Mineralization and Alteration of Cretaceous Rocks of the Taseko Lakes Region, Southwestern British Columbia (NTS 092O/04)

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Introduction

Porphyry copper deposits are the major source of copper in the world today (Titley et al., 1981). They are large hydrothermal systems intimately related to the exsolution of fluids from high in the crust. Tectonic environments, magma composition and crustal environment of emplacement all play a role in determining the metal endowment of these deposits (Richards, 2003). From the distribution of porphyry deposits around the world, it is clear that the magmatic-hydrothermal systems responsible for their genesis occur in pulses restricted in time and space. The western Cordillera of Canada has several large porphyry deposits (e.g., Highland Valley, Galore Creek, Island Copper and Gibraltar), the majority of which are associated with alkaline magmatism and are of Mesozoic age (Lowell and Guilbert, 1970). There are less well-known occurrences of large copper porphyry deposits in other terranes of British Columbia (BC) that are spatially associated with the Coast Plutonic Complex (CPC); the largest of these is the Prosperity deposit (Figure 1). With estimated resources of 9.4 million ounces of gold and 3.5 billion pounds of copper (MINFILE 092O 041; MINFILE, 2008), Prosperity could become BC's largest producing porphyry deposit. The Prosperity deposit is a calcalkaline porphyry characterized by the intrusion of quartz diorite and plagioclase porphyry into surrounding Lower Cretaceous marine shale and marine to nonmarine Lower to Upper Cretaceous andesitic pyroclastic rocks with intercalated massive to porphyritic flows (MINFILE 092O 041; MINFILE, 2008). Occurrences of hydrothermal alteration and mineralization have been found within 25 km of the Prosperity deposit in rocks of a similar age and paleogeographic-tectonic setting. These occurrences lie in the Taseko Lakes area and may represent a tectono-temporal suite of porphyry copper deposits in BC. Acquiring a better understanding of their age, their tectonic setting and the degree to which they represent magmatic-hydrothermal systems, will make it easier to access these deposits.

Keywords: porphyry, copper, hydrothermal, Taseko Lakes

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This report is a summary of the results of the main author's Geoscience BC-funded M.Sc. study on a porphyry copper deposit and spatially associated hydrothermal showings that lie in rocks of similar age, composition and tectonic setting to those of the Prosperity deposit. The study area is located in southwestern BC, approximately 50 km south of the town of Williams Lake and 25 km south of the well-defined Prosperity copper-gold porphyry deposit (Figure 1).

The main goals of the project are to
- characterize mineralogical and chemical alteration and their paragenetic relationships;
- understand the physicochemical evolution of the hydrothermal systems;
- determine the age of intrusion, alteration and mineralization;
- define the tectonic and geological framework of hydrothermal activity;
- consider the hydrothermal showings' association to other hydrothermal activity in the same belt of rocks; and
- assess the potential for finding another belt of porphyry copper deposits within BC.

The current paper presents results of geological mapping, petrography, $^{206}Pb/^{238}U$ and $^{40}Ar/^{39}Ar$ geochronology, thermochronology, fluid inclusion analysis and a preliminary stable isotope study. These results indicate that a period of porphyry-related intrusion and mineralization occurred during the Late Cretaceous, around the same time that similar events were taking place in the nearby Prosperity deposit.

Regional Geological Setting

British Columbia is composed of various orogenic belts that are part of a larger geographic area known as the Canadian Cordillera. The Coast Belt forms the core of the lon-

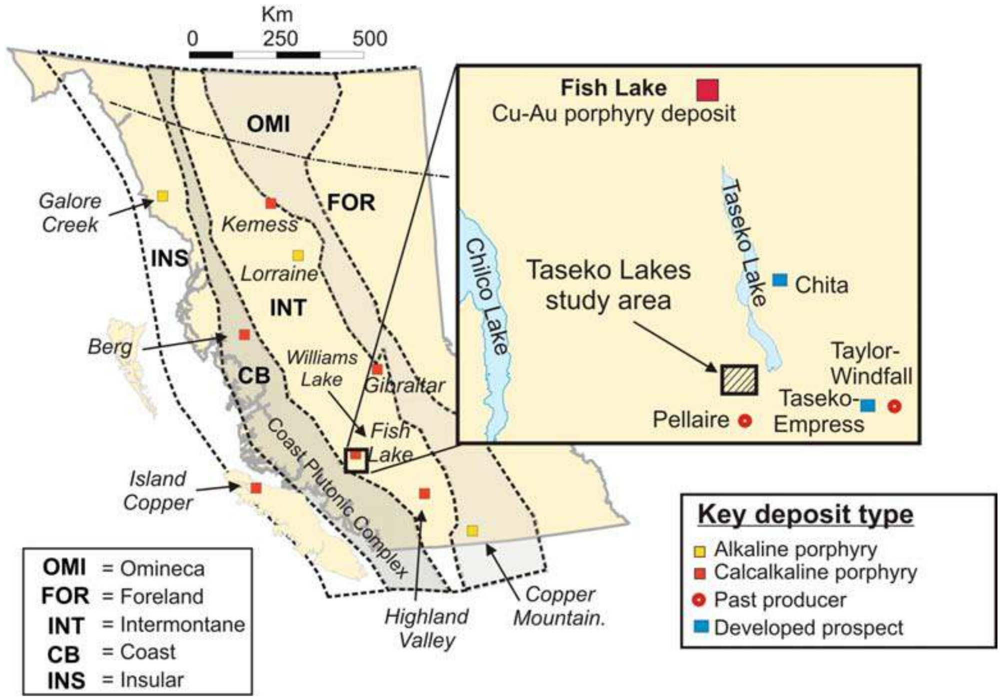


Figure 1. Location of major alkaline and calcalkaline copper porphyry deposits in BC. The inset map shows the location of the Prosperity deposit, past producers Pellaire (gold mine), Taseko-Empress (copper-gold developed prospect) and Taylor Windfall (gold mine), and the Taseko Lakes study area.

gest mountain belt in the western Cordillera (Rusmore and Woodsworth, 1991) and is the suture zone between the Intermontane Belt (to the east) and the Insular Belt (to the west). The Taseko Lakes region of southwest BC is located near the eastern limit of the CPC. It is along this boundary that the Prosperity deposit is located (Figure 1). The batholith is thought to have been produced, from the Jurassic to the Eocene, by the subduction of the Insular Superterrane along the continental margin of North America.

In southwest BC, the Coast Belt is divided into the southwest and southeast Coast belts. The southwest Coast Belt consists of Middle Jurassic to mid-Cretaceous plutonic rocks and Early Cretaceous volcanic rocks. The southeast Coast Belt includes Early Cretaceous arc rocks and clastic rocks. The study area is located within the southeast Coast Belt, and includes rocks that belong to the Cretaceous Tchaikazan River succession and the Powell Creek Formation (Tipper, 1969, 1978; McLaren, 1990; Monger et al., 1994; Schiarizza et al., 1997; Israel, 2001).

Israel (2001) concluded that the study area straddles the boundary between the Gambier arc and the Tyaughton Basin, and suggested that the uplift of Early Cretaceous rocks provided a source of material for the Tyaughton Basin. By mid-Cretaceous time, the plate configuration had changed, leading to dominantly contractional deformation. Dextral strike-slip and contractional fault movements occurred in the area from the mid-Cretaceous to the Tertiary (Journeay and Friedman, 1993; Schiarizza et al., 1997; Israel et al., 2006). During the later Paleocene to Eocene epochs, contractional movement was superseded by dominantly dextral strike-slip movement, forming large-scale faults (e.g., Tchaikazan and Yalakom faults).

Evidence for hydrothermal activity and mineralization is widespread throughout the southeast Coast Belt, highlighted by numerous small metallic showings, developed prospects and altered hostrocks. These are largely associated with, and located proximal to, the intrusions contained within Lower to Upper Cretaceous marine and nonmarine sedimentary and andesitic volcanic rocks, which are particularly well-developed in the Tchaikazan River succession and the Powell Creek Formation.

Local Geology

Rocks in the study area range from Permian to Early Cretaceous in age. The two main units recognized are the Early Cretaceous volcano-sedimentary Tchaikazan River succession and the Late Cretaceous Powell Creek Formation (Figure 2a; McLaren, 1990; Israel, 2001). Several large, north-dipping normal faults are exposed and a large, east-striking thrust sheet, which placed the Tchaikazan River succession on top of the Powell Creek Formation, divides the area. These units host several copper showings, the three largest of which are referred to as Hub, Charlie and Northwest Copper (Figure 2a).

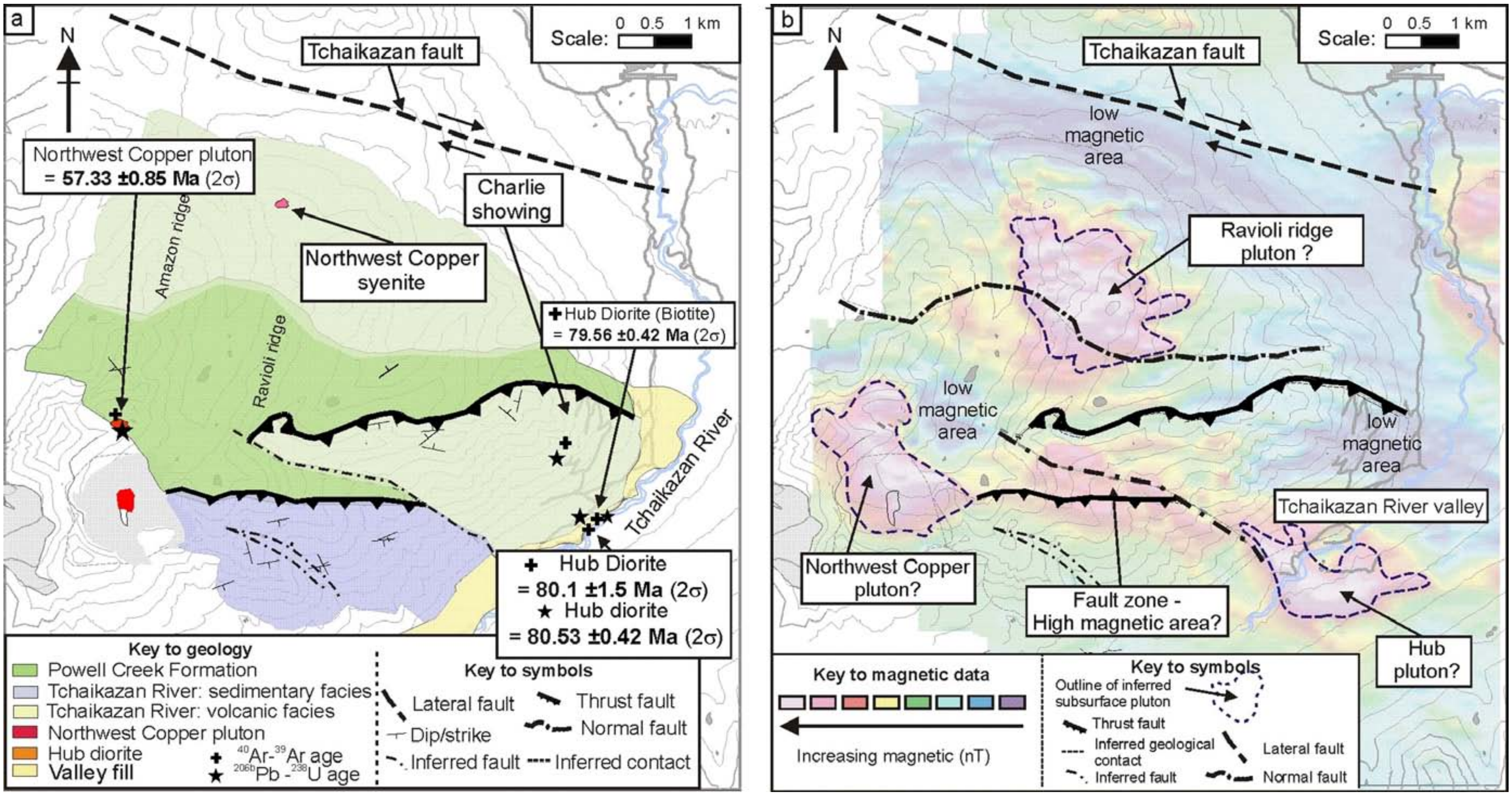


Figure 2. Maps of the Taseko Lakes study area highlighting: **a)** the three mineral showings (Hub, Charlie and Northwest Copper) and the major structural and geological boundaries; **b)** magnetic anomalies that reveal the inferred subsurface extents of igneous bodies.

Lithological Units

Tchaikazan River Succession

The oldest packages of rocks located in the study area are the approximately 1 km thick (Israel, 2001) volcano-sedimentary packages of the Tchaikazan River succession (Figure 2a), which is split into volcanic- and sedimentary-dominated facies. The volcanic facies is characterized by intercalated subaqueous to subaerial volcanic rocks, typically andesitic in composition, and massive andesite flows dominate its upper parts. The sedimentary facies is characterized by marine sedimentary rocks that are highly variable in terms of grain size, bed thickness, structure and rock type (Hollis et al., 2008), including medium to coarse-grained, well-sorted sandstone, conglomerate, siltstone, and mudstone.

Israel (2001) suggested that the Tchaikazan River succession could be as old as 136 Ma, maybe even 146 Ma, and a minimum depositional age is constrained by the Mt. Pilkington intrusion that crosscuts the succession and yields a Pb/U zircon age of 102 ±2 Ma. The Pb/U dating of zircons for this study yielded ages of 80.7 ±0.8 Ma and 76.6 ±0.7 Ma for two feldspar porphyry dikes that crosscut the volcanic facies of the Tchaikazan River succession.

The rocks of the Tchaikazan River succession can be subdivided into three lithological associations: 1) primary volcanic, 2) sedimentary (either volcanic or sedimentary derived) and 3) hypabyssal. Primary volcanic facies are generally the product of effusive volcanic eruption, while hypabyssal intrusions include dikes that are mostly discordant to stratigraphy and sedimentary facies include those formed where volcanic processes have had no influence upon deposition, but can nevertheless comprise volcanic-derived material.

The Tchaikazan River succession likely represents a marine rock sequence deposited near an active arc region. The increase in volcanic material towards the stratigraphic top of the succession suggests a progressive increase in arc-related volcanism. The calcalkaline signatures of the volcanic rocks place them into volcanic arc related and marginal-basin settings.

Powell Creek Formation

The youngest formation in the study area is the Powell Creek Formation, characterized by an extensive package of interbedded, nonmarine, subaerial volcanic and volcaniclastic rocks. Massive volcanic flow units, breccia flows and resedimented volcaniclastic rocks dominate the formation. The Powell Creek Formation is inferred to be at least 93.5 ±0.8 to 89.3 ±1 Ma in age (Schiarizza et al., 1997).

The nonhomogeneous facies of the Powell Creek Formation are highly variable, consisting of massive, poorly sorted, matrix-supported volcaniclastic units of sandstone, siltstone and breccia. The predominantly rounded or angular clasts lack chilled margins, vesicle zonation or radial jointing patterns and are internally massive. Differential weathering of clasts to the surrounding matrix material is frequently observed, causing clasts to protrude from the host matrix (Hollis et al., 2006). The andesite clasts are often plagioclase phyric and hosted within an aphanitic, dark maroon andesite.

The Powell Creek Formation shows aspects of mass flow, traction and suspension, yielding resedimented (syneruptive) volcaniclastic deposits. Sand-sized particles likely dominated sedimentation processes during aggradation, as indicated by the presence of large volumes of coarse crystalline material (particularly feldspar and quartz) shed from the surrounding volcanic environment. The weathering, erosion and reworking of volcanic material produced a widespread volcanogenic sedimentary deposit.

Intrusive Rocks

The study area is host to a variety of intrusive rocks, ranging from dikes to larger plutonic bodies, the largest of which is located within the Tchaikazan River valley and is known as the Hub diorite (Figures 2, 3). It is this diorite that hosts much of the porphyry-style mineralization observed at the Hub porphyry deposit (see below).

Hub Intrusive Centre

A suite of several igneous rocks characterizes the Hub porphyry deposit; outcrops are dominated by coarsely crystalline, massive, porphyritic diorite composed of plagioclase (~50%), biotite (10–25%) and hornblende (25%) phenocrysts in an aphanitic, plagioclase-dominated groundmass. The $^{40}Ar/^{39}Ar$ (biotite and hornblende) and $^{206}Pb/^{238}U$ (zircon) geochronology constrained the age of the Hub diorite to ca. 80 Ma (Figures 3, 4a–c). The Hub diorite is cut by an unmineralized plug of equigranular monzonite as well as by a 5 m wide feldspar-hornblende porphyry dike which, though unmineralized, contains up to 7% pyrite. Samples from this single feldspar-hornblende dike from the intrusive centre yielded an age of ca. 70 Ma. Feldspar porphyry dikes considered to be part of this intrusive centre were also sampled from the Charlie showing area, where they crosscut the Early Cretaceous rocks of the Tchaikazan River succession (see above); these yielded ages of 80.7 ±0.8 Ma, 77.49 ±0.97 Ma and 76.6 ±0.7 Ma (Figure 4–f).

Northwest Copper Intrusive Centre

The youngest intrusive rock in the study area is the Northwest Copper pluton, which is exposed in the western portion of the study area (Figure 2). It is felsic in composition, containing approximately 40% quartz, 30% plagioclase and 30% other minerals, including biotite and hornblende.

This complex intrusion, characterized by several compositional variations, contains numerous round xenoliths of the Powell Creek Formation and crosscutting aplite dikes. The Northwest Copper pluton yielded a Pb/U zircon age of 57.33 ±0.85 Ma (Figure 4g), while a diorite dike proximal to the Northwest Copper pluton gave a $^{40}Ar/^{39}Ar$ hornblende cooling age of 60.01 ±0.46 Ma (Figure 4h). A small plug of equigranular syenite that occurs on the northern part of Ravioli ridge (Figure 2) comprises >60% anhedral nepheline crystals, 30% quartz and 10% hornblende.

Other Intrusive Rocks

Throughout the study area, numerous feldspar-hornblende dikes of unknown age crosscut the Cretaceous volcanic rocks. These dikes are highly altered and do not appear to be related to the igneous centres, but could be related to the Tchaikazan Rapids pluton (ca. 6 Ma; Israel, 2001), which is found to the north of the study area. Subsurface intrusions are inferred from the aeromagnetic data (Figure 2b). Some magnetic highs correspond well to known intrusive bodies even though they are sitting in volcanic rocks; others are interpreted as representing subsurface intrusions (Figure 2 b) that are presumably similar in age to the Hub or Northwest Copper intrusive rocks.

Structure

Thrusts

Large, contractional, north-verging thrust faults placing andesite rocks of the Tchaikazan River succession atop the younger Powell Creek Formation are a dominant feature in the study area. These faults, dipping moderately to the southwest and generally striking east (Figure 2), are characterized by gouge-rich zones that are up to several metres thick. Timing of thrusting is not well constrained, but a sample of fine-grained illite collected from one of these large thrust zones yielded a $^{40}Ar/^{39}Ar$ cooling age of 60.53 ±0.33 Ma (Blevings, 2008).

The northwestern part of the mapped area is dissected by a large normal fault (Figure 2) that juxtaposes the early Tchaikazan River succession next to the Powell Creek Formation; it is inferred to dip steeply to the north and to have a normal offset. The Tchaikazan fault, observed to the north of Ravioli ridge, is a southeast-striking, high-angle, right lateral fault (Figure 2; Israel, 2001). It is the largest structure observed in the area, with a strike length of nearly 200 km and suggested dextral offset of 8 km (Israel, 2001).

Mesoscale striated fault surfaces are common in many parts of the study area, but the lack of good marking units prevents determining the extent of displacement. These fault surfaces are particularly well-developed in the Charlie showing area and around the thrusted area, where faults typically dip >50º, strike northwest and have unknown kinematics. The fault zones are relatively narrow, steeply dipping to the south (>60º) and visible over several tens of metres. Shear zones, brittle fracturing and vein density increase to the northwest of the Tchaikazan River valley.

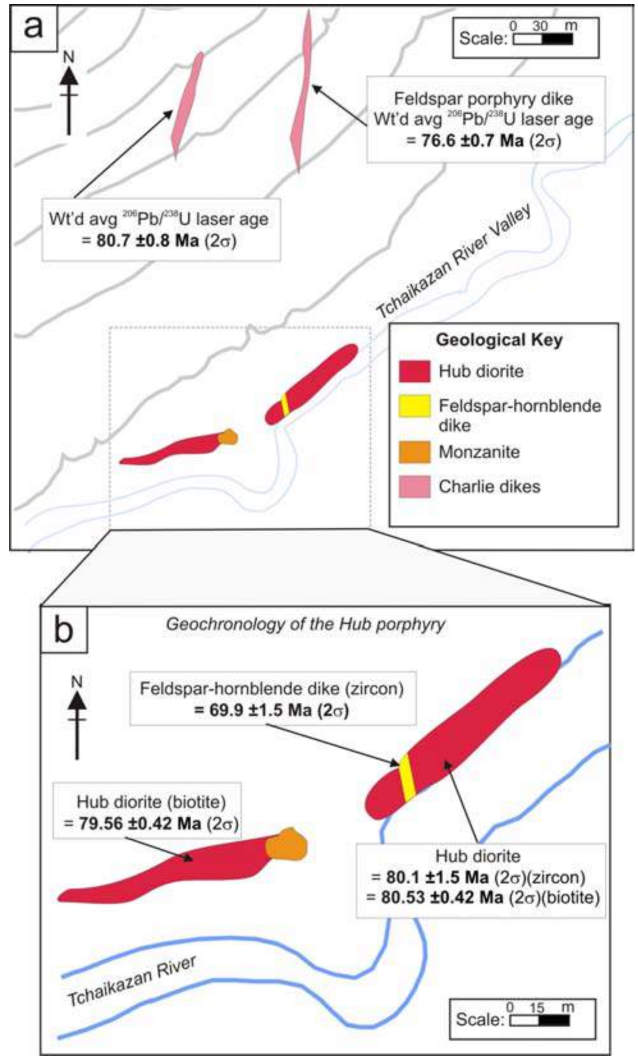


Figure 3. Maps of the Hub porphyry deposit and surrounding Charlie dikes showing: **a)** geological and **b)** geochronological data.

Character of Alteration and Mineralization

The study area can be divided into three domains showing evidence for hydrothermal alteration referred to as the Hub porphyry, the Charlie showing (where gold-bearing veins were previously reported) and the Northwest Copper showing (where native copper and chalcopyrite-bearing veins have been observed).

Hub Porphyry

The Hub porphyry, hosted in the Hub diorite, is located within the Tchaikazan River valley and exposed along the Tchaikazan River itself (Figures 2, 3). Exposure is generally poor and limited to a few hundred metres along man-

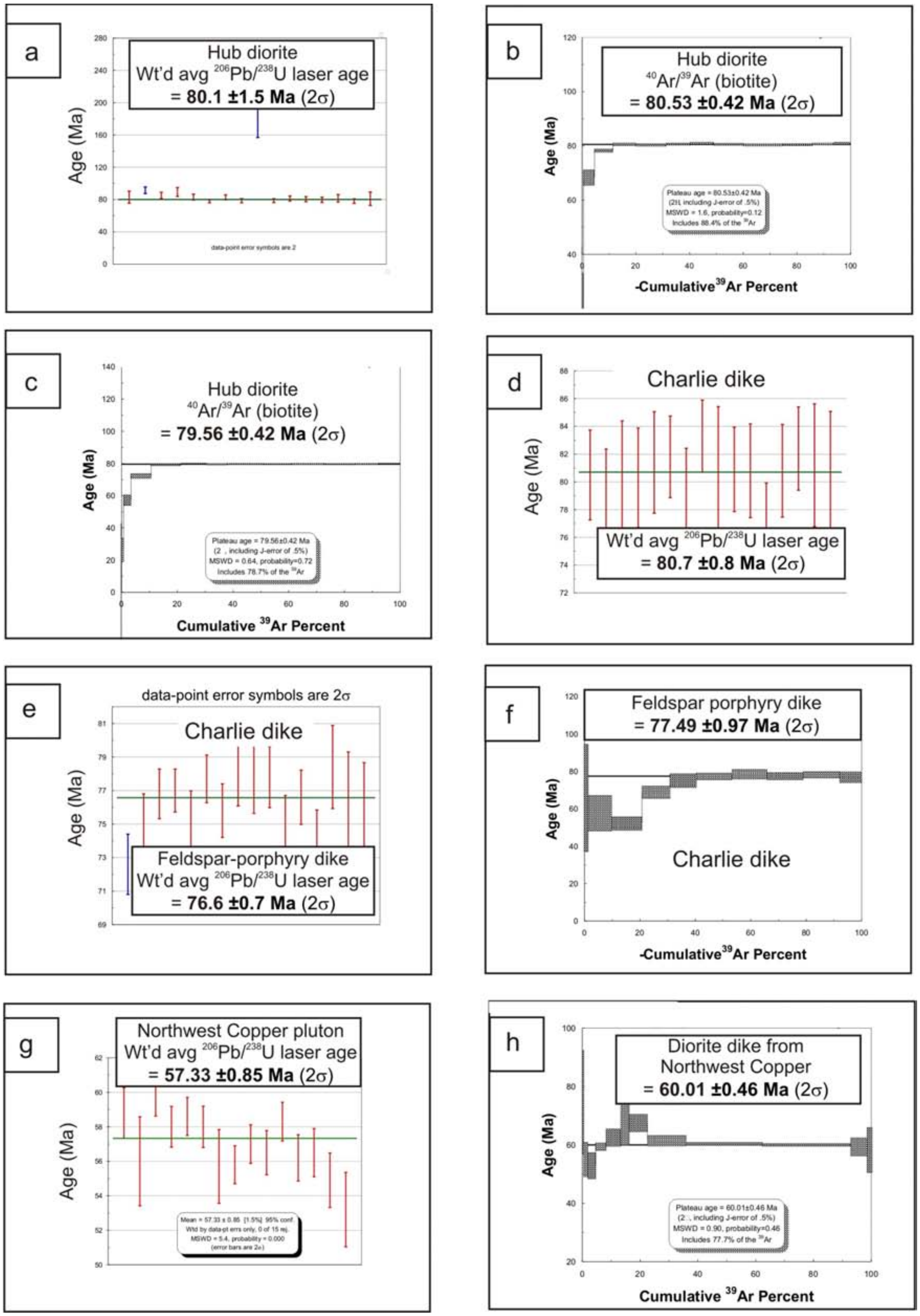


Figure 4. Plots showing geochronological data: **a)** ^{206}Pb/^{238}U age determination for the Hub diorite; **b)** ^{40}Ar/^{39}Ar (biotite) age determination for Hub diorite; **c)** ^{40}Ar/^{39}Ar (biotite) age determination for the diorite phase at the Hub showing; **d)** ^{206}Pb/^{238}U age determination for the crosscutting dike at Charlie showing; **e)** ^{206}Pb/^{238}U (zircon) age determination for a similar feldspar porphyry dike at the Charlie showing; **f)** ^{40}Ar/^{39}Ar (hornblende) cooling age determination for the same dike as in **e); g)** ^{206}Pb/^{238}U (zircon) age determination for the Northwest Copper pluton; and **h)** ^{40}Ar/^{39}Ar hornblende cooling age determination for the diorite dike at the Northwest Copper showing.

made geological trenches and to drillcore from four drillholes. Hydrothermal activity is preserved by a phase of hydrothermal breccia and biotite-magnetite alteration, locally intense sericite and propylitic alteration, and chalcopyrite±bornite±molybdenite mineralization.

Alteration

Hydrothermal Breccia

A magnetite-biotite–altered hydrothermal breccia (Figures 5, 6a, b) is volumetrically the second-most prominent rock type observed at the Hub showing, after the dominant diorite phase (see above). Recent drilling has shown the breccia extends to a depth of at least 260 m (Figure 5). The hydrothermal breccia typically consists of ~60% matrix/cement, 30% clast material and 0–10% open space. Fragments are dominated by compositions reflecting the immediate wallrocks, including fine-grained andesite, diorite, quartz-vein fragments (Figure 6c, d) and rare monzonite. Most of the fragments, especially those of diorite and monzonite, are subangular to subrounded and typically measure a few centimetres in diameter; however, it appears that blocks of andesite (metres in size), likely representing pieces of the host wallrocks, are present within the stratigraphy. The breccia is most common in the upper parts of drillholes, where it forms along the margin of a gently southeasterly (?) dipping sheet of Hub diorite.

Biotite-Magnetite Alteration

Brown, fine-grained biotite is the dominant alteration mineral in the hydrothermal breccia, but it also contains variable amounts of magnetite and quartz (Figure 6). The biotite-magnetite assemblage is confined to the Hub showing. Hydrothermal biotite typically replaces magmatic biotite and hornblende, and is often pseudomorphed by later chlorite.

Sericite Alteration

Sericite partially replaces plagioclase phenocrysts locally within the Hub diorite. Intense sericite alteration is observed within the youngest feldspar-hornblende dike at the Hub showing. Weak to moderate sericite alteration is observed throughout the Hub diorite, where fine-grained sericite selectively replaces plagioclase phenocrysts.

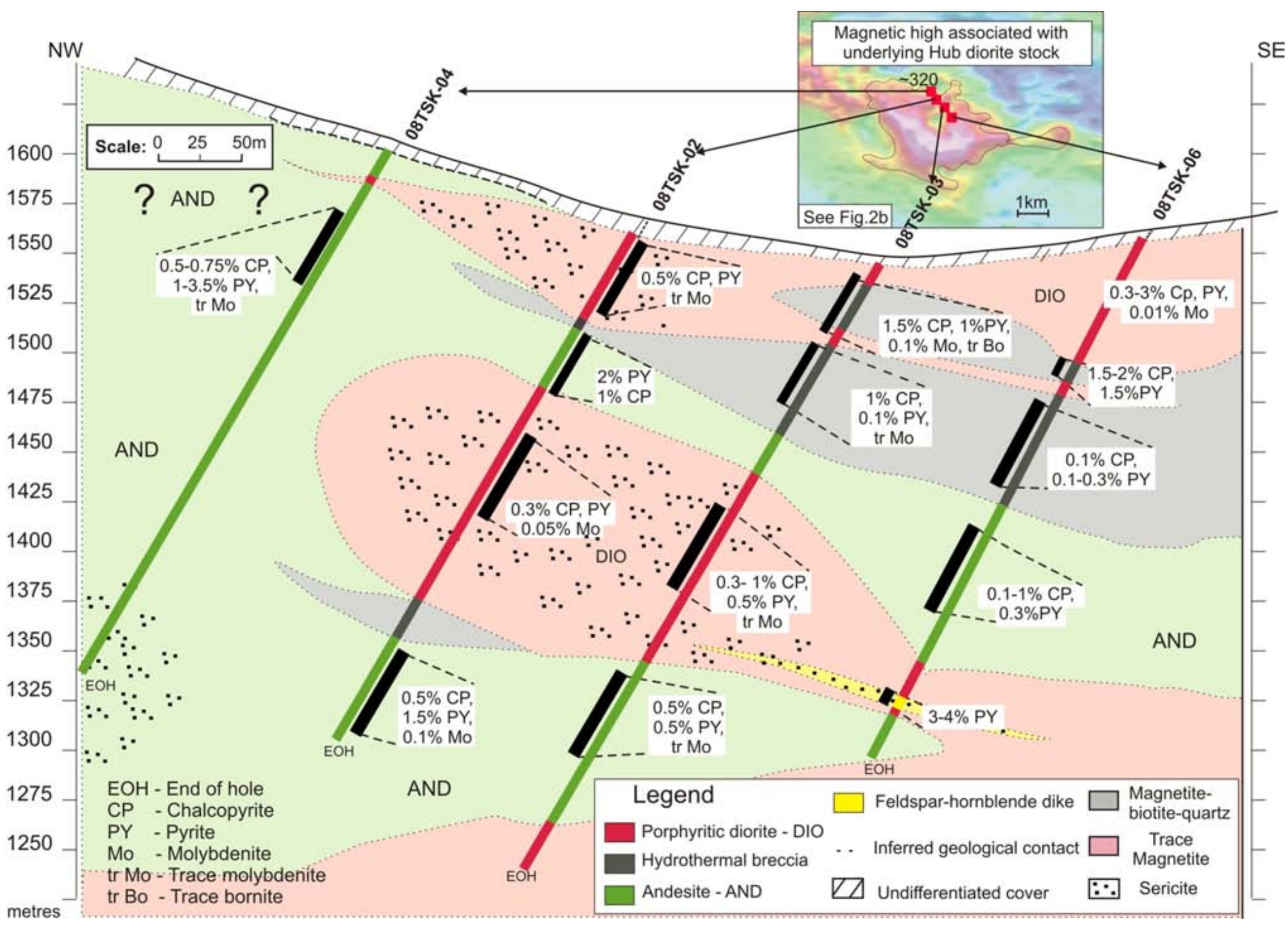


Figure 5. Cross-section of four drillholes from the Hub porphyry looking northeast showing rock types, alteration and mineralization. Inset map shows the inferred magnetic anomaly.

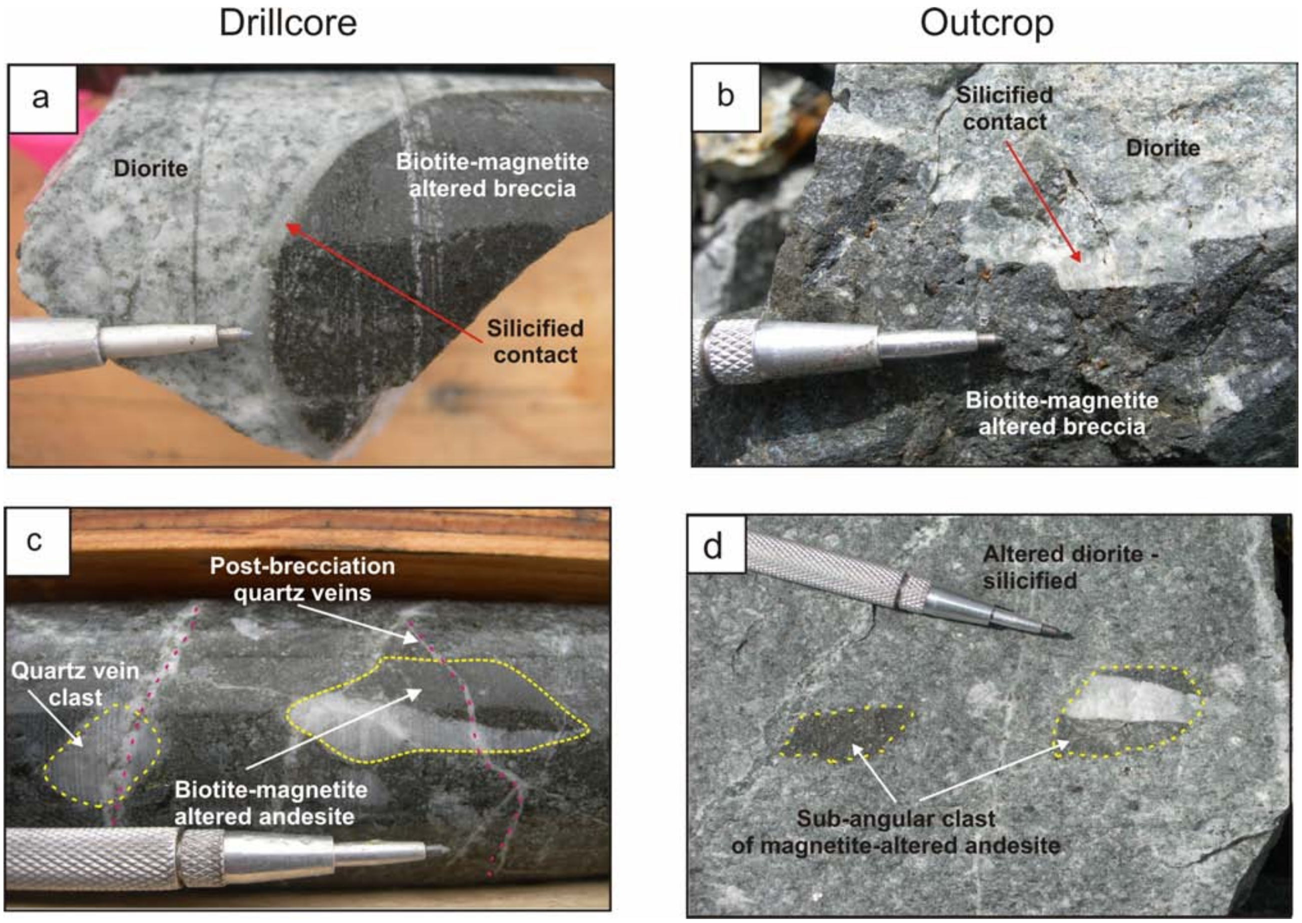


Figure 6. Comparison of features observed from drillcore and outcrop within the magnetite-biotite–altered hydrothermal breccia: **a)** hole 08TSK-02 sample (depth of 100.2 m) showing the contact between the Hub diorite and the hydrothermal breccia; **b)** same relationship as observed in (a) for sample taken from trenches at the Hub showing; **c)** hole 08TSK-06 (depth of 89 m), showing clastic breccia with andesite and quartz vein clasts; and **d)** same textural and compositional relationship as observed in (c).

Chlorite-Epidote (Propylitic) Alteration

Chlorite replaces primary biotite, plagioclase and hornblende locally in the Hub diorite; secondary biotite of the magnetite-biotite alteration is also pseudomorphed by chlorite (see above). Fine-grained epidote alteration is rare. Later chlorite alteration has affected the magmatic, disseminated and vein replacement biotite in the potassic alteration zone.

Mineralization

The Hub porphyry contains copper and molybdenite mineralization. The mineralization takes several forms, including those of sulphide-bearing quartz stockwork veining, disseminated sulphides in the Hub diorite and sulphide phases as cement in the hydrothermal breccia. Chalcopyrite, bornite, molybdenite and galena are among the common sulphide mineral assemblages observed. Disseminated chalcopyrite, pyrite and rare bornite and galena were observed within rocks of the Hub diorite and the hydrothermal breccia. Disseminated sulphides are typically <1 mm in size and located within the groundmass of the rock.

Massive quartz veins containing sulphide minerals, consisting of pyrite, chalcopyrite, molybdenite and rare bornite and galena, are common. The sulphides are often massive in form, with the most commonly observed sulphide assemblage consisting of pyrite and chalcopyrite. Molybdenite is rarely seen in close association with chalcopyrite, but stringers of molybdenite are found locally in association with large quartz veins (>5 cm thick) throughout the drillcore. Fracture-coats of fine-grained molybdenite were observed in the Hub diorite. In the hydrothermal breccia, chalcopyrite and pyrite exhibit void-filling or interstitial textures.

Stable Isotope Results

A total of four quartz veins and one magnetite vein were sampled using standard mean ocean water (SMOW) analysis. The quartz veins typically hosted chalcopyrite mineralization and measured up to 1 cm in thickness. The suite of quartz veins from the Hub diorite displayed ä^{18}O (SMOW) rock values ranging from 8.7 to 10.3, while the magnetite vein yielded a ä^{18}O rock value of 3.4. These values correlate with typical values for hydrothermal fluids derived from a magmatic source.

Depth of Emplacement

The evolution of porphyry copper deposits is strongly affected by the depth of emplacement and the effect this has on the solubility of volatiles and metals in the hydrothermal fluid. Fluid inclusion samples were prepared from several veins from the Hub diorite, but yielded no independent evidence of pressure and, hence, depth. Instead, low-temperature fission-track thermochronology was used in an attempt to reconstruct the depth at which mineralization occurred, as this technique can provide estimates of exhumation.

A sample of the Hub diorite was collected from the valley base for zircon (ZFT) and apatite (AFT) fission track analysis (Figure 7a, b). A sample from the Hub intrusive complex yielded a ZFT date of 85.6 ±1.8 Ma, which corresponds to the time of emplacement of the Hub diorite determined from Ar/Ar and Pb/U dating (Figure 3). In the case of geologically realistic exhumation rates, the closure temperature for ZFT is 200–240ºC (Reiners and Brandon, 2006). The correspondence between Pb/U, Ar/Ar and ZFT determinations implies that the Hub diorite cooled to below 200–240 ºC immediately after emplacement which; for geothermal gradients of 25–30ºC/km, would imply an emplacement depth of <6–9 km. The AFT sample yielded a date of 31.4 ±1.8 Ma, a result significantly younger than the Hub diorite; this sample is therefore thought to be a product of exhumation rather than cooling of the pluton. A closure temperature of ~90–120ºC and a geothermal gradient of 25ºC/km would correspond to a depth of 3–4 km at 31 Ma.

Five additional samples of Cretaceous intrusive rocks from differing elevations were also collected for AFT analysis to assess age-elevation relationships (Figure 7a, b). All six samples produced a near-linear age-elevation relationship corresponding to an average exhumation rate of 40 m/Ma over a period of 55–30 Ma (Figure 7a). This average exhumation rate would imply that the present exposure of the Hub porphyry was at an approximate depth of 5 km at 55 Ma; if the same exhumation rate continued back to the time of emplacement, it would imply an approximate depth of 6 km (Figure 7c). Comparatively, the estimated stratigraphic thickness of the units above the emplacement depth of the Hub porphyry into the Tchaikazan River succession is estimated as ~5 km, an estimate consistent with the AFT result.

Charlie and Northwest Copper Showings Area

This area is located to the northwest of the Hub porphyry (Figure 2). Hydrothermal alteration is variably developed across this area, as are several small polymetallic showings (the range of alteration types is discussed below). Most of the andesite rocks of the area display primary assemblages of plagioclase and hornblende.

Alteration

'Propylitic' Alteration

A chlorite-epidote±calcite–alteration assemblage is widespread throughout the andesitic units of the Charlie and Northwest Copper showings (Figure 8). Typically, these alteration minerals replace primary igneous phases, such as hornblende, biotite and plagioclase (Figure 9a–c). It is difficult to know whether this replacement is related to a regional, low-temperature metamorphic event, or whether it is a distal, lower temperature 'propylitic' component of the magmatic-hydrothermal porphyry system.

Intense Epidote (Ca) Alteration

Strong epidote alteration and vein epidote is most commonly found proximal to large-scale faults, particularly in the area of the Northwest Copper showing (Figure 8). Epidote typically replaces mafic phenocrysts of the andesite rocks assigned to the Tchaikazan River succession and Powell Creek Formation. Fine-grained, massive epidote pods and vein epidote are located near the Northwest Copper pluton (see above). Interestingly, garnet was found in an isolated sample within this alteration assemblage, which suggests the presence of higher temperature calcic alteration components.

Sericite Alteration

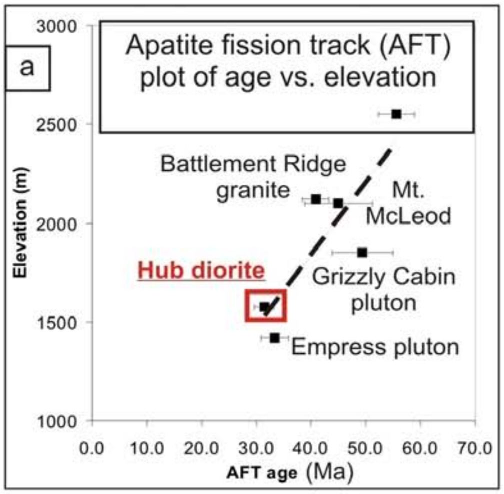
Sericite alteration in the area of the Charlie and Northwest Copper showings is typically expressed as sericite replacement of plagioclase and mafic minerals in andesite and feldspar porphyry dikes, and as quartz-pyrite-sericite alteration in parts of the Tchaikazan River succession sedimentary facies (Figure 9d, e). Sericite also forms selvages to quartz-sulphide veins throughout the area.

'Advanced Argillic' Alteration

Argillic alteration is locally developed on the western flank of the Northwest Copper showing (Ravioli ridge; Figure 8), a zone proximal to a large east-striking normal fault (Figure 2a). The Powell Creek rocks in the hangingwall appear to have undergone significant silicification. Hydrous clay minerals, such as kaolinite, dickite, montmorillonite and halloysite, were identified using shortwave infrared (SWIR) analysis and characterize this alteration zone (Figure 9f). The clay imparts a distinctive colour and texture to the rock resulting in a white/yellow earthy rock that contrasts with the surrounding maroon-coloured Powell Creek Formation.

Mineralization

Mineralization is varied throughout the two areas: The Charlie showing area hosts comb-texture quartz veins, which contain polymetallic sulphide assemblages, and the Northwest Copper showing, as it name implies, hosts milky-coloured, massive quartz veins, which contain native copper, tetrahedrite, digenite, and chalcocite. The main



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Name	Easting	Northing	Elevation	Igneous rock
Hub diorite	453430	5668870	1572 m	Porphyritic diorite
Empress	471890	5661590	1420 m	Porphyritic granite
Grizzly Cabin	457161	5663835	1850 m	Quartz monzodiorite
Mt. McLeod	473567	5660789	2120m	Granodiorite
Mt. McLeod	473633	5658101	2550 m	Coarse granite
Battlement Ridge	456935	5675682	2100 m	Equigranular granite

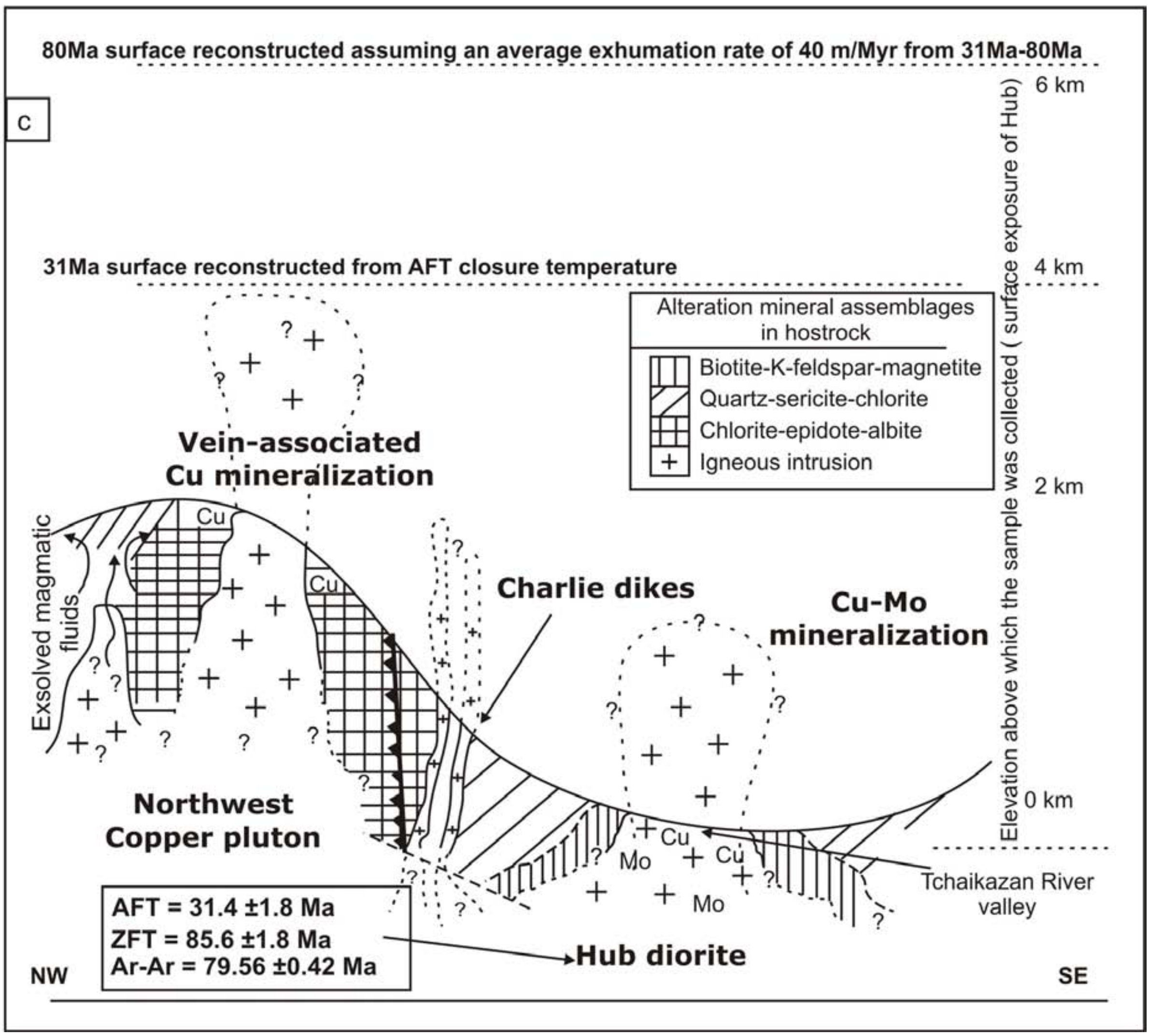

Figure 7. Thermochronology results and related cross-section showing **a)** apatite fission track age vs. elevation plot (m) for five samples of Cretaceous intrusive rocks collected within the Taseko Lakes study area and best-fit line through the data that yields an average exhumation rate of 55 to 30 Ma; **b)** table of the collected thermochronology samples' character, location and elevation; and **c)** schematic cross-section of the study area from northwest to southeast, reconstructing the surface expression at 6 km (80 Ma), 4 km (30 Ma) and present-day.

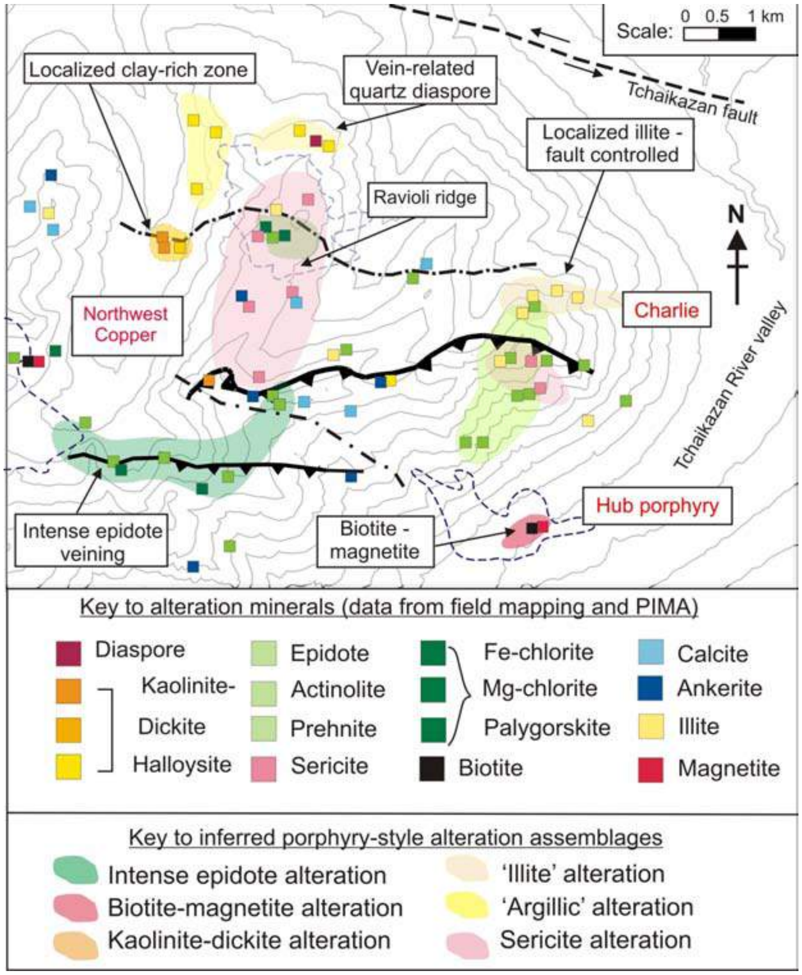

Figure 8. Location of alteration zones in the Taseko Lakes study area showing alteration minerals and alteration assemblages, including the 'propylitic' chlorite-epidote, 'advanced argillic' clay-dominated and 'potassic' biotite-magnetite alteration zones.

styles of mineralization are described in greater detail below:

Comb-texture, sulphide-bearing quartz veins are a style of vein characterized by massive, comb tooth quartz with a centre-fill of chalcopyrite or pyrite, and rare galena. Veins are on average 2 cm thick, reaching a maximum thickness of 5 cm.

Coarse tetrahedrite, malachite, and azurite. Tetrahedrite was located in numerous samples from a subcrop of quartz-diaspore vein material; it is typically coarse-grained and accounts for up to 5% of the vein material. Malachite and azurite were developed in the silicified material surrounding the tetrahedrite-bearing zone.

Stringers of, and disseminated native copper were located in two locations near the Northwest Copper thrust fault. The native copper was associated with milky white, massive quartz veinlets. Malachite and chrysocolla alteration around the veins was an indicator to their copper content. Native copper veins are also reported from the southern part of Ravioli ridge.

Epidote-chalcopyrite-pyrite-magnetite veins occur only within the area of the Northwest Copper showing, proximal to the Northwest Copper pluton. Chalcopyrite is typically coarse grained and associated with pyrite and minor coarse magnetite. Magnetite forms thin, discontinuous stringers associated with the epidote and chalcopyrite. Pyrite forms massive aggregates in centimetre-thick veins. The veins typically exhibit 1–5 cm wide alteration selvages of illite and chlorite.

Fluid Inclusion Analysis

A total of ten doubly polished thin sections of quartz vein material were chosen after petrographic analysis using plane polarized light. Many of the typically coarse-grained and massive veins were host to sulphide mineralization. The fluid inclusions within were variable in type, distribution pattern, homogenization temperature, phase content and volume-percent vapour, a pattern commonly found in other porphyry copper deposits.

Primary fluid inclusions (P) were rarely sufficiently developed, or too small, to be readily analyzed (Figure 10). This is not uncommon in samples from the porphyry environment and is the reason behind the need to analyze larger inclusions. Growth zones in quartz crystals are the usual host to these P inclusions (Figure 10a); however, these were too small for analysis (<5 µm). The inclusions are liquid-rich, two-phased (liquid to vapour ratio), subspherical and lack secondary daughter minerals. A single, small vapour bubble accounts for less than 15% of the inclusion (maximum of 40%). Abundant secondary and fluid inclusions (Figure 10b) are typically small and crosscut crystal boundaries. Measurements of the melting temperature of ice [Tm (ice)] for the liquid-rich, halite-undersaturated inclusions range between –0.8 and –3.4 ºC and homogenize at temperatures between 169 and 193ºC. Melting data provides a sensitive measure of bulk salinities, which range between 1.7 and 5.1 wt. % NaCl equivalents. The inclusions are a record of low-salinity dilute fluids trapped under conditions ranging from 190 to 230 ºC. Fluid inclusion analysis

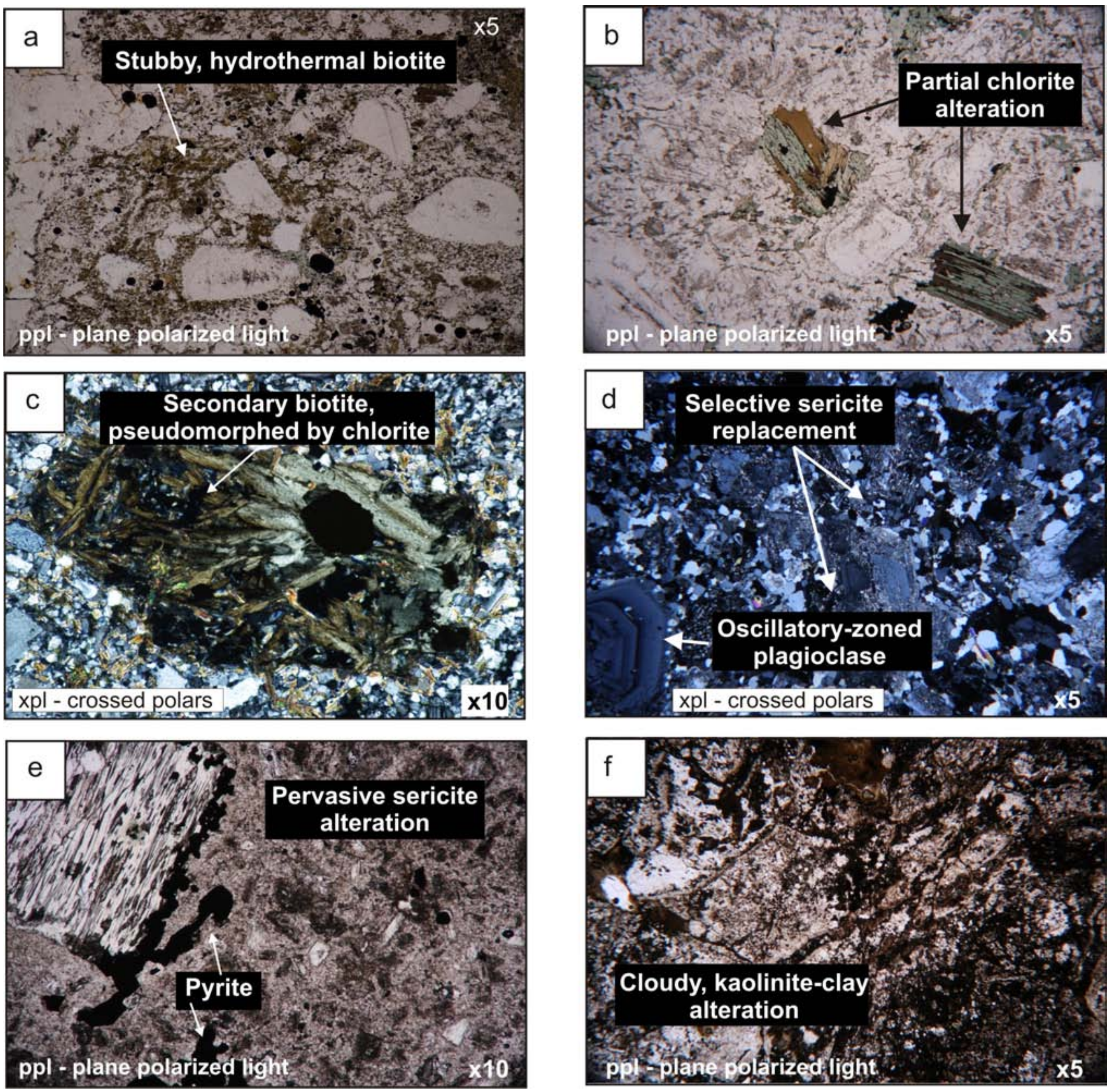

Figure 9. Photomicrographs of the Charlie and Northwest Copper andesite samples showing **a**) stubby, hydrothermal biotite infill (ppl); **b)** partial chlorite alteration of biotite (xpl); **c)** replacement of hornblende by secondary biotite, which is then replaced by subsequent chlorite; **d)** partial, patchy sericite alteration of plagioclase phenocrysts (xpl); **e)** pervasive sericite alteration (ppl); and **f)** pervasive kaolinite alteration (xpl).

proved inconclusive in generating a paleodepth or realistic temperature for the magmatic-hydrothermal system.

Stable Isotope Results

A total of nine samples of vein calcite were taken from areas of the Charlie and Northwest Copper showings (results shown in Figure 11a–c). These veins were typically massive calcite-only veins or quartz veins with a calcite centre-fill. The samples display ä^{13}C fluid values ranging from –9.853 to –3.265, and ä^{18}O fluid values, from 5.891 to 11.088 (Figure 11c). These values are within the range of values suggested as corresponding to a deep-seated or magmatic source for the CO_2 carbon which is characterized by ä^{13}C fluid values ranging from –3 to –8, with a mean at –6 per mil (Ford and Green, 1977; Dreher et al., 2008). However, Kerrich and Wyman (1990) stated that the same signature could be created by leaching of carbonate hostrocks or oxidation of free carbon, and does not necessarily indicate that the CO_2 is of mantle or magmatic origin. Therefore the C and O isotope data presented in this report do not clearly discriminate between the possible fluid sources.

The suite of quartz veins from the Hub showing displayed ä^{18}O (SMOW) rock values ranging from 8.7 to 10.3 (Figure 11a). These veins display typical igneous values (Taylor, 1968), whereas samples taken from the Charlie and Northwest Copper showings revealed ä^{18}O values progressing outward from the Hub porphyry (Figure 11b). Samples from quartz-magnetite veins near the Northwest Copper pluton yielded formation temperatures of 490ºC for ä^{18}O from coprecipitating quartz and magnetite (Figure 11b), calculated using isotope fractionation data to gain an appropriate temperature of formation. A kaolinite mineral sample from the Northwest Copper ‘advanced argillic’ alteration zone yielded a ä^{18}O rock value of 6.6, and a äH rock value of –113 (Figure 11a).

Interpretation

The Hub porphyry system displays the igneous, alteration and metallogenic signatures of a calcalkaline copper porphyry deposit. Mineralization is hosted in the 80 Ma Hub diorite and cut by 69 Ma feldspar-hornblende dikes, constraining the age of mineralization to between ca. 80 and 70 Ma. The Hub diorite appears to have been emplaced at a depth of 5–6 km at this time. Thrusting at approximately 60 Ma led to the placement of the Tchaikazan River succession over the Powell Creek Formation. Subsequent exhumation at a rate of 40 m/Ma from 80 to 31 Ma and of >100 m/Ma from 31 Ma to the present day gives a depth of 3–4 km.

The dominance of the potassic mineral assemblage (higher temperature hydrothermal alteration) at the Hub porphyry is inferred to be proximal to the centre of the porphyry system. Weak sericite alteration occurs as a lower temperature overprint. There is no physical evidence of a fault located between the Hub and Charlie showings, nor would the reconstructed stratigraphic relationships require that one have occurred. Therefore, the ‘propylitic’ and ‘illite’ alterations in the Charlie showing area appear to be placed a true 800 m above the core zone of potassic alteration at the Hub showing and are thought to be a distal expression of the magmatic-hydrothermal system. The strong vein-associated epidote alteration of hostrocks and vein epidote located near thrust faults may well reflect hydrothermal activity associated with the development of these structures post-porphyry activity, around 60 Ma ago. Sericite alteration, which is most developed on Ravioli ridge, may lie above the inferred subsurface intrusion and therefore be a result of the distal effects of magmatic-derived fluids. The ‘advanced argillic’ alteration zone represents a near-surface alteration and its acidic nature was likely a product of acidic magmatic vapour condensation. The epidote alteration appears related to fluid flow around faults, and the Northwest Copper pluton, suggesting a probable hydrothermal alteration age of ca. 60 Ma.

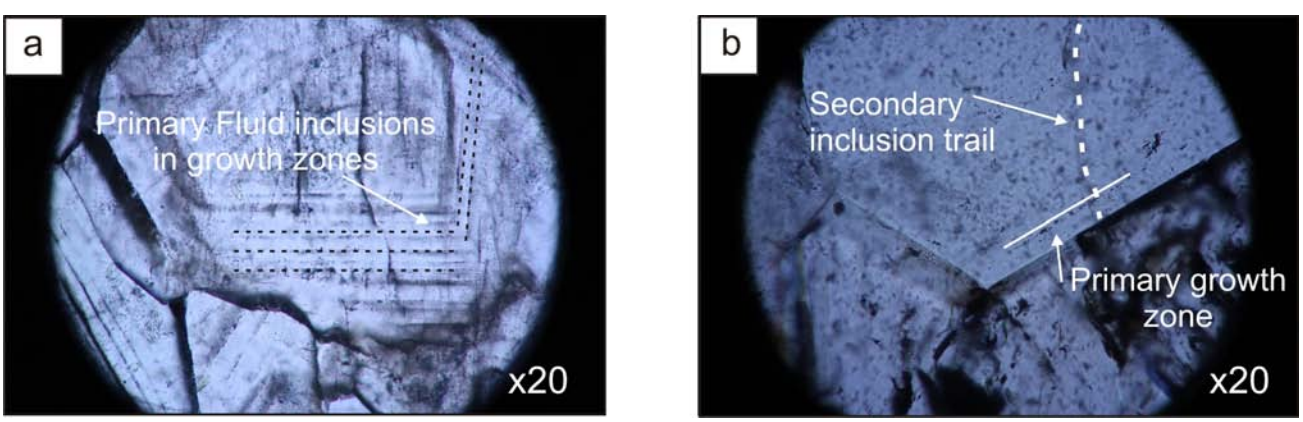

Figure 10. Photomicrographs of fluid inclusions as seen in plane-polarized light: **a)** primary fluid inclusions in growth zones in quartz crystals; and **b)** secondary fluid-inclusion trail crosscutting earlier primary assemblage.

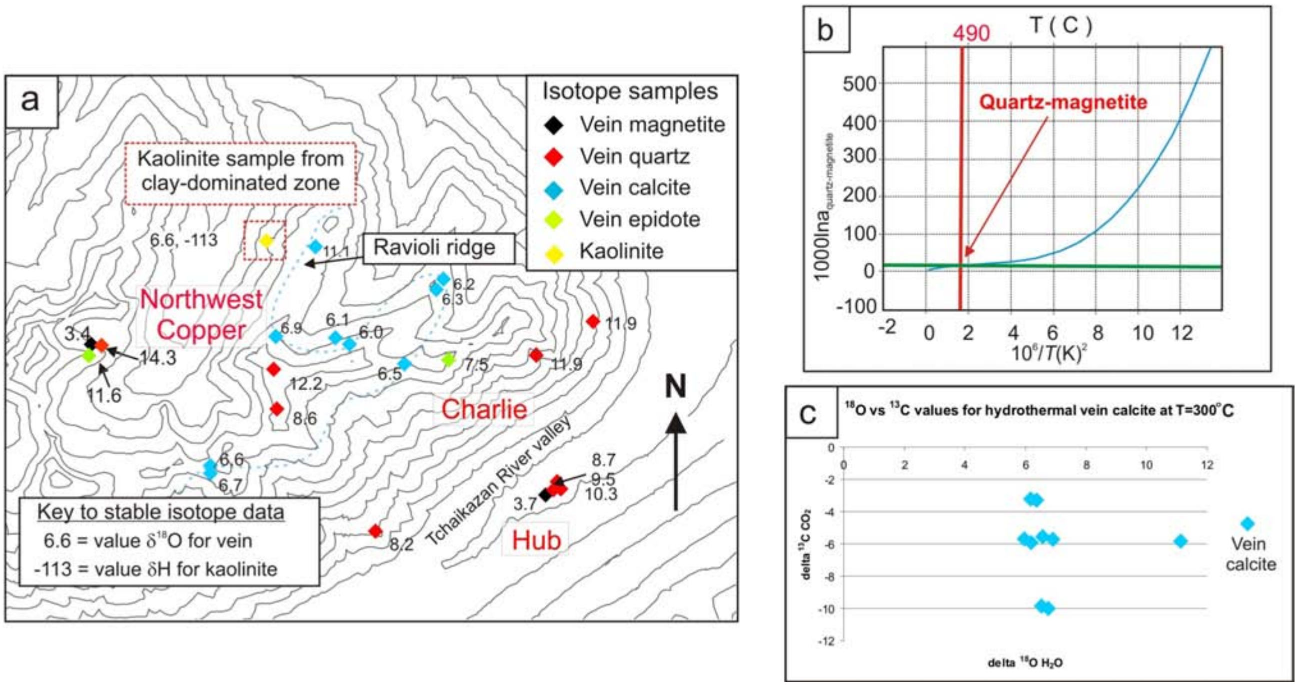

Figure 11. Stable isotope analysis results and hydrothermal fluid temperature plots: **a)** topographic map of the location of stable isotope samples taken from vein material and kaolinite rock sample highlighting the Hub, Charlie and Northwest Copper showings; **b)** ä^{18}O plot for the mineral pair quartz-magnetite showing that the quartz and magnetite veins at the Northwest Copper showing formed at ~490ºC, as determined using equations from Zhang et al. (1989) and Chacko et al. (2004) for Ä(A-B) = 10.8‰ (just within the limits of normal igneous rocks); and **c)** plot of ä^{18}O vs. ä^{13}C values for hydrothermal vein calcite samples (*see* blue squares in(a)) for a hypothesized temperature of 300 ºC.

Discussion and Implications

The similarity of the ages and geological composition of the intrusive rocks of the Hub porphyry to those observed in the Charlie showing area suggests that the mineralization at both localities may be linked to the same period of magmatism responsible for the 77 Ma Prosperity deposit. The Northwest Copper showing is different in terms of mineralogy, alteration and age, and is probably linked to separate magmatic activity, perhaps a younger hydrothermal event related to the thrusting at around 60–55 Ma.

The Hub porphyry deposit is the same age as other deposits in the region, in particular the 80 Ma Taseko-Empress showing (Figure 1; *see* Blevings, 2008) and the larger Prosperity deposit. The same age and similar depth of the Hub porphyry, Taseko-Empress and Prosperity deposits may point to an 80 Ma suite of porphyry deposits formed by subduction-related magmatism that was capable of producing porphyry-style mineralization. The porphyry system at Taseko Lakes formed at the deep end of the spectrum of known porphyry deposits (Sillitoe, 1972, 1973). Given the calculated AFT and ZFT depth of the Hub porphyry, two possibilities arise: Either much of the overlying deposit has been lost, or the porphyry deposit was inherently smaller or perhaps truncated (by thrusting of the late Cretaceous crunch?) porphyry deposit. While these Cretaceous rocks do present evidence of magmatic hydrothermal alteration, the evidence supporting their ability to host Prosperity-style mineralization is limited.

Conclusions

The Cretaceous igneous rocks of the Tchaikazan River succession and Powell Creek Formation are host to copper mineralization which occurred between ca. 80 and 70 Ma (Figure 12). Mineralized centres in this area include the Hub diorite, proximal to the Northwest Copper pluton, and the small, vein-related Charlie showing. The character of the mineralization and the hydrothermal alteration is typical of that attributed to porphyry deposits. High temperature potassic alteration is confined to the core of the Hub porphyry and is characterized by biotite-magnetite alteration of the hydrothermal breccia. Distal regions are altered to a chlorite-epidote-calcite alteration that can, and should, be differentiated from an intense epidote-only alteration assemblage proximal to fault zones. Sericite alteration is locally restricted and is pervasive in late crosscutting feldspar-hornblende dikes associated with the Hub porphyry.

The ages for the structures in the study area are not well-constrained, but an illite (Ar/Ar) age for a thrust fault at the Northwest Copper showing yielded an age of 60.53 ±0.33 Ma, which indicates that mineralization likely occurred post-deformation or during the same period of

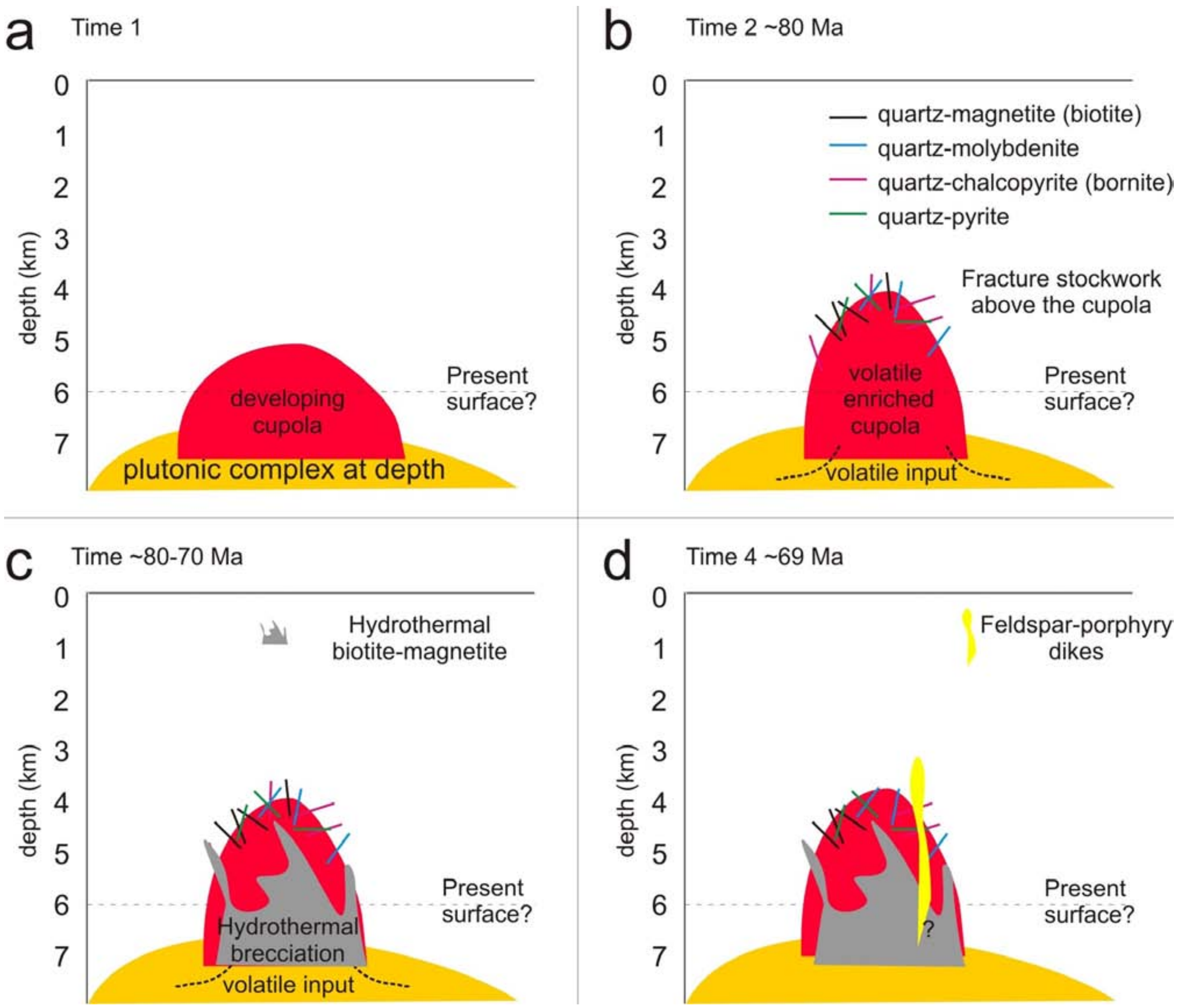

Figure 12. Schematic diagram depicting the evolution of the Hub showing's hydrothermal system in the Taseko Lakes study area: **a)** a large granodiorite pluton at depth develops a cupola at its top; **b)** quartz-magnetite and quartz-sulphide veins form, after volatile input from depth; **c)** brecciation of the granodiorite and surrounding andesite wallrocks occurs, infill of magnetite, biotite and quartz occurs as cement; and **d)** cooling of the magmatic system and intrusion of feldspar porphyry dikes at ca. 70 Ma.

magmatism as the 57 Ma Northwest Copper pluton. This age is consistent with that of the Poison Mountain (Cu±Mo±Au) porphyry prospect, where K-Ar dating (hornblende and biotite) has yielded an age of 59–56 Ma (MINFILE 092O 046; MINFILE, 2008) for the intrusion, potassic alteration and mineralization.

Both stable isotope studies and microthermometric data from fluid inclusion analysis on the Taseko Lakes area proved uncertain. However, low-temperature thermochronology using AFT and ZFT provided an estimated average erosion rate of 40 m/Ma, which indicates that the porphyry system was emplaced at a depth of 5–6 km. The similarity in age, composition, mineralogy and geological setting of the Hub porphyry to that of the neighbouring Prosperity deposit is encouraging, and indicates that Late Cretaceous conditions were conducive to producing large porphyry copper deposits.

The results gathered over three field seasons of work indicate that the Taseko Lakes area displays evidence of porphyry-style intrusion, alteration and mineralization. The relationships derived from field mapping and laboratory work provide a useful background for the effective continued exploration of the study area.

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References

Blevings, S.K. (2008): Geologic framework for Late Cretaceous magmatic-hydrothermal mineralization in the Taseko Lakes region, southwestern B.C.; M.Sc. thesis, University of British Columbia, 244 p.

Chacko, T., Cole, D.R. and Horita, J. (2001): Equilibrium oxygen, hydrogen and carbon isotope fractionation factors applicable to geologic systems; Reviews in Mineralogy and Geochemistry, v. 43, no. 1, p. 1–81.

Dreher, A.M., Xavier, R.P., Taylor, B.E. and Martini, S.L. (2008): New geologic, fluid inclusion and stable isotope studies on the Controversial Igarapé Bahia Cu-Au deposit, Carajá Province, Brazil; Mineralium Deposita, v. 43, no. 2, p. 161–184.

Ford, J. H. and Green, D. C. (1977): An oxygen- and hydrogen-isotope study of the Panguna porphyry-copper deposit, Bougainville; Australian Journal of Earth Sciences, v. 24, no. 1-2, p. 63–80, doi: 10.1080/00167617708728967.

Hollis, L., Blevings, S.K., Chamberlain, C.M., Hickey, K.A. and Kennedy, L.A. (2006): Mineralization, alteration, and structure of the Taseko Lakes region, southwestern British Columbia: preliminary analysis; *in* Geoscience BC Summary of Activities, Geoscience BC, Report 2007-1, p. 297–306.

Hollis, L., Hickey, K. and Kennedy, L.A. (2008): Mineralization and alteration associated with an hypothesized copper (molybdenum) porphyry system in the Taseko Lakes area, southwestern British Columbia (NTS 092O/04); *in* Geoscience BC Summary of Activities, Geoscience BC, Report 2008-1, p. 55–66.

Israel, S. (2001): Structural and stratigraphic relationships within the Tchaikazan River area, southwestern British Columbia: implications for the tectonic evolution of the southern Coast Belt; M.Sc. thesis,, University of British Columbia, 129 p.

Israel, S., Kennedy, L.A., Schiarizza, P., Friedman, R.M. and Villeneuve, M. (2006): Evidence for Early to Late Cretaceous, sinistral deformation in the Tchaikazan River area, southwestern British Columbia: implications for the tectonic evolution of the southern Coast Belt; in Paleogeography of the western North American Cordillera, J. Haggart, R.J. Enkin and J.W.H. Monger (ed.), Geological Association of Canada, Special Paper 46, p. 331–350.

Journeay, J. M. and Friedman, R.M. (1993): The Coast Belt Thrust System: evidence of Late Cretaceous shortening in southwest British Columbia; Tectonics, v. 12, no. 3, p. 756–775.

Kerrich, R. and Wyman, D. (1990): Geodynamic setting of mesothermal gold deposits: an association with accretionary tectonic regimes; Geology, v. 18, no. 9, p. 882–885.

Lowell, D.J. and Guilbert, J.M. (1970): Lateral and vertical alteration-mineralization zoning in porphyry ore deposits; Economic Geology, v. 65, no. 4, p. 373–408.

McLaren, G. P. (1990): A mineral resource assessment of the Chilko Lake planning area; BC Ministry of Energy, Mines and Petroleum Resources, Bulletin 81, 117 p.

MINFILE (2008): MINFILE BC mineral deposits database; BC Ministry of Energy, Mines and Petroleum Resources, URL <http://www.empr.gov.bc.ca/Mining/Geoscience/MINFILE/Pages/default.aspx> [October 2008].

Monger, J. W. H., van der Heyden, P. J., Journeay, M., Evenchick, C. A. and Mahoney, J. B. (1994): Jurassic-Cretaceous basins along the Canadian Coast Belt; their bearing on pre-Mid-Cretaceous sinistral displacements; Geology, v. 22, p. 175–178.

Reiners, P.W. and Brandon, M.T. (2006): Using thermochronology to understand orogenic erosion; Annual Review of Earth and Planetary Sciences, v. 34, p. 419–466.

Richards, J.P. (2003): Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation; Economic Geology, v. 98, no. 8, p. 1515–1533.

Rusmore, M. E. and G. J. Woodsworth (1991): Coast Plutonic Complex: a mid-Cretaceous contractional orogen; Geology, v. 19, no. 9, p. 941–944.

Schiarizza, P., Gaba, R.G., Glover, J.K., Garver, J.I. and Umhoefer, P.J. (1997): Geology and mineral occurrences of the Taseko–Bridge River area; BC Ministry of Energy, Mines and Petroleum Resources, Bulletin 100, 291 p.

Sillitoe, R.H. (1972): A plate tectonic model for the origin of porphyry copper deposits; Economic Geology, v. 67, no. 2, p. 184–197.

Sillitoe, R.H. (1973): The tops and bottoms of porphyry copper deposits; Economic Geology, v. 68, no. 6, p. 799–815.

Taylor, H.P. (1968): The oxygen isotope geochemistry of igneous rocks; Contributions to Mineralogy and Petrology, v. 19, no. 1, p. 1–70.

Tipper, H.W. (1969): Mesozoic and Cenozoic geology of the northeast part of the Mount Waddington map-area (92N), Coast district, British Columbia. Geological Survey of Canada, Paper 68-33.

Tipper, H.W. (1978): Geology of Taseko Lakes map-area (92 O), British Columbia; Geological Survey of Canada, Open File 534.

Titley, S.R. and Beane, R.E. (1981): Porphyry copper deposits; part I, geologic settings, petrology, and tectonogenesis; Economic Geology and the Bulletin of the Society of Economic Geologists, v. 75, 214 p.

Umhoefer, P.J. and Schiarizza, P. (1996): Latest Cretaceous to early Tertiary dextral strike-slip faulting on the southeastern Yalakom fault system, southeastern Coast Belt, British Columbia; Geological Society of America Bulletin, v. 108, no. 7, p. 768–785.

Zhang, X., Nesbitt, B. E. and Muehlenbachs, K. (1989): Gold mineralization in the Okanagan Valley, southern British Columbia: fluid inclusion and stable isotope studies; Economic Geology, v. 84, no. 2, p. 410–424.