the transition between the potassic and propylitic zones where the polymetallic veins are (Esker and Creek vein systems); and the third, propylitic alteration.**

## REFERENCES

DeLONG, R.C., GODWIN, C.I., HARRIS, M.W.H., CAIRA, N.M., and REBAGLIATI, C.M., 1991. Geology and alteration at the Mt. Milligan gold-copper deposit. *In* Geological Fieldwork 1990. British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991-1.

DeLONG, R.C., 1993. Metal zonation, alteration mineral distribution, and possible exploration parameters at the Mt. Milligan copper-gold project. *In* Copper-Gold Porphyry Systems of British Columbia. Annual Technical Report, Year Two, July 1992 - June 1993. The University of British Columbia, Mineral Deposit Research Unit, Vancouver, British Columbia.

GEOLOGICAL SURVEY OF CANADA, 1963. Aeromagnetic Series, Map 1584G, Wittsichica Creek, B.C., 93N/1.

GEOLOGICAL SURVEY OF CANADA, 1992. Airborne Geophysical Survey of the Mount Milligan Area, British Columbia, September 1991, Open File 2435.

GHOSH, D., 1992. Isotope geochemistry. *In* Copper-Gold Porphyry Systems of British Columbia, Annual Technical Report, Year One, July 1991 - June 1992, The University of British Columbia, Mineral Deposit Research Unit, Vancouver, British Columbia.

HOLLAND, S.C., 1976. Landforms of British Columbia: A physiographic outline. British Columbia Department of Energy, Mines and Petroleum Resources, Bulletin 48.

LANG, J.M., 1992. Geochemistry of igneous rocks in the Mount Milligan District. *In* Copper-Gold Porphyry Systems of British Columbia. Annual Technical Report, Year One, July 1991 - June 1992. The University of British Columbia, Mineral Deposit Research Unit, Vancouver, British Columbia.

MCINTOSH, A., 1990. Opaque Mineralogy of some parts of the Mt. Milligan Deposit. Unpublished report, Geology 438 Project, The University of British Columbia, Vancouver, British Columbia.

MONGER, J.W.H., WHEELER, J.O., TIPPER, H.W., GABRIELSE, H., HARMS, T., STRUIK, L.C., CAMPBELL, R.B., DODDS, C., GEHRELS, G.E. and O'BRIAN, J., 1991. Part B. Cordilleran Terranes. *In* Upper Devonian to Middle Jurassic Assemblages, Chapter 8 of Geology of the Cordilleran Orogen in Canada. *Edited by* H. Gabrielse and C.J. Yorath. Geological Survey of Canada, Geology of Canada, No. 4, p. 281-327 (also Geological Society of America, The Geology of North America, V. G-2).

MORTIMER, N., 1987. Late Triassic arc related potassic igneous rocks in the North American Cordillera. Geology, 14, p. 1035-1038.

NELSON, J., BELLEFONTAINE, K., GREEN, K. and MACLEAN, M., 1991. Regional geological mapping near the Mt. Milligan copper-gold deposit (93K/16, 93N/1). *In* Geological Fieldwork 1990. British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991-1.

NELSON, J., BELLEFONTAINE, K., REES, C. and MACLEAN, M., 1992. Regional geological mapping in the Nation Lakes area (93N/2E,7E). *In* Geological Fieldwork 1991. British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1992-1.

PLACER DOME INC., 1992. Unpublished company report, Placer Dome Inc.

REBAGLIATI, C.M., 1983. Summary Report, Phil Copper-Gold Porphyry Project, Nations Lakes Region, Central British Columbia. Unpublished company report, Selco Inc.

REBAGLIATI, C.M., 1990. Continental Gold Corp. Summary Report, Mt. Milligan Project, Omineca Mining Division, British Columbia, Canada. Statement of Material Facts and Prospectus report, Continental Gold Corp., February 28, 1990.

REBAGLIATI, C.M., HARRIS, M.W. and CAIRA, N.M., 1990. Interim Geological Report, Mt. Milligan Project. Unpublished company report, Continental Gold Corp.

SKETCHLEY, D.A., 1992. Geology and alteration of the Mt. Milligan copper-gold porphyry deposit. *In* Porphyry Copper Model Case Studies and Regional Settings. Northwest Mining Association Short Course, December 1992.

STANLEY, C.B. and DeLONG, R.C., 1993. A crystal chemical analysis of hydrothermal biotite from the MBX and 66 zones, Mt. Milligan copper-gold porphyry deposit. *In* Copper-Gold Porphyry Systems of British Columbia. Annual Technical Report, Year Two, July 1992 - June 1993, The University of British Columbia. Mineral Deposit Research Unit, Vancouver, British Columbia.