# Nature and Origin of the Brucejack High-Grade Epithermal Gold Deposit, Northwestern British Columbia (NTS 104B)

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## Introduction

A major challenge in understanding the genesis of epithermal gold deposits is that existing genetic models do not satisfactorily explain the mechanisms responsible for high-grade gold deposition and transport at temperatures characteristic of the epithermal realm (150–300°C). Although transport by dissolution in an aqueous hydrothermal liquid is the widely proposed mechanism for mobilizing gold within Earth's upper crust (e.g., Helgeson and Garrels, 1968; Krupp and Seward, 1987; Sillitoe and Hedenquist, 2003; Simmons and Brown, 2006; Williams-Jones et al., 2009; Zhu et al., 2011), experiments have shown that the solubility of gold is too low in hydrothermal liquids at temperatures less than approximately 400°C to account for the extraordinarily high grades observed in some epithermal deposits (e.g., Seward 1973; Gammons and Williams-Jones, 1995; Heinrich et al., 2004; Stefánsson and Seward, 2004; Zezin et al., 2011; Hurtig and Williams-Jones, 2014). It is therefore necessary to consider alternative explanations for the high grades, including 1) that the temperatures commonly assumed for gold transport greatly underestimate the true temperature because they are based on estimates of the conditions of deposition; 2) that high fluid fluxes and steep physicochemical gradients can be maintained in single fractures for exceptional periods of time (unlikely); and 3) that the capacity of a fluid to transport gold is not controlled by simple solubility, either in a vapour or a liquid, but is also determined by other processes. For example, the development of boiling-mediated nanoparticle suspensions (colloids) could greatly increase the capacity of the fluid to carry gold. Resolving the issue of how exceptionally high grade epithermal gold deposits form will be an important step in elucidating the broader question of how these deposits truly relate to the higher temperature copper–molybdenum±gold porphyry systems with which they are commonly associated.

The Brucejack deposit of Pretium Resources Inc. (MINFILE 104B 193 and 104B 199; BC Geological Survey, 2016), currently undergoing preproduction mine development in the Stewart–Eskay Creek district of northwestern British Columbia (Figure 1), is host to one of the highest grade (up to 41 000 g/tonne Au) and best exposed intermediate-sulphidation or possibly low-sulphidation epithermal gold deposits in the world. The well-explored nature of epithermal gold mineralization on the Brucejack property, combined with its proximity to well-explored, world-class copper-gold-molybdenum porphyry deposits (Snowfield and Kerr-Sulphurets-Mitchell; Figure 2) of the Stikine Arc, offer an unparalleled opportunity to study the genesis of epithermal gold deposits, investigate their hydrothermal evolution and, importantly, test their relationship to spatially associated porphyry systems.

This paper presents preliminary results from a recently initiated study of the Brucejack deposit, the purpose of which is to petrographically and chemically (including isotopically) characterize its ores and associated hydrothermal alteration, and determine the composition of its mineralizing fluids through fluid-inclusion analysis. These data will be used to reconstruct, through thermodynamic analysis, the physicochemical conditions that controlled gold mineralization, and to quantitatively test plausible models of ore formation. If successful, the study will improve on existing models for the genesis of epithermal Au deposits and the strategies that guide their exploration.

## Regional Geology

The Brucejack deposit is situated in the Stewart–Eskay Creek district of the northwestern Stikine terrane (Figures 1, 2), a paleo–island arc system akin to that of the modern-day Philippine archipelago (Marsden and Thorkelson, 1992). The Stikine terrane formed as an intraoceanic island arc in the mid-Paleozoic and was accreted to the western

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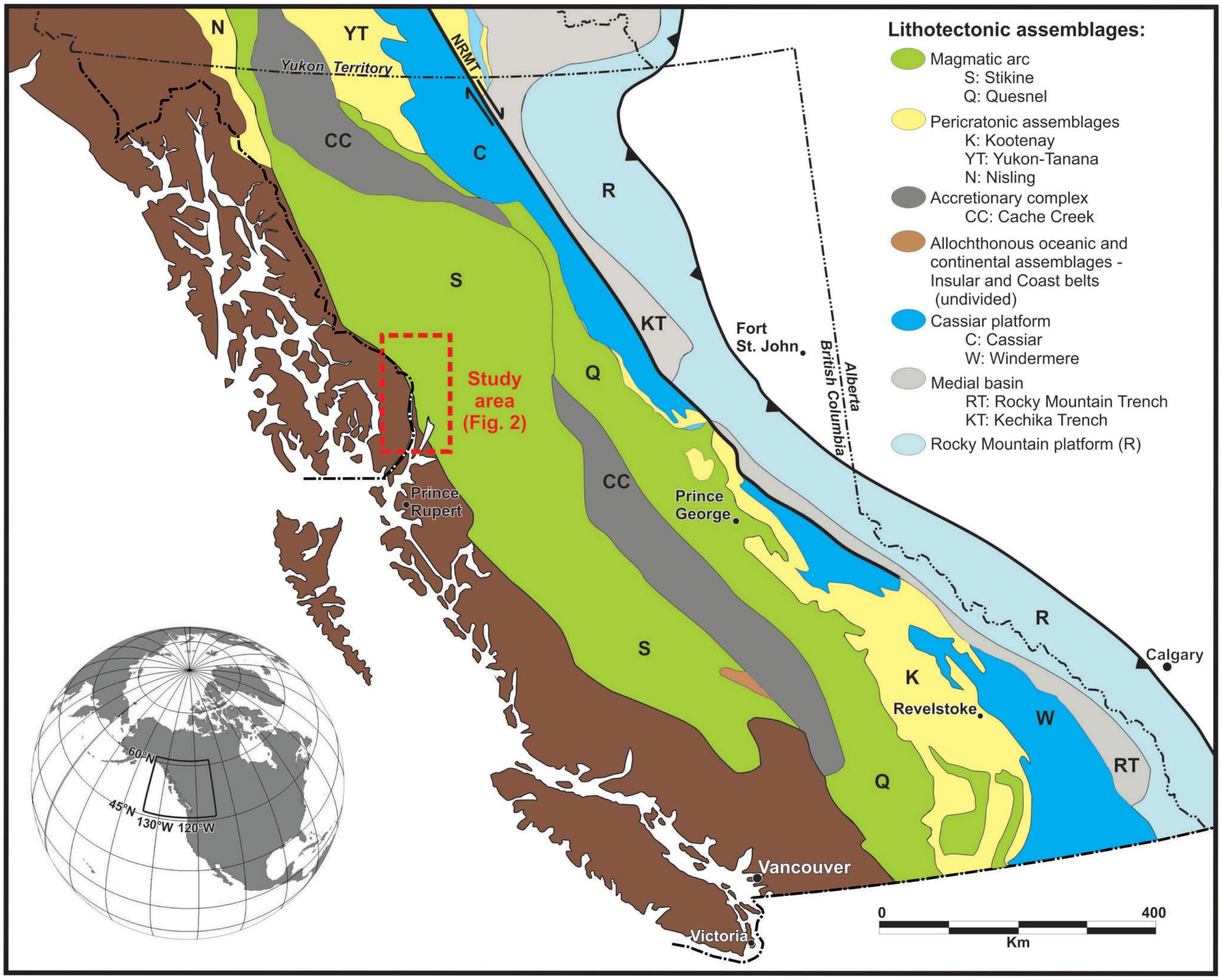


**Figure 1:** Location of the study area in reference to the major lithotectonic subdivisions of the Canadian Cordillera (modified after McLeish, 2013 with lithotectonic boundaries from Johnston, 2008). Abbreviation: NRMT, Northern Rocky Mountain Trench (fault).

continental margin of Laurentia in the Middle to Late Jurassic (Monger et al., 1991; Anderson, 1993). Volcano-sedimentary rocks of the Late Triassic Stuhini Group and Early Jurassic Hazelton Group dominate the stratigraphy of the Stikine terrane. Two distinct episodes of magmatism in the Late Triassic and in the Jurassic (229–221 Ma and 195–175 Ma, respectively; Macdonald et al., 1996) affected the Stuhini-Hazelton succession, which was deformed in the Middle to Late Jurassic during accretion and during later Cretaceous compressional tectonism (Greig and Brown, 1990; Alldrick, 1993). Porphyry magmatism is known to span ca. 220–186 Ma on a terrane scale (Logan and Mihalynuk, 2014); however, within the Stewart–Eskay Creek district, uranium-lead ages for porphyry intrusions are generally limited to the ca. 197–193 Ma range (Kirkham and Margolis, 1995).

## Brucejack Property Geology

Five zones of mineralization have been explored in detail at Brucejack (West, Valley of the Kings, Bridge, Gossan Hill and Shore zones; Figure 3), all of which are hosted within hornblende- and/or feldspar-phyric volcanic flows, lapilli tuff, locally derived pyroclastic and volcanic conglomerate, volcanic sandstone, siltstone and mudstone of the lowermost Hazelton Group, proximal to the regional-scale unconformity between the Stuhini and Hazelton groups (Board and McNaughton, 2013). To the immediate west and northwest of these zones, monzonitic, syenitic and granitic rocks of the Mitchell suite intrude volcaniclastic rocks of the Stuhini and Hazelton groups; these intrusions are closely associated with porphyry-style copper-gold-molybdenum mineralization on the adjacent Kerr-Sulphurets-

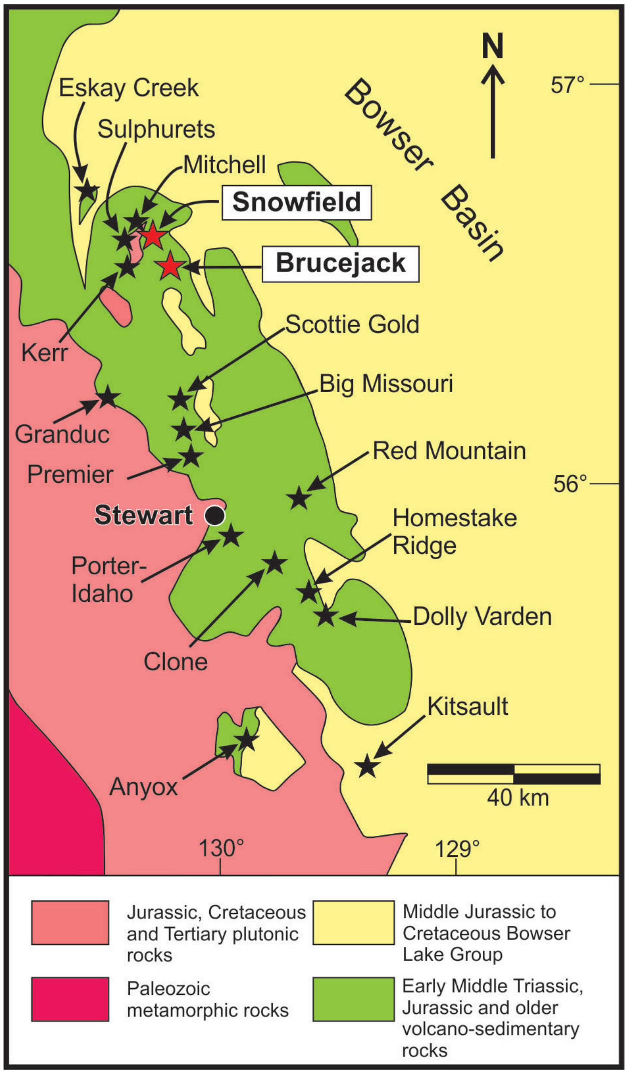


**Figure 2:** Major porphyry, epithermal and volcanogenic massive-sulphide deposits of the Stewart–Eskay Creek district (modified after Ghaffari et al., 2012), with the locations of the Brucejack and Snowfield properties highlighted.

Mitchell and Snowfield properties (Kirkham and Margolis, 1995). Uranium-lead zircon ages from various phases of these intrusions suggest that the porphyry-style mineralization was emplaced at 195–192 Ma (Margolis, 1993; Macdonald et al., 1996). Large areas of hydrothermal alteration affected and surround the intrusive complexes of the Mitchell suite. These consist of 1) early potassic alteration closely associated with porphyry copper and gold mineralization; 2) locally overprinting propylitic and chlorite-sericite alteration; and 3) widespread and well-developed, late quartz-sericite-pyrite alteration that pervasively overprints earlier alteration and extends distally into the surrounding hostrocks of the Stuhini and Hazelton groups (Ghaffari et al., 2012).

The intrusions of the Mitchell suite and the surrounding rocks of the Stuhini and Hazelton groups were strongly deformed during Cretaceous tectonism. This deformation is manifested by the development of 1) schistose and mylonitic fabrics within the weakest, most intensely altered intrusions and wallrocks; 2) prominent east-verging thrust faulting, including the Mitchell and Sulphurets thrusts, which penetrate and offset the Kerr-Sulphurets-Mitchell deposit; and 3) steeply dipping to vertical, north-trending, late-stage brittle faults, including the Brucejack fault (Board, 2014; Febbo et al., 2015). The third group of structures has been interpreted to have reactivated a system of pre-existing syndepositional basin-margin growth faults that were initially active during deposition of the Hazelton Group rocks (Nelson and Kyba, 2014).

## Deposit Mineralization

Within the Valley of the Kings zone (VOK; Figure 3), gold mineralization is hosted by extensive, predominantly subvertical, quartz-carbonate-sulphide vein stockworks and subordinate vein breccias. Five stages of veins have been recognized in the VOK: 1) discontinuous pyrite-stringer veins containing carbonate and quartz ($Vn_0$); 2) electrum-bearing quartz–carbonate±sericite sheeted, stockwork and brecciated veins ($Vn_{1a}$, $Vn_{1b}$ and $Vn_{1c}$, respectively); 3) zinc–lead±copper sulphide veins containing common silver sulphosalts and electrum ($Vn_2$); 4) carbonate±quartz veins containing abundant orange-coloured, manganese-bearing calcite, and electrum ($Vn_3$); 5) post-mineral, Cretaceous, orogenic quartz±carbonate shear veins with rare, remobilized pyrite, electrum and base-metal sulphides in thrust-related shear bands ($Vn_{4a}$, $Vn_{4b}$) and subhorizontal, barren, white bull-quartz tension-gash veins with adjacent chlorite alteration ($Vn_{4c}$; classification modified after Tombe et al., 2014). The $Vn_0$, $Vn_{1a\text{-}c}$, $Vn_2$ and $Vn_3$ veins are largely undeformed to weakly deformed, except within localized strain zones where they are moderately to rarely strongly deformed. Evidence from crosscutting relationships paired with hostrock uranium-lead zircon and vein-hosted molybdenite rhenium-osmium age determinations have constrained the age of $Vn_{1a\text{-}c}$, $Vn_2$ and $Vn_3$ vein formation to ca. 188–183 Ma (Board, 2014; Tombe, 2015). Variably developed but generally intense quartz-sericite-pyrite alteration occurs throughout the deposit but is strongest proximal to the Brucejack fault and the unconformity between the Stuhini and Hazelton groups, which suggests that these structures may have acted as important fluid conduits during hydrothermal alteration and mineralization. Preliminary paleotemperature vectors derived from alteration, mineralization and vein textures suggest a down-temperature thermal gradient toward the east (up stratigraphy) and away from the Snowfield and Kerr-Sulphurets-Mitchell higher temperature porphyry centres, located northwest of the deposit (Board and McNaughton, 2013).

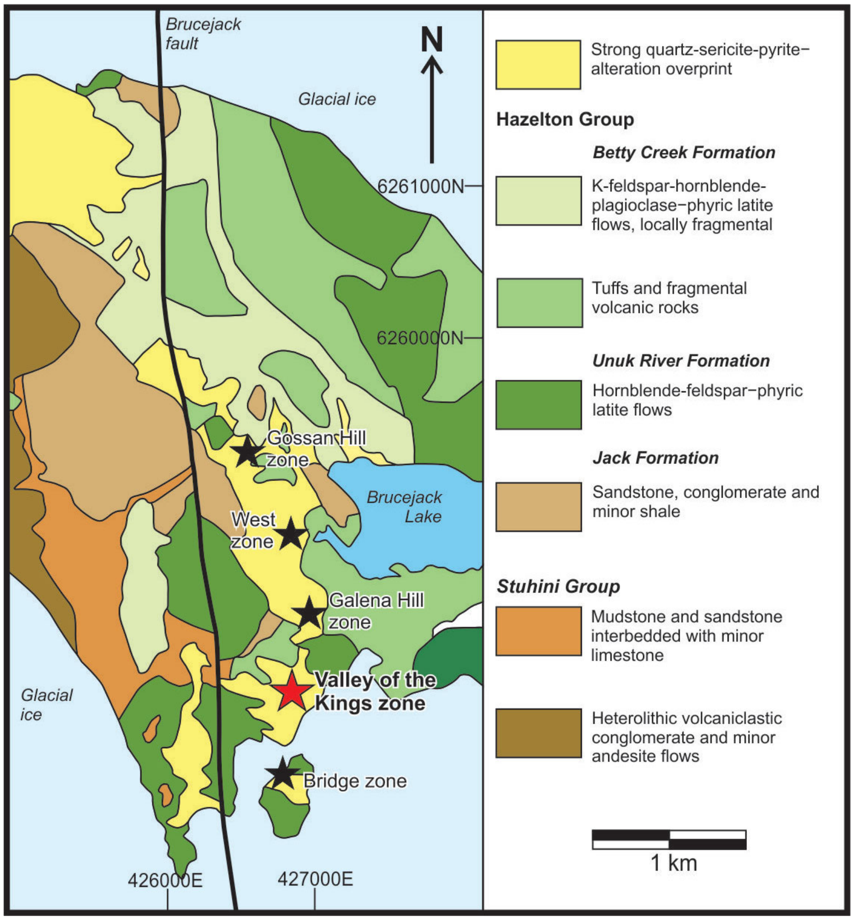


**Figure 3:** Geology of the Brucejack deposit area (modified after Tombe, 2015), showing five main zones of mineralization that are hosted within a moderately to strongly sericite-quartz-pyrite–altered sequence of hornblende- and/or feldspar-phyric volcanic flows, lapilli tuffs, locally derived pyroclastic and volcanic conglomerate, volcanic sandstone, siltstone and mudstone of the lowermost Hazelton Group. All zones are proximal to a regional-scale unconformity between the Stuhini and Hazelton groups.

## Methods and Preliminary Findings

### Fieldwork

Fieldwork completed to date has involved logging selected north-south and east-west drillcore transects of the VOK, and targeted mapping of mineralized showings on surface and in the VOK underground-development workings. This work has allowed for initial, field-level characterization of the alteration, ore and temporal relationships of the five vein stages, as well as familiarization with the broader lithological nature, including pervasive alteration, of the major mineralized zones on the property. Sampling of drillcore, underground workings and a limited number of outcrops has been carried out on the different vein and alteration types for the purpose of detailed petrographic and geochemical investigations (discussed below). This has been complemented by logging of core from selected drillholes and mapping. Reconnaissance visits have also been made to the adjacent Snowfield porphyry deposit to collect samples for comparison.

### Petrography and Mineral Chemistry

Textural relationships among the various ore, gangue and alteration minerals are currently being established using a combination of optical and scanning electron microscopy. Results of this work will be used to develop a detailed mineral paragenesis for each vein stage. This information will provide important insights into the physicochemical evolution of the fluids responsible for each vein stage.

From the work completed to date, there are several important petrographic observations that point to a complex, multistage evolution of the Brucejack hydrothermal system during the ca. 188–183 Ma mineralizing event. In brief, these are 1) at least three texturally distinct generations of quartz, in veins representing the $Vn_1$ electrum-mineralization stage, that are locally well-organized into discrete millimetre-scale domains, which may cut one another (Figure 4c, d); 2) evidence for silica dissolution as part of the electrum-precipitation event(s), in the form of textures reflecting extensive corrosion of quartz-grain boundaries

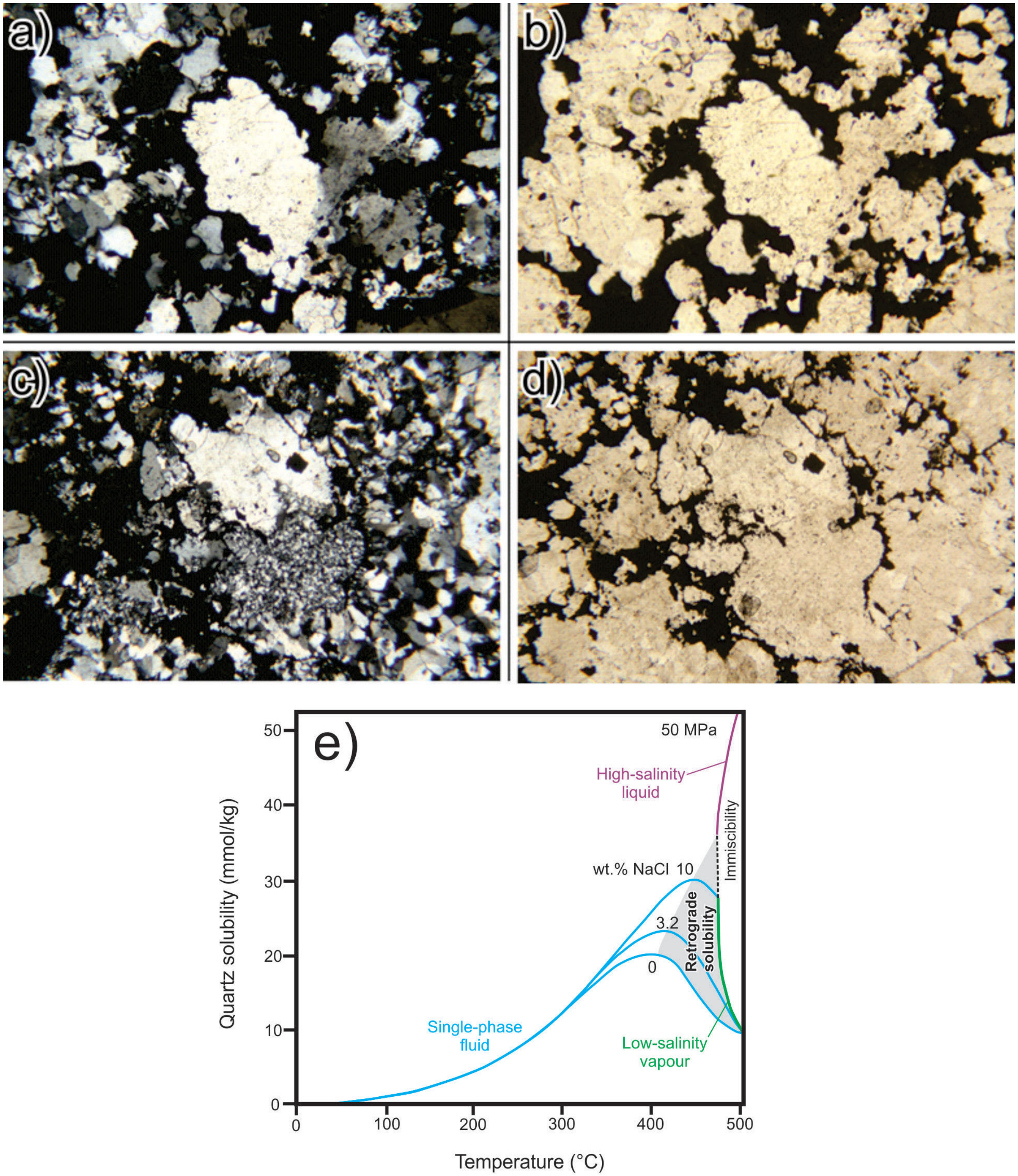


**Figure 4:** Photomicrographs of quartz and electrum (dendritic opaque mineral) in Brucejack (Valley of the Kings zone) $Vn_{1c}$ veins and plot of quartz solubility versus temperature at 50 MPa: **a)** and **b)** large quartz grain in centre of images has highly irregular, corroded grain boundaries where in contact with electrum; **c)** and **d)** at least three texturally distinct types of quartz are clearly evident, the finest grained type appearing to be cut by the medium-grained type at the bottom of the images. **e)** isobaric quartz solubility plotted as a function of temperature in pure $H_2O$, $H_2O$ + 3.2 wt. % NaCl, and $H_2O$ + 10 wt. % NaCl fluids (modified after Steele-MacInnis et al., 2012). Images on the left and right are in cross-polarized and plane-polarized light, respectively, and all have a 1 mm wide field of view. See text for further explanation.

where they are in contact with electrum (Figure 4a, b); 3) well-developed arsenic zonation in abundant early pyrite, which is cut by electrum and locally destroyed by possible chemical resorption (Figure 5); 4) an apparently regular, systematic variation in the gold:silver ratio of electrum among different vein stages and substages (Figure 6); and 5) variations in the style of electrum mineralization, both within and among vein stages, including volumetrically dominant, dendritic electrum, lesser proportions of coarse subhedral clots and aggregates, and rare subhedral to euhedral sheet- to plate-like crystals.

Although preliminary, these observations point to the possibility that electrum mineralization was strongly influenced by fluid overpressure, as does the corroded nature of the quartz (see below). The randomly oriented nature of dendritic to arborescent electrum radiating into, and dying out in, masses of quartz is suggestive of potential hydraulic fracturing associated with the influx of the mineralizing fluids.[1] The multiple, distinct domains of fine-, medium- and coarse-grained quartz indicate that multiple pulses of fluid were likely involved in the formation of each of the individual vein types. In samples from the $Vn_1$ vein generation, the very fine grained to cryptocrystalline quartz appears to have been locally cut by coarser grained quartz. Collectively, these textures are consistent with a model in which conditions varied between those of prograde and retrograde solubility of quartz (Figure 4e; Steele-MacInnis et al., 2012; Seward et al., 2014) during the evolution of the $Vn_1$ vein generation. The very fine grained quartz is interpreted to indicate extremely rapid cooling under conditions of prograde solubility (high levels of quartz-grain nucleation and no significant quartz-grain growth), which was probably caused by adiabatic expansion that led to fluid pressure–induced fracturing of the rocks. In principle, quartz dissolution should imply heating. However, at temperatures above 350°C and relatively low pressure (such as might be associated with fracturing of the rocks) and low salinity, quartz undergoes retrograde solubility (~370–500°C; Figure 4e). It is therefore tentatively proposed that the observed dissolution textures reflect this retrograde effect of cooling. Thus, a regime is envisaged in which pressure oscillated from values that exceeded the strength of the rock to hydrostatic values and, in the process, controlled temperature and ultimately the nature of quartz growth and dissolution.

## Summary and Future Work

Results from the preliminary petrographic and mineral-chemistry studies of mineralized quartz–electrum±carbonate veins from the Brucejack deposit indicate that the deposit formed from a hydrothermal system that had a complex history comprising multiple and possibly long-lived mineralizing events. The formation of the five synmineral vein stages and substages defined from drillcore logging and underground mapping ($Vn_{1a}$, $Vn_{1b}$, $Vn_{1c}$, $Vn_2$, $Vn_3$) appear to have resulted from multiple pulses of fluid that circulated through the deposit under dynamic physicochemical conditions, including possible fluid-overpressure and silica-dissolution events. Although the chemical evolution of individual vein stages is not well constrained at present, evidence from preliminary pyrite and electrum mineral chemistry from vein samples across the Valley of the Kings zone suggests that vein composition varied temporally and possibly spatially during formation of the Brucejack deposit. Finally, the observation that electrum appears to postdate most of the pyrite in veins and along vein margins supports the suggestion by Board (2014) that widespread premineral phyllic alteration of the Brucejack country rock, likely related to earlier emplacement of the neighbouring Snowfield and Kerr-Sulphurets-Mitchell porphyry deposits, pre-sulphidized the Brucejack hostrocks and increased the ability of mineralizing fluids at Brucejack to transport elevated concentrations of gold as a bisulphide complex ($Au(HS)_2^-$), following the model of Heinrich et al. (2004).

Future petrographic, mineral-chemistry, fluid-inclusion and thermodynamic-modelling studies will further test these interpretations and explore for other insights into the physicochemical evolution of the fluids responsible for each vein stage. In particular, the composition of key ore and alteration minerals, and their evolution through the different stages in the paragenesis, will be determined using a combination of electron microprobe wavelength-dispersive spectrometry and laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) analysis. Petrographic, chemical and microthermometric analysis of fluid inclusions will be carried out in an attempt to determine the composition and temperatures of the fluids forming different veins. Sulphur and oxygen isotopic compositions will be analyzed using ICP-MS and thermal-ionization mass spectrometry in order to obtain temperature data from the different vein stages using appropriate mineral pairs (e.g., sphalerite-galena and quartz-adularia). High-resolution transmission electron microscopy imaging of electrum and cryptocrystalline silica will be carried out to explore for evidence of colloid formation (presence of nanocrystals). Ultimately, the aim is to complement all of this work with thermodynamic analyses of mineral equilibria to evaluate the evolving physicochemical conditions in the Brucejack hydrothermal system, particularly those accompanying gold mineralization. This information will provide the basis for thermodynamic-path modelling that will incorporate mineral and aqueous species, and will be used to evaluate potential mechanisms for ore deposition, including boiling, fluid mixing and fluid-rock interaction (e.g., Heinrich,

*[1]Dendritic electrum textures have also been cited as evidence for gold transport by colloidal processes at Brucejack (Harrichhausen et al., 2016).*

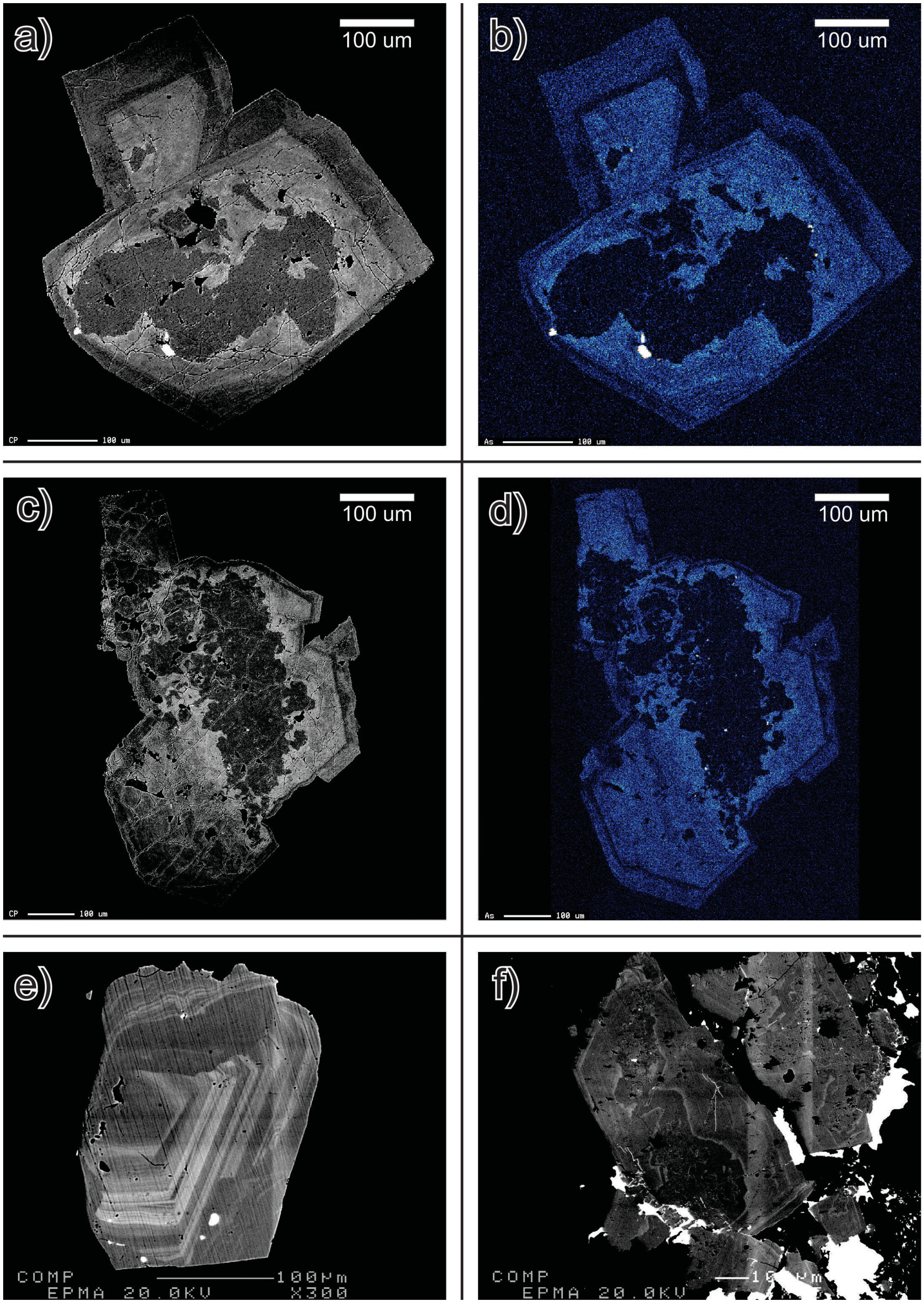


**Figure 5:** Images of the $Vn_1$ vein generation at Brucejack (Valley of the Kings zone): **a)**, **c)** and **e)** electron microscope back-scattered electron (BSE) images of pyrite showing complex internal zoning patterns; **f)** BSE image of electrum cutting arsenic zonation and filling fractures in pyrite; **b)** and **d)** electron-microprobe maps showing relative levels of arsenic in grains (a) and (c), respectively.

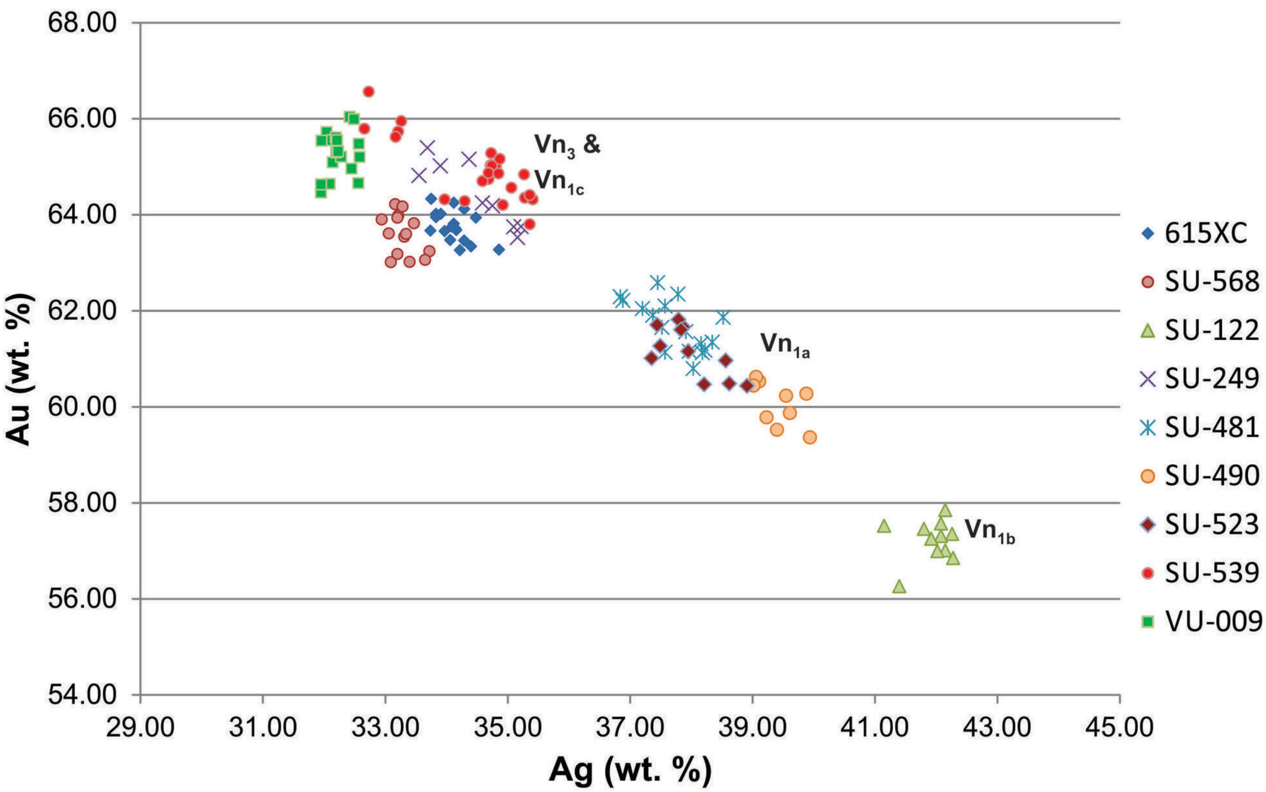


**Figure 6:** Preliminary results from electron-microprobe wavelength-dispersive spectrometry (WDS) analysis of Brucejack (Valley of the Kings zone) electrum: gold:silver ratio of electrum appears to vary considerably with vein type; further investigation will determine whether or not this variation is also reflective of a spatial zonation in gold:silver across the deposit; no significant variation in the gold:silver ratio of electrum is observed within individual samples; analyses were taken across electrum grains (rim-core-rim) for both quartz matrix–hosted and pyrite inclusion–hosted electrum with no obvious gold:silver differences observed.

2005). In particular, the modelling will address the fundamental question of whether the large, high-grade Brucejack resource can be explained using simple solubility considerations.

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