Review of the Structural Geology of the Brucejack Intermediate-Sulphidation Epithermal Deposit, Northwestern British Columbia (NTS 104B)

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Introduction

Epithermal Au deposits form at shallow crustal levels (0–2 km) and are associated with hydrothermal-fluid temperatures ranging from <150 to 300°C (White and Hedenquist, 1995). Since these deposits are emplaced at high crustal levels, older epithermal systems are commonly eroded away and there is a bias toward discovery of young (Mesozoic age) deposits (Sillitoe and Hedenquist, 2003). Formation and spatio-temporal relationships of these deposits are linked to key stages in orogenic cycles (Nelson et al., 2013). In general, epithermal deposits form in convergent-margin settings associated with continental and island-arc magmatic systems (Sillitoe and Hedenquist, 2003). Epithermal deposits can form in extensional intra-arc and back-arc environments, as well as in compressive-arc regimes (Sillitoe and Hedenquist, 2003). The state of stress (tensile versus compressive) is determined based on whether an arc is retreating or advancing (Collins, 2002). Retreating arcs undergo extension in response to rollback of the lower plate, promoting the development of back-arc basins (Cawood et al., 2009). In contrast, advancing arcs undergo contraction in response to coupling with, and overriding of, the down-going plate. Flat-slab subduction and high rates of plate convergence are responsible for the development of an advancing arc (Cawood et al., 2009).

In compressive- and extensional-arc settings, there is a variety of controls that influence the formation, distribution and orientation of epithermal systems. Rheological characteristics of rocks, structural processes and stress regime are some of the more important controls on orebodies (Corbett, 2012). Competent hostrocks more readily fracture via brittle failure, opening conduits for migrating fluids (Ramsay and Huber, 1987) and thereby facilitating the passage of metal-rich fluids (Corbett, 2012). Linear ore shoots form where feeder-fault structures intersect permeable or chemically favourable horizons and other planar features such as dikes and faults (Corbett, 2012). Epithermal deposits can be hosted along extensional structures such as listric- and bookshelf-style normal faults and subsidiary vein systems, but also in compressional structures, including thrusts, shear zones and dilation jogs (i.e., releasing bends) in strike-slip faults (Corbett, 2012).

Brucejack is a high-grade (electrum) intermediate-sulphidation epithermal deposit hosted in early to-mid-Jurassic Hazelton Group volcanic and volcano-sedimentary rocks within the Intermontane Belt (Stikine terrane) of the Canadian Cordilleran Orogen (Tombe et al., 2018; Figure 1). The deposit is located in the Sulphurets mineral district of northwestern British Columbia (BC), a major exploration camp that has been prospected since the 1800s (Kirkham and Margolis, 1995). Electrum is hosted in mildly deformed carbonate and quartz-carbonate stockwork and breccia systems (Tombe et al., 2018).

This paper presents a comprehensive review of the structural relationships that characterize the Sulphurets mineral district, with emphasis placed on the Brucejack deposit. Folds, cleavage, and fault and vein relationships are discussed from tectonic to property scale and then the observations are compared with available interpretations. Published evolutionary models for the Brucejack deposit are discussed and key questions are identified that remain to be resolved regarding the structure of the Brucejack deposit.

Tectonic Setting

The Canadian Cordillera records the complex evolution and interactions of pericratonic and allochthonous island-arc terranes and associated oceanic assemblages that have accreted to the North American continent (Monger et al., 1972). The Brucejack deposit resides in the western domain of the Stikine arc terrane (Stikinia) of the Intermontane Belt (Tombe et al., 2018; Figure 1). The Stikine terrane is flanked to the west by the Coast Plutonic Complex and to the east by Triassic–Jurassic arc-related rocks of the Quesnel terrane (Quesnellia; Nelson and Kyba, 2014). Stikinia formed as an island-arc in the paleo–Pacific Ocean from the

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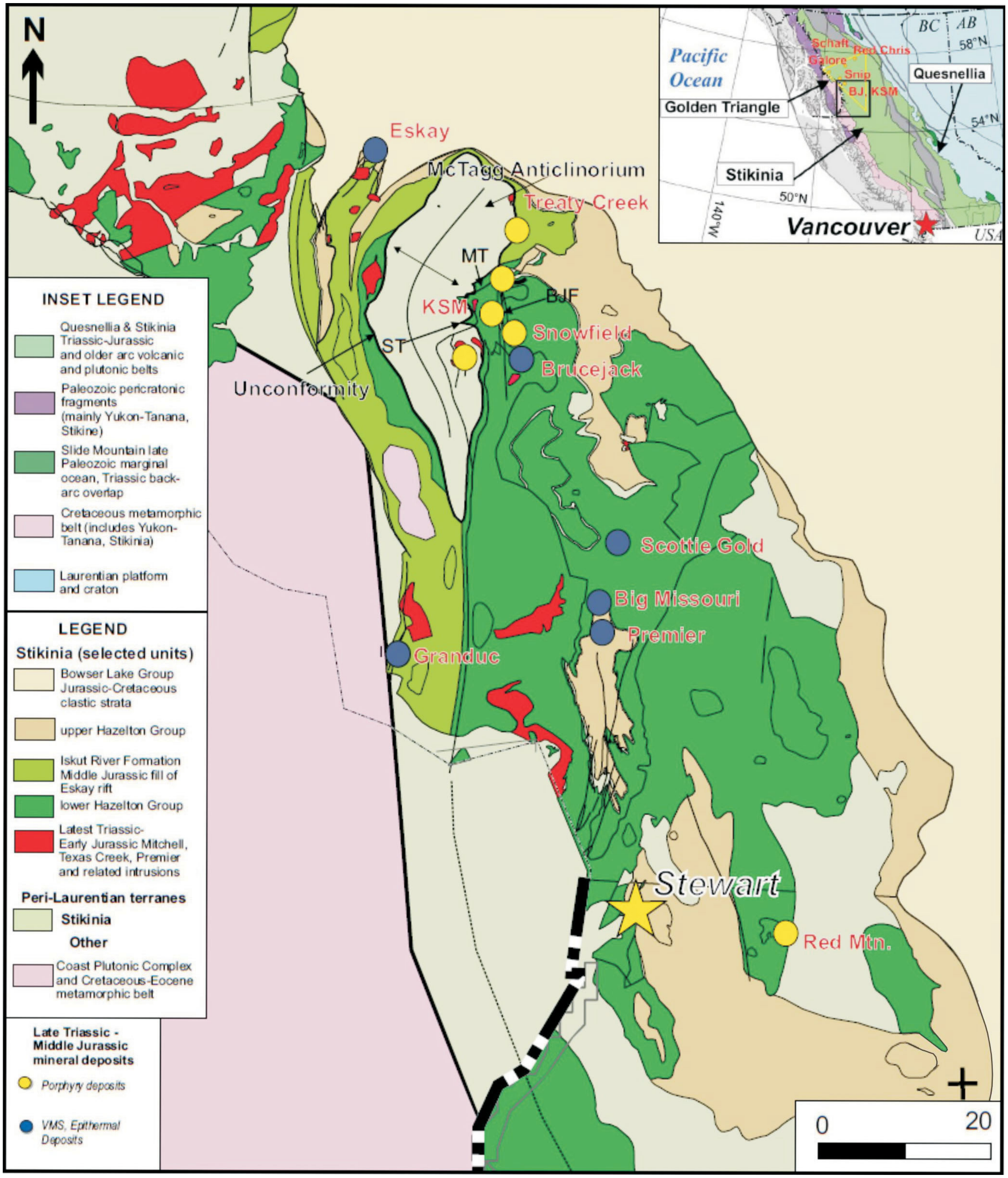

Figure 1. Geology of the McTagg Anticlinorium, showing the Brucejack deposit on the eastern flank of the anticlinorium (labelled) and other well-known prospects in the area. Small inset map in top right corner shows location of the McTagg Anticlinorium in the Canadian Cordillera (modified after Board et al., in press).

mid-Paleozoic to the Mesozoic (Monger et al., 1972). Early to Middle Jurassic subduction beneath Stikinia is indicated by arc magmatism and the development of the Cache Creek accretionary complex (Marsden and Thorkelson, 1992). Early Jurassic subduction caused Stikinia to rift, forming an extensional basin known as the Hazelton Trough, with synchronous volcanism along both of its margins (Marsden and Thorkelson, 1992). The Hazelton Trough is interpreted as an inter-arc basin (Marsden and Thorkelson, 1992). Rocks of Stikinia were deformed by a mid-Jurassic orogenesis (Evenchick, 1991). This is consistent with formation of the Bowser Basin (foreland basin) and the termination of island-arc magmatism within the Hazelton Group (Nelson and Colpron, 2007; Gagnon et al., 2012).

The Skeena fold-and-thrust belt (SFTB) is a 160 km wide fold-and-thrust zone mapped in the Stikine terrane (Evenchick, 1991). It is likely the result of a major mid-Cretaceous collision that variably strained the incompetent sedimentary rocks of this terrane. Rocks of the Bowser Lake Group were shortened by ~44%, whereas the more competent volcanic and volcaniclastic Hazelton Group rocks exhibit much less deformation (Evenchick, 1991). In the Bowser Lake Group, rocks are folded and imbricated along northwest- and southeast-striking faults that likely merge with a sole thrust at a branch point at depth, possibly at the boundary between the Hazelton and Bowser Lake groups (Evenchick, 1991). The one exception is in the northwestern domain of the Bowser Basin, where folds and faults trend and strike northeast (Evenchick, 2001). It is probable that progressive loading during SFTB orogenesis formed the Sustut foreland basin in a newly formed flexure (Evenchick, 1991).

Sulphurets Mineral District

The Sulphurets mineral district occupies the mountainous region of the Canadian Cordillera 70 km north of Stewart, BC (Figure 2; latitude 56°30′N, longitude 130°15′W; Kirkham and Margolis, 1995). This district hosts well-defined, world-class, Cu-Au–porphyry mineralization, including the Kerr–Sulphurets–Mitchell–Iron Capp (Febbo et al., 2019) and Snowfields deposits (Jones, 2013), as well as high-grade Au-Ag epithermal mineralization, including the Brucejack deposit (Tombe et al., 2018). Placer Au prospecting began in the Sulphurets region in the 1880s (Kirkham and Margolis, 1995). More extensive Cu, then Mo and later Au and Ag exploration began in the 1950s (Kirkham and Margolis, 1995). The first Cu-Au–porphyry targets were drilled in the 1960s and, during 2006, Seabridge Gold Inc. drilled the Mitchell porphyry deposit (Febbo et al., 2019). Gold-silver mineralization was first reported near Brucejack in 1959 (Roach and Macdonald, 1992). Subsequent exploration programs by Esso Minerals Canada Ltd. and Granduc Mines Ltd. from 1960 to 1985 identified multiple Au-Ag showings on what is now the Brucejack property, currently owned by Pretium Resources Inc. (Pretium Resources Inc., 2014).

Lithostratigraphy

The lithostratigraphic relationships of the Stikine assemblage and the Stuhini, Hazelton and Bowser Lake groups are important in understanding the structural geology of the Sulphurets mineral district. The district is underlain by rocks of the Stuhini and Hazelton groups (Kirkham and Margolis, 1995). However, the relationships between the Stikine and Stuhini groups (Brown and Greig, 1990), as well as the Hazelton and Bowser Lake (Evenchick, 1991) groups, are described from observations of the immediate region. Figure 3 illustrates the stratigraphic relationships between the Stikine assemblage and the Stuhini, Hazelton and Bowser Lake groups. The lithostratigraphic development of rocks in the Sulphurets mineral district is described below.

The Stikine assemblage is the basement of the Stikine terrane (Nelson and Kyba, 2014). It consists of mostly Devonian to Mississippian arc-related plutonic and volcanic rocks that are unconformably overlain by arc-related volcanic, pyroclastic and sedimentary rocks of the Stuhini Group (Figures 2, 3; Brown and Greig, 1990). In the Sulphurets mineral district, the Stuhini Group consists of dark grey turbiditic siltstone interbedded with minor limestone, subaqueous pyroclastic rocks and intermediate porphyritic flows (Kirkham and Margolis, 1995).

The latest Triassic to middle Jurassic Hazelton Group unconformably overlies the Stuhini Group (Figures 2, 3; Grieg and Brown, 1990). The Hazelton Group is divided into lower and upper components (Figure 3; Nelson et al., 2018). The lower Hazelton Group includes the Jack and Betty Creek formations (Nelson et al., 2018). The Jack Formation consists of volcaniclastic cobble to boulder conglomerate and arkosic sandstone overlain by thinly bedded siltstone with local interbeds of intermediate pyroclastic rocks (Nelson et al., 2018). The Betty Creek Formation unconformably overlies the Jack Formation (Board et al., in press) and is subdivided into the Unuk River andesite and Brucejack Lake felsic units (Figure 3; Nelson et al., 2018).

The Unuk River andesite unit is characterized by intermediate pyroclastic and epiclastic rocks (Nelson et al., 2018). The epiclastic rocks are typically near the top of the unit, though the transition is only recognized in underground workings at the Brucejack property (Board et al., in press). The overlying Brucejack Lake felsic unit consists of potassium feldspar– and hornblende-phyric flows and welded to nonwelded felsic tuffs (Macdonald, 1993; Nelson et al., 2018). Pyroclastic rocks of the Unuk River andesite unit have detrital zircons that range in age (U-Pb) from 188 to 184 Ma (Tombe et al., 2018). Near the Sulphurets mineral district, the upper Hazelton Group includes the Spatsizi,

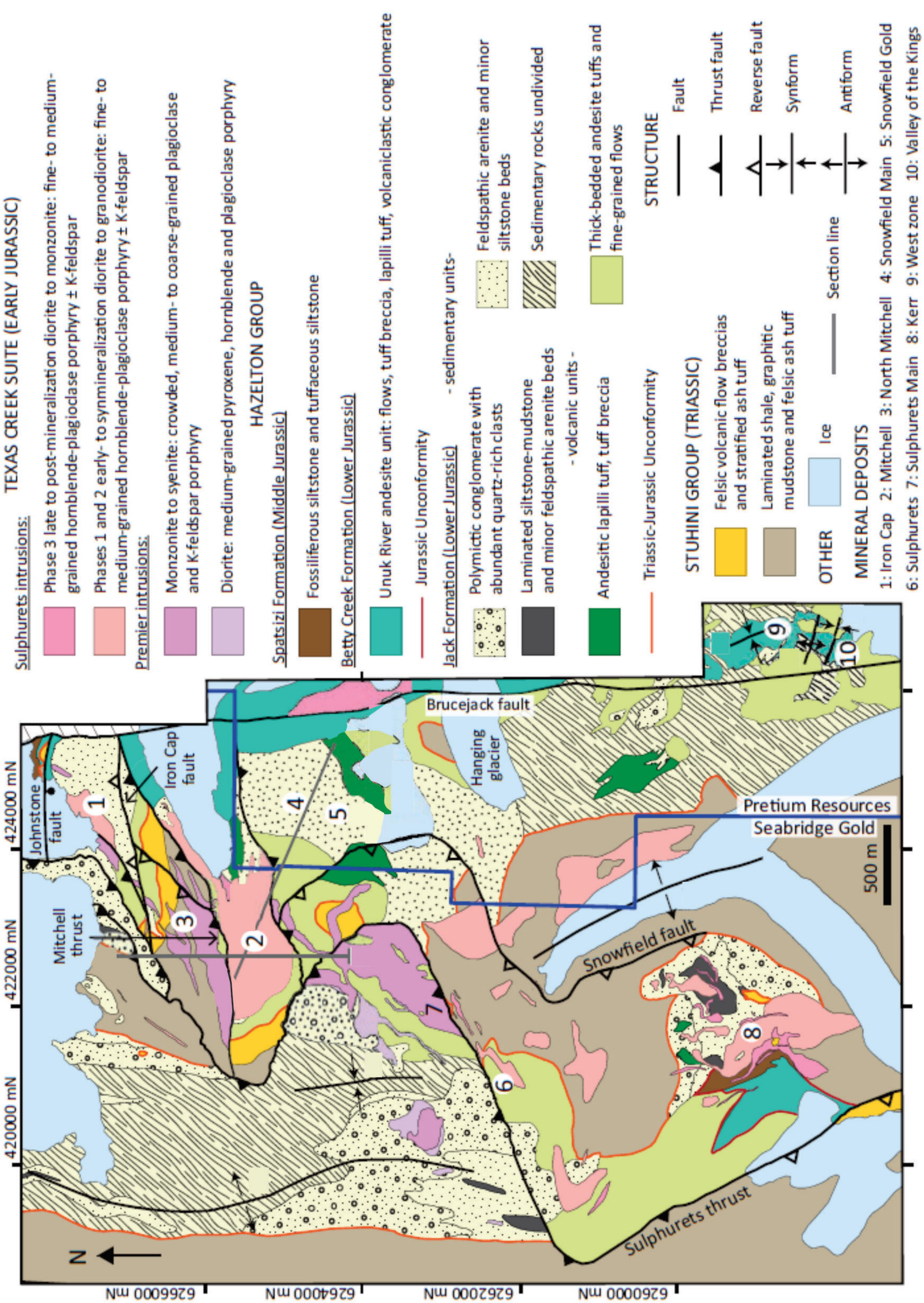

Figure 2. Lithological and structural relationships of the Sulphurets mineral district, with emphasis on known mineral deposits (1–10) and major faults and folds in the area (modified after Febbo et al., 2019).

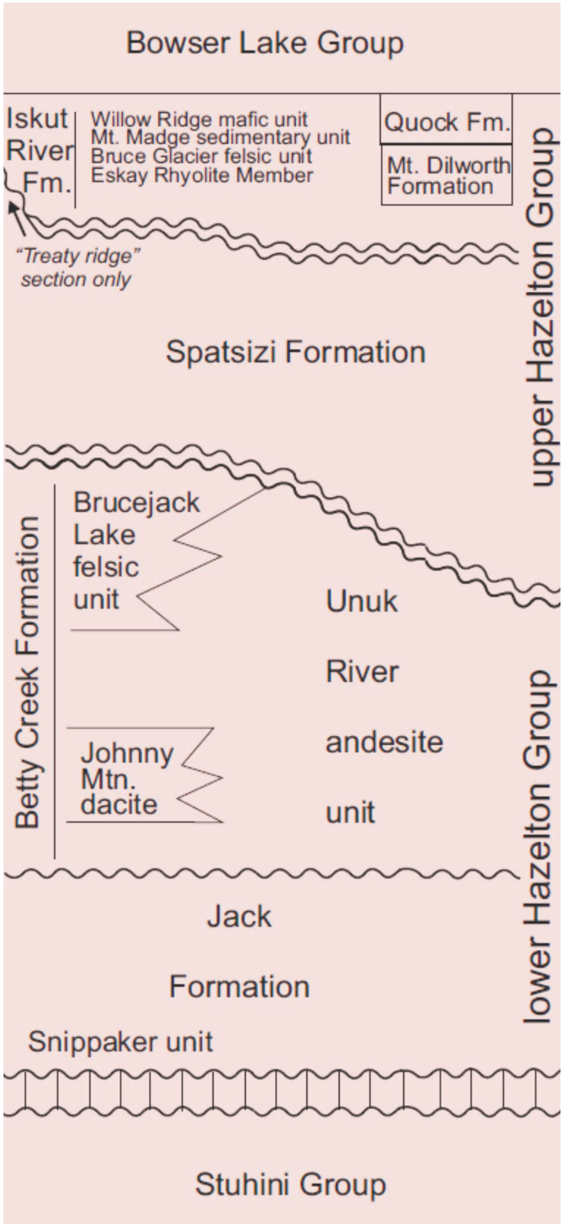

Figure 3. Stratigraphic relationships in the Sulphurets mineral district (modified after Nelson et al., 2018). Abbreviations: Fm., Formation; Mt., Mount; Mtn., Mountain.

Iskut River and Quock formations (Figure 3; Nelson et al., 2018). The Spatsizi Formation unconformably overlies the Betty Creek Formation (Nelson et al., 2018). It consists of volcaniclastic conglomerate, sandstone and siltstone-mudstone rhythmites with local limestone (Nelson et al., 2018). The Spatsizi Formation is overlain by the ca. 179–173 Ma Iskut River Formation (Gagnon et al., 2012). It consists of bimodal volcanic rocks (basalt and rhyolite) and sedimentary rocks, including grey sandstone, siltstone and mudstone (Gagnon et al., 2012). The Quock Formation overlies, and is locally a facies equivalent to, the Iskut River Formation (Gagnon et al., 2012). The Quock Formation includes thin- and medium-bedded mudstone with thin grey tuffaceous layers (Thomson et al., 1986; Gagnon et al., 2012). The Iskut River and Quock formations are restricted to the Eskay Rift, a mid-Jurassic paleo–back-arc basin (Gagnon et al., 2012).

The Bowser Lake Group both unconformably and conformably overlies Hazelton Group rocks (Figure 3; Evenchick, 1991). It is a package of onlapping successions of fossiliferous conglomerate, sandstone, siltstone and mudstone that were likely deposited in a subsiding foreland basin during the mid-Jurassic (Evenchick, 1991). Fossils constrain deposition of the Bowser Lake Group to the mid-Jurassic to lower Cretaceous (Nelson and Kyba, 2014).

Intrusive Rocks

Arc-related intrusive rocks are documented throughout the Sulphurets mineral district (Figure 2; Davies et al., 1994; Kirkham and Margolis, 1995). Many plutons are of the Texas intrusive suite, which includes the Premier and Sulphurets intrusions (Figure 2; Kirkham and Margolis, 1995; Febbo et al., 2019). The alkaline Premier intrusions include plagioclase- and potassium feldspar–phyric monzogranite to syenite, as well as pyroxene-, hornblende- and plagioclase-phyric diorite (Figure 2; Febbo et al., 2019). Stocks associated with Premier intrusions host the main Sulphurets porphyry mineralization (Febbo et al., 2019). The Sulphurets intrusions comprise three main phases of plutons, diorite to monzodiorite, granodiorite and diorite, which all cut the Premier intrusions (Figure 2; Febbo et al., 2019). These rocks host porphyry-style mineralization of the Mitchell deposit (Febbo et al., 2019).

Three distinct igneous bodies intrude stratified rocks on the Brucejack property (Figure 4; Macdonald, 1993; Davies et al., 1994; Nelson et al., 2018; Board et al., in press). The informally named 'Office and Bridge zone porphyries (P1)' are characterized by light green plagioclase– and hornblende-phyric diorite (Figure 4; Davies et al., 1994; Board et al., in press). The informally named 'P2 porphyry' comprises potassium feldspar– (locally plagioclase) and hornblende-phyric rocks (Figure 4; Davies et al., 1994; Board et al., in press). The informally named 'flow dome complex' is an intrusion mapped north, south and east of Brucejack Lake (Figure 4; Macdonald, 1993). It consists of flow-banded and flow-folded plagioclase- and potassium feldspar–phyric rocks that are likely the subvolcanic equivalent of the Brucejack Lake felsic unit (Macdonald, 1993). The flow-dome complex has a U-Pb age of ca. 183–188 Ma (Lewis, 2013).

Structural Geology

The Sulphurets mineral district resides on the eastern flank of the McTagg Anticlinorium (Figure 1; Nelson and Kyba, 2014). The anticlinorium is an arcuate, fault-bounded, kilometre-scale culmination that likely formed during a mid-

Cretaceous orogenesis (Evenchick, 1991; Febbo et al., 2019). Internal structural relationships within the anticlinorium suggest a long and protracted deformation history that started in the latest Triassic (Brown and Grieg, 1990) and extended into the Cenozoic (Kirkham and Margolis, 1995). This deformation includes multiple contractional events (latest Triassic and mid-Cretaceous) and a major extensional event (latest Triassic to middle Jurassic) that formed many generations of folds, cleavages, faults and veins with varying structural styles and orientations (Davies et al., 1994; Kirkham and Margolis, 1995; Nelson and Kyba, 2014; Febbo et al., 2019). This section is a re-

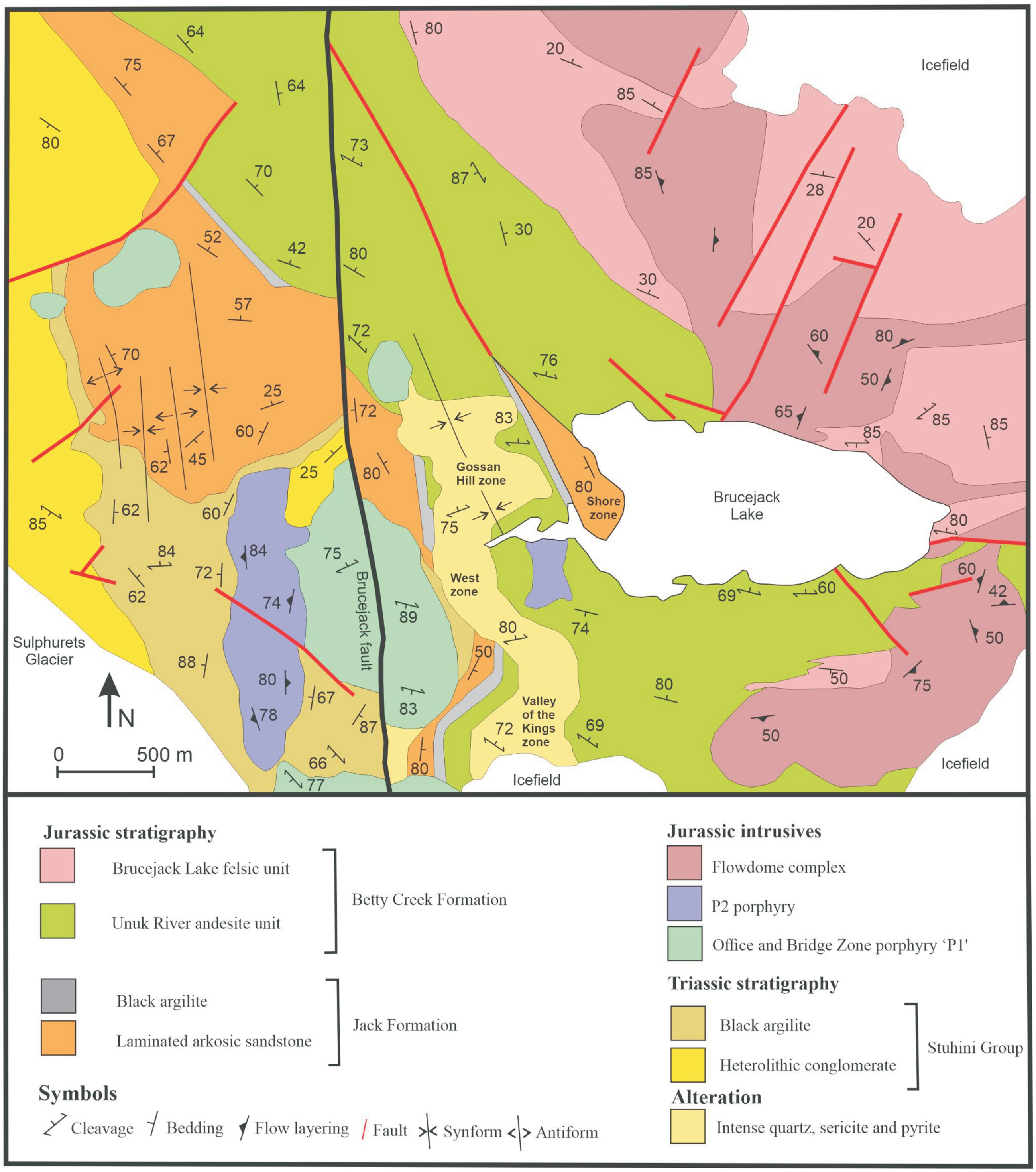

Figure 4. Detailed geology of the Brucejack property, showing lithological and structural relationships (modified after Davies et al., 1994). The Brucejack deposit comprises the Gossan Hill, West, and Valley of the Kings zones, the latter of which is currently being mined.

view of structural observations and interpretations of the Sulphurets mineral district outside the Brucejack deposit.

The oldest documented folds affect the Stuhini Group strata and formed prior to the deposition of Hazelton Group strata (Brown and Greig, 1990; Davies et al., 1994). These north-plunging folds record a major east-west contractional event that occurred during the latest Triassic and earliest Jurassic (Brown and Grieg, 1990). Deformation of Jurassic vein systems (Mitchell deposit), plutons (Premier and Sulphurets suites) and Jurassic Hazelton Group strata post-date the basal Hazelton unconformity (Kirkham and Margolis, 1995; Febbo et al., 2019). Workers have attributed these younger structures to progressive mid-Cretaceous SFTB deformation (Kirkham and Margolis, 1995; Febbo et al., 2019). Rocks were folded first about west-plunging axes (north-south shortening) and later about north-plunging axes (east-west shortening; Kirkham and Margolis, 1995: Febbo et al., 2019). This is best documented at the Mitchell deposit, where dome-and-basin fold-interference patterns are observed (Febbo et al., 2019). At this deposit, west-plunging small-scale buckle folds of veins have a weak to strong west-northwest-striking axial-planar flattening cleavage (Kirkham and Margolis, 1995; Febbo et al., 2019). Veins hosted in competent potassic-metasomatized rocks are relatively undeformed, whereas those hosted in quartz-sericite-pyrite–altered rocks are tight to isoclinally folded (Febbo et al., 2019). Likewise, a west-northwest-striking cleavage is absent in potassically altered rocks and well-developed in quartz-sericite-pyrite rocks (Kirkham and Margolis, 1995; Febbo et al., 2019). This cleavage has been documented throughout the entire Sulphurets district, including mid-Jurassic rocks north of the Iron Cap deposit (Kirkham and Margolis, 1995; Lewis, 2013; Febbo et al., 2019). North-plunging folds of the Sulphurets district have been recognized at multiple scales (Davies et al., 1994; Febbo et al., 2019). Regional-scale, open, north-plunging folds define the structural grain of the Sulphurets mineral district, though small-scale folds have been documented in veins at the Mitchell deposit (Figure 2; Davies et al., 1994; Kirkham and Margolis, 1995; Febbo et al., 2019). An approximately north-striking, nonpenetrative, spaced axial-planar fracture cleavage is observed locally (Kirkham and Margolis, 1995; Febbo et al., 2019).

South-verging (north-south compression) and east-verging (east-west compression) thrusts, mapped throughout the Sulphurets mineral district, have been attributed to progressive SFTB deformation (Kirkham and Margolis, 1995; Febbo et al., 2019). South- and east-verging faults are thought to be coeval with west- and north-plunging folds, respectively (Febbo et al., 2019). South-verging thrusts are rare, the largest being the Iron Cap fault near the Mitchell deposit (Figure 2; Febbo et al., 2019). In contrast, east-verging thrusts are common, including the Sulphurets and Mitchell thrust faults and the Mitchell basal shear zone (Figure 2; Kirkham and Margolis, 1995; Febbo et al., 2019). The Sulphurets thrust lies at the highest structural position and displays 1 km of top-to-the-east displacement (Febbo et al., 2019). The Mitchell thrust (1.6 km displacement) and the Mitchell basal shear zone (1–2 km displacement) are foreland-propagating splays positioned in the footwall of the Sulphurets thrust (Febbo et al., 2019). The Snowfields porphyry deposit is in the hanging wall of the Mitchell thrust and is thought to be the upper, displaced part of the Mitchell porphyry deposit that resides in the fault's footwall (Febbo et al., 2019). The Mitchell porphyry is truncated and displaced by the Mitchell basal shear zone at depth (Febbo et al., 2019).

The east-striking Johnstone fault and the north-striking Brucejack fault are two subvertical orthogonal structures (Figure 2; Kirkham and Margolis., 1995; Febbo et al., 2019). The Johnstone fault is located in the northeasternmost corner of the Sulphurets mineral district on the west side of the Brucejack fault and is suspected to link with the Brucejack fault at a branch point (Figure 2; Febbo et al., 2019). Near the Mitchell Glacier, there is ~500 m of west-side-up reverse displacement on the Brucejack fault, the most recent movements thought to be Eocene (Kirkham and Margolis, 1995). However, the Johnstone and Brucejack faults are interpreted to be long-lived structures that were active during deposition of the Hazelton Group units and were subsequently reactivated during later deformation (Nelson and Kyba, 2014; Tombe et al., 2018; Febbo et al., 2019). Nelson and Kyba (2014) reported that the Sulphurets thrust fault reactivated an early basin-bounding normal fault, the Sulphurets proto-fault. The configuration of early north-striking faults (Brucejack fault and Sulphurets proto-fault) and east-striking subsidiary faults (Johnstone fault) may have been crucial in controlling both the emplacement of porphyry-epithermal systems, including Kerr–Sulphurets–Mitchell–Iron Capp and Snowfields porphyries in the Jurassic, as well as stress distribution during the mid-Cretaceous SFTB (Nelson and Kyba, 2014; Febbo et al., 2019). It is likely that strain first focused on east-west basement faults (early north-south compression) and later focused on north-striking faults (later east-west compression) during progressive SFTB deformation (Febbo et al., 2019).

Brucejack Property Geology and Mineral Zones

The Brucejack property has been subdivided into 10 mineral zones, located in an arcuate north-trending belt of altered Hazelton Group rocks proximal to the Brucejack fault (Figure 4; Jones, 2013). The geology of the property is commonly discussed in relation to these zones, which have distinct geological and structural characteristics. The following discussion of some of the major zones, including the Valley of the Kings, West, Gossan Hill and Shore zones, focuses on vein paragenesis, composition and mineralogy, as well as lithology and alteration.

Valley of the Kings Zone

The Valley of the Kings stockwork systems are hosted in the siliciclastic rocks of the Jack Formation and intermediate pyroclastic and epiclastic rocks of the Unuk River andesite unit (Figure 4; Board et al., in press). Veins are also hosted in hornblende- and plagioclase-phyric intrusive or hypabyssal volcanic flows along the northern (Office porphyry) and southern (Bridge Zone porphyry) boundaries of the Valley of the Kings (Board et al., in press). Tombe et al. (2018) classified and described the veins of this zone in six main stages: 1) barren quartz-carbonate-pyrite stringers; 2) barren translucent microcrystalline veinlets; 3) quartz-carbonate-dolomite electrum-rich veins, stockworks and breccias; 4) quartz–calcite–base metal–Ag sulphosalt–electrum veins; 5) calcite (local Mn-rich calcite)–electrum veins; and 6) barren quartz-carbonate-chlorite ‘orogenic style’ shear and extensional veins. The youngest unit that hosts veins of all six stages is the 188–184 Ma Unuk River andesite unit (Tombe et al., 2018). Stages 1–5 are cut by mafic to intermediate dikes with a U-Pb age of 183 Ma (Board et al., in press). This constrains the main electrum vein stages (stages 3–5) to the Jurassic (Board et al., in press). Because stage 3, 4 and 5 veins and the dikes are all similarly oriented and have mutual crosscutting relationships, they are interpreted to be broadly coeval (Tombe et al., 2018). The hostrocks are affected by pervasive phyllic alteration, including white mica, pyrite, quartz and calcite, that locally destroyed primary rock textures (Board et al., in press). Pods of intense silicification are particularly prevalent in the Conglomerate unit and locally in the underlying Volcaniclastic unit, usually near the boundary between the two (Board et al., in press).

West Zone

West zone mineralization is hosted in the volcaniclastic sandstone and argillite of the Jack Formation, intermediate volcanic and pyroclastic rocks of the Unuk River andesite unit, and the P2 porphyry (Figure 4; Jones, 2013; Nelson et al., 2018). The West zone comprises 10 major quartz-carbonate veins and associated stockworks, the largest of which has a strike length of 250 m and can reach 6 m in thickness (Jones, 2013). Mineralized veins of the West zone have 650 m of known vertical continuity (Roach and Macdonald, 1992). The alteration system is ~100–150 m wide and has a silica core that transitions to sericite (± quartz and carbonate), then to chlorite (± sericite and carbonate; Jones, 2013). Quartz-carbonate veins host electrum, pyrite, sphalerite, chalcopyrite and galena, as well as Ag-bearing tetrahedrite, pyrargyrite, polybasite and sparse stephanite and acanthite (Jones, 2013).

Gossan Hill Zone

The Gossan Hill zone is a circular zone (400 m in diameter) of mineralization, hosted in the Unuk River andesite unit, that is overprinted by intense quartz-sericite-pyrite alteration (Figure 4; Jones, 2003; Nelson et al., 2018). There are 11 deformed quartz veins that strike west, dip steeply north and can have strike lengths of 250 m and thicknesses of 20 m (Jones, 2013). The veins contain electrum, pyrite, sphalerite and galena, as well as Ag-rich tetrahedrite, pyrargyrite and polybasite (Jones, 2013).

Shore Zone

Shore zone mineralization is hosted mainly in intensely quartz-sericite-pyrite–altered Jack Formation and, to a lesser extent, the Unuk River andesitic unit (Figure 4; Nelson et al., 2018). Here, a relatively small quartz-stockwork zone is coincident with a major northwest-trending lineament near the western shore of Brucejack Lake (Jones, 2013). The vein and alteration system together have a 530 m strike length and can be 5 m thick (Jones, 2013).

Structural Geology of the Brucejack Property

Folds and Cleavage

Rocks underlying the Brucejack property record multiple phases of Triassic to Eocene deformation (Figure 4; Brown and Greig, 1990; Kirkham and Margolis, 1995). The earliest deformation is documented in the Stuhini Group to the west of the Brucejack deposit (Davies et al., 1994). The Stuhini Group rocks are imbricated and tightly folded about north-northwest-plunging fold axes (Davies et al., 1994). Folds have wavelengths of tens of metres and are truncated against an angular unconformity that separates them from the overlying Hazelton Group (Davies et al., 1994). The Hazelton Group strata of the Brucejack property are also deformed (Britton and Aldrick, 1987; Roach and Macdonald, 1992; Davies et al., 1994; Kirkham and Margolis, 1995; Harrichhausen, 2015; Tombe et al., 2018). They constitute a concave-to-the-west arcuate, northerly trending belt of eastward-younging and openly folded rocks (Figure 4; Davies et al., 1994; Jones, 2013). East of the Brucejack fault and west of Brucejack Lake, the belt is characterized by a regional-scale, north-plunging syncline. The core of the syncline houses the West zone showing (Figure 4; Davies et al., 1994; Jones, 2013). The western limb of the syncline continues south through an alteration zone near the Brucejack deposit, whereas the eastern limb is cut out against a fault along strike to the north and south (Figure 4; Davies et al., 1994). Although Davies et al. (1994) described folds in the northerly belt as open, their bedding-orientation data indicate that tightly folded domains exist along the axial trace of the syncline (Figure 4). Northerly trending folds lack a penetrative axial-planar fabric. Tombe et al. (2018) interpreted the Brucejack deposit, as well as the West zone showing, to reside within a series of east-southeast-trending synclines that lie along the axial trace of the north-trending syncline mapped by Davies et al. (1994). However, the synclinal features have also been interpreted as a series of east-southeast-striking paleo–half grabens (Board et al., in press).

A weakly to well-developed, ubiquitous, east-southeast-striking planar fabric can be mapped throughout the Brucejack property (Roach and Macdonald, 1992; Davies et al., 1994; Tombe et al., 2018; Board et al., in press). Early vein and foliation studies by Roach and Macdonald (1992) defined a high-strain region in the West zone. In this high-strain zone, there is a strong east-southeast cleavage that parallels mineralized veins and their margins (Roach and Macdonald, 1992). They interpreted that the high-strain zone, including the mineralized veins and cleavage, formed during simple shear (non-coaxial deformation; Roach and Macdonald, 1992). In contrast, Davies et al. (1994) described the east-southeast-striking cleavage as a flattening fabric (coaxial deformation) that is axial planar to buckle folds observed in veins. This is consistent with fold- and fabric-orientation data collected in stockwork zones on the Brucejack property by Harrichhausen (2015). Davies et al. (1994) argued that the east-southeast-striking cleavage is postmineralization and attributed it to the mid-Cretaceous SFTB deformation (Evenchick, 1991). Davis (2017) defined two east-southeast-striking flattening fabrics (S_1, east-southeast; S_2, southeast) at the Brucejack deposit. He documented both foliation-parallel and discordant relationships between mineralized veins at the Brucejack deposit and suggested that both fabrics predate mineralization (B. Davis, unpublished report prepared for Pretium Resources Inc., 2017).

Faults

The Brucejack fault is subvertical and passes through the entire property west of Brucejack Lake (Figure 4; Davies et al., 1994; Tombe et al., 2018). The fault cuts all rock types, veins and alteration zones, and the most recent movements are believed to be Eocene (Kirkham and Margolis, 1995). At regional scale, map patterns suggest there is ~200 m of dextral strike separation (with unknown dip separation) along the fault west of Brucejack Lake (Figure 4; Davies et al., 1994). North of the Brucejack property, Davies et al. (1994) mapped steeply plunging elongated clasts, suggesting dominantly dip-slip movement at some time during the fault's history.

Minor east-northeast-striking cross faults with both dextral and sinistral movements also affect rocks of the Brucejack property (Figure 4; Davies et al., 1994; Harrichhausen, 2015). The largest of the east-northeast-striking cross faults, mapped north of Brucejack Lake, has normal-dextral shear sense and tens of metres of displacement (Davies et al., 1994).

Proposed Structural Models for the Brucejack Deposit

Roach and Macdonald (1992) conducted a vein and foliation study at the West zone showing and interpreted quartz-carbonate veins of the West zone to have formed in a 130 m wide, southeast-striking and steeply dipping, sinistral, brittle-ductile shear zone. This model interpreted the southeast-striking fabric as synveining and a product of ductile simple shear (Roach and Macdonald, 1992). Extensional veins of the West zone are parallel and subparallel to the orientation of the interpreted shear zone. The veins are described as central and oblique, terms adopted from Hodgson (1989), and are inferred to have formed episodically at elevated fluid pressures through brittle failure (Roach and Macdonald, 1992).

Harrichhausen (2015) studied the structural evolution of mineralized veins of the Brucejack property, placing emphasis on a major east-southeast-striking breccia-stockwork system, Domain 20, at the heart of the Valley of the Kings. This system is well exposed underground but has not been observed at the surface. Higher density of veins at the core of Domain 20, and adjacent lower density systems, are consistent with vein patterns observed in faults and neighbouring damage zones (Harrichhausen, 2015). Inferred offset of lithological units in the hangingwall relative to the footwall of Domain 20 suggests it is a south-side-down normal fault (Harrichhausen, 2015). Harrichhausen (2015) interpreted Domain 20 to have formed in an extensional zone along an east-southeast-striking strike-slip fault. Veins associated with Domain 20 have syntaxial growth textures and likely formed postfaulting during a static period with high fluid pressures and fracture displacement through mode-1 extension (Harrichhausen, 2015). In contrast, other quartz-carbonate stockwork zones mapped at the surface in the Valley of the Kings zone have asymmetries and textures, such as stretched quartz fibres, that suggest they formed during shearing (i.e., synfaulting; Harrichhausen, 2015). Therefore, veins of the Brucejack deposit likely formed in an east-southeast-striking strike-slip system along subsidiary extensional fractures both syn- and postdisplacement (Harrichhausen, 2015).

Davis (B. Davis, unpublished report prepared for Pretium Resources Inc., 2017) reported that veins of the Valley of the Kings formed through two progressive stages of roughly north-south compression prior to and during the main stage of mineralization in the Jurassic. Stage one is characterized by the development of two flattening fabrics, oriented east-southeast and southeast, that formed through northeast-southwest compression. Large-scale, north-striking strike-slip faults, including the 'Cleopatra' vein, formed as transfer structures (i.e., tear faults) bounding distinct structural domains. During stage two, pre-existing north-striking faults were reactivated during sinistral transpression. This implies a switch in kinematics from northeast-southwest to northwest-southeast compression. Here, ore fluids of the Brucejack deposit focused along north-striking faults and southeast-striking extensional veins that formed through episodic brittle failure. Davis (B. Davis, unpublished report prepared for Pretium Resources Inc., 2017) hypothesized that the two fabrics, in part, controlled the orientation of the southeast-striking mineralized extensional veins. Locally, veins are folded and boudinaged parallel to the fabric, suggesting that ongoing progressive deformation was at a high angle to the mineralized veins. Styolitic and asymmetric geometries observed in electrum hosted in extensional veins are interpreted as syndeformational textures. Board et al. (in press) proposed that the approximately north-south compression noted at the Mitchell Au-Cu porphyry by Febbo et al. (2019), who attributed this deformation to the mid-Cretaceous SFTB, is also likely a product of Jurassic deformation (183 Ma) described by Davis (B. Davis, unpublished report prepared for Pretium Resources Inc., 2017).

Febbo et al. (2019) interpreted the west-northwest-striking veins of the Mitchell deposit as having formed during localized north-south extension within a step-over zone between north-striking faults in an overall east-west extensional regime. It is postulated that the east-southeast-striking veins of the Brucejack also formed in a step-over zone similar to the Mitchell deposit (Febbo et al., 2019).

Preliminary Hypothesis Based on Previous Studies

Detailed mapping of the Brucejack property by Davies et al. (1994) indicated that north-northwest-trending folds (arcuate belt) define at property scale the structural grain of the Jurassic stratigraphy that hosts the mineralized zones of the property. These folds are tight, and locally isoclinal, on the map by Davies et al. (1994), suggesting significant east-west shortening. In contrast, the Au-bearing vein networks at Brucejack are relatively undeformed with exceptional continuity (Board et al., in press). Based on these observations, it would not be unreasonable for the significant east-west shortening documented in the hostrocks of the Brucejack deposit to be premineralization or synmineralization. However, folds and faults of the belt are at present considered a product of the SFTB, based on orientation alone (e.g., Davies et al., 1994). Mineralized zones along the belt could have formed as extensional and transtensional vein systems along east-southeast-trending faults, as previously proposed by Harrichhausen (2015), during the waning stages of folding in the north-trending arcuate belt during approximately east-west Jurassic compression.

One of the most difficult things to explain is parallelism of cleavage and veins, since they imply opposite kinematics, a phenomenon observed at the Brucejack property. Roach and Macdonald (1992) proposed that the east-southeast fabric formed during brittle-ductile shearing, although it has since been well documented as a flattening (coaxial deformation) fabric (e.g., Harrichhausen, 2015; Davis, 2017) and therefore unlikely to have formed through simple shear. In order to justify this relationship in the model of Davis (B. Davis, unpublished report prepared for Pretium Resources Inc., 2017) and Board et al. (in press), this would require cyclical changes in kinematics: 1) northeast-southwest compression to form east-southeast cleavages; 2) northwest-southeast compression to reactivate north-south faults as sinistral shear zones and form east-southeast-striking mineralized veins; and 3) northeast-southwest compression to fold and boudinage the veins along an east-southeast-striking cleavage. Because older veins of the Brucejack mineralized system are interpreted to be more deformed than younger ones (Tombe et al., 2018; Board et al., in press), the model would require numerous kinematic changes. It is possible that relatively undeformed and fabric-oblique, as well as deformed, veins are observed along the east-southeast-striking cleavage as a result of strain partitioning during postmineral deformation, consistent with SFTB deformation, as proposed by Febbo et al. (2019). Rather than trying to explain the observations of previous workers (e.g., Board et al,. in press) as being the result of synmineralization deformation, it is possible that mineralized veins that are steeply dipping are symmetrically boudinaged, veins that dip at moderate angles are sheared, and subhorizontal veins are buckled during postmineral deformation. The competency contrast between veins and the hostrock, as well as the spacing of veins in a stockwork zone, will affect whether a vein will partition strain or not, which could explain why many veins are relatively undeformed. Although other interpretations are possible, the authors believe strain partitioning could be a more reasonable alternative for the vein-fabric relationships at the Brucejack deposit and intend to further investigate a strain-partitioning model.

Ongoing and Future Work

This paper summarizes the structural geology of the Sulphurets mineral district, with emphasis on the Brucejack property. It serves as a review for the authors' ongoing research project entitled 'Structural analysis of the Brucejack intermediate-sulphidation epithermal deposit, northwestern British Columbia' as well as a summary of hypotheses and queries that have been developed. The main goal of the project is to define and categorize all structural elements, including folds, faults, cleavage, lineations, fractures and veins, at various scales based on process of formation, structural style, orientation and crosscutting relationships. The aim is to create a holistic kinematic framework that adheres to all structural observations and clearly defines pre-, syn- and postmineral deformation.

To achieve this goal, detailed surface and underground mapping was conducted during the 2018 and 2019 summer field seasons. During the 2018 field season, emphasis was placed on the Valley of the Kings zone. Detailed structural analysis was conducted on cleavage, fold, fault, fracture, vein and dike systems of both surface and underground workings. The 2019 field season focused on detailed lithology and structural mapping at regional scale, covering the area mapped by Davies et al. 1994 (Figure 4). Using these field and underground observations, an evolutionary model (interpretive) will be developed for the mineralization observed at the Brucejack property that follows this structural framework in hopes that it can be used for future exploration of the area.

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