

Geological setting of Late Triassic porphyry Cu-Au mineralization at Miner Mountain, Princeton, southern British Columbia

Mitchell G. Mihalynuk^{1,a} and James M. Logan¹

¹ British Columbia Geological Survey, Ministry of Energy, Mines and Natural Gas, Victoria, BC, V8W 9N3

^a corresponding author: Mitch.Mihalynuk@gov.bc.ca

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Abstract

Porphyry copper style mineralization at Miner Mountain is associated with dioritic intrusions in a predominantly sedimentary arc flank setting, not a predominantly volcanic arc axial setting as has commonly been assumed. It is generally difficult to distinguish epiclastic and pyroclastic (or even flow) units, particularly where altered. Nonetheless, argillaceous beds, limestone layers, and local rounding of clasts in arenites indicate a significant epiclastic component. The mixed sedimentary volcanic setting is akin to the Copper Mountain deposit, ~25 km to the south-southwest. Mineralization that has received the most exploration attention is concentrated on the disrupted western flank of an open syncline that mainly plunges gently to the north. Minor folds and faults produce more locally intense deformation zones. Carbonate-quartz-feldspar alteration predates calcite-chalcopyrite-bornite cementation of fragments in diorite breccias. K-feldspar-magnetite alteration is best developed in mineralized rocks, and these display Au, Pt and Pd enrichments, features typical of British Columbian alkalic porphyry deposits.

Keywords: Miner Mountain, alkalic porphyry copper gold, Nicola Group, Quesnel terrane, Late Triassic, potassic alteration, Copper Mountain intrusive suite

1. Introduction

Geological fieldwork conducted between Merritt and Princeton in 2012 (Fig. 1), forms part of an ongoing province-wide porphyry copper project (Logan and Mihalynuk, 2005). Objectives of this project include defining the geological setting and evaluating the structural and stratigraphic controls on porphyry Cu-Au ±Ag-Mo mineralization in Late Triassic and Early Jurassic arc rocks as an aid to mineral resource evaluation and exploration (Logan and Mihalynuk, 2013). Herein we report on a recent component of the project, including geochemistry, petrography, and geochronology at Miner Mountain, in the southern Nicola belt (Fig. 2). In a companion paper (Mihalynuk and Logan, 2013a, this volume) we provide a similar treatment for mineralization in the Dillard Creek camp, about 20 km north of Miner Mountain.

2. Geological setting

Porphyry copper deposits in British Columbia are predominantly of Late Triassic age and belong to two arc terranes, Quesnel and Stikine (Coney et al., 1980), which extend the entire length of the province. These two terranes share Devonian through Triassic histories and fossil faunas indicating an origin far from the influence of North America. They are now separated along most of their length by a belt of even more exotic oceanic rocks, the Cache Creek terrane. At their northern ends, Stikine and Quesnel terranes appear to merge, Cache Creek terrane disappears, and all three terranes are enveloped by

rocks of pericratonic character; a configuration that has led to the “oroclinal hypothesis” (Mihalynuk et al., 1994). Accordingly, Stikine and Quesnel arc terranes were originally linked and were oroclinally folded (in plan, with a hinge to the north) around the exotic Cache Creek oceanic accretionary complex, most of which accumulated at the Stikine and Quesnel arc trenches. Although Quesnel-Stikine porphyry deposits formed throughout the Late Triassic, one class of porphyry deposits, the Cu-Au alkalic type, formed almost entirely during a remarkable metallogenic epoch near the end of the Triassic, at about 204 Ma (Logan and Mihalynuk, 2013). This event has been attributed to collision of an exotic, extinct arc terrane with the Stikine - Quesnel arc complex. Relics of the colliding arc, known locally as the Kutcho terrane, are now found within the Cache Creek complex. Collision of Kutcho terrane is thought to have interrupted subduction of the Cache Creek ocean plate, causing it to rupture. Hot sub-slab mantle welled up into the rupture and melted parts of the overlying Quesnel-Stikine mantle wedge, especially those metasomatized by metal-rich volatiles exsolved from the subducted Cache Creek ocean plate (Mihalynuk, 2010; Logan and Mihalynuk, 2013). Melts derived by roasting of the metasomatized mantle are inclined to be rich in Cu-Au and Pt-Pd elements (e.g., McInnis et al., 2005). Thus, volcanic strata of Latest Triassic age and coeval intrusive rocks are important targets for porphyry Cu-Au exploration. Such rocks are believed to underlie Miner Mountain (also known as Mt. Miner, Allison Mountain,

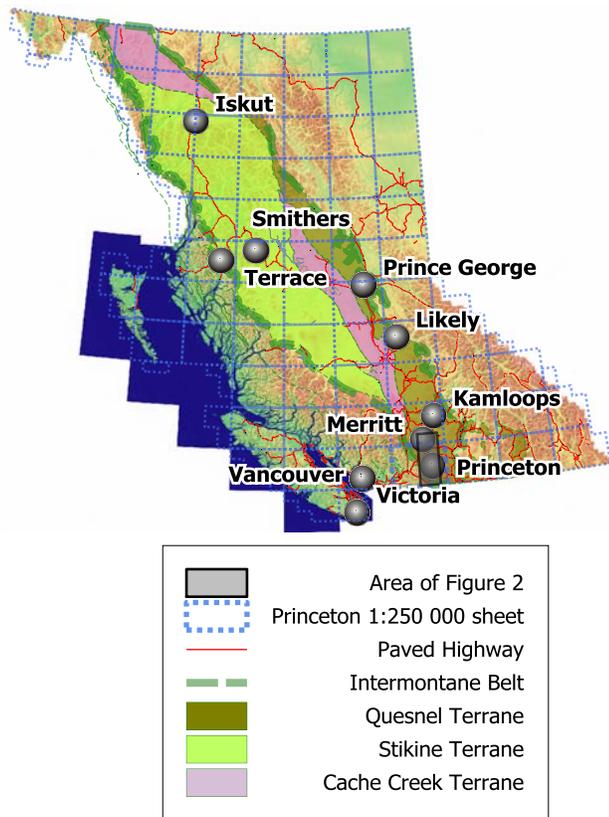


Fig. 1. Tectonic setting of southern Quesnel terrane and study area. Terrane boundaries modified after (Tipper et al., 1981). Area covered by Figure 2 is outlined by transparent grey box.

or Bald Mountain).

Late Triassic Nicola Group arc strata near Princeton are juxtaposed on their west side with Eocene volcanic and sedimentary rocks of the Princeton Basin (Fig. 2). Much of the contact is the north northeast-trending Boundary fault which dips westerly between 45° (Preto, 1979) and 68° (Read, 2000). To the east, the Nicola Group is intruded by the granodioritic Bromley pluton, with an Early Jurassic crystallization age, and to the northeast by the Late Jurassic Osprey Lake intrusion (193 ± 1 Ma and 166 ± 1 Ma respectively; Parrish and Monger, 1992). Approximately 25 km along strike to the south-southwest is the Copper Mountain mine, currently in operation and with past production of more than 650 million kg of Cu, 264 million g Ag and 16 million g Au (MINFILE 092HSE001) and a reported proven and probable reserve of 211 Mt grading 0.36% Cu (Copper Mountain Mining Corporation, 2009). Most mineralization at Copper Mountain is hosted within eastern facies mixed tuffaceous and sedimentary rocks of the Nicola Group (Preto, 1972) and is coeval with intrusive phases between 201 and 205 Ma (Mihalynuk et al., 2010). Mineralization at Miner Mountain is hosted in a potentially correlative volcanosedimentary succession that currently lacks age control. Principal objectives of our field work were to map volcanosedimentary facies

and to sample both volcanic and mineralized intrusive phases for isotopic age determination.

3. Location and access

Miner Mountain property (MINFILE 092HSE203) is on the eastern outskirts of Princeton, about 280 km east of Vancouver, at the junction of highways 3 and 5A. Easy access to the property, only ~5 km from the town's centre, is via an all-season paved and gravel road network to grassy ranchland and a microwave tower. Miner Mountain is a relic of the plateau dissected by the Similkameen River to the south and Allison Creek to the west. Vegetation is sparse, with forested areas of predominantly lodgepole and ponderosa pine, aspen, and fir, and open slopes commonly supporting the growth of prickly pear cacti, owing to the dry climate. With the exception of cliff sections along the incised valleys, the area is easily negotiated by 4x4 vehicles or on foot. Mineralization has been extensively explored in zones southwest, northwest, and north of the Miner Mountain peak.

4. Previous exploration work

Popular mining lore tells of disseminated bornite discovered circa 1914 in diorite at a working face of United Empire Coal Mine's Red Triangle coal deposit on the northwestern flank of Miner Mountain (Dolmage and Campbell, 1963). It is rumoured that as underground mining cut eastward, two coal seams in the Eocene Princeton basin strata were lost at a fault, later named the "Boundary Fault". This west-side-down fault (McMechan, 1983) locally delimits the western flank of the coal-bearing volcano-sedimentary basin, and offsets mineralized Late Triassic rocks towards the surface (Fig. 3). Dismayed by the lack of coal, the miners, who had no interest in the copper they found, abandoned their coal mining effort in 1914, after two years of operation (MINFILE 092HSE218). Most of the coal produced from the Red Triangle deposit is reported to have been sold to British Columbia Portland Cement Company to produce cement from their limestone quarry ~750 m to the south (MINFILE 092HSE169).

Exploration work on Miner Mountain began at least as early as 1905 (Preto, 1975), with the earliest reported assessment work recorded 53 years later (Fahrni, 1958). In 1951, extensive trenching, and diamond drilling by Granby Consolidated Mining, Smelting and Power Co. Ltd. (henceforth "Granby") revealed two disappointing zones of "very low grade" oxidized copper mineralization. As a result, 60 of 66 claims were allowed to revert to the Crown. However, the slopes of Miner Mountain are blanketed in glacial till and alluvium, with less than 1% outcrop (see Fig. 3), so in 1958, Granby conducted magnetic and electromagnetic surveys to look for buried mineralization. Two magnetic spot highs with highly irregular texture were attributed to glacially transported "boulders or slabs of magnetite bearing material which occur close to the surface ..." (p. 17,

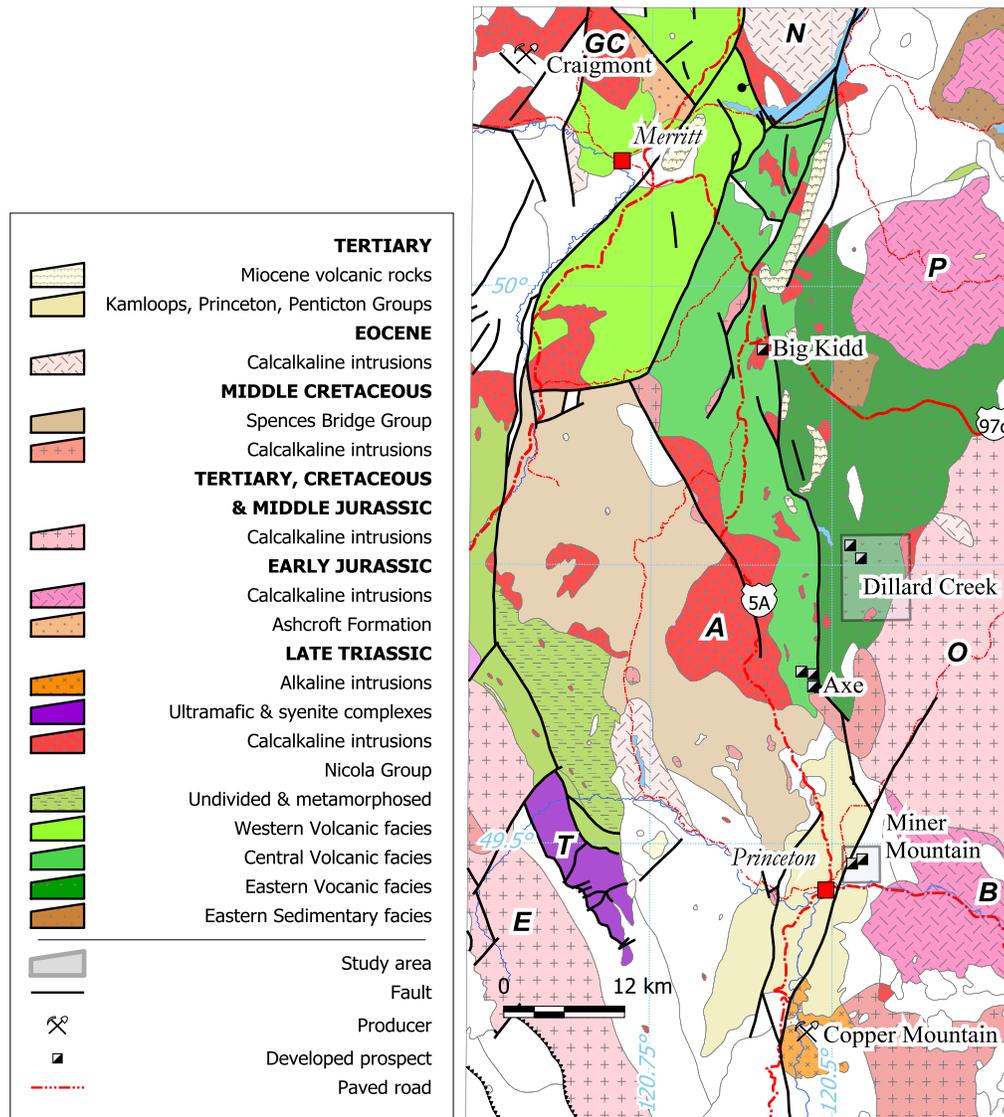


Fig. 2. Geological setting of 2012 field mapping in the Miner Mountain area between Princeton and Merritt. Western, Central and Eastern belts of the Nicola arc as defined by Preto (1979) are shown for reference. Adapted from Massey et al. (2005). Abbreviations denote major plutons: A = Allison Lake, B = Bromley, E = Eagle, GC = Guichon Creek, N = Nicola, O = Osprey Lake, P = Pennask, T = Tulameen.

Fahmi, 1958; Regal 2 claim). Later opinions favoured a gravity slide origin (Dolmage and Campbell, 1963; Preto, 1975; Christopher, 1981; Tribe, 2010) because mineralized blocks of Nicola Group lithologies up to ~10 m across were apparently deposited atop Eocene Princeton Basin strata. Electromagnetic and self potential surveys failed to yield responses that could be unambiguously attributed to in situ mineralization, but weak correlated responses were found south of the old workings (Regal 4 M.C.).

Over the next five decades, work on or adjacent to Miner Mountain included: 1) an aeromagnetic survey by Kennco Explorations (Western) Ltd. (Anderson and Gower, 1959); 2) further geophysical work by Climax Copper Mines N.P.L. (Nicholls and Gregotski, 1963;

Dolmage and Campbell, 1963), Great Slave Mines Ltd. (Cochrane, 1968), and Quintana Minerals Corporation, (Nielsen, 1977); 3) comprehensive exploration, including drilling and construction of an ill-fated copper leaching plant by Joy Mining Ltd. (Taylor, 1988); 4) drilling by Bethlehem Copper Corp. (Taylor, 1988); 5) soil and litho geochemistry (Livingstone, 1981); 6) soil geochemistry by Mingold Resources Inc. (Taylor, 1988; Reynolds, 1990; and Hopper, 1996); and 7) exploration, including drilling, by Golden Kootenay Resources Inc. and Nustar Resources Inc. (McLeod, 2000; McLeod, 2002). Since 2007, a multi-faceted exploration program has been undertaken by Segor! Resources Inc. (Christopher, 2012).

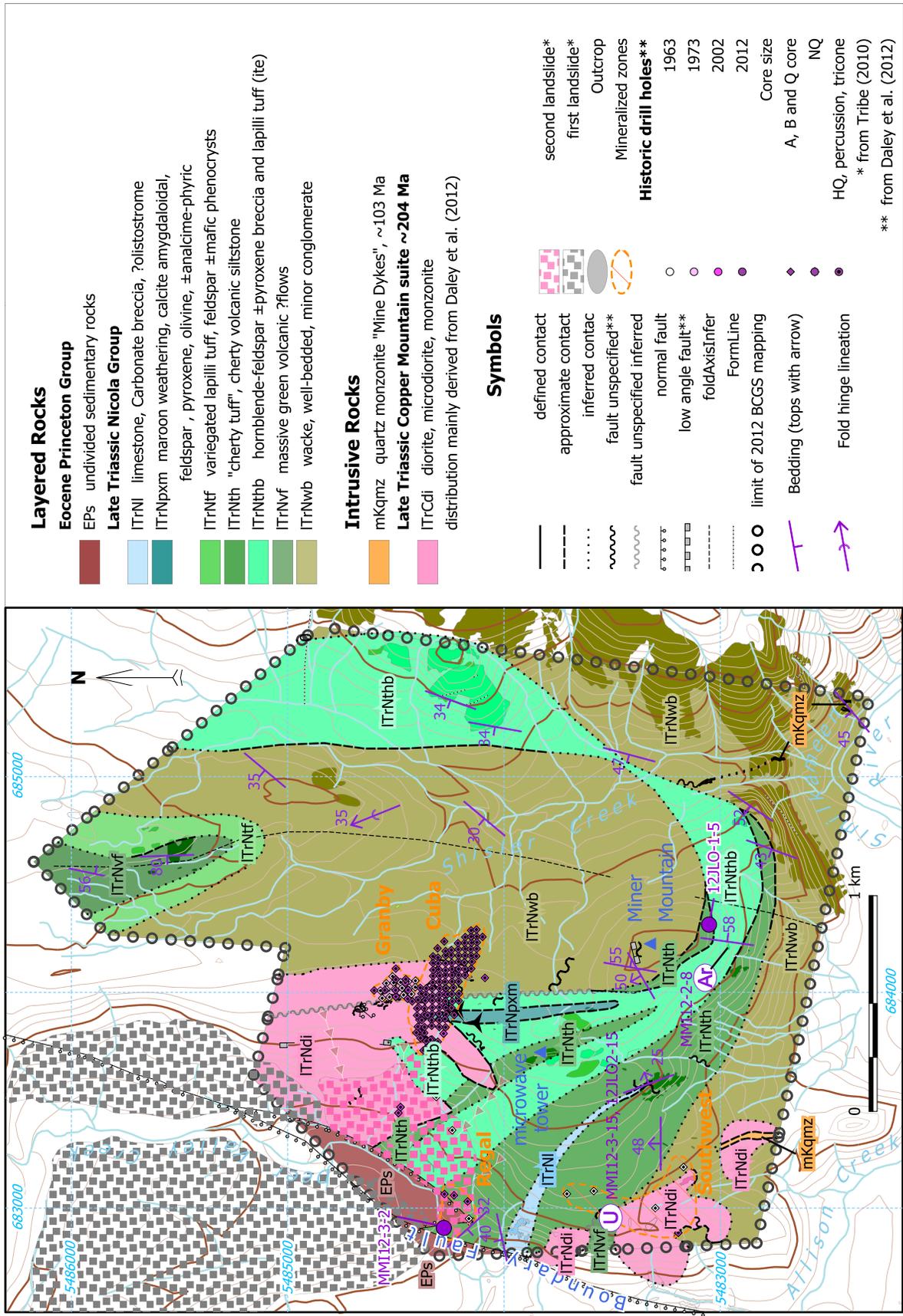


Fig. 3. Geology of Miner Mountain includes new British Columbia Geological Survey mapping, and new property mapping by Sego! Resources (Daley et al., 2012). Distribution of intrusive rocks is based largely upon mapping of trenches by Sego! Resources and others before trenches were reclaimed (prior to 2012).

4.1. Previous systematic mapping

Regional-scale published maps that include contemporary work in the Miner Mountain camp are lacking. Systematic regional mapping in the area dates to that of Rice (1947) and Monger (1989). We present a synopsis of the regional geology of Miner Mountain, parts of which are extracted from compiled property-scale mapping (Daley et al., 2012) and incorporated into Figure 3.

Previous work at Miner Mountain mapped most of the property as underlain by igneous rocks, mainly andesite and diorite. Field observations in 2012 lead us to reinterpret much of the succession as sedimentary, with subordinate volcanic and intrusive rocks. Similar conclusions were drawn by Rodgers (2000) who recognized felsic volcanic rocks interbedded with limestone and calcareous debris flows when the area north of the property was assessed for potential subaqueous volcanogenic massive sulphide mineralization (none was found).

Well-bedded strata are exposed on all flanks of Miner Mountain, but particularly to the south and east (Fig. 3). Alteration commonly obscures primary sedimentary features, and even in the absence of alteration, it can be very difficult to distinguish epiclastic from pyroclastic rocks; for example, a coarse arkose (Fig. 4) from a crystal lithic ash tuff. However, at several localities argillaceous interbeds (Fig. 5), and carbonate layers imply sedimentation in standing bodies of water. This interpretation is supported by petrographic observations of rounding and sorting of volcanic grains (including in graded layers), suggesting aqueous transport and deposition (Fig. 6). However, a coarse monomictic volcanic breccia on the south slope of Miner Mountain is interpreted as an autoclastic flow breccia, and a vesicular flow layer extending from near the microwave tower to the Granby zone have also been mapped. If correctly interpreted, these units confirm the presence of primary volcanic units.

5. Geological units

Miner Mountain is near the boundary between the backarc facies, “eastern belt” comprising predominantly sedimentary rocks and the arc-axis facies or “central belt” comprising predominantly volcanic rocks (terminology of Preto, 1979). This relationship is borne out at the property scale as mineralized diorite cuts predominantly sedimentary rocks. Intercalated with this sedimentary package, are sparse primary volcanic units. Key units are described here, starting with what are interpreted as the lowest, oldest units in the succession. (Discussions of sedimentary grain sizes conform to the Wentworth/ISO scale where sand grains range from 0.063 to 2 mm in diameter. Igneous grain size designations “fine”, “medium”, and “coarse” are divided at 1 mm and 5 mm grain diameters.)



Fig. 4. a) Parallel-stratified coarse arkosic volcanic sandstone. Typical beds are more massive. **b)** Coarse lithic volcanic wacke overlain by indurated siltstone (locally referred to as “cherty tuff”).

5.1. Layered rocks

5.1.1. Volcanic conglomerate to siltstone

The lowest sedimentary unit consists of pebble-cobble conglomerate, sandstone, siltstone (Fig. 4) and rare



Fig. 5. Recessive and rusty, well-bedded argillaceous section with more massively bedded volcanic sandstone above and below. View is easterly along the top of the cliffs south of Miner Mountain. Height of cliff section shown in photo foreground is about 8 metres.

argillite (Fig. 5). Most common are fine- to medium-grained arkosic volcanic sandstone containing 1-3 mm subrounded grains. Outcrops are typically grey- to green- or brown-weathering, blocky, and form cliffs along the south and east parts of the map area. Along the cliff tops of the southern map area, carbonate alteration produces orange-weathering outcrops. Here too is one of the few exposures of black argillite (Fig. 5).

Except in areas with mainly fine-grained rocks, bedding is commonly indistinct, with tabular beds decimetres to metres thick. Siltstone and rare argillaceous beds are laminated on a sub-centimetre scale. Low-angle trough cross-stratification is displayed locally in sandstones, but is rarely well enough developed to permit unambiguous determination of paleoflow directions. Graded bedding is normal, with few exceptions. Scours and soft-sediment deformation structures confirm younging directions. Clasts are derived from volcanic or hypabyssal intrusive protoliths, mainly feldspar and lesser hornblende or pyroxene porphyries, or intraformational sedimentary sources.

Most conglomerate is matrix supported (<10% clasts), although rare crystal-rich (75% 1-3 mm white plagioclase) and volcanic fragment-rich beds are clast-supported. Some laminated siltstone beds are cherty; these are described separately below.

5.1.2. “Cherty tuff”

Pale green to white cherty volcanic siltstone forms blocky to rubbly, angular outcrops. It commonly displays obvious centimetre-scale bedding and may be finely laminated (Fig. 7). Beds may display grading: both normal and lesser reverse grading is developed. Local

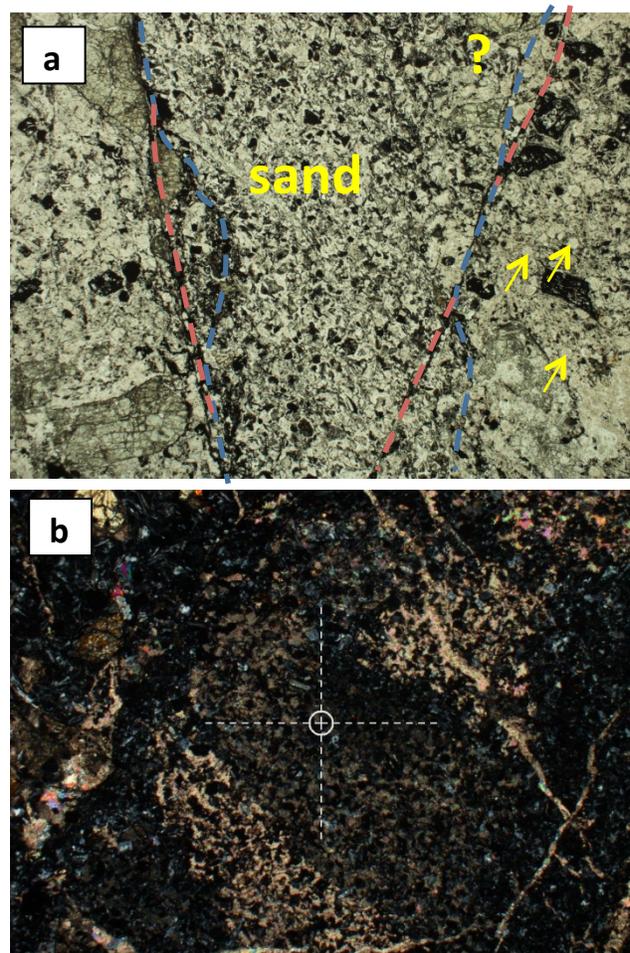


Fig. 6. a) Photomicrograph showing V-shaped infill of immature volcanic sandstone (labelled “sand”) between flow-top breccia fragments. Blue dashed lines mark clast margins and red lines highlight small-scale faults that modify the contacts between the breccia fragments and sandy infill. Note rounding of many of the sand grains, as well as very angular shards (presumably minimally transported). In area identified by “?” the breccia fragment is breaking apart, contributing to the matrix infill. Rounded grains marked by arrowheads within the breccia clasts may be altered analcime. Field of view represents ~4 mm. **b)** Slightly enlarged view of a) in cross polarized light. High birefringence dark and bright domains are optically continuous carbonate cement in which fine sand-sized grains are supported. Irregular carbonate veinlets cut the sandstone. Circle at crosshairs has a radius of 100 μ .

disrupted beds may record synsedimentary faults. Bedding is not accentuated by parallel fractures; instead, fractures commonly intersect bedding at high angles producing angular talus, probably on account of its high level of induration. Staining for potassium shows low but pervasive potassium content, perhaps due to finely disseminated K-bearing mineral phases or diffuse alteration. “Cherty tuff” can be observed as interbeds in coarse sandstone at many localities (Fig. 4b), and on the west flank of Miner Mountain, it is overlain by carbonate clast conglomerate. Farther north, it is overlain by augite-phyric volcanoclastic rocks; at one locality south of Miner Mountain it is intruded by sills of crowded, coarse augite



Fig. 7. Sandstone (beneath pencil tip) overlain by mm-scale graded couplets (yellow arrows) of coarse siltstone (dark) to fine siltstone (light), which are overlain by uniform light green "cherty tuff" (fine siliceous siltstone). Top of photo is a bed of coarse sandstone that cuts down into the "cherty tuff" (base of bed highlighted by dotted line).

porphyry more than 1 m thick. "Cherty tuff" occurs at various stratigraphic levels and, therefore, should not be used as a marker horizon. A water lain pyroclastic origin is suspected, with crystal shards, lithic grains, and outsized clasts visible in thin section (Fig. 8).

5.1.3. Limestone

Light grey to maroon hematitic limestone is exposed on steep dip slopes east of Allison creek. It is medium grained where recrystallized. It contains rectangular single carbonate crystals that may be relic crinoids. Limestone beds are massive to irregularly jointed and commonly hematite-stained. Where cut by fracture

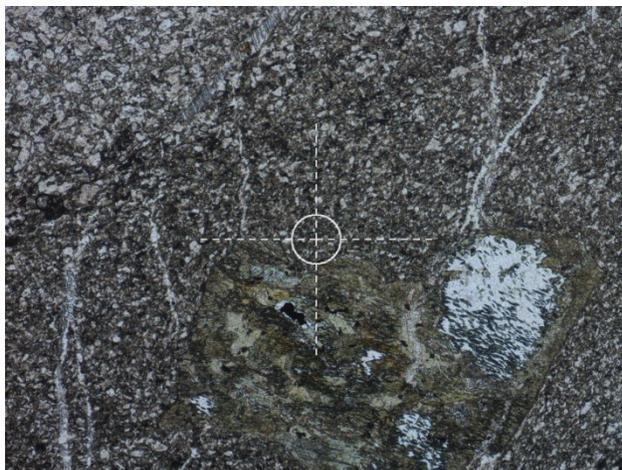


Fig. 8. Photomicrograph of "Cherty tuff" siltstone in plane polarized light. Many silt-sized grains are very angular and crystal shards are common. Bedding, defined by clast size, extends diagonally from middle left to upper right. An outsized clast of foliated, epidote-altered country rock is in the bottom central part of the image. Circle at crosshairs has a radius of 100 μ .

networks, the limestone is replaced by white sparry calcite with maroon to purple hematitic envelopes. At contacts with volcanoclastic rocks, the limestone is dirty green and contains abundant volcanic lithic and crystal fragments; white calcite lenses and vein stockworks, including veinlets of hematite, are also common. Individual limestone beds are 3-5 m thick; it remains unclear if repeated interlayering of three limestone and calcareous, hematitic to green, fine-grained volcanoclastic rock successions are primary or result from structural repetition. Mineralization is locally developed near the bed tops where in contact with volcanic rocks; it occurs as disseminated to blebby magnetite with traces of chalcopyrite. A 10 m thick quartz microdiorite cuts the unit (see following).

5.1.4. Carbonate breccia and conglomerate

At least one broken, irregular layer of carbonate and conglomerate, crops out sporadically on the west flank of Miner Mountain 1 km from the peak. In this layer, angular limestone clasts are slightly deformed, probably flattened, and are mixed with green or red oxidized volcanic detritus. Overlying and underlying medium- to coarse-volcanic sandstone layers are carbonate cemented. Interlayered with the base of this calcareous section are well-exposed outcrops of cherty siltstone. Perhaps only 2 m in maximum thickness and discontinuous along strike (both thickness and continuity are exaggerated on Figure 3), this carbonate breccia unit is important because it demonstrates a probable subaqueous origin (like the limestone unit described above); in this case likely as an olistostrome. No macrofossils were found in the clasts. At one locality, an undisturbed carbonate layer is up to 15 cm thick (Fig. 9).

5.1.5. Polymictic lapilli tuff

Grey to pale orange-weathering and massive to thickly bedded lapilli tuff is characterized by variegated, angular to subrounded lapilli clasts floating in an arkosic wacke matrix (Fig. 10). Plagioclase may comprise 30-40% of the matrix, and also occurs as phenocrysts together with 20-30% hornblende and/or pyroxene crystals that range between 2 and 6 mm long. Fragments include: fine aphyric black basalt; plagioclase-phyric basalt; augite and plagioclase-phyric basalt; and altered pink hypabyssal diorite. Alteration includes: epidote flooding of the matrix and plagioclase; hematite dusting of plagioclase and along fractures; and K-feldspar flooding of the matrix plus replacement of some clasts. Magnetite and chalcopyrite are sparsely disseminated; malachite patches are common on fracture surfaces. Zones of calcite as veinlets and breccia infills postdate lithification.

5.1.6. Pyroxene-phyric volcanic breccia

A coarse mafic fragmental unit can be traced along the southern and eastern portions of the map area. It is pale green and contains dark, coarse-grained hornblende and pyroxene-porphyry blocks and lapilli within a crystal-rich tuff matrix. Breccia layers are 10s of metres thick and



Fig. 9. Light grey to white carbonate layer extends from above head of hammer to lower right corner of the photo. Adjacent rocks are, in part, cemented by carbonate.



Fig. 10. Polymictic lapilli tuff cut by late calcite veins.

are overlain by bedded sedimentary rocks. Elsewhere, sections of basaltic andesite, decimetres thick, contain 2-4 mm hornblende phenocrysts as the predominant mafic mineral and occur together with subhedral 1-2 mm pyroxene crystals. Both breccia types also contain plagioclase (1-2 mm, 10-20%), which is especially abundant in hornblende-phyric varieties. Disseminated magnetite is also common, giving the unit a relatively high magnetic susceptibility (~ 20 to 45×10^{-5} SI). Locally, the unit is cut by white centimetre-thick quartz veins. Alteration of the fine-grained matrix and phenocrysts by chlorite and/or epidote and pyrite is pervasive, whereas patches and fracture controlled epidote \pm pyrite and magnetite are only locally developed. It is unknown if the alteration represents a broad propylitic alteration halo, or greenschist-grade metamorphism.

5.1.7. Hornblende-feldspar porphyry

Dark grey, blocky and indurated acicular hornblende-feldspar-phyric breccia and lapilli tuff (Fig. 11) is a mappable unit ~ 20 m thick, best exposed on the south flank of Miner Mountain. Layers containing both medium-grained euhedral hornblende and lesser coarse augite ($\sim 15\%$ combined) are generally less than a metre thick. Petrographic analysis shows that hornblende in these layers have cores of pyroxene. Plagioclase is relatively fresh, although turbid, and displays strong oscillatory zoning.

Along the eastern part of the map area the hornblende porphyry crops out as a well jointed, massive, 25 m thick flow with a blocky weathering flow-top breccia that passes upwards into hornblende plagioclase phyric lapilli tuff.

Locally the mafic minerals are vitreous, but more commonly they are chlorite-epidote \pm actinolite-altered along with the feldspar and matrix. Medium-grained plagioclase is generally more abundant than hornblende crystals, especially in crystal rich layers. Staining shows that the alteration mineral assemblage includes K-feldspar. Where the unit contains vitreous hornblende, it was sampled for $^{40}\text{Ar}/^{39}\text{Ar}$ dating (sample MMI12-2-8; Table 1).



Fig. 11. Hornblende-phyric breccia displays acicular hornblende with trachytic alignment in direction of arrow, and patches of green-yellow epidote alteration.

Table 1. Major oxide analyses from Inductively Coupled Plasma-Mass Spectroscopy following lithium metaborate fusion of sample. Analyses performed at Activation Laboratories, Lancaster, Ontario. All values reported are weight %. UTM coordinates are zone 10, North American Datum 1983. See (Mihalynuk and Logan, 2013b) for a digital table of the complete suite of elements analyzed.

StatNum	Unit	UTME	UTMN	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3(T)}	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	LOI	Total
12JLO-1-5		684314	5483052	51.22	16.26	9.67	0.192	4.02	9.1	3.37	1.52	0.903	0.37	2.1	98.72
12JLO-3-31	ITrNth	685028	5485107	66.11	17.63	2.92	0.072	0.96	4.14	5.12	2.46	0.258	0.12	1.18	101
MMI12-2-8	ITrNhb	684236	5482960	52.28	17.6	9.38	0.163	4.15	8.02	3.33	2.28	0.831	0.36	1.85	100.2
MMI12-3-15	ITrCdi	682955	5483506	54.86	15.69	4.96	0.083	2.66	7.03	6.5	0.94	0.488	0.46	6.53	100.2
Std MRG-1				38.59	8.43	17.42	0.167	13.26	14.72	0.71	0.18	3.705	0.07	1.45	98.71
STD WGB-1				48.83	10.91	6.33	0.135	9.14	16.34	2.15	0.91	0.885	0.09	3.8	99.51
				0.01%	0.01%	0.01%	0.001%	0.01%	0.01%	0.01%	0.01%	0.001%	0.01%	%	0.01%

5.1.8. Pyroxene-phyric flow rocks

An ochre-coloured basalt flow unit crops out east of the microwave tower. Also known as the “brick red unit”, it is maroon to tan or dark grey on weathered and fresh surfaces, and is typically fine grained and sparsely amygdaloidal. Phenocryst content varies markedly along strike to include coarse-grained augite (\pm hornblende, to 10% combined), glomeroporphyritic feldspar (up to 20%), and greasy green relics after olivine. Petrographic analysis reveals rounded crystals <1 mm in diameter that are interpreted as analcime, altered to a low birefringence mineral aggregate (Fig. 6a). Amygdules are less than 1 cm in diameter and comprise \sim 10% of the basalt. They are composed of calcite, commonly rimmed by epidote. This unit is chlorite altered, with late brittle fractures containing hematite and calcite and patchy epidote replacements of feldspar and mafic minerals. Its brecciated upper contact may interfinger with fine sandstone (Fig. 6a) or dust tuffite.

Similar rocks comprise some of the structurally highest rocks mapped on the property. These are augite-phyric flows and breccia that grade upwards into monomictic augite-phyric breccia and interlayered massive flows. They occur within the core of a shallowly north-plunging syncline near the northern limit of the map area.

5.2. Intrusive rocks

We describe the intrusive stocks and major dikes by relative age, from oldest to youngest. Volumetrically minor dikes, typically displaying variable contents of pyroxene, hornblende, and plagioclase phenocrysts, are not included. Some rocks formerly described as “microdiorite” on property maps can be shown to be arkosic volcanic sandstones with graded bedding. Small hornblende porphyry intrusions probably have irregular outlines, and are difficult to portray accurately on Figure 3 due to inadequate exposure.

5.2.1. Porphyritic diorite

Diorite, and locally quartz diorite, occurs at several localities, but some of the best exposures are of a 10 m

thick dike that cuts the limestone unit. This dike is a quartz-bearing leucocratic diorite with a fine-grained salt and pepper texture. White, equant plagioclase crystals (1-2 mm) comprise much of the rock (\sim 45%); it also contains weakly chlorite-altered hornblende (0.5-1 mm, 30%) and intergranular quartz (5-10%). Hornblende is altered to lath-shaped clots of chlorite 2-3 mm across (10-15%); orthoclase is 3-5 mm (\sim 5%), and white plagioclase (overprinted by green epidote alteration, 2-3 mm, 30%). Fine-grained hematite disseminations likely replace magnetite. Trachytic fabric is well displayed on some surfaces.

Northwest of Miner Mountain, along the property access road, are low, rubbly outcrops, probably of microdiorite. However, the moderate degree of alteration and broken outcrop precludes positive identification in the field.

On the southwest flank of Miner Mountain, outcrops and trenches expose tan, green and orange-weathering hornblende diorite. Petrographic analyses of a sample of mineralized diorite shows pervasive brecciation such that most individual plagioclase crystals are floating in a comminuted matrix that is altered or cemented by calcite-feldspar-quartz- \pm chalcocopyrite or fine white mica, (or various combinations thereof). Plagioclase crystals display corroded margins and may be bent or show other optical evidence of strain. Whether this brecciation is due to deep-seated hydromagmatic fracturing (e.g., breccia pipe) or to interaction with wet sedimentary country rocks (e.g. peperite) has not yet been determined (see also “Mineralization” section).

5.3. Mine dikes

Also known as “Candy Stripe dykes” where well exposed along strike to the south-southwest, in the open pits of the Copper Mountain mine, the mine dikes are composed of distinctive, white to orange-weathering, quartz-feldspar-porphyritic rhyolite (Fig. 12). Coarse K-feldspar, coarse quartz eyes, and altered mafic minerals comprise \sim 20%, 3-5%, and \sim 2-3% of the rock respectively. These dikes form swarms with individual tabular bodies typically 5-10 metres thick. In the Miner



Fig. 12. Quartz-eye feldspar porphyry; correlated with the ~103 Ma Mine Dykes at Copper Mountain.

Mountain area, they appear to be restricted mainly to the Shisler Creek valley and ridges to the east (Fig. 3).

5.4. Depositional setting

Volcanic and sedimentary rocks in the Miner Mountain area were likely deposited in an arc flank setting. Very immature volcanoclastic input during arc construction eventually built out to override the flanking sedimentary basin to the east. Intrusion of mineralized diorite may have locally interacted with the wet sedimentary pile, causing the ubiquitous brecciation in the intrusions.

6. Lithochemistry

Samples collected for major oxide and trace element analysis were selected to represent the diorite and hornblende and pyroxene-phyric breccia units in the Miner Mountain study area. Major oxide analyses are reported in Table 1. Major and trace element analyses are available in downloadable format from Mihalynuk and Logan (2013b).

Following the classification of Peccerillo and Taylor (1976), and assuming that these porphyritic units are representative of their source magmas, the breccia units are high-K calcalkaline basalt (12JLO-1-5) or andesite (MMI12-2-8), and the porphyritic diorite is calcalkalic (MMI12-3-15) and compositionally equivalent to a basaltic andesite. Because the ratio of Na_2O to K_2O is near unity, the breccia units are shoshonites when their

non-normalized compositions are considered in total-alkalis – silica space (not shown; LeBas et al., 1986). However, when compared to the trace element alkalinity index Nb/Y (Pearce, 1996), neither the breccia units nor diorite are especially alkaline. Low Nb likely arises from the strong arc signature with deep Nb depletion, as shown on the primitive mantle – normalized spider diagram (Sun and McDonough, 1989) of Figure 13c. Other arc characteristics include Ta and Ti depletion and enrichment in large ion lithophile elements shown on the left side of the diagram (e.g., Cs, Rb, Ba, K, Sr). Lack of an Eu anomaly suggests that feldspar was not a residual phase in the source area, nor was it removed from the crystallizing melt. All units are uniformly light rare earth element enriched as compared to chondrite values (Fig. 13d; Sun and McDonough, 1989), and all display a common parentage (Figs. 13c and 13d).

7. Mineralization

The four main zones of mineralization on the property that have received most of the exploration development are Regal, Granby, Southwest, and Cuba (Fig. 3). We have few new observations to report as most mineralization is poorly exposed and the aim of our brief study was to establish regional geologic setting, not mineral resource potential. However, first impressions of the broad propylitic alteration zone (chlorite-epidote-actinolite-pyrite \pm quartz-calcite) are favourable and K-feldspar-magnetite alteration is locally intensely developed. Secondary biotite is rare. For detailed descriptions of mineralization the reader is directed to the many Assessment Reports cited herein, especially drill core logs.

7.1. Regal zone

Mineralization of the Regal zone (Fig. 3) is particularly intriguing. It is a blanket of chaotic, mineralized intrusive blocks. Copper oxides within this blanket are reported to grade to 1% Cu (Dolmage and Campbell, 1963); historical production includes construction of a leaching plant (Anonymous, 1972) in an attempt to leach oxidized mineralization, which was apparently unsuccessful (Taylor, 1988). This chaotic debris has been consistently interpreted as a landslide deposit (Dolmage and Campbell, 1963; Tribe, 2010). Drill holes are reported to penetrate through the oxide blanket into till and underlying Eocene Princeton Group volcano-sedimentary strata, and the occurrence of mineralization diagonally up-slope of the Regal zone (in the Granby “crush zone”; see below; Fig 3), appears to support this interpretation (Dolmage and Campbell, 1963). However, during our brief examination we did not observe in situ Cu mineralization in rocks of the Granby zone that matched the mineralized blocks in the Regal zone.

We did sample a mineralized block from the Regal zone (Fig. 3). The block, ~0.5 m in diameter, sat in colluvium atop undisturbed till, within ~0.5 m of underlying bedrock of presumed indurated Nicola Group volcano-sedimentary rock; clearly not the poorly lithified,

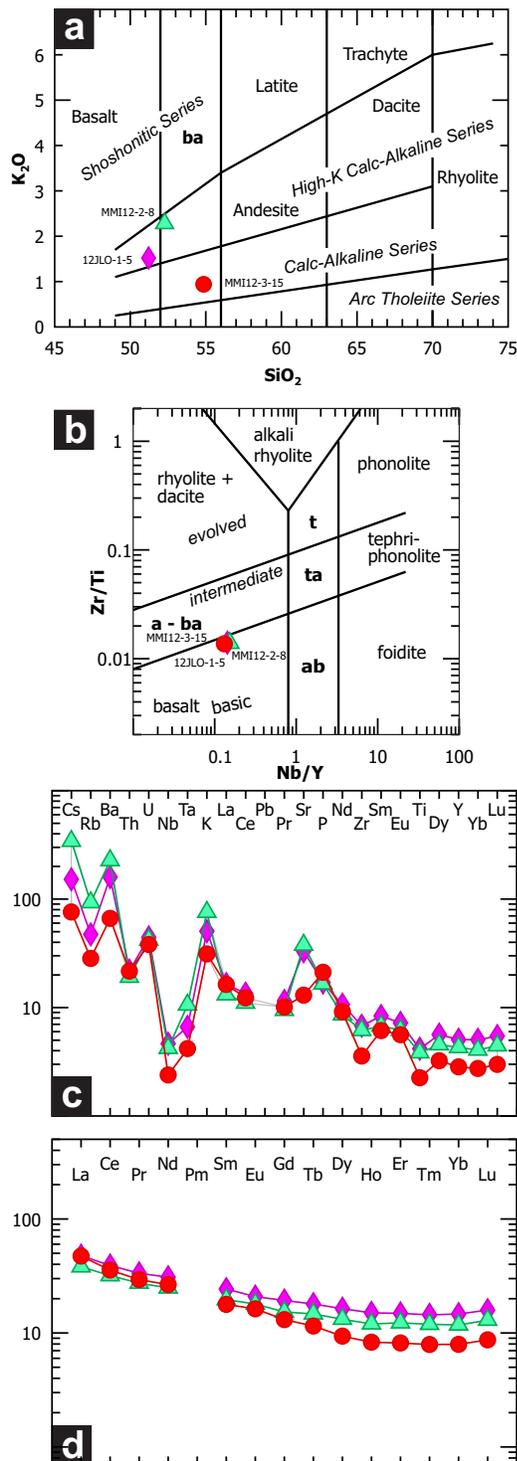


Fig. 13. Geochemical character of diorite (solid circle) and coarse breccia with predominantly feldspar-hornblende-pyroxene (diamond) or feldspar-hornblende (triangle). **a)** plot of K_2O versus SiO_2 , fields after Peccerillo and Taylor (1976), with oxides normalized with removal of components lost on ignition (LOI, see Table 1). **b)** Zr/Ti versus Nb/Y with fields after Pearce (1996). **c)** Primitive mantle normalized spider diagram and **d)** chondrite-normalized rare earth element plot using normalization factors of Sun and McDonough (1989). Abbreviations: a = andesite, ab = alkali basalt, ba = basaltic andesite, t = trachyte, ta = trachy-andesite.

dark red-brown, coaly Princeton Group strata that crop out ~100 m to the southwest. Both the style of mineralization and alteration of this block are similar to the Southwest zone. This block displays pervasive matrix flooding by calcite and white K-feldspar/albite (Fig. 14), but the original plagioclase crystals are relatively unaltered, although fractured. Chalcopyrite is uniformly distributed between the corroded margins of the feldspar crystals (Fig. 14c). Post-mineralization brecciation seems to have had little effect on destruction or beneficiation of mineralization. Analysis of the block yielded >1% copper (Table 2; MMI12-3-2b compare with 12JLO2-15 from the Southwest zone).

It is worthwhile to question again the origin of the mineralized blocks comprising the Regal zone. Could they have been derived from immediately up-slope, in an area that has received no drilling and very limited trenching (Fig. 3)? Could mineralized monzonite of the Southwest zone extend to this area?

7.2. Southwest zone

Host rocks for the Southwest zone mineralization (Fig. 3) are described above (see section 5.2.1. Porphyritic diorite). Stringers and veins and coarse blebs of chalcopyrite occur in rusty diorite in a >5 m zone exposed by trenching. Chalcopyrite is also disseminated in the matrix and as a replacement of mafic minerals. Broken outcrop may weather orange where cut by limonitic calcite-coated fractures, commonly with malachite staining. Alteration minerals include epidote as patchy matrix flooding veins, and together with calcite on most fractures. K-feldspar/albite rims plagioclase and floods the matrix (Fig. 15). A propylitic alteration assemblage of chlorite-epidote-calcite and disseminated pyrite (<1%, fine-grained) near the stock contact is overprinted by potassium alteration with introduction of chalcopyrite. Calcite and hematite occur along late fractures, in some instances with chalcopyrite (Fig. 15). Microscopic analysis of mineralized porphyry reveals that brecciation has produced corroded and sutured, but relatively unaltered plagioclase, like at the Regal zone (see above). Intercrystalline spaces are occupied by secondary calcite, feldspar, quartz, magnetite (oxidized to hematite/goethite), and chalcopyrite (Fig. 15). Despite evidence of widespread oxidation of magnetite to hematite, this unit is relatively magnetic, averaging 3.4×10^{-5} SI. It has been sampled for U-Pb isotopic age determination (MMI12-3-15, Table 1).

7.3. Cuba zone

Mineralization at the Cuba Zone does not crop out. It is a discovery made mainly through testing a geophysical anomaly using percussion drilling (Christopher, 2012). Figure 3 shows the known extent of Cuba Zone mineralization in the subsurface.

7.4. Granby zone

Mineralization at the Granby zone is also covered by glacial till. A westward continuation of the Granby Zone is the shallow, high grade, “crush zone” that does crop out

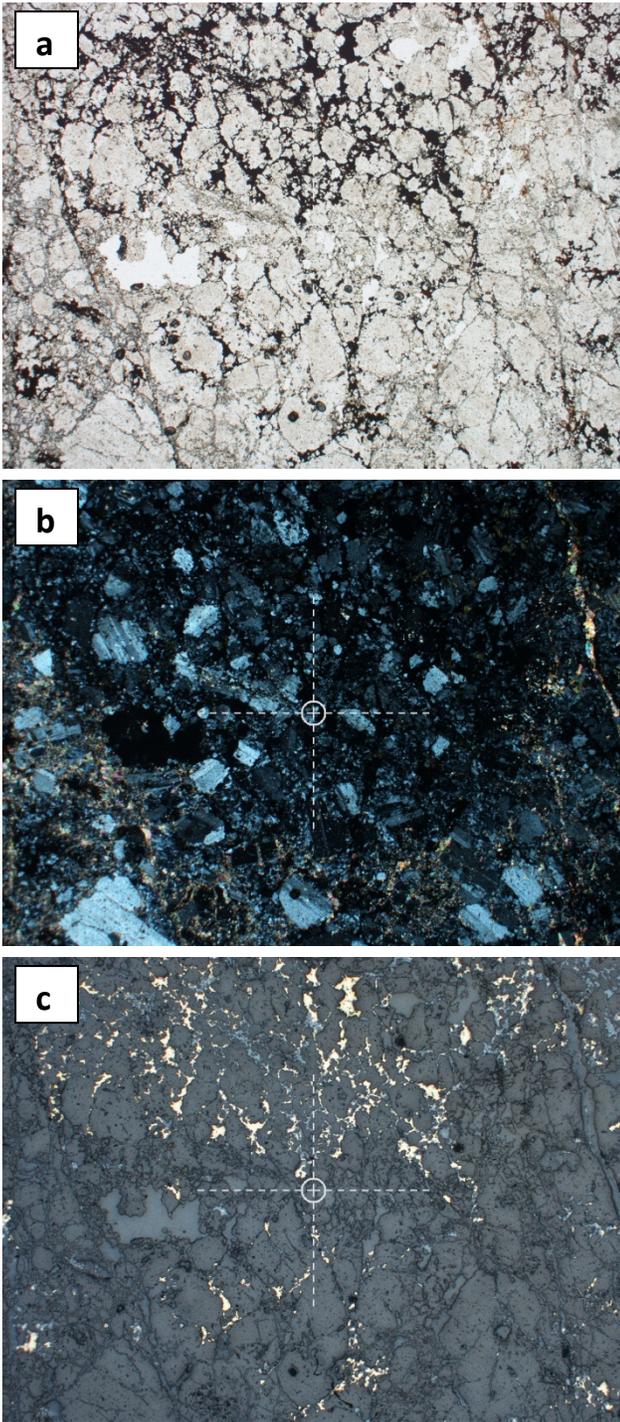


Fig. 14. Photomicrographs of Regal zone block showing the same field of view. **a)** In plane polarized light, brecciated feldspar porphyry shows corroded grain margins and intergranular calcite and fine-grained K-feldspar and albite. **b)** Cross polarized light showing high birefringence of intergranular calcite and calcite veinlet on right. **c)** Plane polarized reflected light showing disseminated yellow chalcopyrite mantled by bright grey and medium grey Fe-oxide/hydroxide minerals (mainly goethite and hematite) that probably formed during interaction with meteoric waters (dark grey minerals are non-reflective silicates). Calcite and isotropic epoxy have lower relief than silicate minerals. Circle at crosshairs has a radius of 100 μ .

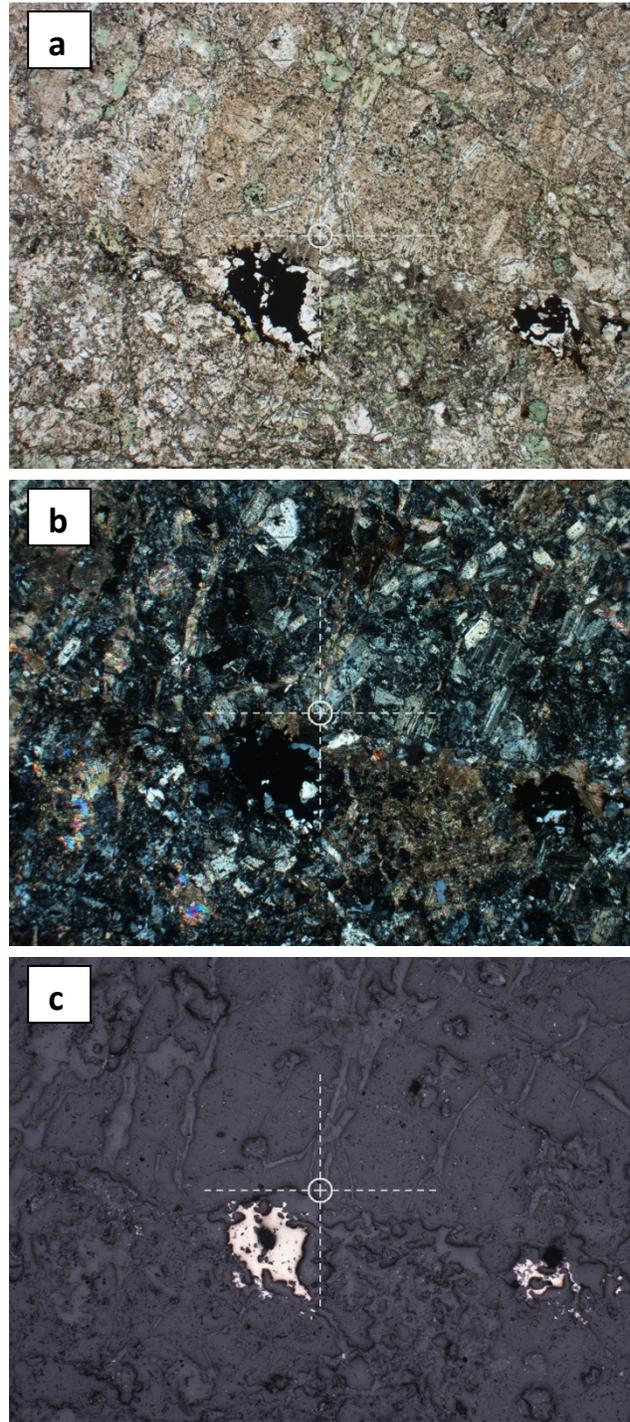


Fig. 15. Photomicrographs of mineralized porphyritic monzodiorite in Southwest zone. **a)** Plane polarized light view of dusty feldspar phenocrysts and matrix extensively cut by calcite veinlets. Chlorite alteration is widespread, but especially around opaques. **b)** Cross polarized light view shows trachytic alignment of plagioclase and admixture of high birefringence calcite with chlorite, and extensive calcite veinlets. **c)** Plane polarized reflected light view showing yellow chalcopyrite and minor domains of purple bornite alongside low relief patches of chlorite. Hematite occurs as fine dusting of bright blue-grey specks. Calcite veinlets are also visible as low relief linears. All images are the same field of view. Circle at crosshairs has a radius of 100 μ .

Table 2. Base metal and Pt, Pd analytical values from select samples. Analyses performed by Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS) at Acme Analytical Laboratories Ltd., Vancouver. For a full suite of elements analyzed see Mihalynuk and Logan (2013b). Det. Lim. = detection limit. Coordinates are UTM zone 10, North America Datum 1983.

StatNum	UTME	UTMN	Mo	Cu	Pb	Zn	Ag	Fe	As	Au	Sb	Bi	Ca	P	Mg	Na	K	S	Hg	Pd	Pt
			Det. Lim.	0.01	0.01	0.01	0.1	2	0.01	0.1	0.2	0.02	0.02	0.01	0.001	0.01	0.001	0.01	0.02	5	10
			ppm	ppm	ppm	ppm	ppb	%	ppm	ppb	ppm	ppm	%	%	%	%	%	%	ppb	ppb	ppb
12JLO-2-15	682954	5483511	0.5	8899	2.37	24.3	997	3.16	2.7	3.5	0.04	0.09	4.32	0.154	1.6	0.066	0.1	0.67	10	45	3
MMI12-3-2	682908	5484278	0.28	288	5.37	51.2	229	5.01	1.8	26.1	0.16	0.15	7.73	0.133	1.99	0.019	0.09	2.53	14	11	6
MMI12-3-2b	682908	5484278	5.58	>10000	1.96	3.4	1938	2.19	2.2	42.9	0.49	0.37	2.88	0.112	0.19	0.067	0.07	0.58	21	15	4
MMI12-4-12	684661	5482763	0.64	116	2.57	56.9	60	3.97	19.9	9.4	0.26	0.04	4.44	0.168	2.34	0.047	0.18	0.05	15	<10	8
Std WGB-1			0.85	7204	11.27	79.4	3046	7.98	3.8	181.1	0.86	0.29	1.71	0.058	2.56	0.007	0.02	3.04	154	431	212
Std BCGS till 1999			0.85	202	236.64	352.5	1752	7.35	66.9	62	11.12	0.28	0.36	0.119	2.74	0.004	0.05	<0.02	371	<10	<2
Std GSBtill99			0.73	183	220.27	334.4	1660	7.34	61.9	27.1	7.86	0.22	0.35	0.114	2.84	0.01	0.05	<0.02	295	<10	<2
Std DS9			15.24	111	140.49	345.5	1981	2.34	28.4	140	5.69	8.03	0.74	0.09	0.62	0.085	0.4	0.17	224	135	405
Std DS9			12.97	113	130.1	312.9	1793	2.38	27	108.8	5.25	5.94	0.72	0.087	0.63	0.083	0.41	0.17	206	124	332

in a trench west of the main Granby Zone. At this locality, intensely fractured siliceous, and clay-altered rocks with veinlets of cryptocrystalline quartz contain substantial disseminated and veinlet chalcopyrite and malachite staining.

7.5. Mineralization geochemistry

PGE analysis was a focus of work by Nustar Resources Inc., (McLeod, 2000) who found that gold, palladium, and to a lesser extent, platinum, correlate with copper grade. Analyses reported here also show elevated Pd, up to 45 ppb, and to a lesser extent Pt in mineralized samples (Table 2, compare 12JLO-2-15 from the Southwest zone with BCGStill99 standard). Elevated Pd and Pt seems to be a hallmark of the alkalic family of porphyry Cu-Au deposits in British Columbia (Nixon and Laflamme, 2002; Nixon, 2003), although Pt-Pd content does not always correlate with Cu content (Nixon, 2003).

8. Structure

Miner Mountain and the adjoining ridge to the north are near the core of an open syncline with regionally shallow north plunges, although some bedding orientations suggest local steep to moderate plunges. Strata maintain constant strike and dip on the eastern limb, but the western limb (west of Miner Mountain) is disrupted by multiple faults that cut bedding at high angles (Fig. 16a). Across these faults, bedding has rotated to variable degrees, such that dip directions vary along strike (Fig. 3). This regional fold has an unknown age relative to apparent small-scale folds intersected by drill core.

Near the bottom of vertical drillhole DDH MM09-11 is a folded tuff or tuffaceous sedimentary rock with a poorly developed, subhorizontal spaced cleavage (Fig. 16b). Petrographic analysis of this cleavage indicates evidence of minimal recrystallization and reorientation, opening the possibility of a soft sediment origin. It is possible that the fold was formed by syndepositional slumping. However, in the same drill hole, discrete subhorizontal ductile shear zones are consistent with significant subhorizontal shortening (or extension) which

could be related to the folds in drill core. Subvertical, quasi-ductile fabric in bornite-chalcopyrite-clay mineralization (Fig. 16a) indicates that some tectonic fabrics developed during or subsequent to mineralization. Given the incompetent nature of the mineralization, the fabric developed therein could have formed at low differential stresses.

Cherty tuff west of Miner Mountain peak is cut by brittle-ductile shears. These shears dip moderately to the northeast and may be related to southwest-directed thrusting (Fig. 17). Unfortunately, unambiguous shear sense indicators were not observed.

Previous mapping outlined the approximate trace of the Boundary Fault along the western side of the map area. This is a steep to moderately west-dipping fault that forms part of the eastern margin of the Eocene Princeton Basin. Its orientation and offset is consistent with the history of Eocene east-west extension across southern British Columbia. We expect that related, subsidiary structures are present, but were unable to confidently identify any.

9. Geochronology

We are unaware of any age determinations from geological units in the area mapped around Miner Mountain. In an effort to provide age context for the stratigraphic section and mineralized intrusions we have collected and submitted samples for ⁴⁰Ar-³⁹Ar age determination of the hornblende porphyritic breccia and U-Pb determination of the mineralized porphyritic diorite (see Fig. 3 for sample locations). Results are pending.

10. Summary

A six man-day mapping program was conducted in the area around Miner Mountain. Field observations, confirmed by petrographic work, necessitate a reinterpretation of the geological setting of Miner Mountain. Host rocks of the deposit appear to have been deposited mainly in a subaqueous arc flank setting not a subaerial arc axis setting as previously mapped. This setting is more like that of the Copper Mountain deposit, 25 km to the south-southwest. Quartz-deficient intrusions

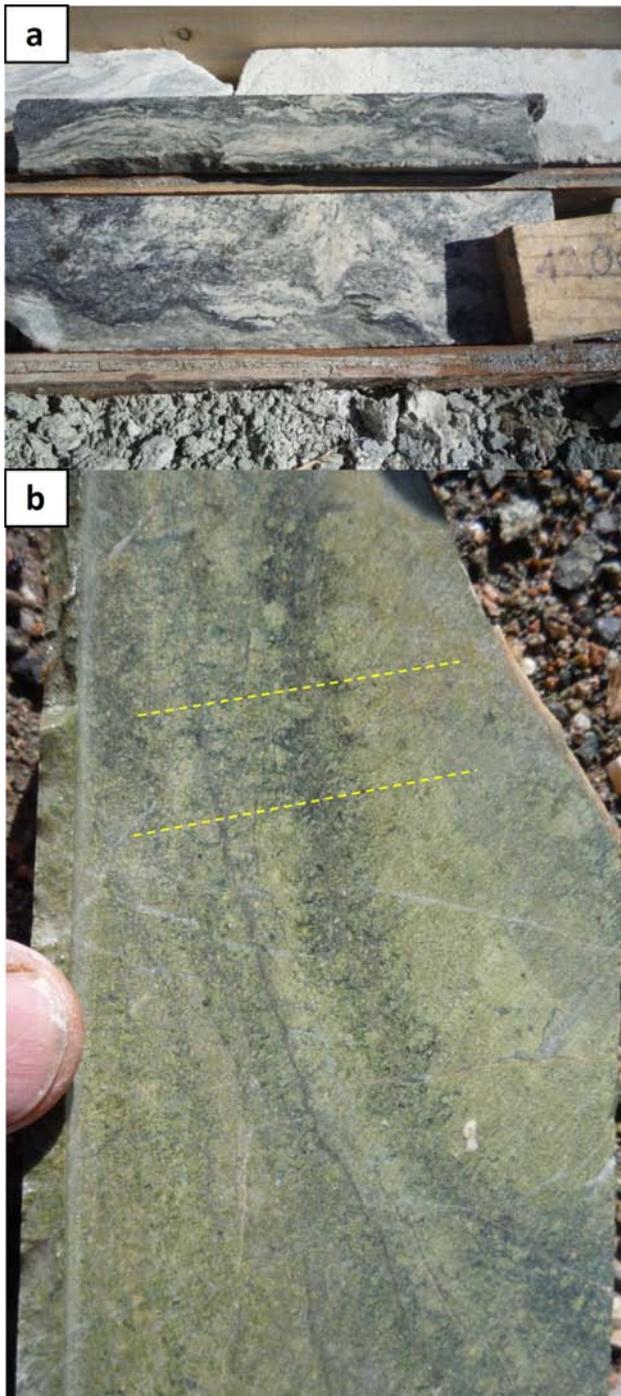


Fig. 16. a) Ductile fabric developed within siliceous, bornite-rich clay alteration zone. b) Strong epidote-chlorite alteration of folded tuffaceous rock possibly preserving a weak axial planar fabric as highlighted by yellow lines.

and a K-feldspar-magnetite alteration overprint of a more widely-developed propylitic mineral assemblage are typical of alkalic porphyry mineralization. Copper mineralization with elevated platinum-group element content also support an alkalic association; however, secondary quartz within mineralized diorite breccia is atypical of a British Columbia-type quartz deficient alkalic porphyry system (Logan and Mihalynuk, 2013).



Fig. 17. Low angle brittle shear zone within section containing "cherty tuff" and aphanitic, dark green rocks of probable volcanic origin.

Lack of biotite in the alteration assemblage may indicate that only high levels of the alteration system have been so far exhumed. Mineral exploration at Miner Mountain is ongoing. For latest exploration results refer to the company website, currently www.SegoResources.com.

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