MINERALOGICAL CHARACTERIZATION AND PARAGENESIS OF THE CRIPPLE CREEK DEPOSIT, COLORADO

By

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ABSTRACT

The world-class Cripple Creek gold telluride deposit in central Colorado is centered on an Oligocene alkaline-magmatic system composed of diatremal Breccia that is intruded by dikes and sills that range in composition from phonolite to lamprophyre. The deposit has historic production of >24 Moz of gold, making it the third most productive gold deposit in the United States. Most of this production came from underground mining operations that started with the discovery of the deposit in 1891, and continued until the early 1960’s. The discovery of broad low-grade, bulk tonnage deposits in the 1980’s led to renewed mining in the form of open pit operations, which remain active on a large scale. Two styles of mineralization are therefore recognized within the deposit: high-grade gold telluride veins that were historically mined underground, and low-grade bulk tonnage “disseminated” gold that is targeted by current pit mining operations.

Geological study of the deposit began shortly after its discovery, and has continued through the present day. Much of this research has focused on describing and analyzing the alkaline rock suite that hosts mineralized ore bodies, and describing the ore bodies themselves. More recently there has been extensive work in describing the magmatic and hydrothermal evolution of the deposit. This work also revealed that gold-bearing As-rich pyrite exists within some ore zones. Through multiple studies, several different models have been proposed for the mineralizing history of the deposit, and many of the previously published paragenetic sequences that describe the relationship of different ore, gangue, and alteration minerals are contradictory. Conflicting parageneses and deposit models indicate that revision is needed in order to better understand how the Cripple Creek deposit became mineralized.

This thesis aims to address some of the existing discrepancies, with focus on refining the paragenetic sequence of mineralization and developing a new model that describes the mineralogical evolution of the deposit. In addition, this thesis explores the nature of gold-bearing As-rich pyrite as sampled from different regions within the deposit.

This thesis presents information derived from detailed mineralogical characterization of ore, gangue, and associated alteration minerals from five sampling locations. Samples that were analyzed in this study preserve evidence of seven distinct mineralizing stages. These stages are characterized by: 1) Early trace element-poor pyrite formation that formed through sulfidation of preexisting iron-rich minerals such as hematite, specular hematite, and biotite across broad zones of rock, 2) The formation of trace element-rich gold-bearing As-rich pyrite as overgrowths on trace element-poor pyrite followed by the formation of microcrystalline hypogene gold- these minerals are restricted to fractures and wall rock adjacent to fractures within broad zones of early trace element-poor pyrite, 3) The development of micron-scale Ag-
Pb-(Au) telluride minerals hessite, altaite, and petzite with galena within micro-fractures that cut fracture-hosted pyrite grains formed during the previous stage of mineralization, 4) The formation of tetrahedrite-bearing quartz veins, 5) The growth of additional stages of trace element-poor and trace element-rich pyrite, confined purely fractures and veins that would later host gold telluride minerals, 6) The large-scale development of gold telluride minerals within quartz ± fluorite veins that may or may not contain trace element-rich pyrite from the second and fourth stages of mineralization, and 7) Molybdenum, copper, and silver-rich base metal sulfide and sulfosalt deposition within veins of quartz ± fluorite ± barite that cut all previously formed minerals.

Recognition of these distinct stages allows for several refinements to be made to the existing deposit model. Key refinements include: (1) the recognition that the deposition of gold-bearing As-rich pyrite associated with microcrystalline hypogene native gold is not paragenetically related to gold telluride mineralization, (2) recognition that at least three different types of quartz exist within the deposit, (3) recognition that quartz within gold telluride veins was deposited before the gold telluride minerals themselves, and (4) recognition that textural relationships between compositionally distinct stages of pyrite growth can be used to track the mineralizing history of the deposit through time and thus add constraint to the paragenetic sequence of mineralization.

Characterization of gold-bearing As-rich pyrite from the Cripple Creek gold telluride deposit has revealed that trace element-rich pyrite is likely common in the deposit. Scanning electron microscope and electron microprobe analyses conducted during this study demonstrate that at least five distinct generations of pyrite exist within the deposit. In addition, electron microprobe analyses reveal that most of the gold contained within pyrite is in solid solution as opposed to existing as nano- to sub-micron-scale inclusions of native gold. The relatively high concentrations of gold within As-rich pyrite indicate that gold-bearing As-rich pyrite may be a significant and previously unrecognized resource within the deposit. A model was created to estimate the mass of gold that is contained within gold-bearing As-rich pyrite, and indicates that between 1.0 and 4.7 g/ton of gold may be contained within gold-bearing As-rich pyrite from specific sampling locations, thus providing strong evidence that pyrite within mineralized areas is in fact a significant gold resource.
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CHAPTER 1

INTRODUCTION

Alkaline magmatic deposits represent a significant worldwide gold resource, containing a disproportionately large fraction of the world’s giant gold deposits relative to the small volume of alkaline rocks exposed on the earth’s surface as compared to other felsic to mafic igneous rocks (Sillitoe, 2002). Examples of world-class alkaline magmatic deposits include Ladolam on Lihir Island (Papua New Guinea), the Emperor deposit (Fiji), and Porgera-Mt. Kare (Papua New Guinea). The Cripple Creek deposit of Colorado is also host to a world-class epithermal gold deposit that is associated with Oligocene alkaline magmatism. Despite extensive research on the deposit dating back to Cross and Penrose (1895) disagreement still exists over paragenetic models for the formation of the deposit.

To address this disagreement, a detailed mineralogical characterization study was conducted that targeted high-grade ore zones and spatially associated low-grade mineralized rock to determine a paragenetic relationship between ore, gangue and alteration minerals from different ore zones within the deposit. In addition, a micro-analytical study of ore-associated pyrite from targeted ore zones was used as a tracer of mineralizing events within the deposit, and revealed a typically neglected gold resource in the form of gold-bearing As-rich pyrite. This detailed case study has implications for our general understanding of alkaline volcanic-hosted epithermal gold telluride deposits, as well as implications for developing in-pit characterization tools for identifying high-grade ore zones within the Cripple Creek deposit.

1.1 Research Problem & Aims

The genesis of mineralized alkaline intrusions, including those related to rifting in the western United States, is poorly understood. Some of these alkaline systems are highly enriched in gold and critical elements such as tellurium, while others are essentially barren. Moreover, alkalinity alone does not dictate whether an intrusion will be mineralized. To understand these deposit types requires knowledge of ore mineral development and spatial variation amongst alteration assemblages related to mineralization, as understood through paragenetic relationships. The complexity in how these features relate to one another has hindered the development of clear models for the evolution of these deposit types.

At Cripple Creek, a great deal of work has been devoted to describing the mineralogical relationships present within the deposit (Cross and Penrose, 1895; Lindgren and Ransome, 1906; Loughlin and
Koschmann, 1935; Thompson et al., 1985; Saunders, 1986; Geller, 1993; Kelley, 1996; Kelley et al., 1998; Jensen, 2003, and others). However, there is significant disagreement between individual studies. For example, between 3 and 8 separate mineralizing stages have been independently described, each of which exhibit strong spatial variation. The development of a better understanding of these mineralizing stages is undermined by a lack of a clear definition of the common mineral assemblages associated with the primary ore types and definition of a reliable four-dimensional paragenetic sequence of the ore types within the deposit. These outstanding discrepancies suggest that mineralogical relationships within the deposit are more complex than previously thought. Moreover, this poor understanding of the spatial and temporal relationships between different mineral associations hinders the development of a coherent genetic model for this and other mineralized rift-related alkaline deposits.

A key unknown factor in the Cripple Creek deposit is the relationship between high-grade gold telluride ore that is hosted in quartz veins, and a low-grade “disseminated” ore type that may or may not occur in association with the high-grade gold occurrences. These low-grade but economic concentrations of gold that occur in association with pyrite are best developed at structural intersections and along major NW-trending shear zones (Pontius, 1992; Burnett, 1995; Kelley, 1996; Kelley et al., 1998), and have been interpreted to represent upper level, and/or lateral expressions of the high-grade gold telluride veins (Pontius, 1992; Kelley, 1996). These zones have conversely been interpreted as fine-scale expressions of high-grade gold telluride veins (Jensen, 2003).

This thesis presents a detailed mineralogical characterization of targeted samples from high-grade and other associated ore zones within the Cripple Creek deposit. These data are used to:

1) establish clear paragenetic relationships between ore, gangue, and alteration minerals, including a spatial and temporal separation of high-grade gold telluride ores and “disseminated” gold ores,
2) develop a new model that describes the mineralogical evolution of the Cripple Creek deposit, and
3) develop a better understanding of gold-bearing As-rich pyrite within the deposit.

1.2 Background

The Cripple Creek deposit, Colorado, is hosted within an Oligocene alkaline volcanic complex, one of several mineralized alkaline intrusions that occur in the western United States. Alkaline magmatism is interpreted to be related to partial melting of the upper mantle during asthenospheric upwelling, where fractional crystallization and minimal interaction between these magmas and continental crust during ascent can lead to enrichment of Na and K relative to SiO₂. Alkaline magmatic systems generally form in rift environments and at locations of oceanic and continental intraplate magmatism (Cappa, 1998), with
magmatism associated with the formation of mantle plumes, or in regions affected by sub-solidus partial melting of hydrated mantle following slab rollback.

In Colorado, intraplate alkaline magmatism has occurred along the axis of the Rio Grande Rift, and in adjacent areas (Figure 1.1). It is important to note that while some of the intraplate alkaline systems are temporally related to the opening of the Rio Grande Rift, which initiated at ~30 Ma, several of the alkaline magmatic deposits are significantly older than the initial stages of rift formation. These older intraplate deposits were formed by a variety of processes that were not directly related to rifting. Examples of alkaline intrusions related to pre-rift intraplate magmatism include the Pikes Peak Batholith (~1.08 Ga; Smith et al., 1999), alkalic complexes exposed in the Wet mountains to the southeast of Cripple Creek (~520-500 Ma; Brock and Singewald, 1968), several Paleocene stocks and dikes in the vicinity of the Idaho springs and Central City mining districts (~63-59 Ma; Sims et al., 1963), and alkaline sills in the vicinity of the La Plata range (~70-60 Ma; Cunningham et al., 1994).

Figure 1.1: Map of alkaline provinces in Colorado. Alkaline units are shown in black, and the approximate axis of the Rio Grande Rift is shown in red. Modified after Cappa (1998).
1.2.1 Regional geology

The Cripple Creek deposit is hosted by an alkaline magmatic diatreme that developed between ~32.5 – 28.2 Ma (Kelley et al., 1998), interpreted to be part of a magmatic system related to the onset of extension along the Rio Grande Rift (Kelley, 1996; Kelley et al., 1998; Jensen, 2003). The Cripple Creek diatreme occurs at the structural junction of four Precambrian units (Figure 2): a metasedimentary and metavolcanic unit with metamorphism dated at ~1.75 Ga (Hedge et al., 1967), the ~1.65 Ga Ajax Granite (Hutchinson and Hedge, 1968; Wobus et al., 1976; Karlstrom and Humphreys, 1998), the ~1.43 Ga monzonitic Cripple Creek Granite (Hutchinson and Hedge, 1968; Wobus et al., 1976), and the ~1.08 Ga Pikes Peak Granite (Smith et al., 1999; Beane et al., 1999).

Magmatism within the Cripple Creek diatreme and surrounding areas involved the intrusion of several alkaline igneous bodies ranging in composition from phonolite to lamprophyre (Lindgren and Ransome, 1906; Kelley, 1996; Kelley et al., 1998; Jensen, 2003). Geochemical analysis has shown the rocks to be peralkaline and dominantly sodic. The compositional range has been explained by the differentiation of basic parent magma recharged at depth (Kelley, 1996; Cappa, 1998; Jensen, 2003).

![Interpretive Geologic Map of the Cripple Creek deposit](image)

**Figure 1.2**: Interpretive Geologic Map of the Cripple Creek deposit, showing the outline of the Cripple Creek diatreme and Precambrian host rocks. *Modified after Jensen (2003)*
The Cripple Creek diatreme is dominated by a heterolithic volcanic breccia that is intruded by volcanic and subvolcanic rocks of variable composition. The diatreme breccia extends to depths of greater than 3,000 feet and this depth has been used as evidence to suggest that short intervals of explosive volcanism within the diatreme periodically interrupted much longer and more prevalent intervals of volcanic quiescence. These quiet intervals were characterized by lacustrine sedimentation and subsidence of the diatreme (Koschmann, 1949). This is in contrast to earlier views that the evolution of rocks within the diatreme involved a single, violent eruption that created a “volcanic crater” (Cross and Penrose, 1895; Lindgren and Ransome, 1906). The deposit also contains two additional types of breccia. Hydrothermal breccias dominate the area near Globe hill in the northwest region of the deposit (red areas, Figure 2), and are interpreted to be the result of the overpressuring of hydrothermal fluids (Jensen, 2003). A late mafic to ultra-mafic diatremal breccia pipe is found in the south-central portion of the deposit (green oval, Figure 2). This feature is known as the “Cresson Pipe”. The ultra-mafic breccia contains clasts of alkali basalt and preexisting Oligocene volcanics with rock flour. The breccia pipe both cuts and is cut by dikes of late alkali basalt (Lindgren and Ransom, 1906; Saunders, 1986; Kelley, 1996; Jensen, 2003).

1.2.2 Mineralizing stages and ore types

Gold, the primary economic commodity at Cripple Creek, occurs as three different styles or associations:

- Disseminated free (native) gold interpreted to be associated with intense potassic alteration near large structures and micro-fractures in the upper regions of the deposit (Kelley, 1996; Jensen, 2003)

- High-grade gold telluride and gold silver telluride veins found along NW- and NE-trending fissures and sheeted fracture zones (Lindgren and Ransome, 1906; Koschmann, 1949; Geller, 1993; Kelley, 1996; Jensen, 2003)

- Refractory gold (not retrievable through cyanide leaching) occurring as physical inclusions and trace substitutions in pyrite (Jensen, 2003).

Early investigations in the Cripple Creek deposit suggest that 3-8 stages of mineralization could be associated with the formation of the deposit (Lindgren and Ransome, 1906; Loughlin and Koschmann, 1935; Lovering and Goddard, 1950). Mineralizing stages have been previously described to have involved deposition of early quartz ± fluorite ± adularia ± carbonate, followed by sulfide deposition, and ending with the formation of gold (± silver) telluride minerals and rare hypogene native gold. However, more recent investigations demonstrate that paragenesis is significantly more complex than the interpretations made by early researchers, and that most of the major mineralized structures in the deposit
were formed through multiple stages of mineralization (Jensen, 2003; this study). For example, Jensen (2003) suggested that very few of the veins at Cripple Creek show all of the mineralizing stages described by previous authors. Furthermore, gold- and gold-tellurium-bearing minerals have been interpreted to be associated with most of these stages, including the early stages of gangue formation, previously described as “barren”.

Two interpretations have been presented to describe the relationship between disseminated and high-grade gold occurrences within the Cripple Creek deposit. Kelley (1996) interpreted that disseminated microcrystalline gold deposits formed on a deposit scale within permeable host rocks adjacent to major mineralized structures, and that these deposits are mineralogically distinct from gold telluride veins. Kelley (1996) also reported that the disseminated low-grade ore zones may be a vertical or lateral expression of high grade gold telluride veins. In contrast, Jensen (2003) interpreted that the disseminated deposit formed through the coalescence of alteration halos surrounding small veins and veinlets which branch off of larger high-grade veins (thus making no mineralogical distinction), and that the disseminated gold is therefore similar, and equivalent in timing, to high-grade gold telluride vein mineralization, but reflected at a different scale. Although both authors agree that the disseminated gold ore zones are likely related to the formation of high-grade veins at depth, there is uncertainty about the paragenetic relationship of the two ore types.

Alteration of host rocks within the Cripple Creek diatreme is pervasive, with many of the alteration minerals thought to have been introduced during the early stages of hydrothermal activity. Protracted hydrothermal activity led to mineralization along major structures, accompanied by continued hydrothermal alteration of wall rock (Kelley, 1996; Jensen, 2003). The dominant alteration types are:

- **Potassic**: formation of secondary hydrothermal biotite as a replacement of mafic phenocrysts, and crystallization of adularia ± specular hematite in veins and in solution cavities, and replacement of plagioclase and albite by K-feldspar (thought to have occurred late in the mineralizing sequence) (Kelly 1996; Jensen, 2003)

- **Pyrite**: replacement of mafic phenocrysts in phonolite, phonotephrite, and tephriphonolite by pyrite ± carbonate (Jensen, 2003)

- **Minor Argillic**: development of dickite, kaolinite, montmorillonite, nontronite and other clay minerals along major structures and as replacements of feldspar and feldspathoid phenocrysts due to late hydrothermal processes and surface weathering. This alteration type is prevalent in igneous clasts within hydrothermal breccias, and as clay replacement of plagioclase (Jensen, 2003).
1.3 Approach and Methodology

To address the aim of characterizing the paragenetic relationships between ore, gangue, and alteration minerals, including a spatial and temporal relationship between high-grade gold telluride ores and “disseminated” gold ores, an approach that integrated field mapping, mineralogical characterization and geochemistry was used.

1.3.1 Sampling

Sampling was designed to target zones of high-grade ore (>0.1 opt gold) to enhance the potential to intersect multiple minerals that host gold and/or tellurium. Potential sampling sites in zones of high-grade ore were located using fire assay data from a combination of historic diamond drill core, blast pattern drilling chips, and on-site channel sampling. Target zones were chosen based on macroscopic differences in ore mineral associations, morphological differences in quartz gangue, the degree and type of associated alteration, and the extent of surface weathering and oxidation.

Sampling efforts were focused on high-grade areas located:

• to the north of the Cresson pipe;
• along a fractured contact between a major aphanitic phonolite dike and adjacent heterolithic diatremal breccia;
• high-grade gold telluride veins within historic drill core from the Altman pit; and
• drill core intercepts of high-grade gold telluride veins within the Gold Bug ore zone in the northern region of the deposit.

1.3.2 Geochemistry

Geochemical analysis was carried out using two approaches:

1) Analysis of existing drill core pulp samples identified on the basis of Au-assay data, and

2) Analysis of new pulp samples collected through channel sampling and examination of historic and new research drill core.

Whole-rock geochemistry included analysis for major elements (Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K, S, P) and selected trace elements (e.g., Cu, Mo, Sb, As, Pb, Hg, Cr, Ba, Sr, F, W, Au, Ag, and Te). The highlighted trace elements have been identified as potentially important pathfinder elements by Jensen
(2003) and others. Whole rock geochemistry was performed by Actlabs, Canada using a combination of fusion inductively coupled plasma mass spectrometry (for refractory elements) and total digestion mass spectrometry (for volatile elements). Full geochemical results are included in the digital appendix.

1.3.3 Petrographic analysis

Sample material was used to produce 52 polished thin sections which were prepared at Spectrum Petrographics in Vancouver, WA. Thin sections included representative samples from all target areas. Transmitted and reflected light microscope petrography was carried out on all thin sections, and full descriptions of rock type, alteration assemblage, mineral occurrence, mineral associations, modal abundances, and inferred paragenetic sequences were produced. Following preliminary petrographic analysis, a sub-suite of representative samples were selected for further analysis using electron-beam instrumentation.

Scanning electron microscopy (SEM) using energy dispersive spectrometry (EDS) was used to confirm mineral identifications made during optical petrographic work. In addition, backscattered electron (BSE) images of important textural relationships between minerals were also collected. High-resolution BSE imaging was also used to characterize trace element-zoning patterns in pyrite from across the different sample contexts.

Automated mineralogical analysis (using Quantitative Evaluation of Mineralogy by SCANning, or QEMSCAN) was conducted on all thin sections that contained important mineral associations and/or significant paragenetic relationships. This technique allowed quantification of several important mineralogical parameters including modal abundance, grain size, and statistical information related to mineral associations. False-colored QEMSCAN mineral maps were created as part of each measurement and used to confirm and refine the paragenesis of the mineral associations and alteration sequence for each sample.

Electron microprobe (EMP) analysis was used to obtain quantitative mineral chemistry data. This work concentrated on trace element compositions in pyrite (e.g., Au, As, Sb, Cu, and Te).

Optical Cathodoluminescence (CL) imaging was also used to further constrain the paragenesis of specific samples. In particular, CL was used to differentiate between different generations of quartz within high-grade gold telluride veins, allowing the relationships between different generations of quartz, fluorite, barite and/or sulfide minerals to be related to different episodes of gold deposition.
1.4 Thesis Organization

This thesis is written with a focus on two independent papers, presented in Chapters 2 and 3. General conclusions are included in Chapter 4, the final chapter of the thesis.

Chapter 2 presents detailed mineralogical characterization of ore, gangue, and alteration minerals, and emphasizes the development of a new paragenetic sequence of mineralization within the Cripple Creek deposit. In addition, chapter 2 outlines possible formational mechanisms involved in specific mineralizing stages.

Chapter 3 presents a detailed mineralogical characterization study of gold-bearing As-rich pyrite from high-grade ore zones within the deposit, with emphasis on trace element zoning patterns, the use of trace element-rich pyrite as a record of the mineralizing history of the deposit, and the potentially significant gold resource that may be contained within gold-bearing As-rich pyrite within the deposit.

Chapter 4 presents a synthesis of conclusions from each chapter, and includes implications for future exploration in the deposit based on new concepts developed within this thesis.

1.5 REFERENCES CITED


CHAPTER 2

CONTRASTING ORE TYPES AT THE ALKALINE-HOSTED CRIPPLE CREEK GOLD DEPOSIT, COLORADO

The world-class Cripple Creek gold telluride deposit in central Colorado has produced >24 Moz of gold since its discovery in 1891. Most historic production came from high-grade gold telluride veins that were mined underground until the early 1960's. The discovery of broad low-grade, bulk tonnage deposits in the 1980’s led to renewed mining in the form of open pit operations, which remain active on a large scale. Due to the rare nature of this type of deposit, the Cripple Creek deposit has been a site of significant research for more than 120 years. Much of this research has focused on describing and analyzing the alkaline rock suite that hosts mineralized ore bodies, and describing the ore bodies themselves. Although several different models have been proposed regarding the mineralizing history of the deposit, many of the previously published paragenetic sequences of mineralization are contradictory.

A detailed mineralogical characterization of ore, gangue, and associated alteration minerals from five sampling locations has identified four separate ore types within the deposit. These preserve evidence of seven stages of mineralization. These stages are characterized by: 1) early pyrite and base metal sulfide deposition with no gold, 2) gold-bearing As-rich pyrite deposition that shifted toward the deposition of hypogene native gold, 3) localized formation of hessite, altaite, petzite, and galena, 4) the formation of tetrahedrite-bearing quartz veins, 5) a second stage of gold-bearing As-rich pyrite growth, 6) large-scale gold telluride formation, and 7) molybdenum-, copper-, and silver-rich base metal sulfide formation.

By defining the overarching mineralizing sequence of the deposit, several refinements and additions are made to the existing deposit model. Key refinements include: 1) recognition that the deposition of gold-bearing As-rich pyrite associated with hypogene native gold which occurs in some regions of the deposit is not paragenetically related to gold telluride mineralization, 2) textural indications that quartz within gold telluride veins was deposited before the gold telluride minerals themselves, and 3) evidence that pervasive secondary K-feldspar alteration occurred between stages 3 and 5. In addition, it was found that patterns of trace element enrichment in pyrite track the mineralogical evolution of the deposit, and that high-grade gold telluride mineralization post-dates primary quartz veining, suggesting that fluid inclusion studies in quartz at Cripple Creek represent a poor proxy for defining fluid conditions at the time of gold telluride formation.
2.1 Introduction

The world class Cripple Creek gold telluride deposit in central Colorado has been the focus of research since its discovery in 1891. Early accounts (Cross and Penrose, 1895; Lindgren and Ransome, 1906; Loughlin and Koschmann, 1935) described the petrology of the alkaline rock suite that hosts gold-bearing mineralized structures, as well as the nature and mineralogy of high-grade gold telluride veins that were mined throughout the late 19th to mid-20th century. Renewed exploration interest in the Cripple Creek deposit in the mid 1980’s through the early 1990’s led to the discovery of large, low-grade gold deposits that could be worked economically through open pit mining. More recent research has focused on describing the mineralogy and structure of the low-grade deposits (Pontius, 1992; Burnett, 1995), dating of alkaline host rocks and vein-stage gangue minerals (Kelley, 1996; Kelley et al., 1998), and the magmatic and hydrothermal evolution of the deposit (Jensen, 2003). Despite the large amount of research conducted in the deposit, there remain several outstanding questions related to how mineralization was developed. Three to five stages of mineralization have been recognized by previous authors (Table 2.1). Most authors have reported that base metal sulfide minerals and pyrite predate telluride mineralization, but there is little agreement between the timing of telluride and native gold mineralization, as well as the paragenetic relationships between different telluride mineral species. Jensen (2003) reported a general paragenesis for the deposit (Table 2.1), but recognized up to 8 stages of mineralization within specific veins (See Jensen, 2003, Table 5.3 for a review). There is general agreement that the mineralizing processes in the deposit were the result of variably composed fluid pulses (i.e. compositional variations led to different paragenetic “stages”), but it is not clear whether these pulses were sourced from a single, evolving hydrothermal fluid, or from several compositionally distinct hydrothermal fluids that were derived from more than one source. The source of the gold and tellurium in the deposit is also unclear.

This paper presents detailed mineralogical characterization of the ore, gangue, and alteration minerals present at several sampling locations across the Cripple Creek deposit, with the aim of refining the paragenetic model of the deposit. The research adds to the existing body of knowledge on the role that hydrothermal fluids played in developing the mineralized zones within the shallow portions of the Cripple Creek epithermal system.

2.2 Regional Geology

The Cripple Creek deposit is centered on an Oligocene alkaline volcanic diatreme with distal satellite bodies that were intruded along the structural intersection of four Precambrian units (Figure 2.1). The
Table 2.1: Previous paragenetic Interpretations (modified after Jensen, 2003)

<table>
<thead>
<tr>
<th>Loughlin and Koschmann (1935)</th>
<th>Dwelley (1984); Bobtail and Newmarket veins, Ajax Mine</th>
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<tr>
<td>Stage 1</td>
<td>Stage 2</td>
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<tr>
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<td>quartz</td>
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<tr>
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<td>light purple fluorite</td>
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<td>spherelite</td>
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<td>pyrite</td>
<td>galena</td>
</tr>
<tr>
<td>dolomite</td>
<td>+/r siderite</td>
</tr>
<tr>
<td>chalcopyrite</td>
<td>calaverite</td>
</tr>
<tr>
<td>gale</td>
<td>krenmerite</td>
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<td>phalerite</td>
<td>tetrahedrite</td>
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<table>
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<tr>
<th>Saunders (1986); Cresson Mine</th>
<th>Nelson (1989); Cresson Mine</th>
<th>Kelley (1996); Based on literature review</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>Stage 2</td>
<td>Stage 3</td>
</tr>
<tr>
<td>quartz</td>
<td>quartz</td>
<td>petzite</td>
</tr>
<tr>
<td>pyrite</td>
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<td>calaverite</td>
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</tr>
<tr>
<td>chalcopyrite</td>
<td>krenmerite</td>
<td>native gold</td>
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<td>quartz</td>
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</table>

<table>
<thead>
<tr>
<th>Jensen (2003); general paragenesis</th>
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<tr>
<td>Vein margin</td>
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<tr>
<td>adularia</td>
</tr>
<tr>
<td>dolomite-ankerite</td>
</tr>
<tr>
<td>barite</td>
</tr>
<tr>
<td>celestite</td>
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rocks of a ~1.7 Ga metasedimentary and metavolcanic package are exposed to the west and northwest of the deposit (Hedge et al., 1967). The ~1.65 Ga granodioritic Ajax Granite (Hutchinson and Hedge, 1968; Wobus et al., 1976; Karlstrom and Humphreys, 1998) is exposed to the southwest and east of the deposit which, along with the metamorphic rocks, is intruded by the ~1.43 Ga monzonitic Cripple Creek Granite to the west and southwest (Hutchinson and Hedge, 1968; Wobus et al., 1976). The northern portion of the deposit is flanked by the ~1.08 Ga Pikes Peak Granite (Smith et al., 1999; Beane et al., 1999) that intruded the previous three Precambrian units.

The central and southern regions of Colorado have a long history of alkaline magmatism that include the Mesoproterozoic intrusion of the strongly potassic Pikes Peak Batholith (Smith et al., 1999), and the alkalic complexes exposed in the Wet Mountains southwest of Cripple Creek that were intruded between ~520-500 Ma (Brock and Singewald, 1968). Additional alkaline magmatism became broadly developed from the late Cretaceous through the middle Eocene during the Laramide Orogeny, and involved the emplacement of numerous calc-alkaline to alkaline intrusive centers along a northeast-trending zone known as the Colorado Mineral Belt that is aligned diagonally across the mountainous regions of the state (Tweto and Sims, 1963). Restricted magmatism continued through the Holocene epoch with the intrusion of numerous alkaline bodies related the Rio Grande Rift. The Oligocene magmatic system at Cripple Creek is thought to coincide with a regional transition from Laramide compression to extension that coincided with the earliest stages of rifting along the Rio Grande Rift axis (Kelley, 1996; Jensen, 2003).

2.3 Deposit Geology

Oligocene volcanism in the Cripple Creek deposit (Figure 2.1) began at ~33 Ma (Kelley, 1996), with the emplacement of large volumes of heterolithic breccia within the volcanic diatreme, forming what is termed the Cripple Creek Breccia. The Cripple Creek Breccia is a clast-supported heterolithic diatremal breccia. Clasts within the Breccia are dominantly composed of phonolite, with lesser though locally significant amounts of Tertiary syenite and Precambrian granite, schist, and gneiss. The clasts are sub-angular to rounded, and are hosted in a very fine-grained matrix comprised of rock flour, white mica, and K-feldspar cement. Phonolite clasts are dominantly porphyritic, containing phenocrysts of alkali and plagioclase feldspars with minor feldspathoid minerals, within a groundmass of trachytic albite and K-feldspar. Most of the plagioclase and feldspathoid phenocrysts have been pseudomorphed by very fine-grained potassic white mica (identified by SEM-EDX and hereafter referred to as sericite).

Early workers interpreted that the evolution of rocks within the diatreme began with a single, violent eruption that created a “volcanic crater” (Cross and Penrose, 1895; Lindgren and Ransome, 1906). However, continued development of underground mines through the mid-1940’s revealed that the
Diatremal breccia extended to depths of >1000m, and locally contained large blocks that displayed fluvial textures initially developed at the surface of the deposit. Koschmann (1949) used these observations as evidence that the diatreme formed through periodic subsidence and infilling wherein short intervals of explosive volcanism were followed by much longer and protracted intervals of volcanic quiescence.

Diatremal breccia formation was followed by the intrusion of hundreds of individual alkaline igneous bodies that range in composition from phonolite to lamprophyre (Lindgren and Ransome, 1906; Loughlin and Koschmann, 1935; Kelley, 1996, Jensen, 2003). The alkaline intrusive rocks are dominantly peralkaline, nepheline-normative, and sodic (Jensen, 2003). The earliest preserved intrusions consist of large and irregular porphyritic bodies that range in composition from phonolite to tephriphonolite, and were intruded between 32.5 ± 0.1 Ma and 30.9 ± 0.1 Ma (Kelley, 1996; Kelley, et al., 1998). Jensen (2003) reported that the earliest of these intrusions were felsic and evolved toward more mafic compositions, interpreting that the change from phonolite to phonotephrite to tephriphonolite resulted from the progressive magmatic evolution of a deeply emplaced magmatic body with the composition of nepheline syenite.

Jensen (2003) reported a later stage of volcanism that ended at ~28.4 Ma (Kelley et al., 1998 reported 28.2 Ma), which is characterized by the intrusion of tabular dikes and sills with compositions ranging from early phonolite to late lamprophyre. The gross change from large irregular intrusive bodies to spatially constrained dikes and sills is suggested to represent a change in the degree of lithification of the diatremal host breccia (Jensen, 2003). The final stages of volcanism in the deposit involved the localized emplacement of lamprophyre breccia pipes, which cut all previously formed volcanic rock types (Loughlin and Koschmann, 1935; Saunders, 1986; Nelson, 1989; Jensen, 2003).

Three dominant styles of mineralization have previously been recognized at Cripple Creek: 1) high-grade vein-hosted gold telluride, 2) disseminated gold with pyrite, and 3) hydrothermal breccia-hosted ore that is dominated by base-metal sulfide minerals. Based on cross-cutting relationships, all gold mineralization is interpreted to have developed after the intrusion of lamprophyre (Jensen, 2003).

2.3.1 High-grade gold telluride veins

High-grade gold telluride veins have produced the most significant proportion of historic production (~20 Moz; Jensen, 2003 and references therein). The veins occur as discontinuous and anastomosing bodies within the Breccia and along lithological contacts, in zones of shattered rock. The veins generally occur near the centerline of the shattered rock zones (which are commonly referred to as “sheeted fracture
Figure 2.1: Geological map of the Cripple Creek district, with sampling locations (modified after Jensen, 2003). Points A through E indicate sampling sites used in this study; see text for a description of each sampling site.
zones” in the literature), along planes that have high joint density. Koschmann (1949) emphasized the use of the term “vein zones” to describe areas where veins hosted in sheeted fractures have remarkable continuity along strike. Vein zones radiate around a central ‘island’ of Precambrian rock (Koschmann, 1949) and may coalesce at depth into single, vertically continuous veins (Koschmann, 1949; Jensen, 2003). Historically, between three and five stages of mineral deposition were recognized within high-grade veins, one or more of which can occur within individual veins (Table 2.1; Loughlin and Koschmann, 1935; Dwelley, 1984; Saunders, 1986; Nelson, 1989; Burnett, 1995; Kelley, 1996; Jensen, 2003).

Early barren stages are generally characterized by quartz, adularia, fluorite, dolomite and coarse-grained pyrite. In subsequent paragenetic stages, these minerals are overgrown by a mixture of milky to smokey quartz, fluorite, fine-grained pyrite, dolomite, ankerite, celestite and barite, along with sphalerite, galena, tetrahedrite, telluride minerals, and rare roscoelite. Jensen (2003) recognized that fine-grained pyrite in high-grade gold telluride veins may be locally auriferous and enriched in arsenic and other trace elements, and additionally confirmed that most of the “marcasite” identified in previous studies (based on its anisotropic nature) was actually gold-bearing As-rich pyrite. Telluride minerals typically occur as overgrowths on quartz, fluorite, adularia and dolomite crusts and appear to have grown into open spaces in veins and in dissolution cavities in Breccia (Lindgren and Ransome, 1906; Kelley, 1996; Jensen, 2003). Native gold, quartz, chalcedony, fine-grained pyrite, calcite, and rare cinnabar characterize latter stages. Ore minerals are interpreted to be confined to fractures, with only minor wall-rock replacement (Jensen, 2003).

Previously identified alteration minerals associated with high-grade veins include relatively abundant sericite and pyrite, minor secondary K-feldspar (as wall rock replacement and as euhedral crystals of adularia within veins) and rare roscoelite (Lindgren and Ransome, 1906; Thompson et al., 1985; Kelley, 1996). In contrast, Jensen (2003) suggested that sericitic alteration is somewhat uncommon in areas of vein development, indicating instead that veining is strongly associated with the development of intense secondary K-feldspar alteration halos. Interpretation of alteration mineralogy and textures suggests that mafic minerals (e.g. biotite, amphibole and pyroxene) were replaced by dolomite, magnetite, pyrite and fluorite, and feldspars and feldspathoids were replaced by sericite and/or adularia (Lindgren and Ransome, 1906; Thompson et al., 1985; Saunders, 1986; Jensen, 2003).

2.3.2 Disseminated gold ore

In addition to high-grade gold telluride veins, Pontius (1992) and Burnett (1995), with further refinements by Kelley (1996) and Kelley et al. (1998), described low-grade but economic concentrations
of gold in association with pyrite that exist as “disseminated” ores which are best developed at structural intersections and along major NW-trending shear zones. These low-grade ores have been interpreted to represent upper level, and/or lateral expressions of high-grade gold telluride veins (Pontius, 1992). Despite the interpreted association between disseminated ore zones and high-grade gold telluride veins, the disseminated ore zones are reported to be mineralogically distinct, containing microcrystalline native gold and pyrite (Pontius, 1992; Kelley, 1996), but lacking telluride minerals (Harris et al., 1993). In contrast, Jensen (2003) interpreted the lower grade ‘disseminated’ ore zones to consist of fine-scale expressions of high-grade gold telluride veins, and made no mineralogical distinction between the two ore types.

Alteration associated with disseminated ore was reported to be concentrated in broad permeable zones in breccia adjacent to major mineralized structures (Pontius, 1992) and was interpretively characterized by pervasive flooding of secondary K-feldspar and sericite, with fine- to medium-grained pyrite and biotite (Pontius, 1992; Burnett, 1995; Kelley, 1996). Jensen (2003) suggested that up to two thirds of the diatreme had been affected by K-feldspar alteration and drew a direct link between this potassic alteration and zones that have been mineralized with gold.

2.3.3 Hydrothermal breccias

Hydrothermal breccia-hosted ore can be subdivided into two main types (Trippel, 1985; Jensen, 2003). The first are breccias that contain hydrothermal quartz and fluorite, with pyrite and gold telluride minerals as breccia matrix infill that may also contain clasts of previously mineralized rock. The second are breccia pipes that contain anhydrite, with or without rhodochrosite, in the matrix of re-brecciated quartz-fluorite breccia. A sub-economic molybdenum-base metal sulfide ore is spatially associated with the breccia pipes. This same molybdenum-base metal sulfide mineral association occurs within deposit-wide veins that cut high-grade gold telluride veins, but are themselves truncated by the late breccia pipes.

2.3.4 Other styles of mineralization

In addition to the dominant gold and gold telluride mineralized zones within the upper levels of the system, the deeper parts of the deposit (>1000m) contain broad zones of sub-economic lead and zinc base metal sulfide minerals associated with pyrite in calcite. Base metal sulfide veins are also present along the perimeter of the diatreme and within some of the volcanic satellite bodies outside of the diatreme. The most common base metal sulfides are sphalerite and galena, although molybdenite has been reported in many samples (Lindgren and Ransom, 1906; Jensen, 2003; Robinson, 2010). These zones are also sub-economic with respect to gold, with most of the sampled areas containing gold in concentrations of only a
few ppb; some areas lack detectable concentrations of gold entirely. The base metal sulfide zones at depth grade upward into narrowly focused gold telluride-bearing veins that are interpreted to transition into much broader vein zones of high-grade gold telluride at higher levels of the deposit (Jensen, 2003). This stratification from base metal sulfide associations at depth to gold telluride higher in the system has been interpreted to reflect the effects of a long-lived thermal gradient within the magmatic-hydrothermal system (Jensen, 2003).

2.4 Methods

Sample materials were analyzed in polished thin sections. Trace element zoning in pyrite was characterized by backscattered electron (BSE) imaging. Images were collected using a FEI-Quanta 650 Field-Emission Scanning Electron Microscope (FESEM) located at the USGS Microbeam Laboratory, Denver, CO, using beam conditions of 10-20 kV and 5 nA. Electron microprobe (EMP) analyses were conducted using a JEOL 8900 electron microprobe at the USGS Microbeam Laboratory, Denver, CO. Point analyses were collected using beam conditions of 20 kV and 50 nA, and a beam size of <1 μm. EMP element intensity maps were collected using beam conditions of 20 kV and 100 nA, a step size of 0.5 μm, and dwell time of 750 ms. The detection limits used for the EMP represent concentrations at 99% confidence. Elements with concentrations at less than 99% confidence were detected, showing that they were present, but the precise concentrations of these elements were uncertain due to the low confidence of the measurements. Full details of analytical conditions for trace element analysis of pyrite are presented in the digital appendix. QEMSCAN false-color mineral maps were created using a Carl Zeiss EVO 50 SEM at the Colorado School of Mines QEMSCAN Facility in Golden, CO using beam conditions of 25 kV and 5 nA. Optical cathodoluminescence images were collected using a HC5-LM hot cathode CL microscope equipped with a Kappa DX40C camera at the CL Laboratory, Colorado School of Mines. Whole rock geochemistry was performed by Actlabs, Canada. Refractory elements were analyzed using fusion inductively coupled plasma mass spectrometry (FUS-ICP-MS) and volatile elements were analyzed through Total Digestion Mass Spectrometry (TD-MS). For photomicrographs within figures that accompany the text, the following abbreviations are used: plane polarized light (PPL), crossed polarized light (CPL) and reflected light (RL). A full description of the methods used in this study is provided in the digital appendix.

2.5 Sampling Locations

Potential sample sites in zones of high-grade ore (> 0.1 opt Au) were located using fire assay data from a combination of diamond drill core, blast pattern drilling chips, and on-site channel sampling. Five target zones (Figure 2.1, points A-E) were chosen based on macroscopic differences in ore mineral
associations, morphological differences in quartz gangue, the degree and type of associated alteration, and the extent of surface weathering and oxidation.

Descriptions of samples from the five target zones are as follows: (1) Target zone A samples were taken from drill core that penetrated the Gold Bug ore body, a flat-lying ore body consisting of vein sets hosted by Cripple Creek Breccia that locally grades to monolithic phonolite breccia. The ore body is located at 200 m depth within the newly constructed WHEX open pit; (2) Samples from target zone B were taken from historic diamond drill core from the former Altman Pit, which is also referred to as the East Cresson pit in some literature. Samples from this target zone were taken from mineralized fractures within Cripple Creek Breccia adjacent to a porphyritic phonolite dike; (3) Target zone C is located within radially fractured Cripple Creek Breccia that is focused on the north side of the Cresson Pipe, a lamprophyre matrix breccia blowout pipe on which the historic Cresson Mine was located; (4) Channel samples were collected at target zone D from a mineralized fracture zone that parallels the contact between Cripple Creek Breccia and a major aphanitic phonolite dike, historically referred to as the ‘Blue Bird’ dike; (5) Target zone E sampled the same Breccia-phonolite contact along the Blue Bird dike, as intercepted in research diamond drill core ~160 m the south of target zone D. Six unmineralized background samples were collected from Cripple Creek Breccia adjacent to target zone C. The samples contained hematite and smectite that was visible to the naked eye, but did not contain visible pyrite or signs of secondary K-feldspar alteration. Two additional samples of unmineralized Breccia were collected from drill core AC92-9 (target zone B). Samples taken from diamond drill core included portions of rock that were cut down to size for thin section preparation, and pulp material that was derived from half-core that measured between 0.3 and 2.6 m. 1-3 kg of material was collected for each channel sample. Individual rocks from these samples were cut to size for thin section preparation, and the remainder of the sample was converted into a pulp using on-site pulp preparation machinery for later geochemical analysis.

2.6 Ore Types

Based on observed mineral associations and textural relationships, four different ‘types’ of ore (three of which are gold-bearing) have been defined within the deposit (Table 2.2).

2.6.1 Type 1 ore – gold-bearing

Type 1 ore occurs in target zone C and consists of fine-grained gold-bearing As-rich pyrite and hypogene native gold within and immediately adjacent to mm-scale fractures that cut Cripple Creek Breccia. Gold telluride minerals are rare or absent. Gold grades within samples of this ore type range from 0.16 – 6.24 g/ton (median= 2.18 g/ton, n=27). Clasts within the Breccia are composed of albite-rich
and K-feldspar-rich phonolite. Calcic phonolite clasts within the Breccia and phenocrysts within sodic and potassic phonolite clasts have been strongly pseudomorphed by sericite (Figure 2.2), and albite clasts have been weakly sericitized. The Breccia matrix contains abundant very fine-grained K-feldspar. Pyrite grains, which occur in modal abundances of 1-4.8% throughout the mineralized zone, are typically gold-bearing and arsenic-rich. Samples of unmineralized Cripple Creek Breccia adjacent to the mineralized zone are also composed of albite, K-feldspar, and sericite, but contain hematite and rare magnetite in place of pyrite. In the unmineralized samples, hematite occurs in modal abundances of 1-4.5%, whereas pyrite is typically less than 1% by mode and commonly absent. Hematite locally contains lamellae of ilmenite and Fe-rich TiO₂. Magnetite, also with ilmenite lamellae, is locally preserved and rimmed by hematite, suggesting a potential pseudomorphing by hematite in samples now absent of magnetite.

Gold occurs as grains of hypogene native gold throughout the mineralized zone, and as a trace element within As-rich pyrite that is abundant within and immediately adjacent to mm-scale fractures that cut the host rock. Gold-bearing As-rich pyrite also occurs within sericitized phenocrysts that are situated 1-3 centimeters from mineralized fractures. Where numerous fractures coalesce, the abundance of gold or gold-bearing pyrite increases to form continuous bodies of mineralized rock.

Hypogene native gold commonly occurs as non-porous masses with uniform color, and almost ubiquitously contains low concentrations of silver (<5 wt. %). For simplicity, gold with silver concentrations of <5 wt. % is hereafter referred to as native gold, while gold that contains >5 wt. % silver is referred to as electrum. Hypogene native gold occurs as single grains and as growths on pyrite (Figure 2.3a). Mineralized rocks containing native gold generally extend beyond the zones that contain gold-bearing As-rich pyrite.

Gold-bearing As-rich pyrite grains within fractures and altered phenocrysts are ubiquitously associated with sericite, and in some areas may be associated with iron-rich smectite. Where present, iron-rich smectite forms fracture selvages that have a forest green color in hand sample. However, the presence of iron-rich smectite is not a requisite for the presence of gold-bearing As-rich pyrite. Pyrite that is not enriched in arsenic is a common component of this ore type as well, and locally occurs with gold-bearing As-rich pyrite. Within the groundmass, a notable amount of the As-poor pyrite contains isometrically-oriented lamellae of TiO₂ group minerals (Figure 2.3b). The orientation of the TiO₂ mineral inclusions is identical to those that are found in preserved magnetite with ilmenite exsolution lamellae, and within the more common hematite that has pseudomorphed magnetite (see above). This suggests that locally, As-poor pyrite has pseudomorphed primary magnetite and/or hematite.
Table 2.2: Mineral Associations by Ore Type

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<tr>
<th>Mineral Association</th>
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<th>Type 2 ore</th>
<th>Type 3 ore</th>
<th>Type 4 ore</th>
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<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Gold-bearing As-rich pyrite</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Hypogene native gold</td>
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<td>Hessite, altaite, petzite</td>
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<td>Tetrahedrite + BMS</td>
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<td>Calaverite + associated gold telluride minerals</td>
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<td>Coloradoite + hypogene native gold</td>
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<td>Pervasive secondary K-feldspar alteration</td>
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* BMS = Base metal sulfide minerals
Figure 2.2: Mineral associations in type 1 ore; (A) False-color QEMSCAN (QS) mineral map demonstrating breccia textures and distribution of gold-bearing As-rich pyrite; (B) Close up mineral map, from inset in A; (C) High resolution mineral map of gold-bearing As-rich pyrite grain in association with sericite and Fe-rich smectite, from inset in B. Sample XCR2-13-1.
Figure 2.3: (A) reflected light (RL) image of native gold (Au) overgrowth on pyrite (Py); (B) RL image of isometrically oriented lamellae of leucoxene (Leu) group (TiO$_2$) minerals in pyrite; (C) RL image of silicate inclusion-rich pyrite core; (D) Secondary Electron image of altaite (Alt) and galena (Gn) in micro-fractures that cut BSE-bright pyrite; (E) Backscattered Electron (BSE) image of a simply zoned BSE-bright pyrite grain; (F) BSE image of a complexly zoned BSE-bright pyrite grain; (G,H) BSE image of a complexly zoned BSE-bright pyrite grain with accompanying electron microprobe As element map. Samples XCR2-12 and XCR2-13-1.
Pyrite grains within this ore type have two different compositions: BSE-dark As-poor pyrite and BSE-bright As-rich pyrite. Trace-element concentrations in BSE-dark pyrite are below the detection limits of EMP analysis. BSE-dark pyrite commonly occurs as cores within grains that have BSE-bright rims, within or proximal to fractures. Beyond of the 1-3 centimeter wide mineralized halos that surround fractures, BSE-dark pyrite occurs as complete grains, with no BSE-bright rims. The shape of BSE-dark pyrite locally mimics a bladed texture, possibly reflecting replacement of specular hematite or an iron-rich silicate mineral such as biotite. BSE-dark cores may also have irregular shapes that may or may not reflect pseudomorphed textures of other preexisting minerals.

BSE-dark pyrite is commonly rich in inclusions of silicate and base metal sulfide minerals (primarily galena, with lesser sphalerite, chalcopyrite, and rare bornite) (Figure 2.3c). Silicate mineral inclusions are comprised of sericite, albite, and K-feldspar and thus have the same composition as adjacent wall rock minerals. The silicate inclusions are interpreted to represent portions of the host rock that were encapsulated during pyrite growth. BSE-bright pyrite very rarely contains silicate inclusions, but commonly contains trace abundances of galena inclusions up to several microns in size. BSE-dark and BSE-bright pyrite is locally cut by micro-fractures containing micron-scale grains of altaite (PbTe), hessite (AgTe₂), and rare petzite (Ag₃AuTe₂) in association with galena (Figure 2.3d). These minerals are also commonly observed within the interstitial spaces between grains in pyrite clusters.

BSE-bright pyrite is consistently enriched in As and Au, with some zones containing detectable concentrations of Cu, and Sb. Trace-element enriched pyrite is best developed within zones that have high sericite content. Two distinct types of BSE-bright zoning patterns are preserved in pyrite grains from type 1 ore. Simply zoned pyrite is characterized by BSE-dark cores that are rimmed by BSE-bright pyrite (Figure 2.3e). Complexly zoned pyrite contains BSE-bright zones that comprise a considerable volume of the grains and commonly display irregularly shaped oscillatory zoning patterns (Figure 2.3f,g). Complexly zoned pyrite may be further subdivided into three different zoning types, based on differences in trace element distribution. These are oscillatory zoning (Figure 2.4a), gradational (diffuse) zoning (Figure 2.4b,c), and patched zoning (Figure 2.4d).

Many of the complexly zoned grains have BSE-dark cores that are irregularly shaped (Figure 2.3f), and BSE-dark pyrite may occur as small, discontinuous patches within BSE-bright pyrite (Figure 2.3g). Complexly zoned pyrite is best developed within and immediately adjacent to fractures, whereas simply zoned pyrite is best developed between 0.5–3 cm away from fractures. BSE-bright pyrite disappears completely beyond ~3 cm away from fractures.
BSE-bright zones in pyrite strongly correlate with As-enrichment (Figure 2.3h, Figure 2.5), with As contents ranging from 232 ppm to 4.42 wt % (median=1.30 wt %, n=225). Au content has a general correlation with As-enrichment, and Au contents range from the detection limit of 150 ppm up to 572 ppm (median=228 ppm, n=83). Two analyses had anomalously high Au concentrations outside of this range (7610 ppm and 8706 ppm), likely reflecting subsurface inclusions of sub-micron scale Au. Measured gold concentrations in pyrite that were below the 150 ppm 99% confidence detection limit of the EMP are not included in any calculations due to their uncertainty. However, previously reported data from secondary ion mass spectrometry analyses of gold-bearing As-rich pyrite from the Cripple Creek deposit (Jensen, 2003) showed Au concentrations that ranged from 0.01 to 78.16 ppm (DL <500 ppb; most analyses were between 1-3 ppm), indicating that Au does exist in pyrite at concentrations that are below the EMP detection limit used in this study.

2.6.2 Type 2 ore – gold-bearing

Target zones B, D, and E produced type 2 ore which contains both gold-bearing As-rich pyrite and abundant gold telluride minerals. Gold grades of this ore type range from 0.14 to 546.11 g/ton (median=5.45 g/ton, n=36). Type 2 ore occurs in Cripple Creek Breccia that has been pervasively potassically altered to secondary K-feldspar. A key feature of this alteration is that it was generally not texturally destructive- the original texture of the breccia clasts is retained, but clasts have been replaced by K-feldspar (Figure 2.6). Medium- to coarse-grained euhedral adularia may occur on the walls of mineralized and unmineralized fractures in K-feldspar-altered host rock. However, there is no apparent correlation between the presence of adularia and the presence of gold-bearing minerals.

Type 2 ore commonly contains quartz veins with widths of a few mm’s to ~4 cm, with or without purple fluorite. The veins contain gold telluride minerals and gold-bearing As-rich pyrite. In fluorite-absent samples sericite and gold-bearing As-rich pyrite occupy altered phenocrysts (Figure 2.6a). In fluorite-bearing samples, altered phenocrysts contain a mixture of quartz and fluorite with gold-bearing As-rich pyrite (Figure 2.6b), and sericite is essentially absent.

Gold-bearing As-rich pyrite occurs within veins as intergrowths with quartz (with or without fluorite), within altered phenocrysts in the wall rocks in association with either sericite or quartz-fluorite, and as disseminations adjacent to mineralized veins. Although albite is not generally observed in the potassically-altered wall rocks of these veins, BSE-dark pyrite cores associated with type 2 ore locally contain inclusions of albite (Figure 2.7). Although mineral inclusions are rare in BSE-bright zones, the outermost rim of BSE-bright As-rich pyrite may contain inclusions of K-feldspar and, less commonly,
Figure 2.4: BSE images of the three subtypes of complex trace element zoning in pyrite: (A) Oscillatory zoning, sample CC12-1 70.0; (B, C) Gradational (diffuse) zoning, sample XCR2-13-1 and XCR2-20; (D) Patched zoning, sample XCR2-14-2.
Figure 2.5: Electron microprobe element traverse across a complexly zoned pyrite grain, Sample XCR2-13-1. Shaded gray areas indicate concentrations that lie below the 99% confidence detection limit of the electron microprobe.
Figure 2.6: Mineral associations in type 2 ore: (A) Gold telluride-bearing quartz vein with sericite in altered phenocryst sites, Clv = calaverite, sample AC92-9 149.2-3; (B) Gold telluride-bearing quartz and fluorite vein, with no sericite in altered phenocryst sites, sample XBB-009-01.
Figure 2.7: False-color QEMSCAN mineral map showing albite inclusions in the core of a pyrite grain that is overgrown by trace element-rich pyrite, surrounded by intensely K-feldspar altered matrix, sample XBB-004-02-3.
sericite. It should be noted, however, that these apparent inclusions may actually result from stereological effects, so it is unknown if they represent true, fully encapsulated mineral inclusions.

Pyrite grains in the host rock of type 2 ore show similar zoning patterns as those found in type 1 ore - irregularly shaped, inclusion-rich BSE-dark cores rimmed by BSE-bright, gold-bearing As-rich pyrite that displays oscillatory zoning (Figure 2.8). BSE-bright pyrite in wall rock domains contain As concentrations that range from 248 ppm-5.91 wt % (median=1.22 wt. %, n=196) and Au concentrations that range from 151-1079 ppm, (median=206 ppm, n=31). However, in contrast to As-rich pyrite grains in type 1 ore, those found in type 2 ore locally have fine-scale enrichments in Te ranging from 240-2814 ppm (median=495 ppm, n=23) within discontinuous As-rich growth zones along the outermost edges of the pyrite crystals.

The elevated Te concentrations occur in two ways. In some cases, high Te (>450ppm) together with elevated Ag and Au likely indicate sub-micron scale inclusions of hessite and petzite, which were locally observed as micron-scale inclusions. In contrast, Te also occurs in concentrations of 240-450 ppm, but Ag and Au were below detection. Thus, Te may occur in solid solution within the pyrite.

Vein-hosted gold-bearing As-rich pyrite in type 2 ore is different than wall rock-hosted pyrite in that the vein-hosted pyrite generally lacks pitted BSE-dark cores. The cores are instead composed of occluded As- and Au-rich pyrite grains that have irregular boundaries and are overgrown by trace element-poor, BSE-dark pyrite. This pyrite is in turn rimmed by additional stages of trace element-rich, BSE-bright pyrite (Figure 2.9). Vein-hosted pyrite grains commonly contain micron- to sub-micron-scale inclusions of hessite, petzite, and rare altaite that are generally confined to the interface between As- and Au-rich cores and trace element-poor overgrowths. The telluride mineral assemblage at the interface is similar to the telluride assemblage that occurs within micro-fractures that cut As-rich pyrite in type 1 ore (Figure 2.3d).

BSE-bright zones in vein pyrite from type 2 ore have As contents that range from 221 ppm-5.12 wt. % (median=1.05 wt %, n=68), and Au contents that range from 160-2478 ppm (median=380 ppm, n=29). Te is locally present in concentrations ranging from 346-7940 ppm (median=775 ppm, n=16), and is accompanied by elevated Ag (range 174-10,095 ppm, median=2280 ppm, n=9) and Au (range 153-2968 ppm, median=804 ppm, n=11). Similar to wall rock pyrite, the association between Te with Ag and Au is interpreted to be related to sub-micron-scale inclusions of hessite and petzite. The outermost rims of complexly zoned vein pyrite have high Cu and Sb concentrations (Cu=417-3771 ppm, n=39; Sb=135-3561 ppm, n=28) with elevated Au (≤939 ppm), but are generally As-poor (< 0.4 wt %).
Figure 2.8: BSE images and electron microprobe As element maps of wall rock pyrite grains in type 2 ore; samples XBB-004-02-3 and XBB-002-02-2, respectively. Note the sharp truncation of some As-rich bands.
Figure 2.9: BSE image and electron microprobe As element map of a vein-hosted pyrite grain in type 2 ore, sample XBB-003-02-2. Note that BSE-bright pyrite comprises the core of the grain. Bright spots along the interface between the BSE-bright pyrite core and the initially BSE-dark pyrite overgrowths are micron-scale inclusions of hessite, petzite, and altaite, with rare galena.
Gold telluride minerals in type 2 ore are largely restricted to quartz-fluorite veins (Figure 2.10), and they less commonly occur within altered phenocrysts immediately adjacent to veins in association with quartz, with or without fluorite. The gold telluride mineral association is composed of calaverite (with rare krennerite), with or without coloradoite and hypogene native gold, the latter of which is ubiquitously associated with coloradoite. Calaverite (and to a lesser extent, coloradoite) is locally partially rimmed by an admixture of petzite and hessite, generally at the interface between the telluride minerals and quartz-fluorite gangue. Hessite commonly forms the core of the admixture, though it may occur as crudely lamellar intergrowths with petzite. Coloradoite and hypogene native gold are consistently found as cavity-fill and as overgrowths on crystals of calaverite (Figure 2.10, QEMSCAN image). Calaverite is commonly rooted on (and overgrowing) crystals of quartz and fluorite, but does not occur as an inclusion within these crystals (i.e., calaverite occurs as overgrowths on gangue minerals). Within veins, trace amounts of iron-poor, silver-rich tetrahedrite may also occur with the gold telluride association. Gold-bearing As-rich pyrite is commonly included in calaverite and tetrahedrite, but calaverite and tetrahedrite do not occur as inclusions within pyrite. Further, tetrahedrite occurs as inclusions in calaverite, but no telluride minerals were observed as inclusions in tetrahedrite.

Native gold within type 2 ore commonly occurs in one of three forms: (1) as coherent, non-porous masses with uniform color that is ubiquitously associated with coloradoite, with or without calaverite (Figure 2.11a); (2) as spongiform, porous masses and micron-scale filaments of gold that are intergrown with tellurite (TeO₂) and iron oxide/hydroxide minerals (Figure 2.11b-d); and (3) as native gold micro-crystals within iron oxide/hydroxide pseudomorphs after pyrite. The first form is interpreted to be hypogene, while the second is interpreted to be gold pseudomorphs after gold telluride minerals.

Locally, little (Figure 2.11c) or no (Figure 2.11d) telluride minerals remain; in the latter case only a porous mass of native gold or electrum is present. Petzite may occur at the interface between calaverite and the native gold-tellurite intergrowth (Figure 2.11b). Emmonsite [Fe₂Te₃O₉·2(H₂O)] and associated tellurate minerals, as well as an iron telluro-sulfate mineral (possibly poughite) locally occur adjacent to native gold pseudomorphs. In addition, very fine-grained iron oxide/hydroxide minerals are commonly associated with native gold pseudomorphs, and likely contribute to the “rusty” color of some pseudomorphed grains, which are historically referred to as “mustard” or “rusty” gold based on their color in hand sample (Lindgren and Ransom, 1906).

The observed textures are interpreted to reflect a progressive oxidation of gold telluride minerals. Although calaverite was essentially the only gold telluride mineral observed in this study, experimental investigations (Xu et. al., 2013; Zhao et al., 2013) have demonstrated that the same textures may be
Figure 2.10: False-color QEMSCAN (QS) mineral map of a high grade gold telluride and auriferous pyrite-bearing quartz-fluorite vein in secondary K-Feldspar altered breccia. Inset reflected light (RL) and backscattered electron (BSE) images demonstrate the textural relationships between gold-bearing As-rich pyrite, calaverite (Clv), coloradoite (Col), and tetrahedrite (Ttr). Note the presence of Ag-Pb-(Au) telluride minerals within an annealed micro-fracture that cuts the central pyrite grain in the BSE image; Sample XBB-003-02-2.
Figure 2.11: Forms of native gold in type 2 ore: (A) Hypogene gold with coloradoite (Col) and calaverite (Clv), sample XBB-003-02-2; (B) Calaverite grain with partially oxidized rim of native gold and tellurite (TeO₂), core of grain contains petzite (Ptz) in association with native gold, sample XGC12-1-126R; (C) Calaverite grain with coloradoite showing moderate oxidation to native gold, sample XBB-003-01-4; (D) Pseudomorph of native gold after a gold telluride mineral in association with iron oxide (FeOx), sample XBB-003-04-1; (E) Micro-grains of native gold within iron oxide pseudomorphs after pyrite, sample XBB-003-01-5; (F) BSE image of micron-scale native gold within iron oxide pseudomorph after pyrite, sample CC12-1 67.5.
developed from the oxidation of krennerite (Au$_3$AgTe$_8$) and sylvanite (Au$_{0.75}$Ag$_{0.25}$Te$_2$), respectively. Zhao et al. (2013) reported that petzite commonly forms as an intermediary product during the conversion of sylvanite to Au-Ag alloy (electrum) during oxidative reactions. The localized presence of petzite within some of the pseudomorph textures (Figure 2.11b) suggests that at least some of the native gold and electrum pseudomorphs may have been derived from the oxidation of krennerite and/or sylvanite.

In the third association, native gold micro-crystals occur within iron oxide/hydroxide pseudomorphs after pyrite (Figure 2.11e). This is a common association in oxidized samples from ore zones that contain high abundances gold-bearing As-rich pyrite. Gold microcrystals commonly reside in concentric rings within the pyrite pseudomorphs (Figure 2.11f), with orientations that are similar to trace element zoning patterns within BSE-bright auriferous pyrite.

Tetrahedrite occurs in trace abundances in association with the gold telluride assemblage and as single grains that are intergrown with quartz within type 2 ore. Tetrahedrite is iron-poor, weakly enriched in arsenic, and enriched in silver (up to 7.7 wt. %). Hypogene native gold locally occurs as inclusions within tetrahedrite (Figure 2.12), and is generally associated with pyrite as an overgrowth (similar in texture to what is seen in type 1 ore). The native gold inclusions occur with or without sphalerite and localized hessite, and the sphalerite grains commonly contain exsolution lamellae of chalcopyrite. Locally, tetrahedrite grain boundaries are altered to covellite.

2.6.3 Type 3 ore – gold-bearing

Samples taken from target zone A are defined as being poor in As-rich pyrite, but rich in gold telluride minerals. Samples of type 3 ore were collected from Cripple Creek Breccia (locally grading to monolithic phonolite breccia) in the northern-most portion of the diatreme. Gold grades within samples of this ore type range from 0.17 to 36.03 g/ton (median=0.48 g/ton, n=15). Although whole rock geochemical data indicates that arsenic occurs in concentrations of up to 110 ppm (n=15), no As-bearing minerals were observed.

The host rock of type 3 ore is intensely potassically altered by secondary K-feldspar that is identical in texture to that observed in type 2 ore associations. The host rock contains sericite, with or without trace element-poor pyrite in altered phenocrysts (Figure 2.13). Gold occurs solely as gold telluride minerals and native gold pseudomorphs after gold tellurides. Calaverite is most common, and is confined to quartz veins and seams of quartz breccia that cut the host rock. Calaverite locally contains thin lamellae of relatively silver-rich gold telluride (Ag ~5 wt. %), indicative of krennerite (Cabri, 1965). Pyrite grains within quartz veins are coarse-grained (>1mm), generally have a cubic habit, and are trace element-poor
Figure 2.12: Reflected light (RL) images of native gold inclusions in tetrahedrite: (A) Native gold (Au), pyrite (Py), hessite (Hes), sphalerite (Sp), and chalcopyrite (Ccp) inclusions in a euhedral grain of tetrahedrite (Ttr), sample XBB-007-01-4; (B) Native gold and pyrite inclusions in subhedral tetrahedrite, sample XBB-005-02; (C) Native gold and pyrite inclusions in subhedral tetrahedrite that is locally altered to covellite (Cv), sample XBB-002-04; (D) Scattered inclusions of native gold in anhedral tetrahedrite, sample XBB-002-04.
Figure 2.13: Mineral associations in type 3 ore, sample XGC12-1 126L. Pyrite in this sample is trace element poor (BSE-dark). Calaverite (Clv) grains are highlighted in the QEMSCAN false-color mineral map.
(below detection by EMP). Trace abundances of chalcopyrite and bornite may occur as inclusions within vein pyrite, whereas covellite is locally intergrown with quartz in association with pyrite. Barite, with or without celestite, is a common accessory mineral in the quartz veins.

2.6.4 Type 4 ore – Mo-rich base metal sulfide (Mo-BMS)

Sub-sets of samples taken from target zone D are defined as containing very fine- to fine-grained pyrite that is either weakly enriched in arsenic or is arsenic-poor with minor but pervasive abundances of molybdenite, iron-poor silver-rich tetrahedrite, galena, sphalerite, acenthite, and complex silver sulfosalts that are hosted in quartz veins. Tetrahedrite grains are locally rimmed and embedded by complex silver sulfosalts minerals, suggesting that at least some of these may be derived from the breakdown of tetrahedrite. The ore minerals are intimately associated with barite and lesser fluorite, and are confined to quartz veins with characteristic selvages containing very fine-grained pyrite (Figure 2.14, dark line on edge of vein). Quartz veins containing type 4 ore cross-cut veins that contain gold telluride minerals and gold-bearing As-rich pyrite.

Type 4 ore samples have Au concentrations of 5.2-10.7 g/ton (n=4), As concentrations of 73-122 ppm (n=4), and Te concentrations of 24-38 ppm (n=4). However, most of the As, and most, if not all, of the Au and Te appears to be restricted to the type 2 ore veins that are cut by veins containing type 4 ore minerals.

Within veins that contain type 4 ore minerals, quartz grain boundaries are commonly etched, giving the veins a weakly porous texture, and ore minerals with associated barite are primarily confined to the etched grain boundaries between adjacent quartz crystals (Figure 2.15).

2.7 Geochemistry of Ore Types

Whole rock samples from each of the ore types were analyzed for major and trace elements. Each has a distinct geochemical signature, which can be correlated with mineralogy (Figure 2.16a-g). Type 1 ore (sample site C, sample prefix XCR2, Figure 2.16a) is moderately to strongly enriched in Au, Te, and As, and the transition metals are very weakly enriched, relative to unmineralized Breccia (n=8). This enrichment profile correlates with the presence of native gold and gold-bearing As-rich pyrite as the most abundant ore minerals, and Te enrichment is likely, in part, due to the presence of micro-crystals of hessite, altaite, and petzite. Although no gold telluride minerals were observed, the high degree of Te enrichment relative to the enrichment of Ag and Pb suggests that telluride minerals are more abundant within type 1 ore zones than were observed in thin section. However, the average Au:Te in the whole-rock data is ~1, and therefore, the presence of calaverite (AuTe2) can likely be ruled out.
Figure 2.14: Mineral associations in type 4 ore, sample XBB-005-01. Opaque inclusions that occur between quartz crystals consist of Mo-, Cu-, and Ag-rich base metal sulfides with barite and very fine-grained pyrite.
Figure 2.15: Images of Mo-, Cu-, and Ag-rich base metal sulfide minerals and pyrite, in association with barite and fluorite. These minerals occur within the interstitial spaces between adjacent quartz crystals; sample XBB-005-02. (A) False color QEMSCAN (QS) mineral map, molybdenite (Mo) is highlighted within the circles; (B) Reflected light (RL) image of inset area in the QEMSCAN mineral map; (C) Plane polarized light (PPL) image of the same area, showing the association between BMS and barite-fluorite; (D) Crossed polarized light (CPL) image of the same area, highlighting the location of the BMS-barite-fluorite intergrowths between adjacent quartz crystals.
Figure 2.16: Enrichment plots by ore type: Each plot contains the enrichment profile of individual samples by sampling location (colored lines), along with the average of the enrichment profiles (black lines). Enrichment factors were calculated by normalizing geochemical data from mineralized zones against geochemical data from unmineralized breccia. (G) plot of element concentration ranges by sampling location (shaded regions), in comparison to average element concentrations in unmineralized breccia.
Type 2 ore is generally characterized by moderate to very strong Au and Te enrichment, which correlates with the presence of calaverite (and possibly other gold telluride minerals), whereas moderate to strong As enrichment correlates with the presence of gold-bearing As-rich pyrite. Type 2 ore samples additionally show systematic enrichment in K$_2$O coupled with depletion in Na$_2$O, which correlates with K-feldspar replacement of albite.

Type 2 ore samples may be subdivided based on three contrasting enrichment profiles. The first is from the north portion of the Blue Bird dike (sample site D, sample prefix XBB, Figure 2.16b), where several samples are very strongly enriched in Au and Te relative to other sample sets, due to the presence of abundant calaverite and/or other gold telluride minerals.

Relative to type 2 ore samples from the Altman Pit (sample site B, sample prefix AC92-9, Figure 2.16c) and from the southern portions of the Blue Bird Dike (sample site E, sample prefix CC12-1, Figure 2.16d), samples from the northern portions of the Blue Bird Dike are strongly enriched in Mo and Ag, which may be the result of cross-cutting veins of type 4 ore (compare with XBB-002/005; Figure 2.16f). The weak enrichment of Mo and Ag in other groups of type 2 ore (Group 2 and 3; Figure 2.16c,d) most likely also reflects the presence of type 4 ore veins. Sb is enriched in all samples of type 2 ore. Samples that are also enriched in Cu (with or without Ag) are likely tetrahedrite-rich, explaining at least some of the Sb enrichment. However, Cu enrichment is erratic, which suggests that at least some of the Sb may be present in a mineral phase other than tetrahedrite. Trace element-rich, BSE-bright pyrite may also have some contribution to Sb enrichment, but the samples likely contain other Sb-bearing minerals that were not identified during this study. Weak enrichment in V and W within some samples cannot be attributed to any minerals observed in thin section.

Consistent with type 2 ore, type 3 ore (sample site A, sample prefix XGC12-1, Figure 2.16e) is moderately to strongly Au- and Te-enriched, which can be correlated with the presence of calaverite. Sb, Pb, Bi, Ag, Cu, W, Ba, and Sr are moderately enriched, correlating with silver-rich tetrahedrite, galena, barite, and celestite in these samples. The sources for W and Bi were not identified. Although no As-rich pyrite was observed in samples of this ore type, the samples are moderately enriched in As. This may suggest that thin section samples excluded As-rich pyrite-bearing zones that are present in the larger drill core intercepts from which samples for geochemical analysis were taken, or that As is present in minerals not identified in this study. Weak enrichment in V and W within some samples cannot be attributed to any minerals observed in thin section.

Type 4 ore (sample site D, sample prefix XBB-002/005, Figure 2.16f) is distinct from the other three ore types in being strongly Sb-, Mo-, Ag-, and Cu-enriched, correlating with high modal abundances of molybdenite, silver-rich tetrahedrite, and Ag sulfide and sulfosalt minerals. Pb, Ba, and Sr are moderately
enriched, due to associated galena and barite/celestite. Au, Te, and As enrichment in this ore type is interpreted to be an artifact of the spatial association between type 2 and 4 ores; quartz veins containing the type 4 mineral assemblage cut veins that contain the type 2 ore assemblage.

2.8 Hydrothermal Quartz in the Cripple Creek Deposit

Transmitted light microscopy and cathodoluminescence (CL) imaging were used to characterize the morphology and CL signature of hydrothermal quartz gangue associated with type 2, 3, and 4 ore, respectively (hydrothermal quartz does not occur in type 1 ore). Quartz occurs within and near mineralized veins and breccia structures, and in association with auriferous pyrite, native gold, gold-silver telluride minerals, and gold telluride minerals. Three distinct types of quartz (Q1, Q2, and Q3) have been defined based on differences in morphology and CL response.

2.8.1 Q1 – radial quartz

Q1 quartz is characterized by radiating, bladed sub-grains within individual quartz grains, which show anomalous extinction that generally occurs in opposing sectors (Figure 2.17a). When viewed down the c-axis, the radiating blades emanate from the core of the quartz crystals. Grain boundaries generally have a rough diamond shape with curved and bowed edges, but also occur as complex, irregular polygons. Rarely, crystals of Q1 quartz have hexagonal grain boundaries, but maintain an internal radial habit. Q1 quartz contains secondary fluid inclusions that lie parallel to radiating sub-grains, along the contact between adjacent blades. Q1 quartz may also contain unoriented cavities that cut across several quartz grains, giving the quartz a grossly pitted texture in plane polarized light.

Q1 quartz has a distinct CL signature when compared with other quartz types, consisting of medium lavender to light powder blue zones that contain abundant oscillatory growth bands (Figure 2.19a,b). The lighter blue-to-purple colors are short-lived, and fade to muted lavender with continued beam exposure. Radial sub-grains appear as sub-parallel linear bands that are orthogonal to oscillatory zoning, and alternate between light powder blue and lavender colors.

Locally, Q1 quartz grain boundaries have a distinct red color in CL and contain scattered, opaque mineral inclusions. These regions correlate with the sulfide-barite intergrowths that are characteristic of type 4 ore. In some samples, zones of vibrant blue short-lived quartz occur as isolated islands that are in sharp contact with lavender Q1 quartz. The blue zones show little to no banding, and are commonly composed of sub-domains of medium blue quartz surrounded by deep blue quartz. In rare cases, the characteristically lavender color of Q1 quartz grades outward to the vibrant blue color associated with these “islands” (Figure 2.19b; upper portion of CL image).
2.8.2 Q2 – anhedral and prismatic quartz

Q2 quartz is the most common type of quartz that was observed in the deposit, where it occurs within tabular veins, altered phenocrysts adjacent to veins, and as a hydrothermal matrix mineral within brecciated host rock. This type of quartz is characteristically composed of broad zones of interlocking anhedral grains that grade to zones of euhedral prismatic crystals along vein centerlines and other areas of open space.

Within open spaces, Q2 quartz has a comb texture, which is locally overgrown by chalcedonic quartz (Figure 2.17b). In several samples, euhedral Q2 quartz contains faint oscillatory zoning defined by layers of sub-micron fluid inclusions that lie parallel to crystal faces. Within breccia fill, clasts of rafted host rock are rimmed by prismatic crystals of Q2 quartz that commonly radiate from the clast surface (Figure 2.17c). Fine-grained anhedral interlocking quartz crystals occur as a matrix mineral between breccia clasts.

A notable feature of Q2 quartz is the localized presence of oriented bands of densely packed fluid inclusions, which occur as linear features of approximately equal length that lie perpendicular to crystallographic faces, bounded within individual growth bands (Figure 2.18a,b,c). Under crossed polarized light, domains of Q2 quartz crystals containing these features commonly display anomalous sub-domain extinction (Figure 2.18c). Bands containing the linear fluid inclusion textures frequently alternate with bands of inclusion-free quartz (Figure 2.18d). Compared with Q1 quartz, cavities and fluid inclusions tend to be much more densely packed, and are concentrated in narrower areas.

Quartz grains that contain densely packed fluid inclusions appear milky white in hand samples, whereas quartz grains that do not have abundant fluid inclusions are generally clear to light tan or smokey. Locally, prismatic Q2 quartz contains continuous bands of fluid inclusions that are oriented parallel to crystal faces (Figure 2.18e). These zones correlate with weakly opaque quartz crystals in hand sample.

Large, irregular cavities associated with secondary fluid inclusions are a very common component of Q2 quartz (Figure 2.18f). The cavities are not oriented, and are developed over broad zones of Q2 quartz, producing a grossly pitted or etched texture.

Q2 quartz has several distinct CL characteristics. Subhedral to anhedral crystals have a short-lived deep blue CL signature. With continued exposure to the electron beam, the deep blue color fades to muted, deep lavender. In contrast, prismatic crystals of Q2 quartz have a short-lived vibrant blue color, and commonly display oscillatory bands that are powder blue to light pink in color (Figure 2.20a). The
Figure 2.17: Plane polarized and crossed polarized transmitted light images of different quartz morphologies observed in the Cripple Creek deposit: (A) Quartz crystals with a radial habit that show anomalous subdomain extinction, sample XBB-005-02; (B) Euhedral, prismatic quartz crystals with chalcedonic quartz overgrowths, sample AC92-9 149.2; (C) Anhedral, interlocking quartz as matrix to breccia clasts that are surrounded by euhedral, prismatic quartz, sample XGC12-1-127R; (D) Two types of chalcedonic quartz, banded and hemispherical, on a substrate of prismatic quartz, sample AC92-9 149.6.
Figure 2.18: Transmitted light photomicrographs of quartz crystals that contain oriented fluid inclusions: (A) Overview image of a gold telluride-bearing quartz vein with quartz crystals that contain abundant, crystallographically oriented fluid inclusions, sample XBB-007-01-4; (B,C) Closeup view of oriented bands of fluid inclusions from the inset in image A. Note the anomalous subdomain extinction of the quartz crystals; (D) Alternating bands of oriented fluid inclusions and inclusion-free quartz from a high grade gold telluride vein, sample XBB-009-01-1; (E) Continuous bands of fluid inclusions that are parallel to crystallographic quartz faces, sample XGC12-1-127; (F) Irregularly shaped, densely packed cavities in prismatic quartz (position highlighted by the red arrows). These cavities appear as opaque inclusions due to their tendency to scatter transmitted light, sample AC92-9 149.6.
Figure 2.19: Plane polarized light (PPL), crossed polarized light (CPL), and cathodoluminescence (CL) images of (A,B) type Q1 radial quartz, sample XBB-005-01; (C,D) type Q3 chalcedonic quartz, samples AC92-9 149.6 and XBB-007-01-4, respectively.
Figure 2.20: Plane polarized light (PPL), crossed polarized light (CPL), and cathodoluminescence (CL) images of (A) type Q2 prismatic quartz with bands of fluid inclusions that lie parallel to crystallographic quartz faces, sample XGC12-1-126L; (B,C) Prismatic Q2 quartz crystals with densely packed, oriented fluid inclusions, sample XBB-007-01; (D) Prismatic Q2 Quartz crystals containing abundant, irregularly shaped cavities (best developed in the lower right of the image), sample AC92-9 149.2.
vibrant blue color fades to a muted navy blue color with maroon growth bands. In rare cases, prismatic Q2 quartz contains growth bands with a long-lived yellow CL signature. Sector zoning is locally developed, appearing as contrasting zones of medium and light blue colors.

Zones of Q2 quartz that contain oriented fluid inclusions have distinct yellow to light pink colors that are best developed at the interface with inclusion-poor quartz crystals. The sharp contacts grade outward to zones where the quartz is characterized by linear bands that are medium blue in color (Figure 2.20b,c).

Portions of prismatic Q2 quartz crystals that contain unoriented cavities and secondary fluid inclusions are characterized by a mottled CL signature composed of yellow, lavender, and blue colors that are similar to the color of Q1 quartz (Figure 2.20d). These “pitted” zones commonly cut across oscillatory and sector-zoned blue quartz crystals, suggesting that the unoriented cavities were developed after the initial formation of the quartz crystals. Pitted regions within anhedral to subhedral Q2 quartz crystals are generally very deep blue in color, with small points of yellow to green CL that correlate with the position of large cavities.

2.8.3 Q3 – chalcedonic quartz

Chalcedonic quartz (Q3) occurs as banded or colloform growths of amorphous quartz and fine quartz crystallites. Q3 quartz is generally found as partial cavity-fill within veins and breccia, forming a coating on a substrate of Q2 quartz crystals (Figure 2.17d). Q3 quartz occurs in two forms: Q3a and Q3b. Q3a quartz is composed of banded layers of amorphous quartz and crystallites with finely intercalated brown to orange iron oxide minerals. Q3a quartz has a distinctly fibrous appearance in crossed polarized light, defined by oriented crystallites that occur within successive bands. In contrast, Q3b quartz occurs as hemispherical overgrowths of amorphous quartz on Q3a quartz. In several samples, multiple hemispheres are combined within compacted growths, producing a mammillary habit. Bands of fluid inclusions commonly occur parallel to the outer boundary of the hemispheres. Intercalations of iron oxide minerals are rare. Under crossed polarized light, anomalous extinction within the hemispheres gives the appearance of densely packed, oriented needles. The overall texture is visibly coarser than the fibrous extinction of Q3a.

The CL signature of Q3 quartz is strongly dependent on its form. Banded growths of Q3a have a deep blue to purple color, whereas hemispherical growths of Q3b have a deep to medium yellow color (Figure 2.19c,d). Deep yellow Q3b is most common within the core of the hemispherical growths, while lighter shades of yellow are most common in the rims. The CL colors seen in Q3 quartz are long-lived, and persist with continued beam exposure.
2.9 A Revised Paragenetic Sequence for the Cripple Creek Deposit

A number of mineralogical models have been proposed for the Cripple Creek deposit (Table 2.2). However, there is disagreement regarding the paragenetic relationships between specific minerals within these models. For example, different studies have differing interpretations regarding the number of mineralizing stages, including how many stages of telluride and gold telluride mineralization occurred. In addition, there is uncertainty over the timing of hypogene gold mineralization with respect to the gold telluride minerals, and discrepancies regarding the relationship between gold and gold telluride mineralizing events and the formation of base metal sulfide and sulfosalt minerals. These discrepancies illustrate the need for a more comprehensive understanding of paragenetic relationships within the deposit.

The current deposit model (Kelley, 1996; Kelley et al., 1998; Jensen, 2003) includes two distinct types of gold mineralization: low-grade, bulk tonnage “disseminated” ore bodies, and high-grade gold telluride-bearing veins. Although the authors generally agree on which minerals are present within the high-grade veins, they do not provide a detailed paragenetic description for the relationships between the minerals within the veins.

In addition, previous publications do not agree on the mineralogy of the “disseminated” deposits. Kelley (1996) and Kelley et al. (1998) interpreted the low-grade deposits to consist of disseminated gold in the form of micron-scale native gold with pyrite, which exists in permeable rocks adjacent to major high-grade gold telluride-bearing structures, emphasizing that telluride minerals are essentially absent within the low-grade zones. In contrast, Jensen (2003) argued that the “disseminated” ores are composed of fine-scale mineralized fractures that are mineralogically similar to high-grade telluride-bearing veins, and their fine scale creates the appearance of a “disseminated” ore body.

There is also disagreement about the types and importance of different alteration styles associated with the two types of gold mineralization. Kelley (1996) and Kelley et al. (1998) reported that pervasive secondary K-feldspar alteration is best developed around the “disseminated” deposits, and is only weakly developed within the wall rock of high-grade gold telluride veins. Jensen (2003) argued that pervasive secondary K-feldspar alteration occurs in all rocks that host high-grade veins (regardless of the scale of the veins), and that K-feldspar alteration is one of the best indicators of nearby gold-bearing structures.

The current study outlines several ore types that are mineralogically distinct and contain minerals that were formed during distinct mineralizing stages. The study presents a revised paragenetic model for the deposit that is based on detailed mineralogical and textural investigation of these different ore types.
addition, this study defines high-grade ore zones that are not related to pervasive secondary K-feldspar alteration, which contrasts with data presented by Kelley (1996), Kelley et al. (1998) and Jensen (2003). The nature and paragenesis of gold-bearing As-rich pyrite has also been defined in much greater detail than in previous studies of the deposit. The recognition of multiple stages of pyrite growth (and dissolution) allow for much greater constraint to be placed on mineralizing stages than in previous studies of the deposit, with multiple stages of pyrite growth (and dissolution) being recorded in trace element zoning patterns.

Five stages of pyrite growth have been defined based on trace element signatures (Figure 2.21; Chapter 3). **Stage 1** pyrite is BSE-dark and trace element-poor, and generally contains inclusions of sulfide and silicate minerals, creating a grossly pitted appearance in BSE and reflected light images (Figure 2.3b,c,e). **Stage 2** pyrite is BSE-bright and trace-element rich, and is commonly oscillatory and/or gradationally zoned. **Stage 3** pyrite is also BSE-dark and trace-element poor (similar to Stage 1), but occurs as overgrowths on stage 2 pyrite and does not contain inclusions of silicate minerals. **Stage 4** pyrite is BSE-bright and trace element-rich, and forms overgrowths on stage 3 pyrite. **Stage 5** pyrite occurs as rare discontinuous outer rims that are strongly enriched in copper, antimony, and gold and only weakly enriched in arsenic. Pyrite stages 3-5 are restricted to gold telluride-bearing veins. For simplicity, pyrite stage 1 will hereafter be referred to as “Py1”, pyrite stage 2 will be referred to as “Py2”, and pyrite stages 3-5 will be grouped and referred to as “Py3”.

Based on detailed observations of ore minerals and their associated alteration minerals, as well as the textural relationships between different minerals, a paragenetic sequence has been derived that reflects a series of distinct and overprinting mineralizing stages (Table 2.3). Two of these stages are responsible for depositing most if not all of the gold in the deposit. Evidence for each of these stages is preserved as distinct mineral associations within the different ore types. In addition, the trace element chemistry of pyrite and textural relationships between different stages of pyrite growth (Figure 2.22) are used to further constrain the relationships between different mineralizing stages. This work therefore allows for revision of the preexisting mineralogical model of the deposit by outlining a new paragenetic sequence of mineralization, the stages of which are described in chronological order below.

### 2.9.1 Stage 1 - pre-gold event(s)

Magmatic breccias within the Cripple Creek diatreme, including those in unmineralized areas, are pervasively sericite altered. Sericite alteration is best developed as a replacement of magmatic calcium-rich plagioclase feldspar and feldspathoid minerals within breccia clasts, and as partial replacement of interstitial minerals between breccia clasts. Commonly, albite clasts are weakly sericitized, primarily...
along clast rims. Albite clasts are almost ubiquitously composed of trachytic microlites of albite, making it difficult to distinguish if the clasts are purely magmatic, or if they experienced some degree of albitization prior to sericite alteration. Albitization has been observed as an early alteration event elsewhere in the deposit (see Jensen, 2003; Rahfeld, 2013).

Sericite is commonly associated with hematite pseudomorphs after igneous magnetite in samples that were not subsequently overprinted by later mineralizing stages. This demonstrates that sericite alteration was widespread, and not strictly confined to zones that were later mineralized.

Table 2.3: Revised paragenetic sequence of the Cripple Creek deposit

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
<th>Stage 6</th>
<th>Stage 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>sericite</td>
<td>pyrite 2 (Py2)</td>
<td>petzite</td>
<td>tetrahedrite</td>
<td>purple fluorite</td>
<td>calaverite</td>
<td>quartz (Q1)</td>
</tr>
<tr>
<td>pyrite 1 (Py1)</td>
<td>hypogene gold</td>
<td>hessite</td>
<td>quartz 1 (Q1)</td>
<td>quartz 2 (Q2)</td>
<td>krennerite (rare)</td>
<td>molybdenite</td>
</tr>
<tr>
<td>altaite</td>
<td>petzite</td>
<td>altaite</td>
<td>pyrite 3 (Py3)</td>
<td>pyrite 3 (Py3)</td>
<td>coloradoite + hypogene gold</td>
<td>tetrahedrite</td>
</tr>
<tr>
<td>galena</td>
<td>petzite</td>
<td>galena</td>
<td>K-feldspar alt?</td>
<td>K-feldspar alt?</td>
<td>tetrahedrite</td>
<td>galena</td>
</tr>
</tbody>
</table>

BSE-dark Py1 occurs within sericite altered rock that remained unmineralized, and within rocks that were later mineralized with gold and gold telluride minerals. This pyrite is barren of either hypogene gold inclusions or trace concentrations of gold in solid-solution. The common association between Py1 and sericite suggests that Py1 formation may be related to the formation of sericite. However, inclusions of sericite within the cores of many Py1 grains (Figure 2.3c) appear to indicate that sericite alteration predated pyrite formation. Py1 occurs within zones that were later mineralized with gold, and occurs within a halo around these zones, grading outward toward hematite. The implication is that broad zones of Py1 developed prior to the onset of gold mineralization. Paragenetically, Py1 associated with pre-ore mineralization was the first stage of pyrite that was formed in the deposit.

Py1 in all samples that were analyzed commonly occur as pseudomorphs of hematite and possibly mafic silicate minerals (Figure 2.21a), indicating that most grains of Py1 formed through sulfidation of these minerals. This correlates with observations made by Jensen (2003), who suggested that pyrite formed as the result of sulfidation of mafic igneous minerals such as biotite and amphibole. The shift to
Figure 2.21: BSE images (A1, B1, C1) with colored overlays (A2, B2, C2) highlighting different stages of pyrite growth. Different stages are defined by having unique trace element signatures. (A1,A2) Fracture-hosted pyrite from type 1 ore with a BSE-dark core composed of a sulfidized mafic mineral, sample XCR2-13-1; (B1,B2) Fracture-hosted pyrite from type 1 ore with a partially resorbed BSE-dark core, sample XCR2-13-1; (C1,C2) Vein-hosted pyrite from type 2 ore with a partially resorbed BSE-bright core overgrown by additional stages of pyrite growth, sample XBB-003-02-02. Note that stages 3-5 are grouped together as “py3” in the text.
Figure 2.22: Schematic illustration of pyrite evolution, demonstrating how progressive textural and mineralogical development within pyrite grains may be used to track the paragenetic relationships between different mineralizing events.
pyrite growth at the expense of hematite and mafic minerals indicates an early change in fluid composition from one that was oxidizing (and possibly sulfur-poor) to one that was reducing and sulfur-rich. Furthermore, the observation that Py1 is ubiquitous in mineralized zones formed during subsequent stages suggests that many of the structures that would later become mineralized with gold were formed during this point in deposit genesis.

2.9.2 Stage 2 – introduction of gold

The onset of gold mineralization is characterized by gold-bearing trace element-rich Py2 overgrowths on Py1. In mineralized zones, within and immediately adjacent to fractures, Py1 occurs as irregularly shaped cores within Py2. The irregular Py1 cores are interpreted to reflect a stage of pyrite dissolution prior to regrowth of new trace element-rich Py2 (Figure 2.22). Composite Py1-2 grains (such as those in Figure 2.21a,b) are accompanied by paragenetically later micron-scale grains of hypogene native gold. This association is best preserved in type 1 ore that does not contain quartz or fluorite gangue. In addition, samples of type 1 ore have not been pervasively altered to K-feldspar, indicating that K-feldspar alteration postdated the formation of Py2 and hypogene native gold. The shift from Py1 dissolution to Py2 growth represents a change in fluid conditions from one that was aggressive toward pyrite to one that was pyrite-saturated. However, in contrast to the fluid associated with Py1 growth, the fluid(s) that deposited Py2 growth contained appreciable concentrations of arsenic, gold, and associated trace elements.

Hypogene gold associated with this stage of mineralization occurs as single grains and as overgrowths on grains of Py1 and composite Py1-2; it does not occur as visible inclusions within the pyrite grains themselves. In addition, hypogene native gold micro-crystals occur beyond zones containing Py2 and into zones that only contain Py1. The volume of Py2 overgrowths on Py1 cores decreases with distance from fractures. This suggests that within and proximal to fractures, the fluids were pyrite-saturated. Initially, gold carried by this fluid was incorporated into the structure of Py2 as a trace element, but as hydrothermal fluids penetrated the wall rock the fluid became progressively pyrite-undersaturated and gold that had been in solid-solution with pyrite thereby precipitated as native gold. The observation that Py1 also occurs in halos that surround fractures that have been mineralized with Py2 and hypogene native gold appears to indicate that the fluids which were active during stage 2 did not penetrate the wall rocks as deeply as those involved in stage 1, indicating decreasing wall rock permeability with time.

2.9.3 Stage 3– Ag-Pb-(Au) telluride and galena formation

In samples of type 1 ore, hessite, altaite, petzite, (hereafter referred to as the “Ag-Pb-(Au) telluride minerals”) and galena occur within micro-fractures that cut composite grains of Py1-2, and may occur
within the interstitial spaces between grains in pyrite clusters. In rare cases, hessite also occurs as overgrowths on Py2. These textures indicate that the Ag-Pb-(Au) telluride minerals postdate those formed during stage 2.

The Ag-Pb-(Au) telluride minerals also occur within pyrite that is associated with the gold telluride-bearing veins of type 2 ore. Most commonly, the Ag-Pb-(Au) telluride minerals occur within annealed micro-fractures in this environment, suggesting that while the Ag-Pb-(Au) telluride minerals formed post-Py2, they must pre-date the gold telluride stage of mineralization. Paragenetically, it is interpreted that the Ag-Pb-(Au) telluride minerals formed after Py2 in both type 1 and type 2 ore.

The development of Ag-Pb-(Au) telluride minerals appears to mark the onset of precipitation of tellurium in the mineralizing system. However, Ag-Pb-(Au) telluride minerals have a highly restricted distribution, and are limited to fracture sets and veins that contain minerals from the first stage of gold mineralization. This suggests that hydrothermal fluids that deposited Ag-Pb-(Au) telluride minerals exploited the same fracture sets as those that precipitated minerals during the first gold stage. This association is preserved in type 1 ore that has not been pervasively altered to K-feldspar, indicating that K-feldspar alteration postdated the formation of the Ag-Pb-(Au) telluride minerals and associated galena.

2.9.4 Stage 4 – tetrahedrite-quartz veins

Silver-rich tetrahedrite grains in association with Ag-Pb-(Au) telluride minerals occur within veins of Q1 hydrothermal quartz that generally lack gold telluride minerals. Therefore, the tetrahedrite-quartz veins appear to represent a distinct type of vein that pre-dates the gold telluride stage of mineralization. The tetrahedrite grains within these veins commonly contain inclusions of native gold with or without pyrite (Figure 2.12b,c,d) and locally contain inclusions of hessite and petzite. In rare cases, tetrahedrite grains contain composite inclusions of all previously formed minerals- pyrite (with associated base metal sulfides) overgrown by native gold, which was in turn overgrown by hessite (Figure 2.12a). These textural relationships indicate that tetrahedrite is paragenetically late with respect to the Ag-Pb-(Au) telluride minerals. In addition, the presence of euhedral crystals of tetrahedrite within hydrothermal quartz and the lack of quartz inclusions within tetrahedrite indicates that tetrahedrite most likely formed pre- or syn- quartz, during a distinct event that post-dates Ag-Pb-(Au) telluride formation. Paragenetically, it appears that quartz within these veins represent the first time that quartz was deposited during the mineralizing stages.

Geochemical analyses and petrographic observations reported by Lindgren and Ransome (1904; 1906) showed that tetrahedrite from several areas of the deposit is “auriferous and strongly argentiferous”,

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providing evidence that the occurrence of hypogene gold inclusions within tetrahedrite may be relatively widespread, demonstrating that the paragenetic relationships outlined above may be common in the deposit.

In contrast to type 1 ore, where tetrahedrite and quartz are absent and there is little to no K-feldspar alteration of wall rock, samples containing tetrahedrite-quartz veins have been extensively altered to K-feldspar, demonstrating a change in the alteration style. It is unclear whether the secondary K-feldspar alteration developed during tetrahedrite-quartz precipitation, or occurred during an unrelated and overprinting hydrothermal event. However, this may be the earliest point in time that K-feldspar alteration was developed.

2.9.5 Stage 5 – fluorite-quartz-pyrite 3

Veins that host gold telluride minerals also host quartz, with or without fluorite and Py3. Calaverite and associated telluride minerals occur as overgrowths on quartz, fluorite, and Py3, but not as inclusions within these minerals, indicating that these minerals formed as part of a distinct stage of mineralization that occurred prior to gold telluride mineralization.

Where present, euhedral fluorite occurs along vein margins, and commonly contains euhedral inclusions of Py1-2. In most samples, fluorite is fractured and rafted within Q2 quartz, but does not contain inclusions of quartz. Therefore, fluorite is interpreted to have formed after Py1-2 (deposited in stage 2), but prior to quartz within these veins. Type Q2 quartz is the most common form of quartz within these veins, where it occurs as anhedral to subhedral groupings that encapsulate and overgrow fluorite, locally grading to prismatic quartz crystals along open vein centerlines.

Pyrite grains in the wall rock of these veins occur as euhedral crystals of composite Py1-2. Within the veins, composite Py1-2 grains have been strongly resorbed and overgrown by oscillatory zoned Py3 (Figure 2.21, 2.22c), except where composite Py1-2 grains occur as inclusions in fluorite. The absence of these textures in pyrite-included fluorite indicates that Py1-2 dissolution and Py3 formation occurred syn- or post-quartz formation.

Trace element compositions and textures within pyrite provide important evidence for the timing of secondary K-feldspar alteration. Py1-2 grains within the veins show strong dissolution textures and have been overgrown by Py3 (except where pyrite is included in fluorite), but dissolution textures and Py3 overgrowths do not occur in the wall rock pyrite grains. This indicates that the wall rocks were impermeable to the fluid(s) responsible for Py1-2 dissolution and Py3 overgrowths. Some of the growth bands in Py3 contain As-enrichment that is similar to that in Py2, but Py3 preserves discontinuous As-
poor outer rims that are enriched in Cu, Sb, and Au with little As. This textural-compositional relationship clearly demonstrates a shift in fluid composition and/or physiochemical condition between the growth of Py2 and Py3, providing further evidence for the late timing of Py3 growth.

Rock that is altered by secondary K-feldspar is strongly impermeable, and this is the style of alteration that occurs in the wall rocks of these veins (Figure 2.6). Along with the observation that Py1-2 is only resorbed and overgrown by Py3 within the veins appears suggest that K-feldspar alteration developed after Py1-2 formation (and the Ag-Pb-(Au) telluride minerals with galena), but before Py1-2 dissolution and Py3 overgrowths. This contrasts with previous interpretations that secondary K-feldspar alteration either developed with microcrystalline native gold and pyrite (Kelley, 1996) or that it developed in association with the formation of the gold telluride minerals (Jensen, 2003). The presence of large bodies of K-feldspar altered rock that is not mineralized (Jensen, 2003) indicates that some areas were altered to K-feldspar by a fluid that did not coincidently form ore minerals. This is interpreted to mean that some fractures through which K-feldspar altering fluids had traveled closed prior to the formation of Py3 and the gold telluride minerals; only new fractures in K-feldspar altered rock and fractures that remained open (or reopened) after the K-feldspar alteration event were mineralized with Py3 and gold telluride minerals.

Micron-sized grains of hessite, altaite, petzite, and galena, which are preserved within micro-fractures that cut Py1-2 and within partially annealed micro-fractures within vein-hosted Py2, also occur at the irregular interface between Py2 and Py3. Where the Ag-Pb-(Au) telluride minerals occur in partially annealed micro-fractures in vein-hosted pyrite, it is interpreted that these inclusions were formed during the Ag-Pb-(Au) telluride stage (stage 3) and that the micro-fractures within the pyrite became annealed during exposure to later hydrothermal fluids. Where the Ag-Pb-(Au) telluride minerals occur near the irregular interface between resorbed Py2 and Py3 overgrowths, it is interpreted that the inclusions formed during stage 3 and were drawn toward the retreating Py2 grain boundary during stage 5 vein-hosted pyrite dissolution. Therefore, additional Ag-Pb-(Au) telluride minerals are not interpreted to have formed during this stage of deposit genesis.

2.9.6 Stage 6 – gold telluride formation

The most common gold telluride mineral within veins is calaverite, which is locally associated with coloradoite (HgTe) and hypogene native gold. These telluride minerals occur as overgrowths on Q2 quartz (with or without fluorite), Py3, and tetrahedrite. The veins cross-cut K-feldspar altered rock that may or may not contain minerals formed during previous mineralizing stages. In rare cases, petzite occurs in direct contact with calaverite, and in exceptionally rare cases, calaverite contains partial rims of a hessite-petzite admixture at interfaces between calaverite and substrate quartz. Calaverite may also very
rarely contain inclusions of lamellar intergrowths of hessite and petzite. The contact association between calaverite and hessite-petzite provides evidence that silver-bearing telluride minerals precipitated prior to the formation of the gold telluride minerals, although it likely was not widespread as evidenced by the rare occurrences of hessite-petzite. It is possible that low modal abundances of silver-bearing telluride minerals were deposited during the earliest portion of this stage of mineralization, such that the fluids were initially enriched in silver and evolved to gold rich compositions. Similar conclusions were reported by Dye and Smyth (2012) based on paragenetic analysis of telluride vein samples from the Dr. Jackpot Mine in the SW portion of the deposit.

Within gold telluride veins, euhedral Py3 grains occur as inclusions within calaverite, but calaverite does not occur as inclusions within pyrite (Figure 2.10), demonstrating that calaverite formation post-dated pyrite growth. Calaverite most commonly occurs as prismatic crystals that radiate toward open vein centers, but locally occurs as subhedral grains that have entirely filled open spaces. Locally, euhedral post-telluride quartz and fine-grained (BSE-dark) cubic pyrite may form partial overgrowths on calaverite, most commonly near the tip of prismatic calaverite crystals. This suggests that there was localized cyclical deposition between gold telluride minerals and associated gangue minerals. Coloradoite with hypogene native gold locally cross-cuts calaverite, and more commonly occurs as partial overgrowths on euhedral prismatic calaverite crystals, indicating that, where present, coloradoite and hypogene native gold post-date calaverite.

Tetrahedrite commonly occurs as inclusions within anhedral Q2 quartz, and in rare cases may be associated with earlier formed ore minerals (e.g. pyrite, hypogene gold, and hessite). These associations suggest that at least some tetrahedrite within gold telluride veins formed during an earlier stage of mineralization (e.g., after the Ag-Pb-(Au) telluride stage). However, tetrahedrite may occur along and near vein centerlines in close association with calaverite, indicating that some of the tetrahedrite may have formed early during the gold telluride stage. Calaverite does not occur as inclusions within tetrahedrite, suggesting that calaverite formation post-dates tetrahedrite. This textural relationship was also reported by Dye and Smyth (2012) in samples from the Dr. Jackpot Mine in the southwest portion of the deposit.

2.9.7 Stage 7 – Mo-rich base metal sulfide veins

Weakly As-enriched pyrite and the base metal sulfide minerals molybdenite, Ag-rich tetrahedrite, galena, sphalerite, acanthite, and complex silver sulfosalts were deposited during the last mineralizing stage. These minerals are almost ubiquitously associated with barite. The Mo-BMS minerals occur within veins of predominantly Q1 quartz that commonly contain fluorite. Mo-BMS minerals are generally confined to the interstitial spaces between Q1 quartz crystals, occurring primarily in zones where the
outermost edges of the quartz crystals have been altered and partially etched (Figure 2.15). The Mo-BMS veins cut gold telluride veins, as well as all other previously formed mineral associations, a relationship noted by Jensen (2003) throughout the deposit.

2.10 Mineral Formation Mechanisms

The following section describes possible mechanisms involved in the formation of key minerals within the deposit based on literature review, including (1) the formation of different stages of pyrite, (2) the formation of hypogene native gold, and (3) the formation of the telluride minerals.

2.10.1 Pyrite 1 formation

Common textural evidence indicates that Py1 initially developed through sulfidation of hematite (Figure 2.3b), which is widely preserved distal to mineralized zones. The early widespread formation of hematite is interpreted to have formed through oxidation of igneous magnetite (see Jensen, 2003) and indicates presence of an early oxidized fluid. However, the replacement of hematite by pyrite indicates a shift to a more reduced, sulfur-bearing fluid.

There are several metal-complex-mediated processes by which Py1 may have formed. It is widely recognized that H2S plays a crucial role in sulfide development in many epithermal systems (Rickard and Luther, 2006; Cooke and McPhail, 2001; Ohmoto, et al., 1994; Graham and Ohmoto, 1994; and others). For example, Graham and Ohmoto (1994) demonstrated that iron (bound within hematite or other iron-bearing minerals) may become sulfidized through interaction with polysulfide complexes derived from aqueous H2S via the following coupled reactions:

\[
\text{(1)} \quad n\text{H}_2\text{S}_{(aq)} \rightarrow \text{H}_2\text{S}_{n(aq)} + (n-1)\text{H}_2 \\
\text{(2)} \quad \text{Fe}^{2+} + \text{H}_2\text{S}_{n(aq)} \rightarrow \text{FeS}_2 + 2\text{H}^+ 
\]

In these reactions H2S_{n(aq)} represents aqueous polysulfide complexes. Pyrite formation in epithermal environments is interpreted to be most efficient at temperatures between 250-350°C, and may occur at acidic, neutral, or slightly alkaline conditions (Reed and Palandri, 2006; Cooke and McPhail, 2001; Ohmoto et al., 1994). However, direct pyritization of hematite can only occur at near-neutral to alkaline conditions, suggesting that Py1 most likely formed under conditions that are incompatible with attendant acid-mediated sericite formation. In addition, Py1 development appears to have been fractured-controlled, which contrasts with the more pervasive development of sericite alteration.
2.10.2 Trace element-rich pyrite 2 and pyrite 3 formation

Py2 is developed within and immediately adjacent to mineralized fractures as overgrowths on Py1, and is commonly associated with micro-grains of hypogene native gold. Similar to Py1, Py2 most likely formed through the interaction of iron with polysulfide complexes (Graham and Ohmoto, 1994). However, Py2 does not contain pseudomorph textures after iron-bearing minerals, which indicates that most of the iron in Py2 must have been sourced from hydrothermal fluids. The trace elements that are bound within Py2 are also inferred to have been sourced from hydrothermal fluids, demonstrating that the fluids responsible for Py2 formation were compositionally and/or physiochemically distinct from those which formed Py1.

Py2 compositions indicate that the source fluids were enriched in Fe, S, As, Au, Sb, and Cu. In epithermal systems, it is common for metals to form complexes with both chlorine and sulfur. However, numerical calculations by Reed and Palandri (2006) indicate that in the presence of magmatically-derived forms of aqueous H₂S, metals that exist as metal-chloride complexes should break down and re-complex as metal-bisulfide during simple cooling. Moreover, the formation of gold-bearing As-rich pyrite is commonly interpreted to be governed by metal-sulfur complexes (Simon, et al., 1999; Reich et al., 2005; and others). For these reasons, it is interpreted that gold-bearing As-rich pyrite at Cripple Creek formed dominantly from metal-sulfur complexes.

Several metal-sulfur complexes have been proposed in the formation of gold-bearing As-rich pyrite. Seward (1973) and Tauson et al. (1996) suggest that Au may be incorporated via the reaction of single Au-As-sulfide complexes such as Au(AsS₃)²⁻ and Au(AsS₂)⁰, respectively. Other authors, including Reich et al. (2005), suggest that Au incorporation in pyrite involves the coupled reaction of As-sulfide and Au-bisulfide complexes, as in the following equation:

\[
(3) \quad Fe^{2+} + 2HAsS₂(aq) + 2Au(HS)_0(aq) + 2H₂(g) = Fe(S₂As)₂·Au₂S₀ + 3H₂S(aq) + 2H^+ \quad (Reich et al., 2005)
\]

Pyrite 3 is interpreted to have formed through the same mechanisms as Py2. However, the distinct trace element compositions preserved within Py3 demonstrate that hydrothermal fluid compositions and/or physiochemical conditions shifted with time.

Pyrite in the Cripple Creek deposit has been shown to be of dominantly magmatic origin based on isotopic studies of sulfur (see Jensen, 2003), and sulfur-complexes may therefore be expected to play a dominant role in pyrite formation. However, to date there have been no sulfur isotope analyses of pyrite from different paragenetic stages, or from different stages of pyrite growth. Therefore, it is unknown if
Py2 and Py3 formed from a dominantly magmatic source, a dominantly meteoric source, or perhaps a combination of the two.

Solid-solution gold in As-rich pyrite has been reported as a major ore component in several large gold telluride deposits, including the Emperor (Fiji: Pals et al., 2003), Porgera (Papua New Guinea: Richards and Kerrich, 1993; Fleming et al., 1986), and Yangzhaiyu deposits (China: Shi-Jian Bi, et al., 2011). The identification of gold-bearing As-rich pyrite from the Cripple Creek deposit suggests it might be a more common component of telluride deposits than previously reported.

2.10.3 Hypogene Native Gold Formation

Within and near mineralized fractures formed during the second mineralizing stage, native gold occurs in direct association with composite Py1-2 grains. The fluids involved in As-rich Py2 formation are interpreted to have been enriched in Au-bisulfide and other metal-sulfur complexes. Within these fluids Au exists as Au$^{1+}$, allowing for the Au to be incorporated into pyrite. Native gold may be formed through de-sulfidation of Au-bisulfide-rich fluids. Through de-sulfidation, the Au-bisulfide complex is destabilized, reducing Au$^{1+}$ to Au$^{0}$, allowing for native gold precipitation. It is therefore interpreted that gold-bearing As-rich Py2 and the native gold associated with it formed from the same hydrothermal fluid, and that de-sulfidation of the fluid allowed for a transition from Au$^{1+}$ incorporation into Py2, to native gold (Au$^{0}$) precipitation.

Rae et al. (2011), Reed and Palandri (2006), and Cooke and McPhail (2001) suggest that fluid de-sulfidation is commonly mediated by phase separation (or “boiling”) of a fluid, as metal-sulfide complexes become destabilized through the loss of H$_2$S gas. This is a plausible process for native gold precipitation at Cripple Creek, as Dwelley (1984) and Thompson et al, (1985) reported that quartz fluid inclusions associated with the early stages of ore mineral formation showed evidence of “weak boiling”. Furthermore, Jensen (2003) reported that in deeper levels of the deposit (>1000m) gold rarely occurs in economic concentrations. This may indicate that a depth of ~1000m was the lowermost base of a boiling horizon during native gold precipitation. Together, these observations suggest that thermal gradients played a significant role in localizing and concentrating native gold within the upper levels of the deposit.

2.10.4 Ag-Pb-(Au) Telluride and Gold Telluride Formation

The Ag-Pb-(Au) telluride minerals (hessite, altaite, and petzite) that occur in association with grains of Py1-2 and tetrahedrite-quartz veins were deposited during stage 3 (as defined above). The phase relationships between hessite and petzite are well constrained, based on experimental work by Cabri (1965) in the Au-Ag-Te system. However, experimental studies between hessite/petzite and altaite are
lacking. Interpretations of the relationship between these minerals are therefore limited, but textural evidence suggests that all of these minerals formed during the same stage. Limited studies on the thermodynamic relationships between several of the telluride minerals, including hessite with petzite, and altaite with galena, allows for some degree of additional interpretation. Thermodynamic relationships have also been defined for the gold telluride minerals.

2.10.4.1 Phase relationships between hessite and petzite

Hessite and petzite are stable with respect to one another over a broad temperature range (Cabri, 1965). Within the temperature range common for epithermal deposits, hessite and petzite each occur as one of two polymorphs: “intermediate” polymorphs are stable at temperatures of 145-802°C (hessite) and 210-319°C (petzite), and “low” polymorphs are stable at temperatures of 25-145°C and 25-210°C (hessite and petzite, respectively). The crystallographic change from the “intermediate” polymorphs to the “low” polymorphs is facilitated by cooling below specific inversion temperatures. Cabri (1965) also reports that a metastable Ag-Au-Te phase (called the “χ” phase) is stable between ~400°C and ~75°C, and that this metastable phase is capable of breaking down into an admixture of hessite and petzite.

This experimental work demonstrates that the mineral combination hessite-petzite may form at temperatures in excess of 300°C. This is close to the upper limit of the temperatures typical of epithermal systems, and is compatible with the temperatures at which sulfide minerals such as pyrite are expected to form. Fluid inclusion studies in “telluride” stage quartz from the deposit (Jensen, 2003; Saunders, 1986; Thompson et al., 1985; Dwelley, 1984) suggested that the telluride minerals formed at temperatures of ~105-225°C (most commonly at <175°C). No direct fluid data are available for the Ag-Pb-(Au) telluride stage, so the temperature of Ag-Pb-(Au) telluride formation is unknown. However, it is at least possible that these minerals formed at much higher temperatures than have been previously inferred.

2.10.4.2 Thermodynamic relationships between hessite, petzite, altaite, and galena

Although the temperatures of fluids that deposited Ag-Pb-(Au) telluride minerals are unknown, published thermodynamic models provide insight into possible fluid compositions. Based on studies of the Emperor deposit in Fiji, Ahmad et al. (1987) presented a phase relationship model for the telluride minerals that is based on the activity of Te$_2$ and S$_2$. In this model, the stability fields for hessite-petzite and altaite-galena overlap (shaded regions, Figure 2.23), indicating that co-precipitation of these minerals might be possible. In addition, the hydrothermal fluids that deposited the Ag-Pb-(Au) tellurides at Cripple Creek may have contained relatively high concentrations of Te, approaching Te saturation at which point native Te would be deposited. The thermodynamic relationships demonstrate that coupled fluctuations in
Te and S concentrations can dictate whether Pb is deposited as a telluride or sulfide mineral (arrows, Figure 2.23), indicating that fluctuations may have driven formation of galena that is associated with altaite. Together, these data are interpreted to imply that that Ag-Pb-(Au) telluride minerals and galena were formed from a compositionally and/or physiochemically distinct fluid.

Additional thermodynamic modeling by Zhang and Spry (1994) involved recalculation of the stabilities for aqueous tellurium species, and the specific forms of Ag-complexes involved in hessite deposition (see Zhang and Spry, 1994, for a full description). Their modeling suggested that at temperatures of <300°C, the Ag component of hessite is derived from aqueous Ag(HS)_2^+, indicating a strong bisulfide component in the fluid. At moderately reducing conditions, the Te component is derived from aqueous H_2Te when the fluids are strongly acidic, and from aqueous HTe^- when the fluids are weakly acidic to moderately alkaline. The calculations also showed that aqueous Te_2^2- may be involved in Te transport at weakly oxidizing conditions, but that hessite will not form at moderately to strongly oxidizing conditions. This suggests that the fluids which deposited hessite at Cripple Creek were relatively reduced.

2.10.4.3 Thermodynamic relationships between calaverite and coloradoite-native gold

Thermodynamic modeling of aqueous Te species by Zhang and Spry (1994) indicated that favored gold complexes involved in calaverite formation are HAu(HS)_2^0 and AuHS_2^- (the latter also reported by Cooke and McPhail, 2001). Zhang and Spry (1994) additionally suggested that thermodynamically favored Te sources are aqueous H_2TeO_3 in slightly to strongly acidic conditions and Te_2^2- at near neutral to alkaline conditions. It has also been reported that calaverite and associated gold telluride minerals may form from aqueous Au-tellurium complexes such as AuTe_2^- (Saunders, 1986). However, the thermodynamic modeling performed Cooke and McPhail (2001) suggested that unless aqueous Au-tellurium complexes exist at concentrations that are several orders of magnitude higher than Au-bisulfide, they are not likely to be involved in calaverite (or associated gold telluride) formation. Thus, Au-bisulfide appears to be the most realistic Au transporter involved in gold telluride formation.

To the best of the author’s knowledge, there has been no experimental work involving the synthesis of coloradoite, and therefore phase diagrams that might explain the association between calaverite with late coloradoite-native gold are lacking. However, Ahmad et al. (1987) used a series of thermodynamic calculations to demonstrate the relationship between calaverite and coloradoite-native gold with respect to the activities of Te_2 and S_2 (Figure 2.24). These calculations indicated that calaverite forms from fluids with very high Te concentrations (approaching concentrations high enough to form native Te), and is not necessarily dependent on S concentrations. According to Ahmad et al. (1987), the change from calaverite
Figure 2.23: Log vs. Log diagram of overlying telluride mineral stability fields demonstrating relative phase stabilities in the S-Te system, calculated at 250°C. (modified after Ahmad et al., 1987). The relationships between the silver telluride minerals are shown using black lines. The relationship between silver-gold and gold telluride minerals are shown using a red line, and the relationship between lead telluride and lead sulfide are shown using a blue line. The pyrrhotite-pyrite boundary is shown with a gray line.
Figure 2.24: Log vs. Log diagram of overlying telluride mineral stability fields demonstrating relative phase stabilities in the S-Te system, calculated at 250°C. *(modified after Ahmad et al., 1987).* The relationship between calaverite and native gold is shown using a black line. The relationship between coloradoite and cinnabar is shown using a blue line. The pyrrhotite-pyrite boundary is shown with a gray line. Note that coloradoite and native gold are stable within an overlapping region.
to coloradoite-native gold that is described in the revised paragenetic sequence requires a drop in the concentration of Te within the fluid, and may or may not require a change in S concentration. This indicates that the fluids responsible for the deposition of the gold telluride minerals initially had high Te concentrations that dropped with time. The inferred influx of a fluid with high a Te concentration indicates that the fluid(s) responsible for gold telluride formation were compositionally (or possibly physiochemically) distinct from the fluids responsible for forming Py3.

Loughlin and Koschmann (1935) reported cinnabar (HgS) as a post-telluride mineral in the vicinity of the Dante Collapse Breccia (near the Blue Bird Dike), which may indicate that coloradoite deposition was followed by localized cinnabar deposition, and this would have required a drop in the S concentration of the hydrothermal fluid(s) as well (Figure 2.24, arrow).

### 2.10.4.4 Telluride mineral precipitation mechanisms

Thermodynamic modeling by Cooke and McPhail (2001) simulated ore producing fluid compositions and formational mechanisms for telluride and base metal sulfide minerals at the Acupan gold mine in the Philippines. Their modeling suggested that magmatic Te is only weakly soluble in magmatic aqueous fluids, such that Te is strongly partitioned into the vapor phase and is transported to the upper levels of the system as Te$_2$ and H$_2$Te gas. Following transport, telluride mineral formation results from condensation of gaseous Te species into metal-bearing meteoric waters in the near-surface environment. Upon condensation, aqueous Te species similar to those proposed by Zhang and Spry (1994) are formed, and are proposed to interact with metal-bisulfide complexes in the meteoric water to precipitate telluride minerals. Several other authors, including Hedenquist et al. (1994) have also suggested that magmatic vapor condensation in meteoric waters is an important process in forming ore fluids from a degassing magma, suggesting that this type of process may be relatively common.

It is important to note that other telluride precipitation mechanisms have been proposed by previous authors. These include simple oxidation of tellurium- and metal-bearing fluids, and oxidation due to boiling (Saunders, 1986), fluid dilution and cooling (Richards and Kerrich, 1993), and fluid mixing of magmatic and meteoric waters (Dwelley, 1984; Afifi et al., 1988; Zhang and Spry, 1994). Fluid mixing appears to be the most commonly reported precipitation mechanism (Kelley, 1996), and is compatible with Cooke and McPhail’s (2001) proposed mechanism of Te gas condensation into meteoric water. Jensen (2003) preferred this mechanism in the formation of telluride minerals at Cripple Creek, and also emphasized that telluride minerals disappear almost entirely at depths of >1000m. This observation provides further evidence that meteoric waters in the uppermost levels of the system may have played an important role in localizing telluride formation.
2.11 Implications of Textures in Quartz

Lindgren and Ransome (1906, p. 181) were the first to report quartz with a radial habit in the Cripple Creek deposit, and they interpreted it to have formed through replacement of celestite. However, cathodoluminescence imaging performed during this study shows that many of the radial quartz grains preserve hexagonal oscillatory growth zones that cross sub-grain boundaries (Figure 2.19a,b), indicating that the radial texture is a growth feature of the quartz, and is not developed through replacement. Individual blades of Q1 quartz in the Cripple Creek deposit have uniform extinction in crossed polarized light (Figure 2.17a), indicating that each blade is an individual and optically homogeneous crystal. However, CL imaging of Q1 quartz shows that individual blades retain the original structure of several much thinner and more fibrous crystallites (Figure 2.19a, CL image). This provides evidence that the bladed texture may have formed through recrystallization of finer, preexisting quartz crystallites.

Although the radial quartz habit has not been widely reported in the Cripple Creek deposit, vein quartz with this same texture has been described in several other epithermal deposits, including the Camp Bird Mine, Colorado (Ransome, 1901, p. 71-72), the Rawhide mine in Nevada, the Weehawken mine in New Jersey (Rogers, 1911, p. 795, 797), and the National district, Nevada (Vikre, 1985, p. 388). Additionally, Adams (1920, p. 628-630; plates XXII and XXIII) reported the texture in samples from White Rock (Australia), Kingman (Arizona), the Aspen Mine in Silverton (Colorado), and the Caledonian and Talisman mines (New Zealand).

In a detailed petrographic study of radial quartz in silver-bearing amethyst veins from Creede, Colorado, and in quartz-adularia-gold veins from the Round Mountain Mine, Nevada, Sander and Black (1988) concluded that similar radial textures are formed through recrystallization of chalcedony. This appears to be the recrystallization mechanism responsible for Q1 quartz formation at Cripple Creek, which possibly formed through recrystallization of hemispherical Q3b chalcedony.

Several of the gold telluride veins analyzed in the current study contain optically continuous crystals of Q2 quartz, which is characterized by interlocking anhedral grains that grade to prismatic crystals towards open space (Figure 2.17b). In some veins, anomalous crystallographically oriented fluid inclusions occur within distinct growth bands (Figure 2.18a-d). Sander and Black (1988) reported that this type of fluid inclusion banding has been observed in several epithermal deposits, and they interpreted that the inclusions also form through the recrystallization of chalcedony. However, in contrast to the recrystallization textures of Q1 radial quartz wherein quartz crystallites appear to emanate from single nuclei, the textures displayed by type Q2 quartz appear to indicate recrystallization of “banded” Q3a chalcedony on substrate crystalline quartz (c.f. Figure 2.17d). When viewed in CL, zones containing
oriented fluid inclusions preserve the structure of fibrous crystallites (Figure 2.20b,c). Cyclical deposition between crystalline quartz and banded chalcedony is thought to produce the locally layered texture of some growth bands (e.g. Figure 2.18d).

The interpretation that chalcedony has been locally recrystallized within the deposit contradicts several previously published paragenetic sequences, which proposed that chalcedony was only formed as a late-stage post-telluride mineral (Table 2.1). Instead, the observations and interpretations reported here indicate that the history of quartz formation in the Cripple Creek deposit may have been significantly more complex than previously reported, most importantly that what may previously have been interpreted as single crystals are in fact composites that represent several generations of quartz growth.

2.12 Relationship of telluride minerals and vein quartz

The opaque nature of native gold and gold-bearing minerals such as the gold tellurides and auriferous pyrite preclude fluid inclusion studies of these minerals. Furthermore, fluid inclusion work on associated gangue minerals must rely on assumptions about the paragenetic relationship between the ore and gangue minerals.

In the Cripple Creek deposit, vein quartz is most commonly used to infer fluid conditions at the time of gold telluride formation. However, there are contrasting views regarding the paragenetic relationship between calaverite (and associated telluride minerals) and quartz within gold telluride-bearing veins. As emphasized throughout this paper, textural evidence developed in the current study indicates that calaverite (as well as associated hessite-petzite and coloradoite-native gold) formed at a paragenetically later time than quartz, fluorite, and pyrite substrate minerals. Stereological effects may at times create the appearance of telluride mineral inclusions in quartz, but detailed petrographic study and CL imaging has revealed that these apparent inclusions are actually the roots of larger telluride crystals that are embedded between adjacent gangue minerals. Therefore, there is no evidence to suggest that calaverite and quartz formed simultaneously.

This is not a unique point of view, as several previous researchers in the deposit have also reported that the telluride minerals occur as late-stage growths on substrates of quartz and associated gangue minerals, citing the common occurrence of telluride minerals as projections into open vug space (Jensen, 2003; Lindgren and Ransom, 1906). Interpretations have also been made that infer telluride minerals which are locally “embedded” in quartz, fluorite, or dolomite crystallized simultaneously with these gangue minerals (Lindgren and Ransom, 1906). However, textural evidence from this study shows that cyclical deposition between telluride minerals and gangue is a more likely cause for this type of texture.
Despite the relatively common observation that calaverite may have not formed simultaneously with quartz (or its associated gangue minerals), previous research in the deposit has presented fluid inclusion data derived from quartz as evidence of the fluid conditions during telluride formation (Dwelley, 1984; Thompson et al., 1985; Saunders, 1986 and others). Based on the observations in this study, these data are interpreted to characterize the fluid compositions and temperatures during quartz precipitation only. While it is possible that telluride and substrate quartz formation occurred under similar fluid conditions, further research is needed before accurate conclusions can be drawn.

2.13 Conclusions

This study has defined seven distinct mineralizing stages in the Cripple Creek deposit. From oldest to youngest, these are:

1) Early Py1 and base metal sulfide with no gold,
2) Gold-bearing As-rich Py2 followed by microcrystalline hypogene native gold,
3) Ag-Pb-(Au) telluride and galena deposition,
4) Formation of cross-cutting tetrahedrite-quartz veins,
5) Formation of hydrothermal quartz (± fluorite) and oscillatory zoned Py3 within veins that would later host gold telluride minerals,
6) Gold telluride formation,
7) Molybdenite-rich base metal sulfide formation.

Within mineralized zones, progressive mineralizing stages either cut or overprint the minerals formed during previous stages, and it is common for minerals from more than one stage to be present. However, it is rare for minerals from all stages to be present. In addition, there may be localized cyclical deposition between gold telluride minerals and associated gangue minerals. For these reasons, individual samples may appear to preserve contradicting paragenetic relationships, and this may be the cause for discrepancies among previously published paragenetic sequences of the deposit.

There are two dominant alteration styles associated with mineralized zones: (1) sericite alteration, and (2) pervasive K-feldspar alteration. Sericite alteration appears to have developed prior to the formation of Py1 as evidenced by inclusions of sericite and other wall rock silicate minerals within the cores of Py1. Textural relationships between different stages of pyrite growth, and the relative timing relationships between different ore minerals, demonstrate that pervasive K-feldspar alteration developed after stage 3 mineralization, but before stage 6 mineralization. Specific mineralogical, textural, and relative timing
relationships indicate that K-feldspar alteration developed during stage 4, between stages 4 and 5, or in the earliest part of stage 5.

Textural, mineralogical, and relative timing relationships between different minerals in gold telluride-bearing veins additionally indicate that the gold telluride minerals did not form coincidently with quartz, fluorite, or pyrite within these veins. This indicates that while fluid inclusion studies in vein quartz and fluorite are helpful in understanding fluid conditions at the time of gangue mineral formation, they may not serve as a good proxy for fluid conditions at the time of gold telluride formation. Variable textures within quartz that is associated with ore minerals also suggests that several generations of quartz growth may be present within single veins, and that multiple quartz recrystallization events may have occurred. This demonstrates that the history of quartz deposition may have been significantly more complex than previously recognized.

The newly defined paragenesis of the deposit has important implications, because it has demonstrated the following:

- Multiple mineralogically distinct mineralizing stages were involved in the mineralizing history of the deposit, each representing the influx of hydrothermal fluids with distinct compositions and/or physiochemical profiles.

- Pyrite and microcrystalline hypogene native gold, which were originally described as “disseminated ores” that mantled high-grade gold telluride-bearing structures as lateral and/or vertical expressions of gold telluride mineralization, are not paragenetically related to the introduction of the gold telluride minerals.

- Trace element enrichment profiles in pyrite can be used to track the mineralogical evolution of the deposit.

- K-feldspar alteration developed between the two major gold mineralizing stages (2 and 5) in the deposit, and is not directly associated with the gold and gold telluride mineralizing stages as previously described.

- The mineralizing history of quartz within the deposit is significantly more complex than previously reported, and that fluid inclusion studies in telluride vein quartz (and fluorite) may be poor proxies for inferring fluid conditions at the time of gold telluride mineralization.
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CHAPTER 3
EXAMINATION OF GOLD-BEARING As-RICH PYRITE IN THE CRIPPLE CREEK GOLD TELLURIDE DEPOSIT, TELLER COUNTY, COLORADO

Detailed mineralogical characterization of gold-bearing As-rich pyrite from the Cripple Creek gold telluride deposit in Colorado has revealed that trace element-rich pyrite is common in the deposit, and may represent a significant and previously unrecognized gold resource. Electron microprobe data has demonstrated that the majority of gold associated with pyrite is most likely in solid solution and does not occur as micro- or nano-inclusions. Modeling based on electron microprobe data indicates that trace element-rich pyrite may contribute as much as 4.7 g/ton gold in some mineralized areas of the deposit. Mineralogical characterization has also revealed that at least five stages of pyrite growth are present, and that the trace element profiles of these pyrite stages can be used to track the mineralogical evolution of the deposit through time.

3.1 Introduction

The trace element geochemistry of pyrite reflects in part the conditions that accompany pyrite growth, and the geochemical and physical properties of pyrite have been used in a number of studies both as an indicator of formational processes and of the passage of mineralizing fluids (e.g., Large et al., 2009; Agangi et al., 2013; Deditius, et al., 2014). Large et al. (2009) utilized trace elements (As, Ni, Co, Pb, Zn, Ag, Mo, Te, V, and Se) to distinguish between diagenetic pyrite and pyrite formed during metamorphism and/or hydrothermal fluid flow in orogenic deposits. Trace element signatures (e.g., As, Ni, Co, Pb, Sb, Tl, Mn, Mo, Cu, and Ag) and zoning patterns in pyrite from the Witwatersrand Basin, South Africa, have been used to discriminate between detrital pyrite and post-sedimentary pyrite formed during authigenic and later metamorphic processes (Agangi et al., 2013).

Gold is a common trace element within pyrite from numerous types of ore deposits including epithermal, orogenic, porphyry copper, volcanic-hosted massive sulfide, and sediment-hosted ore deposits (Deditius et al., 2014, and references therein). Gold in pyrite is commonly strongly associated with arsenic enrichment (Simon et al., 1999; Reich et al., 2005; Deditius et al., 2014). Many authors have adopted the term “invisible gold” to describe cases wherein the gold component of pyrite is not readily visible by reflected light microscopy or in high magnification images collected by scanning electron microscopy (SEM).
Although transmission electron microscopy has directly imaged nano-scale inclusions of gold within As-rich pyrite from the Carlin Trend in Nevada (Bakken et al., 1989; Palenik et al., 2004), gold has also been shown to occur as a direct substitution into the crystal structure of pyrite (i.e., gold in solid solution with pyrite; Reich et al., 2005; Deditius et al., 2014; Barker, et al., 2009). Reich et al. (2005) defined the upper solubility limit of gold in As-rich pyrite from the Carlin Trend. This gold-solubility curve allows quantitative element concentration data from electron microprobe (EMP), secondary ion mass spectrometry (SIMS), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to be used to determine whether gold is in solid solution with As-rich pyrite or occurs as nano-scale inclusions.

Gold-bearing As-rich pyrite is common within mineralized zones in the Cripple Creek gold telluride deposit (Jensen, 2003; Chapter 2), but has received little attention. With the development of a revised deposit paragenesis that has enabled a more detailed understanding of relationships between ore, gangue, and alteration mineralogy (Chapter 2), the role of pyrite as a recorder of mineralizing stages and its contribution to overall gold resource can now be evaluated more robustly. The current study presents detailed mineralogical characterization of gold-bearing As-rich pyrite and demonstrates that the trace element geochemistry of pyrite can be used to track the mineralogical evolution of the deposit. In addition the study suggests that gold in pyrite represents a significant resource at Cripple Creek.

3.2 Geologic Setting

The Cripple Creek gold telluride deposit in central Colorado is centered on an Oligocene alkaline volcanic diatreme intruded into Precambrian crust. Alkaline magmatism in this area is interpreted to be related to the formation of the Rio Grande Rift during a shift in tectonic regime from Laramide compression to the earliest stages of extension related to rifting along the Rio Grande Rift axis (Kelley, 1996; Jensen, 2003). Oligocene volcanism in the Cripple Creek deposit began at ~33 Ma (Kelley, 1996; Kelley et al., 1998), with the emplacement of large volumes of heterolithic Cripple Creek Breccia within a volcanic diatreme. Diatremal breccia formation was followed by the intrusion of hundreds of individual alkaline igneous bodies that range in composition from phonolite to lamprophyre (Lindgren and Ransom, 1906; Loughlin and Koschmann, 1935) between ~32.5 ± 0.1 Ma and 28.2 Ma (Kelley, 1996; Kelley et al., 1998). Early intrusions were relatively felsic and evolved to progressively more mafic compositions with time, possibly resulting from the evolution of a deeply emplaced parental nepheline syenite body (Jensen, 2003).

The earliest alkaline igneous intrusions consisted of large irregular bodies that intruded into unconsolidated diatremal breccia, while later intrusion of tabular dikes and sills probably reflect a change
in the degree of lithification of the diatremal breccia (Jensen, 2003). The final stages of volcanism in the deposit involved the emplacement of lamprophyre dikes and sills that were locally cut by lamprophyre breccia pipes. Crosscutting relationships indicate that essentially all gold mineralization in the deposit occurred after the emplacement of lamprophyre (Jensen, 2003).

Two mineralization styles have been previously recognized in the deposit: microcrystalline native gold with pyrite that is also referred to as “disseminated gold” (Pontius, 1992; Kelley 1996; Kelley et al., 1998) and high-grade gold telluride-bearing veins (Cross and Penrose, 1895; Lindgren and Ransome, 1906; Loughlin and Koschmann, 1935; Koschmann, 1949; Kelley 1996; Kelley et al., 1998; Jensen, 2003). Kelley (1996) reported that microcrystalline hypogene gold has a strong spatial association with secondary K-feldspar alteration, and that K-feldspar alteration is only weakly developed in alteration halos surrounding high-grade gold telluride veins. In contrast, Jensen (2003) reported that high-grade gold-telluride-bearing veins and fractures are ubiquitously associated with pervasive secondary K-feldspar alteration. The revised paragenesis of the deposit (Chapter 2) indicates that hypogene gold with pyrite formed earlier than high-grade gold telluride veins. Therefore, the conflicting observations of Kelley (1996) and Jensen (2003) make the timing of secondary K-feldspar alteration unclear.

A revised model for the evolution of the Cripple Creek deposit (Chapter 2) suggests that seven key mineralizing stages occurred: (1) sulfidation of hematite and possibly mafic silicate minerals to form trace element-poor pyrite; (2) appearance of appreciable concentrations of gold in the form of gold-bearing As-rich pyrite overgrowths on trace element-poor pyrite. Late events of this stage resulted in deposition of hypogene native gold as discontinuous overgrowths on pyrite and as isolated grains; (3) localized precipitation of micron-scale grains of hessite (AgTe₂), altaite (PbTe), petzite (Ag₃AuTe₂), as well as galena within micro-fractures that cut previously formed pyrite grains; (4) the formation of cross-cutting tetrahedrite-quartz veins; (5) growth of additional gold-bearing As-rich pyrite within fractures that would later host gold telluride minerals; (6) large-scale fracture- and vein-hosted gold telluride mineralization; and (7) the development of molybdenum, copper, and silver-rich base metal sulfide minerals associated with trace-element poor pyrite and barite within quartz veins that cut all previously formed minerals. Stages 2 and 5 are interpreted to be responsible for depositing the majority of the gold within the deposit.

Each of these stages likely involved an influx of compositionally and/or physiochemically distinct hydrothermal fluids (Chapter 2). Mineralized zones are structurally controlled, and mineralizing fluids appear to have followed different structural pathways at different times during the formation of the deposit. Fracture sets in some areas of the deposit contain minerals from multiple mineralizing episodes, indicating that these fractures either remained open during multiple mineralizing stages, or that the
fractures locally underwent cycles of opening and closing such that minerals formed during late mineralizing stages overprint or cut those formed during earlier mineralizing stages. As a consequence, gold-bearing As-rich pyrite generally exists within zones that contain composite mineralization profiles representing areas affected by two or more distinct hydrothermal fluids.

3.3 Sampling and Analytical Methods

Pyrite-bearing samples were studied from four sampling sites within the Cripple Creek deposit (Figure 3.1). Sites and samples were chosen based on gold grade (>0.1 troy ounces of gold per short ton) to target pyrite that may be present in association with high-grade gold telluride veins and fractures. Sampling site 1 (samples indicated as XCR2-xxx) is located ~65 m to the north of the Cresson lamprophyre breccia pipe. Samples from this site contain pyrite, gold-bearing As-rich pyrite, and hypogene native gold within quartz-fluorite absent radial fracture sets that emanate from the breccia pipe. Sampling site 2 (samples indicated as XBB-xxx) is located along the margin of the Blue Bird dike, where pyrite- and gold telluride-bearing quartz vein material was collected from the fractured interface between the aphanitic phonolite dike and adjacent diatremal Cripple Creek Breccia. Sampling site 3 (samples indicated as CC12-1-xxx) is also located at the interface between the Blue Bird dike and adjacent Breccia, as intercepted in research drill core ~160 m south of sampling site 2. Sampling site 4 (samples indicated as AC92-xxx) yielded samples of gold telluride-bearing quartz vein material as intercepted in historic diamond drill core from the Altman Pit.

Sample materials were analyzed in polished thin sections, and trace element zoning in pyrite was characterized by backscattered electron (BSE) imaging. Images were collected using a FEI-Quanta 650 Field-Emission Scanning Electron Microscope (FESEM) located at the USGS Microbeam Laboratory, Denver, CO, using beam conditions of 10-20 kV and 5nA. Electron microprobe (EMP) analysis of pyrite was conducted (including point analyses, traverses across grains, and element mapping) to determine trace element compositions and to evaluate potential correlations between trace elements that may reflect the conditions present during gold mineralizing stages. Grains from all sampling locations were analyzed, including grains with different trace element zoning patterns. Grains were specifically chosen to represent the different settings in which As-rich pyrite occurs. EMP analyses were conducted using a JEOL 8900 electron microprobe at the USGS Microbeam Laboratory, Denver, CO. Point analyses were collected using beam conditions of 20 kV and 50 nA, and a beam size of <1μm. EMP element intensity maps were collected using beam conditions of 20 kV and 100 nA, a step size of 0.5 μm, and dwell time of 750 ms. Full details of analytical conditions for trace element analysis of pyrite are presented in the digital appendix.
3.4 Results

Data on trace element zoning in pyrite were utilized to demonstrate how pyrite composition varies throughout the paragenetic sequence of mineral deposition at the Cripple Creek deposit, and to determine whether gold in pyrite at Cripple Creek occurs in solid solution or as sub-micron-scale inclusions.

3.4.1 Trace element zoning in pyrite

Pyrite grains analyzed in this study consistently display pronounced zoning in high resolution, high-contrast backscattered electron (BSE) images. Zoning in BSE images is characterized by two basic forms: simply zoned pyrite wherein high BSE intensity (BSE-bright) pyrite forms a rim on weak BSE intensity (BSE-dark) pyrite (Figure 3.2a), and complexly zoned pyrite wherein BSE-bright pyrite displays irregular zoning patterns in BSE images (Figure 3.2b). Complexly zoned pyrite can be further subdivided into three additional zoning types based on appearance in BSE images (Figure 3.2c-f).

The first and most common subtype of complexly zoned pyrite is oscillatory zoning (Figure 3.2c). In BSE images, oscillatory zoned pyrite displays narrow (2-5 μm), sharply distinct bright bands within broad domains of BSE-dark pyrite that are commonly mantled or rimmed by zones dominated by BSE-bright banding. In some examples, a weakly-diffuse banding produces more subtle oscillatory zoning (Figure 3.2b). The second type of complex zoning is referred to as gradational (or diffuse) zoning, where brightness gradients in BSE images between dark pyrite and bright pyrite are subtle and typically unidirectional, commonly grading from a BSE-darker core to a BSE-bright edge (Figure 3.2d,e). In some grains of this sub-type, BSE-bright pyrite may be embayed and truncated by texturally younger BSE-dark pyrite (e.g., Figure 3.2e).

The third subtype is referred to as patched zoning, due to the patchy appearance of BSE-bright zones within zones that are BSE-dark (Figure 3.2f). The BSE-dark pyrite components of these pyrite grains commonly form bladed and other non-isometric textures, interpreted to result from sulfidation of specular hematite and other iron-rich minerals. The homogeneous optical properties of these grains indicate the bladed cores are not marcasite. Many of the grains that were analyzed show components of more than one zoning type. For example, oscillatory and diffuse zoning are common in grains from the XCR2 sampling site and patched zoning may occur within domains of gradational (diffuse) zoning (e.g., Figure 3.2f).

EMP measurements of zoned pyrite demonstrate that BSE-bright domains are enriched in trace and minor elements, most commonly arsenic, relative to BSE-dark domains that are trace element-poor (Figures 3.3 and 3.4). Within BSE-bright domains, measured arsenic concentrations range from below
Figure 3.1: Geological map of the Cripple Creek district (modified after Jensen, 2003). Locations 1 through 4 indicate sampling sites that produced gold-bearing As-rich pyrite used in this study. Sample name designations are as follows: location (1) XCR2-xxx; location (2) XBB-xxx; location (3) CC12-1-xxx; location (4) AC92-9-xxx.
Figure 3.2: BSE images of the different types of trace element zoning in pyrite: (A) simple zoning, sample XCR2-13-1; and (B) complex zoning, sample XCR2-13-1. Images C-F demonstrate subtypes of complex zoning: (C) oscillatory zoning, sample CC12-1 70.0; (D,E) gradational (diffuse) zoning, samples XCR2-13-1 and XCR2-20; (F) patched zoning, sample XCR2-14-2.
detection limit of the electron microprobe (195 ppm) to as high as 5.9 wt % (median = 1.14 wt. %, n= 541). Complexly zoned pyrite generally contains higher concentrations of arsenic relative to simply zoned pyrite.

Arsenic-rich zones in pyrite may also be variably enriched in gold, copper, antimony, and thallium in trace concentrations. Some grains were also enriched in tellurium and silver at specific measurement points. At these points, tellurium was typically only detected in domains that were also enriched in silver and gold; enrichment in all three elements suggests the presence of sub-micron inclusions of petzite (Ag$_3$AuTe$_2$) that occur in association with micron-scale inclusions of petzite. Thallium showed an irregular distribution throughout all analyzed pyrite grains, and thallium zoning patterns showed no systematic correlation with other trace elements. For this reason, thallium will not be discussed in detail.

3.4.2 Relationships between pyrite and mineralized zones

Compositional zoning patterns in pyrite vary depending on the structural setting and mineralogy of different mineralized samples (Figures 3.3, 3.4, and 3.5). Trace element-rich pyrite grains from mineralized zones that do not contain high-grade gold telluride veins (represented by XCR2 and CC12-1 sampling locations) occur within fractures and adjacent wall rock. In this setting, pyrite grains are spatially associated with hypogene native gold, and mineralized fractures do not contain hydrothermal quartz or fluorite, both of which are associated with paragenetically late gold telluride mineralization. At the XCR2 sampling site, the host rock has been weakly to moderately sericitized, but does not preserve strong evidence of any other alteration styles. In contrast, the host rock at the CC12-1 sampling site has been pervasively altered to secondary K-feldspar. Mineralized fractures at the CC12-1 sampling site occur in close proximity to high-grade gold telluride veins, but no gold telluride minerals occur within the fractures.

In this structural-mineralogical setting, pyrite grains may be simply or complexly zoned, and are characterized by trace-element poor pyrite nuclei that have been overgrown by trace-element rich pyrite. The inner nuclei of trace-element poor pyrite are commonly irregular or rounded in shape, suggesting a period of resorption prior to precipitation of trace element-rich pyrite. In addition, the degree of resorption and the volume of new trace element-rich pyrite growth decrease with distance from mineralized fractures, grading to un-resorbed trace element-poor pyrite with no trace-element rich pyrite overgrowths outside of ~3 cm away from fractures. Distal to the fractures, pyrite is not present, and hematite is the dominant Fe-bearing phase.
Figure 3.3: (A,B) Electron microprobe element traverses across two fracture-hosted complexly zoned pyrite, Sample XCR2-13-1. The mineralized fractures have no spatial association with gold telluride-bearing veins. Shaded gray areas in plots indicate concentrations that are below the 99% confidence detection limit of the electron microprobe. Detection limits: As = 195 ppm; Au = 150 ppm; Cu = 400 ppm; Sb = 130 ppm; Tl = 250 ppm.
Figure 3.4: Electron microprobe element traverses across two complexly zoned pyrite grains. (A) Traverse across a fracture-hosted pyrite grain proximal to a gold telluride vein, sample CC12-1 70.0. (B) Traverse across a very complexly zoned pyrite grain that is hosted within a gold telluride vein, sample XBB-003-02-2. Dashed lines demonstrate a correlation between Au, Ag, and Te that indicates inclusions of petzite (Ag$_2$AuTe$_2$). Fine dashed line demonstrates slight offset of Au and As enrichment relative to petzite inclusions. Shaded blue regions bound by dashed lines represent zones with a unique correlation between As, Au, and Cu. Shaded gray areas in plots indicate concentrations that are below the 99% confidence detection limit of the electron microprobe. Detection limits: As = 195 ppm; Au = 150 ppm; Cu = 400 ppm; Sb = 130 ppm; Tl = 250 ppm; Ag = 495 ppm; Te = 200 ppm.
Figure 3.5: BSE image and electron microprobe element maps of complex trace element zoning in gold telluride vein-hosted trace element-rich pyrite. Brighter colors represent higher trace element concentrations. The specific trace element zoning patterns seen here were used to define different stages of pyrite growth. Correlating bright spots in Au and Te maps are inclusions of petzite. Red arrows point to regions that are strongly enriched in Cu, Sb and Au, but only weakly enriched in As.
Pyrite grains generally contain trace concentrations of gold in association with arsenic, and higher gold concentrations generally occur in zones with high arsenic concentrations. Detectable concentrations of copper and antimony (up to 922 ppm and 609 ppm, respectively) commonly, but not universally, occur at the interface between the As-rich zones and the trace-element poor pyrite cores. Where present, copper and antimony are not coincident with gold and arsenic enrichment (Figure 3.3a,b, 3.4a). Pyrite grains from the CC12-1 sampling location contain little to no detectable concentrations of tellurium, despite their close spatial association with gold telluride-bearing veins.

The second structural-mineralogical setting in which trace element-rich pyrite occurs is within high-grade gold telluride-bearing quartz veins and the immediately surrounding host rock (represented by samples from XBB and AC92-9). In this setting, pyrite grains have complex and unusual zoning patterns (Figure 3.4b, 3.5). Pyrite grains that occur within gold telluride-bearing veins commonly contain irregularly shaped cores composed of trace-element rich pyrite with overgrowths of additional pyrite with oscillatory zoning. In BSE images, bright spots may occur along the interface between the irregular core and the additional pyrite growth (Figure 3.5). The bright spots are enriched in gold, silver, and tellurium and are interpreted to represent tiny inclusions of petzite. Compositional traverses and EMP element maps across the complexly zoned vein-hosted pyrite grains reveal contrasting trace element zoning patterns compared with pyrite grains from other sampling locations. In general, the irregular cores of these grains contain As and Au, and may be locally although weakly enriched in Cu. Later trace element-rich pyrite overgrowths also contain As and Au, with variable concentrations of Cu (Figure 3.4b, 3.5). Locally, outer discontinuous rims are strongly enriched in Cu, Sb, and Au (Figure 3.5; Table 3.1, 3.2). Complexly zoned pyrite grains with trace element-rich cores are not observed in wall rock adjacent to gold telluride veins. Instead, wall rock pyrite grains are characterized by depleted cores and enriched rims similar to those preserved in the first structural-mineralogical setting.

A third structural-mineralogical setting is characterized by quartz veins that cut high-grade gold-telluride veins and contain molybdenum, copper, and silver-rich sulfide and sulfosalt minerals. Within these quartz veins, pyrite grains commonly contain BSE-dark cores that are overgrown by oscillatory growth bands that are weakly enriched in arsenic. Rarely, pyrite grains contain trace element-rich cores with BSE-dark, trace element-barren overgrowths (similar to Figure 3.2e). The latter texture suggests partial resorption of the original pyrite cores.

3.4.3 Stages of pyrite growth

Five stages of pyrite growth have been defined based on trace element signatures (Figures 3.6 and 3.7; Table 3.1; Table 3.2). A sixth stage may also be present in cross-cutting Mo-rich base metal sulfide veins.
**Stage 1** pyrite is trace element-poor and generally contains inclusions of sulfide and silicate minerals, creating a grossly pitted appearance in BSE and reflected light images (Figure 3.2a,b). Stage 1 pyrite forms the cores of grains that are rimmed and mantled by pyrite that is trace element-rich. On the basis of textural relationships it is interpreted to have formed prior to the onset of gold mineralization, during a period in which iron-bearing minerals were sulfidized to pyrite. **Stage 2** pyrite growth, which forms rims or mantles on Stage 1 pyrite, is commonly oscillatory and/or gradationally zoned, and is moderately to strongly enriched in arsenic that may be associated with detectable concentrations of gold. Locally, stage 2 pyrite may also contain detectable but low concentrations of copper and antimony. In rare cases, stage 2 pyrite is overgrown by additional barren pyrite (Figure 3.2e) that may be equivalent to stage 3 pyrite. However, the timing of these barren pyrite overgrowths is unclear. **Stage 3** pyrite is also trace-element poor (similar to Stage 1 and the late pyrite in stage 2), but occurs as overgrowths on stage 2 pyrite. **Stage 4** pyrite is moderately to strongly enriched in arsenic and moderately enriched in gold and copper. Antimony concentrations are below detection limit. Stage 4 pyrite is distinguished from stage 2 pyrite by its higher concentrations of copper (shaded blue regions bound by dashed lines, Figure 3.4b) and absence of coincident antimony. **Stage 5** pyrite occurs as rare discontinuous outer rims that are strongly enriched in copper, antimony, and gold and only weakly enriched in arsenic. This type of pyrite was rarely observed and only occurs within gold telluride veins. Barren, BSE-dark rims on pyrite in molybdenum, copper, and silver-rich base metal sulfide-bearing quartz veins that cut high-grade gold telluride veins may reflect a sixth stage of pyrite growth.

Pyrite grains within mineralized fractures and in wall rocks to fractures and high-grade gold telluride veins typically display stages 1 and 2 only. However, pyrite from high-grade gold telluride veins with quartz and fluorite generally preserves four or five stages of growth.

### Table 3.1: Defining characteristics of different pyrite stages

<table>
<thead>
<tr>
<th>Pyrite Type</th>
<th>BSE Zoning Characteristics</th>
<th>Type of Trace Element Enrichment</th>
<th>Corresponding Mineralizing Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>BSE-dark; unzoned</td>
<td>Barren</td>
<td>Stage 1</td>
</tr>
<tr>
<td>Stage 2</td>
<td>BSE-bright: Oscillatory, gradational, and patched</td>
<td>Moderate to strong As ± low to moderate Au, Cu, and Sb</td>
<td>Stage 2</td>
</tr>
<tr>
<td>Stage 3</td>
<td>BSE-dark; unzoned</td>
<td>Barren</td>
<td>Stage 4</td>
</tr>
<tr>
<td>Stage 4</td>
<td>BSE-bright bands of complex zoning</td>
<td>Strong As, moderate Au and Cu</td>
<td>Stage 4</td>
</tr>
<tr>
<td>Stage 5</td>
<td>BSE-bright; Moderately banded</td>
<td>Strong Cu, Sb, and Au; weak As</td>
<td>Stage 4</td>
</tr>
<tr>
<td>Stage 6</td>
<td>BSE-dark; Weakly zoned</td>
<td>Barren</td>
<td>Stage 7 (?)</td>
</tr>
</tbody>
</table>
Figure 3.6: Backscattered Electron (BSE) images with false-colored (FC) overlays highlighting different stages of pyrite growth. Different stages are defined by unique trace element signatures. (A,B) Pyrite grains from mineralized fractures in a zone that does not contain gold telluride minerals, sample XCR2-13-1. These grains formed early in the deposit paragenesis (mineralizing stage 2). Note that bright inclusions in BSE images are a mixture of Ag-Pb-(Au) telluride minerals and galena, which occur in micro-fractures that cut the pyrite grains.
Figure 3.7: Backscattered Electron (BSE) images with false-colored (FC) overlays highlighting different stages of pyrite growth. Different stages are defined by unique trace element signatures. (A) Pyrite grain from a fracture proximal to a gold telluride vein, sample CC12-1 70.0; (B) Pyrite grain from a quartz vein that contains abundant gold telluride minerals, sample XBB-002-2. Note that the pyrite grain from the gold telluride vein environment exhibits more than two growth stages.
3.4.4 Trace element correlations

An aim of this study was to determine whether element correlations in pyrite could serve as broader indicators of (or vectors toward) gold-bearing mineralized zones. Based on bivariate plots of selected trace elements, a clear negative correlation is apparent between As and S (Figure 3.8a), reflecting the substitution of As for S in pyrite. There is a weakly defined relationship between As and Au among combined samples, and a strong correlation between As and Sb in the AC92-9 sub-population (Figure 3.8b,c). No other relationships or correlations were observed. A positive correlation between As and Au is expected for some samples based on the spatial coincidence of Au- and As-enrichment in select zones within pyrite as discussed above (Figures 3.3, 3.4). However, the opposite is also true; several EMP measurements indicate that As may be moderately to strongly enriched in pyrite domains that are not coincidently enriched in Au. As a consequence, there does not appear to be any direct relationship between Au and As aside from the observation that higher Au concentrations tend to coincide with higher As concentrations.

3.4.5 Gold contents in pyrite: solid-solution gold vs. sub-micron inclusions

Determination of whether gold enrichment within pyrite at Cripple Creek is due to nano-inclusions or substitution into the pyrite crystal structure was be evaluated using the method of Reich et al. (2005), according to the relationship:

\[ C_{Au} = 0.02 \cdot C_{As} + 4 \times 10^{-5} \]

Table 3.2: Summary of trace element concentrations by pyrite stage

<table>
<thead>
<tr>
<th>Property</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
<th>Stage 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>As detection limit</td>
<td>195 ppm</td>
<td>195 ppm</td>
<td>195 ppm</td>
<td>195 ppm</td>
<td>195 ppm</td>
<td>195 ppm</td>
</tr>
<tr>
<td>As range</td>
<td>N/A</td>
<td>201-59,101 ppm</td>
<td>N/A</td>
<td>2139-42,265 ppm</td>
<td>1350-14,672 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>Median As content</td>
<td>N/A</td>
<td>13,119 ppm</td>
<td>N/A</td>
<td>14,379 ppm</td>
<td>3060 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>N</td>
<td>N/A</td>
<td>320</td>
<td>N/A</td>
<td>16</td>
<td>7</td>
<td>N/A</td>
</tr>
<tr>
<td>Au detection limit</td>
<td>150 ppm</td>
<td>150 ppm</td>
<td>150 ppm</td>
<td>150 ppm</td>
<td>150 ppm</td>
<td>150 ppm</td>
</tr>
<tr>
<td>Au range</td>
<td>N/A</td>
<td>151-1,085 ppm</td>
<td>N/A</td>
<td>159-1,073 ppm</td>
<td>793-1,389 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>Median Au content</td>
<td>N/A</td>
<td>227 ppm</td>
<td>N/A</td>
<td>334 ppm</td>
<td>962 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>N</td>
<td>N/A</td>
<td>126</td>
<td>N/A</td>
<td>12</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>Cu detection limit</td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>400 ppm</td>
</tr>
<tr>
<td>Cu range</td>
<td>N/A</td>
<td>409-3,625 ppm</td>
<td>N/A</td>
<td>448-1,709 ppm</td>
<td>2,134-3,771 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>Median Cu content</td>
<td>N/A</td>
<td>760 ppm</td>
<td>N/A</td>
<td>553 ppm</td>
<td>3,046 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>N</td>
<td>N/A</td>
<td>10</td>
<td>N/A</td>
<td>7</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>Sb detection limit</td>
<td>130 ppm</td>
<td>130 ppm</td>
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<td>130 ppm</td>
<td>130 ppm</td>
<td>130 ppm</td>
</tr>
<tr>
<td>Sb range</td>
<td>N/A</td>
<td>139-926 ppm</td>
<td>N/A</td>
<td>N/A</td>
<td>270-3,561 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>Median Sb content</td>
<td>N/A</td>
<td>212 ppm</td>
<td>N/A</td>
<td>N/A</td>
<td>1,886 ppm</td>
<td>N/A</td>
</tr>
<tr>
<td>N</td>
<td>N/A</td>
<td>31</td>
<td>N/A</td>
<td>N/A</td>
<td>6</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*N/A = Barren with respect to specific trace element
where \( C_{Au} \) and \( C_{As} \) refer to the concentration (in parts per million) of gold and arsenic, respectively, in pyrite. This relationship defines a curve on Au-As bivariate plots that represents the maximum solubility of gold for a given arsenic concentration. According to this relationship, compositions that plot above the curve indicate that nano-scale to sub-micron-scale inclusions of native gold must be present. Compositions that plot below the curve indicate that gold is likely in solid solution within As-rich pyrite.

The Cripple Creek EMP dataset showed the majority of the measurement points lie below the solubility curve (Figure 3.9), which suggests that most of the pyrite-hosted gold is in solid solution, if the Reich et al. (2005) model is indeed correct. Numerical evaluation of the data indicates that 79% of the total sample population \((n=169)\) have Au:As indicative of gold that is in solid solution. With respect to the sample sub-populations, the following percentages indicate solid solution gold: 89% of the measurement points from the XCR2 subset \((n=82)\); 63% of the points from the XBB sampling location \((n=51)\); and 80% of the points from the CC12-1 sampling location \((n=26)\).

### 3.4.6 Gold contents in pyrite: modeling total contained gold

The relatively high concentrations of Au contained within trace element-rich pyrite analyzed during this study suggest that pyrite could be a significant source of gold in the Cripple Creek deposit. To assess the potential contribution of pyrite-hosted gold, a model was developed to estimate the weight of gold that could be contained within trace-element rich pyrite for any given sampling location.

To develop this model, thin sections of targeted samples were analyzed by QEMSCAN to collect high-accuracy modal abundance data of pyrite in each sample. High-contrast BSE maps over entire thin sections were also collected to estimate the percentage of trace element-enriched pyrite relative to trace element-poor pyrite (Figures 3.10, 3.11). These maps were integrated with higher magnification BSE images of select pyrite grains to determine the average grain size of pyrite within the different structural-mineralogical settings. The high-magnification BSE images were also used to determine the average percentage of different zoning types within pyrite grains from each setting, based on the following types of pyrite: 1) trace-element poor pyrite with no enrichment, 2) simply zoned pyrite with thin overgrowths of enriched pyrite, 3) oscillatory zoned pyrite, and 4) complexly zoned pyrite with thick overgrowths of enriched pyrite. Median concentrations for gold and arsenic in enriched pyrite for a given sample were calculated from EMP data from multiple pyrite grains, giving robust and independent estimates of gold enrichment in different target samples.
Figure 3.8: Bivariate trace element correlation plots demonstrating: (A) a strong negative correlation between As and S, (B) the absence of a correlation between As and Au, and (C) a strong correlation between Sb and As in the AC92-9 sample population. The cause for the Sb/As correlation within a single sample population is unclear. Individual sample populations are broken out by color.
Figure 3.9: Plot of Au vs. As developed from EMP measurements of gold-bearing As-rich pyrite in the Cripple Creek deposit. The curve represents Au:As of ~0.02. At this scale, the curve appears as a line. All points that lie below the Au:As molar ratio curve represent gold that is in solid solution with pyrite. Points that plot above this curve represent nano-scale to sub-micron inclusions of gold.
The model made the assumption that pyrite occurs as spheres, which is considered the best ‘simplified’ geometric approximation for the generally pyritohedral pyrite grains. High-resolution BSE images were used to estimate the average width of “barren” cores and the average width of enriched bands or “rinds”, such that the width of the core plus the width of the rinds(s) equals the average grain size. These estimates were made independently for each pyrite type. The widths of the core and the rind(s) were used to calculate the volume of the barren core and the volume of the enriched rind(s). The precise nature of the volume calculations varies with pyrite type and geometry. Assuming a density of 5.25 g/cm³ for As-rich pyrite (calculated as the density of pure pyrite, 5.0 g/cm³, plus ~25% of the difference between the density of barren pyrite and the density of arsenopyrite, 6.07 g/cm³), the mass of enriched pyrite, and the mass of the remaining barren core(s) were calculated. The mass percent of each barren sphere or enriched rind was calculated by dividing the mass of each barren core and enriched rind by the mass of the entire grain, generating the percentage of the total mass that is represented by each core or enriched band (or rind) within a single grain. For example, this calculation may show that 60% of the total mass is represented by enriched pyrite, and 40% of the total mass is represented by barren pyrite.

To determine the proportion of each pyrite type within a sample, the modal abundance of all pyrite in the thin section (as derived from QEMSCAN data) was separated into mode by pyrite type. For example, if the modal abundance of all pyrite in a thin section is 4.0 % and barren pyrite accounts for 50% of the total modal abundance, then barren pyrite represents 2.0% of the total sample mode. The model assumed that the total modal abundance of pyrite in each thin section is equal to the modal abundance of pyrite in a short ton of ore. This value was then used as a scalar value in decimal form (0.02 in this example) to represent the amount of a short ton (short ton = 1.0) that is composed of barren pyrite. This process was repeated for each pyrite type.

Calculating a scalar value for each type of pyrite ensures that pyrite mass and element mass calculations are constrained by the actual amount of pyrite that is assumed to exist in a short ton, while still accounting for differences in mass by pyrite type.

The mass per short ton of ore that is represented by each type of pyrite was calculated by multiplying the total mass of a short ton (907,184.74 grams) by the scalar value that was calculated for each pyrite type. This yielded the mass contribution of each pyrite type within a short ton of ore. The element mass contribution from each type of pyrite was then calculated by multiplying the pyrite mass per short ton by the mass percentages for each pyrite type (barren vs enriched). This value was multiplied by the median concentration (in ppm) of each element of interest. The result yielded the total mass of each element that is contained within each type of pyrite, and when these values are summed, the model yielded the mass of
Figure 3.10: High contrast, false-color BSE map of gold-bearing As-rich pyrite in sample XCR2-13-1. Lighter colors correspond to higher BSE values (stronger trace-element enrichment). Inset Images (A,B,C) demonstrate the complex trace element zoning textures that are common within mineralized fractures that have no spatial relationship with gold telluride veins. The relative percentages of each type of pyrite trace element zoning in the map were used to visually estimate the total percent of enriched pyrite in this thin section.
Figure 3.11: High contrast, false-color BSE map of gold-bearing As-rich pyrite within a gold telluride vein, sample XBB-003-02-2. Lighter colors correspond to higher BSE values (stronger trace-element enrichment). Pink color marks the location of gold telluride minerals. Inset images (A,B) highlight the complexly zoned nature of pyrite grains within the vein, and the relatively simple oscillatory zoning patterns of pyrite grains outside of the vein.
each pyrite-hosted element as it may exist within a short ton of ore. Note, only the mass of enriched zones were assigned median gold and arsenic values.

Data from thin sections from two separate samples (XCR2-13-1, Figure 3.10; XBB-003-02-2, Figure 3.11) were used as model inputs (Table 3.3). The model indicated that approximately 1.0 g/ton gold is contained within pyrite at the XCR2-13 sampling site, and that approximately 4.7 g/ton gold is contained within pyrite from the XBB-003 sampling site. The element mass contribution of arsenic in pyrite was also calculated for each thin section using the model, assuming that all of the arsenic in measured whole rock geochemical data is contained within As-rich pyrite. The calculated values were compared to actual measured concentrations of arsenic from whole rock geochemical data for each of the two sampling sites, to check for similarity between calculated and measured As values. In this way, the difference between calculated and measured arsenic values can be used to check the relative accuracy of the calculated mass of gold contained within the pyrite. The model-calculated mass of arsenic in sample XCR2-13-1 was 119% of the measured mass of arsenic at that sampling site. The close similarity between calculated and measured arsenic values for the XCR2-13 sample demonstrates that model-calculated gold mass of 1.0 g/ton can be considered relatively accurate. The calculated mass of arsenic in sample XBB-003-02-2 was 55% of the measured mass of arsenic at that sampling site, demonstrating that model-calculated mass for gold contribution from pyrite was not as accurate as in the previous example.

Table 3.3: Data used for modeling gold content

<table>
<thead>
<tr>
<th>Properties</th>
<th>XCR2-13-1</th>
<th>XBB-003-02-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pyrite modal abundance</td>
<td>3.57%</td>
<td>2.62%</td>
</tr>
<tr>
<td>Modal percent, barren</td>
<td>64%</td>
<td>2%</td>
</tr>
<tr>
<td>Modal percent, simple</td>
<td>32%</td>
<td>25%</td>
</tr>
<tr>
<td>Modal percent, oscillatory</td>
<td>0%</td>
<td>73%</td>
</tr>
<tr>
<td>Modal percent complex, discontinuous cores</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Median Au content</td>
<td>238 ppm</td>
<td>332 ppm</td>
</tr>
<tr>
<td>Median As content</td>
<td>25832 ppm</td>
<td>14672 ppm</td>
</tr>
<tr>
<td>Calculated Au mass</td>
<td>1.0 g/ton</td>
<td>4.7 g/ton</td>
</tr>
<tr>
<td>Actual Au mass from bulk sample</td>
<td>6.24 g/ton</td>
<td>338.9 g/ton</td>
</tr>
<tr>
<td>Calculated As mass</td>
<td>107 g/ton</td>
<td>208 g/ton</td>
</tr>
<tr>
<td>Actual As mass from bulk sample</td>
<td>90 g/ton</td>
<td>382 g/ton</td>
</tr>
</tbody>
</table>

*Note: Actual gold mass includes hypogene gold and/or gold telluride minerals*
It is important to note that the calculated gold values are only considered first approximations, even though the accuracy of the calculated gold contribution from pyrite in sample XCR2-13 is considered high. In addition, the values represent calculated gold contribution based on single thin sections, so caution should be exercised when extrapolating the modeled gold content across even short distances within a sampling location.

### 3.5 Discussion

Several stages of pyrite growth have been defined within the Cripple Creek deposit based on trace element zoning patterns and chemically distinct trace element profiles (Table 3.1, 3.2). When integrated with textural relationships between pyrite and other ore, gangue and alteration minerals, this sequence of pyrite deposition can be used to track the mineralogical evolution of the deposit through time, and reveals a complex mineralization history.

#### 3.5.1 Trace element zoning patterns

High-resolution BSE imaging, quantitative EMP measurements, and EMP element mapping have demonstrated that several types of trace element zoning occur within pyrite in the Cripple Creek deposit. Whereas some zoning patterns may be readily explained by simple fluctuations in fluid composition or temperature (e.g., oscillatory zoning or some examples of gradational zoning), other zoning types are less easily explained. More complex zoning types require further consideration of other factors that may control the distribution of trace elements in pyrite. These complex types include gradational zoning where the zoning pattern can be diffuse and patchy (Figure 3.2d), distinct patched zoning (Figure 3.2e), and very complex zoning types that contain multiple stages of pyrite growth (Figure 3.5, 3.7b).

Gradational zoning is interpreted to involve crystallographically controlled chemical diffusion gradients within pyrite, though the exact nature of how diffusion occurs is unclear. Distinct patchy zoning, wherein BSE-dark (stage 1) pyrite has an irregular and generally bladed texture overgrown by trace element-rich stage 2 pyrite is interpreted to reflect pseudomorphs formed through sulfidation of iron-bearing minerals such as specular hematite and biotite. In cross-section, these sulfidized minerals would appear as blades or sheeted structures defined by BSE-dark pyrite. Very complex zoning involving four or more stages of pyrite growth can be attributed in part to periods of pyrite resorption followed by renewed pyrite growth. Strongly enriched rims along resorption interfaces, and the localized presence of numerous petzite inclusions (bright spots in BSE image, Figure 3.7b), may be an artifact of the apparent resorption events, possibly representing diffusion of trace elements toward the retreating pyrite grain-boundary interface.
3.5.2 Trace element correlations

Bivariate plots developed from EMP data demonstrate a strong negative correlation between As and S in all As-rich pyrite grains that were analyzed, regardless of whether other trace elements are present (Figure 3.8a). This correlation has been documented in several studies of As-rich pyrite (e.g., Reich et al., 2005; Cepedal et al., 2008). The correlation likely results from the substitution of arsenic for sulfur due to the similar ionic radii of the two elements. However, bulk data bivariate plots comparing combinations of As, Au, Ag, Cu, Sb, Te and Tl show very few correlations (as demonstrated in Figure 3.8b, c). The correlation between Au, Ag, and Te discussed previously is interpreted to represent inclusions of petzite. The absence of a correlation between the other trace elements is interesting, as it demonstrates that plotting bulk data may be an ineffective approach in characterizing trace element correlations in As-rich pyrite, primarily because bulk data plots do not preserve any spatial context from within the data. For example, an absence of correlation between As and Au in bulk data bivariate plots has been reported in As-rich pyrite from epithermal and other deposit types, even though these studies used analytical methods with significantly lower detection limits than were used in the current study (Simon et al., 1999; Reich et al., 2005; Cepedal et al., 2008; Deditius et al., 2014). However, Large et al. (2009) constructed bivariate plots of trace element correlations within single stages of pyrite growth, and these show moderate to strong correlations in various trace element pairs, including As and Au. Reanalysis of As-rich pyrite grains from the Cripple Creek deposit, in which trace element data from high-resolution EMP or LA-ICP-MS traverses is plotted by pyrite stage, may allow definition of previously unrecognized trace element correlations within pyrite from the deposit.

3.5.3 Pyrite as a record of hydrothermal fluid events

The multiple stages of pyrite growth within the Cripple Creek deposit are a preserved record of hydrothermal fluid events. When integrated with the textural relationships between ore, gangue or alteration minerals (Chapter 2), these different stages of pyrite can be used to track the mineralogical evolution of the deposit with time.

Stage 1 pyrite preserves a record of the first major hydrothermal fluid event that preceded gold mineralization. In mineralized domains distal to high-grade gold telluride-bearing quartz veins, pyrite occurs within and proximal to fractures, outboard of which the dominant iron-bearing phase is hematite. Pyrite from this stage occurs as pseudomorphs of preexisting iron-rich minerals that were sulfidized (Figure 3.2f). Where gold mineralization overprints the sulfidized zones, stage 1 pyrite is ubiquitous and commonly forms cores to stage 2 pyrite. The restricted development of stage 1 pyrite likely indicates that
fracture density and wall rock permeability had a first order control in localizing the formation of stage 1 pyrite.

In many of the analyzed samples, stage 1 pyrite is embayed and displays ragged or rounded boundaries with stage 2 pyrite (see BSE images in Figure 3.6b and Figure 3.7a). In many grains, this resorption texture is evidenced by the presence of multiple and irregularly shaped discontinuous cores within domains of stage 2 pyrite (Figure 3.2b and 3.6a). This textural relationship suggests that some degree of resorption occurred after the initial formation of stage 1 pyrite, and indicates a shift from pyrite formation through sulfidation to pyrite resorption. This indicates changing fluid conditions at some point between the formation of stage 1 pyrite and stage 2 pyrite. The irregular interface between stage 1 and stage 2 pyrite is commonly enriched in copper and/or antimony (Figure 3.3, 3.4a). In some cases, antimony enrichment is slightly offset with respect to copper (Figure 3.3a, 3.4a). The location of these increased elemental concentrations with respect to the interface between stage 1 and 2 pyrite indicates that these elements may have been enriched during the resorption event (potentially through diffusion back into the retreating pyrite grain boundary), or were deposited at some time after the resorption event. Copper and antimony could also have been introduced during the initial growth stages of stage 2 pyrite.

Resorption textures in stage 1 pyrite are best developed within fractures that host stage 1-2 pyrite. In addition, the degree of stage 1 pyrite resorption and the volume of stage 2 pyrite growth decreases with distance from these fractures.

There is a general gradation from fracture-hosted complexly zoned pyrite to wall rock-hosted simply zoned pyrite, which grades outward to wider halos of stage 1 pyrite pseudomorphs with no trace element-enriched overgrowths. The halos that only contain stage 1 pyrite grade outward to hematite as the dominant iron-bearing phase. This suggests that host rock permeability likely played a role in governing the wall rock penetration depth of the hydrothermal fluids, and appears to reflect decreasing wall rock permeability with time during these early hydrothermal events.

Stage 2 trace element-rich pyrite overgrowths preserve a number of zoning patterns (e.g., oscillatory, gradational; Table 3.1), suggesting that although stage 2 pyrite has consistently similar trace element compositions across several sampling locations, the mechanism for trace element incorporation into pyrite may have varied. Stage 2 pyrite is consistently enriched in As with low to moderate concentrations of Au, Cu, and Sb. However, no consistent trace element correlations exist between these elements. The absence of a correlation between As and Au suggests that As and Au were not always coupled during growth of trace element-rich pyrite. A likely cause for the decoupled behavior of As and Au is fluctuating physiochemical conditions within the fluid. Distinct BSE-bright bands within stage 2 pyrite (e.g., the type
seen in Figure 3.7a), were all As-rich, but only some of these bands contain detectable concentrations of Au. Reich et al. (2005) and Deditius et al. (2014) reported that gold-bisulfide complexes (or similar Au complexes that carry Au\(^{1+}\)) potentially play a major role in the formation of gold-bearing As-rich pyrite. If gold is truly absent in some As-rich zones, it would therefore imply that there were times during As-rich pyrite formation when Au-bearing complexes were not present in the hydrothermal fluid. While As is likely to have been readily available within the mineralizing fluids due to its mobile nature, the Au component of pyrite may be the result of pulses of Au\(^{1+}\) into the system.

Stage 2 pyrite shows no evidence of resorption except where it occurs within gold telluride veins, suggesting that the fluids responsible for stage 2 pyrite dissolution were restricted to fractures and veins that would later host gold telluride minerals. A key observation is that the wall rocks of gold telluride veins are strongly altered to secondary K-feldspar. Within the K-feldspar altered wall rock, stage 1-2 pyrite is preserved and there is no observable dissolution of stage 2 pyrite; stage 2 pyrite dissolution textures were only observed within the veins. This indicates that the wall rock to fractures which would later host gold telluride minerals were already altered to secondary K-feldspar by the time that the stage 2 pyrite dissolution event began. Further, this indicates that K-feldspar alteration began after the formation of pyrite stages 1-2 (and associated microcrystalline hypogene gold) that are preserved in the wall rock, but before the onset of stage 2 pyrite dissolution within the veins. Pyrite grains that exhibit stage 2 pyrite dissolution and stage 3-5 pyrite growth are associated with hydrothermal quartz that has been shown to have formed prior to the introduction of gold telluride minerals (Chapter 2). Therefore, K-feldspar alteration must have already developed prior gold telluride mineralization. This interpretation contrasts with previous research (e.g., Lindgren and Ransome, 1906; Loughlin and Koschmann, 1935; Kelley, 1996; Jensen, 2003) that suggested that secondary K-feldspar alteration either coincided with the formation of microcrystalline hypogene gold and pyrite, or that it coincided with gold telluride mineralization. Instead, detailed examination of pyrite at Cripple Creek indicates that K-feldspar alteration occurred at some point between these two stages.

Within veins that contain partially resorbed stage 2 pyrite, petzite commonly occurs as visible inclusions inboard of the dissolution interface (bright spots in BSE image, Figure 3.7b). These may be a relic of the Ag-Pb-(Au) telluride stage (Chapter 2), or they may represent a renewed stage of petzite formation prior to stage 3 pyrite regrowth. Textural relationships indicate that in mineralized zones distal to high-grade gold telluride-bearing veins, Ag-Pb-(Au) telluride minerals occur along micro-fractures that cut stage 2 pyrite or occur on stage 2 pyrite grain boundaries (Chapter 2). The preferred interpretation is that the petzite inclusions preserved at the grain-boundary interface of partially resorbed stage 2 pyrite within gold telluride-bearing veins are relics of the earlier Ag-Pb-(Au) telluride stage, possibly formed
through diffusion of Au, Ag, and Te derived from preexisting petzite inclusions back into the retreating pyrite grain boundary.

Stage 3 pyrite marks renewed deposition of trace element-poor pyrite within the system, demonstrating a shift from fluid conditions that were capable of dissolving pyrite to those capable of forming pyrite. The absence of trace elements in stage 3 pyrite may indicate that trace elements (and the ligands responsible for their transport) may have been absent in the hydrothermal fluids. Close examination of stage 3 pyrite shows subtle dissolution textures along interfaces with stage 4 pyrite, suggesting a third resorption event prior to renewed pyrite growth. This suggests another shift in fluid conditions with time.

Stage 4 pyrite overgrowths are again enriched in trace elements (As, Au, and Cu). However, unlike stage 2 pyrite, detectable concentrations of Sb are absent. Additional, though subtle dissolution textures exist on the outer edge of stage 4 pyrite growth, where stage 4 pyrite is in contact with discontinuous stage 5 pyrite. Stage 5 pyrite has a unique trace element signature characterized by strong enrichment in Cu, Sb, and Au with weak enrichment in As (Table 3.2).

The sequence of pyrite formation, dissolution, and re-precipitation demonstrates a much more complex history of hydrothermal fluid events prior to the onset of gold telluride mineralization than has been previously recognized.

3.5.4 Gold in solid solution

Using the method of Reich et al. (2005) EMP measurements of gold-bearing As-rich pyrite from Cripple Creek have shown that the majority of the gold component in pyrite is in solid solution. The XCR2 sampling site has the highest proportion of gold in solid solution (89% of the sub-population), followed by the CC12-1 sampling site (80% of the sub-population). At these sampling locations, two stages of pyrite growth (1 and 2) are present (Figure 3.6, 3.7a). There is no evidence of stage 2 pyrite dissolution, and the pyrite grains occur within and adjacent to mineralized fractures associated with paragenetically later hypogene native gold without gold telluride minerals. In contrast, the XBB sampling site has the lowest proportion of solid solution gold (63% of the sub-population). This sampling site contains vein-hosted gold telluride minerals and thus reflects a different environment of formation as compared to the other sampling locations. The variability in the percentage of gold in solid solution from the different sampling sites may also reflect differences in the number of measurements that were taken from pyrite from each site, or possibly slight differences in fluid composition and/or the amount of time that the fluids spent in contact with pyrite grains at each sampling location.
Reich et al. (2005) and Deditius et al. (2014) reported that hydrothermal fluids do not need to be saturated with gold in order to produce gold-bearing As-rich pyrite. Instead, they reported that the solid solution gold component is likely derived from gold-bisulfide complexes in which gold carries a 1+ charge (Au\(^{1+}\)) and that this charge is maintained within the crystal structure of pyrite to maintain electrical neutrality. Deditius et al. (2014) further reports that within epithermal environments, the composition of pyrite preserves the Au/As signature of mineralizing magmatic-hydrothermal fluids. The absence of non-pyrite As-bearing mineral phases indicates that gold-bearing As-rich pyrite in the Cripple Creek deposit most likely formed from fluids that are compositionally distinct from fluids which deposited visible grains of hypogene native gold and gold telluride minerals. Given these observations, it may be possible that gold-bearing As-rich pyrite formation is simply a precursor to stages of mineralization that involve gold (and possibly Te) saturation.

3.5.5 Application of gold grade model

The model for estimating the weight of contained gold within As-rich pyrite that was developed during this study (Table 3.3) has demonstrated that gold-bearing As-rich pyrite may be a significant gold resource within the Cripple Creek deposit. Modeling based on analysis of thin section XCR2-13-1 demonstrated that approximately 1.0 g/ton gold is contained within pyrite at the XCR2-13 sampling site. The calculated mass of arsenic contained in pyrite is slightly over-estimated at 119 % of the measured mass of arsenic in the bulk XCR-13 sample, but the close similarity between the calculated and measured arsenic contents suggest that the modeled gold content may be considered relatively accurate. The modeled gold content calculated from thin section XBB-003-02-2 (4.7 g/ton) is considered less accurate due to the higher degree of variation between calculated and measured arsenic values (55%).

Possible causes for the depressed mass of As in the model include consideration that roughly 2/3 fewer EMP measurements were used in modeling gold content within XBB-003-02-2 compared to XC2-13-1 (n=31 vs. n=90), the potential presence of additional As-rich minerals such that not all of the As in the sample is contained within pyrite, or the possibility that thin section XBB-003-02-2 is not representative of the actual pyrite mode within the XBB-003-02 bulk sample. It is also possible that the higher percentage of complexly zoned pyrite in the thin section (73 % in XBB-003-02-2 vs 4 % in XCR2-13-1) creates difficulty in determining areas within grains that are very weakly enriched in arsenic, such that large volumes of pyrite with weak arsenic enrichment were not accounted for in the model.

It is important to note that the calculated gold contents in these two thin sections cannot be accurately extrapolated across their respective sampling zones (i.e., the XCR2 and XBB sampling sites) due to variation in pyrite modal abundance, median gold and arsenic values, and percentage of pyrite types.
preserved within different samples. To achieve a relatively accurate representation of gold content in pyrite across an entire sampling location, several samples would have to be collected at closely-spaced intervals, with thin section analysis of each sample. Ideally, more than one thin section would be analyzed for each sample so that the median gold contribution from pyrite can be calculated from a statistically significant sample population.

3.6 Conclusions

This study has demonstrated that trace element-rich pyrite may be a common constituent within mineralized zones at Cripple Creek. Detailed mineralogical characterization indicates that at least five stages of pyrite developed during the formation of the deposit, and that the structural and mineralogical context in which these pyrite stages are found can be used to track the mineralogical evolution of the deposit. EMP data indicates that the majority of the gold contained in pyrite is solid solution, indicating that gold-bearing pyrite most likely formed from hydrothermal fluids that were undersaturated with respect to gold, thus indicating that it did not form coincidently with hypogene gold or gold telluride minerals. Through modeling, EMP data has further demonstrated that gold contained in pyrite may represent a significant and previously unrecognized resource within the Cripple Creek deposit.

3.7 REFERENCES CITED


CHAPTER 4

SUMMARY AND CONCLUSIONS

This chapter provides a synthesis of new observations, interpretations, and conclusions and makes recommendations that may be useful for in-pit exploration at the Cripple Creek deposit.

4.1 Summary

The overall goal of this study was to develop a refined paragenetic model that characterized the mineralizing history of the Cripple Creek deposit. Specific mineralogical associations that were observed in samples from one or more of the targeted sampling sites were used to define four different ore types:

1) Ore composed of microcrystalline hypogene gold in association with gold-bearing As-rich pyrite in sericitically altered host rock that has not been strongly altered to secondary K-feldspar,

2) Ore composed of microcrystalline hypogene gold and gold-bearing As-rich pyrite in association with abundant gold telluride minerals within quartz ± fluorite veins where wall rock has been extensively altered to K-feldspar,

3) High-grade gold telluride veins that do not contain microcrystalline hypogene gold or gold-bearing As-rich pyrite, and

4) Quartz ± fluorite ± barite veins that contain molybdenum, copper, and silver-rich sulfide and sulfosalt minerals, but contain no appreciable gold.

Through characterizing mineralogical relationships among the four ore types, and by characterizing the nature of trace element-rich pyrite, a revised paragenetic model of the Cripple Creek deposit was developed which outlines seven distinct mineralizing stages. In chronological order, these stages are:

1) Early trace element-poor pyrite formation that formed through sulfidation of preexisting iron-rich minerals such as hematite, specular hematite, and biotite across broad zones of rock,

2) The formation of trace element-rich gold-bearing arsenical pyrite, with a late shift to formation of microcrystalline hypogene gold that is restricted to fractures and wall rock adjacent to fractures within broad zones of early trace element-poor pyrite,

3) The development of micron-scale Ag-Pb-(Au) telluride minerals and galena within micro-fractures that cut fracture-hosted pyrite grains formed during the previous stage,
4) The formation of tetrahedrite-bearing quartz veins

5) The growth of additional stages of trace element-poor and trace element-rich pyrite, confined purely fractures and veins that would later host gold telluride minerals,

6) The large-scale development of gold telluride minerals within quartz ± fluorite veins that may or may not contain trace element-rich pyrite from the second and fifth stages of mineralization,

7) Molybdenum, copper, and silver-rich base metal sulfide deposition within veins of quartz ± fluorite ± barite that cut all previously formed minerals.

Each of these stages is interpreted to represent the influx of hydrothermal fluids with specific compositions under variable physiochemical conditions. The progressive spatial restriction of minerals formed during each stage indicates that the host rock within the deposit became progressively less permeable with time. In addition, the recognition that gold-bearing As-rich pyrite and microcrystalline hypogene gold formed *early* in the mineralizing sequence and *predates* gold telluride formation, resolves the question of whether the gold and pyrite style of mineralization, previously referred to as “disseminated gold”, coincided with gold telluride mineralization. The revised paragenetic model presented in this thesis additionally indicates that a period of early, widespread sericitization formed prior to the first mineralizing event (barren pyrite formed through sulfidation of iron-rich minerals).

Furthermore, detailed mineralogical characterization of different pyrite stages and the minerals associated with them suggests that large-scale K-feldspar alteration, previously suggested to have occurred synchronously (or associated with) disseminated microcrystalline gold and pyrite or with high-grade gold telluride vein formation, occurred after the Ag-Pb-(Au) telluride mineralizing stage but before large-scale gold telluride mineralization. Thus, K-feldspar alteration is not paragenetically related to either of mineralization styles to which it was previously attributed.

Detailed analysis of gold telluride and base metal sulfide quartz veins additionally indicate that at least three types of quartz are present in the deposit: Q1 radial quartz, Q2 anhedral to prismatic quartz, and Q3 chalcedonic quartz. CL characterization of these quartz types has indicated there were several growth generations within each type of quartz, and that crystalline quartz formation may have been periodically interrupted by chalcedonic quartz deposition, which was later recrystallized to quartz bands that contain densely-packed oriented fluid inclusions. These types of fluid inclusion bands sometimes occur between generations of crystalline quartz growth, demonstrating that quartz within at least some gold telluride veins likely formed during several independent quartz-forming stages. Further, paragenetic interpretations in chapter 2 indicate that vein quartz formed before the gold telluride stage, as gold telluride minerals are
commonly rooted upon substrates of quartz and associated gangue minerals, but do not occur as inclusions within quartz and associated gangue minerals. Therefore, the observations that fluid inclusion assemblages in quartz are significantly more complex than previously recognized and that quartz did not form simultaneously with gold telluride minerals, demonstrates that analyses of fluid inclusion assemblages in quartz is a poor proxy for determining the fluid conditions present at the time of gold telluride formation.

Detailed characterization of pyrite using BSE imaging and trace element analysis by EMP demonstrated that at least five compositionally distinct stages of pyrite occur across the four ore types within the deposit. The first stage of pyrite is characterized as trace element-poor pyrite grains that formed as pseudomorphs during sulfidation of iron-rich minerals (e.g., hematite). This first stage of pyrite development correlates with the first mineralizing stage outlined above. The second stage of pyrite is characterized as trace element-rich overgrowths on stage 1 pyrite, which within mineralized fractures has interfaces with stage 1 pyrite that indicate a preceding period of pyrite dissolution. The second stage of pyrite growth generally contains moderate to strong As-enrichment with low to moderate enrichment in Au, Cu and Sb. Formation of stage 2 pyrite grains (with cores of stage 1 pyrite) are correlated with the second mineralizing stage and appear to be a common component within many mineralized zones. These composite pyrite crystals generally preserve outer grain boundaries that are euhedral. However, within gold telluride-bearing quartz veins, composite stage 1-2 pyrite grains commonly show evidence for additional dissolution that occurred prior to overgrowth by additional stages of trace element-poor and trace element-rich pyrite (pyrite stages 3-5) that formed during the fifth mineralizing stage. Within pyrite stages that are rich in trace elements, the relationship between gold and arsenic enrichment indicates that the majority of gold analyzed in pyrite is in solid solution. The complex trace element signatures and dissolution textures preserved within the five stages of pyrite that occur within gold telluride veins indicate a complex history of hydrothermal fluid evolution within the deposit, and characterization of the different stages of pyrite has demonstrated that pyrite in the Cripple Creek deposit can be used to track the evolution of the deposit with time.

Pyrite characterization additionally demonstrated that euhedral grains of composite stage 1-2 pyrite are preserved within the strongly K-feldspar altered wall rock to veins containing trace element-rich pyrite and gold telluride minerals, which indicates that large-scale K-feldspar alteration developed after the third stage of mineralization (which produced the Ag-Pb-(Au) telluride minerals with galena, and postdates the formation of trace element-rich stage 2 pyrite and microcrystalline hypogene gold), but prior to or at the beginning of the fifth stage of mineralization (which included partial dissolution of stage 2 pyrite, followed by renewed pyrite growth represented by stage 3-5 pyrite). This is an important observation that
for the first time constrains the timing relationship between secondary K-feldspar and other mineralizing stages, which was previously ambiguous.

Modeling of gold content in trace element-rich pyrite has additionally demonstrated that 1.0 - 4.7 g/ton of gold may be contained within trace element-rich pyrite from specific sampling locations, therefore demonstrating that gold-bearing As-rich pyrite may represent a significant and previously unrecognized resource within the Cripple Creek deposit.

4.2 Implications for in-mine Exploration at Cripple Creek

One of the aims of this study was to develop macroscopic indicators of areas that are mineralized with gold. However, the study found that aside from very high-grade material there is very little correlation to gold grade and what is seen in hand specimen. Sample pulp geochemical analysis may be a good substitute for visual indicators, as this study has demonstrated that moderate to high As concentrations in whole rock geochemical data derived from drill core pulps is likely a good indication of areas that have been mineralized with gold. Because drill core pulp sampling lengths are generally much larger than the mineralized fractures and veins contained within a given sample length, dilution may depress gold concentrations to the point that the sample (and its corresponding location) is not considered to be economically viable. However, because As concentrations in pyrite are generally 1-2 orders of magnitude higher than gold concentrations, As will still exist in detectable concentrations of several dozen or more ppm. For this reason, As is considered to be a good indicator of structures that have been mineralized with gold, even in instances where sample intercepts do not contain economically viable concentrations of gold. Therefore, on the basis of results in this study, As is considered to be the best pathfinder element in the Cripple Creek deposit, and multi-element geochemical assays of sample pulps may significantly aid in delineating previously unrecognized mineralized structures and ore zones. Handheld X-Ray Fluorescence analysis of drill core and in-pit structures may also prove useful in rapid determination of As-bearing (and thereby potentially gold-bearing) veins and structures.

This study has also shown that pervasive K-feldspar alteration occurred between stage 3 and stage 5 mineralization, and thus predates large-scale gold telluride mineralization. It has also been reported that large bodies of unmineralized rock have been altered to K-feldspar. Consequently, it appears that at least some of the fractures that acted as fluid conduits for K-feldspar altering fluids were closed at the time of gold telluride mineralization. Therefore, pervasive K-feldspar alteration is not necessarily a direct vector toward, or an indicator of nearby high-grade gold telluride veins. Furthermore, this study has shown that some high-grade ore zones have experienced little to no secondary K-feldspar alteration. Therefore, areas that have not experienced K-feldspar alteration should not be assumed to be barren of gold.
SUPPLEMENTAL ELECTRONIC FILES

All appendix material for this thesis is included in digital format in the accompanying digital appendix. The supplemental material is categorized by folder and a description of each folder’s contents is outlined below:

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Analytical Methods</td>
<td>A PDF file describing the sampling methods and analytical methods used in this study. This document also contains descriptions of instrument operating conditions.</td>
</tr>
<tr>
<td>Supplemental Images</td>
<td>Folders containing categorized supplemental images.</td>
</tr>
<tr>
<td>BSE Images</td>
<td>Additional high contrast backscattered electron (BSE) images of pyrite, telluride minerals, and thin sections (JPEG and TIFF).</td>
</tr>
<tr>
<td>CL Quartz Images</td>
<td>Additional optical cathodoluminescence (CL) images of quartz from telluride and non-telluride-bearing quartz veins (JPEG and TIFF).</td>
</tr>
<tr>
<td>QEMSCAN Mineral Maps</td>
<td>JPEG versions of all false-color mineral maps produced through Quantitative Evaluation of Minerals by SCANning (QEMSCAN), as well as a JPEG image of the color key for these maps.</td>
</tr>
<tr>
<td>Scans of Thin Sections</td>
<td>Digital scans of each thin section used in this study, scanned using non-polarized transmitted light.</td>
</tr>
<tr>
<td>Supplemental Data Files</td>
<td>Files containing supplemental data in PDF form.</td>
</tr>
<tr>
<td>EMP Pyrite Data</td>
<td>PDF file containing element concentration data for all Electron Microprobe (EMP) measurements collected from trace element-poor and trace element-rich pyrite analyzed in this study.</td>
</tr>
<tr>
<td>Whole Rock Geochemistry</td>
<td>PDF file of element concentration data from each sample analyzed in this study. See METHODS for description of geochemical analysis techniques.</td>
</tr>
</tbody>
</table>