GEOLGY, VEIN PETROGRAPHY AND MINERAL CHEMISTRY OF THE
NORTH AMETHYST DEPOSIT, CREED MINING DISTRICT, CREED, COLORADO

by
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A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

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ABSTRACT

The Oligocene Creede mining district represents one of the most prolific intermediate sulfidation-state epithermal silver and base metal mining districts worldwide. The district is located in the Central San Juan Mountains of southwestern Colorado. Since 1889, the mining at Creede yielded approximately 4.1 million tonnes of ore containing 2,400 t Ag and approximately 139,000 t Pb, 41,000 t Zn and 2,500 t Cu. The base metal and silver production has come from a number of major base metal and silver rich deposits in the central and southern parts of the Creede district located close to the town of Creede. However, the North Amethyst deposit, located at the northern end of the Creede district is known to contain significant precious metal (Au-Ag) mineralization.

The ores of the North Amethyst deposit are crustiform banded, intermediate sulfidation-state epithermal veins. The veins filled dilatant zones of the Amethyst and Equity faults at or near the intersection of the two major structures. The vein zones occur at elevations from 11,288 to 8,820 ft which are hosted in a flow-laminated to massive dacite to rhyolite lava dome and a rhyolitic ash flow tuff. Mineral exploration drilling conducted from 2011-2013 at the North Amethyst deposit allowed for the unique opportunity to reevaluate how the Au-rich veins of the North Amethyst deposit formed.

Macroscopic study of the drill core, combined with detailed microscopic and microanalytical techniques resulted in the definition of multiple epithermal vein stages that occurred at the North Amethyst deposit and the identification of a paragenetic sequence of mineral formation. The mineralogical and textural characteristics of the vein stages were determined by optical microscopy and back-scatter electron imaging on a scanning electron microscope. The petrographic analyses included the documentation of quartz, adularia and calcite textures to determine boiling and non-boiling conditions and interpret correlations between texture and metal grades. Electron microprobe analysis was performed on sulfide minerals to determine the geochemical characteristics of the vein stages. Particular emphasis was placed on the compositional analysis of sphalerite to constrain the temperature and sulfidation state of the hydrothermal liquids which formed the various ore bearing vein stages.
Four sulfide bearing vein stages were observed at the North Amethyst deposit and are each punctuated by a breccia or a gangue stage. The earliest of the four sulfide bearing veins is the Alpha stage which was observed from the deep to shallow elevations of the deposit. Alpha stage veins exhibit boiling textures at all depths. The hydrothermal liquids forming the Alpha stage are interpreted to have cooled as they ascended from deep to shallow levels of the deposit, acquiring a higher sulfidation state (1.3 to 0.24 mole % FeS). Following the Alpha stage, the precious metal (Au-Ag) bearing vein stage known as Beta stage was formed. The Beta stage is weakly mineralized at depth but is well developed in the shallow portions of the deposit. Beta stage veins are spatially associated with Alpha stage veins. Compositional variations in the sphalerite are less pronounced. However, the paragenesis of Beta stage indicates a shift from high to low sulfidation states through the transition from argentite-acanthite to native silver at the end of the mineral deposition sequence. The late base metal sulfide-rich Stage-1 was observed in the deep part of the deposit and the Fe-poor Base Metal Sulfide stage was observed at mid-elevation of the North Amethyst deposit. These two base metal and silver stages correlate with those recognized in the central and southern parts of the Creede mining district.
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Units

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<thead>
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<th>Description</th>
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<tr>
<td>Å</td>
<td>Angstroms</td>
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<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeters</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>δD</td>
<td>Hydrogen isotope ratio</td>
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<tr>
<td>δ₁⁸O</td>
<td>Oxygen isotope ratio</td>
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<tr>
<td>elev</td>
<td>Elevation</td>
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<tr>
<td>EMP</td>
<td>Electron microprobe</td>
</tr>
<tr>
<td>ft</td>
<td>Feet</td>
</tr>
<tr>
<td>g/t</td>
<td>Gram per (metric) ton</td>
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<tr>
<td>HCl</td>
<td>Hydrogen chloride</td>
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<tr>
<td>H₂S</td>
<td>Hydrogen sulfide</td>
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<tr>
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<td>m</td>
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</tr>
<tr>
<td>Ma</td>
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<tr>
<td>μm</td>
<td>Micrometer</td>
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<tr>
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<td>Millimeters</td>
</tr>
<tr>
<td>nA</td>
<td>Nano amps</td>
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<tr>
<td>NaCl</td>
<td>Sodium chlorite</td>
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<td>oz</td>
<td>Ounce</td>
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<tr>
<td>%</td>
<td>Percent</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>t</td>
<td>(Metric) ton</td>
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<tr>
<td>T</td>
<td>Temperature</td>
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<tr>
<td>U-Pb</td>
<td>Uranium-Lead</td>
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<td>wt%</td>
<td>Weight percent</td>
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---

xii
Elements
As    Arsenic
Ag    Silver
Au    Gold
Bi    Bismuth
Ca    Calcium
Cd    Cadmium
Cl    Chlorine
Cu    Copper
Fe    Iron
H    Hydrogen
Mn    Manganese
Na    Sodium
Pb    Lead
Se    Selenium
Sb    Antimony
Te    Tellurium
W    Tungsten
Zn    Zinc

Drill cores
EQU    Equity Underground
NAU    North Amethyst Underground
WE1031 West Equity 1031

Rock units
Qt    Quaternary Sediments
Tba    Andesite of Bristol Head
Tbc    Campbell Mountain welding zone
Tbcb   Basal Campbell Mountain
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<td>Tbcx</td>
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<td>Intracaldera sedimentary rocks of the Bachelor caldera</td>
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<tr>
<td>Tbw</td>
<td>Willow Creek welding zone</td>
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<td>Tbwg</td>
<td>Windy Gulch welding zone</td>
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<tr>
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<tr>
<td>Tcid</td>
<td>Captive Inca Lava Dome</td>
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<tr>
<td>Tfg</td>
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<td>Trc</td>
<td>Rat Creek Tuff</td>
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<tr>
<td>Tsv</td>
<td>Stewart Peak Andesite</td>
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<td>Wason Park Tuff</td>
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Calderas

- B  Bachelor
- C  Creede
- Co Cochetopa
- LC Lake City
- LGn La Garita North
- LGs La Garita South
- PL Platoro
- S  Silverton
- SJ San Juan
- Sm Summitville
- SR South River
- SL San Luis
- Un Uncompahgre
Grain sizes and textures

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<td>Comb</td>
<td>Comb Quartz</td>
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Minerals

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<tr>
<td>Sp</td>
<td>Sphalerite</td>
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<td>Uytenbogaardtite</td>
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**Vein Stages**

α  Alpha stage  
β  Beta stage  
B.M.S.  Base metal-silica association  
Br-1  Breccia-1  
Br-2  Breccia-2  
Br-3  Breccia-3  
Fe-poor B.M.S  Iron-poor Base metal sulfide stage  
Mn-Au  Manganese-gold association  
Stg-1  Stage-1  
Stg-2  Stage-2  
Stg-3  Stage-3
ACKNOWLEDGEMENTS

I am grateful to my advisor Dr. Thomas Monecke for accepting me into the graduate program and overseeing this project to completion and Jonathan Moore at Rio Grande Silver Inc. for allowing me to conduct this research on the exploration drill cores. I appreciate the unique and exciting opportunity to conduct and finish this project. Thank you for your support, insights and encouragement from project start to finish. I appreciate the continued guidance and discussions from my committee members Drs. Katharina Pfaff and Elizabeth Holley throughout the process of this thesis. I greatly appreciate the analytical assistance I received for this research by Dr. Alex Blum at the United States Geological Survey, Boulder, for X-ray diffraction analysis, Dr. Julien Allaz at the University of Colorado-Boulder for electron microprobe analysis and Mr. Gary Zito at the Colorado School of Mines for help with the scanning electron microscope.

I am grateful for the financial support provided by the Society of Economic Geologist’s Graduate Student Research Grant, Colorado Scientific Society and Rio Grande Silver Inc.

Lastly, I would like to thank those who have supported me with love and friendship throughout my graduate career including my encouraging and loving parents, Nicolas and Yong, my brother Daniel and my colleagues at the Colorado School of Mines, Robert Charnock and Ben Frieman for their support and friendship throughout this project which has made it a wonderful experience. I would also like to thank former mentors and professors who inspired me to pursue a career in geoscience their knowledge, support and encouragement has helped lead me to this point; Drs. Hannan LaGarry, Susan Beatty, Suzanne Anderson, Stephen Mojzsis, Matthew Pranter, Joseph Smyth, Kevin Mahan, Alex Blum, Dennis Eberl, Jonathan Caine and William Atkinson.
CHAPTER 1
INTRODUCTION

This chapter provides an introduction to the research carried out as part of this thesis. The key scientific problems are identified and the scope of the research is summarized. This chapter also details the organization of the thesis.

1.1. The Creede Mining District

The Oligocene Creede mining district, located in the central San Juan Mountains of southwestern Colorado, represents one of the most prolific intermediate sulfidation-state epithermal silver and base metal mining districts worldwide. The district has been mined since 1889 (Steven and Ratte, 1965), and has yielded approximately 4.1 million tonnes of ore containing 2,400 t Ag. In addition, approximately 139,000 t Pb, 41,000 t Zn, and 2,500 t Cu have been recovered throughout Creede's mining history (Barton, 2000). The epithermal veins of the Creede mining district are localized along north-trending normal faults which constitute an apical graben hosted in rhyolitic to rhyodacitic ash flow tuffs of the upper Oligocene Bachelor caldera (Steven and Ratte, 1965; Heald et al., 1987).

Extensive exploration and mining in the Creede district has revealed the presence of a pronounced metal zonation. Historically, the central and southern parts of the Creede district have been the most productive with a number of major base metal and silver rich deposits located close to the town of Creede. Gold has only been recovered as a byproduct, with a total past production of about 4.7 t Au (Barton, 2000). However, the discovery of the North Amethyst vein system in 1983 by Homestake Mining Company established the occurrence of high-grade gold and silver veins in the northern part of the district.

At the recently delineated North Amethyst deposit, high-grade Au-Ag epithermal vein zones occur along the intersection of two steeply dipping faults, namely the north-south-striking extension of the Amethyst normal fault and the east-west-striking Equity reverse fault. Economic precious metal grades occur over an elevation difference of at least 600 m. Although the
geochemical conditions of silver and base metal mineralization in the central and southern parts of the Creede district are well known, the processes of vein formation at the North Amethyst deposit and the reasons for gold enrichment in this part of the district are currently poorly understood.

1.2. Scope of Study

Previous research on the North Amethyst deposit has established that precious metal enrichment is confined to an early vein stage that is characterized by the occurrence of fine-grained ore minerals within a brownish-red, pink or light colored gangue mineral association dominated by Mn-rich carbonate and silicate minerals. These veins are crosscut by crustiform banded, coarse-grained base metal-rich sulfide veins that contain a gangue mineral association of quartz, chlorite, and hematite (Foley, 1990). The paragenesis of the late, base metal veins and the subsequent vein stages at the North Amethyst deposit share many mineralogical and geochemical similarities to the vein stages and paragenesis observed in the central and southern parts of the Creede mining district. Based on this observation, it has been suggested that this district-wide correlation is the result of a distinct hydrothermal event that postdated the previous manganese-rich and precious metal-rich veins in the north (Barton, 2000).

Although the vein system of the North Amethyst deposit has been previously investigated from underground exposures in exploration drifts (Foley, 1990), new diamond drill cores obtained during a recent (2011-2013) precious metal exploration program by Rio Grande Silver Inc. now provides the opportunity for a comprehensive examination of the vein system over hundreds of meters of elevation difference, spanning a wider study area than previous research conducted by Foley (1990).

The present study aims to provide a detailed description of macroscopic and microscopic vein textures to establish the paragenetic sequence for the early precious metal veins and late base metal rich veins at the North Amethyst deposit. Samples from the different vein stages at different elevations within the deposit were obtained and analyzed petrographically to determine their ore and gangue mineralogy and the paragenetic relationships between the different phases.
present. In addition, microanalytical work was conducted to characterize the compositional variability of some of the main ore minerals formed throughout the paragenesis at different elevations within the deposit. The paragenetic study carried out as part of this research provides new insights into the evolution of the North Amethyst epithermal system, in particular temporal changes in sulfidation state during the formation of the deposit. This research contributes towards a better understanding of intermediate sulfidation state epithermal deposits and provides new guidelines for brownfields exploration at Creede.

1.3. Thesis Organization

This thesis is written as a monographic thesis and comprises several chapters. Chapter 1 provides an introduction and background to the study and describes the organization of the thesis. The subsequent two chapters describe the regional geology and tectonic setting of the Creede mining district (Chapter 2) and the geology of the North Amethyst deposit (Chapter 3). Chapter 4 provides a macroscopic description of the different vein types encountered at the North Amethyst deposit and their crosscutting relationships as observed in the field. The main research results of this thesis are summarized in Chapter 5 which describes the ore and gangue mineralogy of the different vein types encountered at the North Amethyst deposit as well as the textural observations that have been used to derive a paragenetic model for this deposit. The research described in Chapter 5 is primarily based on the application of optical petrography using transmitted and reflected light as well as scanning electron microscopy that was implemented to visualize textural relationships that could not be easily observed by optical techniques. Chapter 6 summarizes mineral chemical data obtained by electron microprobe analysis on minerals such as sphalerite, chalcopyrite, pyrite, galena, and electrum. The last two chapters of the thesis discuss the field observations and analytical results (Chapter 7) and summarize the findings (Chapter 8). Analytical data are provided in the Appendix.
CHAPTER 2
REGIONAL GEOLOGY

This chapter introduces and describes the evolution of the San Juan volcanic field and the regional and structural setting of the Creede mining district. In addition, this chapter presents and describes the main vein systems of the Creede mining district.

2.1. San Juan Volcanic Field

The Creede Mining District is located in the central San Juan Mountains of southwest Colorado (Fig. 2-1). The San Juan Mountains are a large erosional remnant of a once nearly continuous volcanic field that extended over much of the southern Rocky Mountains in the middle Tertiary (Lipman, 1970). The San Juan volcanic field lies mostly within the southwestern border of Colorado but extends into portions of northwestern New Mexico and covers an area of more than 25,000 km$^2$ (Fig. 2-1). The San Juan field is one of several major volcanic fields that developed along the eastern Cordilleran margin of the North American plate in the Tertiary which also includes the Sierra Madre Occidental, Mogollon-Datil and Challis fields (Lipman, 2000). The volcanic activity which formed the San Juan volcanic field and the other Tertiary fields of western North America was initiated by the changing subduction geometry along its western plate margin (Lipman, 2000).

Volcanism in the San Juan volcanic field started at 35 Ma with eruptions of predominantly andesitic lavas from scattered central volcanoes. The erupted lava flows and flanking volcanioclastic breccias coalesced which partly buried the volcanic centers and formed a large composite volcanic field between 35–30 Ma (Bethke et al., 1976; Barton et al., 2000). These early intermediate extrusive rocks constitute about two-thirds of the volume of volcanic rocks in the San Juan Mountains (Barton, 2000). At 30 Ma, volcanic activity changed to explosive, caldera forming, ignimbrite eruptions, which persisted until about 26 Ma (Lipman, 1970). The ignimbrite eruptions are dacitic to rhyolitic ash flow sheets and overlie the intermediate composition extrusive rocks (Lipman, 1970, 2000). The episodic ash flow eruptions in the San Juan volcanic field formed within clusters of intermediate-composition volcanoes and produced
three main regions of caldera complexes or clusters (Lipman, 2007). Ignimbrite activity started in the southeast region at 29 Ma and created the Platoro caldera complex, followed by eruptions from the western San Juan calderas and progressively focused in the central San Juan region at 27.8 Ma (Fig. 2-1; Lipman, 2007). The structures of the earlier calderas served to further nest younger ignimbrite eruptions and caldera subsidence (Lipman, 2007). At the Platoro caldera complex, five ignimbrites erupted sequentially within ~1.0 m.y. In the western San Juan volcanic field, the younger Silverton and Lake City calderas were each nested within earlier collapse depressions. In the central San Juan volcanic field, seven major eruptions occurred within the La Garita caldera (Lipman, 2007).

A general pattern of ignimbrite volcanism has been interpreted and reported of the San Juan volcanic field which begins with pre-caldera volcanism as eruptions of intermediate composition lavas from central volcanoes, followed by caldera forming rhyolitic-dacitic ignimbrite eruptions and post-collapse volcanism of intermediate composition lavas (Lipman, 2000, 2007). Another characteristic in this caldera forming pattern is resurgence within calderas which may result in a symmetrical dome or as a more complex geometrical form due to renewed magma ascent (Lipman, 2000). Following the period of recurrent caldera forming ignimbrite eruptions, volcanism in the San Juan volcanic field shifted to a bimodal assemblage of trachybasalt and silicic rhyolite at 26 Ma. This shift is interpreted to have occurred in response to regional extension during the establishment of the Rio Grande rift (Lipman, 2000). The result of the pre-caldera, intra-caldera and post-caldera eruptions is a succession of superimposed welded ash flow sheets (welded tuffs), interleaved with lava flows, volcanic breccias, air-fall pyroclastic rocks and sedimentary deposits (Steven and Ratté, 1965).

2.2. The Central San Juan Caldera Cluster

The Central San Juan caldera cluster is the last of the three major caldera clusters developed in the San Juan volcanic field. It possessed the highest frequency of caldera-forming eruptions and produced the largest volume of ash flow tuffs. The Central San Juan caldera cluster is primarily composed of lavas and ash flow sheets that are associated with nine major ignimbrite
eruptions that occurred between 28.3 and 26.5 Ma. The ignimbrite eruptions are dacitic to rhyolitic in composition and occurred concurrently with the episodes of caldera subsidence. The result is a cluster of overlapping calderas that encompasses an area of ~4,620 km².
2.2.1. Masonic Park Tuff

The Masonic Park Tuff represents the first deposit formed by a caldera-forming ignimbrite eruption in the central San Juan Mountains at 28.3 Ma (Lipman, 2000). It is a compositionally homogenous crystal-rich mafic dacite (62–65% SiO$_2$; 30–40% plagioclase, biotite, clinopyroxene). The tuff sheet shows a well-developed cooling zonation and flow-unit partings (Lipman, 2000). The source of the Masonic Park Tuff is not well constrained, but may have been located under the southern La Garita caldera (Lipman, 2000).

2.2.2. Pre-Carpenter Ridge Unit

The Pre-Carpenter Ridge Unit represents a flow-laminated to massive dacite to rhyolite unit located only in the northern portion of the Creede mining district (Fig. 2-2). The unit was first encountered by Homestake Mining Company during subsurface mineral exploration in 1987. It was described and referred to as a highly altered porphyritic dacite which was too altered to date isotopically (Lipman, 2000). Early reports interpreted the Pre-Carpenter Ridge Unit as a shallow and late intrusion (Lipman, 2000). However, more recent geological investigations from drill intercepts suggest that the Pre-Carpenter Ridge Unit is a lava dome or a hypabyssal intrusion that stratigraphically underlies, and is concordant with, the Willow Creek welding zone of the Carpenter Ridge Tuff (J. Moore, pers. comm. 2015).

The Pre-Carpenter Ridge Unit does not contain pumice or fiamme, but pyroclasts and breccias are clearly recognizable in the upper parts of this unit. The Pre-Carpenter Ridge Unit is crystal-rich and contains biotite, hornblende, plagioclase and quartz phenocrysts with a secondary alteration assemblage of fine-grained chlorite, minor phenocrysts of epidote and disseminated amounts of pyrite which had formed in response to hydrothermal alteration in the vicinity of the North Amethyst deposit (J. Moore, pers. comm. 2015). Zircon grains separated from the Pre-Carpenter Ridge Unit yielded U-Pb ages of 29.34–27.80 Ma, implying that this unit is broadly age-equivalent to the Masonic Park Tuff or perhaps the Fish Canyon Tuff (J. Moore, pers. comm. 2015). Currently, no surface exposure of the Pre-Carpenter Ridge Unit has been
Fig. 2-2: Stratigraphy of the volcanic host rocks of the Creede mining district showing the lithologic units, caldera sources and available age information (modified from Rio Grande Silver Inc., 2014).
recorded, but more information needs to be gathered to clarify the geological significance of this unit within the district geology of Creede and of the Central San Juan caldera cluster. Most importantly, the Pre-Carpenter Ridge Unit represents one of the host-rocks for the epithermal veins of the North Amethyst deposit.

2.2.3. La Garita Caldera (27.6 Ma)

The large (35x75 km) La Garita caldera formed at about 27.6 Ma through the eruption of the voluminous Fish Canyon Tuff (5,000 km$^3$). This tuff is gray to light brown and compositionally uniform. It is a crystal-rich silicic dacite (67.5–68.5 wt.% SiO$_2$), containing 35–50% plagioclase, sanidine, quartz, biotite, hornblende, sphene, apatite, zircon and Fe-Ti oxides (Lipman, 2000, 2006). Although the Fish Canyon Tuff is a single, weakly welded ash flow sheet which likely formed from a single sustaining eruption (Lipman, 2000), the overall geometry of the La Garita caldera is complex. The caldera is elongate and is characterized by three semi-equant segments as a result of a progressive sequence of subsidence from south to north (Lipman, 2000).

2.2.4. Bachelor Caldera (27.35 Ma)

The Bachelor caldera lies between the San Luis and Creede calderas and is the source of the highly differentiated rhyolite ash flows of the 27.35 Ma Carpenter Ridge Tuff that spread widely into adjacent areas and accumulated within the developing caldera as an intra-caldera tuff to a thickness of more than 1.5 km (Steven and Eaton, 1975). The Carpenter Ridge Tuff is a compositionally uniform crystal-poor rhyolite (72–74 wt.% SiO$_2$; 3–5% phenocrysts: sanidine, plagioclase and biotite).

Three distinct welding zones are distinguished within the Carpenter Ridge Tuff (Lipman, 2000). At the base of the Carpenter Ridge ash flow sheet is the Willow Creek welding zone which is light-gray with a fluidal texture whereby the pumice-flattening ratios are >10:1, and commonly 100:1 (Lipman, 2006). The middle of the ash flow sheet, the Campbell Mountain welding zone, is strongly to moderately welded with compacted pumice lapilli that have a
eutaxitic texture (Steven and Ratté, 1965; Lipman, 2000, 2006). The tuffs of the Campbell Mountain welding zone contain two distinct breccia zones. The Crystal-Rich Breccia Member is characterized by dark gray, feldspar-phyric, interleaved dacitic-latitic autobreccia flows. The Basal Campbell Mountain Member is a chaotic volcanic breccia, consisting of heterolithic volcanic clasts in a matrix supported by crystal ash of incipient Campbell Mountain eruption material with occasional clasts of Carpenter Ridge Tuff of the Willow Creek welding zone (J. Moore, pers. comm. 2015). Near the top of the ash flow sheet is the gray, porous, slightly to non-welded Windy Gulch welding zone (Lipman, 2000, 2006).

2.2.5. Blue Creek Tuff (27.2 Ma)

The Blue Creek Tuff (27.2 Ma), is a dacitic ash flow sheet (Lipman, 2000). The caldera source for the Blue Creek Tuff is completely concealed, but inferred to be beneath the southern parts of the Creede caldera (Lipman, 2000, 2006). The Blue Creek Tuff is densely welded and marked by the occurrence of a basal vitrophyre and a well-developed overlying flow-unit (Lipman, 2000). The Blue Creek Tuff has a maximum stratigraphic thickness of 200 m (Lipman, 2000). The tuff is fairly uniform and rich in phenocrysts, containing 30–40% plagioclase, biotite and augite. Compositionally, the Blue Creek Tuff is a dacite (65–68% SiO$_2$). Biotite Ar-Ar dating yielded an age for the Blue Creek Tuff of 27.11±0.16 Ma (Lipman, 2000).

2.2.6. South River Caldera (27.1 Ma)

The Wason Park Tuff is the product of an ignimbrite eruption (>500 km$^3$) which formed the South River caldera (Figs. 2-1 and 2-2; Lipman, 2000). It reaches its maximum thickness of 600–700 m as an intracaldera fill of the South River caldera (Lipman, 2000). The intracaldera dacitic tuff (63–67 wt.% SiO$_2$) is a dark gray massive densely welded tuff that comprises 30–40% plagioclase, sanidine, biotite and clinopyroxene (Lipman, 2006). Typical outflow tuff is characterized as a red-brown phenocryst-rich rhyolite which grades upward into silicic dacite (68–74 wt. % SiO$_2$) and comprises 10–30% plagioclase, sanidine, biotite and clinopyroxene (Lipman, 2006). The Wason Park Tuff has been dated at 27.17±0.12 Ma (Lipman, 2006).
2.2.7. San Luis Caldera (27–26.8 Ma)

The San Luis caldera cluster is situated around the intersection of the northern terminus of the Bachelor caldera and the northwestern margin of the La Garita caldera (Lipman, 2000). The caldera complex is a composite of three sizable and overlapping calderas which were formed by the eruption of three rapidly successive ignimbrites (Lipman and Sawyer 1988; Lipman, 2000; Lipman and McIntosh, 2008). The three ash flow tuffs that characterize the San Luis caldera cycle (27.0–26.8 Ma) are, from oldest to youngest, the Rat Creek Tuff, the Cebolla Creek Tuff and the Nelson Mountain Tuff. The three ash flows of the San Luis complex contain similar phenocryst assemblages and have compositions that vary from rhyolite to dacite (Lipman, 2000). They occur as outflow and intra-caldera ash flow sheets (Lipman, 2000). Post-collapse resurgence occurred after the infill of the caldera by the Stewart Peak Andesite (Lipman, 2000).

*Rat Creek Cycle*

The eruptive events of the San Luis caldera complex began roughly at 27.0 Ma. The caldera is the composite source of three sizable and rapidly successive ash flow sheets, referred to as the Rat Creek Tuff, the Cebolla Creek and the Nelson Mountain Tuff (Lipman, 2000). These ash flow eruptions occurred within less than 0.5 m.y. (\(^{40}\)Ar/\(^{39}\)Ar radiometric dating; Lipman, 2000).

The earliest ignimbrite to erupt from the San Luis complex is the Rat Creek Tuff (27.0 Ma), a light tan, non-welded to weakly welded crystal-poor rhyolite that grades upward into a more crystal-rich dacite (Lipman, 2000, 2008). Dark gray pumice fragments of andesitic appearance occur near the top of the tuff sheet where it is weakly welded (Lipman, 2000). The Rat Creek Tuff is the smallest of the San Luis ignimbrites in volume and the most restricted in regional extent (Lipman, 2000, 2008). The distribution of the Rat Creek Tuff is restricted due to erosion or is blocked by the precursor lava domes but it is well exposed in the southern and western margins of the San Luis complex (Lipman, 2000). Evidence for the Rat Creek caldera is limited because of cover by younger rocks, but excellent exposures of truncated and onlapping successions of Rat Creek rock units are present in the south and west (Lipman, 2000). The
northeast and northwest margins are inferred to be buried within younger subsidence structures related to Cebolla Creek and Nelson Mountain eruptions (Lipman, 2000).

Captive Inca Lava Dome

Precursor caldera volcanism occurred prior to the eruption of the Rat Creek Tuff, which resulted in the formation of four lava domes, referred to as the McKenzie Mountain dacite, the Captive Inca lava dome, the Table Mountain rhyolite and the Bristol Head andesite (Lipman, 2000). The lava domes are exposed near the southern margin of the San Luis caldera complex and its intersection with the western margins of the La Garita and Bachelor calderas (Lipman, 2000). Of the four lava domes, the Captive Inca lava dome is present within the map area of the North Amethyst deposit. The Captive Inca lava dome shows flow-banding with basal and upper carapace breccias (Lipman, 2000). The central area is defined by steeply inclined flow-banding and consists of glassy and devitrified zones that alternate at a centimeter to meter scale (Lipman, 2000).

Lavas and interleaved tuffs overlie the Rat Creek Tuff within the exposed portion of the Rat Creek caldera. The lavas are known as the Mineral Creek dacite which constitute the post-caldera volcanic rocks of the Rat Creek caldera (Lipman and Sawyer, 1988; Lipman, 2000, 2008). The Mineral Creek dacite is interpreted to have erupted shortly after the collapse of the Rat Creek caldera and it consists of biotite-rich porphyritic flow-banded lavas and intercalated lithic tuffs (Lipman, 2000). The Mineral Creek dacite is more silicic and biotite-rich than the overlying lava flows of the Stewart Peak Andesite, which are the post-caldera flows of the late Nelson Mountain caldera (Lipman, 2000).

Cebolla Creek Cycle

The deposition of the ash flows and lavas associated with the Rat Creek caldera was followed by the eruption of the Cebolla Creek ignimbrite at 26.9 Ma, which formed the second, overlapping caldera of the San Luis complex. The Cebolla Creek Tuff is a compositionally uniform, gray to light brown dacite that contains abundant plagioclase, hornblende and biotite phenocrysts (Lipman, 2000, 2008). The relative lack of sanidine is a distinctive characteristic of
the Cebolla Creek Tuff in comparison to the other dacite tuffs of the San Luis complex (Lipman, 2000, 2008). The Cebolla Creek Tuff overlies non-welded rhyolitic Rat Creek Tuff and is overlain by the younger Nelson Mountain Tuff described below (Lipman, 2000). The Cebolla Creek Tuff is believed to be distributed as widely as the younger, overlying Nelson Mountain Tuff, but its weak welding caused significant early erosion (Lipman, 2000). Most of the preserved outflow tuff is exposed in the northeast of the North Amethyst deposit. The densely welded intracaldera tuff crops out in only two small areas (Lipman, 2000).

Two groups of lava flows and associated rocks overlie the Cebolla Creek Tuff, namely the Mineral Mountain Rhyolite to the northwest and the dacite of East Willow Creek to the southeast (Lipman, 2000). The Mineral Mountain Rhyolite is a thick flow that is layered with phenocryst-poor silicic lava flows and minor amounts of interleaved tuffs with a base that is composed of volcanioclastic deposits (Lipman, 2000). The Mineral Mountain Rhyolite contains individual bulbous flows which can be several hundred meters thick and includes voluminous traction and carapace flow breccia (Lipman, 2000). Thick perlitic glass zones exist at the flow margins which are interpreted to reflect interaction with wet sediments or shallow lake deposits (Lipman, 2000). The flows of the Mineral Mountain Rhyolite are interpreted to represent post-collapse volcanism within the Cebolla Creek depression (Lipman, 2000). The dacite of East Willow Creek is a single phenocrysts-rich lava flow and overlies the intracaldera Cebolla Creek Tuff (Lipman, 2000). The East Willow Creek dacite is also more silicic than the Cebolla Creek Tuff (Lipman, 2000). The East Willow Creek dacite erupted shortly after caldera collapse with maximum exposed thickness at 75m but its areal extent is unknown (Lipman, 2000).

The margins of the Cebolla Creek caldera are largely concealed beneath the Nelson Mountain caldera. The caldera is inferred to be the largest caldera of the San Luis complex, with dimensions of 12 x 17 km (Lipman, 2008). The caldera walls are only partially preserved, but intact segments exist on the north, south and west sides (Lipman, 2000). Much of the evidence for the location and extent of the walls are seen by the truncation of the units of the Cebolla Creek cycle against younger sequences or by landslide breccias (Lipman, 2000).
Nelson Mountain Cycle

The third and last caldera forming eruption of the San Luis complex is the Nelson Mountain Tuff (26.8 Ma). The Nelson Mountain Tuff is the largest and most densely welded tuff of the San Luis complex (Lipman, 2000, 2008). This tuff unit includes a compositionally zoned regional outflow sheet and an approximately 800-m-thick intracaldera fill (Lipman, 2008). The outflow Nelson Mountain tuff is compositionally zoned in a similar manner to the Rat Creek Tuff as it grades from rhyolite upward into dacite (Lipman, 2000). The cap-rock commonly consists of a densely welded, dark, crystal-rich dacite (Lipman, 2000). A weakly welded and crystal-poor rhyolite tuff is located immediately below the cap-rock (Lipman, 2000, 2008). The exposed intracaldera Nelson Mountain Tuff is a thick crystal-rich dacite but the basal portion of the fill is more silicic (Lipman, 2000). The intracaldera dacite is referred to as the Equity facies of the Nelson Mountain Tuff which is truncated by the outflow Nelson Mountain Tuff along the caldera walls in some areas (Lipman, 2000).

Stewart Peak Andesite

The intracaldera and proximal outflow Nelson Mountain Tuff are overlain by lava flows to the southwest and northeast sides of the Nelson Mountain caldera (Lipman, 2000). Two types of volcanic deposits were identified, namely the Stewart Peak Andesite and the Baldy Cinco Dacite. The Stewart Peak Andesite contains lavas, breccias and associated flanking volcanioclastic deposits (Lipman, 2000). The Stewart Peak Andesite is aphanitic to porphyritic, with plagioclase and augite being the dominant phenocryst phases (Lipman, 2000). The Stewart Peak Andesite is overlain by younger rocks of the Baldy Cinco Dacite near its western depositional limit (Lipman, 2000). The Baldy Cinco Dacite constitutes a younger, large stratovolcano along the west side of the San Luis complex. These rocks are coarse-grained and porphyritic, with sparse and large sanidine phenocrysts (Lipman, 2000).

The Nelson Mountain caldera is the youngest collapse structure of the San Luis complex and therefore has the most clearly defined caldera margins. The Nelson Mountain caldera is a subequant area of about 7–8 km in diameter with well defined inward facing walls around the
entire perimeter of the caldera, except where locally overlapped by post-collapse lavas (Lipman, 2000). The southern caldera wall is especially well understood due to extensive exploration drilling in this area (Lipman, 2000). The south wall dips slightly northward (5–15°), but has an irregular map trace due to the combination of later faulting along the Creede graben and the rugged present day topography (Lipman, 2000). Lenses of landslide breccia are interleaved with the intracaldera Nelson Mountain Tuff in the lower intracaldera rhyolitic unit and are interpreted to have slid from over-steepened walls during caldera subsidence (Lipman and Sawyer, 1988). Two types of landslide breccias have been observed and reported by Lipman and Sawyer (1988). One consists of monolithic fragments of Fish Canyon Tuff, from the northeast caldera wall and the other contains early lava flows associated with the Rat Creek and Cebolla Creek cycles (Lipman, 1988, 2000).

**Resurgence of the San Luis Caldera**

The resurgence of the San Luis caldera occurred after the infilling of the Nelson Mountain caldera by the Stewart Peak Andesite (Lipman, 2000). The southern parts of the Nelson Mountain caldera underwent the highest amount of uplift (Lipman, 2000). Faults with large displacements bound the southern, western and eastern sides of the structurally highest block (Lipman, 2000). Much of the resurgence involved the Stewart Peak Andesite, which is cut by resurgent faults and tilted (Lipman, 2000). Several late granodiorite-monzonite intrusions (26.8–25.0 Ma) are exposed within and adjacent to the uplifted margins and are interpreted to represent late intrusions into the Stewart Peak Andesite (Lipman, 2000, 2007). Additionally, several small granodiorite bodies intruded the uplifted core of the San Luis caldera which may represent the high points of a larger resurgent intrusion (Lipman, 2000). These intrusive high points are associated with pyrite, argillic-altered rocks, faults and well-defined fractures but significantly mineralized rocks are absent (Lipman, 2000).

**2.2.8. Creede Caldera (26.7 Ma)**

The Creede caldera is the last caldera to form in the central San Juan caldera cluster. The caldera is a nearly circular block 10–12 miles in diameter and is positioned to the south of the
Bachelor caldera (Fig. 2-3; Steven and Ratté, 1965). The main subsidence of the Creede caldera is attributed to the ash flow eruption of the Snowshoe Mountain dacite (26.7 Ma) which accounted for 6,000 ft of welded tuff (Steven and Ratté, 1965). The Snowshoe Mountain Tuff is recognized as a strictly intra-caldera fill tuff. Its remnants are not found outside the Creede caldera (Steven and Ratté, 1965). The Snowshoe Mountain tuff is intercalated with sedimentary rocks, talus and avalanche debris in the upper 2000 ft (Steven and Ratté, 1965).

After subsidence, but before resurgence, the core of the caldera was a depressed floor and was occupied by shallow lakes and playas as well as carbonate-rich springs which formed travertine deposits (Barton et al., 2000). The sedimentary fill of the caldera floor is referred to as the Creede Formation. The sedimentary deposits include stream and lake sediments, tuffs and travertine (Steven and Ratté, 1965). The sediments filled the moat which was created by the subsidence and later resurgence of the central block of the Creede caldera. The trace of the moat is outlined by the present day Rio Grande River (Bethke, 1976). Post-collapse volcanic flows erupted through the ring fractures of the central dome and occurred concurrently with the accumulating sediments in the moat area (Steven and Ratté, 1965). The lavas and breccias of the 26.3 Ma Fisher dacite are interleaved with the sedimentary units of the Creede Formation (Steven and Ratté, 1965).

2.3. Structure

The structural boundaries of calderas are single ring faults or composite ring fault zones that dip steeply (Lipman, 2000). Caldera resurgence is due to renewed magmatic pressure and ring vent eruptions of ash or lava flows are common during these events (Lipman, 2000). The formation of the La Garita caldera and its associated structures are the earliest documented period of large scale faulting in the central San Juan Mountains (Lipman, 2000). The structures associated with the collapse of the La Garita caldera are interpreted to have influenced the trends of all subsequent faulting events associated with the younger calderas (Lipman, 2000). Post-caldera faults of the La Garita caldera trend north-northwest which parallel the southwest caldera margin (Lipman, 2000). The South River, Bachelor, San Luis and Creede calderas developed in a N–S orientation along the western structural margin of the La Garita caldera. The Bachelor, San
Luis and Creede calderas are better preserved and are also the most significant for providing the structural control for the mineralization of the Creede district veins (Steven and Eaton, 1975; Lipman, 2000).

The regional pattern of northerly trending normal faults are the most dominant structural features in the Central San Juan caldera cluster and appears to be a result of caldera subsidence and resurgence (Lipman, 2000). A series of normal faults formed in response to the resurgence of the Bachelor caldera define a keystone graben, referred to as the Creede graben (Lipman, 2000). The core of the Bachelor caldera domed during resurgence which resulted in the collapse of a series of blocks near the top of the dome and created longitudinal normal faults extending N–NW along the crest axis of the elongate dome (Steven and Eaton, 1975; Lipman, 2000).

The faults which characterize the Creede graben are the Alpha-Corsair and Bulldog Mountain faults and the west dipping Amethyst and Solomon Holy Moses faults (Fig. 2-3; Steven and Ratté, 1965; Lipman, 2000). These faults underwent a complex history of movement and reactivation (Lipman, 2000). The displacement of these faults involves major offsets of all tuff sheets deposited after the formation of the Bachelor caldera, including the Wason Park and Nelson Mountain Tuffs. Movement along the faults continued during vein mineralization at 25.1 Ma (Lipman, 2000).

2.3.1. Alpha-Corsair Fault

The Alpha-Corsair fault defines the western margin of the Creede graben (Fig. 2-3). The Alpha-Corsair fault trends N–NW and dips between 50–60° to the northeast (Steven and Ratté, 1965). Movement of the Alpha Corsair fault occurred after eruption of the Fisher dacite (Steven and Ratté, 1965). The fault displaces about 1,000–1,200 ft of Fisher dacite, the Wason Park rhyolite and the Windy Gulch and Campbell Mountain welding zones of the Carpenter Ridge Tuff (Steven and Ratté, 1965). The Alpha-Corsair fault splits in two main branches, a western and eastern branch which then appear to reconverge in the north (Fig. 2-3; Steven and Ratté, 1965). The northern limit of the Alpha Corsair fault has not been determined (Steven and Ratté, 1965). The hanging wall block is highly damaged and consists of subsidiary faults and shear
zones that are at low angles and trend parallel to the main fault (Steven and Ratté, 1965). These associated structure of the hanging-wall host breccias and variable amounts of mineralized rock (Steven and Ratté, 1965).

2.3.2. Bulldog Mountain Fault

The Bulldog Mountain fault is composed of two well-defined curved faults and defines one of the east dipping normal faults of the Creede graben (Steven and Ratté, 1965). The western fault is convex to the west and the eastern fault is convex to the east, enclosing a lens-shaped block that pinches out in both directions (Fig. 2-3; Steven and Ratté, 1965). The faults trend N–NW. The western fault dips 60–70° to the east while the eastern fault dips 65° to the east (Steven and Ratté, 1965). These faults displace the Creede Formation, Wason Park Tuff and the Carpenter Ridge Tuff (Steven and Ratté, 1965). On the western branch, the rock units are offset about 240 ft, while the eastern branch has an offset of about 120 ft (Steven and Ratté, 1965). In the north, at the junction of the two main branch faults, the Bulldog Mountain fault extends northward near the latitude of the Equity fault. The northern section of the fault displaces the Carpenter Ridge Tuff and rocks of the San Luis caldera.

2.3.3. Amethyst Fault

The Amethyst fault is one of the west dipping normal faults of the Creede graben (Fig. 2-3). The fault trends S–SE with dip angles that range between 50–70° to the southwest (Steven and Ratté, 1965). The Amethyst fault extends from just outside the vicinity of the town of Creede and continues past the Equity fault within the San Luis caldera, making it the longest fault in the district and the only fault of the Creede graben to extend beyond the Bachelor caldera. The Amethyst fault was active during subsidence of the Bachelor caldera (Ancestral Amethyst) and periods of reactivation coincided with the subsidence and resurgence of the Creede caldera (Steven and Ratté 1965). The Amethyst fault displaces the Fisher Dacite, the Creede Formation and the older volcanic units of the Bachelor and San Luis calderas (Steven and Ratté, 1965). The northern segment of the Amethyst fault branches out and then reconverges near the intersection with the Equity fault. The total displacement on the Amethyst fault is greater than any other fault.
on the east side of the Creede graben (Steven and Ratté, 1965). Although the total displacement remains uncertain, the Wason Park rhyolite has been displaced by as much as 600–700 ft. The Amethyst fault is associated with preexisting structures created by subsidence of the Bachelor caldera and the trace of the Amethyst fault is controlled by late movement of those preexisting faults (Steven and Ratté, 1965).

The hanging-wall of the Amethyst fault is highly fractured. In the southern segment, the fractures are subparallel to the fault, but dip more steeply. Minor antithetic faults are also found which are nearly vertical or dip steeply to the northeast (Steven and Ratté, 1965). Many of these fractures are filled by veins (Steven and Ratté, 1965). In the northern segment, hanging-wall fractures form a highly sheared zone as much as 100 ft wide adjacent to the main fault (Steven and Ratté, 1965). Farther in the hanging wall, subsidiary faults form intersecting, nearly vertical conjugate fractures. These structures have formed a “maze” of intersecting veins (Steven and Ratté, 1965). Areas of highly concentrated conjugate fractures have provided some of the most productive veins in the district, one of which is the OH vein, a mineralized zone of integrated fractures that extends 4,500 ft northwest from the Amethyst fault (Steven and Ratté, 1965). The OH fracture zone experienced strike-slip movement (Steven and Ratté, 1965).

2.3.4. Solomon-Holy Moses Fault

The Solomon-Holy Moses fault is a N-S striking normal fault that defines the east margin of the Creede graben (Fig. 2-3). The Solomon-Holy Moses fault has a dip of about 60° to the west and it forms a well-defined middle segment which splits into many branches in the north and south (Steven and Ratté, 1965). The fault displaces the intra-caldera Carpenter Ridge Tuff. The displacement of the Campbell Mountain and Willow Creek welding zones is as much as 300–400 ft (Steven and Ratté, 1965). The fault has been interpreted to have been active during subsidence of the Bachelor caldera and reactivated during the resurgent period of the Creede caldera.
Fig. 2-3: Map of the Creede mining district showing the Creede graben and the locations of the San Luis and Creede calderas. Mineralized zones are highlighted (modified from Rye et al., 2000).
2.3.5. Equity Fault

The Equity fault is a steep north-dipping apparent reverse fault that extends across the northern part of the Creede mining district, transverse to the normal faults of the Creede graben (Fig. 2-3; Steven and Ratté, 1965). The Equity fault is assumed to have formed as a result of magmatic intrusion at depth during the resurgence of the San Luis caldera (Steven and Rate 1965; Lipman, 2000). The fault exposes the Carpenter Ridge Tuff on the north side of the fault on the hanging-wall side and the Nelson Mountain Tuff in the footwall to the south. The hanging-wall of the Equity fault is structurally much higher with about 1,300 ft of throw (Steven and Ratté, 1965). The Equity fault is interpreted to have experienced both normal and reverse movements at different locations and times influenced by the intersecting faults at its eastern and western margins, the Deerhorn and Amethyst faults, respectively, and subsidence of the Creede graben (Steven and Ratté, 1965).

2.4. Deposits of the Creede Mining District

The ore zones of the Creede mining district occupy highly permeable zones of the N–S-striking faults that define the Creede graben, or are located at the intersection of the northern extension of the Amethyst fault and the Equity reverse fault. Mineralization occurred approximately 1.5 Ma after the collapse of the Creede caldera. The Creede ores are intermediate sulfidation state epithermal veins, which display crustiform or colloform textures or occur as coarse-grained crystals in vugs.

The veins of the Creede mining district are dominantly hosted in the Carpenter Ridge Tuff which has undergone extensive potassic alteration through the formation of secondary feldspars (Barton and Bethke, 1977; Lipman, 2000). The Creede mining district is primarily known as a silver and base metal producer, where the overwhelming majority of metal production has come from the Amethyst, Bulldog Mountain, OH-and P-veins (Barton and Bethke, 1977). The Alpha-Corsair, Solomon-Holy Moses and the junction of the Amethyst and Equity faults are mineralized, but have not contributed significantly to the overall production in the district (Barton and Bethke, 1977).
The district exhibits a strong metal zonation from north to south. The Amethyst deposit is located in the north of the district at the intersection of the northern extension of the Amethyst fault with the Equity fault. The veins at the deposit contain early manganese and precious metal-rich assemblages which are not present in the deposits to the south. The veins south of the North Amethyst deposit primarily consist of native silver, argentite, galena, sphalerite, chalcopyrite, tetrahedrite and sulfosalts in a gangue of quartz, chalcedony, barite, rhodochrosite, chlorite, pyrite, hematite, fluorite, siderite and adularia (Barton et al., 2000). The mineralized faults in the central portion of the district, which includes the middle segment of the Amethyst and OH faults, contain veins that are dominantly characterized by base metal sulfides associated with chlorite and hematite gangue. The Bulldog Mountain and the southern segment of the Amethyst fault contain veins that are dominantly characterized by high-grade silver minerals with barite gangue.
CHAPTER 3
GEOLOGY OF THE NORTH AMETHYST DEPOSIT

This chapter introduces and describes the geological setting of the North Amethyst deposit. The different rock units present within the deposit and its immediate vicinity are described. The chapter also discusses the structural setting of the deposit and reviews the subsurface geology of the North Amethyst deposit known from previous mining and exploration activity.

3.1. Exploration History

The North Amethyst deposit is located in the northern part of the Creede mining district, about 11 km to the northwest of the town of Creede. The deposit is located on the eastern side of upper West Willow Creek, immediately south of the Continental Divide.

Precious metal mineralization at the North Amethyst deposit was discovered in the early 1900’s. The ore zones were accessed by a 725-ft-long tunnel. The mine portal was located at an elevation of 12,150 ft, north of the Equity fault (Steven and Ratté, 1965). Mining activity of the historic Equity Mine was abandoned in 1930 due to low silver prices (Steven and Ratté, 1965). The mine did not produce large volumes of ore and did not yield high profits in comparison to the mines further to the south, but was known for its anomalously high Au and Ag grades (Steven and Ratté, 1965).

In 1974–1988, the North Amethyst area was revisited by Homestake Mining Company which resulted in the discovery of gold-rich epithermal veins during exploration drilling in 1983. This discovery led to the development of a new portal and underground workings and the establishment of the current Equity decline, which is located at lower elevation south of the historic Equity Mine portal. The new portal entrance was established by Homestake Mining Company in 1986, which is located at an elevation of 11,126 ft (Fig. 3-1). A 8,136 ft downward spiral ramp with a 15% declination was drifted to access the ore down to the 10,000 ft level. Mineral exploration and further mine development at the deposit ceased in 1988 due to the low silver prices (Barton, 2000).
Access to the Amethyst veins was closed until 2011 when Rio Grande Silver Inc., a subsidiary of Hecla Mining Company, began to conduct an extensive exploration drilling program at the North Amethyst deposit. The new exploration campaign significantly expanded on the work by Homestake Mining Company which led to a better understanding of the vein geometries and grade distributions in the known ore bodies along the Equity and Amethyst faults and in the deep portions of the deposit.
3.2. Surface Geology

The intermediate sulfidation epithermal veins of the North Amethyst deposit represent the northernmost known ores along the N-S-striking Amethyst fault. The ore zones are primarily localized along the intersection between the Amethyst fault and the E-W-striking Equity fault, which defines a strong structural control on the occurrence of this epithermal deposit.

3.2.1. Equity Fault Block

The northern extension of the Amethyst fault defines the western boundary of the Equity fault block, which is a distinct, fault-bounded uplift area that has a triangular shape in map view. The fault block is bounded to the south by the Equity reverse fault. The Deerhorn normal fault represents the eastern limit of the fault block (Fig. 3-1). At its surface, ash flows of the 27.35 Ma Carpenter Ridge Tuff are exposed within the Equity fault block. Rocks of the Willow Creek welding zone predominate in the west while the stratigraphically overlying tuffs of the Campbell Mountain welding zone are exposed in the eastern portion of the Equity fault block (Fig. 3-1).

Early workers have speculated that the uplift of the Equity fault block was the result of the emplacement of an intrusion during the resurgence of the San Luis caldera complex or caused by a later intrusion associated with the Creede mineralizing event (cf. Lipman, 2000). The hypothesis for the existence of an intrusion at depth below the Equity fault block was apparently substantiated by the discovery of an altered porphyritic dacite by Homestake Mining Company in 1987 (Lipman, 2000). This unit has been widely viewed as being the likely heat source for the Creede hydrothermal system (Foley et al., 1993; Lipman, 2000). However, more recent work has established that the porphyritic dacite is an older unit, described as the 29.34–27.80 Ma Pre-Carper Ridge unit in the previous chapter (J. Moore, pers. comm. 2015).

3.2.2. Amethyst Normal Fault

To the south of the North Amethyst deposit, the northern segment of the Amethyst fault splits and then reconverges near the intersection with the Equity fault. In this area, the Amethyst
Fig. 3-2: Geology of the North Amethyst deposit area and the Equity fault block. Cross-sections of the North Amethyst deposit along A-A’ and B-B’ are shown in Figures 3-3 and 3-4, respectively.
fault displaces rocks of the 26.8 Ma Nelson Mountain Tuff (Fig. 3-1; Steven and Ratté, 1965). The Amethyst fault then continues northward and traverses along a talus flanked ridge along upper West Willow Creek (Steven and Ratté, 1965). This segment of the Amethyst fault dips to the west and juxtaposes intracaldera Equity facies of the Nelson Mountain Tuff with the Campbell Mountain and Willow Creek welding zones of the Carpenter Ridge Tuff. The Amethyst fault on the western edge of the Equity fault block defines a convex shaped, west dipping lens of displaced Carpenter Ridge Tuff that pinches out in the north and south. The Amethyst fault continues north, where it intersects the Deerhorn normal fault (Fig. 3-1). The northernmost continuation of the Amethyst fault extends near the Continental Divide where it consists of several northeast-trending strands that are associated with pyrite-bearing altered volcanic rock (Lipman and Sawyer, 1988).

3.2.3. Equity Reverse Fault

The east-west striking Equity reverse fault forms the boundary between the flat-lying caldera fill of the Nelson Mountain Tuff to the south and the asymmetrically uplifted caldera fill of the Willow Creek and Campbell Mountain welding zones of the Carpenter Ridge Tuff to the north. The Equity fault cannot be traced confidently westward across the northern Amethyst fault or eastward across the Deerhorn fault (Lipman and Sawyer, 1988; Lipman, 2000).

The Equity fault is a steep north-dipping reverse fault (N 80°E). The surface expression of the fault is clearly visible above the Equity Mine portal (Fig. 3-2), which juxtaposes iron oxide-stained tuff of the Willow Creek welding zone of the Carpenter Ridge Tuff to the north against the Nelson Mountain Tuff to the south (Steven and Ratté, 1965).

3.3. Underground Geology

The underground geology of the North Amethyst deposit is well-known from underground exposures in the historic Equity Mine as well as Homestake’s Equity Mine. In addition, extensive drilling conducted by Rio Grande Silver Inc in 2011–2013 permits constraints on the deposit geology over 2,530 ft of vertical exposure from an elevation of 11,350 to 8,820 ft.
3.3.1. Geology of the Historic Equity Mine

The historic Equity Mine was accessed by a portal at a surface elevation of 12,105 ft, north of the iron-stained, surface exposure of the Equity fault (Steven and Ratté, 1965). A 725-foot-long tunnel was driven east-southeast, along the Equity fault, which crosses from tuff of the Willow Creek welding zone on the hanging-wall side of the fault into the Campbell Mountain welding zone on the footwall side at about 520 ft from the portal entrance (Steven and Ratté, 1965). The fault zone is marked by a zone of highly argillic-altered rock (Steven and Ratté, 1965). At the end of the tunnel, drifts were developed to the north and south. The southern crosscut extends south from the fault for nearly 340 ft into tuffs of the Campbell Mountain welding zone and follows a zone rich in gold and silver (Steven and Ratté, 1965; Foley, 1990). A drift located 30 ft north at the end of the tunnel intersected a zone of highly silicified fault breccia about 10–30 ft wide along the Equity fault. Workings along the Equity fault exposed similar silicified breccia over a length of about 420 ft (Steven and Ratté, 1965). A crosscut is driven about 280 ft north into the tuff of the Willow Creek welding zone from the Equity fault workings, which exposes bleached and slightly altered rocks cut by some minor mineralized fractures (Steven and Ratté, 1965).

3.3.2. Geology of Homestake’s Equity Mine

An exploration ramp was developed into the Amethyst and Equity faults by Homestake Mining Company in 1986. This ramp has a 15% declination and is 8,136 ft in length. Exploration workings consist of a series of levels which start at the Equity Mine portal at 11,126 ft elevation and end at the 10,000 ft level. The underground workings expose ore over a length of roughly 600 m along strike of the Equity (200 m) and Amethyst (400 m) vein systems (Foley, 1990). The majority of the underground workings are hosted in the footwall block of the Amethyst fault (Fig. 3-3). From the 10,750 ft level to the 10,400 ft level, the workings are within the Campbell Mountain welding zone of the Carpenter Ridge Tuff. At the 10,400 ft level, the workings extend 30 m north into the hanging wall of the Campbell Mountain welding zone. From the 10,400 ft level to the 10,000 ft level, the underground workings are hosted within the tuff of the Willow Creek welding zone in the Amethyst footwall (Fig. 3-3). The workings in the 10,250 ft level
extend 135 ft north into the Amethyst hanging wall which are hosted within the Campbell Mountain welding zone. The North Amethyst fault dips west and offsets the San Luis caldera rocks on the hanging wall side from the Campbell Mountain welding zone on the footwall side by approximately 550 ft.

3.3.3. Results of the 2011–2013 Exploration Program

Most of the Creede mining district is currently held by Rio Grande Silver Inc. The property includes a 21 square mile consolidated land package, which encompasses a large portion of the Bulldog, northern extension of the Amethyst, Equity and northern Alpha Corsair veins. Rio Grande Silver Inc. reopened and rehabilitated Homestake’s Equity Mine in 2011 to conduct an exploration drilling campaign for the purpose of defining the precious metal resources along the Amethyst and Equity veins and to test the continuity of the gold-silver ore zones established by Homestake Mining Company. The surface and underground exploration drilling campaign conducted in 2011–2013 outlined multiple zones of high-grade gold and silver bearing veins, but did not generate sufficient tonnage to justify immediate development (J. Moore, pers. comm. 2015). Three zones of significant gold and silver mineralization were recognized in the North Amethyst deposit which include the mid-elevation levels (10,165–10,620 ft above sea-level) of the Amethyst normal fault, at high elevations (10,540–11,165 ft above sea-level) within the Equity reverse fault and the low elevation (8,820–9,280 ft above sea-level) intersection of the Amethyst and Equity faults.
Fig. 3-3: Cross-section of the North Amethyst deposit at a high angle to the Equity reverse fault (section A-A’). See Figure 3-2 for location. Abbreviations: Tbw = Willow Creek welding zone; Tbc = Basal Campbell Mountain Member; Tbc = Campbell Mountain welding zone; and Tn = Nelson Mountain Tuff.
Fig. 3–4: Cross-section of the North Amethyst deposit at a high angle to the Amethyst normal fault (section B-B’). See Figure 3-2 for location. Abbreviations: Tbw = Willow Creek welding zone; Tbc = Basal Campbell Mountain member; Tbc = Campbell Mountain welding zone; Tbcx = Crystal-Rich Breccia Member; Tcid = Captive Inca lava dome; and Tn = Nelson Mountain Tuff.
CHAPTER 4
MACROSCOPIC CHARACTERISTICS AND DISTRIBUTION OF EPITHERMAL VEINS AT THE NORTH AMETHYST DEPOSIT

This chapter describes the macroscopic characteristics of the different vein types present at the North Amethyst deposit and their distribution within the deposit from recently obtained exploration drill cores. The macroscopic description of the veins provided the basis for the detailed petrographic and paragenetic study conducted as part of this thesis research.

4.1. Classification of Epithermal Veins

The ores of the North Amethyst deposit are crustiform banded, intermediate sulfidation-state epithermal veins. The veins filled dilatant zones of the Amethyst and Equity faults at or near the intersection of the two major structures. The vein zones occur at elevations from 11,288 to 8,820 ft (Fig. 4-1). Based on ore and gangue mineralogy, different vein types can be identified at the North Amethyst deposit.

Initial classification of vein types at the North Amethyst deposit was presented by Foley (1990). Her research focused on the portion of the deposit that was accessible during and shortly after the period of operation by Homestake Mining Company. The research conducted in the present study is based on the analysis of diamond exploration drill core obtained by Rio Grande Silver Inc. during their exploration campaign in 2011–2013. The exploration drilling yielded an extensive set of vein intercepts from known areas of the deposit which had been previously explored by Homestake Mining Company in the 1980’s and new intercepts from the deep portions of the deposit. Careful drill core inspection, compounded by microscopic investigations, confirmed that the classification scheme of Foley (1990) could also be used, with minor modifications, to describe the different vein types encountered in drill core. To be consistent with previous research, the nomenclature by Foley (1990) was adapted for the present study (Table 4-1).
Previous research (Foley, 1990) documented the occurrence of two types of vein mineralization at the North Amethyst deposit. Early veins are characterized by the occurrence of Mn-rich gangue minerals. These veins may have elevated precious metal grades although not all veins having this gangue mineral association are necessarily mineralized. The Mn-rich veins which may contain precious metal grades are referred to as the Mn-Au association by Foley (1990). The veins of this association have only been recognized in the North Amethyst deposit and are not present in the central and southern portion of the Creede mining district (Foley, 1990; Foley and Ayuso, 1994).
Veins of the Mn-Au association have formed during three distinct stages of mineralization (Table 4-1). Early Alpha stage mineralization resulted in the formation of rhodochrosite, manganocalcite, kutnohorite, rhodonite, pyroxmangite and minor quartz, with minor amounts of sphalerite, galena and pyrite that occur within the Mn-rich gangue mineral association. The Alpha stage was followed by two fine-grained ore stages, both of which contain electrum, uytenbogaarditie, tetrahedrite, Ag-sulfosalts and Ag- and base metal sulfides. These two stages of mineralization are referred to as Beta-1 and Beta-2 stages and are separated by a brecciation event, referred to as Breccia-1 (Foley, 1990).

The early veins of the Mn-Au association are crosscut by veins that show distinct enrichment in base metals. These veins belonging to the Base Metal-Silica (B.M.S.) association of Foley (1990) consists of three stages of mineralization, punctuated by periods of brecciation (Table 4-1). The stages that define the B.M.S. association of the North Amethyst deposit correspond to the mineralization stages observed in the central and southern portions of the Creede mining district. The textures, ore and gangue mineralogy, mineral compositions and fluid inclusion properties of the veins are nearly identical (Foley, 1990; Foley and Ayuso, 1994).

The formation of the B.M.S. association at the North Amethyst deposit was initiated with a brecciation event, consisting of fine-grained black quartz cement and fragments of Alpha and Beta stage vein material and wall-rock (Breccia-2) which is referred to as the “Transitional Breccia” since it marks the transition from the Mn-Au association to the B.M.S. associations (Foley, 1990). This is followed by a coarse-grained base metal sulfide assemblage (Stage 1) that primarily consists of sphalerite showing extensive chalcopyrite disease (Barton and Bethke, 1988), galena, pyrite and chalcopyrite as well as an Fe-bearing assemblage that consists of hematite, chlorite, pyrite and quartz (Foley, 1990). The base metal sulfide and Fe-rich assemblage of Stage 1 is followed by a breccia event, consisting of quartz and chlorite cement with fragments of wallrock and Stage 1 vein material (Breccia-3). Next is the open-space filling of calcite, adularia, fluorite and quartz (Stage 2). Stage 2 is brecciated and consists of Mn-calcite cement and fragments of earlier vein assemblages (Breccia-4). Late hydrothermal activity at the North Amethyst deposit is recorded by the local occurrence of Stage 3 which occurs as a lining...
Table 4-1: Classification of mineralization and brecciation events at the North Amethyst deposit (modified from Foley, 1990).

<table>
<thead>
<tr>
<th>Stage</th>
<th>North Amethyst Vein Mineral Assemblage</th>
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<tbody>
<tr>
<td></td>
<td>Base Metal-Silica (B.M.S.) association:</td>
</tr>
<tr>
<td>3</td>
<td>Mn-calcite &gt;&gt; quartz &gt; pyrite</td>
</tr>
<tr>
<td>Breccia-4</td>
<td>Mn-calcite cement, fragments of earlier assemblages, breccias and minerals, [wallrock]</td>
</tr>
<tr>
<td>2b</td>
<td>Quartz &gt; calcite &gt; rhodochrosite &gt; adularia &gt; fluorite &gt; chlorite = pyrite</td>
</tr>
<tr>
<td>Breccia-3</td>
<td>Quartz + chlorite cement, fragments of wallrock and coarse Stage-1 sulfides</td>
</tr>
<tr>
<td>1b</td>
<td>Quartz &gt; sphalerite &gt; galena &gt; pyrite &gt; chalcopryite &gt; tetrahedrite</td>
</tr>
<tr>
<td>1a</td>
<td>Quartz &gt; pyrite = hematite &gt; chlorite</td>
</tr>
<tr>
<td>Breccia-2</td>
<td>Quartz cement, fragments of α- and β-stages, wallrock, sedimentsed structures, black quartz breccia</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage</th>
<th>Mn-Au association:</th>
</tr>
</thead>
<tbody>
<tr>
<td>β-2</td>
<td>Sphalerite &gt; galena &gt; chalcopryite &gt; pyrite &gt; tetrahedrite &gt; Ag- and Au-minerals &gt; electrum {magnetite, hematite}</td>
</tr>
<tr>
<td>Breccia-1</td>
<td>Quartz cement, fragments of α- and β-1 stages</td>
</tr>
<tr>
<td>β-1</td>
<td>Sphalerite &gt; galena &gt; chalcopryite &gt; pyrite &gt; tetrahedrite &gt; Ag- and Au-minerals &gt; electrum {magnetite, hematite}</td>
</tr>
<tr>
<td>α</td>
<td>Rhodochrosite = quartz &gt; Mn-calcite = rhodonite &gt; K-feldspar &gt; sphalerite &gt; pyrite &gt; galena [barite]</td>
</tr>
</tbody>
</table>

Abbreviations: >>, much greater than; >, greater than; =, approximately equal; {} distribution unknown, local occurrence; [], molds.

of vugs or as crusts on earlier assemblages, is characterized by quartz, manganocalcite, trace pyrite, rhodochrosite and gypsum (Foley, 1990).

4.2. Spatial Distribution of Vein Types

High-grade intersections in the drill core obtained by Rio Grande Silver Inc. were closely examined as part of this study. The veins were evaluated based on grade, metal ratios, texture, as well as ore and gangue mineral assemblages. Based on the classification of Foley (1990), each vein intersection was initially classified to belong to the Alpha stage, the Beta stage, the B.M.S. association, or a combination thereof. The distribution of the different vein types was visualized by contouring their distribution in long sections along the Amethyst and Equity faults (Fig. 4-2).
Fig. 4-2: Sections through the North Amethyst deposit. A. Equity fault long section showing the locations of all the exploration drill holes intersecting the Equity fault and the vein types encountered. B. Amethyst fault long section showing the locations of all the exploration drill holes intersecting the Amethyst fault and the vein types encountered. The N3 and S2 orebodies were originally defined by Homestake Mining Company. The drill holes surrounded by the red squares were sampled for the present study.
The North Amethyst deposit comprises three main ore zones located along the Amethyst and Equity faults. The upper level of the deposit contains a narrow, but vertically extensive ore shoot that is associated with the E-W striking Equity reverse fault and is located at an elevation of 11,288 to 10,217 ft (upper and lower drill hole intercepts). This upper level ore body is known as the 108 ore shoot and it is composed of veins of the Mn-Au association. The middle-level veins are hosted in structures related to the N-S striking Amethyst normal fault. The mid-level veins are located at 10,706 to 9,872 ft elevation and are distributed approximately 400 m along strike. The ore zone defining the middle portion of the deposit contains veins of both the Mn-Au and B.M.S. associations. The veins in the deep portion of the deposit are located along the intersection of the Amethyst and Equity faults. The high-grade vein intercepts occur at elevations of 9,280 to 9,270 ft, with an additional intercept at 8,820 ft yielding modest grades. The deep level veins are dominantly composed of coarse-grained base metal sulfide minerals that are commonly associated with crustiform banded chlorite, hematite and fine-grained Mn-rich gangue mineral assemblage. The high-grade veins of the deep portion of the deposit occupy a relatively small area in comparison to the veins in the upper- and mid-levels due to the angle of the drill intercept. The deep level veins possess gangue assemblages that resemble both the Mn-Au and B.M.S. associations due to the presence of manganese gangue minerals and base metal sulfides with chlorite and hematite.

4.3. Description of Vein Intercepts

The following section contains a description of the vein intercepts investigated as part of the present study. The mineral and textural characteristics of the vein intercepts are described and the location of the vein samples collected in this study are presented (Table 4-2). Metal concentrations reported in this section are fire assay data and provided by Rio Grande Silver Inc.

4.3.1. Upper-Level Veins

High-grade Au-Ag vein intercepts in the upper portion of the deposit originate from a mineralized structure associated with the Equity fault known as the 108 orebody. The 108 orebody is narrow in width, but is a vertically extensive vein and breccia zone. The mineral and
textural characteristics along with metal grades dominantly reflect the Mn-Au association. The mineralization of the 108 orebody extends between 11,288 ft and 10,217 ft in elevation (Figs. 4-1 and 4-2). The veins intercepted in the 108 orebody have crustiform textures and are composed of fine-grained sphalerite, galena, chalcopyrite, Au-Ag minerals and pyrite in a gangue mineral assemblage of quartz, adularia, fluorite, calcite and Mn-rich carbonates. The veins are relatively narrow, approximately 0.2–1 ft in width, which filled fractures or breccias. The veins of the 108 ore shoot do not contain the Mn-rich silicate minerals rhodonite, inesite, caryopilite and pyroxmangite reported by Foley (1990), which comprise the Alpha stage of the Mn-Au association. The veins of the 108 orebody also do not contain the B.M.S. association.

Vein samples were collected from seven drill cores intercepting the 108 orebody between 11,165 and 10,540 ft in elevation (Figs. 4-1 and 4-2; drill holes EQU1285, EQU1255, EQU1260, EQU1147, EQU1262, EQU1263 and EQU1264). The drill cores yielded some of the highest concentrations of Au-Ag from the drill campaign which contains the Alpha and Beta stages of the Mn-Au association. The veins have a crustiform texture and appears as black, wavy streaks of fine-grained base metal sulfides and Au-Ag rich minerals that are hosted by a gangue assemblage consisting of manganese rich carbonates (rhodochrosite, kutnohorite and Mn-calcite), quartz, adularia, calcite and fluorite which have white, cream, beige and pink colors. The veins sampled from the 108 orebody consist of a fine-grained assemblage of Au-Ag minerals in a dominantly base metal-rich sulfide assemblage. This is considered to represent Beta stage mineralization of the Mn-Au association which usually appears black and fine-grained. The samples of Beta stage yielded concentrations from 7–207 ppm Au with an average of roughly 48 ppm Au. The samples were taken from the high-grade intervals from each of the seven drill core vein intercepts (Fig. 4-3A-J).

Drill hole EQU1285 contained a narrow high grade interval of Beta stage in a cloudy white matrix of fine-grained quartz, adularia, fluorite, calcite and Mn-rich carbonate minerals. The drill hole intersects the 108 orebody at an elevation of 11,165 ft (Fig. 4-2A). The Beta stage interval occurs at the 288.5–289 ft and this interval yielded 7 ppm Au, 657 ppm Ag, 169 ppm Cu, 310 ppm Pb and 360 ppm Zn (Fig. 4-3A). The Beta stage appears as a highly concentrated (5 mm) wide band of Beta mineralization which is in contact between gray, brecciated tuff of the
Willow Creek welding zone and light colored gangue matrix of Alpha stage. The brecciated wall rock contains gray, subrounded clasts of tuff in a white color, fine-grained quartz and Mn-carbonate matrix with minor argillic alteration and calcite present while the Alpha stage consists of fine-grained quartz, Mn-rich carbonates, calcite, fluorite and adularia.

Drill hole EQU1255 is located at an elevation of 10,940 ft in the 108 orebody (Fig. 4-2A). Three samples were collected from three intervals of the drill hole. At 241.5–242 ft, fine-grained black colored speckles of Beta stage minerals that faintly line across a fine-grained quartz-rich matrix and gray chalcedony of Alpha stage were sampled. The vein cuts brecciated tuff of the Willow Creek welding zone (Fig. 4-3B). This interval yielded 12 ppm Au, 0.14 wt.% Ag, 185 ppm Cu, 600 ppm Pb and 885 ppm Zn. A sample was also collected from 242.5–242.7 ft. The interval appeared dark red to black in a matrix of gray to white quartz-rich Alpha stage which is hosted in brecciated tuff of the Willow Creek welding zone (Fig. 4-3C). This interval yielded 50 ppm Au, 3,780 ppm Ag, 592 ppm Cu, 868 ppm Pb and 1282 ppm Zn. A sample was also collected from a very high grade interval from 245.2–245.7 ft, which appeared as a dark gray to black Beta-rich stage vein in a quartz-rich matrix of Alpha stage with minor amounts of Mn-rich carbonate minerals (Fig. 4-3C). This interval yielded 207 ppm Au, 1.5 wt.% Ag, 0.5 wt.% Cu, 1.6 wt.% Pb and 1.97 wt.% Zn. The Alpha stage gangue minerals are dominantly quartz-rich with minor amounts of Mn-rich carbonate minerals.

Drill hole EQU1260 is located at an elevation of 10,850 ft in the 108 orebody (Fig. 4-2A). One sample was collected from this drill hole at the 277–277.2 ft. Similar to EQU1255-241A, the vein is narrow (0.5–1 inch) and dominated by a quartz and calcite within an open fracture of a brecciated tuff of the Willow Creek welding zone. The quartz and calcite gangue is speckled with fine-grained black sulfosalts of Beta stage (Fig. 4-3E). The mineral and textural characteristics from this interval are similar to EQU1255-241A. This interval yielded 19 ppm Au, 0.17 wt.% Ag, 190 ppm Cu, 0.13 wt.% Pb and 0.22 wt.% Zn.

Drill hole EQU1147 is located at an elevation of 10,820 ft in the 108 orebody (Fig. 4-2A). Three samples were collected continuously from 284.3–284.8 ft which accounts for the full
Table 4-2: Summary of the vein intercepts analyzed in this study. The drill holes, elevations, orebody, samples and respective metal grades are given.

<table>
<thead>
<tr>
<th>Drill Hole</th>
<th>Elevation</th>
<th>Samples</th>
<th>Metal grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQU1285</td>
<td>11,165 ft – 108 orebody</td>
<td>EQU1285-288A</td>
<td>7 ppm Au, 657 ppm Ag, 169 ppm Cu, 310 ppm Pb, 360 ppm Zn</td>
</tr>
<tr>
<td>EQU1255</td>
<td>10,940 ft – 108 orebody</td>
<td>EQU1255-241A</td>
<td>12 ppm Au, 0.14 wt.% Ag, 185 ppm Cu, 600 ppm Pb, 885 ppm Zn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EQU1255-242A</td>
<td>50 ppm Au, 0.4 wt.% Ag, 592 ppm Cu, 868 ppm Pb, 0.13 wt.% Zn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EQU1255-245A</td>
<td>207 ppm Au, 1.5 wt.% Ag, 0.5 wt.% Cu, 1.6 wt.% Pb, 1.97 wt.% Zn</td>
</tr>
<tr>
<td>EQU1260</td>
<td>10,850 ft – 108 orebody</td>
<td>EQU1260-277A</td>
<td>19 ppm Ag, 0.17 wt.% Ag, 190 ppm Cu, 0.13 wt.% Pb, 0.22 wt.% Zn</td>
</tr>
<tr>
<td>EQU1247</td>
<td>10,820 ft – 108 orebody</td>
<td>EQU1147-284A, B, C</td>
<td>20 ppm Au, 0.2 wt.% Ag, 198 ppm Cu, 0.11 wt.% Pb, 0.16 wt.% Zn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EQU1147-294A, B</td>
<td>2 ppm Au, 350 ppm Ag, 102 ppm Cu, 214 ppm Pb, 293 ppm Zn</td>
</tr>
<tr>
<td>EQU1262</td>
<td>10,740 ft – 108 orebody</td>
<td>EQU1262-318A</td>
<td>29 ppm Au, 0.3 wt.% Ag, 0.18 wt.% Cu, 0.60 wt.% Pb, 1.0 wt.% Zn</td>
</tr>
<tr>
<td>EQU1263</td>
<td>10,650 ft – 108 orebody</td>
<td>EQU1263-393A, B</td>
<td>29 ppm Au, 0.19 wt.% Ag, 287 ppm Cu, 0.18 wt.% Pb, 0.29 wt.% Zn</td>
</tr>
<tr>
<td>EQU1264</td>
<td>10,540 ft – 108 orebody</td>
<td>EQU1264-493A</td>
<td>37 ppm Au, 0.16 wt.% Ag, 0.11 wt.% Cu, 0.40 wt.% Pb, 0.73 wt.% Zn</td>
</tr>
<tr>
<td>NAU12148</td>
<td>10,620 ft – S3 orebody</td>
<td>NAU12148-574A</td>
<td>38 ppm Au, 0.2 wt.% Ag, 652 ppm Cu, 0.4 wt.% Pb, 0.48 wt.% Zn</td>
</tr>
<tr>
<td>NAU12150</td>
<td>10,450 ft – S2 orebody</td>
<td>NAU12150-642A</td>
<td>13 ppm Au, 0.14 wt.% Ag, 282 ppm Cu, 0.3 wt.% Pb, 0.4 wt.% Zn</td>
</tr>
<tr>
<td>NAU12158</td>
<td>10,190 ft – S2 orebody</td>
<td>NAU12158-835A, 837A</td>
<td>5 ppm Au, 830 ppm Ag, 295 ppm Cu, 0.2 wt.% Pb, 0.5 wt.% Zn</td>
</tr>
<tr>
<td>NAU12158</td>
<td>10,190 ft – S2 orebody</td>
<td>NAU12158-839A</td>
<td>18 ppm Au, 0.3 wt.% Ag, 526 ppm Cu, 0.5 wt.% Pb, 0.8 wt.% Zn</td>
</tr>
<tr>
<td>NAU12166</td>
<td>10,250 ft – N3 orebody</td>
<td>NAU12166-242A</td>
<td>1 ppm Au, 61 ppm Ag, 184 ppm Cu, 0.16 wt.% Pb, 1.5 wt.% Zn</td>
</tr>
<tr>
<td>NAU12173</td>
<td>10,165 ft – N3 orebody</td>
<td>NAU12173-371A</td>
<td>0.1 ppm Au, 72 ppm Ag, 191 ppm Pb, 0.15 wt.% Pb, 0.4 wt.% Zn</td>
</tr>
<tr>
<td>NAU12175</td>
<td>10,350 ft – N3 orebody</td>
<td>NAU12175-244A, B</td>
<td>1 ppm Au, 380 ppm Ag, 143 ppm Cu, 0.18 wt.% Pb, 0.53 wt.% Zn</td>
</tr>
<tr>
<td>WE1031</td>
<td>9,280 ft – Deep intersection</td>
<td>WE1031-2034 A, B, C, D, E, F</td>
<td>5 ppm Au, 31 ppm Ag, 0.5 wt.% Cu, 1.7 wt.% Pb, 2.1 wt.% Zn</td>
</tr>
<tr>
<td>WE1031</td>
<td>9,275 ft – Deep intersection</td>
<td>WE1031-2040A, B, C, D, E</td>
<td>6 ppm Au, 26 ppm Ag, 450 ppm Cu, 0.7 wt.% Pb, 0.8 wt.% Zn</td>
</tr>
<tr>
<td>WE1031</td>
<td>9,270 ft – Deep intersection</td>
<td>WE1031-2044A, B, C, D, E, F</td>
<td>11 ppm Au, 0.1 wt.% Ag, 0.4 wt.% Cu, 0.4 wt.% Pb, 3.2 wt.% Zn</td>
</tr>
<tr>
<td>WE1031</td>
<td>8,820 ft – Deep intersection</td>
<td>WE1031-2531A</td>
<td>2 ppm Au, 8 ppm Ag, 1.0 wt.% Cu, 244 ppm Pb, 487 ppm Zn</td>
</tr>
</tbody>
</table>
width of the vein with wall rock contacts present at both ends. The vein interval is crustiform banded with Beta and Alpha stages. The Beta stage comprises fine, black sulfosalts with low base metal content (<0.15 wt.%). The Alpha stage is white, cream and beige color and consists of fine-grained Mn-calcite, quartz, adularia, purple quartz amethyst and minor amounts of calcite and rhodochrosite. The Alpha and Beta veins are hosted in a brecciated tuff of the Willow Creek welding zone (Fig. 4-3F). This interval yielded 20 ppm Au, 0.2 wt.% Ag, 198 ppm Cu, 0.11 wt.% Pb and 0.16 wt.% Zn.

Two samples were collected from 294.9–295.4 in drill hole EQU1147. This interval is dominated by pink Mn-rich carbonate minerals of the Alpha stage with fine-grained platy texture and fine-grained quartz (Fig. 4-3G). The Beta stage is fine-grained and lightly disseminated in the carbonate-rich gangue as black colored sulfosalts. There is sugary textured quartz and a pyrite pocket. This interval yielded 2 ppm Au, 350 ppm Ag, 102 ppm Cu, 214 ppm Pb and 293 ppm Zn.

Drill hole EQU1262 intersected the 108 orebody at an elevation of 10,740 ft (Fig. 4-2A). One sample was collected from 318.5–318.7 ft. The vein interval is narrow, approximately 3 inch wide, which formed in a fracture of brecciated tuff of the Willow Creek welding zone (Fig. 4-3H). The interval is rich in Beta stage which appears red-dark red and black in color and is hosted in a fine-grained quartz-rich matrix of Alpha stage, which is not highly visible due to the high abundance of Beta stage minerals. The minerals of the Beta stage are fine-grained base metal sulfides, with abundant pyrargyrite and silver sulfosalts. No visible gold or native silver was observed in hand specimen. This interval yielded 29 ppm Au, 0.3 wt.% Ag, 0.18 wt.% Cu, 0.60 wt.% Pb and 1 wt.% Zn.

Drill hole EQU1263 is located at an elevation of 10,650 ft in the 108 orebody (Fig. 4-2A). Two samples were collected continuously from 392.6–393 ft, which accounts for the full width of the vein with wall rock contacts present at both ends (Fig. 4-3I). This vein interval has a crustiform texture with Beta stage veins at the walls against gray colored tuff of the Willow Creek welding zone and contains a core of white, cream, beige colored Alpha stage. The Beta mineralization is highly enriched on the both sides on the contact with the host rock. The core is
composed of fine-grained quartz, Mn-rich carbonate minerals, calcite with some calcite bladed texture and purple color quartz amethyst. This interval yielded 29 ppm Au, 0.19 wt.% Ag, 787 ppm Cu, 0.184 wt.% Pb and 0.29 wt.% Zn.

Drill hole EQU1264 is located at an elevation of 10,540 ft in the 108 orebody (Fig. 4-2A). One sample was collected from 493.4–493.6 ft, which accounts for the full width of the vein with wall rock contacts present at both ends (Fig. 4-3J). This vein interval has a crustiform texture and contains high-grade Beta stage which appears as a highly concentrated black colored band consisting of fine-grained base and precious metal minerals. This black colored streak of Beta stage is in contact with a dominantly white colored Alpha stage matrix dominated by Mn-rich carbonates and calcite. The Alpha and Beta stage veins is narrow and filled within a fracture that cuts gray colored tuff of the Willow Creek welding zone. This interval yielded 37 ppm Au, 0.16 wt.% Ag, 0.11 wt.% Cu, 0.40 wt.% Pb and 0.73 wt.% Zn.

4.3.2. Mid-Level Veins

Veins intercepted from the mid-levels of the deposit contained both the Mn-Au and the B.M.S. associations (Fig. 4-2). The veins are located at elevations of 10,706–9,872 ft. Mid-level mineralization extends roughly 400 m along strike of the Amethyst fault, but the ore bodies are concentrated at the northern and southern ends (Fig. 4-2). The veins at the northern end are located in the N3 orebody and at the southern end the veins are located in the S2 and S3 orebody (Figs. 4-1 and 4-2).

In comparison to the 108 ore shoot, the mid-level Amethyst veins are mineralogically diverse. More minerals are present in Alpha stage and there are veins from both the Mn-Au and B.M.S associations. Since the majority of the research conducted on the North Amethyst deposit by Foley (1990) was limited to the analysis of mid-level Amethyst veins, the vein textures and mineralogy encountered in the present study from this portion of the deposit are similar to previous reports. For example, the Alpha and Beta stage veins that were evaluated during the sampling process from the mid-level Amethyst veins contained the complete range of minerals reported by Foley (1990). However, Stage-1 veins that were described in Foley (1990) were not
observed in the cores from the mid-level Amethyst veins during this study. However, a different type of base metal-rich veins was encountered in the N3 orebody. These veins do not contain chlorite and hematite which are characteristic of Stage-1 in the B.M.S association.

Veins of the Mn-Au association are mostly localized in the southern end of the mid-level Amethyst veins, primarily in the S2 and S3 orebodies. A total of three drill core intercepts were sampled for the present study which are located at an elevation of 10,620 and 10,190 ft (Fig. 4-2B; drill holes NAU12148, NAU12150 and NAU12158). The vein samples contained typical Beta stage mineralization, but were associated with different gangue mineralogy than the Beta veins in the 108 ore shoot. The ranges of Au and Ag concentrations from the sampled vein intercepts are 5–37 ppm and 830–3,146 ppm respectively which reflect a Au:Ag ratio of around 1:100.

Drill hole NAU12148 contained a narrow high-grade interval at 10,620 ft elevation in the S3 orebody (Fig. 4-2B). The Beta stage is hosted by a Alpha stage matrix of fine-grained sugary textured quartz, sericite and fine-grained calcite that is ~12 cm in width. The Beta stage occurred as black, thin streaks and patches in the matrix of a white gangue mineral assemblage consisting of quartz, sericite and fine-grained calcite. This fault-vein zone yielded 38 ppm Au, 0.2 wt.% Ag, 652 ppm Cu, 0.4 wt.% Pb and 0.48 wt.% Zn. Beta stage mineralization is relatively narrow, ~1.5 ft wide and is bounded by brecciated tuff of the Campbell Mountain welding zone with black quartz fill and severe argillic alteration. One sample was collected from the high-grade Beta interval at 574.3–574.5 ft (Fig. 4-3K; NAU12148-574A).

Drill hole NAU12150 consisted of a 3-ft-wide breccia zone of dark gray-black chalcedonic quartz cement with clasts of wall rock tuff, Alpha and Beta stage mineralization. The drill hole intersected the S2 orebody at an elevation of 10,450 ft (Fig. 4-2B). The clasts of the breccia zone are relatively small (0.5–1 cm in diameter) and were subrounded to subangular. This zone likely reflects the breccia event after the Mn-Au association and before the B.M.S. association which has been designated as the Breccia-2 by Foley (1990). This interval yielded 13 ppm Au, 0.14 wt.% Ag, 282 ppm Cu, 0.3 wt.% Pb and 0.4 wt.% Zn. One sample was taken from the black quartz breccia at 642–642.5 ft (Fig. 4-3L; NAU12150-642A).
Drill hole NAU12158 contained highly concentrated Beta stage mineralization within a 4-ft-wide zone associated with Alpha mineralization, representing the typical Mn-Au association reported by Foley (1990). The drill hole intercept is located at 10,190 ft elevation in the S2 orebody (Fig. 4-2B). The Alpha stage consists of a massive, reddish-brown, fine-grained mixture of Mn-rich silicate minerals such as rhodonite, pyroxmangite and inesite as well as carbonate minerals such as kutnohorite, rhodochrosite and calcite. The other gangue minerals of the Alpha stage which are also present are quartz, chlorite, adularia and sericite. The high-grade interval of the intercept displays crustiform textures of Alpha and Beta stage mineralization and yielded a range of 5–18 ppm Au, 830–3146 ppm Ag, 295–526 ppm Cu, 0.2–0.5 wt.% Pb and 0.5–0.8 wt.% Zn. Within the first two feet of the 4 ft wide zone (835–837 ft), Beta stage mineralization occurs as fine-grained Au-Ag black sulfosalts hosted primarily by fine-grained, massive Mn silicate and carbonate minerals that are light brown/tan with abundant fine-grained quartz, minor Fe-oxides, adularia and chlorite which are white with hints of green. The vein transitions into a classic type Alpha stage from 837–838.5 ft which is dominated by a fine-grained, massive, Mn-rich silicate and carbonate gangue with fine-grained quartz which is reddish brown. The Au and Ag concentrations increase following this transition of mineral intensity from 5–18 ppm Au and 830–3,146 ppm Ag from the first half to the second half of the 4-ft-wide zone. The first half of the 4-ft-wide interval (835–837 ft) yielded 5 ppm Au, 830 ppm Ag, 295 ppm Cu, 0.2 wt.% Pb and 0.5 wt.% Zn. The second half (837–838.5 ft) yielded 18 ppm Au, 0.3 wt.% Ag, 526 ppm Cu, 0.5 wt.% Pb and 0.8 wt.% Zn. Four samples were taken from the Beta-rich interval, two from the Mn-silicate-poor half (Fig. 4-4A; NAU12158 - 835A and 837A) and two from the Mn-silicate dominate half (Fig. 4-4B; NAU12158-838A and 839A).

Three vein intercepts were sampled from the northern end of the mid-level Amethyst veins, in the N3 orebody (drill holes NAU12166, NAU12173 and NAU12175). The three holes intercepted the ore body at elevations between 10,165 and 10,350 ft (Fig. 4-2B). The ore minerals present in the base metal veins of NAU12173 and NAU12175 are coarse-grained and only consist of pyrite and base metal sulfides (sphalerite, galena and chalcopyrite). The base metal veins from the N3 locality of the North Amethyst deposit do not contain significant precious Au-Ag minerals. These veins are shown as yellow dots in Figure 4-2B with grades of
≥10,000 ppm Cu+Pb+Zn. These veins are different than the base metal veins described as Stage-1 in Foley (1990) in which they do not contain hematite or chlorite. The N3 orebody is dominantly comprised of base metal veins while the S2 orebody contains Alpha and Beta veins with significant Au-Ag grades and a mineral assemblage which closely resembles those of Foley (1990).

Drill hole NAU12166 contains a high-grade, dominantly base metal-rich interval which is 1 ft wide (242–243 ft), which intersects the N3 orebody at an elevation of 10,250 ft (Fig. 4-2B). The vein consists of fine-grained black sulfosalts in fine-grained calcite and quartz matrix, producing a white and black, cloudy or blotchy appearance. This zone closely resembles the “Black Quartz Breccia” described by Foley (1990) which is a late breccia event of Breccia-2. Coarse-grained base metal sulfides, calcite and quartz fill small vugs. The sulfide minerals present are galena, sphalerite, chalcopyrite and pyrite, with sphalerite being most abundant. This high-grade interval is located within brecciated tuff of the Willow Creek welding zone and yielded 1 ppm Au, 61 ppm Ag, 184 ppm Cu, 0.16 wt.% Pb and 1.5 wt.% Zn. From the footwall side, the breccia contains clasts of the tuff surrounded by fine-grained calcite and silica cement. The hanging-wall side consists of a breccia with fine-grained rock flour, including clasts of the tuff in a cement of calcite and silica along with disseminated base metal sulfides. One sample was taken from the high-grade base metal interval (Fig. 4-4C, NAU12166-242A).

Drill hole NAU12173 contains a highly concentrated interval of coarse-grained base metal sulfides. The hole intersects the N3 orebody at an elevation of 10,165 ft (Fig. 4-2B). Pyrite and galena are the most abundant minerals, but sphalerite and chalcopyrite are also present. The base metal sulfides are hosted by a white to cream gangue assemblage consisting of fine-grained calcite, adularia and quartz. This high-grade base metal interval is 1.5 ft wide (390.8–392.3 ft) and is hosted by tuff of the Campbell Mountain welding zone. The tuff has been highly brecciated, milled and healed with quartz cement with veinlets of chlorite and calcite. This hole revealed a wide mineralized zone much of which consists of breccias and thick veins of gangue minerals, particularly calcite, Mn-calcite and quartz with variable amounts of adularia and is punctuated by several feet wide voids. Three samples were taken from the high-grade base metal sulfide vein (NAU12173-392A, 392B and 392C), which yielded 2 ppm Au, 92 ppm Ag, 0.15
wt.% Cu, 2.6 wt.% Pb and 1.8 wt.% Zn. One sample was collected from a vein segment of Mn-rich gangue minerals which resemble Alpha stage. The sampled interval (370.8–372.6 ft) yielded 0.1 ppm Au, 72 ppm Ag, 191 ppm Cu, 0.15 wt.% Pb and 0.4 wt.% Zn (Fig. 4-4D; NAU12173-371A).

Drill hole NAU12175 is located at 10,350 ft elevation and intersects the N3 orebody (Fig. 4-2A). The mineralized interval is characterized by a 4-ft wide breccia-vein zone (243–246.8 ft) which is composed of fragments of gray colored quartz and altered wall rock in a white, quartz-rich cement with fine grained disseminated base metal sulfides and minor calcite. Two samples were collected from the 243.5–244 ft interval, which yielded 1 ppm Au, 380 ppm Ag, 143 ppm Cu, 0.18 wt% Pb and 0.53 wt% Zn. The sulfide minerals include fine- to medium-grained sphalerite, galena, chalcopyrite and pyrite which are disseminated through a breccia containing tuff clasts of the Willow Creek welding zone and filled by fine-grained calcite and gray “smoky” quartz cement. This interval is bounded by a intensely brecciated interval of tuff of the Willow Creek welding zone that has been chloritized in the footwall. The breccia fill is a tan silica cement and is cross cut by calcite veinlets that contain minor black sulfosalts. In the hanging wall, the host rock is intensely argillic-altered, with minor calcite which is highly fractured and converted into rubble. Two samples were taken from the base metal-rich interval (Fig. 4-4E; NAU12175-244A and 244B).

4.3.3. Deep-Level Veins

The deep portion of the North Amethyst deposit was intercepted by drill hole WE1031. The drill platform of the hole was located on the surface of the deposit and pierced veins located at the deep intersection of the Amethyst and Equity faults (Fig. 4-1). The drill hole intercepted high-grade mineralization hosted by the Pre-Carpenter Ridge Unit at drilled depths of 2,034–2,046 ft, which corresponds to an elevation of 9,280–9,270 ft. This high-grade intercept is located along the deep intersection of the Equity and Amethyst faults. An additional high-grade ore zone was intercepted at 2,531–2,532 ft, which corresponds to elevations of 8,820 ft (Fig. 4-1).
The vein material recovered by drill hole WE1031 represents a unique style of mineralization which appears to consist of the Mn-rich gangue mineral association of the Alpha stage with the ore stages resembling the B.M.S. association. Assay data showed that the ore intercept is base metal-rich, but also contains elevated gold and silver concentrations. Gold grades are higher than the veins of the typical B.M.S. association described by Foley (1990). The veins have a higher Au:Ag metal ratio (1:10) than the Beta Stage veins of the upper and middle levels (1:100).

Systematic sampling was conducted along high-grade intervals of drill hole WE1031. A total of 17 vein samples were taken along the 2,034-2,046 ft high-grade interval for further petrographic investigation, covering three texturally and mineralogically distinct zones.

The vein interval from 2,034–2,035.5 ft is characterized by a crustiform banded texture comprising coarse-grained sulfide minerals and bands of chlorite, hematite, calcite, Mn-calcite, coarse- and fine-grained quartz and adularia. This interval assayed at 5 ppm Au and 31 ppm Ag, with base metal grades of 0.5 wt.% Cu, 1.7 wt.% Pb and 2.1 wt % Zn. The coarse-grained sulfide minerals included galena, chalcopyrite, sphalerite and pyrite. The sulfide minerals form black, silver or yellow crystals set in a white gangue mineral association of adularia, quartz and calcite. Streaks of red hematite are present. In total, six vein samples were collected from this interval (Fig. 4-4F; samples WE1031-2034A, B, C, D, E and F).

The vein interval from the 2040.3–2041.9 ft is characterized by a crustiform banded texture which consists of very thin veinlets of dominantly fine-grained base metal sulfide crosscutting a Mn-rich gangue mineral association. Texturally, the Mn-rich gangue mineral association resembles the Alpha stage. The vein interval is dominantly pink and wavy with green bands that are rich in fluorite and white bands rich in fine-grained quartz, adularia and calcite, minor hematite. The interval yielded 6 ppm Au and 26 ppm Ag, with base metal concentrations of 450 ppm Cu, 0.7 wt.% Pb and 0.8 wt.% Zn. A total of five samples were collected from this interval, representing what appeared to be both the Alpha stage and the B.M.S. association (Fig. 4-4G-I; samples WE1031-2040A, B, C, D and E).
The core interval from 2044.7–2045.8 ft exhibits a crustiform banded texture with dominantly pink colored, Mn-rich gangue minerals at the opposite ends and a black colored base metal sulfide-rich core. The zone of Mn-rich gangue minerals is composed of fine-grained quartz, adularia, Mn rich silicates and carbonates, calcite, chlorite and hematite. Fine-grained ore minerals, including sphalerite, galena, chalcopyrite, pyrite and silver sulfosalts, are present in the Mn-rich gangue mineral assemblage. The general appearance is pink, green and gray, with an overall wavy texture. The base metal-rich core contains abundant medium- to fine-grained pyrite, sphalerite, galena and chalcopyrite. The base metal-rich core is black, with a crustiform texture and is associated with fine-grained chlorite, hematite, quartz, adularia, Mn-calcite and calcite. The gangue minerals are less abundant then the ore minerals. The interval grades 11 ppm Au and 1,090 ppm Ag, with base metal grades of 0.4 wt% Cu, 0.4 wt.% Pb and 3.2 wt.% Zn. A total of six vein samples were collected from this interval, continuously covering the Mn-rich gangue mineral assemblage and the base metal rich-core (Fig. 4-4J, K; samples: WE1031-2044A, B, C, D, E and F).

One additional vein sample was collected from a chalcopyrite-rich breccia vein in the deeper part of the WE1031 core at the depth of 2531.5 ft (Fig. 4-4L; sample WE1031-2531A). The interval is typified by brecciated fragments and clasts of medium- to coarse-grained chalcopyrite, host rock fragments, quartz, adularia and calcite which are supported by a fine-grained matrix of dominantly chlorite, with minor amounts of fine-grained hematite. Epidote appeared to be present in drill core from this interval. The interval yielded 2 ppm Au and 8 ppm Ag, with base metal grades of 1.0 wt.% Cu, 244ppm Pb and 487ppm Zn.
Fig. 4-4: Photographs of epithermal veins from the North Amethyst deposit. A. Two samples from NAU12158 (NAU12158-835A, 837A). B. Two samples from NAU12158 (NAU12158-838A, 839A). C. One sample from NAU12166 (NAU12166-242A). D. Two samples from NAU12173 (NAU12173-392B, C). E. Two samples from NAU12175 (NAU12175-244A, B). F. Six samples from WE1031 (WE1031-2034A, B, C, D, E, F). G. One sample from WE1031 (WE1031-2040A). H. 2 samples from WE1031 (WE1031-2040B,-C). I. Two samples from WE1031 (WE1031-2040D, E). J. 4 samples from WE1031 (WE1031-2044A, B, C, D). K. Two samples from WE1031 (WE1031-2044E, F). L. One sample from WE1031 (WE1031-2531A).
CHAPTER 5
VEIN MINERALOGY AND PETROLOGY

The present chapter summarizes the mineralogy and petrological characteristics of the veins at the North Amethyst deposit. The textures of the minerals identified are described in detail, especially replacement features that were used to derive a paragenetic sequence of mineral precipitation. The identification of the various minerals was based on a combination of optical microscopy and energy-dispersive X-ray spectroscopy on a scanning electron microscope.

5.1. Materials and Methods

The vein intercepts from 14 drill cores were sampled for petrographic and mineral analysis. The sampling of the 14 vein core intercepts represented the various vein stages and locations along varying depths of the North Amethyst deposit. The vein samples were cut and trimmed into 45 billets (27x46mm). The billets were then sent to Spectrum Petrographics for the preparation of polished thin sections.

The thin sections were used for optical microscopy, scanning electron microscopy and QEMSCAN mineral analysis at the Colorado School of Mines. A JEOL JSM-7000F scanning electron microscope was used for back-scatter electron (BSE) imaging and the semi quantitative chemical analysis by energy-dispersive X-ray (EDS) spectroscopy. The instrument was operated at an accelerating voltage of 20 kV and at a current of 100 nA. QEMSCAN mineral analysis was performed on one thin section sample; EQU1264-493A, in which uytenbogaardtite was detected. The analysis was performed with a Carl Zeiss EVO 50 scanning electron microscope equipped with four Bruker X275HR silicon drift X-ray detectors. The instrument was operated at a voltage of 25 kV, with a current of 5 nA.

In addition to the microscopic technique, X-ray diffraction (XRD) experiments were conducted. Initially, exactly 1 gram of sample was ground with 4 ml of methanol in a McCrone micronizing mill for 5 minutes. The mixture was poured into a 50 ml beaker and air dried at 60° Fahrenheit. Each of the dried samples was then transferred to a polypropylene scintillation vial
with three acrylic balls and 625 microliters of Vertrel (a hydrofluorcarbon solvent). The vials were clamped in a Spex 8000D mixer/mill and shaken for 10 minutes, air dried and shaken again for 10 minutes to produce a randomly oriented sample. The powdered sample was the sieved through a 500 micrometer mesh sieve and side loaded into holders. The samples were measured on a Siemens D-500 X ray diffractometer using a CuKα source with a wavelength of 1.54 Å and a monochromator over a range of 5 to 65 °2Θ at a 0.02 degree step size and a 2 second count time. Mineral phases were identified from the peak positions using Material Data Inc. Jade software.

5.2. Petrography of the Alpha Stage

The first vein filling event at the North Amethyst deposit occurred through movement and fracturing of the volcanic wallrock, accompanied by the introduction of Mn-rich fluids precipitating a fine-grained, cryptocrystalline, banded mixture of rhodochrosite, Mn-calcite, rhodonite, pyroxmangite and quartz (Foley, 1990). Isolated vug spaces contain coarse-grained adularia and quartz (Foley, 1990). This early, Mn-rich gangue assemblage is known as the Alpha stage and represents the earliest manifestation of the Mn-Au association (Foley, 1990).

Petrographic analysis of Alpha veins sampled in the North Amethyst deposit for the present study showed that they are composed of a fine-grained, cryptocrystalline, banded mixture of Mn-calcite, calcite, rhodochrosite, quartz, adularia and fluorite, with variable amounts of kutnohorite and Mn-silicates. The fine-grained, Mn-rich cryptocrystalline gangue mixture of Alpha stage forms crustiform bands or has a massive texture. Fine-grained sulfide minerals, including pyrite, chalcopyrite, sphalerite and galena are present. The sulfide minerals belonging to the Alpha stage are observed as stringers, localized along microfractures (e.g., EQU1147) or occur disseminated throughout the matrix (e.g., NAU12173-371A).

Alpha veins are present in all levels of the deposit but vary by texture and mineralogy with elevation. The largest deviations occur between the Alpha veins in the upper levels of the North Amethyst deposit, hosted in the Equity fault, and the Alpha veins in the middle and deep portions, hosted by the Amethyst fault and represented by the deep intersection, respectively.
The Alpha veins hosted in the upper levels of the deposit contain a mineral assemblage of Mn-calcite, calcite, kutnohorite, rhodochrosite, quartz, adularia, fluorite, while the Alpha veins in the middle and deeper levels of the deposit contain a mineral assemblage of rhodonite, Mn-calcite, calcite, kutnohorite, rhodochrosite, quartz, adularia and fluorite. The systematic difference in the mineralogical make-up of the veins with elevation were not reported by Foley (1990), because her study was limited to the mid-level veins.

The Alpha veins sampled from the uppermost area of the deposit (EQU) consist of a cryptocrystalline mixture of Mn-calcite, kutnohorite, rhodochrosite, quartz, adularia and fluorite. Some of the Alpha veins are dominated by quartz while others are dominated by carbonate. Quartz-dominated Alpha veins with Beta stage seams are noted in the EQU1255, EQU1260 and EQU1262 vein segments (Fig. 5-1A). A carbonate-dominated Alpha vein is present in the EQU1264 vein intersection, which is cut and filled by a highly concentrated Beta stage minerals (Fig. 5-1B). Alpha veins with roughly equal proportions of quartz and carbonate minerals characterize the remaining Alpha veins sampled at high elevations (i.e., EQU1147, EQU1263 and EQU1285). The upper level Alpha veins along the Equity fault are light colored and range from beige, cream-yellow, cloudy white and light pink (Fig. 5-1C).

The Alpha stage veins of the mid-levels of the North Amethyst deposit are dominated by a fine-grained cryptocrystalline mixture of rhodonite, Mn-calcite, kutnohorite, rhodochrosite, calcite, quartz, adularia and sericite, with minor amounts of fluorite and inesite. Pyroxmangite has been reported to be a common mineral in the Alpha assemblage but was not unequivocally identified in the present study. The mid-level Alpha veins are darker in color than the upper level Alpha veins and appear reddish brown, tan, light brown, light red or dark pink in color (Fig. 5-1D-E). The darker color of the mid-level Alpha veins in the North Amethyst deposit is likely related to the presence and abundance of rhodonite. The Alpha stage veins in the mid-levels of the deposit contain abundant rhodonite which occurs as a dark red to pink fine-grained groundmass or as clear, semitransparent acicular needles in plane polarized light. Both types of rhodonite may occur together (Fig. 5-1F).
Fig. 5-1: Textural characteristics of Alpha stage veins at the North Amethyst deposit. A. Quartz-rich Alpha vein with fine-grained Beta stage with location of sample EQU1255-241A. B. A Carbonate-rich Alpha vein with a highly concentrated Beta stage vein filling a fracture hosted by tuff of the Willow Creek welding zone. Location of sample EQU1264-493A is highlighted. C. Alpha vein with fine-grained Beta stage seam. Locations of samples EQU1147-284A-C are shown. D. Alpha vein segment from drill core NAU12158 showing a transition of white to cream color to a dark red color. The richest portion containing Beta stage minerals is located in the dark red zone. E. Spatially overlapping vein and breccia stages of the Mn-Au and B.M.S. associations. Alpha stage veins are pink and orange-red. The dark gray and black colors belong to the B.M.S. association. F. Photomicrograph of rhodonite in plane polarized light, forming a fine-grained brown mass and tiny needles in fine-grained quartz-rich matrix of the Alpha substage-2.
The mid-level Alpha stage intersection in drill hole NAU12158 is the widest Alpha vein encountered in the present study, spanning a width of 4 ft. The interval changes mineralogically and texturally with increasing depth, from a fine-grained light colored white and light brown, with thinly banded crustiform texture to a darker color, dark red and massive texture. The color and textural gradation correlate to the relative concentrations of Mn-carbonates and Mn-silicates, as determined petrographically and through XRD. The light colored areas were found to have a higher carbonate content and occurs as a fine-grained cryptocrystalline mixtures of dominantly Mn-calcite, rhodochrosite, calcite, quartz, adularia and lesser amounts of rhodonite while the darker colored portions of the Alpha stage consists primarily of a fine-grained cryptocrystalline mixture of rhodonite with Mn-calcite, rhodochrosite, kutnohorite, calcite and lesser amounts of quartz and adularia (Figs. 5-1D, 5-2 and 5-3).

A mid-level Alpha stage vein in the northern end of the deposit at an elevation of 10,250 ft showed a light brown to tan color, related to the occurrence of a fine-grained cryptocrystalline mixture of Mn-silicate minerals, Mn-carbonate minerals, quartz, adularia, calcite and fluorite (Fig. 5-4A). The petrographic analysis of the vein segment revealed the presence of a diverse assemblage of Mn-silicate minerals, including rhodonite, inesite and caryopilite (NAU12173-371A; Fig. 5-4B,C). The Alpha vein is not associated with Beta stage.

Alpha veins in the deep portion of the deposit dominantly consist of a fine-grained cryptocrystalline mixture of rhodonite, Mn-calcite, rhodochrosite, kutnohorite, rhombic calcite and microcrystalline to crystalline quartz, with vugs lined with acicular needles of rhodonite and filled by coarse-grained quartz and adularia or sphalerite and hematite (Fig. 5-4D). Coarse-grained sphalerite in the deep level Alpha veins is 2–2.5 mm in size and displays a brownish-green or a dark yellow-green color. The sphalerite fill vug spaces and is associated with coarse-grained adularia and quartz (described as Alpha substage-1; Foley, 1990).

In addition to the systematic difference in the occurrence of Mn-silicate minerals with elevation, a significant textural difference between the Alpha veins from the upper to mid and
Fig. 5-2: Cross-section sketch of NAU12158 drill core interval with sample locations and petrographic evidence of Alpha minerals and textures for each of the four samples NAU12158-835A,-837A,-838A, -839A. A. Photomicrograph of sample NAU12158-835A consisting of fine-grained rhodonite (Rdn) and fine-grained cryptocrystalline mixture of Mn-calcite and rhodonite. PPL. B. Photomicrograph of sample NAU12158-837A consisting of fine-grained cryptocrystalline mixture of Mn-calcite and rhodonite. PPL. C. Photomicrograph of sample of NAU12158-838A consisting of brecciated rhodonite in a matrix of quartz and rhodonite needles, interpreted as Alpha substage-2. PPL. D. Photomicrograph of sample NAU12158-839A consisting of fine-grained cryptocrystalline mixture of Mn-calcite and rhodonite. PPL.
The peaks correspond to the major minerals of Alpha stage which are circled and labeled. This diagram provides a mineralogical explanation to the color differences expressed in the wide Alpha vein segment. The light colored areas are dominated by carbonates (Mn-calcite, calcite, kutnohorite and rhodochrosite) and the dark red colors contain rhodonite with the carbonate assemblage. A. XRD pattern of sample NAU12158-835A containing significant carbonate minerals and undetectable rhodonite. B. XRD pattern of sample NAU12158-837A containing significant carbonate minerals and undetectable rhodonite. C. XRD pattern of sample NAU12158-838A containing significant rhodonite as well as carbonate minerals. D. XRD pattern of sample NAU12158-839A containing significant rhodonite as well as carbonate minerals.
Fig. 5-4: Textural characteristics of Alpha stage veins at the North Amethyst deposit. A. Drill core image of an Alpha vein segment from drill hole NAU12173 which was sampled for petrographic analysis (sample NAU12173-371A). B. Photomicrograph of caryopilite \((\text{Mn, Mg})_3(\text{Si}_2\text{O}_5)(\text{OH})_4\), which exhibits a reddish brown color and forms small matted clumps and radiating sheaths. PPL. C. Photomicrograph of inesite \((\text{Ca}_2\text{(Mn, Fe)}_7\text{Si}_{10}\text{O}_{28}(\text{OH})_2 \cdot 5\text{H}_2\text{O})\), which forms long radiating sheaths, clear and semi-transparent with light gray to light brown wispy texture. PPL. D. Photomicrograph of rhodonite in plane polarized light. Two forms of rhodonite are present, a red-brown fine-grained groundmass and coarse-grained rhodonite needles along the edges of fine-grained rhodonite and within quartz.

deep levels is the minerals which fill the vug spaces. Vugs in the upper part of the deposit consist of coarse-grained adularia, quartz and lattice bladed carbonate. Vugs in mid-level Alpha veins are filled with quartz and fine-grained rhodochrosite (NAU12158-839A). No lattice bladed calcite is observed in the mid- and deep-levels. The vug spaces in the deep levels of the deposit (WE1031) are filled with coarse-grained quartz, subrhombic adularia, sphalerite and hematite.
5.2.1. Substages

Previous research suggested that the Alpha stage consists of two substages, referred to as Alpha-1 and Alpha-2 substages (Foley, 1990). Alpha-1 substage is described as a crystallization progression from the walls in toward the center of the veins leaving open spaces (Foley, 1990). The open spaces are filled with 1–2 mm adularia rhombs, coarse (~2–3 cm) amethyst, rhodochrosite (1–5 mm) and locally fluorite (1–2 mm) and sphalerite (1–2 mm). The Alpha-2 substage is characterized as a fine-grained mixture of quartz, rhodochrosite and Mn-silicate minerals around fragments of Alpha-1 substage and wallrock and is interpreted to be the result of a second influx of Mn-rich fluids (Foley, 1990). The Alpha-2 substage is noted as being more quartz rich than the earlier Alpha-1 substage and has a greater proportion of base metal sulfides (Foley, 1990).

The majority of the Alpha veins encountered in the present study do not have the same gangue mineralogy and textural characteristics as those described by Foley (1990). As a consequence, no consistent distinction between the Alpha-1 and Alpha-2 substages could be made. However, some of the Alpha stage veins encountered in the present study did resemble the two substages and are discussed in more detail below.

Alpha-1 Substage

Several vein intervals of the exploration drill holes sampled in the present study were observed to have the mineralogical and textural features comparable to the Alpha-1 substage as proposed by Foley (1990). The sampled vein segments which best reflect the fine- to coarse-grained Alpha-1 substage are EQU1147, EQU1263 and WE1031-2040. Although texturally similar, the Alpha veins in the EQU samples consist of a different mineral assemblage than the deep, WE1031 samples. The Alpha-1 substage observed in the EQU samples consists of a fine-grained cryptocrystalline mixture of dominantly Mn-calcite with rhodochrosite, kutnohorite, calcite, quartz and adularia on the vein selvages and more coarse-grained in the core (Fig. 5-5A). The core consists of coarse-grained (300 μm–1.5 mm) subrhombic adularia, euhedral (0.5–2
mm) quartz, lattice bladed calcite and Mn-calcite (0.3–2 mm) and rhombic calcite (0.4–2 mm; Fig. 5-5B).

The Alpha-1 substage observed in WE1031-2040 vein interval consists of a fine-grained cryptocrystalline mixture of dominantly rhodonite which also included Mn-calcite, rhodochrosite, kutnohorite, calcite, quartz and adularia (Fig. 5-5C). Open spaces are lined with rhodonite needles and filled with coarse-grained subrhombic adularia, quartz or sphalerite and hematite (Fig. 5-5D). The EQU vein segments are coarser-grained and appear as crustiform bands with a dominantly fine-grained assemblage near the walls and a coarse-grained assemblage in the core without Mn-silicate minerals. The Alpha-1 substage in the WE1031-2040 vein interval is more fine-grained with a rhodonite-rich assemblage that appears pink to dark red in color and has a massive texture.

**Alpha-2 Substage**

The Alpha-2 substage was reported to represent a second influx of Mn-rich fluids that deposited a fine-grained mixture of quartz, rhodochrosite and Mn-silicate minerals around fragments of Alpha-1 substage and wallrock (Foley, 1990). The Alpha-2 substage is characterized as being more quartz-rich and possessing a greater proportion of base metal sulfides (Foley, 1990).

In the present study, the Alpha-2 substage was only recognized in the NAU12158 drill hole located in the mid-level (10,250 ft elevation) of the North Amethyst deposit. The Alpha-2 substage observed in the samples from this hole dominantly consists of a matrix of fine-grained (50–200 μm) quartz-adularia and (50–400 μm) acicular rhodonite needles surrounding fragments of Alpha 1 substage (Fig. 5-5E-G). The quartz-adularia and needles of rhodonite are associated with minor amounts of fluorite and fine-grained calcite and Mn-carbonates (Fig. 5-5H). The quartz and adularia matrix of the Alpha-2 substage are recrystallized and exhibit a jigsaw-fit texture. The acicular needles of rhodonite are dispersed throughout the quartz-adularia matrix and line the edges of fragments of the Alpha-1 substage. The rhodonite needles appear clear in
Fig. 5-5: Photomicrographs of the mineral and textural features of Alpha substage-1 and Alpha substage-2. A. Alpha substage-1 in upper level. Fine-grained cryptocrystalline mixture of Mn-calcite and microcrystalline (mctyl) and crystalline (ctyl) quartz matrices located on the vein wall. CPL. B. Alpha substage-1 in upper level. Coarse-grained matrix of euhedral quartz crystals, subhombic adularia, lattice bladed calcite and rhombic calcite, located in the vein core. CPL. C. Alpha substage-1 in deep level. Fine-grained red-brown rhodonite groundmass with quartz-rich vugs lined with rhodonite needles. PPL. D. Alpha substage-1 in deep level. Coarse-grained rhodonite as white colored needles. Small, black matted clumps are fine-grained rhodonite masses which are associated with coarse-grained yellow-brown sphalerite in a matrix of quartz and adularia. PPL. E. Alpha substage-2 in mid level. Brecciated fragments of fine-grained, black to red-brown colored rhodonite hosted in a quartz rich matrix with brown rhodonite needles. PPL. F. Alpha substage-2 in mid level. Same sample as image E. Image shows quartz matrix texture and rhodonite needles in black or orange colors. The large black masses are fine-grained rhodonite fragments. CPL. G. Alpha substage-2 in mid level. Crystalline quartz texture and fluorite. CPL. H. Alpha substage-2 in mid level. Rhodonite needles in quartz matrix and the black grains are sphalerite. PPL.
plane polarized light and yellow to yellowish-red in crossed polarized light. They form small radiating patches of needles.

5.2.2. Mineralogy of the Alpha Stage

The following sections describe the mineralogy and textural features of the Alpha stage.

Quartz (SiO$_2$)

Quartz of Alpha stage exhibits several textural forms and is associated with adularia, calcite, fluorite, Mn-rich carbonates and $\pm$ Mn-silicates. The quartz has been recognized to form three types of matrices; microcrystalline (<25 $\mu$m), crystalline (25–100 $\mu$m) and coarse-grained (100–500 $\mu$m; Fig. 5-6A-B). Other forms include, large prismatic crystals (>100 $\mu$m–2mm; Fig. 5-6C). Fine-grained microcrystalline and crystalline quartz are the most common quartz forms and may show jigsaw texture (Fig. 5-6D). Chalcedony is another form of quartz which is characterized by fine-grained (15–600 $\mu$m) oblate shapes and shows cross hatch textures (Fig. 5-6E). Coarse-grained quartz forms a euhedral to subhedral interlocking matrix with or without euhedral shaped crystals (>100 $\mu$m in length). Coarse-grained quartz matrix with euhedral shaped crystals can be found locally filling small open spaces or fractures. The coarsest grained variety of quartz with euhedral crystals was observed in the center of Alpha vein (EQU1147), which also contain amethyst. The mineral and textural features of EQU1147 reflect a progression of crystallization from the walls toward the center similarly to Alpha-1 stage described by Foley (1990). However, there are no Mn-silicates or coarse-grained molds of quartz-adularia or sphalerite.

Adularia (KAlSi$_3$O$_8$)

Adularia commonly occurs with quartz and is most obvious when it occurs as subrhombic crystals (0.05–3 mm). The most common appearance of adularia in the vein samples
Fig. 5-6: Photomicrographs of the mineral and textural features of Alpha stage. A. Microcrystalline and crystalline quartz matrices in fine-grained cryptocrystalline Alpha matrix on vein wall. EQU1147-284A. CPL. B. Crystalline and coarse-grained quartz matrices in Alpha matrix at the vein core. EQU1147-284B. CPL. C. Coarse-grained euhedral quartz crystals in coarse-grained rhombic calcite in Alpha vein core. EQU1147-284B. CPL. D. Microcrystalline and crystalline jigsaw quartz matrix. EQU1255-251A. CPL. E. Chalcedony forming thin and fine-grained euhedral quartz crystals in a cross hatch texture. EQU1255-251A. CPL. F. Alpha matrix of subhombic adularia, lattice bladed calcite, fine-grained calcite in brown and euhedral quartz crystals. PPL. G. Same image highlighting the subhombic adularia crystals which express a zonal feature and twinning. CPL. H. A subhombic adularia crystal with albite twins in Alpha matrix, associated with calcite and quartz grains and is surrounded by fine-grained dark brown cryptocrystalline mixture of rhodonite, Mn-calcite, calcite and microcrystalline quartz.
is the subrhombic crystal shape which is commonly associated with crystalline or coarse-grained
euhedral quartz, calcite, Mn-carbonates, ± Mn-silicates and fluorite (Fig. 5-6F-G). Adularia
appears clear, colorless or semi-transparent in plane polarized light and exhibits a gray color in
crossed polarized light with some faint twins (Fig. 5-6H). Common adularia textures of the
Alpha stage are (1) microcrystalline (≤25μm) euhedral adularia; (2) crystalline (25–100 μm)
euhedral adularia; (3) coarse-grained (100–500 μm) euhedral adularia; and (4) coarse grained
(100 μm–3mm) subrhombic adularia.

*Calcite (CaCO$_3$)*

Calcite is most commonly intergrown with Mn-calcite, rhodochrosite, ±kutnohorite and ±
rhodonite (Fig. 5-7A). Fine-grained (≤50 μm) calcite is clear in plane polarized light with
rhombic-subrhombic shapes. Coarse-grained calcite occurs as 1–2 mm rhombs or 0.2–2mm
lattice bladed crystals and ranges from light brown, light pink or light gray in color in plane
polarized light (Fig. 5-7B-C). Coarse-grained rhombic calcite displays characteristic cleavage
patterns and twinning, which can be a distinguishing feature from the other carbonate group
minerals (cf. MacKenzie and Guilford, 1980). The color of the calcite appears to reflect
variations in Mn concentrations. In plane polarized light, brown or light gray calcite occurs in a
matrix dominated by kutnohorite, while lighter brown or pinkish calcite is intergrown with
rhodochrosite.

*Mn-calcite ($(Ca,Mn)CO_3$)*

Mn-calcite is present throughout all the vein samples and is the most abundant carbonate
mineral. Mn-calcite is fine-grained and exhibits a range of colors from white, cream and light
yellow to pink in hand sample. The Mn-calcite appears as a light to dark brown fine-grained
mass in plane polarized light and has a darker brown color in crossed polarized light (Fig. 5-7D).
Fine-grained rhodochrosite and calcite occur in the fine-grained groundmass of Mn-calcite which
exhibits bright interference colors; pink, green, yellow interference when viewed under crossed
polarized light. Mn-calcite is very fine-grained (≤50 μm) and forms grains without well-defined
crystal faces (Fig. 5-7E). Mn-calcite has several different forms. Mn-calcite occurs between grain boundaries of quartz matrix which appears to surround or swarm the quartz and adularia matrix. It was also observed as very thin veinlets cutting gangue minerals or as halos around ore minerals. The very fine-grained, massive and light brown Mn-calcite is common in all Alpha vein samples, but is most abundant in the Alpha veins in the upper level (EQU samples).

Coarse-grained Mn-calcite occurs as platy crystals or has lattice bladed textures (Fig. 5-7F). Platy and lattice bladed Mn-calcite was observed in two vein segments (EQU1147-294 and EQU1263), where this mineral is pink and cream-yellow colored in hand sample, respectively. Blades of Mn-calcite are light brown in plane polarized light and dark brown in crossed polarized light and range in length from 90–600 μm. These textures are associated with open space filling (EQU1147) and may be located in the vein center (EQU1263).

*Kutnohorite* (*Ca*(Mn,Mg,Fe)(CO$_3$)$_2$)

Kutnohorite is present throughout the majority of Alpha vein samples. Kutnohorite has been identified by optical microscopy, EDS analysis and XRD experiments. Kutnohorite exhibits a brown or light gray color in plane polarized light and occurs as fine-grained and massive aggregates, sometimes with a wispy texture (Fig. 5-7G). Kutnohorite is an abundant gangue mineral, particularly in the upper and middle level vein samples. It has been observed to dominate most of the gangue matrix in some samples from the upper and middle levels. In the upper level veins, kutnohorite is intergrown with fine-grained calcite and rhodochrosite (EQU1264). In the middle level vein samples, kutnohorite is intergrown with fine-grained calcite, rhodochrosite and Mn-rich silicate minerals such as rhodonite (NAU12158). Kutnohorite rarely occurs as isolated grains except in one sample (NAU12175-244A). In crossed polarized light, kutnohorite does not show bright interference colors like calcite or rhodochrosite. It has a distinctly darker brown color than in plane polarized light.
Fig. 5-7: Photomicrographs of the mineral and textural features of Alpha stage. A. Close-up of cryptocrystalline carbonate-rich gangue matrix of Alpha vein wall. Black to dark brown masses are fine-grained Mn-calcite, calcite are lighter colored grains pale, light pink with cleavages. Rhodochrosite is very fine-grained and has bright second order blue, pink, orange and red interference colors. EQU1147-284C. CPL. B. Lattice bladed calcite associated with coarse-grained matrix of adularia and quartz in the core of Alpha vein. EQU1147-284B. CPL. C. Large rhombs of calcite crystals in Alpha vein sample in contact with Beta rich seam hosted by fine-grained Mn-calcite and kutnohorite. EQU1264-493A. CPL. D. Light and dark brown Mn-calcite in fine-grained Alpha matrix at vein wall. EQU1147-284A. PPL. E. Close-up of Mn-calcite which appears as cloudy brown to dark brown mass and contains small sphalerite grains. EQU1263-392B. PPL. F. Platy Mn-calcite associated with fine-grained quartz matrix. EQU1147-294A. PPL. G. Kutnohorite exhibiting wispy texture, opaque phases are sulfides and white and gray areas are fine-grained quartz matrix. EQU1264-493A. CPL. H. Fine-grained rhodochrosite in Alpha vein associated with rhodonite (black) and freibergite (frei) within and on wall of quartz vug. NAU12158-839A. PPL.
Rhodochrosite \((MnCO_3)\)

Rhodochrosite is present in the majority of Alpha vein samples. The rhodochrosite is primarily fine-grained, forming \( \leq 50 \mu m \) large crystals with poorly defined crystal shapes. The rhodochrosite is usually intergrown with other carbonate minerals and Mn-rich silicate minerals. Fine-grained rhodochrosite crystals are clear to semi-transparent with a murky brown color in plane polarized light (Fig. 5-7H). The rhodochrosite may be difficult to distinguish from fine-grained calcite. However, rhodochrosite crystals appear to have lower, second order interference colors, which appear bright green and pink as opposed to calcite, which appears with third order interference colors with a lighter pink and green hue in crossed polarized light.

Caryopilite \((Mn,Mg)_3(Si_2O_5)(OH)_4\)

Caryopilite appears as red brown radiating sheaths in plane polarized light. Caryopilite crystals have blurry or fuzzy grain boundaries and are found in small matted clumps. Individual crystals range from 10–300 \( \mu m \) in length, while the matted clumps are 1–2 mm in width (Fig. 5-8A). Caryopilite is a hydrated layer silicate which was identified in samples from the mid-level veins of the North Amethyst deposit and is a characteristic mineral of the Alpha gangue assemblage of the Mn-Au association.

Inesite \((Ca_2(Mn,Fe)_{7}Si_{10}O_{28}(OH)_2 \cdot 5H_2O)\)

Inesite occurs as radiating sheaths that are generally clear and semi-transparent with light gray to light brown wispy texture in plane polarized light (Fig. 5-8B). Inesite forms acicular crystals that range from 0.1–2 mm in length and occurs intergrown with fine-grained carbonate minerals. In cross-polarized light, inesite has flesh, light pink colors. The crystal boundaries are well-defined and sharp with some bending and curling amongst the coarsest grains. The mineral has been identified in two of the mid-level vein samples (NAU12173-371 and NAU12148-574A) which are assigned to the Mn-Au association.
**Pyroxmangite** \((\text{MnSiO}_3)\)

Pyroxmangite has been identified by optical petrography and XRD analysis. Pyroxmangite is fine-grained and light brown to yellow-orange in plane polarized light (Fig. 5-8C). It is intergrown with fine-grained rhodonite, quartz, adularia and carbonate minerals. Optically, it can be distinguished from rhodonite based in its lighter and brighter brown and orange colors in plane polarized light. Pyroxmangite was identified from a mid-level Alpha vein sample (NAU12158-839A), which is cut by Beta stage.

**Rhodonite** \((\text{MnSiO}_3)\)

Rhodonite is the most abundant Mn-silicate mineral of the Alpha stage. It primarily occurs in a cryptocrystalline mixture of quartz, carbonate minerals and other Mn-silicate minerals, characterized by a deep red color in hand sample. In plane polarized light, rhodonite appears as a dark brown, dark gray, black and red fine-grained, cryptocrystalline mass (Fig. 5-8D). In crossed polarized light, the fine-grained cryptocrystalline mass of rhodonite exhibits a darker colors than in plane polarized light. Rhodonite does not show bright interference color. Rhodonite in Alpha-2 substage appears as fine-grained clumps with coarser needles on the edges and is hosted by a fine-grained quartz matrix (Fig. 5-8E). Coarse-grained rhodonite needles also line vugs filled with quartz, adularia and/or sphalerite (Fig. 5-8F). The needles range from 50–400 μm in length and are clear in plane polarized light, but have yellow to red interference colors in crossed polarized light. Rhodonite is the dominant mineral to comprise the Alpha stage veins in the middle and deeper level veins sample, but is absent in the Alpha veins located at the upper levels of the North Amethyst deposit.

**Sulfide Minerals**

Sulfide minerals present in the Alpha stage have been reported to occur in stringers in the matrix composed of Mn-carbonate minerals, Mn-silicate minerals and quartz (Foley, 1990). The sulfide minerals reported are pyrite, sphalerite and galena (Foley, 1990). The sulfides minerals of Alpha stage have been observed to occur in two types of settings. One as described by Foley
Fig. 5-8: Photomicrographs of the mineral and textural features of Alpha stage. A. Caryopilite showing a red-brown color of tiny fuzzy radiating sheaths and matted clumps in a quartz-rich matrix. NAU12173-371A. PPL. B. Inesite forming white radiating sheaths which host some isolated grains of sphalerite. NAU12173-371A. PPL. C. Pyroxmangite (Pxm) shown in light orange in rhodonite- and quartz-rich Alpha matrix. NAU12158-839A. PPL. D. Rhodonite forming a red-brown fine-grained groundmass with vugs of quartz and rhodonite needles. WE1031-2044A. PPL. E. Rhodonite in Alpha substage 2 appears as isolated red-brown groundmass rimmed with radiating rhodonite needles and is hosted in a quartz matrix. NAU12158-838A. PPL. F. Vug space in rhodonite containing coarse-grained matrix of subhombic adularia, quartz and rhodonite needles, which is characteristic of Alpha substage-1. WE1031-2040E. CPL.
(1990) as stringers cutting the Alpha stage gangue. However, the sulfide minerals are also present as disseminated grains in the cryptocrystalline matrix of Mn-carbonate, Mn-silicate and quartz. Stringers of sulfide minerals have been observed from a vein sample in the upper area of the deposit (EQU1147), which cuts the fine-grained quartz and Mn-carbonate dominated Alpha stage matrix. The disseminated sulfides were observed from a vein sample from the middle level of the deposit (NAU12173). In both examples, the sulfide minerals are fine-grained (50–500 µm) and occur as isolated grains or sharing grain boundaries. The textural features of the Alpha stage sulfide minerals suggest that they co-precipitated late during Alpha stage mineralization (NAU12173) or even after the Alpha stage (EQU1147). Elemental analysis of the Alpha stage sulfide minerals proved to be useful in determining the difference between Alpha and Beta stage sulfides (see Chapter 6).

5.3. Petrography of the Beta Stage

The Alpha stage in the veins from the North Amethyst deposit are cut by black seams of fine-grained precious and base metal sulfides, sulfosalts and Fe-bearing sulfides which are referred to as the Beta stage (Foley, 1990). The Beta stage represents the first economically important stage of mineralization at the North Amethyst deposit. The widths of the Beta seams vary from a few millimeters to tens of centimeters (Foley, 1990), although most Beta stage intervals recognized in the present study have widths of 10–140 mm. The Beta stage seams always cut Alpha stage veins, but not all Alpha stage veins are cut by Beta stage seams.

The Beta stage consists of a complex association of base metal sulfides, native silver, silver sulfides, silver sulfosalts and the gold bearing minerals electrum and uytenbogaardtite. Highly concentrated Beta veins appear as dark gray to black seams, which streak across light colored, pink, white or red-brown Mn-rich Alpha matrix (Fig. 5-9A-C). In one instance, a dark red Beta seam was observed, with the color being caused by the abundant presence of pyrargyrite (Fig. 5-9D). The fine-grained mineral assemblage of Beta contains a slightly higher proportion of base metal sulfides to precious metal minerals. Sphalerite is the most abundant ore mineral, followed by pyrite then galena and in lesser amounts chalcopyrite. The Beta seams at certain locations have yielded Zn concentrations that are nearly equivalent to the amount of silver
The Au to Ag ratios of Beta stage are 1:100 and this proportion has appeared consistently in the assay results from nearly all the Beta intercepts sampled in this study.

The Beta seams encountered in the exploration drill cores are texturally different from those reported by Foley (1990) and Foley et al. (1993). According to previous reports, Beta stage veins are localized in the center of Alpha veins because the vuggy cores of Alpha served as a structural weakness infilled by the Beta stage (Foley, 1990). However, the Beta seams encountered in the present study were not observed in the vuggy cores of Alpha stag veins. Nine drill core intercepts containing Beta seams were sampled in this study. Seven drill core intercepts of Beta stage are located in the upper level of the North Amethyst deposit, localized along the Equity fault (EQU samples) and two drill core samples are located in the middle levels at the southern end of the deposit at an elevation of 10,250 ft level (NAU12148 and NAU12158). Of the nine drill core intercepts, none showed Beta confined to a vuggy Alpha stage core. However some core intercepts showed the opposite relationship where Beta seams were confined to the margins of the Alpha stage vein. Beta stage ore minerals are weakly present as lightly disseminated grains of base and precious metal minerals in the vuggy core of drill core EQU1147 and EQU1263, but it does not occur as seams which is the primary occurrence of Beta stage observed in this study and Foley (1990).

The most frequent and highly concentrated Beta stage veins are located in the upper levels of the deposit confined to the Equity fault which yields the greatest concentrations of Au-Ag minerals. In this part of the deposit, the Beta stage is hosted by Alpha stage veins that lack Mn-silicate minerals. Petrographic analysis of the Beta stage seams revealed that the highest grades occur where significant amounts of sphalerite and fine-grained brown colored Mn-calcite are present. High-grade Beta stage veins are also present in the middle portion of the deposit and the southern end of the deposit at the 10,250 ft elevation (NAU12148, NAU12158). In these mid-level veins, the Beta stage is hosted in Mn-silicate rich Alpha veins.

Distinct Beta stage seams were not observed in the deep portion of the deposit (Fig. 5-9E-H). The presence of Beta stage minerals in the deep level veins is limited to isolated and subtle
Fig. 5-9: Mineralogical and textural features of Beta stage. A. Drill core image of NAU12158 containing thin, black Beta seams in a Alpha matrix consisting of fine-grained cryptocrystalline mixture of rhodonite, quartz, adularia, calcite, Mn-calcite and rhodochrosite. Samples NAU12158-837A (left) and NAU12158-838A (right) are highlighted. The sample taken on the right is hosted by a rhodonite-rich Alpha matrix which has a dark red color while the sample taken on the left is hosted by a greater proportion of Mn-carbonate rich minerals to rhodonite and has a white, cream color. B. Beta seam that is 3mm wide Beta seam, which is bounded by a quartz-rich Alpha assemblage to the left and brecciated tuff of the Willow Creek welding zone on the right. NAU12158-838A. PPL. C. Beta seam that is 3 mm wide and outlined in pink. The seam mostly consists of sphalerite (gray) and pyrite (light yellow), chalcocyanite (dark yellow), galena and silver minerals (light gray-silver) in Mn-rich Alpha matrix. NAU12158-838A. RL. D. Red Beta seam in drill core intercept EQU1262 in contact with highly brecciated rock flour of tuff of the Willow Creek welding zone. E. Drill core WE1031 at 2040 ft. Two thin section samples; 2040D (top) and 2040C (bottom) were analyzed from core in the middle column, which contains Alpha matrix crosscut by a late calcite and chlorite vein. F. Breccia-3 in sample WE1031-2040D. Alpha stage material appears black on left side, Breccia-3 quartz matrix containing fragments of Alpha, Beta and Stage-1 in sharp contact with a crystalline quartz cement matrix in the upper right. PPL. G. Drill core WE1031 at 2044 ft. Three thin section outlines are in view; 2044A,-B and -C (from bottom to top). The three samples are part of a continuous sample transect along the width of a multi-stage and spatially overlapping vein segment of both the Mn-Au and B.M.S. associations. H. Breccia-2 in sample WE1031-2044A. Fine-grained angular Beta fragments of silver (box in pink with close-up photo insert in reflected light) which is hosted by rhodonite needles and crystalline quartz matrix and it is in contact with fine-grained cryptocrystalline Alpha matrix predominantly consisting of rhodonite. PPL
occurrences where fine-grained brecciated fragments of the Beta stage are hosted in a quartz-rich matrix. The veins in the deep portion of the deposit are dominantly composed of the later B.M.S. association with remnants of Alpha stage and a weak presence of Beta stage. Fine-grained brecciated fragments of the Beta stage were observed in quartz cement of Breccia-2 and Breccia-3, which are in contact with Alpha matrix as observed through petrographic analysis of samples from the 2,040 and 2,044 ft intervals of drill core WE1031 (Fig. 5-9E-H). However, a significant sample from a deeper part of the drill hole at the 2531 ft interval yield 2 ppm Au and 8 ppm Ag in a chalcopyrite-rich breccia. A copper-rich stage has so far not been recognized in the Mn-Au or B.M.S. associations and it is presently unclear how the precious metal enrichment in this one intersection relates to the overall paragenesis. The Beta stage in the deep portion of the deposit is brecciated and weakly mineralized as opposed to Beta in the mid and upper elevations of the deposit which occur as fully intact seams.

There is no direct evidence of a gangue assemblage being associated with the Beta stage. Foley (1990) has reported that the Beta stage is associated with minor quartz and carbonate gangue. Throughout the present study, a gangue component of the Beta stage is not present or is very ambiguous. Some samples show Beta stage minerals being associated with fine-grained dark brown Mn-calcite, which occurs as halos around individual Beta stage grains or around Beta stage stringers that cut Alpha stage matrix. However, it is difficult to discern for sure that the Mn-calcite halos do not belong to the Alpha stage (Fig. 5-13A-B).

5.3.1. Substages

The Beta stage is reported to occur as two substages, referred to as the Beta-1 and Beta-2 substages (Foley, 1990). The two substages have similar vein mineralogy, but are separated by a period of brecciation (Foley, 1990). The breccia that developed between the two Beta substages is referred to as Breccia-1. It is unsorted and characterized by a mixture of subangular to rounded pieces of fine-grained Beta stage material, angular fragments of bleached and unbleached wallrock and fragments of Alpha stage vein material cemented by microcrystalline quartz (Foley, 1990). Breccia-1 is not observed macroscopically in the cores investigated, but has been identified through petrographic analysis.
Breccia-1 occurs as thin (30–900 μm), quartz-rich breccia zones containing fine-grained (0.1–2 mm) angular to subrounded fragments of Alpha and Beta material. As these veinlets crosscut Alpha stage matrix and a Beta stage seam, the brecciation has to postdate the Beta stage (Fig. 5-14A). The quartz cement associated with this breccia is fine-grained, with individual grains ranging from 50–500 μm in size. The petrographic characteristics of the quartz cement are the same as those described for Breccia-1 by Foley (1990). The microscopic Breccia-1 was observed in one mid-level sample (NAU12158-839A) and one upper level sample (EQU1255-245A) from the North Amethyst deposit. The Breccia-1 from the mid level of the deposit contains Alpha stage material with rhodonite, but Breccia-1 observed in the upper portion of the deposit contains fine-grained pieces of Mn-calcite and no rhodonite since the Alpha veins in the upper levels do not contain Mn-silicate minerals (Fig. 5-14B).

A distinction between the Beta-1 and Beta-2 substages as proposed by Foley (1990) could not be made in the present study. A second crosscutting Beta stage mineral assemblage was not observed in the vein samples collected in this study and Breccia-1 was only observed under the microscope.

The Beta-2 substage was identified by Foley (1990) based on outcrops exposed in the underground workings. The Beta-2 substage was described by her as competent seams that crosscut Breccia-1 quartz matrix which contained rounded cobbles of Beta-1 substage and fragments of Alpha veins and wallrock (Foley, 1990). Beta-2 substage was described to be texturally and mineralogically identical to the Beta-1 substage (Foley, 1990).

5.3.2. Mineralogy of the Beta Stage

The following section describes the mineralogy and textural characteristics of the Beta stage.
Pyrite ($\text{FeS}_2$)

Pyrite is the first ore mineral to form in the North Amethyst deposit and it occurs as euhedral shaped grains and has a brassy yellow color in reflected light. Although predominantly euhedral, pyrite forms subhedral or anhedral grains in some instances. Pyrite crystals range in size from a few micrometer to 1 mm. However, most grains range between 100 μm and 1 mm. Pyrite grains often have fractures or pits, which contain inclusions of base metal sulfides, gold or silver-bearing minerals (Fig. 5-10A). Some pyrite grains contain pitted cores with smooth outer rims. BSE images of those pitted pyrites reflect a chemical compositional variation where the rims are more enriched in arsenic (Fig. 5-11A). Detailed textural observations of pyrite reveal replacement textures by most of the late ore minerals identified in the North Amethyst deposit, including sphalerite, chalcopyrite, marcasite, galena, electrum, freibergite, polybasite, pyrargyrite, jalpaite, acanthite and native silver. The relative sequence of mineral precipitation is most obvious in cases where pyrite is crosscut by fracture filled with these minerals or where these minerals replace pyrite along its edges.

Sphalerite ($\text{Zn,FeS}$)

Sphalerite occurs after pyrite and forms subhedral or anhedral grains that are generally iron poor (0.05–2.66 mole % FeS; see Chapter 6). Sphalerite is the most abundant ore mineral in Beta stage and it forms closely spaced clusters. Sphalerite is commonly intergrown with anhedral grains of galena, which occurs along grain boundaries of the sphalerite or infills cracks (Fig. 5-10B). Sphalerite of the Beta stage is fine-grained (10–500 μm) and is light brown or light gray in plane polarized light. Chalcopyrite, marcasite, galena, electrum, freibergite, polybasite, pyrargyrite, jalpaite, acanthite and native silver are observed to occur after sphalerite, based on textural relationships such as fracture fill, mineral edge replacement and cross-cutting relationships (Fig. 5-10C).
**Chalcopyrite (CuFeS₂)**

Chalcopyrite formed after pyrite and sphalerite in the Beta stage. Chalcopyrite crystals have copper yellow colors in reflected light and range from 5–500 μm in size. Chalcopyrite has a variety of grain morphologies and appears in different textural settings. For example, chalcopyrite crystals have been observed to occur as isolated subhedral or anhedral grains, or form as clusters, but are more widely spaced and less abundant than pyrite or sphalerite. Occasionally, chalcopyrite occurs in contact with pyrite, sphalerite, marcasite, galena and electrum. Chalcopyrite occurs as thin fine-grained slivers that fill fractured pyrite or sphalerite and serves as a fine-grained matrix to marcasite (Fig. 5-10D). Coarser grained chalcopyrite crystals are commonly pitted and may contain inclusions of sphalerite, galena and pyrite. Chalcopyrite is replaced by galena and silver-bearing minerals by mineral edge replacement (Figs. 5-10E,G and 5-11C,D,G).

**Marcasite (FeS₂)**

Marcasite appears coeval with chalcopyrite. It forms tabular and euhedral shaped crystals which are hosted in a fine-grained chalcopyrite matrix (Fig. 5-10D). Marcasite crystals also appear scattered in gangue and as micrometer-sized grains that infill fractures cutting across pyrite and sphalerite. The crystals range from a few micrometers to 100 μm in size and have a brassy yellow color in reflected light. Some of the larger crystals contain patches of small pits and have minor fractures and rough grain boundaries. The marcasite can be identified based on its anisotropic characteristics in crossed polarized reflected light, which distinguishes it optically from pyrite. Marcasite crystals are fine-grained and show well-developed oscillatory zoning patterns (Fig. 5-11B). The replacement textures of marcasite include mineral edge replacement by galena and silver-bearing minerals.

**Galena (PbS)**

Galena occurs as fine-grained (0.5–1 mm), isolated, euhedral to subhedral grains or as fine anhedral grains and forms after pyrite, sphalerite, chalcopyrite and marcasite (Fig. 5-10B,
E). Fine-grained anhedral galena commonly occurs in contact with, or replacing, sphalerite grains (Fig. 5-10B). Galena has been observed to preferentially replace fine-grained chalcopyrite matrix and leaving behind marcasite which appear as inclusions in the galena. Galena is replaced by silver sulfosalts and silver (Fig. 5-10E). Polybasite replaces galena, often from the grain margins inward towards the core (Figs. 5-10E, 5-11C). This type of replacement texture has been explained as a guided replacement texture (Bastin, 1957), where polybasite is replacing galena along its cleavages from the grain rims towards the core.

Electrum (Au$_{0.3-0.5}$Ag$_{0.7-0.5}$)

Electrum occurs as anhedral grains that replace pyrite (Fig. 5-12C), sphalerite (Fig. 5-12B) and galena (Fig. 5-11D) or appear isolated and scattered in the gangue matrix. The electrum grains can range from a few microns to 300 μm in size and have a bright golden yellow color in reflected light (Fig. 5-10G). Tarnished electrum grains are blue or reddish orange. The textural relationships observed in BSE images indicate that electrum occurs after the deposition of pyrite, sphalerite, galena, native silver and silver sulfosalts (Fig. 5-11E). Electrum is observed to replace pyrite, sphalerite and galena by mineral edge replacement (Figs. 5-12B-C and 5-11D). BSE imaging of electrum grains revealed that many grains have silver-rich rims and silver minerals are replacing electrum which displays a penetrative replacement texture (Fig. 5-11F). Electrum has been observed to be replaced by uytenbogaardtite, freibergite, polybasite, pyrargyrite, acanthite and native silver therefore electrum is interpreted to occur before these minerals. Electrum has not been observed in contact with jalpaite, mckinstryite and marcasite. Chalcopyrite is observed along the rim of electrum grain, but it does not appear to be replacing electrum.

Uytenbogaardtite (Ag$_3$AuS$_2$)

Uytenbogaardtite is a fine-grained gold-silver sulfide (Ag$_3$AuS$_2$), which was tentatively identified by BSE imaging and semi-quantitative EDX analysis. In BSE images, uytenbogaardtite occurs as dark gray rims or spots (0.7–3 μm in width) on electrum grains in an upper level vein sample (EQU1264-493A; Fig. 5-11F). The textural appearance of
uytenbogaardtite indicates that it formed after electrum by mineral replacement. The uytenbogaardtite was too fine-grained for detection by optical light microscopy. Its optical properties can, therefore, not be reported.

*Freibergite (Ag,Cu,Fe)_{12} (Sb,As)_{4} S_{13}*

Freibergite occurs after electrum and uytenbogaardtite. Freibergite has been observed to fill fractures in base metal sulfides and forms complex intergrowths with silver sulfosalts and silver (Fig. 5-10F). Freibergite crystals are fine-grained (10–50 μm) and exhibit anhedral shapes. BSE imaging of freibergite revealed that this mineral is replaced by all the other silver-bearing minerals identified in the North Amethyst deposit, including polybasite, pyrargyrite, jalpaite, acanthite and native silver (Figs. 5-11E,G and 5-12G). It appears that freibergite occurs before polybasite because polybasite forms scalloped surfaces on freibergite (Fig. 5-10F). However, they appear roughly coeval because there are sometimes islands of polybasite in freibergite.

*Polybasite (Ag,Cu)_{16} (As,Sb)_{2} S_{11}*

Polybasite occurs after freibergite and forms small, anhedral grains that range in size from 10–150 μm in length. In BSE images, freibergite exhibits a dark gray color as opposed to polybasite which is light gray. Polybasite has not been observed to occur as isolated grains scattered in gangue matrix, it commonly appears as intergrowth with other silver-bearing minerals, most notably freibergite, pyrargyrite and native silver (Fig. 5-10F). Polybasite is commonly observed to replace base metal sulfides and freibergite (Figs. 5-10E,F and 5-11C). The replacement texture seen for pyrite, sphalerite, chalcopyrite and marcasite are fairly symmetrical, forming thin rims around the grains. The replacement texture is more dramatic in the case of galena, where polybasite is observed protruding inward from the grain boundaries (Figs. 5-10E and 5-11C). Polybasite is replaced by jalpaite, acanthite and native silver (Fig. 5-12G). Polybasite appears to form contemporaneously with pyrargyrite and has not been observed in contact with electrum.
**Pyrargyrite (Ag$_3$SbS$_3$)**

Pyrargyrite forms after freibergite and polybasite and appears as fine-grained anhedral crystals (10 μm–0.5 mm). Pyrargyrite crystals are ruby red under plane polarized light and are light gray in reflected light. Pyrargyrite occurs as isolated grains, which are scattered throughout Alpha matrix or in contact with base metal sulfides, electrum and silver sulfosalts. Pyrargyrite replaces the base metal sulfides, electrum and freibergite. However, it is intergrown with polybasite (Fig. 5-11G). Pyrargyrite was not observed to be in contact with jalpaite, acanthite or native silver.

**Mckinstryite (Ag$_{1.2}$Cu$_{0.8}$S)**

Mckinstryite occurs as fine-grained (100–500 μm) brecciated fragments or as angular crystals in quartz-rich matrix. BSE imaging revealed that mckinstryite forms a fine-grained matrix to jalpaite and acanthite. The jalpaite occurs as fine-grained matted clumps, with individual crystals being a micrometer or less in size. Acanthite crystals exhibit cubic shapes and range from 5–10 μm in size. They form on the surface of the fine-grained mckinstryite grains (Figs. 5-11H and 5-12D-G).

**Jalpaite (Ag$_3$CuS$_2$)**

Jalpaite forms small, acicular needles that typically radiate outward from a common center. The needles are a few microns in size (5–10 μm) and exhibit a dark green color in plane polarized light (Fig. 5-12G). Jalpaite also forms fine-grained aggregates and individual crystals (≤1 μm) overgrowing mckinstryite (Fig. 5-11H). Jalpaite occurs as an overgrowth of freibergite, polybasite and mckinstryite and infills fractures crosscutting base metal sulfides. Native silver replaces jalpaite. As a result of this mineral replacement, jalpaite sometimes forms small inclusions in native silver (Fig. 5-12G).
Acanthite (Ag$_2$S)

Acanthite forms late in the sequence of silver minerals and occurs as thin rims replacing base metal sulfides or as very fine-grained (5–10 μm) platy crystals that overgrow freibergite, polybasite, mckinstryite, jalpaite, native silver or electrum (Figs. 5-11C,E-F,H, 5-12D,H, 5-13D-H). The platy needles are commonly seen with other silver minerals, but also occur along fractured euhedral pyrite. Acanthite also appears as intergrowth with other silver sulfosalts such as polybasite, freibergite and native silver. However, textural relationships indicate that acanthite replaces freibergite, polybasite, mckinstryite and jalpaite but it is itself replaced by native silver. Acanthite has not been observed in contact with pyrargyrite.

Native Silver (Ag)

Native silver is the last hypogene mineral to form and occurs as fine, anhedral grains. The native silver has a bright yellow to slightly orange colors in reflected light and ranges between a few microns to 300 μm in size (Figs. 5-10F, 5-11D-F, 5-12D,F-H). Native silver replaces base metal sulfides, electrum, uytenbogaardtite, silver sulfosalts and silver sulfides but no direct contact with pyrargyrite has been observed. Dendritic silver crystals, 10–50 μm in length, form isolated grains in gangue matrix or overgrow anhedral silver, electrum or silver sulfosalts grains.

Covellite (CuS)

Covellite occurs late in the ore mineral paragenesis at the North Amethyst deposit. It has a light blue to indigo blue color in reflected light and occurs as a thin, fine-grained mass that line the rims of silver and base metal sulfides (Fig. 5-10H). The occurrence of covellite appears to be the result of supergene enrichment.

5.4. Petrography of Breccia-2 and Black Quartz Breccia

Breccia-2 is a brecciation event that occurred after the Beta-2 substage and it marks the transition from the Mn-Au association to the B.M.S. association (Foley, 1990). The Breccia-2
Fig. 5-10: Reflected light photomicrographs of North Amethyst ore minerals. A. Pyrite (Py) with grain edge replacement by sphalerite (Sp) and galena (Gn) and containing inclusions of sphalerite (Sp), galena (Gn) and chalcopyrite (Cp). B. Clusters of iron-poor sphalerite (Sp) which appear intergrown with galena (Gn). C. Sphalerite (Sp) crosscut by fine-grained marcasite (Mrc), chalcopyrite (Cp) and galena (Gn) and being replaced on its grain boundaries. D. Tabular marcasite (Mrc) with anhedral chalcopyrite (Cp) matrix replaced by polybasite (Plb). E. A coarse-grained, anhedral galena (Gn) with inclusions of marcasite (Mrc) and chalcopyrite (Cp) replaced by polybasite (Plb). F. Replacement of freibergite (Frei) by polybasite (Plb) which exhibits a scalloped texture. Both freibergite and polybasite are replaced by native silver (Ag). G. Electrum (El) intergrown with galena (Gn) and being replaced by freibergite (Fbg). H. Mineral edge replacement of pyrite by polybasite (Plb), chalcopyrite (Cp), galena (Gn) and covellite (Cov), which has an indigo blue color.
Fig. 5-11: BSE images of the North Amethyst ore minerals. A. Pyrite (Py) grain with compositional zoning. The lighter colored rims are arsenic-rich. (b) Tabular marcasite (mrc) crystals exhibiting well developed growth zoning are hosted in a matrix of chalcopyrite (Cp). C. Fragmented pyrite (Py) rimmed and filled by galena (Gn), marcasite (mrc) and chalcopyrite (Cp). Galena displays guided replacement by polybasite. The base metal sulfides are replaced by polybasite (Plb) and acanthite (Ac) which shows a mineral edge replacement texture. D. Galena replacement by electrum, jalpaite, native silver (Ag), polybasite and freibergite. Replacement is occurring along the cleavage planes of galena by guided replacement. E. Electrum replacement by chalcopyrite, native silver (Ag), acanthite and freibergite. F. Electrum (el) with silver rich-rims replaced by freibergite (Fbg), native silver (Ag), acanthite (Ac) and uytenbogaardtite (Utyn). G. Coeval appearance of pyrargyrite (pyr) and polybasite (plb) which is present among pyrite, chalcopyrite, freibergite and electrum. H. McKinstryite (McK) with matted and individual crystals of jalpaite (Jal) and cubic acanthite (Ac) on its surface.
Fig. 5-12: Photomicrographs of replacement textures observed in base and precious metal minerals. A. Pyrite occurring as inclusions in sphalerite. Pyrite and sphalerite are penetrated and replaced by galena. RL. B. Pyrite and sphalerite replacement by galena and mineral edge replacement of sphalerite by electrum. RL. C. Pyrite replacement by electrum (white) and silver minerals (gray). BSE. D. Close-up of electrum replaced by native silver, acanthite (Ac) and freibergite (Fbg). BSE. E. Mineral edge replacement of electrum by pyrargyrite (pyr) and chalcopyrite (cp). BSE. F. Freibergite (Fbg) replacement by polybasite (Plb) which exhibits a scalloped texture. Freibergite and polybasite are replaced by native silver, which exhibits a rim to core replacement texture. BSE. G. Replacement of freibergite (Fbg), polybasite (Plb) and jalpaite (Jal) by native silver, which exhibits a core to rim replacement texture. Jalpaite (Jal) occurs as tiny radiating, acicular crystals. BSE. H. Replacement of acanthite (Ac) by native silver (Ag) and sphalerite (Sp). BSE.
Fig. 5-13: Photomicrographs of replacement textures observed in base and precious metal minerals. A. Fine-grained dark brown Mn-calcite and Beta stage minerals that cut a quartz-rich Alpha matrix. EQU1255. PPL. B. Same field of view highlighting the ore minerals of Beta stage which cut a quartz-rich Alpha matrix. RL. C. Contact between a Mn-rich Alpha matrix (dark red) and a quartz-rich breccia which contains pieces of silver minerals belonging to Beta stage. WE1031-2044A. PPL. D. Mckinstryite and acanthite in the quartz-rich breccia matrix in contact with Mn-rich Alpha stage. RL. E. Close-up of mckinstryite and acanthite in previous image. The two minerals have different phase contrast. The darker gray mineral is mckinstryite and the lighter gray is acanthite. The tiny crystals on its surface are acanthite. BSE. F. Brecciated silver minerals, dominantly acanthite which is hosted in the quartz-rich breccia in contact with Mn-rich Alpha stage. WE1031-2044A. BSE. G. Close-up of a silver grain from previous image, which consists of large, coarse-grained cubes of acanthite and smaller crystals of jalpaite on the surface of mckinstryite. BSE. H. Fine- and coarse-grained acanthite (white) inclusion in hematite (dark gray) observed. WE1031-2044A. BSE.
event reflects a period of extensive brecciation and sedimentation in the veins of the North Amethyst deposit (Foley, 1990). Breccia-2 is comprised of several breccia types that show sedimentary features and a late black quartz breccia (Foley, 1990). The breccias are characterized by angular to rounded fragments of all earlier stages of mineralization and wallrock, most of which were plucked near the site of deposition (Foley, 1990).

Three varieties of breccias have been described for the Breccia-2 stage. One breccia type is a matrix-supported breccia that contains fragments of bleached and unbleached volcanic wallrock, rounded and altered pieces of Alpha stage, rounded to subrounded cobbles of sulfide-rich Beta stage (up to 15 cm in width) and fragments of Breccia-1 (Foley, 1990). The pieces are supported by a muddy, quartz-rich cement and some fine-grained quartz cement showing graded bedding (Foley, 1990). The second type of breccia has pronounced sedimentary features and it is characterized by layers of muddy quartz that displays graded bedding, soft sediment deformation and other textures which indicate the material settled out of solution as the larger cobbles and blocks provides the base (Foley, 1990). This type of breccia appears as a closely spaced matrix-supported breccia as previously described but capped with a layer of muddy quartz that shows graded bedding. The third type of breccia has silt-to-gravel sized fragments that settled out in large graded beds of at least four cycles that extend for 30 meters along a vein wall and are greater than 10 feet in height (Foley, 1990). Foley (1990) reports that the tops and bottoms were not visible in exposure. It is unknown if this feature is a result of normal or reverse grading, but this is the highly water-laden type of breccia in the Breccia-2 event where the water-deposited beds show minor soft-sediment deformation and fine-graded sediment.

These three breccia types described above are not in paragenetic order, but are the main varieties of breccias forming the Breccia-2 stage by Foley (1990). A final breccia has been reported which is separate and distinct from the Breccia-2 and it is known as the black quartz breccia. This breccia is a transitional breccia which falls between the Mn-Au association and the B.M.S. associations, but it is treated separately from Breccia-2 because it occurs after the breccias and it does not express sedimentary features other than containing pieces of Breccia-2.
Black quartz breccia is dominantly composed of fine-grained microcrystalline quartz cement that comprises 50–90 modal% and 10–50 modal% brecciated fragments of Alpha and Beta stage material, earlier breccias and wallrock (Foley, 1990). The cements are light gray to black in hand sample, which is due to the amount of ore minerals present (Foley, 1990). Foley (1990) reported her uncertainty of the sulfide aggregates as clastic or precipitates but suggested that they are clastic due to their shapes and are interpreted as broken and ground (Foley, 1990). Through petrographic analysis of black quartz samples collected in this study, it is confirmed that the sulfide aggregates are clastic and probably represent brecciated and ground Beta seams.

Two exploration drill cores (NAU12150 and NAU12166) were observed to contain breccias from the transitional period between the Mn-Au association and the B.M.S. association and both were sampled for petrographic analysis. The breccia segment in core NAU12150 shows textural features of the matrix supported muddy quartz breccia which is the first breccia type described above. The breccia is characterized by a fine-grained, dark gray to black quartz matrix with abundant subrounded clasts of light gray Alpha quartz cobbles (0.5–2.5 cm wide) and black, Beta stage sulfide cobbles (3–6 mm wide) as well as, white bleached wall rock (1 cm wide) and unbleached tuffaceous wall rock (1.5 cm wide; Fig. 5-14C). The muddy quartz matrix exhibits some minor and faint banding textures, but it is uncertain if it is crystallized sedimentary bedding or an inherent feature of this kind of cryptocrystalline quartz matrix. In thin section (sample NAU12150-642A), the muddy quartz breccia matrix is composed of 25–200 μm large quartz grains with Alpha fragments of quartz and altered Mn-rich clasts along with fine-grained and disseminated pieces of Beta stage material. Also contained in the muddy quartz matrix are disseminated, fine-grained masses that appear to be mainly carbonate minerals, but may contain clay minerals which are localized between quartz grain boundaries (Fig. 5-14D). The overall texture of the muddy quartz matrix can be described as a fine-grained groundmass with a greater volume percent of quartz than carbonates and clays. In crossed polarized light, the fine-grained intergranular carbonates and clays of the muddy quartz matrix are light brown with some speckles of high order blue, yellow and orange interference colors. Vug spaces in the muddy quartz matrix are lined with (75–180 μm) euhedral or prismatic quartz crystals (Fig. 5-14D).
Fig. 5-14: Photomicrographs of the mineral and textural characteristics of Breccia-1, Breccia-2 and black quartz breccia. A. Contact between the fine-grained Mn-rich, cryptocrystalline Alpha matrix (dark red) with a Beta seam. Both are cut by a fine-grained quartz matrix, which is characteristic of Breccia-1. NAU12158-839A. PPL. B. Contact between quartz-rich Alpha (white) stage and a Beta seam (β-1). Both are cut by a thin, quartz veinlet containing clasts of Alpha and Beta, which is characteristic of Breccia-1. EQU1255-245A. PPL. C. Breccia-2 showing a black, muddy quartz matrix with abundant subrounded clasts of light gray Alpha quartz cobbles (0.5–2.5 cm wide) and black Beta sulfide cobbles (3–6 mm wide) as well as, white bleached wall rock (1 cm wide) and unbleached tuff wall rock (1.5 cm wide). NAU12150 (642–642.5 ft). D. Breccia-2 which is composed of a fine-grained quartz matrix with fine-grained disseminated carbonate minerals and possibly organic-rich clays (light brown) which also contains vugs and sulfides. NAU12150. CPL. E. Black quartz breccia in drill core NAU12166 (242–242.5 ft). This breccia is a quartz rich matrix with a black streak which is composed of black sulfide rich dust of Beta stage. F. Quartz-rich matrix of the black quartz breccia.. The quartz matrix is characterized by euhedral to subhedral crystalline to coarse-grained quartz matrix that also contains some sub-rhombic adularia crystals in the coarse-grained matrix. NAU12166-242A. CPL. G. Beta stage sulfide fragments which are dominated by pyrite, chalcopyrite, sphalerite and galena. NAU12166 242A. RL. H. Close-up of the same area. The crystal shapes, size and morphology are identical in appearance to Beta samples. RL.
A breccia intercepted in drill core NAU12166 exhibited features that resemble the black quartz breccia described by Foley (1990), which appears as a streak of black, sulfide mineral-rich dust in a fine-grained white quartz matrix (Fig. 5-13E). The black cloudy streaks contain fine-grained fragments of base metal sulfides and Au-Ag minerals in a quartz cement with a more granular texture than the muddy quartz matrix observed in NAU12150. The quartz cement is composed of a fine-grained (45–550 μm) matrix of quartz grains and 300–400 μm sub rhombic adularia crystals (Fig. 5-14F). Fine-grained precious and base metal sulfides comprise the black cloudy texture in the quartz and adularia matrix. The ore minerals are fine-grained (1 μm–1 mm) and exhibit subrounded to angular crystal shapes (Fig. 5-14G). The ore minerals comprising the band of sulfide dust have morphologies and textural replacement features observed in competent Beta seams. For example galena is observed to fill in the fractures of sphalerite (Fig. 5-14H). The shape, size and appearance of the sulfide minerals are similar to sulfides in intact Beta seams. Fragments of Alpha, Breccia-1, Breccia-2 or wall rock were not observed in the black quartz breccia in this sample, but were noted by Foley (1990).

The two drill cores which contain the transitional breccias are located at opposite ends of the mid-level of the North Amethyst deposit. The muddy quartz breccia present in drill core NAU12150 is located in the southern end of the deposit (S2 orebody) at an elevation of 10,250 ft, which is about 250 ft above high-grade Beta seams recovered in drill hole NAU12158. The black quartz breccia is located in the northern end of the deposit (N3 orebody) at 10,250 ft elevation. This area of the North Amethyst deposit did not yield cores with Beta seams but is dominated by base metal-rich veins.

5.5. Petrography of B.M.S. Association

The B.M.S. association occurs after the black quartz breccia and it has been observed to crosscut all the preceding stages of breccias and vein types (Foley, 1990). In the present study, the B.M.S. association was observed to crosscut the Alpha veins, Beta seams and Breccia-1 stages of the Mn-Au association, but it was not observed to cut the transitional breccias of Breccia-2 and the black quartz breccia. The B.M.S. association is reported to consist of three mineralogical stages which are each punctuated by a breccia event (Foley, 1990). The three
mineralogical stages are characterized by (1) dominantly base metal sulfides, iron-oxide and quartz (Stage1a,b), (2) Ca-, Mn-, and Fe-bearing carbonates, fluorite and quartz (Stage-2) and (3) Mn-calcite, quartz and pyrite (Stage-3) (Foley, 1990).

A major difference between this study and Foley (1990) is the location and presence of the stages of the B.M.S. association. In Foley (1990), Stage-1a,b, Breccia-3 and Stage-2 of the B.M.S. association were identified and reported from the 10,250 ft level of the North Amethyst deposit but those stages were not observed in that location in this study. The breccias and stages of the B.M.S. association as described by Foley (1990) were only observed in the deep level veins from the WE1031 drill core. In the present study, the mid-level of the North Amethyst deposit was observed to contain the Mn-Au association, the transitional breccias of Breccia-2, the black quartz breccia and Stage-3.

5.5.1. Petrography of Stage-1

The B.M.S. association begins with the mineralogical stage known as Stage-1 and it is characterized by the abundant presence of base metal sulfides, argentian tetrahedrite, hematite, chlorite and quartz (Foley, 1990). Stage-1 is divided into two substages, referred to as Stage-1a and Stage-1b (Foley, 1990). Stage-1a is described as a chlorite, hematite and quartz assemblage which was deposited prior to and concurrently with the period of base metal mineralization (Stage-1b) that resulted in a crustiform sequence of sphalerite, galena, pyrite, chalcopyrite and tetrahedrite (Foley, 1990).

Stage-1 veins in the present study were identified in veins intercepted in the deep intersection of the Amethyst and Equity faults at an elevation of 9275 ft (2034 and 2044 ft intervals of the WE1031 drill core). The petrographic analysis of the Stage 1 vein did not clearly reveal chlorite, hematite and quartz (Stage-1a) as an event prior to the base metal sulfides, but appeared texturally concurrent. Therefore, the term Stage-1 as stated in this thesis will be used for both substages as defined by Foley (1990). In contrast to Foley (1990) who described Stage-1a chlorite, hematite and quartz (which also includes Mn-calcite) to be fine-grained cryptocrystalline and not crustiform, petrographic analysis of the vein in drill core WE1031
showed that the entire Stage 1 vein represents a crustiform sequence of quartz, hematite, chlorite, sphalerite, pyrite, chalcopyrite, galena and a fine-grained Mn-rich mineral assemblage containing calcite and rhodochrosite (Figs. 5-15, 5-16A). The petrographic analysis of the Stage-1 vein from the WE1031 exploration core revealed further that the vein is closely spaced or spatially overlapped by breccias and stages of the B.M.S. association (Fig. 5-15). The ore minerals of Stage-1 occur as a crustiform sequence of base metal sulfides. Some bands range from several cm thick to 1 mm or less and show either multi phase bands, consisting of multiple base metal sulfides that appear intergrown with one another, or single phase bands, consisting of just one sulfide mineral (Figs. 5-16G-H).

**Quartz**

Quartz exhibits several textural features in Stage-1. One of the primary occurrences of quartz are crustiform bands that consists of different grain sizes. A 900 μm wide crustiform band of quartz that lies between a band of hematite and chlorite is composed of a crystalline matrix consisting of different grain sizes (Fig. 5-16A). This crustiform band consists of a matrix with crystal sizes ranging from 43–100 μm in width and includes some coarser grains that are up to 450 μm in size (Fig. 5-16B). A thick band of coarse-grained quartz with crystal sizes ranging from 300 μm–1.3 mm occurs (Fig. 5-16B). The coarse-grained band also contains coarse grains of adularia. Very thin (145 μm thick) bands occur as microcrystalline size matrix with grains ranging from 20–50 μm (Fig. 5-16B). Quartz also exhibits large euhedral and prismatic crystals (~800 μm; Fig. 5-16C). Quartz within the (Mn-, Ca-) carbonate matrix occurs as a crystalline to coarse-grained matrix (63–250 μm) and is in association with the rhombic calcite and rhodochrosite. The coarser-grained crystals have euhedral shapes and a coarse, 800 μm prismatic quartz crystal is situated on the edge of a carbonate rich patch of calcite and rhodochrosite rhombs (Fig. 5-16E). These patches of rhombic calcite, rhodochrosite and crystalline quartz are present within the crustiform bands of Mn-calcite and appear to be the result of open space crystal growth during Stage-1.
(Mn-, Ca-) Carbonate Minerals

Mn-calcite has a light pink color in hand sample and occurs as a fine-grained cryptocrystalline mixture of quartz, calcite, rhodochrosite and chlorite in thin section. Minor amounts of sub-rhombic adularia occur within quartz-rich matrix. The fine-grained light pink cryptocrystalline mixture forms one of the crustiform bands of Stage-1 veins. Mn-calcite occurs as a fine-grained (few microns in size) groundmass with a light brown color in plane polarized light (Fig. 5-16D). In crossed polarized light, Mn-calcite has a dark brown color. Mn-calcite is the most abundant carbonate mineral in Stage-1 veins and dominates the cryptocrystalline mineral assemblage.

Calcite exhibits rhombic and tabular crystals that cluster and occupy small areas within the Mn-calcite rich groundmass. Calcite crystals range from 15–600 μm in length. Calcite has a light gray or smoky tinge color with well-defined grain boundaries and higher relief than the surrounding Mn-calcite. In crossed polarized light, calcite has a blend of tan, light green and pink third order interference colors but does not exhibit well-defined cleavage planes. The small areas occupied by rhombic calcite crystals are in association with a crystalline quartz matrix, rhodochrosite and chlorite.

Rhodochrosite is the least abundant carbonate gangue mineral but is observed to be intergrown with calcite. It forms small rhombs. Rhodochrosite has a high relief, similar to calcite, but is clear and semi-transparent in plane polarized light. In crossed polarized light, rhodochrosite shows second order bright pink, green, yellow, blue or orange interference colors. Rhodochrosite is the least abundant and most fine-grained (30–250 μm) carbonate mineral of the Stage-1 gangue assemblage.

Hematite

Hematite forms crustiform bands in Stage-1 veins or within the fine-grained Mn-rich carbonate matrix. Hematite forms red, acicular or tabular crystals which range from 0.1–2 mm in
size (Fig. 5-16F). Hematite also forms tiny needles that are lightly disseminated in the quartz and Mn-calcite-rich matrix.

**Chlorite**

Chlorite forms crustiform bands in Stage-1 veins. It appears as green, fine-grained masses in plane polarized light (Fig. 5-16A). Chlorite may also appear lightly disseminated in fine-grained quartz and Mn-calcite rich matrix. In crossed polarized light, chlorite has low order white inference colors.

**Pyrite**

Pyrite occurs as up to 24 mm wide, crustiform bands (Fig. 5-15), individual crystals in chalcopyrite matrix or intergrown with other sulfide minerals (Fig. 5-16G). Pyrite has a bronze yellow color (Fig. 5-15) in hand sample, forming coarse-grained, euhedral shaped crystals. Optical microscopy revealed that the pyrite crystal sizes range from 10 μm–2 mm.

**Sphalerite**

Sphalerite occurs as up to 8 mm wide, crustiform bands or intergrown with other sulfide minerals (Fig. 5-16G-H). Sphalerite has a yellow orange color in hand sample (Fig. 5-15) and forms coarse-grained, anhedral crystals (Fig. 5-16G-H). Sphalerite crystal sizes observed microscopically range from 3–7 mm.

**Chalcopyrite**

Chalcopyrite occurs as up to 11 mm wide, crustiform bands and serves as a matrix for pyrite cubes (Fig. 5-15). Chalcopyrite has a brassy yellow color in hand sample forms coarse-grained crystals with anhedral shapes. Chalcopyrite crystal sizes observed in thin section range from 1–7 mm.
Fig. 5-15: Cross-section sketch of a sampled drill core segment of core WE1031 from 2034–2036 ft which outlines the spatially overlapping stages and breccias present in this vein interval. Six thin section samples were sampled along the vein width (WE1031-2034A,B,C,D,E,F). The photomicrographs are provided as a representation of the main textural and mineralogical features of the stages or breccias identified for each of the six thin sections. A. Sample WE1031-2034A crustiform texture Stage-1 consisting of bands of Mn-calcite, hematite, quartz, chlorite and sulfides (pyrite and sphalerite). PPL. B. Sample WE1031-2034B coarse-grained Breccia-3 with angular fragments of sphalerite and galena in a coarse-grained quartz matrix. PPL. C. Sample WE1031-2034C showing coarse-grained Breccia-3 with angular brecciated fragments of sphalerite in a coarse-grained matrix of quartz and sub rhombic adularia. PPL. D. Sample WE1031-2034D showing fine-grained Breccia-3 (Br-3) with small bits of Stage-1 sulfides, chlorite and hematite. PPL. E. Sample WE1031-2034E showing fine-grained Breccia-3 (Br-3) with small bits of Stage-1 sulfides, chlorite and hematite. PPL. F. Sample WE1031-2034F fine-grained Breccia-3 consisting dominantly of fine-grained Mn-calcite (Mn-calc) and chlorite (Chl). PPL.
Fig. 5-16: Photomicrographs of the mineral and textural characteristics of Stage-1. A. Crustiform banded assemblage of Stage-1. The bands consists of fine-grained Mn-calcite (light brown), hematite (acicular and dark red), quartz (white), chlorite (green), sphalerite (dark yellow-brown) and pyrite (black/opaque). PPL. B. Quartz band which consists of microcrystalline, crystalline and coarse-grained matrices. CPL. C. Large prismatic quartz crystal surrounded by acicular hematite and pointing into fine grain rhombs of calcite. CPL. D. Stage-1 Mn-calcite which appears as a light brown groundmass with fine-grained calcite and quartz crystals. PPL. E. Calcite-rich patch rimmed by hematite which are present in the Mn-calcite rich band. PPL. F. Hematite crystals from the hematite band of Stage-1. Hematite forms bladed crystals with a dark red or ruby red color. PPL. G. Multi-phase crustiform band of Stage-1 consisting of sphalerite and pyrite. RL. H. Single-phase crustiform band of Stage-1 which consists only of sphalerite. PPL.
Galena occurs as up to 8 mm wide crustiform bands or intergrown with other sulfide minerals (Fig. 5-15). Galena has a silvery metallic color in hand sample. Galena crystals are coarse-grained with cubic shapes and crystal sizes ranging from 2–8 mm. Its optical properties reveal well defined triangular pits and cleavage planes.

### 5.5.2. Petrography of Breccia-3

A fracturing event occurred after Stage-1 which produced a breccia consisting of fragments of coarse base-metal sulfide and chloritized wallrock that is cemented by a fine-grained cryptocrystalline mixture of quartz, chlorite and pyrite (Foley, 1990). The cement is reported to have a green hue due to the presence of chlorite (Foley, 1990). Breccia-3 is reported to contain angular to subangular fragments of base metal sulfides and rounded wallrock fragments. An additional and significant observation is that Breccia-3 is mostly found with Stage-1 veins (Foley, 1990). Therefore, Breccia-3 does not contain the preceding stages and breccias of Breccia-2 and the Mn-Au association.

In this study, Breccia-3 is observed in the deep level veins from the WE1031 drill core. The three sampled vein segments at 2034ft, 2040ft and 2044ft contained Breccia-3. The vein segments at these footages contained different and overlapping vein and breccia stages of the Mn-Au association and/or the B.M.S. association which was distinguished by petrographic analysis. Each of the segments contained stages and breccias of the B.M.S. association, but the 2040 ft and 2044 ft sampled intervals also contained the Mn-Au association.

Breccia-3 is observed to consist of two varieties based on grain size and abundance of Stage-1 fragments and the grain size of the Breccia-3 quartz rich cement. These two varieties are (1) fine-grained Breccia-3 (FG Breccia-3) which consists of fine-grained, dark reddish black quartz cement with Stage-1 fragments and (2) a coarse-grained Breccia-3 (CG Breccia-3) which consists of a coarse-grained, white colored quartz cement (Fig. 5-15). The sampled interval at the 2034 ft contained both FG and CG Breccia-3, 2040 ft contained FG Breccia-3 and 2044 ft
contained FG and CG Breccia-3. The following section presents and describes the mineral and textural characteristics of the FG and CG Breccia-3 from hand sample and thin section observations.

**Fine-grained Breccia-3**

Fine-grained Breccia-3 is a matrix supported breccia which is dark red to black in hand sample and contains fine-grained fragments of Stage-1 minerals (hematite, chlorite, base metal sulfides). The abundance of Stage-1 fragments gives the breccia its dark reddish black color. The fragments of Stage-1 range in size and shape which occur at 1 mm or less and exhibit subrounded to angular and subangular shapes. The fragments of Stage-1 are supported by a fine-grained quartz cement which has a dark reddish black hue. The breccia is observed to juxtapose or crosscut Stage-1 veins which are only present in the deep level veins in this study although these two stages are reported to exist in the 10,250 ft level (Foley, 1990). The petrographic analysis of the breccia revealed a high density of fine-grained Stage-1 fragments which includes chlorite, hematite and angular to subangular base metal sulfides (Fig. 5-17A).

Base metal sulfides of Stage-1 have a range of morphologies and shapes. The brecciated base metal sulfide fragments can appear with sharp and angular grain shapes or may appear subrounded, all of which are isolated and supported by the Breccia-3 quartz cement (Fig. 5-17A). The base metal sulfide fragments in Breccia-3 are observed to range from a few micrometers to 1 mm in size.

The quartz cement of the fine-grained Breccia-3 occurs as a crystalline and coarse-grained matrix with grain sizes ranging from 30–285 μm. The coarse-grained quartz matrix exhibits euhedral to subhedral crystals and contains subhombic adularia, the grain sizes range between 170–285 μm. The coarse-grained quartz matrix coexists with a crystalline quartz matrix (30–100 μm; Fig. 5-17B). Quartz also forms comb textures in the fine-grained Breccia-3 matrix. Comb quartz consist of a row of fairly symmetrical euhedral crystals (1.5–3 mm; Fig. 5-17C).
Chlorite occurs as matted masses in a tabular shape with grain sizes that range from 140–650 μm in length and 90 μm in width (WE1031-2040A). Hematite is present in close proximity to chlorite or in contact with chlorite which form as thin and very fine-grained fibrous mats which appear isolated or outline tabular shape chlorite (WE1031-2034D; Fig. 5-17D). The cryptocrystalline mixture of quartz, chlorite and pyrite which characterizes Breccia-3 as described by Foley (1990) appeared slightly different in this study. A cryptocrystalline mixture is present in Breccia-3 but it occurs as a cryptocrystalline mixture of quartz, chlorite and Mn-calcite which has a green and pink hue. This is not a common feature of Breccia-3 observed in this study and it may be difficult to distinguish from the cryptocrystalline mixture of quartz, chlorite, Mn-calcite of Stage-1 since they are spatially overlapping. The most common occurrence of Breccia-3 is a reddish black quartz-rich cement that hosts fine-grained fragments of Stage-1 base metal sulfides, chlorite and hematite.

**Coarse-grained Breccia-3**

WE1031-2034C is the best example of the coarse-grained Breccia-3 (Fig. 5-15). The breccia is white to light gray in hand sample and it is observed as a 20 mm wide band that cross cuts a coarse-grained, crustiform sequence of base metal sulfides (Fig. 5-15). The fragments of Stage-1 base metal sulfides are observed as 80 μm–3 mm, angular-subangular fragments hosted by the coarse-grained Breccia-3 quartz-rich cement (Fig. 5-17G-H). The breccia is characterized by coarse-grained quartz and adularia crystals. Quartz occurs as a microcrystalline (12–25 μm), crystalline (25–100 μm) and coarse-grained matrix (100 μm –2 mm), or forms large (800 μm –3 mm) prismatic quartz crystals that support fragments of angular-subangular Stage-1 base metal sulfides (Fig. 5-17E-F). Adularia grains exhibit coarse-grained (490 μm–1.2 mm) and well-defined subrhombic crystal shapes (Fig. 5-17G). Hematite and chlorite are also present in the quartz cement. Hematite forms red, fine-grained masses with radiating, acicular needles (370 μm) and chlorite occurs as green felt-like masses which rim subrhombic adularia or outline quartz matrix.
Fig. 5-17: Photomicrographs of Breccia-3. A. Fine-grained Breccia-3 consisting of subrounded, subangular to angular fragments of Stage-1 hematite, chlorite, Mn-Ca-carbonate and sulfide minerals in a quartz-rich matrix. PPL. B. Fine-grained Breccia-3 quartz matrix which consists of crystalline and coarse-grained quartz. CPL. C. Comb quartz in fine-grained Breccia-3. CPL. D. Tabular chlorite masses (green) with hematite rims (dark red-black) in quartz matrix of fine-grained Breccia-3. PPL. E. Coarse-grained Breccia-3 showing quartz matrix (white) with large prismatic quartz crystals that cut and filled Stage-1 crustiform banded sphalerite (dark yellow-brown). PPL. F. Same as previous image. CPL.G. Brecciated Stage-1 sphalerite (dark yellow-brown) with sharp angular fragments hosted in coarse-grained Breccia-3 quartz matrix which also contains coarse-grained subhrombic adularia outlined by chlorite (green). PPL. H. Coarse-grained Breccia-3 quartz matrix containing subangular to angular Stage-1 galena and sphalerite. PPL.
5.5.3. Petrography of Stage-2

Stage-2 represents a second veining stage in the B.M.S. association which occurred after Breccia-3 (Foley, 1990). The Stage-2 mineral assemblage does not contain ore minerals but is reported to consist of coarse-grained quartz, calcite, rhodochrosite and fluorite which are all intergrown with minor amounts of adularia, chlorite and pyrite (Foley, 1990). Manganosiderite is also reported to be present in the Stage-2 assemblage which occurs within calcite (Foley, 1990). Stage 2 is observed to be deposited on Breccia 3 and Stage 1 (Foley, 1990).

In this study, Stage-2 is present in a sampled vein segment from a deep level vein intercept in drill core WE1031. Stage-2 is recognized from petrographic analysis of a vein sample from the 2044ft interval of WE1031, confirming the observation by Foley (1990) that Stage-2 is spatially overlapping Breccia-3 and Stage 1 (Fig. 5-18). However, the mineral assemblage and abundance of the minerals observed in Stage-2 are different to Foley (1990). Stage-2 is observed as a discontinuous and convoluted veinlet of a dominantly coarse-grained quartz matrix with a cloudy white and light gray color in hand sample (Fig. 5-18). The Stage-2 veinlet is observed within Breccia-3 and Stage-1 (Fig. 5-18).

All minerals observed in Stage-2 are intergrown and form a coarse-grained matrix dominated by quartz and adularia with minor amounts of fluorite, calcite and Mn-calcite. The deposition of these minerals appears to occur broadly contemporaneously. This contrasts the paragenetic relationships reported by Foley (1990). She proposed that the deposition of quartz, chlorite and calcite occurred prior to fluorite and additional quartz. Pyrite and chlorite are not observed in Stage-2.

The coarse-grained quartz and adularia which fill the vug spaces in Alpha veins are reported to be crystallized during Stage-2 (Foley, 1990). She noted that the quartz and adularia are texturally identical to Stage-2 minerals and that they contain similar fluid inclusion salinities and homogenization temperatures. The petrographic analysis of the quartz-adularia vug spaces in Alpha veins conducted as part of the present study, however, does not reveal strong textural similarities. For instance, the quartz grains in the Alpha vugs do not express feathery textures
Fig 5-18: Cross-section sketch of a sampled drill core segment of core WE1031 from 2044–2046 ft, outlining the spatially overlapping stages and breccias present in this vein interval. Six thin section samples were taken along the vein width (WE1031-2044A,B,C,D,E,F). The photomicrographs are provided as a representation of the main textural and mineralogical features of the stages or breccias identified for each of the six thin sections. A. Sample WE1031-2044A showing brecciated Beta fragment (acanthite and mckinstryite) in Alpha rhodonite (Rdn) and late, B.M.S. stage quartz matrix (Breccia-3 quartz). PPL. B. Sample WE1031-2044B showing brecciated Stage-1 veinlet (Breccia-3) in Stage-2 matrix of coarse-grained quartz and sub rhombic adularia. PPL. C. Sample WE1031-2044C Stage-1 crustiform texture with sphalerite, Mn-calcite and quartz. D. Sample WE1031-2044D showing Breccia-3 quartz matrix with brecciated fragment of Stage-1 chlorite and hematite. CPL. E. Sample WE1031-2044E showing a crustiform banded texture of sphalerite, hematite and quartz PPL. F. Sample WE1031-2044F showing Stage-1 sphalerite crystals cutting Alpha matrix of rhodonite (Rdn). PPL.
which are well-developed in Stage-2. The adularia grains are coarse-grained (1–4 mm) and exhibit subrhombic shapes in both the Alpha vugs and Stage-2. However, the extinction angles appear to be smaller in Alpha vug spaces which fan around adularia grains at every 20° as opposed to 45° (Fig. 5-19G-H).

Quartz

Quartz appears as a coarse-grained matrix with a cloudy white to light gray color in hand sample. Petrographic analysis of quartz reveals a wide variety of textures. Quartz occurs as microcrystalline (22–25 μm), crystalline (25–100 μm) and coarse-grained (0.1–3 mm) matrices with euhedral-subhedral shapes, an exotic form of feathery quartz texture and flamboyant quartz texture is also present (Fig. 5-19A-C). The feathery quartz texture is a unique type which shows layered feathers that appears similar to a birds feather pattern (Fig. 5-19C). The quartz matrices which exhibit feathery and flamboyant textures are observed in the coarsest quartz grains (0.27–3 mm). These matrices are associated with well-defined subrhombic adularia and euhedral fluorite.

Adularia

Adularia grains are present in the quartz-rich matrix of Stage-2 and occur in significant quantities. Adularia is white to semi-transparent in plane polarized light and exhibits faint simple twins in crossed polarized light. Adularia is most noticeable in a coarse grain size (0.3–1.5 mm) and exhibits well-defined subrhombic crystal shapes (Fig. 5-19D-E). Adularia maybe present in the microcrystalline quartz matrix but it is difficult to distinguish from quartz. Stage-2 dominantly consists of a coarse grained matrix of subrhombic adularia and a coarse-grained quartz matrix that shows euhedral-subhedral, feathery and flamboyant textures.

Calcite

Calcite is coarse-grained (0.3–2 mm) with platy texture. Calcite appears clear to white in plane polarized light and has third-order pink and green interference colors and shows
Fig. 5-19: Photomicrographs of Stage-2. A. Stage-2 quartz and adularia matrix which filled around a brecciated Stage-1 veinlet which contains a crustiform assemblage of chlorite, hematite, Mn-calcite and base metal sulfides. PPL. B. Stage-2 quartz and adularia matrix, which shows a dominantly subhedral crystalline matrix. CPL. C. Coarse-grained feathery quartz texture with lattice bladed calcite. CPL. D. Subhombic adularia. PPL. E. Stage-2 matrix consisting of a coarse-grained assemblage of feathery quartz, euhedral quartz and subrhombic adularia. CPL. F. Well-defined fluorite cubes in a matrix of quartz, adularia and fine-grained Mn-calcite which shows faint lattice bladed texture. PL. G. Alpha substage-1 vug, which contains a very coarse-grained subhombic adularia crystal and quartz, which are lined with rhodonite needles. WE1031-2040. CPL. H. Alpha substage-1 vug from which contains an assemblage of coarse-grained subhombic adularia crystals and euhedral quartz, which are lined with rhodonite needles. WE1031-2040. CPL.
characteristic cleavage planes (Fig. 5-19C). Calcite occurs locally in the quartz- and adularia-rich matrix and is not a major mineral constituent of the Stage-2 assemblage.

\textit{Mn-calcite}

Mn-calcite occurs as a brown, fine-grained groundmass in the quartz- and adularia-rich matrix. Mn-calcite is less abundant than quartz and adularia. Mn-calcite is fine-grained and white to cream in color in hand sample. It appears as a light to dark brown fine-grained mass in plane polarized light and a darker brown color in crossed polarized light. Mn-calcite also occurs as small (50–120 μm), fine-grained platy or fibrous texture (Fig. 5-19F).

\textit{Fluorite}

Fluorite occurs in minor quantities but is present in the quartz and adularia matrix of the Stage-2 assemblage. Fluorite is semi-transparent to white in plane polarized light and is isotropic in crossed polarized light. Fluorite observed in hand sample in this study is colorless, but it has been reported to also be pale green or purple (Foley, 1990). Coarse-grained fluorite (250–600 μm) exhibit well defined euhedral crystals in thin section (Fig. 5-19F). Fine-grained fluorite exhibits subrounded shapes and sizes range from 60–110 μm.

5.5.4. Fe-poor Base Metal Sulfide Stage

Veins of the Fe-poor B.M.S. stage have been identified in two exploration drill cores (NAU12175 and NAU1217) that pierced the Amethyst fault at the northern end of the North Amethyst deposit at the 10,250ft elevation (N3 orebody). The drill holes intercepted base metal-rich veins that occur in association with a fine-grained gangue assemblage. The veins have a crustiform texture and the intercept widths range from 1–1.5 ft wide (Fig. 5-20A-B). These veins are base metal-rich but they do not resemble the base metal veins of Stage-1 which were reported in Foley (1990). Stage-1 veins contain hematite and chlorite and the various minerals form as bands in a crustiform sequence. The petrographic results reveal that the Fe-poor B.M.S. veins consist of a gangue assemblage of quartz, adularia, calcite, Mn-calcite, fluorite and scarce
amounts of rhodochrosite that is cut by an ore assemblage of pyrite, sphalerite, galena and chalcopyrite (Fig. 5-20C-D). Chlorite and pyrite are absent. The gangue and ore assemblage is cut by late, calcite veinlets. The nature of the crosscutting relationships of the Fe-poor B.M.S stage whereby the early quartz and adularia rich assemblage is cut by a base metal rich stage, resembles how the Alpha stage is cut by the Beta stage with no breccia present between the two events.

**Quartz**

Quartz occurs as a fine-grained, cryptocrystalline matrix with a light gray color in hand sample. Quartz forms microcrystalline and crystalline matrices with crystals sizes ranging from 16–100 μm in size. The fine-grained matrices contain some coarser-grained quartz crystals which range from 145–160 μm. The quartz grains within this fine-grained matrix form euhedral to subhedral crystals. Coarse-grained euhedral crystals line vug spaces and range from 150–370 μm in length or form veinlets. Individual crystals range from 175–800 μm in length (Fig. 5-20E). Some coarse-grained euhedral shaped quartz crystals exhibit a feathery texture and are 0.9–1 mm in length (Fig. 5-20F). Quartz also occurs as chalcedony which forms fine-grained, thin euhedral crystals with a cross hatch texture.

**Adularia**

Adularia occurs as a fine-grained, cryptocrystalline matrix with a light gray color in hand sample and is intergrown with quartz. Adularia forms subhombic, rhombic and tabular shaped crystals. However, rhombic and tabular shaped crystals were not observed together. NAU12173 possessed subhombic and tabular adularia while NAU12175 contained subhombic and rhombic shaped adularia crystals (Fig. 5-20G, 5-20H, 5-21A). Subhombic adularia is observed in both the Fe-poor B.M.S. stage veins. Subhombic adularia grains range from 160–775 μm and display faint or strong simple twins in crossed polarized light (Fig. 5-20G). Subhombic adularia was primarily observed with coarse-grained subhedral to euhedral quartz which occurred in matrix, veinlets or line vugs. Subhombic adularia may be present in the fine-grained, microcrystalline to crystalline quartz matrices but it is difficult to discern from quartz. Tabular adularia is observed
Fig. 5-20: Photomicrographs of the textural characteristics of the Fe-poor B.M.S. A. Drill core NAU12173 with the locations of thin section samples being highlighted. B. Drill core NAU12175 with the locations of thin section samples being highlighted. C. Close-up photo of NAU12173 (393–393.5 ft) which shows a vein with crustiform textures that consists of base metal sulfides, quartz, adularia and calcite. D. Fe-poor B.M.S. stage which consists of a sulfides, quartz, adularia and calcite. CPL. E. Vug lined by a coarse-grain assemblage of euhedral quartz and sub rhombic adularia. CPL. F. Feathery quartz texture. CPL. G. Coarse-grained, sub-rhombic adularia crystal. CPL. H. Tabular adularia crystals. CPL.
from one location in the North Amethyst deposit from drill hole NAU12173. Tabular adularia is one type of gangue mineral that is in association with the base metal sulfides of the Fe-poor B.M.S stage. The crystals of tabular adularia are euhedral to subhedral and have been referred to as “lath shaped” (c.f. Dong and Morrison, 1995). Tabular adularia crystals range from 70–335 μm in size and occur locally in crystalline quartz matrix (Fig. 5-20H). Rhombic adularia is observed from one location in the North Amethyst deposit from drill hole NAU12175 which lies 144 ft above NAU12173 at the northern end of the 10,250 ft level (N3 orebody). Rhombic adularia is very fine-grained and exhibits well-defined rhombic shapes (Fig. 5-21A). Rhombic adularia crystals occurs as tiny (20–25 μm) rhombic crystals which are found tightly spaced with one another and occur within a quartz-rich matrix.

Fluorite

Fluorite occurs as small (45–90 μm), subrounded crystals in quartz-rich crystalline matrix. Fluorite is semi-transparent to white in plane polarized light and exhibit isotropic extinction in crossed polarized light. Fluorite may also be present in other settings such as lining vugs with subrhombic adularia or euhedral quartz.

Calcite

Calcite is abundant in the base metal veins of the Fe-poor B.M.S. stage, particularly in drill core NAU12173. Calcite is white and fine-grained in hand sample and forms thin (14–20 mm) veinlets which appear to occur later than the quartz-adularia-fluorite gangue assemblage and the base metal sulfides of the Fe-poor B.M.S. stage. Petrographic analysis of calcite bands in samples of the stage reveals that calcite forms 300 μm–1.5 mm rhombic crystals (Fig. 5-21B-C). Individual rhombic crystals form as chains or clusters and have light gray colors with cleavage planes in plane polarized light (Fig. 5-21B). Calcite rhombs have third order pink and green interference colors and second order orange, blue and yellow interference colors in crossed polarized light (Fig. 5-21C).
Calcite is inferred to occur after the deposition of the quartz-adularia-fluorite gangue and the base metal sulfides from drill core observations and the textural relationships observed in thin section. However, the petrographic analysis does not reveal clear cross-cutting relationships. There are some textural indications that suggest calcite is cutting into the quartz-adularia matrix, but it is difficult to confirm with high certainty since this texture appears similarly to Alpha stage where the quartz-adularia and carbonate relationship is contemporaneous. However, from the petrographic analysis of the samples containing rhombic calcite in Alpha veins (EQU1147, EQU1264), the occurrence of rhombic calcite in the Fe-poor B.M.S. stage is similar in textural appearance and is interpreted to be the last event after the deposition of the quartz-adularia-rich gangue assemblage and base metal sulfides as opposed to a late and separate event.

Mn-calcite

Mn-calcite occurs as a fine-grained groundmass and forms a cryptocrystalline mixture with quartz and adularia. Mn-calcite is less abundant than quartz and adularia. Mn-calcite is fine-grained and white to cream color in hand sample. It appears as a light to dark brown fine-grained mass in plane polarized light and a darker brown color in crossed polarized light. Mn-calcite is very fine-grained, ≤50 μm and poorly crystalline without well-defined crystal edges. Mn-calcite occurs in several different forms. Mn-calcite tends to be localized along grain boundaries which are well highlighted in samples dominated by quartz-adularia which appears to surround or swarm the quartz and adularia matrix (Fig. 5-21D). In addition, Mn-calcite forms small acicular or fibrous grains (125–205 μm; Fig. 5-21E, 5-21F).

Pyrite

Pyrite is fine-grained with a bronze yellow color. It forms cubic crystals in hand sample. Crystal sizes range from 1–5 mm in drill core. Pyrite forms euhedral crystals in thin section and shares grain boundaries with the other sulfide minerals or appears as inclusions galena, sphalerite and chalcopyrite (Fig. 5-21G,20H,5-22A).
**Sphalerite**

Sphalerite is fine-grained with a light brown color in plane polarized light. It forms subhedral to anhedral grains in thin section. Crystal sizes were observed to range from 130 μm–5 mm in thin section. Sphalerite grains share grain boundaries with the other sulfide minerals or appears as inclusions in chalcopyrite, pyrite and galena (Fig. 5-22A-C).

**Galena**

Galena is fine-grained with a silver color and has a cubic crystal habit in hand sample. Crystal sizes were observed to range from 1–7 mm wide in drill core. Galena has euahedral crystal shapes in thin section with well-defined cleavage planes and triangular pits. Galena crystals share grain boundaries with other base metal sulfides and/or appear as inclusions in the other sulfide minerals, including chalcopyrite, sphalerite and pyrite (Fig. 5-22D-F).

**Chalcopyrite**

Chalcopyrite is fine-grained with a copper yellow color in reflected light. It forms subhedral to anhedral grains in thin section. Chalcopyrite is commonly observed as a fine-grained matrix to cubic pyrite grains. Crystal sizes were observed to range from 260 μm–1.5 mm, but sometimes are also ≤50 μm. Chalcopyrite grains share grain boundaries with the sulfide minerals or appears as inclusions in sphalerite and galena (Fig. 5-22G-H). Chalcopyrite was not observed as an inclusion in pyrite.

**5.5.5. Breccia-4**

Stage-2 of the B.M.S. association is followed by a fracturing event, which produced a breccia containing angular fragments of all earlier assemblages. This breccia is known as Breccia-4 (Foley, 1990). The brecciated fragments are cemented by pale to light pink calcite (Foley, 1990). Breccia-4 is reported to be a common occurrence at the northern end of the 10,250 ft level in the North Amethyst vein system (Foley, 1990).
Fig. 5-21: Textural relationships of ore and gangue minerals. A. Tiny rhombic adularia crystals. CPL. B. Coarse-grained rhombic calcite which appears light gray. PPL. C. Coarse-grained rhombic calcite which shows third order green, blue, red and pink interference colors. CPL. D. Fine-grained Mn-calcite groundmass which has a dark brown color in a quartz- and adularia-rich matrix. CPL. E. Coarse-grained Mn-calcite with wispy texture. PPL. F. Fibrous Mn-calcite with lattice bladed texture. CPL. G. Pyrite inclusions in galena. RL. H. Pyrite inclusions in sphalerite. RL.
In the present study, Breccia-4 was identified in two drill cores NAU12166 and NAU12173 from the N3 orebody (Fig. 5-23 A-C). The widths of the pink calcite cement ranged from 0.5 ft in NAU12166 to 9 ft in NAU12173 (Fig. 5-23A-C). Breccia-4 was not sampled in this study and therefore no petrographic descriptions are provided for this stage.

5.5.6. Stage-3

Stage-3 of the B.M.S. association occurs after Breccia-4 and it is known as the last stage of mineralization in the North Amethyst deposit. Stage-3 formed veins of quartz or Mn-calcite with pyrite (Foley, 1990). Foley (1990) described the Stage-3 veins from the northern part of the 10,250 ft level as extensive crusts of pink to pale yellow colored, Mn-bearing calcite, interlayered with thin layers of crustiform pyrite. In the southern part of the deposit, Stage-3 occurs as large quartz crystals which overgrow extremely leached material of all earlier stages and breccias (Foley, 1990). The leaching is reported to consist of bleaching of wall-rock fragments and their alteration to clay minerals. Some of this material was described to contain rare specks of dark sulfides and is associated with a clinker-like siliceous material (Foley, 1990). In the present study, the occurrence of Stage-3 veins has been observed in drill hole NAU12175 intersecting the N3 orebody at the northern end of the 10,250 ft level. Stage-3 is observed as 1 ft-wide pale yellow colored calcite veins with thin (0.25–0.5 inches) wavy bands (Fig. 5-23D-E). Petrographic analysis of Stage-3 was not conducted in the present study.
Fig. 5-23: Drill core photos of Breccia-4 and Stage-3. A. Breccia-4 consisting of pink calcium carbonate vein, highlighted by the red box. NAU12166 (245–245.5 ft). B. Breccia-4 which appears as a pink calcium carbonate matrix and contains large, subrounded clasts of wallrock. NAU12173 (343–358.5 ft). C. Breccia-4 which appears as a pink calcium carbonate matrix and contains clasts of wallrock. NAU12173 (358.3–370.5 ft). D. Stage-3 which appears as a pale yellow, Mn-calcite crust, highlighted by the red box. NAU12175 (246.5–247 ft). E. Stage-3 which appears as a pale yellow, Mn-calcite crust, outlined by a red box. NAU12175 (254.5–255 ft).
CHAPTER 6
MINERAL CHEMISTRY

The present chapter reports the results of an electron microprobe (EMP) study on sphalerite, galena, chalcopyrite and pyrite from the North Amethyst deposit. The microanalytical investigations aimed to establish whether the chemistry of these sulfide minerals vary significantly by vein stage. The data were also used to test for possible correlations between the chemistry of the minerals and the location of the samples within the North Amethyst deposit. Particular emphasis was placed on the analysis of the Fe content of sphalerite to ensure that the North Amethyst deposit can indeed be classified as an intermediate-sulfidation stage epithermal deposit.

6.1. Materials and Methods

All thin sections were carefully studied by optical microscopy to map out the distribution of sulfide grains and to identify mineral grains suitable for microanalysis. Representative vein samples of the different vein stages encountered at the North Amethyst deposit were selected for the EMP investigations. Three Alpha stage vein samples were subject to EMP analysis (Table 6-1).

The quantitative chemical analyses were performed using the JEOL JXA-8600 electron microprobe at the University of Colorado at Boulder. The instrument was operated at an accelerating voltage 20 keV and a current of 100 nA, measured on the Faraday cup. The chemical analyses were conducted using a defocused electron beam (5 or 10 μm). In total, 67 sphalerite, 60 chalcopyrite, 40 pyrite and 59 galena grains were measured from the various vein stages. Typically, several spots on every grain were analyzed to test for possible core-rim variations. In total, 190 point analyses were obtained for sphalerite, 146 point analyses for galena, 143 point analyses for chalcopyrite and 109 point analyses for pyrite. One electrum and one native silver grain were analyzed as part of two traverses studying the diffusion of Ag into galena.
Table 6-1: Samples used for electron microprobe analysis. The table also shows the number of sphalerite (sph), chalcopyrite (cpy), pyrite (py) and galena (gn) grains analyzed per sample and the number of analytical spot.

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<th>Cpy analyses (grains/points)</th>
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</table>

6.2. Mineral Chemistry of Sphalerite of the Alpha Stage

Sphalerite of the Alpha stage was analyzed in samples collected at different elevations within the North Amethyst deposit. The elements and their detection limits for sphalerite analyses are S (0.012 wt%), Mn (0.009 wt%), Fe (0.008 wt%), Cu (0.012 wt%), Zn (0.027 wt%), As (0.013 wt%), Ag (0.011 wt%), Cd (0.011 wt%), Sb (0.011 wt%), Au (0.028 wt%) and Pb (0.025 wt%). Main compositional trends were identified for the FeS and MnS concentration. Most of the trace elements analyzed, including Ag, As, Su, Cd and Sb, did not show spatial trends. The concentrations of As, Au and Sb were typically below the detection limit. Maximum
concentrations of 0.02 wt% As were recorded. The Cd concentrations ranged from 0.13–0.2 wt%.

Sphalerite of the Alpha stage was sampled from a stringer of base metal sulfides in a fine-grained Alpha stage matrix of Mn-carbonate and quartz in sample EQU1147-284A (Table 6-1). The base metal sulfide stringers in Alpha stage matrix are characteristic of Alpha stage sulfides as reported by Foley (1990). The sphalerite is Fe-poor, with concentrations ranging from 0.11–0.57 mole% FeS and a median value of 0.24 mole% FeS (Fig. 6-1). One point analysis with a value of 0.82 mole% FeS is considered to be an outlier. The sphalerite contains low Mn concentrations, ranging from 0.14–0.21 mole% MnS, with a median value of 0.16 mole% MnS (Fig. 6-1). Four of the eight analyses were excluded as outliers (1.4–2.6 mole% MnS). These anomalously high values probably resulted from the use of an unfocused electron beam that integrated over the surrounding Mn-rich gangue matrix.

Mid-level Alpha stage sphalerite contained in sample NAU12173-371A was analyzed. The sample originated from the northern 10,250 ft level (N3 orebody) of the North Amethyst deposit. The sphalerite is fine-grained and disseminated in an Alpha stage matrix of Mn-carbonate, Mn-silicate and quartz. The sphalerite is Fe-poor and very homogenous. The concentrations range from 0.32–0.54 mole% FeS, with a median value of 0.40 mole% FeS (Fig. 6-1). Two point analyses of 0.90 and 1.43 mole% FeS are considered to be outliers. The sphalerite has elevated MnS concentrations, with values ranging from 0.19–0.69 mole% and a median value of 0.46 mole% MnS (Fig. 6-1). The distribution of mole% MnS produced a closely spaced cluster without outliers.

Sphalerite from the deep levels was sampled from coarse-grained vugs which are characteristic of the Alpha-1 substage that also includes adularia rhombs, quartz and fluorite (Foley, 1990). The sphalerite is more Fe-rich than the sphalerite from the mid- and upper levels. It has FeS concentrations ranging from 0.53–1.7 mole% FeS, with a median value of 1.3 mole% FeS (Fig. 6-1). One analysis (2.7 mole% FeS) fell outside the accepted range and is considered to be an outlier. The sphalerite contains low MnS concentrations of 0.066–0.191 mole%, with a
Fig. 6-1: Chemical composition of sphalerite of the Alphas stage. A. Whisker-and-box plot of FeS concentrations (in mole % FeS) in sphalerite collected at different elevations. B. Histogram of FeS concentrations (in mole % FeS) of sphalerite. C. Whisker-and-box plot of MnS concentrations (in mole % FeS) in sphalerite collected at different elevations. D. Histogram of MnS concentrations (in mole % FeS) of sphalerite.

median value of 0.14 mole% MnS (Fig. 6-1). The distribution of MnS is closely spaced and no outliers were identified.

6.3. Mineral Chemistry of Sphalerite of the Beta Stage

Sphalerite contained in Beta stage seams was analyzed in samples collected at different elevations within the North Amethyst deposit. Main compositional trends were identified for the
Fig. 6-2: Chemical composition of sphalerite of the Beta stage. A. Whisker-and-box plot of FeS concentrations (in mole % FeS) in sphalerite collected at different elevations. B. Histogram of FeS concentrations (in mole % FeS) of sphalerite. C. Whisker-and-box plot of MnS concentrations (in mole % FeS) in sphalerite collected at different elevations. D. Histogram of MnS concentrations (in mole % FeS) of sphalerite.

FeS and MnS concentration. Most of the trace elements analyzed did not show spatial trends. The elements As, Au and Sb were below the detection limit. Silver showed a maximum concentration of 0.34 wt.%. Cadmium values ranged from 0.07–0.18 wt%.

The composition of sphalerite of the Beta stage in the upper level veins of the North Amethyst deposit was determined in samples EQU1264-493A and EQU1255-245A. The Beta stage seams in these samples crosscut a Mn-carbonate dominated Alpha stage and a quartz-rich
Alpha stage vein, respectively. The sphalerite generally has low Fe concentrations, with values ranging from 0.3–1.0 mole% FeS. The median value is 0.58 mole% FeS (Fig. 6-2). Three point analyses (1.3, 1.5 and 1.7 mole% FeS) from sample EQU1264-493A are considered to be outliers (Fig. 6-2). The sphalerite has slightly variable Mn concentrations, with values ranging from 0.15–1.7 mole% MnS. The median value is 0.59 mole% MnS (Fig. 6-2). As no outlier were identified, all point analyses collected were included into the statistical analysis.

Sphalerite contained in the mid-level vein samples NAU12148-574A and NAU12158-838A from 10,250 ft elevation (S2 orebody) were used for EMP analysis (Table 6-1). Both samples represent Beta stage seams that cut an Alpha stage matrix of Mn-carbonate, Mn-silicate and quartz. A total of 37 point analyses were obtained. The FeS contents of the sphalerite are generally low and somewhat variable. The concentrations range from 0.04–1.3 mole% FeS, with a median value of 0.51 (Fig. 6-2). Two point analyses (2.25 and 2.65 mole% FeS) from sample NAU12158-838A are outliers. The concentrations of MnS range from 0.11–2.5 mole% with a median value of 0.60 mole% MnS (Fig. 6-2). The sphalerite has a fairly wide distribution of MnS concentrations when compared to the Beta stage sphalerite in the upper level of the deposit. However, the median values are similar. The data set of Mn concentrations has no outliers.

Sphalerite analyses were obtained from sample WE1031-2044A. The sphalerite occurred as brecciated Beta fragments in a quartz-rich breccia, interpreted to be Breccia-3. The brecciated sphalerite fragments were associated with other base metal sulfides and silver minerals. The breccia containing the fragments is juxtaposed against an Alpha stage matrix of Mn-carbonate, Mn-silicate and quartz. The FeS contents of sphalerite are low and homogenous. The concentrations range from 0.34–0.73 mole% FeS, with a median value of 0.67 (Fig. 6-2). All the data points are included in the statistical analysis. The sphalerite has lower MnS concentrations than the sphalerite in upper and mid-levels. The MnS concentrations range from 0.11–0.14 mole%, with a median value of 0.12 mole%. No outliers were identified (Fig. 6-2).
6.4. Mineral Chemistry of Sphalerite of the B.M.S. Association

B.M.S. stage veins do not occur in the upper levels of the North Amethyst deposit. However, two different base metal stages are identified in the mid- and lower-levels of the North Amethyst deposit. Stage-1 of Foley (19990) was observed in the deep level veins of the North Amethyst deposit. In addition, a base metal vein, interpreted to be part of the Fe-poor B.M.S. stage was recognized in the mid-level portion of the deposit.

Compositional trends were identified for the FeS and MnS concentration in sphalerite from Stage-1 and the Fe-poor B.M.S. stage. In Stage-1 sphalerite, most of the trace elements analyzed showed low concentrations. The sphalerite has Cd concentrations ranging from 0.14–0.38 wt%. Most of the trace elements analyzed in sphalerite from the Fe-poor B.M.S. stage also did not show spatial trends and were at concentration levels at or below the detection limit. Maximum Ag concentrations of 0.03 wt% were recorded for sphalerite from the Fe-poor B.M.S. stage. Cadmium values of sphalerite from this stage ranged from 0.10–0.60 wt%.

Crustiform banded sphalerite from Stage-1 in the deep-level veins was sampled from two intervals of the WE1031 exploration drill core which intersected the deep juncture of the Equity and Amethyst faults (Table 6-1). The FeS content of sphalerite is low. The concentrations range from 0.46–1.6 mole% FeS, with a median value of 0.96 mole% FeS (Fig. 6-3). No outlier values were recognized. The Stage-1 sphalerite contains 0.06–0.20 mole% MnS, with a median value of 0.09 mole% MnS. All data were included in the statistical analysis (Fig. 6-3).

Sphalerite of the Fe-poor B.M.S. stage was sampled from two exploration drill cores in the northern end of the deposit at the 10,250 ft level (N3 orebody). The FeS contents of sphalerite are low with concentrations ranging from 0.02–1.6 mole%. The median value is 0.71 mole% FeS (Fig. 6-3). There are no outliers. The sphalerite has MnS concentrations ranging from 0.0–0.25 mole% MnS, with a median value of 0.10 mole% MnS (Fig. 6-3). No outlier values were identified.
Fig. 6-3: Chemical composition of sphalerite of the B.M.S. association. A. Whisker-and-box plot of FeS concentrations (in mole % FeS) in sphalerite collected at different elevations. B. Histogram of FeS concentrations (in mole % FeS) of sphalerite. C. Whisker-and-box plot of MnS concentrations (in mole % FeS) in sphalerite collected at different elevations. D. Histogram of MnS concentrations (in mole % FeS) of sphalerite.

6.5. Chemical Variations Within Individual Sphalerite Grains

The analysis of sphalerite revealed that there are systematic variations in the FeS and MnS concentrations of sphalerite between different vein stages, but that there are also variations
Fig. 6-4: Comparison of the FeS and MnS concentrations of sphalerite of the different vein stages at the North Amethyst deposit. A. Median FeS concentrations of sphalerite of the different vein stages sampled at different elevations. B. Median MnS concentrations of sphalerite of the different vein stages sampled at different elevations.

◆ = Veins in Equity fault  ■ = Veins in Amethyst fault  ▲ = Veins at the intersection of the Equity and Amethyst faults
1=Alpha Stage  2=Beta Stage  3=Stage-1  4= Fe poor BM stage
related to the elevation of the sample location (Fig. 6-4). To test for within-grain variations, individual sphalerite grains from the various vein stages of the North Amethyst deposit were subject to EMP point traverses. The traverses were performed on selected grains to test for chemical variability. The most evident variability was recognized for the MnS concentrations from Beta stage sphalerite.

6.5.1. Alpha Stage in the Deep-Level Veins

Two Alpha stage sphalerite grains from the deep-level veins in drill core WE1031 were subject to EMP traverses (Fig. 6-5). Theses sphalerite grains are located in the vuggy spaces of Alpha stage which occur in association with coarse-grained quartz and adularia rhombs. This mineralogical and textural feature has been described in Foley (1990) as belonging to Alpha substage-1.

The two sphalerite grains were selected for microprobe point analysis from sample WE1031-2040C. 2040C Sp2#1 and 2040CSp2#2 are the same grain but two separate BSE images were taken because the grain was too large to fit in one view (Fig. 6-5). Another grain from the same sample but different vug space is 2040C Sp3. The microprobe point traverses revealed low Mn concentrations (0.124–0.158 mole% MnS) and a fairly flat distribution (Fig. 6-5). The sphalerite grains contain low Mn concentrations in the traverses.

6.5.2. Beta Stage in Upper Level Veins

Three Beta stage sphalerite grains from the upper level Equity veins were subject to EMP point traverses (Fig. 6-6). Two sphalerite grains were selected in sample EQU1255-245, refereed to as EQU1255 Sp4 and EQU1255 Sp3 (Fig. 6-6). One sphalerite grain was chosen in sample EQU1264-493A, refereed to as grain EQU1264 Sp6 (Fig. 6-6 and 6-7).

Grain EQU1264 Sp6 has a Mn-rich rim with a Mn-poor core. However, the two grains from EQU1255 displayed a slight increase in Mn concentrations from the rim (spot 1) to the core
Fig. 6-5: Compositional variations within individual sphalerite grains. A. Sphalerite grain (2040C Sp2 #1) with the locations of three EMP spots from sample WE1031-2040C. B. Sphalerite grain (2040C Sp2 #2) with the location of one EMP spot from sample WE1031-2040C, continued from 2040C Sp2 #1 (point 4). C. Sphalerite grain (WE1031-2040C Sp3) with the locations of three EMP spots from sample WE1031-2040C. D. Core to rim analyses of mole % MnS concentrations in deep level WE1031 veins. Each square is a single microanalysis from deep level Alpha stage sphalerite grain 2040C Sp2, each triangle is a single microanalysis from deep level Alpha stage sphalerite grain 2040C Sp3.
(spot 2; Fig. 6-6). After the small spike in the Mn concentration in spot 2 of the sphalerite grain EQU1255 Sp4, the points 3, 4 and 5 contained low Mn concentrations (Fig. 6-6). In EQU1255 Sp3 the Mn concentration is very high at spot 3 (Fig. 6-6). The following points, 4 and 5, contained low Mn concentrations (Fig. 6-6). The conclusion from the spot traverses of upper level Equity Beta stage sphalerite grains is that the rims or edges may contain high Mn concentrations, but it is not a consistent feature expressed in every sphalerite grain.

6.5.3. Beta Stage in the Mid-Level Veins

Three Beta stage sphalerite grains from the mid level Amethyst veins were subject to EMP traverses (Fig. 6-6). Two sphalerite grains (NAU12148 Sp4 and NAU12148 Sp8) were selected for traverses from sample NAU12148-574A (Fig. 6-6). One sphalerite grain (NAU12158 Sp8) was chosen for point analysis in sample NAU12158-838A (Fig. 6-6). The two sphalerite grains from sample NAU12148 clearly exhibited high Mn concentrations on the grain rims and low Mn concentrations in the cores. The values from rim to core to rim reflect a “V shaped” pattern (Fig. 6-6). The other Beta stage sphalerite grain, NAU12158 Sp8, did not possess a Mn-rich rim or core. All, four points along NAU12158 Sp8 contained similar concentrations between 0.5–0.6 mole% MnS. There were no Mn-rich areas is NAU12158 Sp8 (Fig. 6-6).

6.5.4. Stage-1 in Deep-Level Veins

One sphalerite grain (WE1031-2044B Sp3) which is a brecciated fragment of Stage-1 was used for an EMP traverse from a Breccia-3 sample in the deep level WE1031 veins (Fig. 6-8). The brecciated Stage-1 sphalerite contained low values of Mn throughout the traverse, with values of 0.128–0.152 mole% MnS, and exhibited a fairly flat distribution (Fig. 6-8). The concentrations of Mn in Stage-1 sphalerite grains are low and mineral grains do not reveal Mn-rich cores or rims.
Fig. 6-6: Compositional variations within individual sphalerite grains. A. Sphalerite grain (EQU 1255 Sp4) with the locations of five EMP spots from sample EQU1255-245A. B. Sphalerite grain (EQU 1264 Sp6) with the locations of four EMP spots from sample EQU1264-493A. Sphalerite grain (EQU 1255 Sp3) with the locations of five EMP spots from sample EQU1255-245A. D. Core to rim analyses of mole% MnS concentrations in upper level Equity vein Beta stage sphalerite. Each square is a single microanalysis from sphalerite grain 1255 Sp4, each circle is a single microanalysis from sphalerite grain 1264 Sp6 and each triangle is a single microanalysis from sphalerite grain 1255 Sp3. E. Sphalerite grain (148 Sp4) with the locations of three EMP spots from sample NAU12148-571A. F. Sphalerite grain (148 Sp8) with the locations of four EMP spots from sample NAU12148-571A. G. Sphalerite grain (158 Sp8) with the locations of four EMP spots from sample NAU12158-838A. H. Core to rim analyses of mole% MnS concentrations in mid level Amethyst vein Beta Stage sphalerite. Each square is a single microanalysis from sphalerite grain 12148 Sp4, each diamond is a single microanalysis from sphalerite grain 12148 Sp8 and each triangle is a single microanalysis from sphalerite grain 12158 Sp8.
6.6. Mineral Chemistry of Chalcopyrite

EMP analyses were conducted on chalcopyrite grains from various vein stages and locations in the North Amethyst deposit. A total of 24 chalcopyrite grains were analyzed and 48 point analysis were collected. No unusual concentrations of minor or trace elements were encountered. Silver and Au concentrations were at or below detection limit. The most important enrichments was observed for Bi, which is present at slightly variable concentrations in chalcopyrite of all vein stages (Fig. 6-9).

Bismuth is present in all chalcopyrite grains analyzed from the Beta stage, Fe-poor B.M.S. stage, Stage-1 and the deep chalcopyrite breccia stages and at all depths. The elements and their detection limits for chalcopyrite analyses are S (0.012 wt%), Mn (0.009 wt%), Fe (0.017 wt%), Cu (0.024 wt%), Zn (0.014 wt%), As (0.011 wt%), Se (0.007 wt%), Ag (0.011 wt%), Cd (0.010 wt%), Sb (0.011 wt%), Te (0.012 wt%), W (0.032 wt%), Au (0.025 wt%), Pb (0.023 wt%) and Bi (0.020 wt%). Chalcopyrite was not observed in the Alpha stage sample used in the EMP sessions and consequently not analyzed. The concentrations of Bi did not vary
between stages and the concentrations are low, ranging from 0.033–0.042 wt%. The median Bi values in Beta stage chalcopyrite from the upper-level veins is 0.036 wt%. Chalcopyrite from the Beta stage of the mid-level veins has a median Bi content of 0.036 wt%. Stage-1 has a median Bi value of 0.037 wt%, while the Fe-poor B.M.S. stage has a value of 0.038 wt%. Chalcopyrite in the deep breccia has a median Bi content of 0.036 wt% (Fig. 6-9).

6.7. Mineral Chemistry of Pyrite

EMP analyses were conducted on pyrite grains from the various vein stages and locations in the North Amethyst deposit. A total of 32 pyrite grains were analyzed and 91 point analyses were collected. The elements and their detection limits for pyrite analyses are S (0.012 wt%), Mn (0.009 wt%), Fe (0.017 wt%), Cu (0.011 wt%), Zn (0.013 wt%), As (0.008 wt%), Ag (0.010 wt%), Cd (0.010 wt%), Sb (0.011 wt%), Au (0.022 wt%) and Pb (0.021 wt%). The EMP results did not reveal abnormal concentrations of minor or trace elements. Silver and Au concentrations were at or below their respective detection limits. The most intriguing observation is the
Fig. 6-9: Bismuth concentration of chalcopyrite from the North Amethyst deposit. A. Histogram of Bi concentrations in chalcopyrite grains from the various vein stages. B. Graph of median Bi concentrations in chalcopyrite grain from the various vein stages plotted as function of the elevation of the sample locations.
presence of As from the Beta stage in the upper level Equity veins which yielded the most significant and greatest concentrations out of all the pyrite grains analyzed (Fig. 6-10A-D).

Light colored rims of pyrite grains were observed in Beta stage veins from the upper level Equity veins during petrographic analysis. The pyrite grains were also analyzed by SEM, highlighting the lighter rims on the pyrite grains in BSE images. The pyrite grains were then subject to quantitative elemental analysis by EMP. The spot analyses of the darker colored cores and lighter colored rims of the upper level Beta stage pyrite grains revealed the lighter colored cores contained high amounts of As (Fig. 6-10A-D).

In contrast to the pyrite in the Beta stage veins in the upper level of the North Amethyst deposit, pyrite analyzed from the other vein stages (Alpha stage pyrite, pyrite in Beta stage seams at mid-levels, Beta stage at deep levels, Stage-1 and Fe-poor B.M.S. stage) contained low or non-detectable As concentrations (Fig. 6-11).

6.8. Mineral Chemistry of Galena

Microprobe analyses were conducted on galena grains from the various vein stages and locations in the North Amethyst deposit. A total of 47 galena grains were analyzed and 120 point analyses were collected (Fig. 6-12A-B). The elements and their detection limits for galena analyses are S (0.012 wt%), Mn (0.013 wt%), Fe (0.012 wt%), Cu (0.014 wt%), Zn (0.017 wt%), As (0.011 wt%), Ag (0.044 wt%), Cd (0.020 wt%), Sb (0.017 wt%) and Pb (0.043 wt%).

Galena in all vein stages contains low Sb concentrations. The Sb concentrations are low in galena from the Alpha, Beta and Stage-1 stages. In Alpha stage in the upper level Equity veins, galena contained Sb concentrations of 0.04 and 0.08 wt%. Antimony is absent in the Alpha stage galena grains from the mid-level Amethyst veins. Galena from Beta stage in the upper level Equity veins are almost entirely devoid of Sb, except for one grain with a very low value of 0.026 wt%. A significant number of galena grains from Beta stage in the mid-level Amethyst veins contain Sb even though the concentrations are low (0.02–0.06 wt%). The galena grains containing Sb are all from sample NAU12158-838A, but galena in sample NAU12148-
574A contains no Sb. Galena from Stage-1 in the deep level WE1031 veins are almost entirely devoid of Sb except for one grain which contained a low value of 0.03 wt% Sb. Galena analyzed from the Fe-poor B.M.S. stage in the mid-level Amethyst veins contain 0.02–0.46 wt% Sb.

Silver is detected in galena from all vein stages, but it occurs in low concentrations. Galena of the Alpha stage in the upper level Equity veins and in the mid-level Amethyst veins effectively do not contain Ag. Galena from Beta stage in the upper-level Equity veins are almost entirely devoid of Ag, except for one grain with a very low value of 0.02 wt% Ag. Several galena grains from both samples of the mid-level Amethyst veins (NAU12148-574A and NAU12158-838A) contain Ag. The Ag concentrations from the Beta stage galena in the mid-level Amethyst veins are low (0.02–0.09 wt%). A notable exception is galena in Stage-1 in the deep level WE1031 veins, which contains 0.24–1.2 wt% Ag. However, galena analyzed from the Fe-poor B.M.S. stage in the mid-level Amethyst veins are completely devoid of Ag.

The EMP data obtained on the galena from the various vein stages of the North Amethyst deposit revealed a strong correlation between Ag and Sb in the mid-level Beta stage ($R^2=0.89$) (Fig. 6-13). The Ag concentrations are generally low in all the vein stages, but a few galena grains from Stage-1 contained noticeable concentrations of Ag (0.24–1.0 wt%). One galena grain from sample WE1031-2044E yielded a value of 0.88 wt% Ag.

### 6.9. Diffusion Profiles in Galena

Several galena grains have been observed to share grain boundaries with native silver or electrum, particularly in the high-grade Beta stage samples from the upper level Equity grains. The appearance of the shared grain boundaries between the galena and native silver or electrum appear “blurry” in BSE images, suggesting that diffusion of Ag occurred into the galena crystal structure. To test this hypothesis, an EMP point traverse was conducted across the contact between a galena grain and native silver and a galena grain and electrum.
The traverse from the galena grain to the native silver comprises seven closely spaced point analysis between from the interior of galena and across into the native silver grain (Fig. 6-14). Silver concentrations increase slightly in the galena from the interior towards the contact with native silver (0.109–0.4 wt%; Fig. 6-14B). Between points 1-3, Pb concentrations do not vary but decrease at point 4 near the contact with native silver which also contains the highest Ag concentration of 0.4 wt%. Antimony occurs in minor amounts but does not fluctuate from the galena core to the contact (Fig. 6-14B,C). Copper appears in minor amounts near the contact but is absent in the interior of galena. Iron, Zn and Au concentrations are below the detection limit. As the point traverse continues into native silver, Sb is present at significant concentrations in points 5-7 (0.2–0.14 wt%), the trend mirrors the ratio of Au to Ag (Fig. 6-14C,D). There is a strong correlation between Sb and Au/Ag which produced a $R^2=0.70$.

The results of the EMP analysis confirm a compositional trend in galena that may be indicative of galena alteration during the formation of the younger native silver. The observed compositional trends are consistent with the paragenesis at the North Amethyst vein deposit (Chapter 5).

Seven closely spaced point analyses comprise the traverse from the interior of galena across into the electrum grain (Fig. 6-15A). Points 1-4 are located in the interior of the galena to near the contact with electrum. No Au was detected in the EMP analysis, but Ag and Sb vary from the interior of galena to the contact with electrum (Fig. 6-15B). The concentrations of Sb are slightly above detection limit (0.015–0.026 wt %) and Ag concentrations are low (0.083–0.182 wt%). Galena contains significant values of Zn (1.3–2.2 wt%) and Cu (0.5–0.9 wt%), but no trend in is apparent. The results from the points within the electrum grain (points 5-7), show an enrichment in Au, as the points move toward the interior of the electrum grain (Fig. 6-15B). Iron has the highest concentrations in galena near the contact with electrum (point 4; 0.4 wt%) and in electrum near the contact with galena (point 5; 0.5 wt%; Fig. 41B). The trends of Au, Ag and Pb in the EMP traverse show a sharp decrease of Pb in the electrum grain and a sharp increase in Au (25 wt%) and Ag (72 wt%) in electrum with no presence of Au in galena (Fig. 6-15C). The points 5-7 which move toward the interior of electrum show a increase or
enrichment of Au and a decrease in Ag (Fig. 41C). Silver and other elements analyzed (Zn, Pb, Cu and Fe) decrease towards the core of the electrum grain (Fig. 6-15D).

The results of the EMP analyses do show that Au diffusion into galena does not occur. The distribution of Ag is inconclusive in this particular traverse. A clear diffusion profile could not be identified at the scale of the EMP analyses although the blurry contact observed in BSE images is suggestive for this process.

6.10. Mineral Chemistry of Electrum

In addition to the uytenbogaardtite (Ag$_3$AuS$_2$), electrum represents the main gold host. EMP analysis of electrum revealed that it is Ag-rich with compositions of Au$_{0.3-0.5}$Ag$_{0.5-0.7}$. The Ag content is elevated particularly on the grain rims which is consistent with BSE imaging, which also suggested that the cores of the electrum grains contain higher Au contents than the rims of the grains (Fig. 6-15A,B).
Fig. 6-10: Compositional variations of pyrite. A. BSE image of a Beta stage pyrite grain (Py1) with the location of two EMP spots. Upper level Equity vein sample EQU1255-245A. B. BSE image of a Beta stage pyrite grain (Py2) with the location of two EMP spots. Upper level Equity vein sample EQU1255-245A. C. BSE of a Beta stage pyrite grain (Py3) with the location of two EMP spots. Upper level Equity vein sample EQU1255-245A. D. Table of elemental concentration (in wt.%) and atoms per formula unit for Fe and As.
Fig. 6-11: Graph of median As concentrations in pyrite from the various vein stages plotted as function of the elevation of the sample locations.

- Veins in Equity fault
- Veins in Amethyst fault
- Veins at the intersection of the Equity and Amethyst faults

1 = Alpha Stage  
2 = Beta Stage  
3 = Stage 1  
4 = Fe poor BM stage
Fig. 6-12: Compositional variations of galena from the North Amethyst deposit. A. Histogram of Ag concentrations (in wt.%) in galena grains from the various vein stages. B. Histogram of Sb concentrations (in wt.%) in galena grains from various vein stages.

Fig. 6-13: Scatter plot showing the correlation between Ag and Sb concentrations for galena from mid-level veins of the Beta stage.
Fig. 6-14: EMP traverse across the contact between a galena and native silver grain. A. BSE image of the galena and native silver grains with the location of seven EMP spots. B. Table of EMP data of the galena-native silver traverse. Concentrations of Ag, Sb, Fe, Cu, Pb, Zn and Au are in wt%. C. Chart of Sb concentrations (in wt%) along the traverse. D. Chart of Au/Ag ratios (in wt%) along the traverse. E. Chart of Ag and Pb concentrations (in wt%) along the traverse. F. Chart of Sb (in wt%) versus Au/Ag (in wt%) from the seven point analyses showing a strong correlation.
Fig. 6-15: EMP traverse across the contact between a galena and electrum grain. A. BSE image of a galena and electrum grain with the location of seven EMP spots. B. Table of EMP data of the galena-electrum traverse, Concentrations of Ag, Sb, Fe, Cu, Pb, Zn and Au are in wt%. C. Chart of the distribution of Ag, Pb and Au concentrations (in wt%) along the traverse. D. Chart of the distribution of Au/Ag, Sb, Zn, Cu and Fe concentrations (in wt%) along the traverse.
CHAPTER 7
DISCUSSION

The research of the present thesis focused on the study of the intermediate-sulfidation state epithermal North Amethyst deposit in the northern part of the Creede mining district, Colorado. The study aimed to examine the precious and base metal veins to interpret the physiochemical conditions of ore deposition and to reconstruct the evolution of the hydrothermal fluids in time and space. The research involved the logging and sampling of the 2011–2013 exploration drill core made available by Rio Grande Silver Inc. Macroscopic study of the drill core, combined with detailed microscopic and microanalytical research, permitted the definition of epithermal vein stages occurring at the North Amethyst deposit and the identification of a paragenetic sequence of mineral formation. The present chapter discusses the findings of the research in the light of previous studies conducted at the North Amethyst deposit and the Creede mining district in general. Implications for the deposit model and exploration within the district are discussed.

7.1. Vein Stages at the North Amethyst Deposit

Veins at the North Amethyst deposit can be classified into two distinct mineral associations (Fig. 7-1). The earlier Mn-Au association comprises the Alpha and Beta stages, which are separated by a breccia event (Breccia-1). The transition from the Mn-Au association to the later B.M.S. association was described as an extensive breccia and sedimentation event known as Breccia-2 (Foley, 1990) which has been recognized in several drill core vein intercepts during this study. The B.M.S. association consists of an early base metal stages (Stage-1), followed by a brecciation event (Breccia-3), a non-ore bearing vein stage (Stage-2), an ore bearing event (Fe-poor B.M.S. stage), another brecciation event (Breccia-4) and a late non-ore bearing stages (Stage-3).
Fig. 7-1: Classification of vein types occurring at the North Amethyst deposit. The left column shows the classification as proposed by Foley (1990). The right column shows the classification developed as part of the present research.

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<td>Mn-calcite cement (bright pink), fragments of wallrock and earlier assemblages</td>
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<td>Quartz + chlorite cement, fragments of wallrock and coarse stage 1 sulfides</td>
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<td></td>
<td>β-1</td>
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<td></td>
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<td></td>
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<td>α-upper</td>
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<td></td>
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<td></td>
<td>α-mid + deep</td>
<td></td>
<td>α-mid + deep</td>
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<td></td>
<td>Rhodonite = Quartz &gt; Mn-calcite &gt; Calcite &gt; Adularia &gt; Rhodochrosite &gt; Sphalerite &gt; Pyrite &gt; Galena &gt; Chalcopyrite</td>
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<td>Rhodonite = Quartz &gt; Mn-calcite &gt; Calcite &gt; Adularia &gt; Rhodochrosite &gt; Sphalerite &gt; Pyrite Galena &gt; Chalcopyrite</td>
</tr>
</tbody>
</table>

Abbreviations: >>, much greater than; >, greater than; =, approximately equal; [], distribution unknown, local occurrence; [], molds.

Abbreviations: >>, much greater than; >, greater than; =, approximately equal; [], distribution unknown, local occurrence; [], molds.
7.1.1. Modifications to the Classification Scheme

All the vein intercepts studied in exploration drill core were classified following the classification scheme described above (Fig. 7-1), which is essentially modified from the classification put forward by Foley (1990). Modifications made are described in the following sections.

Alpha Stage

The research of the present study necessitated a modification to the previous definition of the Alpha stage as the mineralogy of the Alpha stage varies with elevation within the North Amethyst deposit. Variations in the mineralogy of the Alpha stage were not noted by Foley (1990) as her study focused only on samples collected at the mid-level of the deposit. Alpha stage veins located in the upper level Equity fault investigated in the present study did not contain Mn-silicate minerals such as rhodonite, pyroxmangite, inesite, bustamite and caryopilite, present in the mid-level veins (Foley, 1990). The Alpha stage in the upper level veins consists of Mn-calcite, kutnohorite, rhodochrosite, calcite, quartz, adularia and fluorite (Fig. 7-1).

The Alpha stage vein from drill core EQU1264 was found to be dominated by Mn- and Ca-carbonate minerals, with a smaller amount of quartz being present. The Alpha stage vein in drill EQU1255 was dominated by quartz with lesser amounts of Mn- and Ca-carbonate minerals. Both these drill core intervals contain the highest precious metal grades of all drill core samples analyzed from the North Amethyst deposit. Thus, there is no relationship between Alpha stage mineralogy and precious metal grade. The presence of Mn-silicate minerals as described for the mid-level veins (Foley, 1990) is not a prerequisite for high precious metal grades.

Beta Stage

Significant Beta stage mineralization is located in the mid-level veins of the Amethyst fault and was observed to be primarily located in the southern end of the 10,250 level in the S2 orebody. However, the Beta stage veins observed in the mid-level veins are not as abundant and
did not contain the very high precious metal grades encountered in the Beta veins hosted in the upper levels of the North Amethyst deposit within the Equity fault.

The Beta stage of the Mn-Au association as defined by Foley (1990) was reported to consist of two substages, referred to as Beta-1 and Beta-2. Both substages have an identical ore mineralogy and similar chemical compositions (Foley, 1990). Both Beta substages are separated by a breccia event, referred to as Breccia-1. In contrast to the underground exposures studied by Foley (1990), a second Beta substage could not be confidently identified in the drill core studied as part of the present thesis. For this reason the two substages were not distinguished in the classification scheme used (Fig. 7-1).

The Beta stage appears as fine-grained, dark gray to black seams which crosscut the light, pink, white, light brown or red, fine-grained Alpha stage. Formation of the Beta stage commenced with the precipitation of pyrite, followed by sphalerite, chalcopyrite and marcasite, galena, electrum, uytenbogaardtite and chalcopyrite, which is observed to rim some electrum grains. Base metal and gold precipitation was followed by freibergite, polybasite, pyrargyrite, mckinstryite and jalpaite. This was followed by acanthite, native silver and late covellite interpreted to be of supergene origin. The present study shows that there is a clear progression towards increasing silver enrichment with time, ending with the precipitation of native silver (Fig. 7-2). Native silver overgrows and replaces all preceding ore minerals.

The paragenesis of Beta stage reported in the present study differs from Foley (1990). She suggested the existence of an essentially coeval assemblage of base metal sulfides, acanthite, pyrargyrite and electrum. Silver sulfosalts appeared midway in the mineral depositional sequence and uytenbogaardtite was envisaged to be late (Fig. 7-3).

Stage-1

In the present study, Stage-1 is not subdivided into two substages as previously proposed (Fig. 7-1). Foley (1990) suggested that Stage-1a consists of chlorite, hematite and quartz that
Fig. 7-2: Mineral depositional sequence of vein stages in the North Amethyst deposit as observed during this study.

Fig. 7-3: Mineral depositional sequence of vein stages in the North Amethyst deposit as reported by Foley (1990).
were formed prior to the ore minerals of Stage-1b, including sphalerite, galena, pyrite, chalcopyrite and tetrahedrite. The petrographic analysis of Stage-1 veins in the present study revealed the presence of a crustiform sequence of a cryptocrystalline quartz-chlorite and Mn-calcite matrix, hematite, quartz, chlorite and sulfide minerals. There was no textural evidence suggesting that the gangue minerals always predate the sulfide minerals. Both the gangue and ore minerals appeared to be broadly coeval.

In contrast to Foley (1990), tetrahedrite was not observed to occur together with the base metal sulfides. However, the crustiform appearance of the bands of sphalerite, pyrite, galena and chalcopyrite documented in the present study conforms to the description of Foley (1990).

It is also important to note that Stage-1 veins were not observed in the drill cores from the mid-level Amethyst veins during the present study despite the fact that Foley (1990) observed Stage-1 veins in this part of the deposit. In the present study, Stage-1 veins were only observed in the deep levels of the North Amethyst deposit.

Breccia-3

In the present study, Breccia-3 was observed to occur in two distinct grain sizes. The fine-grained Breccia-3 and the coarse-grained Breccia-3 have different textures and different colors. The fine-grained Breccia-3 is characterized by a dark red color and contains fine-grained brecciated fragments of Stage-1 (hematite, chlorite and base metal sulfides) in a fine-grained quartz matrix. The coarse-grained Breccia-3 has a cloudy white or light gray color and contains coarse-grained fragments of Stage-1 ore minerals (sphalerite, galena, pyrite and chalcopyrite) in a coarse-grained quartz- and adularia-rich matrix. The quartz occurs as a crystalline to coarse-grained matrix with occasional large prismatic shape quartz crystals. Coarse-grained adularia was observed with subrhombic shapes in the quartz-rich matrix.
Stage-2 and the Fe-poor B.M.S. stage

A new vein stage, the Fe-poor B.M.S. stage, was identified during the analyses of the new exploration drill core intercepting the N3 orebody at the mid-level of the deposit. The Fe-poor B.M.S. stage consists of a suite of essentially coeval sulfides (pyrite, sphalerite, galena and chalcopyrite) which crosscuts a quartz, adularia and Ca-, Mn-carbonate-rich gangue assemblage (Fig. 7-1). This vein assemblages has not been reported in Foley (1990).

The gangue assemblage cut by the ore minerals of the Fe-poor B.M.S. stage is interpreted as Stage-2 because it is distinctly adularia-rich. However, the texture of adularia observed in association with the Fe-poor B.M.S. stage is different than the Stage-2 observed in association with Stage-1 in the deep level veins. Stage-2 was confidently identified in the deep level of the North Amethyst deposit, crosscutting Breccia-3 and Stage-1. This crosscutting relationship is in agreement with the observation by Foley (1990) that Stage-2 was deposited on Breccia-3 and Stage-1. Adularia observed in Stage-2, which is in spatial association with Breccia-3 and Stage-1, is subrhombic at an elevation of 9,270 ft. The adularia texture observed in spatial association with the Fe-poor B.M.S. stage is tabular at an elevation of 10,165 ft and rhombic at an elevation of 10,300 ft. The difference in adularia textures is interpreted to result from variations in the intensity of boiling of the hydrothermal liquids forming Stage-2 (cf. Dong and Morrison, 1995).

According to Dong and Morrison (1995), subrhombic adularia is predominant in deep levels of epithermal systems, reflecting the initiation of boiling and is most common in deep level epithermal systems in low permeable environments (Dong and Morrison, 1995). Tabular adularia is interpreted to form by ascending hydrothermal liquids to a highly permeable environment and boils violently (Dong and Morrison, 1995). Rhombic adularia is interpreted to form when extensive boiling is protracted (Dong and Morrison, 1995).

7.1.2. Correlation between Vein Textures and Grade for the Different Vein Stages

As part of the microscopic investigations, the textures of quartz, calcite and adularia were recorded for the samples of the different vein stages collected throughout the North Amethyst
Fig. 7-4: Quartz, adularia and calcite textures indicative of boiling and non-boiling conditions during mineral precipitation (modified from Dong and Morrison, 1995, and Moncada et al., 2012).

deposit in an attempt to correlate textural features and metal grades (Fig. 7-5). The nomenclature used for the different textures identified in this study (Fig. 7-4) followed Dong and Morrison (1995), (Dong et al. (1995) and Moncada et al. (2012).

The results of the study show that there is no strong correlation between quartz texture, quartz grain size, adularia texture, calcite texture and metal grade (Figs. 7-5, 7-6). This is interpreted to be related to the fact that the ore minerals present in the epithermal veins of the
Fig. 7-5: The occurrence of vein and breccia stages, quartz textures, quartz grain sizes, adularia textures, calcite textures and metal grades in the investigated core samples from the North Amethyst deposit.
<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Drill Cores</th>
<th>Stages</th>
<th>Quartz Textures</th>
<th>Quartz Grain size</th>
<th>Adularia Textures</th>
<th>Metal Grades and Ratios of the sampled vein segments (ppm)</th>
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- Veins in Equity fault
- Veins in Amethyst fault
- Veins at the intersection of the Equity and Amethyst faults

1 = Texture developed in Alpha
2 = Texture developed in Stage-2
3 = Texture developed in Breccia-3

α
upper = Quartz-Adularia-Fluorite-Mn-calcite-Rhodochrosite-Kutnohorite-Calcite

α
mid+deep = Quartz-Adularia-Fluorite-Mn-calcite-Rhodochrosite-Kutnohorite-Calcite-Rhodonite

β = Beta
Br-1 = Breccia-1
Br-2 = Breccia-2
Stg-1 = Stage-1
Br-3 = Breccia-3
Stg-2 = Stage-2
Fe poor = Iron poor Base Metal Stage
BM stg = Base Metal stage
Br-4 = Breccia-4
Stg-3 = Stage-3

Quartz Textures and Grain Sizes:
- Jigg = Jigsaw
- Fth = Feathery
- Flm = Flamboyant
- Comb = Comb
- mc = Microcrystalline (<25μm)
- cc = Crystalline (25-100μm)
- CG = Coarse Grain (100-500μm)
- Lg Prs = Large Prismatic (800μm-4mm)

Adularia Textures:
- Sub-Rmb = Sub Rhombic
- Tab = Tabular
- Rmb = Rhombic

Calcite Textures:
- Lat-Bld = Lattice Bleded
- Rmb = Rhombic

Metals:
- Au = Gold
- Ag = Silver
- Cu = Copper
- Pb = Lead
- Zn = Zinc
North Amethyst deposit did not necessarily co-precipitate with gangue minerals. Out of the three ore-bearing stages in the North Amethyst deposit (Beta, Stage-1 and the Fe-poor B.M.S. stage), only one stage appears to be associated with gangue mineral formation.

The Alpha stage is characterized by a fine-grained Mn-carbonate, Mn-silicate and quartz matrix with minor amounts of base metal sulfides. This essentially barren vein stage is crosscut by the Beta stage which represents the main precious and base metal stage of the Mn-Au association. The ore minerals in the Beta stage have no associated gangue minerals. Stage-1 of the B.M.S. association consists of a crustiform sequence of pyrite and base metal sulfides (sphalerite, galena and chalcopyrite). The ore minerals occur in a cryptocrystalline quartz-chlorite and Mn-calcite matrix containing hematite, quartz and chlorite. It is possible that the gangue and ore minerals of Stage-1 formed as part of the same vein stage. In the case of the Fe-poor B.M.S. stage, the ore minerals pyrite, sphalerite, galena and chalcopyrite clearly postdate the fine-grained matrix consisting of quartz, adularia, and Mn-,Ca- carbonate minerals, which are interpreted to belong to Stage-2 of the B.M.S. association.

7.2. Constraints on the Fluid Evolution at the North Amethyst Deposit

The results of the present study can be used to constrain the evolution of the hydrothermal system at the North Amethyst deposit. In particular, the Fe content of sphalerite measured by electron microprobe analysis constrains the temperature and sulfidation state of the hydrothermal liquids that were forming this mineral. Textural observations were used to constrain whether the hydrothermal system was boiling during mineral precipitation. Mineral stability constraints provide further information on the physiochemical properties of the hydrothermal liquids.

7.2.1. Iron content of Sphalerite

Sphalerite contained in the different vein stages of the North Amethyst veins were found to have low Fe concentrations ranging from 0.02–1.7 mole % FeS. The low Fe content is reflected in the fact that the sphalerite appears transparent in plane polarized light.
Detailed studies by Scott and Barnes (1971), Czamanske (1974) and Einaudi et al. (2003) showed that the Fe content of sphalerite can be related to the sulfidation state of epithermal fluids forming this mineral, assuming that the sphalerite coexists with pyrite or pyrrhotite. Following Einaudi et al. (2003), the sulfidation state $R_s$ of a hydrothermal fluid can be defined as

$$R_s = \log \left( \frac{X_{H_2}}{X_{H_2S}} \right),$$

with $X_{H_2}$ and $X_{H_2S}$ being the uncorrected analytical mole fractions of $H_2$ and $H_2S$ in solution. Sphalerite forming under low sulfidation conditions are expected to have Fe concentrations exceeding approximately 20 mole % FeS (Einaudi et al., 2003). Sphalerite forming at intermediate sulfidation states have Fe concentrations exceeding approximately 0.1 mole % FeS at temperature conditions corresponding to the epithermal environment. High-sulfidation states are achieved by liquids precipitating sphalerite containing less that approximately 0.1 mole % FeS (Einaudi et al., 2003).
Based on the range of Fe concentrations encountered in sphalerite of the different vein stages, it has to be concluded that the epithermal liquids that precipitated the sphalerite were indeed characterized by an intermediate sulfidation state (Fig. 7-7). As mineral precipitation occurred in the epithermal environment where ascending fluids can boil (cf. Simmons et al., 2005), designation of the North Amethyst deposit being an intermediate sulfidation state epithermal deposit is correct.

Electron microprobe analyses showed, however, that the Fe concentration of sphalerite of the Alpha stage varies systematically with depth. The median concentrations of mole % FeS in Alpha stage decrease from 1.3 mole % FeS at 9,270 ft elevation and 0.41 mole % FeS at 10,200 ft elevation to 0.24 mole % FeS at 10,800 ft elevation. Such a systematic decrease of sulfidation state can be most easily explained by cooling of the hydrothermal liquids and associated small increases in sulfidation state (Fig. 7-7).

In contrast to the Alpha stage, the Fe content of sphalerite contained in the Beta stage is fairly uniform. Deep level Beta stage sphalerite contains a median value of 0.67 mole % FeS at 9,270 ft elevation. Sphalerite from the mid-level Beta stage veins contains a median value of 0.51 mole % FeS at 10,200 ft elev. and the upper level Beta stage veins contain sphalerite with a median value of 0.57 mole % FeS at 10,800 ft elev. The distribution of Fe concentrations in sphalerite of this vein stage may suggest that the hydrothermal liquids did not undergo significant cooling during their ascent or that cooling was accompanied by wall-rock buffering, lowering the sulfidation state (see below).

Electron microprobe analyses of sphalerite contained in the veins of the B.M.S. association confirmed that these veins were also formed at intermediate sulfidation conditions. The median Fe concentration in sphalerite from Stage-1 is 0.96 mole % FeS. The median Fe content of sphalerite from the Fe-poor B.M.S. stage is 0.71 mole % FeS.
Fig. 7-7: Sulfidation state (Rs) versus temperature diagram showing mineral sulfidation reactions at 2 kbar in aqueous conditions and contours of mole % FeS in sphalerite coexisting with pyrrhotite or pyrite.

7.2.2. Fluid Temperatures and the Role of Boiling

According to the textures identified, the formation of the Alpha stages was accompanied by boiling of the hydrothermal liquids. The textures identified in Alpha stage are lattice bladed calcite, subrhombic adularia and jigsaw quartz. Some minor amounts of rhombic calcite were identified in Alpha stage veins, but they were not common and may be late because they were not observed to be crosscut by Beta stage minerals. The dominance of Mn-silicates minerals such as rhodonite in the Alpha stage veins located in the deep and mid levels of the North Amethyst deposit indicates that fluids forming this vein stage attained elevated (>320°C). Mn-silicate minerals are completely absent in Alpha stage veins located in the upper levels of the deposit, suggesting that fluid temperatures decreased with elevation. This is consistent with the boiling behavior of hydrothermal liquids that undergo cooling during decompression. A cooling trend is
also supported by the decrease in the Fe concentrations of sphalerite contained in the Alpha stage.

The physicochemical conditions prevailing during Beta stage cannot be deduced from textural features since ore mineral precipitation during this stage was not accompanied by the formation of gangue minerals. However, fluid inclusion work conducted on Beta stage sphalerite by Foley (1990) provided critical constraints on the conditions that prevailed during ore mineral formation. Homogenization temperatures of primary liquid inclusions entrapped in sphalerite varied between 270°C and >350°C. Salinities of the liquid inclusions were low at <2 wt.% NaCl equivalent. Coexistence of vapor inclusions suggests that boiling conditions occurred at least during part of the Beta stage formation (Foley, 1990).

Based on the textural evidence, mineral deposition during Stage-1 of the B.M.S. association appears to have occurred under non-boiling conditions. The ore minerals were observed to be present with crustiform bands of fine-grained Mn-, Ca-carbonate minerals having a rhombic texture. The conclusion that boiling did not occur during Stage-1 is confirmed by fluid inclusion investigations carried out by Foley (1990). Observed homogenization temperatures ranged from 220–280°C. The salinities of the entrapped fluids was constrained to be 5–11 wt.% NaCl equivalent (Foley, 1990).

Mineral formation during Stage-2 vein formation may have involved boiling. Stage-2 quartz is feathery or shows a flamboyant texture. The adularia is subrhombic, which also suggest boiling (Figs. 7-4, 7-5 and 7-6). The occurrence of boiling during Stage-2 formation is also supported by fluid inclusion evidence presented by Foley (1990). Foley (1990) showed that early Stage-2 quartz and fluorite contained primary inclusions that have similar homogenization temperatures and salinities as those encountered in Stage-1. However, quartz of Stage-2 records a relatively sharp decrease in salinity, and quartz precipitated late during Stage-2 contains primary inclusions that have salinities below 3 wt.% NaCl equivalent. The data was interpreted to indicate that the fluids were boiling during the later part of Stage-2 and continued boiling during deposition of Stage-3 quartz and calcite (Foley, 1990). Late Stage-2 quartz and Stage-3
quartz contain primary inclusions homogenizing between 128 and 301°C. The salinities of liquid inclusions are <0.5 wt.% NaCl equivalent (Foley, 1990).

7.2.3. The Role of Fluid and Wall-Rock Buffers

Wall-rock buffering of the hydrothermal liquids forming the different vein stages at North Amethyst was an additional important process influencing the chemistry of the liquids. As discussed by Einaudi et al. (2003), epithermal systems are only capable to achieve intermediate or high sulfidation states if the fluid chemistry is buffered by the presence of H₂S and SO₂, requiring the input of magmatic volatiles into the hydrothermal system. However, upon cooling and increases in transport distance, the sulfidation state of hydrothermal liquids is increasingly influenced by fluid-rock interaction. Fluid-rock interaction at low temperatures causes a decrease in the sulfidation state (Fig. 7-7).

A pronounced shift in the sulfidation state is observed during the formation of the Beta stage. While early ore minerals formed are typical of hydrothermal liquids having an intermediate sulfidation state (low-Fe sphalerite, chalcopyrite, pyrite), a drop in sulfidation state can be documented late in the paragenetic sequence. At temperatures below approximately 200°C (Fig. 7-7), the drop in sulfidation state, interpreted to be related to fluid-rock interaction, causes a shift in mineral precipitation from silver sulfides to native silver.

7.3. Implications to the Creede Model

The Creede mining district has been the subject of a number of sustained research projects that produced a large number of scientific research papers and reports, most of which have focused on the formation of the deposits in the central and southern parts of the Creede mining district, including the Amethyst, Bulldog, OH and P epithermal veins (Barton, 1977; Bethke et al., 1979; Bethke, 1988; Rye et al., 1988; Plumlee 1989, 1994; Hayba, 1997; Campbell et al., 2005). The research on the North Amethyst deposit conducted by Foley (1990) and as part of this present thesis adds important information on the nature of the epithermal veins in the northern part of the Creede mining district.
7.3.1. Correlation of Vein Assemblages and Vein Stages

The present study showed conclusively that the Mn-Au association at the North Amethyst deposit predates the B.M.S association. Unfortunately, the absolute age of the Mn-Au association at the North Amethyst deposit can only be bracketed at this time between 27.35 Ma, which is the age of the Carpenter Ridge Tuff, and 25.1 Ma, which is the age of adularia \(^{40}\text{Ar}/^{39}\text{Ar}\) associated with the B.M.S. association at the North Amethyst deposit (Foley, 1990; Foley and Ayuso, 1994).

The age of the B.M.S. association at North Amethyst corresponds to the age of formation of the silver and base-metal rich veins in the central and southern part of the Creede mining district. K/Ar radiometric age dating of adularia from these veins has yielded an age of 25.1 Ma (Plumlee et al., 1994). In addition to absolute age, the stages of the B.M.S. association at North Amethyst exhibit textures similar to those encountered for the Main Stage veins of the central and southern portions of the district. The mineralogical composition of the ore, the mineral chemistry (Fe and Cd contents of sphalerite, Ag in tetrahedrite etc.) and fluid inclusion properties are also comparable, further suggesting that the late B.M.S. association encountered at North Amethyst correlates with the Main Stage veins of the Creede mining district (Foley and Ayuso, 1994).

Research on the physiochemical conditions of ore formation in the central and southern part of the Creede mining district resulted in a comprehensive understanding of the mineralogical and geochemical characteristics of the veins and the definition of five paragenetic ore stages, referred to as ore stage “A” to “E” (Steven et al., 1975; Bethke et al., 1976; Barton et al., 1977; Bethke et al., 1979; Rye et al., 1988; Plumlee, 1989; Plumlee et al., 1994; Hayba., 1997). Ore stage A consists of quartz and adularia. The main ore stage B is characterized by quartz, sphalerite, chlorite, galena, hematite, tetrahedrite and abundant silver minerals. The ore stage C mostly comprises fluorite, quartz and Mn-siderite. Stage D is characterized by sphalerite, galena, quartz, chalcopyrite and hematite, while ore stage E is composed of pyrite and stibnite.
Based on vein mineralogy, texture, mineral chemistry (Fe and Cd contents of sphalerite, Ag in tetrahedrite etc.) and fluid inclusion characteristic, the different stages of the B.M.S association can be correlated with the different ore stages of the Main Creede veins (Fig. 7-8; Foley and Ayuso, 1994). Stage-1 in the North Amethyst deposit is equivalent to Stage B in the Main Stage veins. Stage-2 in the North Amethyst deposit is equivalent to Stage C in the Main Stage veins. Stage-3 in the North Amethyst deposit is the Stage E of the Main Stage veins. This correlation of the vein stages of the B.M.S association in the North Amethyst deposit with the ore stages from the Creede mining district led Bethke (1988) to propose that the silver and base metal mineralization across the entire district formed from a single large evolving hydrothermal system. This suggestion initially made by Bethke (1988) became an integral part of subsequent model for the formation of the epithermal deposits of the Creede mining district.

As part of the present study, a new base metal-rich vein stage, referred to as the Fe-poor B.M.S. stage, has been observed that has not been previously reported to occur at the North Amethyst deposit. Two exploration drill cores from the northern end of the 10,250 ft level at the N3 orebody contained these base metal sulfide-rich veins that differed in mineralogy and geochemistry from the base metal sulfides of Stage-1. The base metal sulfide rich-veins in the N3 orebody consist of coarse-grained pyrite, sphalerite, galena and chalcopyrite, but do not contain hematite and chlorite which are characteristic for Stage-1. The veins also differ texturally from the Stage-1 veins. The base metal sulfides of the veins do not show a crustiform sequence of minerals like Stage-1. The texture is dominated by close intergrowth of the sulfide minerals. There are no replacement textures observed, possibly indicating that the sulfide minerals of the Fe-poor B.M.S. stage are broadly contemporaneous.

The Fe-poor B.M.S. stage is observed to crosscut a quartz and adularia-rich gangue assemblage with minor amounts of Mn- and Ca-carbonate minerals as well as fluorite. This gangue assemblage is adularia-rich which is a characteristic of Stage-2 and it consists of a similar assemblage to Stage-2 recognized in the deep vein sample. However, the adularia in the Stage-2 deep level vein sample is subrhombic, while the gangue assemblage associated with the Fe-poor B.M.S. stage consists of tabular and rhombic adularia. The difference in adularia texture may not be the result of a different vein stage but as the result of boiling intensity and
permeability (Dong and Morrison, 1995). Therefore, the earlier adularia- and quartz rich assemblage associated with the Fe-poor B.M.S. stage is interpreted as Stage-2. The Fe-poor B.M.S. stage consists of an assemblage similar to Stage D of the OH deposit. Since it is observed to crosscut Stage-2, it is interpreted to be the missing base metal stage in the North Amethyst deposit.

### 7.3.2. Hydrothermal Circulation Model

Ore deposition of the Main Stage of the Creede deposit took place at 25.1 Ma, which is approximately 1.8 m.y. after the collapse of the Creede caldera (Barton, 2000). As a result of the collapse of the Creede caldera, a large lake was formed filling the caldera basin. Stream-channel gravels, landslide breccias, travertine, bedded lacustrine sedimentary rocks and water-laid tuffs, collectively referred to as the Creede Formation, were deposited within the basin (Foley, 1993;
Lipman, 2000). During this period of post collapse and pre resurgence, approximately 1000 km³ of water was evaporated and residual brines and possibly evaporates would have accumulated (Barton et al., 2000). Mineralogical analysis of the Creede Formation revealed the presence of gypsum, ikaite and thenardite. The brines were bicarbonate-rich and saline, but not hypersaline (Barton et al., 2000). The source for the salts is hypothesized as originating from volcanic ash (Barton et al., 2000).

A resurgence of the Creede caldera occurred 0.6 m.y. after its collapse and uplifted the Snowshoe Mountain tuff (Barton, 2000). During uplift erosional debris slumped into the water-laiden Creede Formation and a moat formed around the modern day Snowshoe Mountain (Lipman, 2000). The trace of the moat is outlined by the modern day Rio Grande River. After the Creede caldera resurgence, a small pluton is thought to have intruded beneath the northern part of the Creede district which represented the thermal driver of the Creede hydrothermal system (Barton et al., 2000).

The fluid mixing model proposed by Bethke et al. (2000) is currently the most widely accepted model for the formation of the ore deposits of the Creede mining district, explaining the metal zonation observed in the district and the isotopic and fluid inclusion characteristics of ore and gangue minerals. The model is based on the contributions by Bethke and Rye (1979), Rye et al. (1988), Hayba (1993), Plumlee (1994) and Hayba (1997).

In his seminal work, Rye et al. (1988) identified four end-member liquids in the Creede mining district through their stable isotopic signatures. These include a dilute liquids derived from shallow groundwater (δD = -110‰, δ¹⁸O = -16 ‰), a deep northern recharge liquid (δD = -110‰, δ¹⁸O = -2‰), a deep southern recharge liquid (δD = -50‰, δ¹⁸O = -2‰) and an isotopically heavy, saline liquid thought to be derived from the moat in which the Creede Formation was deposited (δD = -80‰, δ¹⁸O = +8‰). Variable interaction of these four end-member liquids has been interpreted to be the cause of the observed metal zonation of the Creede district.

Bethke et al. (2000) proposed that the fluid inclusion signature and isotopic composition of ore minerals from the Main Stage veins at Creede indicate that the primary ore liquids were
derived from evaporated lake water of the moat (13 wt. %NaCl equiv., δD and δ¹⁸O of at least -50 ‰ and -3 ‰, respectively; Barton et al, 2000). Barton et al. (2000) further suggested that these cool saline brines residing in the deep reservoir of the moat were drawn northward by the emplacement of a shallow intrusion in the North Amethyst area. In the proximity to the pluton, the brines were heated and magmatic volatiles including HCl and CO₂ were added, in addition to sulfur and perhaps metals (Barton et al., 2000). These liquids became buoyant and then ascended through the intersection of the Equity and North Amethyst Faults. As a result of decompression, the liquids underwent boiling. These boiling liquids mixed with shallow meteoric groundwater derived from the topographic highlands and flowed laterally southward, descended into the northern end of the moat to become part of a single large convective cell spanning the entire district. This large convection cell is thought to have been responsible for the formation of the Creede Main Stage veins at 25.1 Ma, characterized by the silver- and base metal-rich ores hosted by a gangue of quartz, chlorite, fluorite, rhodochrosite and barite (Barton et al., 2000).

A lead isotopic study of galena from the North Amethyst vein system by Foley (1994) suggested that this model for the formation of the Creede district may need at least some revision. The lead isotopic composition of galena associated with the Au-rich Beta stage of the North Amethyst is non-radiogenic (²⁰⁶Pb/²⁰⁴Pb ratio of 18.9) and is interpreted to be the result of the hydrothermal liquids interacting with non-radiogenic volcanic wall rock (i.e., Carpenter Ridge and Nelson Mountain tuffs). Galena associated with the younger B.M.S. association of the North Amethyst and Main stage Creede veins is distinctly more radiogenic (²⁰⁶Pb/²⁰⁴Pb ratio of 19.04), requiring a different Pb source. Foley (1994) explained the more radiogenic signature through a model of Pb uptake from Proterozoic source rocks or sedimentary rocks. To explain difference in the Pb isotope compositions between the earlier Beta stage and the later B.M.S. association, Foley (1994) proposed that the precious metal mineralization of the Beta stage was associated with an early and more local hydrothermal system developed above the inferred intrusion at the intersection of the Equity Fault and the Amethyst Fault between 26.1 and 25.1 Ma. By 25.1 Ma, this local hydrothermal cell began to expand and equilibrate thermally with the regional hydrothermal system to deposit the silver and base metals across the entire district as proposed by Bethke (1988).
The drilling at the North Amethyst deposit by Rio Grande Silver Inc. provided a unique opportunity to reevaluate how the gold-rich and base-metal rich ores in the northern part of the Creede district may have formed. Although the research of the present thesis did not focus on the fluid inclusion and isotopic properties of the mineralizing liquids at the North Amethyst deposit, new important constraints on the paragenesis and fluid evolution at the deposit scale were derived, which have implications to the understanding of the mineralizing system in Creede.

The research of the present study supports the concept of Foley (1994) that the conditions of mineral precipitation changed significantly over the duration of vein formation at the North Amethyst deposit. The research established that early veins of the Alpha stage were essentially devoid of ore minerals while the overprinting Beta stage represents the main mineralizing event. Physicochemical conditions of mineral formation must have changed significantly to allow such a change from an essentially barren system to a mineralized system. Subsequent to the veins of the Mn-Au association, the B.M.S. vein stages were formed, highlighting a further change in the nature of the mineralizing liquids. Given the fact that the Mn-Au association at the North Amethyst deposit differs significantly in character from the B.M.S. association, which is more similar to the vein styles encountered elsewhere in the Creede district, it appears questionable whether the different vein stages were indeed formed by a single evolving hydrothermal convection cell as envisaged by Bethke et al. (2000).

In the single hydrothermal convection cell model by Bethke et al. (2000), the area of the North Amethyst deposit was envisaged to be the upflow area for the hydrothermal fluids throughout the formation of the deposits of the Creede mining district. Bethke et al. (2000) indicated that boiling conditions were achieved throughout the upflow zone.

Fluid inclusion data by Foley (1990) suggest that the early Mn-Au association formed at a temperature range of >350°C to 270°C from fluids containing <2 wt.% NaCl equivalent. Mineral deposition indeed largely occurred under boiling conditions (Foley, 1990). However, the younger Stage-1 of the B.M.S. association, comparable to the Main Stage veins at Creede, formed in a temperature range from 280–220°C from fluids having a salinity of 5–11 wt.% NaCl equivalent. Assuming that hydrostatic pressures did not change, mineral deposit during the
B.M.S. stage did not occur under boiling conditions, which is confirmed by the fluid inclusion evidence (Foley, 1990). The textural features observed in Stage-1 veins in the present study confirm that boiling was probably not important during Stage-1 vein formation. No boiling textures were observed for quartz, adularia and calcite.

The temperature of formation of the B.M.S. veins at North Amethyst broadly overlap with the temperature ranges encountered for fluid inclusions hosted by quartz and sphalerite in the Main Stage veins at Creede, which range up to maximum temperatures of about 240–260°C (Barton et al., 2000). If the North Amethyst deposit area indeed represented the upflow zone for the hydrothermal liquids forming the deposits of the Creede mining district, essentially no cooling of the hydrothermal liquids would have occurred during lateral fluid flow from the northern and southern part of the district, which is difficult to envisage and inconsistent with the proposed mixing of the hydrothermal fluids with cooler meteoric water.

It is also important to take into account that the porphyritic dacite encountered in the deep drill holes at the North Amethyst deposit is no longer considered to represent a shallow intrusion emplaced broadly coeval with the mineralization at the North Amethyst deposit (Chapter 3), but probably represents a 29.34–27.80 Ma Pre-Carpenter Ridge unit. The lack of evidence for the existence of a heat source below the North Amethyst deposit area casts further doubt on models placing the upflow zone of the hydrothermal system forming the deposits of the Creede district at North Amethyst. The new drilling performed at North Amethyst further showed that the deep intersections of the B.M.S. veins are not particularly high-grade or associated with extensive hydrothermal alteration of the wall-rocks. Given the appearance of these veins in drill core, it is difficult to imagine that the upflow zone of the hydrothermal cell forming the entire Creede mining district was located at North Amethyst.

7.3.3. Location of the Paleowater Table

Models for the Creede mining district have to take changes in paleotopography into account. The present elevation of the water table is approximately at 11,100 feet, which corresponds to the elevation of Willow Creek near the mine portal.
As discussed above, thermodynamic data suggest that rhodonite is a higher temperature mineral than rhodochrosite. The phase boundary between both phases is located at approximately 320°C (Norman et al., 1983), which is consistent with the temperature of formation of the Mn-Au associations as constrained by fluid inclusion data by Foley (1990). Temperatures of 320°C can only be reached at depth of more than 1,100 m (3,608 ft) below the water table (boiling of a 3.2 wt.% NaCl solution with no CO₂ occurs 1,122 m below the water table; Monecke et al., 2014). The shallowest rhodonite present was observed at an elevation of 10,620 ft in drill hole NAU12148. To allow formation of the rhodonite, the water table must have been located at least 3608 ft above the sampling location, which corresponds to the water table being located at an elevation of 14,228 ft. This is approximately 3,100 ft higher than today’s elevation of Willow Creek.

Although this only represents a first-order estimate, it is clear that the paleotopography must have changed significantly since the deposit formation. The water table at the time of mineralization was clearly at significantly higher elevation than the present water table, not taking regional uplift into account. A more precise conclusion could be drawn based on future microthermometric investigations on fluid inclusions forming boiling assemblages.

A pronounced elevation differences as constrained by the present study has already been suggested in the model proposed by Bethke et al. (2000). In their schematic diagrams of the hydrogeology of the Creede district, the paleosurface was located in excess of 14,000 ft elevation in the North Amethyst area. However, these authors also postulated that erosion across the entire Creede district was similar, implying that the Creede Formation was originally several thousand feet thicker than today.

7.4. Exploration Implications

The findings of the present study have implications for exploration targeting at the North Amethyst deposit. The research demonstrates that epithermal vein structures at Creede represent structural discontinuities that were reopened multiple times. Ore deposition during the main precious metal event, the Beta stage, occurred within preexisting veins that were reopened. The
ore minerals were deposited without associated gangue minerals. This complicates grade control as a direct correlation between macroscopically visible vein textures, which are primarily based on gangue textures of the Alpha stage, and ore grade does not exist. Although the presence of Alpha vein gangue minerals in core is generally encouraging, not all Alpha veins are mineralized as they may lack the presence of Beta seams. The same observation holds true for the main mineralizing event of the B.M.S. association, the Fe-poor B.M.S. stage. Although not economic at the North Amethyst deposit as currently known, the Fe-poor B.M.S. stage exploits preexisting veins. Elevated Au grades may occur where these base metal-rich veins overprint preexisting veins of the Mn-Au association and incorporated the vein material. As Beta seams can be high-grade, incorporation of relatively small amounts of Beta stage material can result in anomalously high, but perhaps scattered, Au grades in veins of the B.M.S. association. Careful core logging and sampling for assaying is needed to correctly interpret grade distribution.

The microanalytical research of the present study also shows that galena can be an important host for Ag. Galena grains from the Beta stage sampled at the mid-levels of the North Amethyst deposit contain a minimum value of 0.019 wt% Ag, a median value of 0.066 wt% Ag and a maximum value of 0.088 wt% Ag (n=8 grains). Using the median value as a guide, a metric ton of galena would contain over 21 oz of Ag. Although the veins overall have a high Ag content, with the silver being mostly contained in silver sulfides or native silver, the partitioning of Ag into galena needs to be taken into account in the design phase of the ore processing as this portion of the overall Ag grade would report to the galena concentrate. At current market price, the Ag content of the galena accounts for 14% of the total metal value of a ton of galena concentrate (combined Pb and Ag).

The results of the present study also have implications for brownfields exploration at the scale of the Creede mining camp. As noted above, models invoking a single hydrothermal convection cell at Creede do not fully explain the observations made at the North Amethyst deposit. The data now available cast at least some doubt on the proposed model for the Creede mineralizing system that assumes that the hydrothermal upflow zone was located in the North Amethyst area and that N-S-oriented lateral fluid flow along the Amethyst fault was the dominant driver for mineralization in the district. It is suggested here that future brownfields
exploration in the Creede district should not be based on a particular hydrogeology model for the
district. The recent discovery of surface outcrops of high-level hydrothermal veins and breccias
in the southeastern part of the Creede caldera by Environmental Geoscience Inc. highlights the
potential for currently untested ground in the historic Creede mining district outside of the area
currently assumed to be fertile.

As discussed by Foley (1990) and Foley and Ayuso (1994), there is the possibility that
veins of the Mn-Au association are more widespread throughout the Creede mining district than
previously thought. It is important to note that these veins may be difficult to recognize in areas
and at elevations overprinted by the younger base metal-rich veins. The textural relationships
documented in the present study suggest that the epithermal veins at Creede can record complex
processes of reopening. For instance, in the deep WE1031 veins, Alpha stage vein material is cut
and incorporated into the younger B.M.S stage veins containing base metal-rich sulfides, chlorite
and hematite. Elevated Au and Ag values may suggest that some Beta stage material was also
incorporated into the breccia. Recognizing the incorporation of high-grade Beta stage material in
Main Stage veins of the Creede district may be difficult macroscopically. As a consequence, the
significance of the elevated Au and Ag values in such complex veins may be easily overlooked
in exploration unless attention is paid to the petrographic characteristics of the veins.
CHAPTER 8
CONCLUSIONS

This thesis represents a comprehensive examination of the intermediate sulfidation stage epithermal veins in the North Amethyst deposit of the Creede mining district, Colorado. Based on recently acquired exploration drill core, this study provides new data on the textural and mineral characteristics of the North Amethyst deposit veins, expanding and modifying the previous classification scheme of vein stages by Foley (1990). Additionally, this thesis refines the ore and gangue mineral paragenetic sequence proposed by Foley (1990) and provides new data on the chemistry of the ore minerals. The thesis interprets the physiochemical conditions of ore deposition and its evolution through time and space and shows that pronounced changes in fluid temperature and sulfidation state occurred over the duration of the deposit formation. The new mineralogical and geochemical data obtained for the North Amethyst deposit provides the basis to better correlate mineralization processes occurring in the northern part of the Creede mining district with the economically most significant central and southern portion of the deposit. The research also provides new insights into the formation of intermediate sulfidation-state epithermal deposits.

Based on detailed core logging and the review and interpretation of exploration data made available by Rio Grande Silver Inc., the following main conclusions on the geological setting of the North Amethyst deposit and structural controls on the formation of the epithermal veins can be drawn:

1) The North Amethyst deposit consists of precious and base metal-rich epithermal veins which mineralized dilatant zones along the intersection of the E-W trending Equity reverse fault and the northern extension of the N-S trending Amethyst normal fault. The intersection of the Equity and Amethyst faults lies within the southern topographic margin of the San Luis Caldera complex (26.9 Ma) and the northern margin of the Bachelor caldera (27.35 Ma). The northern extension of the Amethyst fault defines the western boundary of the Equity fault block, which is a distinct, fault-bounded uplift area that has a triangular shape in map view. The fault block is bounded to the south by the
Equity reverse fault. The Deerhorn normal fault represents the eastern limit of the fault block.

2) The epithermal veins of the North Amethyst deposit are hosted by the 29.34–27.80 Ma Pre Carpenter Ridge Unit and the 27.35 Ma Willow Creek and the Campbell Mountain welding zones of the Carpenter Ridge rhyolite tuff. The rocks present within the North Amethyst deposit also include the 26.8 Ma Nelson Mountain tuff and the 27 Ma Captive Inca Lava Dome which were deposited during the San Luis caldera cycle. Other units exposed in the deposit area also include the 27.6 Ma Fish Canyon tuff, the 27.35 Ma Windy gulch welding zone of the Carpenter Ridge tuff, the 27.1 Ma Wason Park tuff, the 27.0 Ma Rat Creek tuff, the 26.9 Ma Cebolla Creek tuff and the 26.8 Stewart Peak Andesite.

3) Previous research by Foley (1990) documented the occurrence of two vein associations at the North Amethyst deposit, namely the early Mn-Au association and the late B.M.S. association. Careful drill core inspection, compounded by petrographic investigations, confirmed that the classification scheme of Foley (1990) could be used to classify veins intersected in the more recent exploration drill core, with minor modifications. Veins of the Mn-Au association have formed during three distinct stages of mineralization. The early Alpha stage is primarily composed of fine-grained quartz and Mn rich gangue minerals, followed by two fine-grained ore stages, Beta-1 and Beta-2 which contain a fine- grained assemblage of ore minerals. Beta-1 and Beta-2 are separated by a brecciation event, referred to as Breccia-1. The early veins of the Mn-Au association are crosscut by veins belonging to the B.M.S. association. A brecciation event known as Breccia-2 marks the transition from the Mn-Au association to the B.M.S. association. The first veins of the B.M.S. association formed during Stage-1, which are composed of base metal sulfide minerals as well as chlorite and hematite. This was followed by a breccia event, Breccia-3, characterized by quartz and chlorite cementing fragments of wallrock and Stage 1 vein material. Subsequent to this, open-space filling occurred, resulting in the deposition of calcite, adularia, fluorite and quartz of the Stage-2. Base metal-rich veins identified for the first time in the present study in the mid level N3 orebody postdate
Stage-2. These veins of the so-called Fe-poor B.M.S. association lack chlorite and hematite. A subsequent stage of brecciation resulted in the formation of Breccia-4. Late hydrothermal activity at the North Amethyst deposit is recorded by the local occurrence of Stage-3 which occurs as a lining of vugs or as crusts on earlier assemblages and is characterized by the presence of quartz, Mn-calcite, trace pyrite, rhodochrosite and gypsum.

4) Within the uppermost part of the deposit, veins occur in the 108 ore shoot at 11,288 to 10,217 feet elevation. The epithermal veins are hosted in the E-W trending Equity fault, which consists of Alpha, Beta and Breccia-1 stages, which belong to the Mn-Au association.

5) A wide variety of vein types of the Mn-Au and Base-Metal-silica associations is encountered at mid elevations of the North Amethyst deposit between 10,706 and 9,872 ft. elevation. The veins occur along the N-S trending Amethyst fault, forming discrete ore shoots. In the present study, veins studied from the S2 orebody at the southern end of the Amethyst fault were identified to contain the Alpha and Beta stages of the Mn-Au association and the Breccia-2 stage of the B.M.S. association. Veins from the N3 orebody at the northern end of the Amethyst fault were identified to contain veins of the Breccia-2, Fe-poor B.M.S. stage, Stage-3 and Breccia-4 veins, which belong to the B.M.S. association.

6) The deepest currently known vein intercepts occur at 9,280 to 9,270 ft elevation close to the intersection of the Equity and Amethyst faults. The deep-level veins consist of spatially overlapping Alpha and Beta stages of the Mn-Au association and the Stage-1, Breccia-3 and Stage-2 of the B.M.S. association.

A total of 45 representative vein samples from the various vein stages were collected from 14 drill core intercepts from different elevations and locations within the North Amethyst deposit. The samples were subject to optical petrography and scanning electron microscopy to constrain the textural and mineralogical characteristics of the veins and to derive a paragenetic sequence for the North Amethyst deposit. X-ray diffraction experiments were conducted on
selected samples to conclusively identify Mn-bearing carbonate and silicate minerals present in
the early vein stages of the North Amethyst vein system. The study of the vein samples allowed
the following main conclusions to be drawn:

1) The Alpha stage veins in the upper level of the North Amethyst deposit at 11,288 to 10,217
feet elevation are dominated by quartz and Mn- and Ca-carbonate minerals. The absence of
Mn-silicate minerals in the veins at this high elevation indicate formation at moderate
(<320°C) temperatures. Beta stage seams are abundant in the epithermal veins of the upper
levels of the deposit and characterized by a variety of Au and Ag minerals. Gold grades
range from 1.5–15 ppm and Ag grades range from 190–1260 ppm Ag. The Au:Ag ratios
are around 1:100. The paragenetic sequence of Beta stage mineralization commences with
early base metal sulfides (sphalerite, galena and chalcopyrite) and iron sulfides (pyrite and
marcasite). The base metal stage was followed by the precipitation of Au as electrum and
uytenbogaardtite, followed by silver sulfosalts (freibergite, polybasite, pyrargyrite,
mckinstryite and jalpaite), silver sulfides (argentite and acanthite) and the late precipitation
of native silver. No gangue minerals are observed in the Beta stage.

2) The Alpha stage veins from the mid-levels of the North Amethyst deposit at elevations of
10,706 to 9,872 ft. consists of the mineral assemblage already reported by Foley (1990).
The paragenesis includes Mn-silicate minerals, with rhodonite being the most common
phase, followed by inesite and caryopilite. Pyroxmangite is reported to occur in the Alpha
stage (Foley, 1990), but was not confidently identified in the present study. Systematic
XRD experiments showed that the color and hardness of Alpha stage vein intercepts
correlate with mineral composition and abundance. The XRD results obtained from a
samples of a soft, white, cream, light brown colored zone of Alpha stage revealed the
presence of Mn-, Ca-carbonate minerals such as Mn-calcite, kutnohorite and rhodochrosite.
Hard, red colored zones of Alpha stage are rich in the Mn-silicate mineral rhodonite which
occurred together with calcite and rhodochrosite as well as minor amounts of kutnohorite
and Mn-calcite. Gold minerals in the Beta stage seams from the mid-levels of the deposit
were not observed in the present study, although the same paragenetic sequence as in the
upper portion of the deposit was observed otherwise, including the early base metal
sulfides and iron sulfides, the later silver sulfosalts and the late native silver. A new vein stage was identified in two drill cores from the N3 orebody, which exhibited crustiform texture and consists of a coarse-grained sulfide assemblage of pyrite, sphalerite, galena and chalcopyrite that crosscuts a quartz-adularia rich gangue. As this veins stage does not contain chlorite and hematite diagnostic of Stage-1 of the B.M.S. association, this vein stage is referred to as the Fe-poor B.M.S. stage. The Fe-poor B.M.S. stage vein cuts quartz and adularia rich matrix which shares mineral and textural features similar to Stage-2. For this reason, the Fe-poor B.M.S. stage is interpreted to occur after Stage-2 and before Breccia-4 and Stage-3.

3) The deep-level veins of the North Amethyst deposit are texturally and mineralogically complex due to the occurrence of spatially overlapping vein stages of the Mn-Au and B.M.S. associations. The petrographic analysis showed that the veins contain an early Alpha stage that is cut by the vein stages of the B.M.S. associations. Beta stage vein material is present in some deep-level veins and occurs as small brecciated fragments which tend to be present at the contact of Alpha and Stage-1, Breccia-3 or Stage-2. No gold minerals were observed in the deep level veins. However, samples yielded 5–11 ppm Au and 26–1090 ppm Ag.

4) Textural studies on the gangue minerals showed that Alpha stage veins in the upper levels of the North Amethyst deposit formed under boiling conditions. Calcite is lattice bladed, quartz shows a jigsaw texture and adularia is subrhombic. Alpha stage veins from the mid-levels likely also formed under boiling conditions as suggested by the presence of subrhombic adularia. Stage-1 gangue minerals identified in the deep level veins contain no textures indicative for boiling of the hydrothermal liquids. Stage-2 veins identified in the deep level veins formed under boiling conditions, as suggested by the presence of feathery and flamboyant quartz, subrhombic adularia and lattice bladed calcite. The gangue matrix of the Fe-poor B.M.S. stage contains subrhombic, tabular and rhombic adularia crystals which are indicative of boiling. A clear correlation between texture and precious metal grades is, however, not observed as the bulk of the precious metal mineralization occurred
during the Beta stage, which is not associated with gangue minerals. Similarly, the sulfide minerals of the Fe-poor B.M.S. stage are not associated with gangue minerals.

An electron microprobe study was conducted on sphalerite, pyrite, galena and chalcopyrite forming part of the various ore-bearing vein stages at the North Amethyst deposit. It was the main purpose of the microanalytical study to determine the concentration of Fe contained in the sphalerite to confirm that the North Amethyst vein deposit can indeed be classified as an intermediate-sulfidation state epithermal deposit. In addition, the microanalytical research was carried out to test for potential variations in the composition of these minerals by vein stage and location within the deposit. The following main conclusions were drawn:

1) The Fe content of sphalerite from the Alpha stage veins from the deep, middle and upper levels of the deposit are generally low. The median Fe concentrations increase with decreasing elevation from 0.24 mole % FeS at 10,800 ft elevation to 0.40 mole % FeS at 10,200 ft elevation and 1.3 mole % FeS at 9,270 ft. This observation can be best explained by a model that invokes fluid cooling from the deep to shallow elevations and a temperature-controlled decrease of the sulfidation state during the formation of the Alpha stage. In contrast to the Alpha stage, the Fe content of sphalerite in the Beta stage does not vary significantly with elevation. The median Fe concentration of sphalerites of the Beta stage is 0.58 mole % FeS at 10,800 ft elevation, 0.51 mole % FeS at 10,200 ft elevation and 0.67 mole % FeS at 9,270 ft elevation. This potentially implies that changes in the temperature of formation and/or sulfidation stage was less pronounced during the Beta stage vein formation. The median Fe content of sphalerites of Stage-1 of the later B.M.S association is 0.96 mole % FeS, while the Fe content of sphalerites of the Fe-poor B.M.S. stage has a median value of 0.71 mole % FeS. The Fe content in sphalerite from the epithermal veins of the North Amethyst deposit are generally low, confirming that veins of both the Mn-Au and the B.M.S. associations can be classified as intermediate sulfidation stage epithermal veins.

2) Sphalerite from the Alpha stage in the upper level yielded a median value of 0.16 mole% MnS. Mid-level sphalerite is typified by a median value of 0.46 mole% MnS, while
sphalerite in the deep level veins has a median Mn concentration of 0.14 mole% MnS. Beta stage sphalerite in the upper and mid-levels are characterized by systematic variations in the Mn content between core and rim, with the rims typically being enriched in Mn. Beta stage sphalerite in the upper levels of the deposit has a median value of 0.59 mole% MnS. The mid level sphalerite yielded a median value of 0.60 mole% MnS. The deep level veins contain sphalerite with a median value of 0.12 mole% MnS. The Stage-1 sphalerite of the B.M.S. association yielded a median value of 0.09 mole% MnS. The Fe-poor B.M.S. stage sphalerite has a median value of 0.10 mole% MnS. The Mn content in sphalerite is distinctly lower in the late stage veins of the B.M.S. association when compared to the earlier formed sphalerite contained in the veins of the Mn-Au association.

3) Pyrite, galena and chalcopyrite contained in the different vein stages of the North Amethyst deposit are generally characterized by low trace element concentrations. Beta stage pyrite in the upper level veins of the deposit typically show rims that are enriched in As. Maximum concentrations of 0.78 to 1.15 wt.% As were encountered. Mid level Beta stage galena contain significant Ag (up to 0.09 wt.%) and Sb (up to 0.06 wt.%) concentrations. The concentrations of both elements co-vary. Chalcopyrite shows a notable enrichment in Bi, with a maximum value of 0.04 wt.%.

4) EMP point traverses were conducted to study precious metal diffusion into galena. A traverse from galena to native silver revealed that the Ag concentrations increase slightly in the galena from the interior towards the contact with native silver. The findings are consistent with the proposed paragenetic sequence, suggesting that galena formation predated the precipitation of Ag sulfides and native Ag. A traverse from galena to electrum showed that no Au diffusion into galena occurred, which is probably related to the fact that Au cannot substitute for Pb in the galena crystal structure.

The field and analytical findings summarized above permit new insights into the formation of the North Amethyst vein deposit and its genetic links to the other deposits of the Creede mining district. The research also has some important exploration implications:
1) The research of the present study established that the epithermal veins of the North Amethyst deposit formed during multiple events, which typically involved reopening and overprinting of earlier formed veins. Mineralization took place during several distinct events that are separated by periods of brecciation and the formation of barren veins. During two of the three recognized ore stages, precipitation of the ore minerals did not coincide with the formation of the gangue minerals. As a consequence, grade control cannot be reliably based on the gangue mineral textures.

2) Vein formation at the North Amethyst deposit occurred in the shallow, near-surface, epithermal environment. The textural studies conducted as part of the present research and previous fluid inclusion work by Foley (1990) showed that the formation of at least some of the veins types occurred under boiling conditions.

3) The ore mineralogy of the veins is consistent with the North Amethyst deposit being an intermediate sulfidation state epithermal deposit. The temperature of mineralization and the sulfidation state of the hydrothermal liquids represented important factors controlling the nature of mineralization. Boiling hydrothermal liquids ascending along the Equity and Amethyst faults must have undergone cooling as a result of open system decompression. At the same time, the sulfidation state of the liquids was controlled by the decrease in fluid temperature and variations in the degree of wall-rock interaction. The precipitation of native silver late in the paragenesis of the Beta stage suggests that the cooling hydrothermal liquids equilibrated with the wall rocks at comparably low temperatures (<200°C), resulting in a pronounced late decrease in sulfidation state.

4) Paragenetically late silver precipitation during the Beta stage resulted in the alteration of previously formed galena and the diffusion of Ag into the crystal structure of this mineral. Silver enrichment in galena is an important consideration that needs to be taken into account in the design phase of the mine and processing plant at North Amethyst.

5) The veins of the early Mn-Au association are unique to the North Amethyst deposit. In contrast, the veins of the B.M.S. association share many similarities with the Main Stage veins of the Creede mining district. It is suggested here that early mineralization at North
Amethyst deposit did not form from the same hydrothermal system precipitating base metal-rich veins throughout the district. Previously suggested models of single hydrothermal convection cell appear too simplistic, especially since there is little evidence supporting the previous suggestion that the upflow zone of the convection cell was located immediately below the intersection of the Equity and Amethyst faults.

6) It is recommended here that brownfields exploration in the Creede mining district should not be based on a particular hydrogeological model. It appears possible that gold enrichment such as at the North Amethyst deposit is not restricted to the northernmost portion of the Creede mining district.

The findings of the present study provide the basis for future research focusing on the formation of the North Amethyst deposit, the Creede mining district and intermediate sulfidation state epithermal deposits in general. In particular, the following research directions are suggested:

1) Further SEM-based petrographic research should be conducted on the various vein sets encountered in the exploration drill cores. In particular, it is suggested to further analyze the deep-level veins of the North Amethyst deposit to identify the mineralogical sequestration of gold. As part of the present study, no discrete gold minerals were identified in the deep-level veins despite the fact that the veins showed elevated Au assay values.

2) Fluid inclusion petrography and microthermometry should be conducted on quartz, sphalerite, calcite and fluorite from the various vein stages to determine the homogenization temperatures and salinities of the entrapped fluid. Particular emphasis should be placed on the identification of primary boiling assemblages in these minerals to allow a determination of the pressures that prevailed during mineral precipitation. The fluid inclusion investigations on these minerals should be complemented by cathodoluminescence investigations to ensure correct identification of the textural settings of the fluid inclusion assemblages. The cathodoluminescence properties of those
minerals from the various vein stages would further define each vein stage and could be potentially used to identify the presence of multiple mineral generations in each vein stage.

3) High-precision $^{40}$Ar-$^{39}$Ar radiometric age dating should be conducted on adularia grains present in Alpha stage veins to obtain an absolute age for this vein stage. The geochronological research would show whether the formation of the early Alpha veins is separated in time from the formation of the base metal-rich veins, which are known to correlate with the main stage mineralization in the central and southern portions of the Creede district.

4) The interpretation of fluid evolution trends within the North Amethyst deposit could be further enhanced by constraining the mineral stabilities of most Au and Ag minerals present in the Beta stage as function of temperature and sulfidation state. As part of the present thesis, the thermodynamic properties of only selected minerals were compiled. The creation of an internally consistent thermodynamic data base of Au and Ag minerals was beyond the scope of the research.
REFERENCES CITED


APPENDIX A
SUPPLEMENTAL ELECTRONIC FILES

The following data files contain supplemental data in support of the thesis work at the North Amethyst deposit. The files include macroscopic drill core descriptions of the 14 drill cores sampled and analyzed in this study, hand-drawn core log sketches and petrographic descriptions of the 45 thin sections obtained in this study. Additional data files include, back-scatter electron images of analyzed minerals and semi-quantitative elemental data obtained at the Colorado School of Mines, back-scatter electron images of Beta stage pyrite grains obtained at the United States Geological Survey in Lakewood, back-scatter electron images of electrum and uytenbogaardtite obtained by QEMSCAN at the Colorado School of Mines, X-ray diffraction data on the four Alpha stage samples from drill core NAU12158 and electron microprobe analyses of sulfide minerals from the various ore bearing vein stages and breccias at the North Amethyst deposit.

| Appendix A_Macroscopic drill core description.xls | This file contains drill core information of the 14 drill cores analyzed in this study which include elevation, assay values and drill core photographs. |
| Appendix A1_Drill Core Logs | This folder contains hand drawn drill core logs of the 14 drill cores analyzed in this study. |
| Appendix B_Petrographic descriptions.xls | This file contains mineralogical information of the 45 thin sections for petrographic analysis in this study. |
| Appendix C_BSE images and Elemental data | This folder contains pdf files of all the minerals analyzed on the scanning electron microscope at the Colorado School of Mines. |
| Appendix C1_BSE images of Pyrite | This folder contains BSE images of Beta Stage pyrites as tiff files from a scanning electron microscope at the United States Geological Survey, Lakewood. |
| Appendix C2_BSE images of Electrum and Uytenbogaardtite | This folder contains BSE images of Beta stage electrum and uytenbogaardtite as tiff files from the QEMSCAN instrument at the Colorado School of Mines. |
| Appendix D_XRD data_Powder XRD | This folder contains pdf files of powder XRD patterns from Alpha stage samples from drill core NAU12158. |
| Appendix D1_XRD data_LT 2 micron XRD | This folder contains pdf files of the less than 2 micron fraction XRD patterns of Alpha stage samples from drill core NAU12158. |
| Appendix E_Microprobe analysis Alpha.xls | This file contains the electron microprobe results of Alpha stage pyrite, sphalerite and galena. Alpha stage chalcopyrite were not analyzed. |
| Appendix E1_Microprobe analysis Beta.xls | This file contains the electron microprobe results of Beta stage pyrite, sphalerite, chalcopyrite and galena. |
| Appendix E2_Microprobe analysis Breccia-2.xls | This file contains the electron microprobe results of Breccia-2 pyrite, sphalerite, chalcopyrite and galena. |
| AppendixE3_Microprobe analysis Breccia-3.xls | This file contains the electron microprobe results of Breccia-3 pyrite, sphalerite, chalcopyrite and galena. |
| AppendixE4_Microprobe analysis Fe poor BM stage.xls | This file contains the electron microprobe results of Fe-poor B.M.S stage pyrite, sphalerite, chalcopyrite and galena. |
| AppendixE5_Microprobe analysis Stage-1.xls | This file contains the electron microprobe results of Stage-1 pyrite, sphalerite, chalcopyrite and galena. |