Evolution of Porphyry-Epithermal Gold Systems Using Trace Elements: Insights from the Iron Cap Deposit, Kerr-Sulphurets-Mitchell District, Northwestern British Columbia (NTS 104B)

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Graham, H.C., Morgan, D.J., Chapman, R.J. and Banks, D.A. (2019): Evolution of porphyry-epithermal gold systems using trace elements: insights from the Iron Cap deposit, Kerr-Sulphurets-Mitchell district, northwestern British Columbia (NTS 104B); *in* Geoscience BC Summary of Activities 2018: Minerals and Mining, Geoscience BC, Report 2019-1, p. 67–74.

Introduction

Porphyry- and epithermal-style mineral deposits together account for approximately 28% of global gold endowment (based on past production, reserves and resources), making them collectively of comparable importance to orogenic and paleoplacer deposits as a source of gold on the world stage (Lipson, 2014). Similarly in British Columbia (BC), 31.5% of gold produced has originated from porphyry and epithermal deposits (BC Geological Survey, 2015). Porphyries, in particular, tend to be more sought after for their significant copper contents (making up three-quarters of global copper production; Sillitoe, 2010), yet the enrichment of gold in addition to copper makes them highly attractive exploration targets. With both epithermal and porphyry deposits forming from magmatic intrusions and their associated hydrothermal systems at active tectonic margins, there are often recognized spatial, temporal and genetic associations (Sillitoe, 2010). However, the transition from porphyry to epithermal conditions remains a key topic of discussion (e.g., Gammons and Williams-Jones, 1997; Hedenquist et al., 1998; Heinrich, 2005; Pudack et al., 2009; Maydagán et al., 2015). Further understanding of evolutionary processes is hence required to elucidate not only the above, but also the factors controlling the enrichment and distribution of gold in evolving magmatic-hydrothermal systems.

The variability in fluid characteristics, from the deep porphyry to shallow epithermal environments, is one particular aspect of porphyry-epithermal system evolution that lacks sufficient understanding. Change in parameters such as temperature, pH and phase (i.e., liquid vs. vapour) can significantly affect the solubility and transport of metals, as has been discussed by numerous workers in the case of gold (e.g., Gammons and Williams-Jones, 1997; Archibald et al., 2001; Stefánsson and Seward 2003, 2004; Simon et al., 2005; Williams-Jones and Heinrich, 2005). Genetic models tend to outline broad characteristics, such as alteration zones, as indicators of fluid conditions (e.g., Seedorff et al., 2005; Sillitoe, 2010). However, the range of conditions implicit in the accepted nomenclature for porphyry-epithermal alteration does not necessarily correlate with the behaviour of economic metals. Few researchers have succeeded in accurately defining the fluid parameters associated with discrete periods of ore genesis in an evolving magmatic-hydrothermal system. Because fluids are a key control on the distribution and speciation of resources, knowledge of the precise physicochemical conditions that facilitate metal transport and induce deposition in certain parts of a porphyry-epithermal system has significant implications for the advancement of exploration and processing methodologies.

Fluid-inclusion studies have been instrumental in interpreting the conditions of ore formation, since their inception almost half a century ago (e.g., Roedder, 1971; Heinrich et al., 1992; Wilkinson, 2001). However, there remain significant shortcomings with the technique: primarily the ambiguity of associations between the characterized inclusions and adjacent ore minerals. Moreover, primary inclusions that have strong indicated relationships to ore minerals can be relatively scarce. The study of trace elements may provide an alternative, supplementary and potentially more accurate method to interpret fluid conditions at specific points within mineralizing environments. Variations in trace elements have been recognized on the deposit scale, macro scale (e.g., between vein generations) and micro scale (e.g., within individual ore minerals) in numerous deposits worldwide (e.g., Cioaca et al., 2014; Pašava et al., 2016; Sykora et al., 2018; Zarasvandi et al., 2018). However, there remains a paucity of research explaining these

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variations in detail, with the physicochemical characteristics of the fluids likely being a key variable.

This project focuses on a comprehensive sample suite from deep-porphyry to shallow-vein environments at the Iron Cap deposit in the Kerr-Sulphurets-Mitchell (KSM) district, northwestern British Columbia (Figure 1). The research will study the use of trace elements (including gold) to interpret the evolution of the magmatic-hydrothermal system. Specifically, variation in the speciation of certain trace elements (i.e., Au, As, Sb, Pd, Se, Te, Hg) and their subsequent partitioning to ore minerals will be investigated to provide a window to the physicochemical conditions prevalent at different stages of porphyry-epithermal development, both in time and space. In addition, a population of detrital gold grains collected from drainages within the KSM district will be scrutinized to identify geochemical variations and infer the source and formation process of gold, both in the district as a whole and at Iron Cap. Lastly, the thermodynamic properties of the above trace elements will be assessed to determine the suitability of trace element studies for interpreting the conditions of ore formation in a given porphyry-epithermal system. In the present paper, the geology of the case study area at KSM is described, the sampling procedures and rationale are outlined, and the various methodologies and plans for future work are presented.

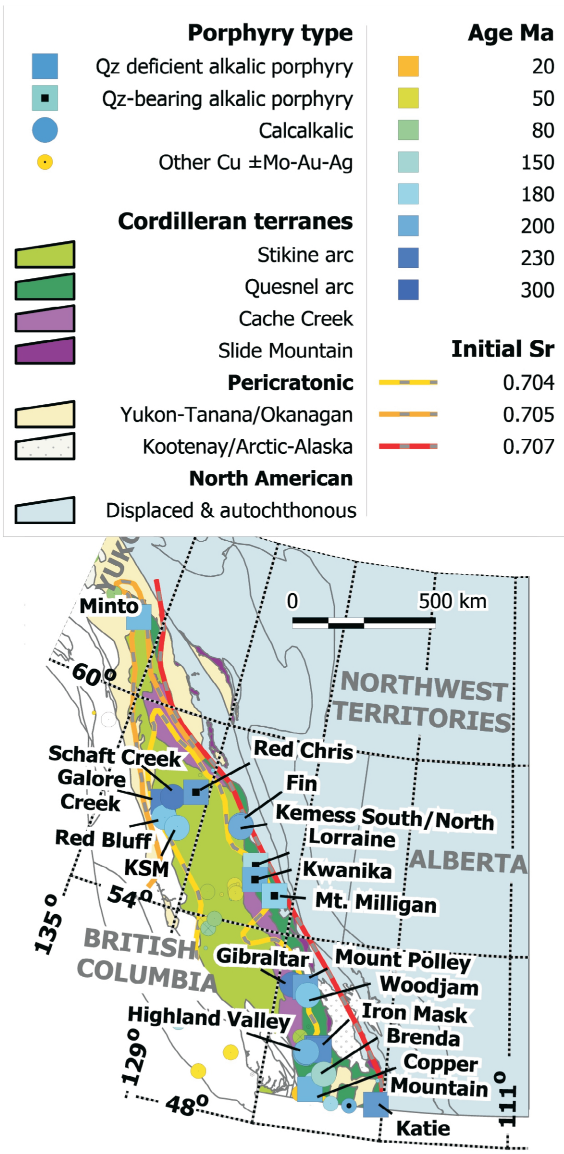

Figure 1. Location of the Kerr-Sulphurets-Mitchell (KSM) district in northwestern British Columbia (modified from Logan and Mihalynuk, 2014). Other porphyry deposits of the Canadian Cordillera are also shown, with porphyry type represented by symbol shape, and the age of deposits depicted by colouration.

Study Area

The Kerr-Sulphurets-Mitchell (KSM) district is host to four Cu-Au, predominantly porphyry-style deposits: Kerr, Sulphurets, Mitchell and Iron Cap. Together they host proven and probable reserves of 38.8 million ounces of Au, 10.2 billion pounds of Cu, 207 million pounds of Mo and 183 million ounces of Ag, at grades of 0.55 g/t Au, 0.21% Cu, 42.6 g/t Mo and 2.6 g/t Ag, making KSM one of the largest undeveloped Cu-Au prospects in the world and particularly one of the most gold rich in terms of total contained metal (Seabridge Gold, 2018b). The Iron Cap deposit at KSM will be studied in detail as part of this research. It has not yet been investigated in terms of the magmatic-hydrothermal system and therefore presents a unique opportunity to characterize the nature of fluids throughout evolution from deep porphyry to shallower, near-epithermal environments.

Regional Geology

The Stikine arc terrane of the Canadian Cordillera is significantly endowed with magmatic-related mineral deposits, including those of the KSM district (Figure 1). Most mineralizing activity occurred during a short ~15 m.y. period at the Triassic–Jurassic boundary, producing the abundance of deposits in western BC that form a 60 km long trend stretching north-northwest from the town of Stewart to the mining district around KSM (Logan and Mihalynuk, 2014; Febbo et al., 2015). The dominant hosts for mineralization within the Stikine terrane are the volcanosedimentary sequences of the Late Triassic Stuhini Group and Early Jurassic Hazelton Group (Nelson and Kyba, 2014). The Stuhini sequences are unconformably overlain by those of the Hazelton, the latter group representing the waning of island-arc magmatism prior to accretion in the Middle Jurassic (Nelson and Colpron, 2007; Nelson and Kyba, 2014). Several deformation events have affected the Stikine successions, the most significant being a mid-Cretaceous sinistral transpression associated with the Skeena fold-and-thrust belt that produced north-northwest-trending structures (Nelson and Kyba, 2014). The present geology of northwestern BC is shown in Figure 2.

Local Geology

The four deposits of the KSM district (Kerr, Sulphurets, Mitchell and Iron Cap) are centred on a series of Early Jurassic diorite to syenite intrusions, with adjacent wallrocks comprising the volcaniclastic and sedimentary units of the Late Triassic Stuhini Group and Early Jurassic Hazelton Group (Figure 3). Radiometric dating suggests that the KSM intrusions, and hence the associated mineralization, were emplaced between 197 and 189.6 Ma (Febbo et al., 2015 and references therein). The porphyry style is dominantly calcalkaline, although discrete areas exhibit features consistent with alkaline-style mineralization (Campbell and Dilles, 2017). The four deposits are hosted mainly within the footwall of the east-verging Sulphurets thrust fault (STF), which is linked to the Skeena fold-and-thrust belt (Kirkham and Margolis, 1995; Febbo et al., 2015). A splay of the STF, the Mitchell thrust fault, also separates the Iron Cap and Mitchell deposits at the northern end of the district (Febbo et al., 2015).

At Iron Cap, mineralization is hosted primarily within porphyritic monzonite, unclassified intrusions containing a high volume (>80%) of quartz veins and, to a lesser extent, the surrounding wallrock of mudstone, sandstone, conglomerate and volcanic breccia (Campbell and Dilles, 2017). The orebody plunges to the northwest, with the central section exhibiting potassic alteration, zoning outward to chlorite±sericite, and peripheral phyllic and silicic alteration in the wallrocks (Campbell and Dilles, 2017). While porphyry-style mineralization dominates, features more characteristic of the upper parts of a magmatic-hydrothermal system, such as sericite-quartz-clay alteration, hydrothermal breccias and increases in sulphosalt minerals, are identified in the near surface (Seabridge Gold, 2018a). This suggests that the Iron Cap deposit may represent a transition from porphyry to epithermal environments.

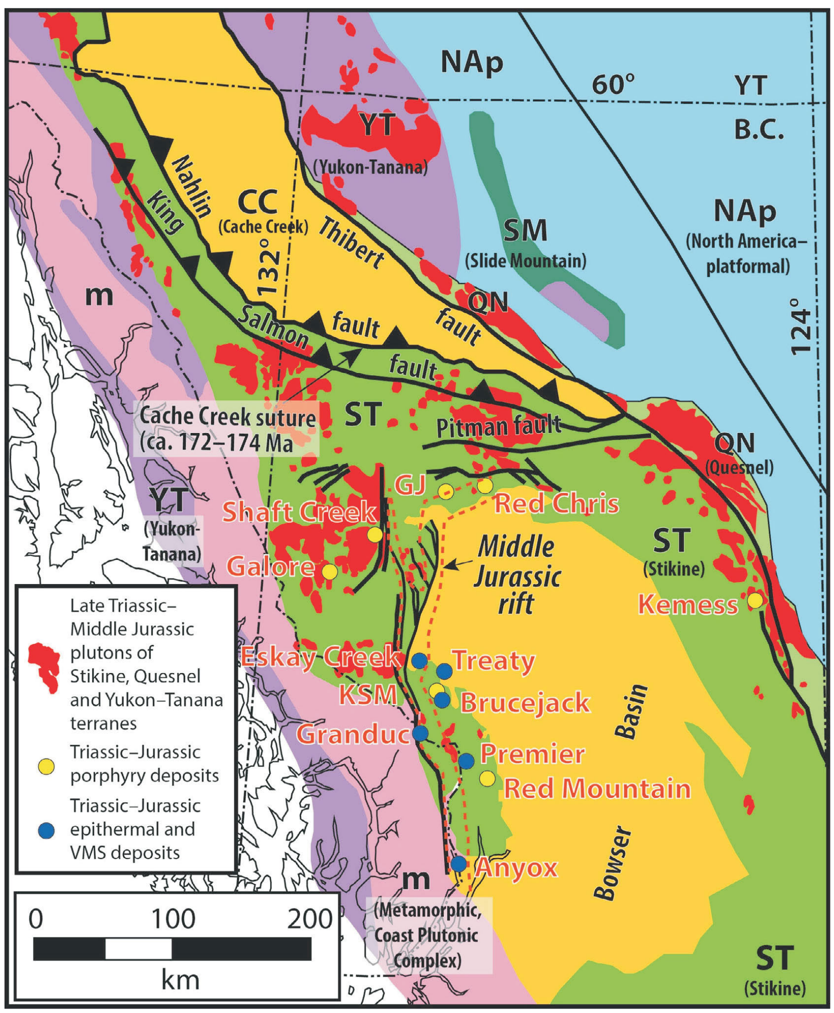

Figure 2. Geology of northwestern BC, showing the general north-northwest-trending terranes and major structures (from Campbell and Dilles, 2017). The locations of the prolific Triassic–Jurassic intrusive rocks are also shown, with associated mineral deposits of porphyry, epithermal and volcanogenic massive sulphide (VMS) types.

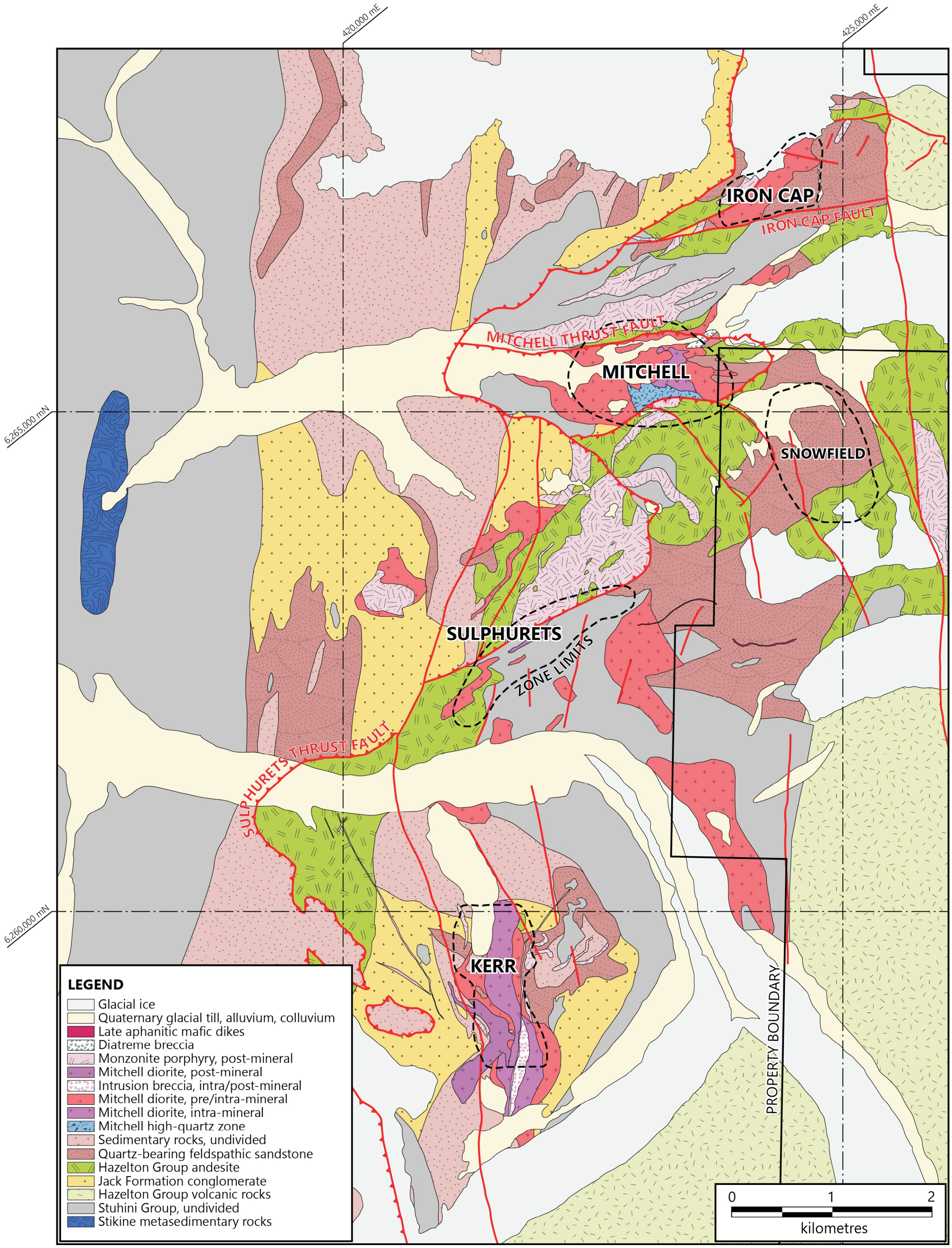

Figure 3. Geology of the Kerr, Sulphurets, Mitchell and Iron Cap deposits within the rocks of the KSM district (modified from Campbell and Dilles, 2017). Snowfield is a porphyry deposit located in the adjacent licence area and is purported to be the displaced cap of the Mitchell deposit (Febbo et al., 2015). UTM zone NAD83-9V.

Sampling

Drillcore

More than 60 samples have been collected from drillcore of the Iron Cap deposit. The selection of certain samples from the available core was informed by various criteria. Firstly, acquiring a transect through a majority of the deposit is necessary to attain a comprehensive understanding of system evolution, so samples were collected from a range of different holes at varied depths, ensuring representation of vertical or lateral variations. Secondly, a number of the targeted trace elements (Au, As, Sb, Pd, Se, Te, Hg) must be present to carry out the proposed analysis, so samples that recorded the presence of these elements (recognized from assays) in varied amounts were selected. Lastly, distinct fluid phases must be distinguished to identify evolutionary processes. The drillcore was therefore scrutinized to ensure that features allowing identification of fluid phases were present, with core containing several vein generations being preferentially sampled. At present, the collected samples are being prepared for analysis.

Detrital Gold

A period of detrital gold sampling was originally planned to be completed during September 2018 but has now been postponed to 2019 due to unforeseen circumstances. Nevertheless, the sampling procedure will not change, focusing on collection of natural gold grains from a range of water courses draining the KSM deposits. The samples will not represent exclusively Iron Cap but a wider population encompassing all four deposits of the district, and likely other nearby deposits (i.e., Snowfield and Brucejack). It may, however, be possible to identify grains that show comparable features (e.g., Au:Ag ratios) to the gold recognized in Iron Cap core samples, and interpretation of the data from detrital gold analysis may establish discrete populations. One possibility is to crush a number of the core samples collected to retrieve an appreciable amount of hypogene gold from Iron Cap for comparison with the detrital. However, there is an issue that gold recovered in this way would mostly not be constrained to an individual vein generation or fluid phase, and thus have limited use in interpreting fluid evolution. Yet, it would allow characterization of Iron Cap gold in a wider sense and provide a benchmark for recognizing gold from Iron Cap in the detrital environment.

Methodology and Future Work

Petrography

A full petrographic study of the drillcore samples will be carried out first, using transmitted and reflected light microscopy, augmented by scanning electron microscopy (SEM). From these data, an initial paragenesis for Iron Cap can be constructed, which will detail the sequence of events that took place during its formation. Importantly, different vein generations will be identified. Each generation will relate to a fluid (or fluids in some cases) that had a different composition and experienced different conditions to the fluids that formed earlier and later vein generations. Understanding the temporal relationship between the veins will ensure that fluid evolution can be studied and interpreted. Linking the veins (and their forming fluids) to certain petrographic features, such as the presence of gold-bearing minerals, will also provide an initial understanding of the physicochemical parameters of the fluids (e.g., gold bearing). The petrographic study thus forms an important basis for subsequent analysis, allowing additional data collected to be placed into a geological context.

Analytical Process

Following core-sample characterization and the initial identification of fluid phases, trace-element analyses will proceed by electron microprobe analysis (EMPA) and laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS). The aim of this analysis is to define the concentration, distribution and speciation of each target element (Au, As, Sb, Pd, Se, Te, Hg) relating to a discrete fluid phase, in order to understand the physicochemical characteristics of that fluid. To begin, EMPA will be used to analyze minerals containing the trace elements, such as sulphides, selenides and tellurides (identified on the SEM). This will define their chemical compositions and highlight targets for further analysis by LA-ICP-MS. As a nondestructive method with a high spatial resolution, EMPA is initially preferred over LA-ICP-MS, which will follow once a target mineral has been characterized by EMPA. The low detection limits of LA-ICP-MS will be used to analyze a suite of minerals, predominantly sulphides such as pyrite and molybdenite, and gold, to identify heterogeneities in their compositions between vein generations and within individual minerals. Such information will highlight differences between fluid phases and describe the changes in a single fluid phase over time.

To complement the trace-element study, fluid inclusions will first be analyzed by cathodoluminescence to identify how inclusions identified in the petrographic study could relate to certain fluid and mineral phases. Microthermometry will then provide an indication of fluid conditions, by measurement of inclusion-trapping conditions and elemental compositions. Lastly, LA-ICP-MS will be applied to specific inclusions, to determine the concentration of elements in the fluid and to identify elements in the fluid that have not precipitated. An element's absence from the petrographic and trace-element analysis but presence in fluid inclusions will raise questions on the solubility, transport and deposition of that element.

The detrital gold grains will be characterized using two approaches. If the grains are sufficiently large to permit sectioning, inclusions of other minerals will be identified by SEM. Determination of gold-alloy compositions will then be established by EMPA. If the gold particles collected are exceedingly small (<50 µm), then information will be gained through ablation of the entire grain. These datasets illuminate the mineralogical context of the hypogene source and, at KSM, they may indicate which of the local potential sources has liberated the most particulate gold. In addition, gold mineralogy at the trace-element level can be used as another window to the trace-element suite present in the mineralizing fluid.

Interpretation

The physicochemical characteristics of the hydrothermal fluid(s) that formed Iron Cap will be interpreted using the acquired data. Fluid phases will be characterized based on petrography, the concentration of trace elements they contained, fluid-inclusion data (where possible) and subsequent consideration of the thermodynamic properties of various trace elements within the system. This information will be evaluated with the aim of defining the fluid conditions in terms of temperature, pressure, salinity, pH, type (liquid or vapour), sulphur fugacity and oxygen fugacity, and interpreting the transport mechanism for gold and the target trace elements.

The next step will be to propose a detailed fluid-evolution model for Iron Cap, describing the processes that took place to induce changes in the fluid, and the deposition of gold and the suite of trace elements in certain sites and states. Fluid-rock interaction, fluid mixing, phase separation, and partitioning are all important processes that can influence fluid changes and element deposition, and they will thus be considered in this context. The outcomes of the Iron Cap study will be subsequently assessed to establish whether a transferrable methodology can be developed.

Conclusions

This project investigates trace-element behaviour in the magmatic-hydrothermal system of the Iron Cap deposit at KSM, to shed light on the evolution from porphyry to epithermal conditions and to improve understanding of the processes leading to gold enrichment and linked deposit formation. A comprehensive sample suite, from deep porphyry to shallow vein environments at Iron Cap, will be analyzed by microscopy, EMPA, LA-ICP-MS and fluid-inclusion microthermometry to determine the concentration, distribution and speciation of trace elements (Au, As, Sb, Pd, Se, Te, Hg) within the deposit, and identify discrete fluid phases. Characterization of detrital gold grains and, if possible, gold from ore will provide additional information on the partitioning of trace elements in the magmatic-hydrothermal system whilst augmenting the existing database of detrital gold in BC to increase its potential as an indicator mineral during exploration. The collected data will be interpreted in light of the thermodynamic properties of the studied elements, to describe the changing fluid conditions during magmatic-hydrothermal evolution and construct a genetic model for the Iron Cap deposit. Subsequent examination of trace-element behaviour may allow characterization of the physicochemical parameters of fluids in a given magmatic-hydrothermal system, enabling prediction of metal transport and deposition, and helping lead to discovery of mineralization. Such a technique would have wide application in exploration and resource targeting on regional and local scales.

Acknowledgments

This project is funded by the Natural Environment Research Council, United Kingdom. The lead author thanks Geoscience BC for funds provided through the scholarship program, and the Society of Economic Geologists is acknowledged for financial support provided through a Graduate Student Fellowship. Seabridge Gold Inc. is gratefully acknowledged for access to the KSM project, and for logistical support and accommodation provided during sample collection. Lastly, T. Torveja is thanked for a helpful review of this manuscript.

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