The Evolution and Structural Modification of the Supergiant Mitchell Au-Cu Porphyry, Northwestern British Columbia

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Abstract

The calc-alkalic Mitchell Au-Cu-Ag-Mo porphyry deposit, hosted in intrusive rocks of the Stikine volcanic arc terrane of northwestern British Columbia, is the largest undeveloped gold resource in Canada, with 40.72 Moz Au and 7,870 Mlbs Cu (Seabridge Gold, 2018), which classify it as a supergiant gold and a giant copper deposit. The deposit, 192.0 ± 1.0 Ma, 191.1 ± 0.8 Ma; Re-Os, molybdenite) ~1,600 m to the east-southeast. Host structures for the KSM trend may have been long-lived, N-striking basement lineaments that provided transcrustal magma and fluid pathways. East-trending intrusions, hydrothermal veins, alteration and metal distribution at Mitchell are attributed to subsidiary E-striking cross faults. These original anisotropies in turn influenced the geometry of Cretaceous faults and flattening domains within the deposit.

Introduction

The Early Jurassic Mitchell Au-Cu-Ag-Mo porphyry is the largest undeveloped gold deposit in Canada (Visual Capitalist, 2013). The 2.3-billion-metric-tonne deposit contains 40.72 Moz Au and 7,870 Mlbs Cu (Seabridge Gold, 2018), which classify it as a supergiant gold and a giant copper porphyry (Singer, 1995). It is in the Iskut mining region of the Stikine island-arc terrane (Stikinia) of northwestern British Columbia, Canada (Fig. 1). Mitchell lies within the Sulphurets district, part of a 200-km-long, NNW-trending corridor in northwestern Stikinia, defined by Cu-Au porphyry and related systems, that extends from Big Bulk in the south to Red Chris in the north (Fig. 1). The Sulphurets district contains the KSM property in the west, a 12-km-long northerly linear porphyry array that comprises the Kerr, Sulphurets, Mitchell, and Iron Cap Cu-Au porphyry deposits. Farther east, the Snowfield property contains the Snowfield Au-Cu porphyry deposit, and the Brucejack property encompasses the Brucejack high-grade gold mine (Valley of the Kings and West zone deposits). Copper-gold porphyry targets in the northern Sulphurets district were first identified by Granduc Mines Ltd. in 1960 (Kirkham, 1963). Subsequent deglaciation exposed Mitchell and led to the first delineation drill campaign completed by Seabridge Gold Inc. in 2006. Between then and 2018, Seabridge Gold Inc. completed 134 definition drill holes to depths of more than 1,600 m at Mitchell. Preexisting structures in Stikinia played an important role in localizing Triassic and Jurassic mineral deposits. Many of these are located on or near sets of nearly orthogonal regional northerly and westerly faults and lineaments (Fig. 1; Alldrick, 2000), which may have originated in the pre-late Paleozoic basement of the Stikine terrane (Nelson, 2014). North-striking faults

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Fig. 1. Regional geology. The Stewart-Sulphurets district trend extends from the past-producing Premier mine ~60 km north to the Sulphurets district (from Nelson and Kyba, 2014). The inset (modified from Colpron and Nelson, 2011) shows the location of the KSM project within the Stikine terrane in northwestern British Columbia. Abbreviations: AB = Alberta, BC = British Columbia, FKF = Forrest Kerr fault, FK/MC = Forrest Kerr-More Creek plutons, HB = Hickman batholith, IRF = Iskut River fault, NWT = Northwest Territories, SF = Sky fault, SHF = South Unuk-Harrymel fault.
form a prominent corridor in western Stikinia, including the Forrest Kerr and South Unuk-Harrynel faults (Fig. 1). The Pitman fault and related structures form an easterly array along the Stikina arch, a long-lived high-standing region (Fig. 1). The Iskut River fault and Sky fault, also east striking, interrupt the main northerly fault system in the Iskut area. These long-lived lineaments appear to have provided magma and fluid conduits throughout the history of Stikinia. Devonian-Mississippian plutons—the Forrest Kerr-More Creek pluton along the Forrest Kerr fault and an unnamed body along the Pitman fault—are strongly elongated parallel to them, and the Tusequah Chief volcanogenic massive sulfide (VMS) deposit (Mississippian) lies within a N-striking fault corridor in far northern Stikinia (Fig. 1). The persistent influence of these faults into recent times is shown by the Mount (Mt.) Edziza volcanic complex (Miocene-Holocene), which parallels and overlaps the northerly trend of the Forrest Kerr-More Creek plutons (Fig. 1). Triassic porphyry deposits—Galore Creek (Logan and Koyanagi, 1994) and Schaft Creek—are spatially associated with long-lived northerly regional-scale faults. The host pluton at Red Chris was emplaced along a minor easterly fault of the Pitman array, the Boundary fault (Rees et al., 2015).

The Sulphurets district lies along a prominent N-trending Early Jurassic mineralized corridor that extends from the Ball Creek porphyry to the north through the Tide-Tennyson porphyry, Premier Au veins, and Red Mountain Au to the Big Bulk porphyry to the south (Fig. 1). Porphyry plutonism and grade shells in the Sulphurets district are ellipsoidal to tabular, and porphyry veins are typically sheeted in both N- and E-trending geometries (e.g., Bridge, 1993; Febbo, 2016). These elongate geometries contrast with many porphyry deposits that are characterized by radial veins and cylindrically shaped intrusions (e.g., Tosdal and Richards, 2001).

Here we present the first deposit-scale magmatic-hydrothermal maps and descriptions, the first Re-Os dates, and the first structural data at Mitchell, integrated with Seabridge Gold Inc. drill results. Recent glacial retreat of deposit-scale outcrops facilitated mapping not exposed during previous district-scale mapping campaigns (e.g., Kirkham, 1963; Margolis, 1993). This new data set also allows us to evaluate the role of preexisting lineaments and hydrothermal alteration domains in the localization of strain in Mitchell during Cretaceous regional transpression. An understanding of the effects of preexisting lineaments and strain-related changes in alteration types is an important tool in the exploration of both structurally controlled and deformed porphyry systems.

Methodology

The data presented in this paper are based on new geologic mapping and core relogging completed by the first author. Surface mapping was carried out at KSM at 1:5,000 scale during 2014 (Fig. 2) and at Mitchell at 1:1,000 scale during 2013 (Fig. 3). Geology beneath the Mitchell thrust is based entirely on new mapping (Figs. 3, 4A). Figure 2 presents new geology on Seabridge Gold Inc. claims and complies both Margolis (1993) for Snowfield and Greig and Greig (2013) for Brucejack. Rock textures and mineralogical identifications in this study were confirmed with petrographic microscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), short-wave infrared (SWIR), and Terraspec. Quartz vein abundance estimates were made on surface by counting vein widths over a 2-m lineation oriented at a high angle to vein trends. Quartz vein abundances in drill core were estimated visually by Seabridge Gold Inc. geologists by counting vein widths over on average 2-m intercepts. Except where absolute displacement is identified from offset markers, fault kinematics on surface were determined from sigmoidal shape fabrics, sigmoidal tension gashes, and rotated foliations. Ambiguous kinematic indicators were characterized with petrographic microscopy. More than 2,500 m of drill core was relogged by the first author.

Regional Geologic Setting

The Canadian Cordillera records a protracted history of subduction, arc magmatism, accretion, and lateral translation of terranes (Nelson et al., 2013). The KSM and Snowfield systems are hosted by small Early Jurassic intrusions and surrounding Late Triassic and Early Jurassic volcano-sedimentary rocks, part of the Stikine volcanic island-arc terrane (Stikinia; Fig. 1; Kirkham, 1963; Alldrick and Britton, 1988, 1991). Stikinia and related Quesnel volcanic island-arc terrane (Quesnellia) form part of the Intermontane belt of the Canadian Cordillera. They are located geographically inboard of the Coast Plutonic Complex and are separated from each other by primitive arc and oceanic rocks of the Cache Creek terrane (Nelson et al., 2013; Fig. 1). Arc magmatism across the Stikinia and Quesnellia led to a multiepipode, Late Triassic to Early Jurassic metallogenic event that generated porphyry deposits that extend for 2,000 km along the axis of the Canadian Cordillera (Logan and Mihalynuk, 2014).

Stikinia developed as a multiphase arc terrane over 200 m.y. from Late Devonian through Early Jurassic time. Three unconformity-bound island-arc volcano-sedimentary successions include the upper Paleozoic Stikine assemblage (Anderson, 1989; Greig, 1992; Logan et al., 2000), the Middle to Upper Triassic Stuhini and Takla groups, and the Uppermost Triassic to Middle Jurassic Hazelton Group (Nelson et al., 2013). Mesozoic arc-related intrusive suites include the Late Triassic Stikine and Galore Suites (coeval and comagmatic with the Stuhini Group) and the latest Triassic Tatogga and Early Jurassic Texas Creek Suites (coeval and comagmatic with the Hazelton Group; Nelson et al., 2018). Stuhini-Takla arc activity was terminated in latest Triassic time (~212–203 Ma) by a regional tectonic, collisional event (Greig, 2014; Logan and Mihalynuk, 2014). This event, expressed as deformation of the Stuhini Group (Greig, 2014) and probably significant crustal thickening, ended at roughly 203 Ma (latest Triassic; Nelson et al., 2018). It was followed by a period of relative tectonic quiescence during the latest Triassic to Early Jurassic development of the Hazelton magmatic arc.

The base of the Hazelton Group is a regional unconformity above Triassic and older rocks (Greig, 2014; Nelson and Kyba, 2014). In some areas, basal Hazelton units include granitoid-cobble conglomerate and interbedded quartz-rich arkose, derived from deeply eroded Triassic plutons. Most notable of these is the Jack Formation, which crops out near the Sulphurets district. The lower Hazelton Group is a latest Triassic to Toarcian arc-related, mainly andesitic sequence, with local felsic centers. The associated Tatogga and Texas Creek Suite intrusions are key mineralizing agents in northwestern Stikinia (Fig. 1).
Arc-related volcanic activity in the Stikine and Quesnel terranes ceased in the late Early Jurassic, prior to mid-Jurassic amalgamation of the Intermontane terranes and their accretion to the western margin of North America (Nelson et al., 2013). The upper Hazelton Group (Pliensbachian to Bajocian) includes widespread sedimentary strata and the Middle Jurassic Iskut River Formation, a bimodal volcano-sedimentary succession that filled the postaccretion Eskay rift and hosts the Eskay Creek and Anyox VMS deposits (Fig. 1). The N-trending Eskay rift was controlled by reactivated lineaments such as the Forrest Kerr and South Unuk-Harrymel faults. The mid-Jurassic to mid-Cretaceous Bowser Lake Group occupies a large area of central Stikinia between the Stikine and Skeena arches, east of the Sulphurets district (Fig. 1). It is a molasseoid, syncollisional sedimentary basin containing debris derived from erosion of a tectonic welt mainly underlain by the Cache Creek terrane to the east (Evenchick et al., 2007).

Postaccretion, the region was subsequently deformed by mid-Cretaceous sinistral transpression that gave rise to the Skeena fold-and-thrust belt, an extensive zone of east-west shortening that extends across most of the central Intermontane belt (Evenchick, 1991a, b). It is kinematically linked to sinistral shearing within the Coast Plutonic Complex to the west (Fig. 1; Chardon et al., 1999; Gehrels et al., 2009; Angen et al., 2014) and continued crustal shortening of the continent margin (Evenchick et al., 2007). Deformation is constrained to have occurred between Early Cretaceous and latest Cretaceous-early Cenozoic time, with a minimum of 44% north-easterly shortening (Evenchick et al., 2007). Sinistral shearing in the Coast Plutonic Complex was active between ~110 Ma and 87 Ma (Chardon et al., 1999) and probably earlier.

Skeena fold-and-thrust belt deformation created strongly contrasting structural regimes in the well-stratified sedimentary Bowser Lake Group compared to the underlying basement of western Stikinia. Bowser Lake Group strata shortened as a thin-skinned Rockies-style fold-and-thrust belt (Evenchick et al., 2007). NW-trending, orogen-parallel folds predominate, with subsidiary, NE-trending folds in western regions (Fig. 1). Areas of dome-and-basin–style folds reflect interference of orogen-normal and orogen-parallel shortening during sinistral transpression (Evenchick, 2001). Thick-skinned deformation styles prevail in older units, including the Stuhini and Hazelton Groups, expressed as discrete high-strain zones of faulting and folding focused on preexisting
Fig. 3. Geology of Mitchell and surrounding area. Geochronologic sample GF-13-02 from outcrop, M-10-116 and M-07-49 from drill core.
Fig. 4. A. Alteration map of the Mitchell zone. Alteration above the Mitchell thrust fault is not shown. B. Alteration along section line A-A’. Stereographic projections of poles to veins. C. Stereographic projection of poles to stage 1B veins within the sheeted vein body. D. Stereographic projection of poles to stage 1B quartz veins outside the sheeted vein body. E. Stereographic projection of poles to stage 2 veins. F. Stereographic projection of poles to stage 3 veins. Mineral abbreviations alb = albite, anhy = anhydrite, bn = bornite, bt = biotite, cal = calcite, chl = chlorite, cpy = chalcopyrite, ep = epidote, gt = garnet, ill = illite, kao = kaolinite, kf = K-feldspar, mo = molybdenite, ms = muscovite, mt = magnetite, para = paragonite, phen = phengite, py = pyrite, pyr = pyrophyllite, qz = quartz, ten = tennantite, tet = tetrahedrite.
lineaments. Folds trend north-northwest in the Stewart area (Alldrick, 1993) and north to northeast in the southern Iskut area, where local culminations include the Eskay anticline and the McTagg anticlinorium (Fig. 1). The Eskay anticline is probably an inverted subbasin of the mid-Jurassic Eskay rift (Nelson and Kyba, 2014). The McTagg anticlinorium is a broad, N-trending, structural culmination. McTagg's interior is a zone of intense deformation and imbrication with a complexly faulted core involving the Stikine assemblage, Stuhini Group, and Jack Formation at comparable structural levels across faults. The regional fold trace of the McTagg is partly bounded by thrust faults that verge away from its hinge, particularly the E-vergent Sulphurets fault that bounds the Sulphurets district to the east (Lewis, 2013; Nelson and Kyba, 2014). The McTagg anticlinorium is convex to the west, widest in the north where the hinge traces north-northeasterly, and narrowest in the south where it traces slightly west of north (Fig. 1). At the southern end of the anticlinorium, bounding faults converge into a single, high-angle sinistral-oblique shear zone. The teardrop-shaped configuration of the McTagg anticlinorium, framed by S-converging faults (Fig. 1), is consistent with that of a positive flower structure within a strike-slip system. A positive flower structure may have functioned as a right-stepping, sinistral restraining bend during Cretaceous Skeena fold-and-thrust tectonics.

Sulphurets district structural geology

Cretaceous transpressional structures of the Skeena fold-and-thrust belt—thrust faults, folds, and domains of flattening fabrics—form the fundamental framework of Mitchell and of the entire Sulphurets district (Fig. 2). The Sulphurets thrust is an E-vergent fault that forms the immediate hanging wall to the porphyry deposits at KSM (Fig. 2). It curves to the northeast and cuts upsection north of the Sulphurets district (Lewis, 2013). The Mitchell thrust is an E-vergent, foreland-propagating splay of Sulphurets that separates Snowfield in its hanging wall from Mitchell in its footwall and has ~1,600 m of displacement (Fig. 2; Savell and Threlkeld, 2013; Febbo et al., 2015). The N-striking, moderately W-dipping Snowfield fault, also interpreted as an eastern (frontal) splay of the Sulphurets fault, extends from Kerr to the E-striking, N-dipping reverse Iron Cap fault (Fig. 2). Postmineralization dolerite sills record ~1,600 m of east-side-down displacement (Kirkham and Margolis, 1995) that juxtaposed Bowser Lake Group and Jack Formation strata (Lewis, 2001, 2013; Nelson and Kyba, 2014). The Johnstone fault forms the northern boundary of the KSM trend (Fig. 2). North of the fault, a thin (<100 m) Lower to Middle Jurassic Hazelton section unconformably overlies Stuhini Group. This relationship contrasts strongly with the thick sequence of Jack Formation south of the fault that hosts the Iron Cap, Mitchell, and Snowfield deposits (Fig. 2). The Johnstone fault is therefore inferred to have been active as a south-side-down normal fault during the Early Jurassic.

Snowfield

The giant Snowfield deposit contains 34.94 Moz Au and 4.09 Blbs Cu (Singer, 1995; Armstrong et al., 2011) and is considered the updip equivalent of Mitchell displaced along the Mitchell thrust (Savell and Threlkeld, 2013; Febbo, 2016). It is composed of a principal body (Main zone) of sheeted, E-striking quartz veins that were emplaced into arenite of the Bowser Lake Group and Jack Formation strata (Lewis, 2001, 2013; Nelson and Kyba, 2014). This intrusion is elongated north-south parallel to the Brucejack fault, consistent with fault activity during the Early Jurassic. Near Iron Cap, the Brucejack fault has >500 m of east-side-down displacement (Kirkham and Margolis, 1995) that juxtaposed Bowser Lake Group and Jack Formation strata (Lewis, 2001, 2013; Nelson and Kyba, 2014). The Johnstone fault forms the northern boundary of the KSM trend (Fig. 2). North of the fault, a thin (<100 m) Lower to Middle Jurassic Hazelton section unconformably overlies Stuhini Group. This relationship contrasts strongly with the thick sequence of Jack Formation south of the fault that hosts the Iron Cap, Mitchell, and Snowfield deposits (Fig. 2). The Johnstone fault is therefore inferred to have been active as a south-side-down normal fault during the Early Jurassic.
at the Snowfield Main zone, and stage 4 low-sulfidation-type veins and disseminated Au at the Snowfield Gold zone and Josephine Ridge (Fig. 2).

**Mitchell Deposit Geology**

**Stratified units**

The Stuhini Group, the oldest unit exposed in the Mitchell area (Figs. 3, 5A), comprises centimetre-scale bedded siltstone, graphitic shales, and minor calcareous mudstones, capped by a >200-m-thick unit of rhythmically bedded felsic tuff, siltstone, and quartz-feldspar porphyry flow breccia (Febbo et al., 2015). Siliciclastic and volcanic rocks of the overlying Jack Formation are divided into five facies (Fig. 3). Massive to thick-bedded, very fine to fine grained felspathic sandstone contains 10 to 45% quartz and 50 to 70% feldspar grains and rare granules. It is 0.3 to 1 km thick, interbedded with quartz-rich conglomerate and andesite lapillif tuff (Margolis, 1993). Rare lenses of conglomerate (up to 10 m thick) contain quartz-rich clasts, felsic volcanic, black chert, and intermediate volcanic clasts in a sandstone matrix. Felsic volcanic clasts were likely derived from the underlying Stuhini felsic volcanic unit. Andesitic flows and flow breccias (Betty Creek Formation, Unuk River unit) overlie the Jack Formation (Fig. 2).

**Premier intrusions**

The alkaline Premier intrusions (Febbo et al., 2015) crop out in the immediate hanging wall of the Mitchell thrust fault (Fig. 3) and are intercepted in drill core in the western flanks of the Mitchell zone, beneath the Mitchell thrust fault. Near Mitchell, NE-striking, W-dipping dolerite dikes and sills and bulbous plutons of the Premier Suite lie along a northeasterly linear trend (Fig. 2). Above the Mitchell thrust, Premier syenites are host to the North Mitchell and Sulphurets Main Au-Cu porphyry zones where Premier syenite porphyry dikes are considered the causative intrusion (Fig. 2; Simpson, 1983; Fowler and Wells, 1995). Premier stocks are characteristically phaneritic with crowded oscillatory zoned plagioclase and common pink or maroon K-feldspar phenocrysts (Fig. 5B; Kirkham, 1963; Simpson, 1983).

**Sulphures intrusions**

The calc-alkaline Sulphures intrusions are the causative intrusions to Mitchell, which therefore is classified as a calc-alkaline porphyry deposit (Febbo et al., 2015, Febbo, 2016). The calc-alkaline Sulphures dioresite, monzodiorite, and granodiorite plutons cut the Premier intrusions and define a 2- × 1-km multiphase stock that is host to Mitchell (Febbo et al., 2015). Based on field geologic relationships, we have distinguished three intrusive phases. Phase 1 includes a pre- to early-mineralization, voluminous hornblende diorite porphyry (Fig. 5C) and younger, early- to synmineralization narrow hornblende monzodiorite dikes that were only observed in drill core. Phase 1 diorite intruded bedded sedimentary rocks of the Stuhini Group and Jack Formation sandstone and andesite breccia (Fig. 3). Phase 1 diorite hosts the sheeted vein body, a swarm of WNW-striking, subparallel veins (Fig. 3). Early-mineralization diorite stocks are characterized by anhedral, irregular-shaped plagioclase and hornblende phenocrysts that have undergone complete hydrothermal replacement (Fig. 5C). The least altered drill intercept of early-mineralization diorite on the western margin of the Mitchell zone contains 20 to 30% plagioclase (An80-An90) phenocrysts (up to 3 mm), 1 to 10% K-feldspar (up to 1 mm), 5% hornblende phenocrysts (up to 3 mm), trace biotite (~1 mm), and trace apatite. Two 50- to 100-m-thick, phase 1 monzodiorite intrusions in drill core are E-striking, ~60° N-dipping planar bodies centered on an older phase 1 diorite (Fig. 5A).

Phase 2 intrusions include an intermineralization hornblende granodiorite plug that occupies the core of the deposit on surface (Fig. 3) and multiple 50- to 200-m-wide, W-striking and 70° to 80° N-dipping synmineralization granodiorite dike sets in drill core (Fig. 5A, D). On surface, phase 2 cuts phase 1 and the sheeted vein body and contains abundant quartz vein xenoliths (Fig. 5E). It is distinguished by a contact breccia, sparser (10–20%) by volume) quartz-chalcopyrite-pyrite veins than phase 1, and uniformly high concentrations of quartz vein xenoliths. A small phase 2 plug outboard of the mappable phase 2 body cuts molybdenite-bearing veins and is in turn cut by molybdenite-bearing veins.

A ~100- × 300-m NE-trending, E-flaring, late-mineralization breccia body (Bone breccia) crops out in the northeastern Mitchell zone (Fig. 3). It cuts phase 2 on its southern margin and cuts sandstone and andesite on its southeastern margin. Diorite clasts with internal quartz stockwork and isolated quartz vein fragments make up ~80% of the rock in the western Bone breccia outcrop, named for the dense, white, bone-shaped vein fragments. Clasts decrease in both abundance and size from 20 to ~2 cm eastward, where ameboid-shaped andesite clasts predominate over quartz vein clasts. Clasts types include (1) andesite volcanic fragments, (2) subrounded quartz-rich sandstones, (3) amoeboid-shaped andesite, (4) quartz-pyrite ± chalcopyrite veins, and (5) diorite with internal stockwork. Disseminated tourmaline and quartz-pyrite-tourmaline veins cut the Bone breccia. Pفت porphyritic textures in the intensely muscovite-chlorite altered groundmass of the western outcrop suggest an igneous matrix. To the east, relic phenocrysts are not preserved. Crst types in the Bone breccia resemble outcrops at Snowfield that contain sandstone clasts, diorite with internal stockwork, and angular andesite clasts at shallow levels, all of which are cut by quartz-pyrite veins (Febbo et al., 2015).

Breccia dikes cut Jack Formation sandstones, Sulphures phase 1 and phase 2 intrusions, and the Bone breccia. The 20- to 50-cm-wide, 2- to 20-m-long breccia dikes are distributed near the margins of, and emanate from, phase 3 diorite. Breccia dikes are cut by pyrite-quartz veins with tourmaline halos, and tourmaline is commonly observed in the groundmass of the dikes.

A small (50 × 125 m) plug of phase 3 diorite cuts the western end of the Bone breccia (Fig. 3) and diorite-cemented breccia dikes. It is overprinted by minor quartz-pyrite-tourmaline stringers. The plug is most easily distinguished by a paucity (<1%) of quartz veins and by abundant clasts of diorite with internal quartz stockwork (up to 20 cm), clasts of Bone breccia (~1 m; Fig. 5F), and clasts of breccia dikes. Emplacement of the plug postdates stage 2 stockwork and predates stage 3 pyrite stringers.

Three postmineralization dolerite dikes were observed in drill core that cut all plutonic rocks at Mitchell (Fig. 5A). They
Fig. 5. A. North-south cross section through the North Mitchell zone and Mitchell. Geochronologic sample M-11-123 from drill core. Legend as in Figure 3. Field photographs of Texas Creek suite intrusions. B. Premier coarse-grained syenite with maroon-colored K-feldspar (kf), cut by a pyrite-chalcopyrite (py-cp) vein; North Mitchell zone, M-12-129, 805 m. C. Sulphurets phase 1 porphyritic hornblende diorite with green, chloritized hornblende and plagioclase phenocrysts; M-07-25, 456.6 m. D. Sulphurets phase 2 crowded, medium-grained, hornblende (hb) granodiorite porphyry has white K-feldspar (kf) phenocrysts; M-15-131A, 1,508.8 m. E. Angular quartz vein xenolith clasts in phase 2 granodiorite; 422958 E, 6265505 N. F. Phase 1 diorite with internal quartz stockwork clasts in Bone breccia and as xenoliths in a phase 3 diorite; 423391 E, 6265561 N.
are dark green, fine grained, and plagioclase-phyric, display aphanitic margins, and contain sparse carbonate amygdules. The 1- to 2-m-wide dikes have westerly strikes and subvertical dips. Similar postmineralization dolerite dikes at Kerr were folded during Skeena fold-and-thrust belt deformation (Bridge, 1993), constraining their age to pre-Cretaceous.

**Hydrothermal stages**

Hydrothermal activity at Mitchell is divided into four main stages (Fig. 4A, B) after Margolis’ (1993) scheme at Snowfield: Cu-Au stockwork and alteration (stage 1), Cu-Mo stockwork and alteration (stage 2), pyrophyllite and kaolinite veins and alteration (stage 3), and Au-rich quartz and barite veins (stage 4). Stage 1, as defined by Margolis (1993), is further subdivided here into stage 1A (Premier-related Cu-Au) and stage 1B (Sulphurets-related Cu-Au; Table 1).

Stage 1A sodic-potassic alteration was a relatively low quartz hydrothermal event that introduced the earliest Cu-Au mineralization peripheral to Mitchell (Fig. 4A; Table 1; Margolis, 1993). Sodic-potassic alteration is restricted to the Premier syenites and their immediate margins. This vein-hosted and disseminated style of mineralization occurs in the Sulphurets Main zone, in the hanging wall of the Sulphurets thrust, and the North Mitchell zone, in the hanging wall of the Mitchell thrust (Figs. 2, 5A). The down-dip equivalent of the North Mitchell alteration is predicted immediately west of Mitchell, beneath the trace of the Sulphurets thrust (Fig. 2).

Stage 1B alteration types are spatially and temporally associated with most of the Cu-Au mineralization in Mitchell. Stage 1B transitional potassic alteration overprinted stage 1A sodic-potassic alteration between North Mitchell and Iron Cap (Figs. 2, 5A). Stage 1B alteration at Mitchell produced a core of potassic alteration, flanked by a transitional potassic assemblage that passes outward to propylitic and skarn assemblages (Fig. 4A; Table 1). Chalcopyrite and pyrite are inversely related; chalcopyrite to pyrite ratios generally decrease from the core outward. Gold is microscopic and typically occurs as electrum inclusions in sulfides or at sulfide grain boundaries. Copper and gold values are positively correlated and have low variability over large intercepts. Gold grades in general are proportional to the volume percent of quartz veins. Stage 1B potassic and transitional potassic-altered rocks are the strongest, most competent rocks at Mitchell.

Stage 1B millimeter- to centimeter-scale sheeted and stockwork quartz veins make up 5 to 95% of the host rock (Fig. 4A; Table 1). The west-northwesterly, moderately dipping sheeted vein body is defined by >60% by volume quartz veins, is semitubular, and measures 1 km × 200 m (Fig. 3). It grades into lower quartz vein abundance stockwork to the west and potassic-altered phase 1 diorite at depth. Vein orientations in the sheeted vein body strike west-northwest and dip steeply north (Fig. 4C) and can be at a high angle to the outline of the sheeted vein body due to abrupt plutonic contacts. The intensely phyllic overprinted sheeted vein body has gradational contacts with potassic-altered rocks; because of this it is considered to have emplaced as part of the potassic alteration event. To the north, sheeted veins are cut by phase 2 plutonism. Stage 1B vein orientations outside of the sheeted vein body are scattered in strike geometry with subvertical northerly and westerly dips (Fig. 4D).

Stage 2 phyllosilicate-rich alteration overprinted stage 1B veins and phase 2 intrusions. Three subtypes, which have gradational contact relationships with each other, have been recognized: phyllic, muscovite-chlorite, and quartz-chlorite assemblages (Fig. 4A; Table 1). White- to yellow-colored phyllic alteration crops out in the eastern, shallower levels of Mitchell and grades westward into narrower replacement domains of rocks with higher vein densities (i.e., the sheeted vein body; Fig. 4A). Yellow-green–colored muscovite-chlorite alteration, distinguished from the phyllic assemblage by the presence of chlorite, crops out to the east of Mitchell (Fig. 4A). The phyllic and muscovite-chlorite–altered rocks have a strong cleavage with a schistose fabric and are the least competent rocks at Mitchell. The quartz-chlorite alteration is distinguished by high quartz to phyllosilicate ratios, the presence of magnetite, and a lower abundance of phyllosilicates than phyllic and muscovite-chlorite assemblages. A molybdenum-rich shell, which envelopes the copper-gold core of the porphyry, is associated with stage 2 alteration assemblages (Fig. 6; see also Margolis, 1993). Molybdenite-pyrite-muscovite veins in eastern Mitchell are hosted in phyllic alteration. Vein orientations for stage 2 cluster on WNW-striking, steeply N dipping geometries (Fig. 4E).

A bornite-cemented breccia body disrupted the stage 1 stockwork and was cut by massive pyrite veins and a narrow phase 3 diorite sill (Fig. 5A). The margins of the bornite breccia contain clasts of quartz stockwork and phase 1 diorite, and the central domain contains clasts of banded and stockwork veins and matrix composed of hydrothermal gangue and sulfide minerals, including anhydrite, fluorite, quartz, and bornite (Table 1). Elevated copper grades in the breccia correspond to high bornite/chalcopyrite ratios and a higher Cu/Au ratio that distinguishes it from surrounding ore.

Stage 3 hydrothermal activity produced small domains of pervasive quartz-pyrophyllite alteration in southeastern Mitchell, along with massive pyrite veins and barren anhydrite

![Fig. 6. Au and Mo metal grades of the Mitchell and Snowfield, after Savell and Threlkeld (2013). For cross section location refer to Figure 2.](https://pubs.geoscienceworld.org/segweb/economicgeology/article-pdf/114/2/303/4671631/303-324.pdf)
<table>
<thead>
<tr>
<th>Event</th>
<th>Description of alteration assemblage and key veins</th>
<th>Spatial distribution</th>
<th>Associated magmatism</th>
<th>Vein geometry and abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1A Cu-Au</td>
<td>Sodic-potassic assemblage of orthoclase + albite + chalcopyrite + pyrite (&lt;1%) + quartz (&lt;5%) + hematite + magnetite ± specularite ± biotite ± fluorite ± barite ± rutile ± scheelite; disseminated vein-hosted</td>
<td>North Mitchell zone; above Mitchell thrust; peripheral to Mitchell and Snowfield</td>
<td>Premier syenite; 193.9 ± 0.5 Ma²</td>
<td>&lt;5% veins; 1–2-mm-wide stringers, low quartz/K-feldspar ratios</td>
</tr>
<tr>
<td>Stage 1B Cu-Au</td>
<td>Potassic assemblage of quartz (&gt;20%) + orthoclase (1–10%) + magnetite + pyrite + chalcopyrite + chlorite ± anhydrite ± albite ± rutile ± electrum</td>
<td>-700-×1,000-m-wide body, core to Mitchell</td>
<td>Sulphurets phase 1 diorite and monzonodiorite: younger than 193.9 ± 0.5 Ma²; dated hosts 196 ± 2.9, 189.0 ± 2.8 Ma²</td>
<td>Sheeted vein geometry; widespread, E to ENE strikes; steep N dips; 30–90% vein abundance typical; diffuse, discontinuous A-type veins, medial sulfide</td>
</tr>
<tr>
<td>Stage 2 Cu-Mo</td>
<td>Phyllic assemblage of quartz + muscovite + illite ± molydenite ± chalcopyrite ± tourmaline ± calcite ± fluorite ± rutile ± apatite; white to yellow, magnetite-destructive</td>
<td>Annular geometry, structurally controlled at depth and to N, absent to S, Mitchell (shallow), Jack Formation host; overprints Snowfield Gold zone spatially overlaps with Sulphurets phase 2 plug</td>
<td>Sulphurets phase 2 granodiorite; dated host 192 ± 2.8 Ma²; molydinite ages between 192 ± 1 and 190.3 ± 0.8 Ma³</td>
<td>Stockwork veins, various strikes, E strike common; subvertical dips; 5–20% vein abundance typical; Mo-bearing veins in halo geometry; Cu-Mo veins inboard</td>
</tr>
<tr>
<td>Stage 3 Pb-Zn-Bi-Te-Sn</td>
<td>Quartz-pyrophyllite assemblage includes pyrite ± woodhouseite/ sphenhite (alunite-like mineral) ± kaolinite ± barite ± Mg-chlorite ± halloysite ± rutile ± calcite; no significant Cu/Au/Mo</td>
<td>Halo to Snowfield; E Mitchell Deep Snowfield; throughout Mitchell N flank of Mitchell at depth</td>
<td>Sulphurets phase 3 diorite (no date); Bone breccia, breccia dikes; 189.6 ± 2.2 Ma plug E of Snowfield¹</td>
<td>Breccia contains stage 1B veins in clasts and overprinted by stage 3 pyrite veins</td>
</tr>
<tr>
<td>Stage 4 Au-Ag-Pb-Zn</td>
<td>Quartz-barite veins ± galena ± sphalerite ± tetrahedrite ± electrum ± acanthite ± pyrrhotite ± Mg-Au-Ag telluride ± manganoo calcite ± chalcopyrite ± pyrite; milky quartz, high-grade Au-Ag Disseminated gold assemblage ± galena ± sphalerite ± tetrahedrite ± acanthite ± barite ± electrum; disseminated-style mineralization</td>
<td>~1 km E Mitchell; Josephine Ridge zone Snowfield Gold zone</td>
<td>Veins rare; monomineralic pyrophyllite stringers¹</td>
<td>Veins absent¹</td>
</tr>
</tbody>
</table>

¹ Margolis (1993)
² Kirkham and Margolis (1995)
³ Febbo et al. (2019)
Stage 3 massive pyrite veins are composed of ~60 to 95% pyrite with lesser quartz and pyrophyllite (Table 1). They cut all phases of plutonism, stage 2 molybdenite veins, the sheeted vein body, and the bornite breccia. Monomineralic pyrophyllite veins were identified at Mitchell by Margolis (1993). Massive pyrite veins dip steeply north, have easterly to southeasterly strikes (Fig. 4F), and are cut by barren anhydrite stringers (Fig. 4B; Table 1).

Stage 4 produced epithermal quartz and barite veins that contain high-grade Au-Ag and are distributed peripheral to Mitchell and Snowfield (Table 1; Margolis, 1993). The veins cut stage 3 pyrophyllite and massive pyrite veins (Margolis, 1993). At Snowfield, stage 4 vein types include barite and quartz-barite and can contain sphalerite, galena, tetrahedrite, electrum, acanthite, pyrargyrite, Hg-Au-Ag telluride, and Mn-rich calcite (Margolis, 1993). Stage 4 veins are associated with high-grade Au-Ag-Pb-Zn-Cu (Margolis, 1993). At Mitchell, jigsaw-fit breccia textures are identified in E-striking stage 4 veins that crop out ~1 km east of the margin of the >0.5 g/t Au contour (Fig. 3), consistent with an epithermal level of emplacement. The stage 4 veins studied by Margolis (1993) crop out more than 1 km south of the Snowfield Main zone at significantly shallower stratigraphic levels.

**Geochronology**

To place absolute time constraints on hydrothermal stages, we conducted radiometric dating of hydrothermal molybdenite from Mitchell and Snowfield. Analytical techniques are presented in Appendix 1 and results in Appendix Table A1. One quartz-pyrite-muscovite-illite-molybdenite vein sample from Mitchell drill core, sample M-10-116 (Fig. 3), was analyzed for Re-Os geochronology at the University of Alberta, Canada. Two surface samples of molybdenite veins, sample S-73 from Mitchell and S-11 from Snowfield (Fig. 2), were collected for Re-Os geochronology (Margolis, 1993; analytical work, AIRIE Program, Colorado State University, this study). Both samples are of quartz-molybdenite veins in a foliated quartz-sericite-pyrite schist (see appendix E in Margolis, 1993). Two samples of quartz-pyrite-molybdenite veinlets in a quartz-muscovite-pyrite–altered host rock at Snowfield were collected by Fretium Resources Inc. geologists and analyzed by ALS Canada Ltd. in Vancouver, Canada (samples SF-12 and SF-21). The Mitchell samples yielded Re-Os ages of 190.3 ± 0.8 Ma (sample M-10-116) and 191.3 ± 0.7 Ma (sample S-73). The Snowfield samples yielded a Re-Os age of 192.0 ± 1.0 Ma (sample S-11) and 191.1 ± 0.8 Ma (samples SF-12 and SF-21).

A Premier syenite from North Mitchell (Fig. 5A), described as intermineralization with respect to stage 1A copper deposition, yielded a relatively precise U-Pb zircon age of 193.9 ± 0.5 Ma (Kirkham and Margolis, 1995). Because Sulphurets intrusions cut Premier syenite at North Mitchell, this age is considered the upper constraint for onset of phase 1 plutonism and related stage 1B hydrothermal activity. Higher-error phase 1 crystallization ages of 196 ± 2.9 Ma (sample M-11-123; Fig. 4) and 189.9 ± 2.8 Ma (sample GF-13-62; Fig. 2) are compatible with this upper limit (Febbo et al., 2019). The 192 ± 2.8 Ma crystallization age of a phase 2 intrusion (sample M-07-49; Fig. 3; Febbo et al., 2019) overlaps within error of phase 1 plutonism and also overlaps with 191.3 ± 0.7 and 190.3 ± 0.5 Ma Re-Os molybdenite ages (stage 2). The Re-Os ages from Snowfield, 192.0 ± 1.0 and 191.1 ± 0.8 Ma, agree within error with molybdenite ages from Mitchell. Stage 3 hydrothermal activity and phase 3 plutonism are younger than the 190.3 ± 0.8 Ma age for stage 2 molybdenite veins. A U-Pb zircon age of 199.6 ± 2.2 Ma was obtained for a postmineralization diorite plug that intruded the Unuk River andesite unit (Margolis, 1993), which appears to correlate with phase 3 magmatism. These age determinations constrain stage 1A to 193.9 ± 0.5 Ma (Kirkham and Margolis, 1995). Stage 1B followed stage 1A, based on relative timing relationships, and ended prior to stage 2 molybdenite mineralization, between 192.0 ± 1.0 and 190.3 ± 0.8 Ma. Overall these age constraints suggest that Cu deposition was a multistage process at Mitchell and Snowfield that took place over ~4 m.y. The main mineralizing event (stage 1B) occurred between ~194 and ~191 Ma, but its actual duration is unknown.

**Cretaceous structural modification (D1, D2, D2b)**

Mitchell was structurally modified by deformation attributed to regional sinistral transpression of the Skeena fold-and-thrust belt. The resulting structures are here separated into two events: D1 and D2 (Table 2). D1 produced the main foliation (S1) and associated F1 folds. D2 is subdivided into a and b; D2a is defined by a second folding phase (F2a), and D2b is defined by the development of discrete thrust faults.

A notable feature of the deposit is the relationship between alteration type and the degree of penetrative strain in the rocks. The intensity of strain is directly correlated with the intensity and type of hydrothermal alteration (e.g., Kirkham, 1963; Bridge, 1993; Margolis, 1993; Fig. 7). Strain is partitioned into portions of the deposit that contain significant amounts of mechanically soft hydrothermal muscovite, chlorite, pyrophyllite, and illite. Thus, stage 2 and 3 phyllosilicate-rich alteration types are intensely foliated and generally have a slaty or schistose fabric, whereas the stronger stage 1 potassic alteration domains generally lack cleavage. Hydrothermal quartz veins are extensively folded because of the competency contrast between phyllosilicate-altered matrix (weak) and hydrothermal veins (strong). In areas where the matrix material is relatively strong (e.g., high K-feldspar content) the competency contrast is small, and veins did not buckle (i.e., fold).

D1: S1 is a pervasive, variably developed cleavage defined by bands of hydrothermal phyllosilicate minerals and sulfides. It strikes westerly and dips steeply to the north and is axial planar to W-plunging buckle folds in veins (Fig. 8A, C). The limbs of isoclinally folded, hydrothermal veins are oblique to S1. The foliation is poorly developed to absent in potassic-altered rocks, moderately to well developed in quartz-chlorite alteration zones, and intensely developed in phyllic and muscovite-chlorite–altered zones (Fig. 7A, B, D). S1 orientation is parallel to the west-northwest geometry of the sheeted vein body and is westerly elsewhere. It is interpreted to be a flattening foliation formed during shortening; there is no evidence for significant noncoaxial shear.

Microstructural observations show S1 is defined by aligned phyllosilicate-rich layers termed “P domains,” alternating with quartz-rich “Q domains” (Fig. 9). Phyllosilicates, sulfides and oxides are commonly concentrated in the P domains as the insoluble residue that was left behind as quartz was dissolved during solution transfer processes. Pyrite and chalcopyrite
contain mode I (i.e., extension) fractures oriented perpendicular to S1 in Q domains and are rimmed by large pressure shadows in P domains. Fibers in pyrite pressure shadows are oriented parallel rather than oblique to S1, consistent with the interpretation that foliation formed from flattening rather than shearing during noncoaxial strain. Quartz commonly has straight to cuspate boundaries where in contact with P domains, indicating dissolution at grain contacts. Chalcopyrite is commonly stretched in an E-trending orientation in pressure solution seams, indicating some remobilization during Table 2. Summary of Structural Features at Mitchell

<table>
<thead>
<tr>
<th>Feature</th>
<th>Event</th>
<th>Geometry</th>
<th>Kinematics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brucejack fault</td>
<td>Tr-Jr, Ter.</td>
<td>N strike, subvertical</td>
<td>~100-m dextral; &gt;500-m normal</td>
<td>~10-km strike length, eroded ~1-m-wide brittle fault zone with subparallel braided brittle faults; offsets Sulphurets thrust</td>
</tr>
<tr>
<td>Johnstone fault</td>
<td>Tr-Jr</td>
<td>E strike, subvertical dip</td>
<td>Normal (N-S extension)</td>
<td>~1.5-km strike length, fault inferred from stratigraphic changes, bounds Iron Cap deposit to the N, cut by the Sulphurets thrust</td>
</tr>
<tr>
<td>Small-scale faults</td>
<td>Stage 1B-2</td>
<td>E and N strikes, subvertical dips</td>
<td>Dextral and sinistral</td>
<td>1–5-m strike lengths; offset stage 1–3 veins and cut by stage 3–4 veins; crop out in potassic and quartz-chlorite alteration types</td>
</tr>
<tr>
<td>Snowfield fault</td>
<td>Stage 2, D3B</td>
<td>N strike, moderate W dip</td>
<td>~50-m sinistral; ~100-m reverse</td>
<td>6–km strike length, 1–3-m foliated cataclasite, sinistral rotated foliation, tectonic veins common; cut by Mitchell thrust</td>
</tr>
<tr>
<td>Glacier shear zone</td>
<td>Stage 3–4</td>
<td>WSW strike, steep N dip</td>
<td>Sinistral shear</td>
<td>~10-m-wide deformation zone of C-S fabrics; crops out in Betty Creek Fm; cut by undeformed stage 3–4 quartz-pyrite vein</td>
</tr>
<tr>
<td>S1</td>
<td>D1</td>
<td>E strikes, steep N dips</td>
<td>Coaxial N-S flattening</td>
<td>Pervasive pressure solution cleavage in phyllosilicate-rich alteration types, axial planar to F1, heterogeneously developed; S1 overprints all porphyry features and the Bruce Glacier unit; S1 overprinted by D1, ductile shear bands and folded by F2a.</td>
</tr>
<tr>
<td>F1</td>
<td>D1</td>
<td>W plunge, moderate to steep</td>
<td>Symmetric folds (coaxial flattening)</td>
<td>Open to isoclinal F1; folds in phyllosilicate-rich alteration types; 1–100-mm fold amplitudes; 2–20-cm fold wavelengths; S, M, and Z folds; noncylindrical where F2 is overprinting</td>
</tr>
<tr>
<td>Iron Cap fault</td>
<td>D1</td>
<td>E strike, steep N dip</td>
<td>Reverse (N-S shortening)</td>
<td>~20-cm-wide cataclastic fault zone; reverse kinematics defined by sigmoidal-shaped clasts in fault, ambiguous strike-slip; offset phyllic alteration and molybdenite grade shells at Iron Cap</td>
</tr>
<tr>
<td>Ductile shear bands</td>
<td>D1 (late)</td>
<td>NW/SW strikes, N dips</td>
<td>Dextral- and sinistral-reverse conjugates</td>
<td>~10-cm deformation zones of rotated veins and S1, strike lengths range millimeter- to meter-scale; offset S1 by D2b strike-slip faults; mutually crosscutting; crop out at sheeted vein body and throughout phyllosilicate-rich alteration types</td>
</tr>
<tr>
<td>F2a</td>
<td>D2a</td>
<td>N/NW plunge, steep to moderate</td>
<td>Coaxial E-W flattening</td>
<td>Gentle folds of veins and S2; abundant in phyllosilicate-rich alteration types only; fold amplitudes of &lt;4 cm and wavelengths 5–15 cm; folds E-striking vein orientations only</td>
</tr>
<tr>
<td>S2a</td>
<td>D2a</td>
<td>N/NW strikes, steep W dips</td>
<td>Coaxial E-W flattening</td>
<td>Poorly developed, spaced fracture cleavage axial planar to F2a; cuts S1 by D1, ductile shear bands and folded by F2a.</td>
</tr>
<tr>
<td>Strike-slip faults</td>
<td>D2b</td>
<td>WNW and WSW strikes, steep N dips</td>
<td>Dextral and sinistral; reverse</td>
<td>50–200-cm-wide foliated cataclasites, traceable over 250 m; sigmoidal shaped clasts of quartz veins and Riedel shear sense kinematic indicators; shallower faults dextral strike-slip, steeper faults sinistral strike-slip; cut S1, cut by D2b, ductile shear bands and folded by F2a.</td>
</tr>
<tr>
<td>Sulphurets thrust</td>
<td>D2b</td>
<td>N/NNE strike, gentle to moderate W dip</td>
<td>&gt; 1-km reverse; sinistral</td>
<td>&gt; 20-km strike length; dip of fault steepens to the S (W of Kerr), sinistral strike-slip at Kerr; E- to ESE-directed thrusting, fault is right-stepping N of Iron Cap</td>
</tr>
<tr>
<td>Mitchell thrust</td>
<td>D2b</td>
<td>N strike, 10° W dip (40° W dip on ramp)</td>
<td>~1,600-m displacement, ESE-directed, reverse</td>
<td>0.1–1.5-m-wide, foliated cataclasite, ~1 km strike length (N-S) exposed, sigmoidal shape fabrics in fault provide kinematics; thrust is curvilinear, contains flats and ramps; N trace has a roof and floor thrust, S trace is a single fault plane; thrust is folded by F3, and cut by the Brucejack fault</td>
</tr>
<tr>
<td>Mitchell basal shear zone</td>
<td>D2b</td>
<td>Subhorizontal</td>
<td>1–2 km displacement (inferred)</td>
<td>20–30-m-thick deformation zone in two drill holes, defined by crenulation of preexisting foliation; marked reduction in grade and alteration intensity across fault</td>
</tr>
<tr>
<td>Reverse faults</td>
<td>D2b</td>
<td>N strikes, gentle/ moderate W dips</td>
<td>E/ESE-directed, reverse, E-W shortening</td>
<td>10–50-cm-wide foliated cataclastic fault zones contain rotated foliation at fault boundaries and sigmoidal shape fabrics in fault; all are oblique either sinistral-reverse or dextral-reverse</td>
</tr>
<tr>
<td>F3b</td>
<td>D2b</td>
<td>Gentle N plunge</td>
<td>Noncoaxial flattening (E-directed shear)</td>
<td>Asymmetric, thrust-related drag folds; 1–10-m wavelengths in footwall of the Sulphurets thrust; &gt;100-m wavelength of one prominent F3b fold of Mitchell thrust (e.g., Fig. 6)</td>
</tr>
</tbody>
</table>

Jr. = Jurassic, Ter. = Tertiary, Tr. = Triassic
deformation. Quartz has extensive undulose extinction and deformation lamellae and is generally equant with serrated grain boundaries, indicating some grain boundary mobility. However, there is limited evidence for dislocation creep or dynamic recrystallization. The lack of microstructures indicative of dislocation creep in quartz indicates that temperatures during D₁ deformation likely did not exceed 350°C (Passchier and Trouw, 2005).

F₁ folds are isoclinal to gentle in geometry, typically occurring as buckle folds in quartz veins in rheologically weak rocks (Fig. 8A). Folds generally plunge steeply west-northwest (Fig. 8D). Fold geometries were controlled by vein orientations, vein thicknesses, and competency contrasts between the quartz veins and host rocks. Veins that strike oblique to S₁ are tightly folded with fold plunge dependent on their initial orientations (Fig. 7A-D), whereas veins that strike parallel to S₁ are boudinaged. Evidence for folding succeeded by boudinage is not seen, suggesting that individual veins did not rotate into the flattening direction in the strain field. F₁ fold closure and wavelengths vary as a function of alteration type (Fig. 7; Table 2). In soft alteration types, F₁ folds are noncylindrical because of interference with well-developed F₂ folds.

Quartz vein abundance was estimated by counting stockwork quartz vein intercepts along marked lines in outcrop and drill core axes. The results were contoured based on >500 counts on surface (Fig. 10A). For drill core, a numeric interpolant of the quartz vein density data was created using Leapfrog Geo v.4.3, producing a three-dimensional model of quartz vein abundance at Mitchell (Fig. 10B). A linear interpolant function was used for the model, with 50-m compositing. Isosurfaces were generated for quartz vein densities between 1 and 80% (Fig. 10B). In competent potassic-altered rocks, west of the sheeted vein body, quartz vein abundance contours trend northerly, whereas individual quartz veins strike west-northwest (Fig. 4C). Similarly, quartz vein abundance contours at depth dip moderately to the north (Fig. 10B), oblique to the steep northerly dip of the veins and alteration boundaries (Fig. 4B). In contrast, in the incompetent phyllic-rich alteration assemblages east of the sheeted vein body, quartz vein abundance contours are tighter and trend

Fig. 7. Qualitative estimate of strain for altered rocks of the Mitchell zone as indicated by cleavage development. A. Phyllic alteration showing tight to isoclinal F₁ folds of veins; 423832 E, 6265290 N. B. Open F₁ folds and gentle F₂a folds in muscovite-chlorite–altered andesite lapilli tuff; 4234630 E, 6265501 N. C. Gentle F₂a folds in the sheeted vein body; 423151 E, 6265163 N. D. Open F₁ and gentle F₂a folds in veins in quartz-chlorite–altered diorite; 423493 E, 6265325 N. E. Quartz-chlorite-chalcopyrite veins that accompany transitional potassic alteration in diorite intrusion are not folded; 423213 E, 6265195 N. F. Unfoliated potassic-altered diorite cut by quartz-K-feldspar-chalcopyrite veins that are not folded; 422532 E, 6265370 N.
westerly, similar to the strikes of individual quartz veins. The consistent westerly strike of veins in both N- and E-trending quartz abundance contours and for both soft and hard alteration types indicates that this vein orientation is coincident with $S_1$, not a product of it.

Ductile shear bands offset $S_1$ and are characterized by conjugate sets of mutually crosscutting NW-striking dextral-reverse and SW-striking sinistral-reverse shear bands (Fig. 8E; Table 2). The acute bisectrix of the conjugate shear band dips $51^\circ$ toward $122^\circ$, which provides an estimate of $25^\circ$ toward $190^\circ$ for $\sigma_1$. The orientation of $\sigma_1$ and the ductile nature of the shear bands is consistent with the north-south compression that formed the $S_1$ fabrics.

The Iron Cap fault ($D_1$), located above the Mitchell thrust, records reverse kinematics along an E-striking brittle fault that is cut by the Sulphurets fault (Fig. 2; Table 2). The reverse movement along the Iron Cap fault is consistent with north-south compression.

$D_{2a}$ $F_{2a}$ folds plunge steeply north to northwest, are variably developed in the limbs of $F_1$ folds, and fold the $S_1$ foliation.
on 13 September 2019 that gave rise to D1 fabrics and structures, the apparent shortening (Table 2). In contrast to the apparent north-south shortening (S2a) strikes north to northwest and dips steeply to the west (Table 2). A poorly developed axial planar fracture cleavage of quartz veins (Fig. 8A-D; 500 µm). The F2a folds have the same trend as the McTagg anticlinorium and other district-scale antilines and synclines (Figs. 1, 2). West of Mitchell, beneath the Mitchell thrust, beds dip moderately east (Fig. 3) and young to the east, consistent with district-scale eastward dips and general eastward younging of strata (Fig. 2) on the eastern limb of the McTagg anticlinorium (Kirkham and Margolis, 1995; Tombe et al., 2018). Metal zonation patterns at Mitchell (Fig. 6) and alteration trends (Fig. 4B) plunge to the west-northwest. The predicted clockwise rotation about a north-south axis during regional F2a folding is consistent with the E-dipping beds and WNW-plunging porphyry patterns. Also, because Mitchell lies in a thrust panel between the Mitchell thrust and the Mitchell basal shear zone (Fig. 5A), it could have been rotated clockwise during E-directed shearing.

D2b: North-striking, W-dipping thrust faults and shear zones that crosscut both S1 and F2a are part of D2b (Table 2). The Sulphurets thrust is in the highest structural position, with the Mitchell thrust and Mitchell basal shear zone as footwall splays. The Snowfield fault is a high-angle frontal ramp that dissects the panel between Sulphurets and Mitchell. The shortening for D2b is ~east-west, based on the eastern vergence of the thrusts.

The Mitchell deposit is exposed in an erosional window through the Mitchell thrust that is truncated to the east by the Brucejack fault (Figs. 2, 3). The Mitchell thrust has a ramp-flat geometry, with a floor and a roof thrust in the northern trace and a single fault trace to the south (Fig. 3). The flats dip ~10° to the west and the ramps dip ~40° to 50° (Fig. 8G). The footwall of the Mitchell thrust contains several imbricate thrust faults that dip moderately west and strike south-southwest to north-northwest (Fig. 3). The panel beneath the Mitchell thrust is imbricated by several reverse-oblique as well as dextral and sinistral slip faults (Fig. 8H; Table 2). Microstructurally, the Mitchell thrust cataclasite is composed of fractured pyrite grains (<5%; <50 µm diam) in a matrix of quartz, feldspar, calcite, hematite, muscovite (<50 µm diam), and clays (10–30 µm diam). Quartz grains have undergone grain size reduction by cataclasis and are highly variable in size, with sutured grain boundaries that indicate limited grain boundary mobility. Based on microstructural observations, the Mitchell thrust formed at a maximum of ~300°C (e.g., Passchier and Trouw, 2005). The Mitchell thrust offset Snowfield (hanging wall) from Mitchell (footwall) by ~1,600 m to the east-southeast, based on correlations of metal zonation patterns (Fig. 6; Savell and Threlkeld, 2013), hydrothermal vein and alteration stages (Febbo et al., 2015), Re-Os ages, and plutons between the two deposits.

The Mitchell deposit is truncated at depth by the Mitchell basal shear zone, located ~1 km below the Mitchell thrust fault (Fig. 5A; Table 2). It was identified in two deep drill holes separated by 200 m on an east-west section (M-08-62 and M-08-67; Fig. 5A) and was confirmed by subsequent drilling results. The shear zone is subhorizontal (~20°), and we speculate that, like other shallowly dipping faults in the area, it has thrust kinematics. The medium-grained muscovite (>1 mm) that defines the foliation is much coarser than in the Mitchell thrust or in S1 P domains. Quartz has undergone limited dynamic recrystallization. Based on the grain size and the microstructures, the temperature during movement is estimated to be ~350°C (Passchier and Trouw, 2005), higher than estimated for the Mitchell thrust. Absolute displacement along the Mitchell basal shear zone is speculated to be in the range of 1–2 km to the east-southeast based on constraints provided by metal grade shells, dimensions of plutonic host...
rocks, and alteration dimensions (Febbo, 2016). The root zone to the Mitchell-Snowfield porphyry system remains an untested exploration target located ~1 to 2 km to the west-northwest of Mitchell, at a depth of ~1 km below the surface.

D$_{2b}$ strike-slip faults and oblique fault zones define linear gullies that cut F$_{2a}$ beneath the Mitchell thrust (Fig. 3). Sinistral strike-slip motion occurred on WNW-striking shears with shallow northerly dips, and dextral strike-slip motion occurred on west-southwest shears with steeper northerly dips (Table 2). The two fault geometries are mutually crosscutting and are interpreted to be conjugates. The acute bisectrix of the average two geometries plunges 74° toward 002°, which provides an estimate of 10° toward 089° for σ$_1$. The crosscutting relationship with F$_{2a}$ and the east-west shortening, comparable to that of the east-directed D$_{2b}$ thrust faults, is consistent with D$_{2b}$ timing for the faults.

F$_{2b}$ folds include asymmetric, thrust-related drag folds in the immediate footwall of the Sulphurets thrust and gentle folding of the Mitchell thrust (Fig. 6; Table 2). F$_{2b}$ folds crop out east of the Iron Cap deposit as open to isoclinal, shallowly plunging asymmetric folds in Stuhini Group calcareous mudstone.

**Eocene structural modification (D$_3$)**

The subvertical Brucejack fault strikes north for at least the length of the Sulphurets district (~12 km; Fig. 2), and latest displacement is inferred to be Eocene (Kirkham and Margolis, 1995). At Brucejack, the fault has ~100-m dextral strike-slip movement (Kirkham and Margolis, 1995). Near the Iron Cap deposit, it has >500-m east-side-down dip-slip displacement (Kirkham and Margolis, 1995) that juxtaposed Bowser Lake Group and Jack Formation strata (Lewis, 2001, 2013; Nelson and Kyba, 2014).

**Synmineralization Jurassic structures**

Strain in Mitchell mainly records the effects of postemplacement, mid-Cretaceous Skeena fold-and-thrust deformation. Earlier fabrics are preserved only in rheologically strong potassic-altered rocks. Porphyry vein geometry, small-scale faults, and the Glacier shear zone provide clues to the structural setting during porphyry emplacement.

West-northwesterly vein orientations (Fig. 4C-D) predominate in the sheeted vein body in relatively undeformed, potassic-altered domains on the western flank as well as in zones of strong D$_1$ flattening to the east (Fig. 4A). Correlation between the strikes of the sheeted veins and the S$_1$ fabric in the stage 2 phyllic/muscovite-chlorite–altered rocks is moderate. These are the weakest rocks on the property, and a stronger correlation would be anticipated if the present vein orientation was a result of mid-Cretaceous flattening. The folded veins show no evidence of boudinage that may be expected if the veins were rotated during flattening to their present orientation. These observations, in addition to the quartz vein contour that the sheeted vein body was emplaced as a steep, west-northwesterly feature of the porphyry system, as opposed to a tectonically flattened stockwork. The clockwise rotation of Mitchell during D$_{2b}$ (Fig. 6) is poorly reflected in sheeted, E-striking vein geometries (Fig. 4C-F) that are orthogonal to this axis of rotation. Only vein orientations that are not easterly striking appear to reflect the rotation in their westerly dips (Fig. 4D, E).

Small-scale, discontinuous strike-slip faults are preserved only in potassic and quartz-chlorite alteration assemblages (Table 2; Febbo, 2016). They offset stage 1 to 3 veins and are overprinted by stage 3 to 4 quartz-pyrite veins (Fig. 7F). The slip planes have both sinistral and dextral strike-slip offsets (1–50 cm displacement) for both easterly and northerly strikes.

Deposit-scale structures that are synmineralization include one segment of the N-striking Snowfield fault (Kirkham and Margolis, 1995) and the ENE-striking, sinistral Glacier shear zone, east of Mitchell (Fig. 3; Table 2). The Glacier shear zone affected a muscovite-chlorite alteration assemblage in Unuk River andesite. It is crosscut by an undeformed, porphyry-related, stage 3 or 4 quartz-pyrite vein. The shear zone was therefore active during or after stages 1 and 2, and movement along it waned during stages 3 and/or 4.

**Discussion**

Mitchell and Snowfield are notable for their large size and easterly geometry within an overall N-trending linear porphyry array as well as for their complex brittle-ductile deformation history that thrust-separated the once-continuous system. This discussion develops a new magmatic-hydrothermal-structural model that integrates relationships recognized at Mitchell in this study and at Snowfield by Margolis (1993).

**Magmatic-hydrothermal evolution of the Mitchell-Snowfield porphyry system**

The Mitchell-Snowfield porphyry reflects typical hydrothermal-magmatic evolution patterns like those described by Gustafson and Hunt (1975), Sillitoe (2010), and many others. Early magmatic-hydrothermal activity is related to subvertical composite plutonism, potassic-propylitic assemblages (stage 1B; Fig. 11A), and the formation of irregular, discontinuous, and segmented veins (“A veins”; Gustafson and Hunt, 1975), primarily as sheeted arrays but also as stockwork. Classic metamorphic assemblages were developed with a core of high Cu/Au ratios that grades vertically lower at Snowfield (Fig. 6). The introduction of molybdenum (stage 2) was accompanied by the transition from dore to granodiorite intrusive activity (Fig. 11B). An annular, magnetite-destructive, phyllic assemblage grades outboard and vertically to muscovite-chlorite assemblages (stage 2; Fig. 11B; Margolis, 1993). Magma volumes declined over the life of the porphyry, and pipe-like breccia bodies, such as the Bone breccia and radiating breccia dikes, were emplaced during high-sulfidation-type alteration (stage 3) that was telescoped on potassic alteration (Fig. 11C).

Breccia dikes at El Salvador also correlate with late plutonism and overlap with high-sulfidation-type alteration (e.g., Gustafson and Hunt, 1975). Such telescoping of advanced argillic assemblages can be ~1 to 2 m.y. younger than the alteration it overprints (Sillitoe, 2010). Our geochronological constraints permit an interval of this duration between stage 1B and stage 3. This increase in sulfidation state between stage 1 and stage 3 can be attributed to a decrease in magmatic-hydrothermal temperatures (Einaudi et al., 2003). The anticipated location for a lithocap to the Mitchell-Snowfield system is overlying the Snowfield Main zone. The shallowest extent of the
Fig. 11. Model for the evolution of Mitchell. Geologic legend as in Figure 3. A. Stage 1A and stage 1B accompanied by Premier syenite and Sulphurets phase 1, respectively. B. Stage 2 and phase 2 granodiorite. C. Stage 3 and phase 3 diorite. D. Skeena fold-and-thrust deformation. Illustration of geometry of structures and plutons in the Sulphurets district. E. Early Jurassic basin growth faults. F. Geometry of Premier intrusions and stage 1A copper. G. Geometry of Sulphurets intrusions; faults active during porphyry emplacement and average geometry of hydrothermal veins. H. Geometry of Skeena fold-and-thrust–related cleavage, folds, and compressional faults.

K = Kerr, S = Sulphurets, BJ = Brucejack, M = Mitchell and Snowfield, IC = Iron Cap
Mitchell-Snowfield that may have hosted the lithocap would have been offset more than 1 km to the east along the Sulphurets thrust. Distal and peripheral to the porphyry core are rare, sporadically mineralized, low-sulfidation-type quartz-barite veins and the disseminated Snowfield Gold zone (stage 4).

One unusual hydrothermal feature of Mitchell is that phyllic, muscovite-chlorite, and anhydrite alteration domains define only a partial ring around its northern and eastern margins (Figs. 3, 4). Possible causes for the asymmetry may relate to the west-northwest plunge of the orebody (Figs. 4B, 6). This geometry exposes deeper alteration types to the west, where phyllosilicate-rich alteration was eroded. In the southern Mitchell, tight quartz vein contours in the footwall of the sheeted vein body indicate a change of 80 to 10% over ~150 m (Fig. 10B). This abrupt reduction in quartz abundance and absence of phyllic alteration may be due to an unidentified late pluton or fault offset that follows an easterly trend, parallel to the sheeted vein body.

**Structural controls in the Sulphurets district**

Sulphurets district Au-Cu porphyry and Au vein deposits were emplaced into a preexisting local framework of roughly orthogonal, first-order northerly and subsidiary easterly lineaments (Fig. 11F) that mirrors regional patterns. The northerly overall trends of the KSM deposits and the Brucejack alteration zones lie along the prominent structural corridor that extends throughout western Stikinia (Fig. 1). Preminer-alization easterly cross structures such as the Johnstone fault correspond to regional easterly faults like the Pitman and Iskut River systems. At Mitchell and Snowfield, veins are sheeted with easterly strikes, interpreted to indicate that the local stress field during emplacement involved north-south extension (i.e., perpendicular to least compressive stress, $\sigma_3$). West-northwesterly epithermal quartz vein swarms at Brucejack (Tombe et al., 2018) developed in a similar stress field. By contrast, at Kerr, N-S-oriented sheeted veins imply that maximum extension was oriented east-west. These orthogonal vein orientations may be due to influence of basement architecture, combined with shifts in structural regime between closely spaced magmatic-hydrothermal events.

The inferred spatial and temporal orthogonal shifts of $\sigma_1$ and $\sigma_3$ could be the result of a local stepover zone in a low-displacement transcurrent fault system between the fault corridor that parallels the McTagg anticlinorium and the proto-Bricejack fault. The northeasterly alignment of the Premier intrusions, sinistral movement on the east-northeastly (antithetic) Glacier shear zone, and slight right-stepping of the KSM deposits trend (Fig. 11F, G) are compatible with a dextral sense of shear across the system. However, total displacements were small, as geologic units are not displaced laterally across the area (see Lewis, 2013). By Early Jurassic time, the intense Late Triassic compressional event had dissipated. Intrusion and mineralization likely took place in a post-tectonic environment of local block faulting controlled by intersecting northerly and easterly crustal weak zones, which also provided permeability corridors to channel magmas and fluids (e.g., Tosdal and Richards, 2001).

The key role of long-lived lineaments and lineament intersections in controlling emplacement of porphyry deposits has been highlighted for the classic porphyry districts of the central and southern Andes (Tosdal and Richards, 2001; Piquer et al., 2015) as well as in island arc-hosted deposits like Cadia (Fox et al., 2015). Large-scale transpressive fault systems, with extension focused in pull-apart basins, can facilitate the rise of porphyry magmas into the upper crust (Richards, 2003; Cloos and Sapiie, 2013). Grasberg in Papua New Guinea is a particularly relevant example in this context: it formed at an extensional jog in a postcollisional strike-slip fault with small total displacement (Sapiie and Cloos, 2013).

**Skeena fold-and-thrust belt deformation at Mitchell**

Deformation of Mitchell and its surrounds occurred as a local manifestation of orogen-scale sinistral transpression of the Cretaceous Skeena fold-and-thrust belt, with cleavage, fold, and fault geometries controlled by preexisting crustal anisotropies. D$_1$ penetrative deformation (E-striking S$_1$; Fig. 8C) and associated F$_1$ folds were followed by the D$_2$ E-vergent motion on the Sulphurets, Mitchell, and Mitchell basal shear zones and Snowfield thrust faults and associated northerly F$_2$ folds (Figs. 8F, Table 2). The north-northwesterly fold and fabric trends in the Sulphurets district (Fig. 2) are distinct from regional orogen-parallel northwesterly and orogen-normal northeasterly trends in the Bowser Lake Group (Fig. 1; Evenchick et al., 2007). We propose that easterly D$_1$ features nucleated on cross structures exemplified by the Johnstone fault, whereas the N-striking Sulphurets and Snowfield faults exploited first-order, lineament-controlled shear zones (Figs. 2, 11H). At the northern limit of KSM, the trace of the McTagg anticlinorium and the strike of the Sulphurets thrust fault are both deflected from north to northeasterly, in a configuration consistent with that of a sinistral restraining bend. The deflection coincides with the zone of easterly faults, veins, fold trends, and S$_1$ cleavage geometry at Mitchell (Fig. 11H). This proposed stepover could have been generated at the intersection of an orthogonal, E-striking cross structure with the first-order, N-trending shear zone.

**Strain partitioning**

Strain partitioning has been an important process at Mitchell in that deformation and localization of strain was highly influenced by alteration type. Rheologically soft rocks have penetrative fabrics (e.g., Fig. 7A, B), whereas rheologically hard alteration types are less strained and retained their emplacement geometry (e.g., Fig. 7F). The microstructures of rheologically soft rocks suggest that solution transfer was the dominant mechanism in development of the S$_1$ cleavage (Fig. 9). Pyrite was brittlely extended parallel to S$_1$ and was insoluble during solution transfer, as suggested by its location generally within the phyllosilicate P domains. Chalcopyrite was also strained during deformation, resulting in mechanical reshaping of the chalcopyrite into lenticular, locally boudinaged, S$_1$-parallel geometries. Similarly, molybdenite was mechanically reshaped into lenticular grains concentrated in P domains. Sulphides are interpreted to have been segregated in soft alteration types by solution transfer processes that resulted in widespread quartz dissolution textures in P domains (Fig. 9) and the abundance of quartz pressure shadows in the Q domains.

Localization of strain at the microscopic scale has implications for the distribution and extraction of metals in deformed
porphyry deposits. At Mitchell, rheologically weak alteration types possess a penetrative pressure solution cleavage associated with loss of silica and, hence, passive enrichment of chalcopyrite, molybdenite, and pyrite along cleavage planes. Gold resides as electrum inclusions in pyrite and chalcopyrite (Febbo et al., 2015), and therefore it is also passively concentrated. The passive enrichment of sulfides associated with the formation of pressure solution cleavages in massive sulfides is well documented (e.g., Lianxing and McClay 1992). Ore located in the strongly cleaved areas at Mitchell has been subjected to solid-state mechanical mobilization where strain is preferentially partitioned into easily deformable sulfide minerals (e.g., chalcopyrite, Roscoe, 1975; molybdenite, Thompkins et al., 2004). In contrast, the more competent pyrite grains have undergone grain size reduction via brittle microfracture and bondindage. Passive enrichment in sulfide minerals because of quartz dissolution is a significant remobilization mechanism within phyllic-altered rocks and in the sheeted vein body. In these alteration domains, flattening estimates between 10 and 70% suggest significant loss of quartz. Therefore, zones of high strain were enriched in sulfides through grain-scale processes of solution transfer, resulting in relatively higher and homogeneous ore grades.

Conclusions

Mitchell is interpreted to be the deeper level of a once-contiguous porphyry deposit that included the shallower, structurally offset Snowfield. Mitchell is hosted by the calc-alkaline Sulphurets diorites that cut the alkaline Premier monzonite and syenite intrusions. Magnatic-hydrothermal activity at Mitchell began after 193.9 ± 0.5 Ma (Kirkham and Margolis, 1995) and continued to at least 190.3 ± 0.8 Ma, with individual stages probably occurring over shorter time spans.

Mitchell was heterogeneously deformed because of sinistral transpression associated with the mid-Cretaceous Skeena fold-and-thrust belt. D1 structures attributed to local north-south shortening include pervasive, steep, W-striking S1 pressure solution cleavage and steep W-plunging F1 folds in quartz veins. Fold geometries and degree of flattening vary with alteration type. In rheologically weak alteration types, a penetrative pressure solution cleavage formed during loss of silica, mechanical remobilization of chalcopyrite and molybdenite, and passive enrichment of chalcopyrite, molybdenite, and pyrite along cleavage planes. D2 structures that formed during east-west compression include steep NNW-plunging F2a, folds and E-directed thrust faults that offset Snowfield ~1,600 m to the east-southeast of Mitchell. Thrust faults further imbricate Mitchell with mineralization terminating at ~900-m depth because of displacement along the Mitchell basal shear zone. The root zone to the Mitchell-Snowfield system remains an untested exploration target.

The presence of N- and E-striking basement structures in Stikinia, including Mitchell, has significant implications for the understanding of the Sulphurets district and exploration for undiscovered Triassic and Early Jurassic Cu-Au porphyry and related systems in the region. This research suggests that basement lineaments have created favorable mineralized corridors, such as the KSM trend, and highlights the significance of orthogonal cross faults that host Mitchell.

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