GOLD-BEARING CARBONATE, SULFIDE, AND SILICATE VEINING IN IGNEOUS AND SEDIMENTARY LITHOLOGIES OF THE HELEN ZONE, COVE DEPOSIT, FISH CREEK MOUNTAINS, NEVADA

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GOLD-BEARING CARBONATE, SULFIDE, AND SILICATE VEINING IN IGNEOUS AND SEDIMENTARY LITHOLOGIES OF THE HELEN ZONE, COVE DEPOSIT, FISH CREEK MOUNTAINS, NEVADA

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ABSTRACT

The Helen Zone is located just northwest of the Cove open-pit Gold mine which is located 35 miles southwest of Battle Mountain in Lander County, Nevada. The Helen Zone consists of horizontal, bedding-replaced, disseminated, Carlin-style mineralization that is hosted in decarbonatized and decalcified carbonate lithologies. Economic mineralization of the Helen Zone is attributed to fluids bearing precious metals associated with two magmatic pulses that formed igneous intrusions ~41.5 and ~39 Ma. The Helen Zone is structurally controlled by steeply dipping thrust and normal faults which aid later hydrothermal fluids coming off igneous intrusions to become mobilized and emplaced in decarbonatized Home Station (T_{Ras}) dolostone and decalcified Favret (T_{Rfv}) limestone. Previous studies of the Helen Zone characterized these igneous intrusions in addition to mineralization that takes place in carbonate lithologies.

This study consisted of twenty samples that were obtained from eight of Premier Gold Mines Limited’s exploratory drill holes from the Helen Zone. Samples were analyzed using transmitted and reflected light microscopy in addition to energy dispersive X-ray analysis (EDAX) for the identification of mineral and vein-types that retain precious metals. Carbonate, sulfide, and silicate vein phases were identified and analyzed for their concentrations in weight percentages of gold (Au), silver (Ag), platinum (Pt), arsenic (As), and other accessory elements in order to characterize the chemistry of the vein minerals. The EDAX analyses yielded results that showed carbonate veins contain highest grades of Ag, sulfide veins contain highest grades of Au and Pt, and silicate veins contain lowest grades of Au, Ag, Pt, and As. Economic mineralization at the Helen
Zone can be attributed to hydrothermal bisulfide fluid complexes that had the capability to mobilize and precipitate precious metals in carbonate host rocks that we see today. Paragenesis of veining at the Helen Zone was determined as having multiple episodic events that took place, based on analyzing carbonate and sulfide vein-types. Relative dating of vein-types suggests that sulfide veins are older than carbonate veins which in turn are older than silicate veins.
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CHAPTER I
INTRODUCTION

The Great Basin is historically known for its production of precious metals and other key mineral deposits, especially in the northern part of Nevada. Gold belts occur in the Great Basin and some of the more illustrious names are the Carlin Trend and the Battle Mountain-Eureka Trend. The notable Battle Mountain-Eureka Trend hosts the McCoy – Cove Project and is located in the Fish Creek Mountains, ~35 miles south of Battle Mountain in Lander County, Nevada (Figure 1) (Thompson, 2013). The McCoy and Cove mining areas are historically known for their economic Au-Ag skarn ore and polymetallic vein-type deposits respectively. McCoy-Cove open-pit and underground mining began in 1987 and continued until 2001, where 3.3 million ounces (Moz) of Au and 108 Moz of Ag were yielded (Johnston et al., 2008). Carlin-style ore is also found at the Cove area, and like the McCoy area, the deposits are hosted in Triassic carbonates and siliciclastic rock types. These Triassic units of the Star Peak Group were deposited in an overlap sequence that overlies the Golconda allochthon during the late Permian (Thompson, 2013).

Located just northwest of the Cove open-pit is an area that consists of horizontal, bedding-replaced, disseminated, Carlin-style mineralization known as the Helen Zone. The Helen Zone is a relatively young area in terms of mineral exploration and consists of the Favret and Home Station Formations that contain high-grades of gold. Recent studies were done by Zoller (2014) and Pacanovsky (2014) in which they studied the geochemistry of igneous intrusions and petrographic analyses of carbonate ore hosts.
Figure 1. Geologic and structural map of Lander County, NV. Taken from Odell et al. (2014), modified from Ludington et al. (2005).
located in the Helen Zone. Igneous intrusions of intermediate and mafic types located in the areas of McCoy-Cove and the Helen Zone were found to be emplaced during different times, with the intermediate event occurring first (Zoller, 2014). Identification of igneous intrusions at the McCoy-Cove mines have been identified as andesites, alkali basalts, and dacites (Zoller, 2014). McCoy pit hosts the andesites that are geochemically similar to the Brown Stock and a younger, alkali basalt that is dominated by a chlorite-sericite alteration. Cove-pit hosts the dacite intrusions, which are characterized by high amounts of sulfidation and contains higher concentrations of silica and potassium (Zoller, 2014). Samples from Pacanovsky (2014) were ball-milled into powders which were then studied by XRD analysis in order to determine mineralogy and composition of altered fine grained samples. Proxy elements that were associated with Au found in the Helen Zone were determined to be Ag, As, Sb, and Tl (Pacanovsky, 2014).

The purpose of this study is to determine which vein-types retain a higher percentage of gold (Au), silver (Ag), platinum (Pt), and arsenic (As) by studying cross-cutting relationships, contrasting mineral species, and detailed weight percents of precious metals in samples collected from the Helen Zone mining area in Lander County, Nevada. Another goal of this study is to determine the paragenesis of microscopic veining that took place during the two phases of mineralization that occurred coeval with the Tertiary Brown Stock intrusion in the Battle Mountain region of the Great Basin dating to ~40 Ma (Johnston et al., 2008; Thompson, 2013). Discovery rates for metals, especially gold, are constantly declining and the cost per discovery is becoming uneconomic. With the declining rate of ore discoveries in unexplored areas and the climbing costs of recent discoveries, the value of the mineral exploration industry is diminishing (Groves and Santosh, 2015). This study may lead to a more economical way of targeting gold deposits by studying detailed petrology results which may help quantify for future field exploration discoveries.
Geologic History of the Great Basin and Range

The Great Basin lies on the western interior of the United States with the majority of its area in the state of Nevada. The Great Basin stretches from the Snake River Plain to the north, towards the Garlock fault and the Mojave block to the south, and from the Colorado Plateau to the east towards the Sierra Nevada to the west, possessing an area of 360,000 km² (Dickinson, 2006). Precambrian basement rock in the Great Basin was formed when a series of accretionary wedges amassed along the western flank of Laurentia that caused sedimentation and a crustal genesis around an Archean continental nucleus (Dickinson, 2006). During the Mesoproterozoic, around the time of the Grenville orogeny, the western flank of Laurentia was then absorbed into the supercontinent of Rodinia (Dickinson, 2006).

Continental rifting occurred throughout the Precambrian during the Proterozoic in the Great Basin. Initial stages of rifting may have affected the basement rock of the Great Basin due to the introduction of mantle-driven magmas metamorphosing the crustal materials (Dickinson, 2006). During the Neoproterozoic, rifting caused the breakup of the Cordilleran margin which allowed for the deposition of a westward-thickening prism of miogeoclinal sediment (Dickinson, 2006). Miogeoclinal sedimentation occurred until the mid-Paleozoic, when the Roberts Mountains and Golconda allochthons formed due to eastward obduction of overthrust subduction complexes during the Antler and Sonoma orogenic events in the late Devonian to early Mississippian and late Permian respectively (Dickinson, 2006).

Due to continuing subduction of the miogeoclinal belt occurring during the mid-late Paleozoic to early Mesozoic, slab rollback caused further movement of the Roberts Mountains and Golconda allochthons towards the continental margin (Dickinson, 2006). The Roberts Mountains allochthon was eventually capped discontinuously by
nonmarine and shallow marine strata termed the Antler overlap sequence during the late Mississippian to Permian. During the Sonoma orogeny (late Permian to early Triassic), deposition of the oceanic Havallah facies capped the Antler overlap sequence through thrust faulting known as the Golconda allochthon (Dickinson, 2006).

As the semi-subducting miogeoclinal sediment prism was tilted and subducted under the Roberts Mountains allochthon, fluids contained within the sediment prism were driven updip to the east away from the zone of subduction (Dickinson, 2006). Precious metals then incorporated into the migrating fluids and were transported over long distances into the carbonate dominated basal layer of the overlying allochthon (Dickinson, 2006). Turbidite sedimentation in west-central Nevada occurred within a deep backarc basin, accompanying the evolution of the western continental-margin arc during the mid-Triassic to mid-Jurassic. At the same time, along the western flank of the basin, continuing subsidence of the basin floor was complimented by backarc extension (Stewart et al., 1997, Oldow and Bartel, 1987; Dickinson 2006). A result of the subducting oceanic Mezcalera plate between the western facing continental-margin arc of Laurentia and the accreted eastern facing intraoceanic arc lead to Mid-Jurassic arc accretion (Dickinson and Lawton, 2001a). Eastward accretion of the intraoceanic arc system caused the Pacific margin of Laurentia to open up, provoking the initial subduction of the Farallon plate (Figure 2) (Dickinson, 2006).

Backarc magmatism spread across the Great Basin to the east of the continental-margin arc-trench system during the mid to late Jurassic. This pulse of backarc magmatism came about due to slab breakoff of the subducting Mezcalera plate which is inferred to have led to the upwelling of asthenosphere and is not related to arc activity during the middle to late Jurassic (Cloos et al., 2005; Dickinson, 2006). During the early-late Cretaceous, a development of retroarc thrusting was initiated along the front of the Sevier Belt (Heller et al., 1986; Yingling and Heller, 1992; Dickinson, 2006). A divergent
Figure 2. Triassic-Jurassic paleotectonic map of the Great Basin area showing subductions and accretions of the Cordilleran magmatic arc during the mid-early Triassic. Taken from Dickinson (2006).
branch of the Sevier thrust belt lying to the west is the Eureka thrust belt of east-central Nevada formed during the Cenozoic (Bartley and Gleason, 1990; Dickinson, 2006). On a local scale, the Cretaceous Eureka thrust belt is another candidate for having induced fluid migration in the Great Basin (Dickinson, 2006).

The Great Basin has a series of mountain ranges separated by sediment filled valleys resulting from Cenozoic extensional tectonism. There are two distinguishable successive phases of extensional deformation in the Great Basin (Dickinson, 2006). The first phase of extensional deformation that occurred is the denudation of crustal basement rock in multiple core complexes of the Great Basin. Dickinson (2006) says that the erosion results from the subduction of the Farallon plate and arc magmatism of intermediate to silicic composition, indicating that the timing would have been viewed as intra-arc or backarc deformation induced by slab rollback (Dickinson, 2002; Dickinson, 2006). Mid-Cenozoic core complexes induced ductile flow of lower crust, indicating a transition from detachment faulting to block faulting. Thermomechanical break in rheological behavior of crust caused thinning and reduction of thickness in the ductile lower crust, ultimately resulting in block faulting (Harry et al., 1993; Spencer et al., 2001; Dickinson, 2006).

The more recent phase of extensional deformation occurred during the early Miocene, which is attributed to the boundary between the Pacific and North American plates of the lithosphere, known as the San Andreas transform system. Throughout the Neogene, tectonism of the Great Basin occurred in a backarc setting. The northern end of the San Andreas transform, known as the Mendocino triple junction, gradually caused the migrating magmatic arc to terminate movement westward and southward (Dickinson, 2006).
Calcareous sedimentary rocks of the Dixie Valley, Favret, Augusta Mountain, Cane Spring, and Osobb Formations form the Triassic units of the Cove Project in the Fish Creek Range (Figure 3) (Odell et al., 2014). Shallow and deep marine lithologies deposited overtop the angular unconformity of the Havallah Sequence (Golconda allochthon); creating a cyclic overlap sequence of conglomeratic clastic alluvial fans. Overlying this unconformity is the Dixie Valley ($T_{Rdv}$) Formation, which is composed of dolomitic sandstone and conglomerate material. Overlying the Dixie Valley Formation are the carbonate formations that host the mineralization in the geological area (Figure 3). At the north end of Cove, Tertiary tuffs and volcanic rocks overly the Triassic units. These Triassic units are crosscut by intrusive bodies from the southeast, the Jurassic McCoy granodiorite pluton, and the late Eocene Brown Stock (Odell et al., 2014). The Triassic units are folded into an anticline trending $S$ 44° $E$, plunging 18° $SE$, with limbs dipping approximately 25° SW and 40° NE and given the name Cove Anticline, which is home to the Helen Zone (Johnston, 2008).

The Helen Zone is located ~2,000 feet northwest of the Cove Mine open pit and hosts horizontal, bedding-replaced, disseminated, Carlin-style mineralization found in steeply dipping higher grade ore shoots (Thompson, 2013). Thompson (2013) says that the Helen Zone is divided into two sections; an upper zone hosted in the Triassic Home Station ($T_{Ras}$) decarbonatized dolostone and a lower zone hosted in the Triassic Favret ($T_{Rfv}$) limestone units of the Star Peak Group. These two formations are separated by conglomeratic terrigenous clastics which were deposited during a time of marine regression. Overlying the mineralized carbonates is a zone near the base that consists of dolomitic sandstone with a cobble rich conglomerate at the top and is known as the
Figure 3. Stratigraphic column of the Triassic units located at the McCoy-Cove-Helen Zone areas with locations of specific geologic intrusions and Ag-Au mineralization described on the left. Figure taken from Thompson (2013) which was modified from Johnston (2008).
Panther Canyon ($T_{rap}$) member (Thompson, 2013), indicating an area of reverse graded bedding.

The structural geology of the Cove deposit consists of a major anticline and three major fault groups; north-striking faults, northeast-striking faults, and northwest-striking faults (Johnston, 2008). The Lighthouse fault complex is the group composed of north-striking normal fault planes that host polymetallic veins and discontinuous dikes which tend to be brecciated by postmineral migration along the fault and dike complex. The most common fault groups in the Cove-pit are the northeast and northwest-striking normal faults. The northeast-striking faults steepen with increasing depth, from 65° to 80° dips. The northeast-striking faults also contain discontinuous dikes and are commonly found to have polymetallic vein-type ores located in their footwalls (Johnston, 2008). Johnston (2008) makes an important point that base metal veins in the hinge zone of the Cove anticline cut the Bay dike, indicating that this group of fault-dike complexes occurred prior to mineralization. The northwest-striking faults tend to be closer to true north than the northeast-striking faults and are found to not steepen with increasing depth. In addition, the northwest-striking faults tend to lack igneous dikes. The faults of the northwest-striking group are all loci of intense quartz-illite-pyrite alteration and commonly contain polymetallic veins (Johnston, 2008). Also, some of the faults in this group displace hypogene ore, indicating that they occurred as postmineral faults (Johnston, 2000; Johnston, 2008). Intersection of these fracture systems caused localized hydrothermal alteration and mineralization adjacent to fold hinges (Thompson, 2013).

Mineralization and Zone Alteration

Early Tertiary igneous activity occurred in two main magmatic pulses. The first pulse formed the central stock and related dikes at the McCoy site and consisted of oxidized
magnetite-series magma (Johnston, 2008). These intrusions of feldspar porphyry dikes and sills that extended to the Cove anticline are associated with gold mineralization (Thompson, 2013). This first pulse of mineralization produced sub-economic skarn at McCoy and was dated at ~41.5 Ma through K-Ar dating. The second pulse consisted of a reduced ilmenite-series magma that produced economic skarn ore at McCoy (Johnston, 2008). Through K-Ar dating of a K-Feldspar (adularia) the second phase of mineralization was dated at ~39 Ma (Brooks, 1994; Johnston, 2008). The late Eocene Brown Stock of McCoy and the polymetallic-vein type and Carlin-style ore of Cove are deemed coeval through 

\[ ^{40}\text{Ar} - ^{39}\text{Ar} \] dating. The driving cause for convective hydrothermal circulation at McCoy-Cove was due to heat associated with the late Eocene magmatism (Johnston, 2008).

The McCoy-pit mineralized zone consists of a gold skarn that contains minimal silver when compared to the large amount of silver found at the Cove area (Odell et al., 2014). Both McCoy and Cove are examples of prograde and retrograde alteration and mineralization is related to the time of cooling of an intrusive emplaced. McCoy pit contains the Eocene Brown Stock where skarn mineralization is hosted in limestone and clastic conglomerates. Cove is a vein dominated area with vertical breccia-hosted polymetallic gold and silver which was deposited along the margins of the McCoy skarn at a younger age (Odell et al., 2014). Illitization and silicification are associated with polymetallic vein-type and Carlin-style orebodies that occur in the vicinity of major faults. Disseminated sulfides and small anhedral masses of quartz in the Panther Canyon member of the Augusta Mountain Formation are located in the walls of polymetallic veins, commonly found in occurrence with intergrown illite and pyrite (Johnston, 2008). Occurring with these breccias located along fault lines are auriferous and manganiferous jasperoids expressed by silicification in the Smelser Pass member of the Augusta Mountain Formation. Illitization causes the dikes and lesser sills to become altered to
quartz-illite-pyrite near the location of polymetallic veins and Carlin-style orebodies. Typically, the dikes predate the occurrence of mineralization and the Carlin-style ore has the same relationship as the intrusions, which is that they both acted as aquitards to the migrating hydrothermal fluids (Johnston, 2008).

The Eocene Brown Stock intruded into fault structures and stratigraphic zones of weakness in the form of dikes and sills between 41–39 Ma (Odell et al., 2014). Deposited during this event were gold, silver, and base metal sheeted veins in brittle clastic rocks of the Dixie Valley and Panther Canyon conglomeratic formations (Odell et al., 2014). Hypogene alteration of the Cove area involves dolomitization, decalcification, minimal silicification, and sulfidation of the carbonate lithologies. In addition, alteration of clastic rocks occurred through processes of argillization, silicification, and sulfidation (Thompson, 2013). Overprinting the hypogene alteration is supergene alteration, located along important fracture sets. This alteration produced various oxides and smectite-group clays as weathering products from sulfides and illite (Thompson, 2013).

Within the Helen Zone, alteration styles of stratabound decarbonatization and decalcification are observed through passive volume loss, collapse breccia, and argillization of intrusive porphyritic granodiorite dikes and sills (Odell et al., 2014). Gold mineralization in the Home Station member of the upper Helen Zone occurs in intervals of passive replacement and collapse brecciation (Odell et al., 2014). Passive volume loss is a replacement style of gold mineralization through a process of dissolution of dolomite and crystallization of sooty, gold rich sulfides, causing a recrystallization of the adjacent dolomite into euhedral dolomite (Odell et al., 2014). The Favret Formation of the lower Helen Zone consists of a fossiliferous limestone unit near the base which is capped by calcareous shale. In the lower Helen Zone, high grade gold mineralization occurs in rhythmically-bedded limestone and calcareous mudstone located in zones where decalcification volume-loss is present in a sooty sulfide (Odell et al., 2014). Collapse
breccia occurs when volume-loss is relatively abundant and is denoted by sub-angular breccia clasts in a sooty sulfide and carbon-rich matrix. Argillized intrusive dikes and sills act as an impermeable barrier to further assist in the migration of hydrothermal fluids (Odell et al., 2014). These dikes and sills that come into contact with hydrothermal fluids can be thought of as an aquitard. Odell et al. (2014) continues to explain that these hydrothermal fluids cause alteration of feldspar crystals to illite clay, which is referred to as QSP (quartz-sericite-pyrite) alteration.

Economic grades of gold at the McCoy-Cove site consist of polymetallic vein-type ore occupying the center of the deposit site and are surrounded by an outer aureole zone of Carlin-style ore (Johnston, 2008). Three principal concentrations of ore grade gold occur in association with the generalized zoning and are found in the following assemblages: (1) native gold is found encapsulated in pyrite at the McCoy site associated with skarn ore (Brooks, 1994; Johnston, 2008); (2) as small particles of native gold and electrum at Cove hosted in polymetallic veins; and (3) as micron size concentrations of gold found in arsenian pyrite and arsenopyrite in the Carlin-style ore at Cove (Johnston, 2008). The most common assemblage that is identified in this study is the “invisible”, micron sized gold found in the prolific Carlin-style ore.
CHAPTER II
METHODS

Data were collected for twenty samples obtained from eight of Premier Gold Mines Limited’s exploratory drill holes (Figure 4) and one surface sample through the following analyses and approaches; hand sample analysis, microscopic analysis, and detailed ESEM work on thin sections. Twenty hand samples were studied and twenty existing thin sections were used to prepare petrographic reports and ESEM analyses. These samples were chosen based on their abundance of microscopic veining visible in thin section.

Petrographic Analysis

Data were collected by using a polarizing microscope with the capability of producing transmitted and reflected light in order to complete petrographic reports. Petrographic reports entail studying macroscopic and microscopic properties through the following: (1) mineral identification and their respective percentages in thin section; (2) presence of introduced fluids represented as veining and alteration textures of minerals in thin section; (3) weathering and/or alteration of minerals to other minerals; (4) petrogenesis of the rock giving details that indicate which minerals crystallized first; and (5) providing a name of the igneous rock being described through the naming convention known as the IUGS classification system.
Figure 4. Image of the Helen Zone showing the location of core holes that were drilled and used for this study. The following are drill cores used in this study: AX-16, AX-21, AX-26, AX-32, AX-35, AX-39, AX-41, and AX-42. Taken from Zoller (2014).
After finishing petrographic reports, photomicrographs of thin sections were taken in plane-polarized light (PPL) and cross-polarized light (XPL) and samples that contained veining were further studied through detailed ESEM work. Data were collected using the Quanta 200 Environmental Scanning Electron Microscope manufactured by FEI. In addition, an Energy-Dispersive X-ray Spectroscopy (EDAX) detector attachment was used in order to better understand the chemistry of the samples. Thin sections were placed onto the loading plate of the ESEM and secondary-electron images (SE) and backscatter-electron images (BSE) were taken.

Data were collected using multiple traverses across veins and into the matrix of thin sections of interest in order to identify weight percentages of Au, Ag, Pt, As, and other accessory elements associated with these precious metals. Voltage was set at 30 kV with a low vacuum setting of $6 \times 10^{-1}$ torr. The data collected from these traverses were 20 minutes long, consisted of 400 data points with a dwell time of 3000 ms, and had a spot size range of 4.5 – 6 µm using the ZAF weight percent data type. The SE and BSE images were taken at various magnifications and were used to correlate line traverses to photomicrographs so that figures may be produced accurately.
CHAPTER III
RESULTS

Ore and Metal Geochemistry

Premier Gold Mines, Ltd has provided assays that contain the data from the drill cores located at the Helen Zone and also the McCoy and Cove mining sites. The data found in this study focuses on detailed geochemistry of veins and associated gangue and differs from the whole rock assay data that was determined by Premier Gold Mines, Ltd (Table 1). The weight percents of precious metals determined in this study were found to be much greater than the assays provided by Premier Gold Mines, Ltd. Eight cores were studied for this research, specifically AX-16, AX-21, AX-26, AX-32, AX-35, AX-39, AX-41, AX-42, and one surface sample F5. Through a series of SEM-EDAX line scans, data were collected and averaged from these drill holes for specific vein and grain types (Table 2). Thirty elements were chosen for the analysis of these line scans and are found in the Appendix. Veins that are the focus of this study include sulfides, carbonates, and silicates (Table 3). Veins were analyzed for their precious metals weight percents in addition to their relative age of origin determined by petrographic analysis in order to relate them to one of two phases of mineralization ~40 Ma.

Precious metal contents located in the gangue of rock samples were also taken into account for this study (Table 4). It was found that the rock gangue of many samples included relatively similar values to the whole rock data (Table 1). When comparing gangue mineralization to vein mineralization (Table 3), we see that sulfide and carbonate
Table 1. Core sample geochemistry data from the Helen Zone based on averages of SEM-EDAX line scans compared to Premier Gold Mines (PGM) whole rock assay data.

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (ft)</th>
<th>Mean Au (%)</th>
<th>PGM Au (ppm)</th>
<th>Mean Ag (%)</th>
<th>PGM Ag (ppm)</th>
<th>Mean Pt (%)</th>
<th>Mean As (%)</th>
<th>Rock Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1281</td>
<td>0.60</td>
<td>0.07</td>
<td>0.69</td>
<td>0.25</td>
<td>0.61</td>
<td>0.26</td>
<td>Silty dolostone</td>
<td>Disseminated Py in dolomitization</td>
<td></td>
</tr>
<tr>
<td>1775</td>
<td>0.66</td>
<td>0.003</td>
<td>0.72</td>
<td>0.25</td>
<td>0.67</td>
<td>0.28</td>
<td>Silty limestone</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>AX-16</td>
<td>1847.5</td>
<td>0.57</td>
<td>0.52</td>
<td>0.25</td>
<td>0.45</td>
<td>0.21</td>
<td>Silty limestone</td>
<td>Decalcification present</td>
<td></td>
</tr>
<tr>
<td>1914</td>
<td>0.65</td>
<td>0.07</td>
<td>0.94</td>
<td>0.25</td>
<td>0.69</td>
<td>0.28</td>
<td>Limestone</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1921</td>
<td>0.76</td>
<td>0.03</td>
<td>0.68</td>
<td>0.25</td>
<td>0.73</td>
<td>0.34</td>
<td>Basalt</td>
<td>Altered olivine phenocrysts</td>
<td></td>
</tr>
<tr>
<td>1580</td>
<td>0.50</td>
<td>0.04</td>
<td>0.23</td>
<td>0.25</td>
<td>0.55</td>
<td>0.21</td>
<td>Dacite</td>
<td>Sooty sulfides; Strong alteration</td>
<td></td>
</tr>
<tr>
<td>AX-21</td>
<td>1591</td>
<td>0.58</td>
<td>0.02</td>
<td>0.59</td>
<td>0.25</td>
<td>0.60</td>
<td>Andesite</td>
<td>Sooty sulfides; Strong alteration</td>
<td></td>
</tr>
<tr>
<td>1601</td>
<td>0.73</td>
<td>0.03</td>
<td>0.22</td>
<td>0.25</td>
<td>0.73</td>
<td>0.40</td>
<td>Dacite</td>
<td>Py blebs; Strong alteration</td>
<td></td>
</tr>
<tr>
<td>1610</td>
<td>0.79</td>
<td>0.05</td>
<td>0.49</td>
<td>0.25</td>
<td>0.76</td>
<td>0.41</td>
<td>Dacite</td>
<td>Py blebs; Strong alteration</td>
<td></td>
</tr>
<tr>
<td>AX-26</td>
<td>1182</td>
<td>0.79</td>
<td>0.006</td>
<td>0.57</td>
<td>0.25</td>
<td>0.74</td>
<td>Basalt</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>AX-32</td>
<td>1248</td>
<td>0.56</td>
<td>0.003</td>
<td>0.56</td>
<td>0.25</td>
<td>0.53</td>
<td>Basalt</td>
<td>Mafic intrusion</td>
<td></td>
</tr>
<tr>
<td>AX-35</td>
<td>1795</td>
<td>0.65</td>
<td>0.007</td>
<td>0.29</td>
<td>0.25</td>
<td>0.67</td>
<td>Basalt</td>
<td>Weak argillization; Strong alteration</td>
<td></td>
</tr>
<tr>
<td>AX-39</td>
<td>2104a</td>
<td>0.62</td>
<td>0.003</td>
<td>0.98</td>
<td>0.25</td>
<td>0.64</td>
<td>Andesite - Dacite</td>
<td>Mafic intrusion</td>
<td></td>
</tr>
<tr>
<td>1536</td>
<td>0.06</td>
<td>0.54</td>
<td>0.53</td>
<td>0.25</td>
<td>0.05</td>
<td>0.03</td>
<td>Silty limestone</td>
<td>Strong decalcification</td>
<td></td>
</tr>
<tr>
<td>1888</td>
<td>0.43</td>
<td>34.21</td>
<td>0.48</td>
<td>5.90</td>
<td>0.42</td>
<td>0.22</td>
<td>Silty limestone</td>
<td>Strong decalcification; sooty sulfides</td>
<td></td>
</tr>
<tr>
<td>1958</td>
<td>0.63</td>
<td>0.54</td>
<td>0.94</td>
<td>1.3</td>
<td>0.60</td>
<td>0.32</td>
<td>Silty limestone</td>
<td>Weak decalcification; stockwork of veins</td>
<td></td>
</tr>
<tr>
<td>1963</td>
<td>0.62</td>
<td>0.10</td>
<td>1.00</td>
<td>0.25</td>
<td>0.64</td>
<td>0.25</td>
<td>Fossiliferous silty limestone</td>
<td>Moderate decalcification</td>
<td></td>
</tr>
<tr>
<td>AX-41</td>
<td>1771</td>
<td>1.82</td>
<td>0.90</td>
<td>1.00</td>
<td>1.30</td>
<td>1.45</td>
<td>Silty dolostone</td>
<td>Brecciated; disseminated sulfides in dolomitization</td>
<td></td>
</tr>
<tr>
<td>2118</td>
<td>0.55</td>
<td>0.007</td>
<td>0.35</td>
<td>0.25</td>
<td>0.57</td>
<td>0.21</td>
<td>Collapse breccia</td>
<td>Stockwork calcite veins</td>
<td></td>
</tr>
<tr>
<td>F5 1</td>
<td>0</td>
<td>0.63</td>
<td>-</td>
<td>0.85</td>
<td>-</td>
<td>0.63</td>
<td>Silty limestone</td>
<td>Surface sample from Favret Fm.</td>
<td></td>
</tr>
</tbody>
</table>

1 Not an actual core; sample was collected at surface levels.
<table>
<thead>
<tr>
<th>Core Depth (ft)</th>
<th>Vein (v) / Grain (g) Type</th>
<th>Au (%)</th>
<th>Ag (%)</th>
<th>Pt (%)</th>
<th>As (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1281</td>
<td>Ca Carbonate (v)</td>
<td>0.59</td>
<td>1.03</td>
<td>0.66</td>
<td>0.30</td>
<td>Partial decalcification throughout vein</td>
</tr>
<tr>
<td></td>
<td>FeS Sulfide (v)</td>
<td>1.07</td>
<td>1.16</td>
<td>0.81</td>
<td>0.24</td>
<td>Veinlet</td>
</tr>
<tr>
<td></td>
<td>Ca Carbonate (v)</td>
<td>1.07</td>
<td>1.16</td>
<td>0.81</td>
<td>0.24</td>
<td>Veinlet</td>
</tr>
<tr>
<td>1775</td>
<td>Ca Carbonate (v)</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>Youngest vein in this stockwork</td>
</tr>
<tr>
<td></td>
<td>FeS Sulfide (v)</td>
<td>0.77</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>Oldest vein in this stockwork</td>
</tr>
<tr>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>Exsolved chalcopyrite blebs</td>
</tr>
<tr>
<td></td>
<td>Sphalerite (g)</td>
<td>4.29</td>
<td>0.88</td>
<td>1.15</td>
<td>0.25</td>
<td>Exsolved chalcopyrite blebs</td>
</tr>
<tr>
<td>1847.5</td>
<td>Ca Carbonate (v)</td>
<td>4.41</td>
<td>0.95</td>
<td>1.27</td>
<td>0.55</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Sphalerite (g)</td>
<td>4.41</td>
<td>0.95</td>
<td>1.27</td>
<td>0.55</td>
<td>-</td>
</tr>
<tr>
<td>1914</td>
<td>Ca Carbonate (v)</td>
<td>0.74</td>
<td>1.05</td>
<td>0.66</td>
<td>0.29</td>
<td>Partial dolomitization / Moderate S replacement</td>
</tr>
<tr>
<td></td>
<td>(Ca,Mg) Carbonate (v)</td>
<td>0.64</td>
<td>0.87</td>
<td>0.67</td>
<td>0.27</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. SEM-EDAX line scans of vein and grain geochemistry data from the Helen Zone.
Table 2. SEM-EDAX line scans of vein and grain geochemistry data from the Helen Zone (continued).

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (ft)</th>
<th>Vein (v) / Grain (g) Type</th>
<th>Au (%)</th>
<th>Ag (%)</th>
<th>Pt (%)</th>
<th>As (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1580</td>
<td>Muscovite (g)</td>
<td>0.44</td>
<td>0.28</td>
<td>0.47</td>
<td>0.17</td>
<td>Strong argillization / seritization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muscovite (g)</td>
<td>0.55</td>
<td>0.22</td>
<td>0.57</td>
<td>0.24</td>
<td>Strong seritization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FeS Sulfide (v)</td>
<td>0.63</td>
<td>0.18</td>
<td>0.67</td>
<td>0.26</td>
<td>Cuts across muscovite vein</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrite (g)</td>
<td>0.62</td>
<td>0.12</td>
<td>0.60</td>
<td>0.28</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1591</td>
<td>Augite (g)</td>
<td>0.61</td>
<td>0.35</td>
<td>0.65</td>
<td>0.29</td>
<td>Strong alteration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.64</td>
<td>0.98</td>
<td>0.68</td>
<td>0.29</td>
<td>Cuts across pyroxene grain</td>
<td></td>
</tr>
<tr>
<td>AX-21</td>
<td>Muscovite (g)</td>
<td>0.74</td>
<td>0.31</td>
<td>0.71</td>
<td>0.36</td>
<td>Strong seritization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FeS Sulfide (v)</td>
<td>0.97</td>
<td>0.09</td>
<td>0.98</td>
<td>0.58</td>
<td>Strong FeS overprinting older carbonate vein</td>
<td></td>
</tr>
<tr>
<td>1601</td>
<td>Ca Carbonate (v)</td>
<td>0.87</td>
<td>0.82</td>
<td>0.82</td>
<td>0.43</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrite (g)</td>
<td>0.90</td>
<td>0.13</td>
<td>0.92</td>
<td>0.45</td>
<td>Cluster of Py grains</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FeS Sulfide (v)</td>
<td>0.84</td>
<td>0.14</td>
<td>0.98</td>
<td>0.66</td>
<td>Moderate alteration present</td>
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</tr>
<tr>
<td>1610</td>
<td>Ca Carbonate (v)</td>
<td>0.72</td>
<td>0.83</td>
<td>0.63</td>
<td>0.41</td>
<td>Older than sulfide vein</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FeS Sulfide (v)</td>
<td>0.79</td>
<td>0.35</td>
<td>0.78</td>
<td>0.48</td>
<td>Younger vein replacing edge of carbonate vein</td>
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<tr>
<td>AX-26</td>
<td>Ca Carbonate (g)</td>
<td>0.91</td>
<td>1.01</td>
<td>0.83</td>
<td>0.42</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.84</td>
<td>1.06</td>
<td>0.80</td>
<td>0.37</td>
<td>Weak dolomitization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Ca,Mg) Carbonate (g)</td>
<td>0.68</td>
<td>0.91</td>
<td>0.67</td>
<td>0.30</td>
<td>Moderate dolomitization</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. SEM-EDAX line scans of vein and grain geochemistry data from the Helen Zone (continued).

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (ft)</th>
<th>Vein (v) / Grain (g) Type</th>
<th>Au (%)</th>
<th>Ag (%)</th>
<th>Pt (%)</th>
<th>As (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX-32</td>
<td>1248</td>
<td>Bastite (g)</td>
<td>0.22</td>
<td>0.47</td>
<td>0.20</td>
<td>0.10</td>
<td>Serpentine alteration</td>
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<td>AX-35</td>
<td>1795</td>
<td>Ca Carbonate (v)</td>
<td>0.54</td>
<td>0.81</td>
<td>0.60</td>
<td>0.22</td>
<td>Weak argillization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FeS Sulfide (v)</td>
<td>0.85</td>
<td>0.08</td>
<td>0.87</td>
<td>0.41</td>
<td>Cuts across carbonate vein</td>
</tr>
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<td>2104a</td>
<td>Ca Carbonate (g)</td>
<td>0.63</td>
<td>1.05</td>
<td>0.64</td>
<td>0.26</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1536</td>
<td>Ca Carbonate (v)</td>
<td>2.18</td>
<td>2.17</td>
<td>2.02</td>
<td>0.99</td>
<td>~0.5-1 mm in width</td>
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<td>AX-41</td>
<td>1888</td>
<td>Ca Carbonate (v)</td>
<td>0.48</td>
<td>0.86</td>
<td>0.64</td>
<td>0.29</td>
<td>Old carbonate vein / sooty sulfides</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.69</td>
<td>0.90</td>
<td>0.58</td>
<td>-</td>
<td>Young carbonate vein / sooty sulfides</td>
</tr>
<tr>
<td></td>
<td>1958</td>
<td>Ca Carbonate (v)</td>
<td>0.67</td>
<td>1.06</td>
<td>0.70</td>
<td>0.28</td>
<td>Weak decalcification</td>
</tr>
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<td>1963</td>
<td>Ca Carbonate (v)</td>
<td>0.63</td>
<td>1.04</td>
<td>0.54</td>
<td>0.22</td>
<td>Youngest carbonate vein in this stockwork</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.62</td>
<td>1.07</td>
<td>0.65</td>
<td>0.26</td>
<td>Middle-aged carbonate vein in this stockwork</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.70</td>
<td>1.07</td>
<td>0.71</td>
<td>0.27</td>
<td>Oldest carbonate vein in this stockwork</td>
</tr>
<tr>
<td></td>
<td>2118</td>
<td>Silicate (v)</td>
<td>0.53</td>
<td>0.29</td>
<td>0.52</td>
<td>0.22</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyrite (g)</td>
<td>0.99</td>
<td>0.14</td>
<td>1.17</td>
<td>0.40</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.62</td>
<td>0.86</td>
<td>0.62</td>
<td>0.26</td>
<td>Oldest carbonate vein in this stockwork</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca Carbonate (v)</td>
<td>0.57</td>
<td>0.97</td>
<td>0.63</td>
<td>0.25</td>
<td>Youngest carbonate veins in this stockwork</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sphalerite (g)</td>
<td>2.21</td>
<td>0.27</td>
<td>0.77</td>
<td>0.45</td>
<td>2-4 µm size grain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca Carbonate (g)</td>
<td>0.55</td>
<td>0.95</td>
<td>0.61</td>
<td>0.21</td>
<td>Included in silicate vein</td>
</tr>
</tbody>
</table>
Table 3. SEM-EDAX line scans mean vein and grain data from the Helen Zone.

<table>
<thead>
<tr>
<th>Vein (v) / Grain (g) Type</th>
<th>Mean Au (%)</th>
<th>Mean Ag (%)</th>
<th>Mean Pt (%)</th>
<th>Mean As (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfide(^1) (v)</td>
<td>0.80</td>
<td>0.22</td>
<td>0.87</td>
<td>0.45</td>
</tr>
<tr>
<td>Carbonate(^2) (v)</td>
<td>0.68</td>
<td>0.98</td>
<td>0.67</td>
<td>0.28</td>
</tr>
<tr>
<td>Silicate (v)</td>
<td>0.52</td>
<td>0.29</td>
<td>0.51</td>
<td>0.20</td>
</tr>
<tr>
<td>Pyrite (g)</td>
<td>0.84</td>
<td>0.13</td>
<td>0.89</td>
<td>0.38</td>
</tr>
<tr>
<td>Sphalerite (g)</td>
<td>4.35</td>
<td>0.91</td>
<td>1.21</td>
<td>0.40</td>
</tr>
<tr>
<td>Calcite (g)</td>
<td>0.70</td>
<td>1.00</td>
<td>0.69</td>
<td>0.29</td>
</tr>
<tr>
<td>Dolomite(^3) (g)</td>
<td>0.68</td>
<td>0.91</td>
<td>0.67</td>
<td>0.30</td>
</tr>
<tr>
<td>Muscovite (g)</td>
<td>0.58</td>
<td>0.27</td>
<td>0.59</td>
<td>0.25</td>
</tr>
<tr>
<td>Bastite(^3) (g)</td>
<td>0.22</td>
<td>0.47</td>
<td>0.20</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\(^1\) Sulfide vein phases are dominantly pyrite
\(^2\) Carbonate vein phases are dominantly calcite and dolomite
\(^3\) Data available for only 1 grain
Table 4. Rock matrix/gangue geochemistry data from the Helen Zone based on SEM-EDAX line scans.

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (ft)</th>
<th>Mean Au (%)</th>
<th>Mean Ag (%)</th>
<th>Mean Pt (%)</th>
<th>Mean As (%)</th>
<th>Rock Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX-16</td>
<td>1281</td>
<td>0.62</td>
<td>0.91</td>
<td>0.64</td>
<td>0.26</td>
<td>Silty dolostone</td>
<td>Disseminated Py in dolomitization</td>
</tr>
<tr>
<td></td>
<td>1775</td>
<td>0.66</td>
<td>0.72</td>
<td>0.66</td>
<td>0.28</td>
<td>Silty limestone</td>
<td>-</td>
</tr>
<tr>
<td>AX-21</td>
<td>1847.5</td>
<td>0.33</td>
<td>0.28</td>
<td>0.22</td>
<td>0.11</td>
<td>Silty limestone</td>
<td>Decalcification present</td>
</tr>
<tr>
<td></td>
<td>1914</td>
<td>0.64</td>
<td>0.94</td>
<td>0.70</td>
<td>0.28</td>
<td>Limestone</td>
<td>-</td>
</tr>
<tr>
<td>AX-21</td>
<td>1921</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Basalt</td>
<td>No matrix data available</td>
</tr>
<tr>
<td>AX-21</td>
<td>1580</td>
<td>0.40</td>
<td>0.27</td>
<td>0.40</td>
<td>0.16</td>
<td>Dacite</td>
<td>Sooty sulfides; Strong alteration</td>
</tr>
<tr>
<td>AX-21</td>
<td>1591</td>
<td>0.42</td>
<td>0.23</td>
<td>0.44</td>
<td>0.17</td>
<td>Andesite</td>
<td>Sooty sulfides; Strong alteration</td>
</tr>
<tr>
<td>AX-21</td>
<td>1601</td>
<td>0.59</td>
<td>0.35</td>
<td>0.54</td>
<td>0.28</td>
<td>Dacite</td>
<td>Py blebs; Strong alteration</td>
</tr>
<tr>
<td>AX-21</td>
<td>1610</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Dacite</td>
<td>No matrix data available</td>
</tr>
<tr>
<td>AX-26</td>
<td>1182</td>
<td>0.80</td>
<td>0.24</td>
<td>0.73</td>
<td>0.38</td>
<td>Basalt</td>
<td>-</td>
</tr>
<tr>
<td>AX-32</td>
<td>1248</td>
<td>0.28</td>
<td>0.44</td>
<td>0.28</td>
<td>0.12</td>
<td>Basalt</td>
<td>Mafic intrusion</td>
</tr>
<tr>
<td>AX-35</td>
<td>1795</td>
<td>0.62</td>
<td>0.30</td>
<td>0.64</td>
<td>0.28</td>
<td>Basalt</td>
<td>Weak argillization; Strong alteration</td>
</tr>
<tr>
<td>AX-39</td>
<td>2104a</td>
<td>0.59</td>
<td>0.51</td>
<td>0.66</td>
<td>0.24</td>
<td>Andesite - Dacite</td>
<td>Mafic intrusion</td>
</tr>
<tr>
<td>AX-41</td>
<td>1536</td>
<td>0.08</td>
<td>0.28</td>
<td>0.08</td>
<td>0.04</td>
<td>Silty limestone</td>
<td>Strong decalcification</td>
</tr>
<tr>
<td>AX-41</td>
<td>1888</td>
<td>0.46</td>
<td>0.48</td>
<td>0.45</td>
<td>0.23</td>
<td>Silty limestone</td>
<td>Strong decalcification; sooty sulfides</td>
</tr>
<tr>
<td>AX-41</td>
<td>1958</td>
<td>0.59</td>
<td>0.82</td>
<td>0.61</td>
<td>0.26</td>
<td>Silty limestone</td>
<td>Weak decalcification; stockwork of veins</td>
</tr>
<tr>
<td>AX-41</td>
<td>1963</td>
<td>0.62</td>
<td>0.98</td>
<td>0.64</td>
<td>0.25</td>
<td>Fossiliferous silty limestone</td>
<td>Moderate decalcification</td>
</tr>
<tr>
<td>AX-42</td>
<td>1771</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Silty dolostone</td>
<td>No matrix data available</td>
</tr>
<tr>
<td>AX-42</td>
<td>2118</td>
<td>0.53</td>
<td>0.31</td>
<td>0.56</td>
<td>0.21</td>
<td>Collapse breccia</td>
<td>Stockwork calcite veins</td>
</tr>
<tr>
<td>F5</td>
<td>0</td>
<td>0.63</td>
<td>0.85</td>
<td>0.63</td>
<td>0.25</td>
<td>Silty limestone</td>
<td>Surface sample from Favret Fm.</td>
</tr>
</tbody>
</table>

1 Not an actual core; sample was collected at surface levels
veins contain higher concentrations of Au and Pt. In addition, sulfide grains (pyrite and sphalerite) were recorded to have higher concentrations of Au when compared to the rock gangue. Values of Ag found in carbonate veins and grains contain higher concentrations when compared to the matrix of the rock. Gangue mineralization is still considered to host Au, although precious metal concentrations recorded from vein-types were determined to be greater than the surrounding rock gangue.

Petrographic Analysis

Twenty samples collected from eight cores and one surface sample were chosen for petrographic analysis using a polarizing microscope with both transmitted and reflected light. Sample selection was based on the amount of veining present in thin sections in addition to cross-cutting relationships between vein-types. Petrographic reports were completed to analyze rock type, vein-type, alterations of certain minerals, identification of minerals, cross-cutting relationships of veins, and inclusions of specific mineral grains. The rule of inclusions and cross-cutting relationships aid in the determination of relative age for vein-types and mineral grains. The following samples were chosen for this study and are labeled by core number and its specific depth (ft) from the surface.

Sample AX-16 1281 is silty dolostone from the Home Station (T_Rahb) member of the Augusta Mountain Formation and is located in the upper Helen Zone. This sample is fine grained and is strongly dolomitized with disseminated pyrite occurring throughout the entire sample. A series of veining is present in which a carbonate vein is cross-cut by a sulfide vein being overprinted by a silicate vein which causes displacement in the earlier carbonate vein (Figure 5). The carbonate vein in this stockwork contains dolomite and shows strong decarbonatization and silica replacement. Mean gold content of veins occurring in this sample range from 0.55-0.59 wt. % Au.
Figure 5. Photomicrograph of sample AX-16 1281 showing a series of veining. Here a carbonate vein is cross-cut by a sulfide vein that was overprinted by a later silicate vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Sample AX-16 1775 is silty limestone that is found in the Favret (T_{Rfv}) Formation which is located in the lower Helen Zone. This sample is fine grained and shows moderate decalcification with disseminated sulfides throughout the entire sample. Carbonate and sulfide veins are 10 - 50 µm in width; a carbonate vein is cross-cut by a later sulfide vein causing about 20 µm of displacement in the carbonate vein (Figure 6). Mean gold concentration of veins occurring in this sample range from 0.75-1.07 wt. % Au.

Sample AX-16 1847.5 is silty limestone that is found in the T_{Rfv} located in the lower Helen Zone. This sample is fine to medium grained, shows moderate decalcification, and carbonate, sulfide, and silicate veins are present. Primary minerals in this rock are calcite, quartz, and pyrite with trace amounts of sphalerite, muscovite, and biotite. Late forming silicate and carbonate veins are found in this sample that cross-cut the fabric of the rock (Figure 7). A large pyrite vein is cross-cut by a large (1 mm in width), later quartz vein. A later carbonate vein is found cross-cutting the previous silicate vein and continues into the gangue of the rock. Found along the edges of this silicate vein are two grains of subhedral sphalerite that contain exsolved chalcopyrite. Mean gold content in sphalerite grains range from 4.29-4.41 wt. % Au. Mean gold concentration of veins occurring in this sample range from 0.42-0.77 wt. % Au.

Sample AX-16 1914 is limestone that is found in the T_{Rfv} located in the lower Helen Zone. The primary mineral in this sample is calcite with accessory amounts of quartz. Carbonate veining is present in this sample and some carbonate veins are overprinted by later sulfide veining (Figure 8). Partial dolomitization and moderate sulfur replacement is present in this sample. Mean gold concentration of veins occurring in this sample range from 0.64-0.74 wt. % Au.

Sample AX-16 1921 is porphyritic basalt that contains fine to medium grained phenocrysts of bastite and olivine. The ground mass of the rock is dominated by trachytic
Figure 6. Photomicrograph of sample AX-16 1775 showing a carbonate vein being cross-cut by a later sulfide vein causing minor displacement. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 7. Photomicrograph of sample AX-16 1847.5 showing a series of cross-cutting relationships. An early sulfide vein is being cross-cut by a silicate vein which is being cross-cut by a later carbonate vein. Sphalerite (Sp) grains are present and occur alongside the quartz vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 8. Photomicrograph of sample AX-16 1914 with a carbonate vein being overprinted by later sulfides. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
anorthite and accessory amounts of augite. Late forming carbonate veins are present in this sample that cross-cut clinopyroxenes (Figure 9). Bastite and olivine grains in this sample are heavily altered. Mean gold content of veins in this sample are high grade.

Sample AX-21 1580 is fine grained dacite that is found near the upper contact of the T

Sample AX-21 1580 is fine grained dacite that is found near the upper contact of the T

Sample AX-21 1591 is fine grained andesite that is heavily altered and is found in the T

Sample AX-21 1591 is fine grained andesite that is heavily altered and is found in the T

Sample AX-21 1601 is fine grained dacite that is found in the T

Sample AX-21 1601 is fine grained dacite that is found in the T

Sample AX-21 1610 is fine grained dacite that is found in the T

Sample AX-21 1610 is fine grained dacite that is found in the T
Figure 9. Photomicrograph of sample AX-16 1921 showing carbonate veins cross-cutting clinopyroxenes (CPX) grains. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 10. Photomicrograph of sample AX-21 1580 showing a sulfide vein cross-cutting a muscovite grain that has been altered. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 11. Photomicrograph of sample AX-21 1591 showing a euhedral pyroxene grain that has been heavily altered and is being cross-cut by a carbonate vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 12. Photomicrograph of sample AX-21 1601 showing muscovite (Ms) grains that have been moderately altered to a more clay-rich composition. Also shown here, late forming carbonate veins are being overprinted by later sulfide veins. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
forming carbonate veins are found being overprinted by younger sulfide veins (Figure 13). Mean gold concentration of veins in this sample range from 0.72-0.79 wt. % Au.

Sample AX-26 1182 is porphyritic basalt that has fine to medium grained phenocrysts of pyroxene, calcite, and dolomite. Primary minerals are anorthite and clinopyroxenes with accessory amounts of alteration products of calcite and dolomite. Late calcite veining is present and is located adjacent to a dolomite grain and shows weak dolomitization (Figure 14). Mean gold concentration of veins in this sample are 0.84 wt. % Au.

Sample AX-32 1248 is porphyritic basalt that contains fine to medium grained phenocrysts of bastite and altered olivines. The primary minerals are found in the gangue of this porphyritic basalt as anorthite and augite. Anorthite crystals in many spots of this sample show a trachytic texture. Late carbonate veining is present and is shown cross-cutting an altered bastite grain (Figure 15). Accessory minerals include calcite and disseminated pyrite.

Sample AX-35 1795 is basalt that contains very fine grains of anorthite and pyroxenes. Primary minerals include anorthite and pyroxenes with accessory amounts of calcite and disseminated pyrite. Carbonate veining is cross-cut by later patchy sulfide veining (Figure 16). No offsetting of the carbonate vein is present. Mean gold content of these veins range from 0.54-0.85 wt. % Au.

Sample AX-41 1536 is silty limestone from T_{Rfv} located in the lower Helen Zone. This sample is fine to medium grained silt with primary mineral phases of calcite and quartz. Accessory minerals include pyrite and muscovite. In addition, this sample shows strong decalcification and is rich in clay minerals. A late carbonate vein is present in this sample and is about 0.5 to 1 mm thick (Figure 17). Mean gold content of veins in this sample are 2.18 wt. % Au.
Figure 13. BSE image of sample AX-21 1610 showing a carbonate vein being overprinted by later sulfides.
Figure 14. Photomicrograph of sample AX-26 1182 showing a calcite (Cal) grain located adjacent to a carbonate vein and dolomite (Dol) grain. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 15. Photomicrograph of sample AX-32 1248 showing an altered bastite grain being cross-cut by a carbonate vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 16. Photomicrograph of sample AX-35 1795 showing a carbonate vein being cross-cut by a later patchy sulfide vein. Anorthite and pyroxenes make up the gangue material. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 17. Photomicrograph of sample AX-41 1536 showing a thick (0.5 – 1mm) carbonate vein cutting across the silty fabric of this rock. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Sample AX-41 1888 is silty limestone from the T\textsubscript{Rfv}. This sample is fine to medium grained silt composed of calcite and quartz. Accessory amounts of disseminated pyrite are present and the sample shows strong decalcification. Late carbonate veining is present and can be seen by two separate carbonate veins with cross-cutting relationships (Figure 18). Mean gold content of veins in this sample range from 0.48-0.69 wt. % Au.

Sample AX-41 1958 is silty limestone from the lower Helen Zone in the T\textsubscript{Rfv}. This sample is fine to medium grained silt and consists of mostly calcite, quartz, and altered clay minerals. This sample shows weak decalcification and contains disseminated pyrite. Multiple late stages of veining occur and are very complex when trying to figure out the relative dating of these veins. Carbonate veins are found cross-cutting sulfide veins and different sulfide veins are found cross-cutting different carbonate veins in this sample (Figure 19). The youngest stage of veining is a sulfide vein cross-cutting the fabric of the entire rock. Mean gold contents for the carbonate vein in this sample is 0.67 wt. % Au. Mean gold content for the sulfide veins are unavailable.

Sample AX-41 1963 is silty limestone with minor fossils present and is located in the T\textsubscript{Rfv} Formation of the lower Helen Zone. This sample has moderate amounts of decalcification and contains fine to medium grained silt. Primary minerals in this sample are calcite and quartz with trace amounts of pyrite. Carbonate veins are present in this sample and are found cross-cutting each other creating displacement in one of the veins (Figure 20). Mean gold content in these carbonate veins range from 0.62-0.70 wt. % Au.

Sample AX-42 1771 is silty dolostone found in the T\textsubscript{Rfv} Formation of the lower Helen Zone. Primary minerals include calcite, dolomite, and quartz. Accessory minerals include disseminated pyrite. This sample contains brecciated clasts and late cross-cutting carbonate veins are present. Later sulfide veins are found cross-cutting the earlier carbonate veins in this sample (Figure 21).
Figure 18. Photomicrograph of sample AX-41 1888 showing late carbonate veins cross-cutting each other and causing minor displacement. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 19. Photomicrograph of sample AX-41 1958 showing multiple cross-cutting relationships that occur between different sulfide and carbonate veins. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 20. Photomicrograph of sample AX-41 1963 with carbonate veins cross-cutting each other and causing displacement. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 21. Photomicrograph of sample AX-42 1771 showing carbonate veins being cross-cut by later sulfide veins in a silty dolostone matrix. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Sample AX-42 2118 is collapse breccia from the lower Helen Zone located in the T_{Rfv} Formation. This sample consists of a fine grained matrix and has angular clasts with very poor sorting. Primary mineral phases for clasts are quartz and calcite fragments. Accessory minerals include pyrite with trace amounts of sphalerite, alkali feldspar, and plagioclase. Late forming carbonate veins are found in a stockwork and are cross-cut by a later silicate vein (Figure 22). Located further down the thin section, the same silicate vein is seen cross-cut by later carbonate veins and causes minor displacement in the silicate vein (Figure 23). Pyrite grains are found included in the later forming silicate vein. Mean gold content in these veins range from 0.53-0.62 wt. % Au.

Sample F5 is an unaltered surface sample collected from the TRfv and is a silty limestone. Primary minerals are calcite and quartz with trace amounts of pyrite and muscovite. Late calcite veining is present and accessory amounts of fossils can be found in the sample. Mean gold content for vein data is not available.

Vein Type Comparison

Data collected in this study were based on selective veins that were chosen through petrographic analysis which was based on cross-cutting relationships and the amount of veining present in thin sections. The Helen Zone is separated into two sections, the upper and lower Helen Zones namely. The upper Helen Zone is hosted in the Home Station (T_{Ras}) dolostone and the lower Helen Zone is dominated by Favret (T_{Rfv}) limestone (Thompson, 2013). In addition to carbonate units, there are also igneous units present in the Helen Zone. The igneous units are divided into two sections, the first being a mafic zone that ranges from basalts to foidites and the second being an intermediate zone that ranges from andesites to dacites (Zoller, 2014). The most common vein-types found in
Figure 22. Photomicrograph of sample AX-42 2118 with a grain of pyrite (Py) found included in a silicate vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 23. Photomicrograph of sample AX-42 2118 with a silicate vein being cross-cut by later carbonate veins in addition to showing carbonate replacement occurring in the silicate vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
the samples from the Helen Zone were carbonates. Sulfide and silicate veins were not as commonly found throughout the available samples.

Carbonate Veins

Twenty carbonate veins were studied for this research, all of which varied in size from a few microns to ~3 mm. Data that corresponds to carbonate veins on average consists of 0.68 wt. % Au, 0.98 wt. % Ag, 0.67 wt. % Pt, and 0.28 wt. % As (Table 3). Carbonate veins were found to retain higher concentrations of Ag than sulfide and silicate veins. Carbonate veins were also found to have less Au, Pt, and As than sulfide veins, but more Au, Pt, and As than silicate veins. After extensive petrographic analysis, it was found that carbonate veins cross-cut both sulfide, silicate, and other carbonate veins.

Sulfide Veins

Seven sulfide veins were studied for this research with multiple line traverses taken across the veins (Figure 24). Data that corresponds to sulfide veins on average consists of 0.80 wt. % Au, 0.22 wt. % Ag, 0.87 wt. % Pt, and 0.45 wt. % As (Table 3). Sulfide veins were found to retain higher concentrations of Au, Pt, and As than carbonate and silicate veins. Sulfide veins were also found to have less Ag than carbonate and silicate veins. Sulfide veins were typically found being cross-cut by carbonate and silicate veins, but not in every sample (Figure 21).

Silicate Veins

Four silicate veins were studied for this research with multiple line traverses taken across the veins. Data that corresponds to silicate veins on average consists of 0.52 wt. % Au, 0.29 wt. % Ag, 0.51 wt. % Pt, and 0.20 wt. % As (Table 3). Silicate veins were found to contain lower concentrations of Au, Pt, and As than carbonate and sulfide veins.
Figure 24. Photomicrograph of sample AX-42 2118 showing a line scan that was taken from A to A’ that goes across a series of silicate and carbonate veining. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Silicate veins were also found to retain higher concentrations of Ag than sulfide veins, but not as much Ag as carbonate veins. Silicate veins are typically found cross-cutting carbonate and sulfide veins, but in some samples this is not true (Figure 23).

Grain Type Comparison

Data collected in this study for certain grains that couldn’t be identified by petrographic analysis was done by using the SEM-EDAX line scans. Mineral grains that were tested were pyrite, sphalerite, calcite, dolomite, muscovite, and bastite. Some of the data for certain grains were tested only once and are annotated in Table 3. Grains that were analyzed ranged from inclusions in veins to being located in the gangue of the rock, with sulfide grains typically showing up as being disseminated whereas other grain-types do not (Figure 25). Grain data was also compared to vein data to see if there are any similarities between the two (Table 3).

Pyrite

Three pyrite grains were analyzed with the SEM-EDAX and consisted of 0.84 wt. % Au, 0.13 wt. % Ag, 0.89 wt. % Pt, and 0.38 wt. % As (Table 3). The three grains of pyrite that were tested here were inclusions instead of disseminated pyrite grains. One grain of euhedral pyrite from core AX-42 2118 is found included in a silicate vein (Figures 22). Another series of pyrite grains that were averaged for one grain of pyrite is found in core AX-21 1601 (Figure 26). Pyrite grain data matches the data of pyrite veins and carry the most Au between all other grain types with the exception of sphalerite grains. Pyrite grains on average consist of 0.38 wt. % As at the Helen Zone. The grains do not display strong As-rimming, unlike the pyrite grains at McCoy-Cove which are found containing higher wt. % As and more prominent As-rimming.
Figure 25. BSE image of sample AX-16 1847.5 showing disseminated pyrite throughout the matrix of the rock found along the right side of the image.
Figure 26. Photomicrograph of sample AX-21 1601 showing non-disseminated pyrite grains occurring in the matrix of the rock adjacent to a pyrite vein. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Sphalerite

Three sphalerite grains were analyzed in this study and showed that unusually high grade gold is present. Two grains of subhedral sphalerite contain exsolved chalcopyrite, also known as “chalcopyrite disease” (Figure 27). Sphalerite grains on average consisted of 4.35 wt. % Au, 0.91 wt. % Ag, 1.21 wt. % Pt, and 0.40 wt. % As (Table 3). Two grains of sphalerite from core AX-16 1847.5 were about 200 µm in size and consistently had high grades of gold (4.29-4.41 wt. % Au) throughout the entire length of the grain (Figure 27). One grain of sphalerite from core AX-42 2118 was two to four microns in size contained 2.21 wt. % Au. In addition to precious metal concentrations of Au, Ag, and Pt, these mineral grains are abundant in zinc (Zn), sulfur (S), and accessory (<5%) amounts of iron (Fe) and copper (Cu).

Calcite

Three calcite grains located adjacent to veins were analyzed in this study and consisted of 0.70 wt. % Au, 1.00 wt. % Ag, 0.69 wt. % Pt, and 0.29 wt. % As (Table 3). Calcite grains are found in samples AX-26 1182, AX-39 2104a, and AX-42 2118 (Table 2). One example of a calcite grain is shown adjacent next to a carbonate vein in sample AX-26 1182 (Figure 14). Calcite grains, like pyrite grains, are found to have very similar metal percentages to its vein-like counterparts. Calcite grains are found to have the most Ag out of all other grain types with the exception of sphalerite grains.

Dolomite

Data was only available for one dolomite grain from core AX-26 1182 and consists of 0.68 wt. % Au, 0.91 wt. % Ag, 0.67 wt. % Pt, and 0.30 wt. % As (Table 3). Dolomite is found to have similar values of metal percentages compared to calcite veins and
Figure 27. Photomicrograph of sample AX-16 1847.5 with subhedral sphalerites (Sp) displaying exsolved chalcopyrite (Ccp) throughout the grain. Disseminated pyrite (Py) is present. Images are shown in reflected light.
calcite grains. Sample AX-26 1182 has a grain of calcite that has slightly undergone dolomitization (Figure 14).

Muscovite

Three muscovite grains were analyzed in this study and consisted of 0.58 wt. % Au, 0.27 wt. % Ag, 0.59 wt. % Pt, and 0.25 wt. % As (Table 3). Muscovite grains are found in samples AX-21 1580 and AX-21 1601 which are both classified as dacites. These muscovite grains appear in the igneous suites and have undergone moderate to strong argillization (Figure 12). Muscovite grains have the lowest concentration of Ag when compared to all other grains with the exception of pyrite grains.

Bastite

Data was only available for one bastite grain and consisted of 0.22 wt. % Au, 0.47 wt. % Ag, 0.20 wt. % Pt, and 0.10 wt. % As (Table 3). Data for this bastite grain came from core AX-32 1248, which is cross cut by a calcite vein (Figure 15). Bastite is an altered mineral that originates from the serpentine family. Bastite was also found to have the least amount of Au, Pt, and As out of all the grains tested in this study.

Carbonate Ternary Plots

Fifty line scans from the SEM-EDAX were used to categorize all samples that were analyzed in order to find the average carbonate mineral-types found in these Triassic units. After plotting the data on the Ca-Mg-Mn ternary diagram, the dominant carbonate mineral-types were calcite and dolomite with trace amounts of rhodochrosite and magnesite (Figure 28). When plotting the data on the Ca-Mg-Fe ternary diagram, the
Figure 28. Ca-Mg-Mn ternary plot showing carbonate mineral phases collected from mole proportions from whole rock data samples. Orange circles are silty limestones, blue circles are silty dolostones, purple circles are collapse breccias, green circles are fossiliferous silty limestones, and red circles are limestones.
same results appear; dominant mineral-types of calcite and some dolomite found with trace amounts of magnesite, siderite, and ankerite (Figure 29).

Energy Dispersive X-Ray Analysis

Twenty-one polished thin sections were chosen for energy dispersive X-Ray analysis (EDAX) in order to identify weight percent of precious metals, vein-type elements, and other accessory elements that can be found in the Appendix. Seventy-four line scans were taken over the period of this study and spot scans were also used to help aid in the elemental identification of certain mineral grains and veins. Line scans were used to draw across veins and grains of interest and even into the gangue of the rock in order to better understand the geochemistry of samples. Gold in this study is of Carlin-style, therefore it is micron size and is difficult to identify without using the EDAX detector. Dot maps were created with this data to help aid in element correlation with precious metals of Au, Ag, and Pt.

A line scan denoted from A to A’ from sample AX-16 1847.5 (Figure 30), where a sulfide vein was cross-cut by a later carbonate vein which was then cross-cut by an even later silicate vein. A dot map has been created and data shows peaks of Ca that correlate with peaks of Ag (Figures 31 and 32). In this same dot map, Fe and S peaks are found to be correlated with peaks of Au and Pt.

Another line scan from the same sample AX-16 1847.5 shows a silicate vein being cross-cut by three carbonate veinlets (Figure 33). A dot map has been created and data shows for the line scan from A to A’ that peaks of Si do not correlate to peaks of any of the four metals analyzed in this study (Figures 34 and 35).
Figure 29. Ca-Mg-Fe ternary plot showing carbonate mineral phases collected from mole proportions from whole rock data samples. Orange circles are silty limestones, blue circles are silty dolostones, purple circles are collapse breccias, green circles are fossiliferous silty limestones, and red circles are limestones.
Figure 30. BSE image of sample AX-16 1847.5 showing a line scan that was taken from A to A’ that starts in a carbonate vein and then goes across a sulfide vein.
Figure 31. Line scan of sample AX-16 1847.5 showing precious metals data gathered from line A (point 0) to A’ (point 400) found in Figure 30. Gold diamonds are Au, red squares are Ag, teal triangles are Pt, and purple circles are As. Ca carbonate veining is present from points 0-260 and FeS sulfide veining is present from points 261-400.
Figure 32. Line scan of sample AX-16 1847.5 showing vein type data gathered from line A (point 0) to A' (point 400) found in Figure 30. Blue diamonds are S, red squares are Fe, green triangles are Si, and purple circles are Ca. Ca carbonate veining is present from points 0-260 and FeS sulfide veining is present from points 261-400.
Figure 33. Photomicrograph of sample AX-16 1847.5 showing a line scan that was taken from A to A’ that starts in a silicate vein and then goes across three Ca carbonate veinlets. Top photo: image shown in PPL. Bottom photo: image shown in XPL.
Figure 34. Line scan of sample AX-16 1847.5 showing precious metals data gathered from line A (point 0) to A’ (point 400) found in Figure 33. Gold diamonds are Au, red squares are Ag, teal triangles are Pt, and purple circles are As. Silicate veining is present from points 0-70, 80-170, 180-255, and 260-400. Ca carbonate veining is present from points 71-79, 171-179, and 256-259.
Figure 35. Line scan of sample AX-16 1847.5 showing vein type data gathered from line A (point 0) to A’ (point 400) found in Figure 33. Blue diamonds are S, red squares are Fe, green triangles are Si, and purple circles are Ca. Silicate veining is present from points 0-70, 80-170, 180-255, and 260-400. Ca carbonate veining is present from points 71-79, 171-179, and 256-259.
CHAPTER IV
DISCUSSION

Origin of Mineralization

The Helen Zone is still fairly unknown and ongoing research is being done on the area to better understand the origin of dikes, sills, veins, and major intrusions that could have caused the economic mineralization that we see today. Two major pulses of mineralization occurred in the late Eocene; one ~41.5 Ma that is believed to create the Brown stock intrusion and a second ~39 Ma that formed an economic Au-skarn deposit (Brooks, 1994; Johnston, 2008). Brooks (1994) dated the economic Au-skarn deposit to be ~39 Ma through K-Ar dating of adularia. In addition, Brooks also dated a biotite grain from an intrusion through K-Ar dating and found that it was ~38 Ma, restricting the timing of the mineralization of the McCoy area between these time periods.

In order to determine the relative age of veining in this study, cross-cutting relationships and the rule of inclusions were used to get a better understanding on the origin of mineralization at the Helen Zone area. Generally, sulfide veins were found to be older than carbonate and silicate veins. However, this is not the case in every sample. Fluid inclusion data for sulfide (pyrite) veins ranged between ~200-430°C with salinities up to ~35 eq. wt. % NaCl (Brooks, 1994). Sample AX-42 1771 shows a series of carbonate veinlets being cross-cut by a later sulfide vein, indicating that the carbonate veins were emplaced before the sulfide vein (Figure 21). In addition, sulfide veins would
show an overprinting property along carbonate vein-types, indicating that the sulfide overprinting occurred last in the sequence of fluid emplacement (Figure 8).

Carbonate veins were the most common type of veining seen in samples from the Helen Zone. In this study twenty carbonate veins were analyzed and all of the carbonate minerals identified included calcite and dolomite. Carbonate veins are typically found cross-cutting sulfide veins and being cross-cut by silicate veins, indicating that carbonate veins would be older than silicate veins but younger than most sulfide veins. Again, this is not the case in every sample and carbonate veins are difficult to date relatively. Calcite bearing fluids will generally deposit at ~330°C with salinities ranging from 19-33 eq. wt. % NaCl (Brooks, 1994). Because sulfide fluids can be emplaced over a much broader range of temperatures; it is possible for carbonate veins to be the oldest and/or youngest veins in some cases.

Silicate (quartz) veins were the least common type of veining seen in the Helen Zone and can be attributed to the fact that so much alteration has taken place. Four quartz veins were analyzed in this research and were found to typically be the youngest out of all three vein-types looked at for this study. Homogenization temperatures for quartz veins taken from fluid inclusions were ~320°C and salinities were found to be as low as ~11 eq. wt. % NaCl (Brooks, 1994). Because calcite and quartz veins are deposited at a relatively similar temperature it is possible that they may have been contemporaneous.

The origins for Au bearing fluids are thought to have come from one of two main magmatic pulses during the late Eocene. The first one, a magnetite-bearing pulse, from a prograde event that occurred at McCoy ~41.5 Ma with data from fluid inclusions of garnet and pyroxene with temperatures at ~330°-600°C and salinities as high as ~40 eq. wt. % NaCl (Brooks, 1994). A second ilmenite-bearing pulse that took place from a retrograde event ~39 Ma had lower temperatures (~360°-450°C) and salinities as low as ~11 eq. wt. % NaCl taken from fluid inclusion data of epidote (Brooks, 1994). Both of
these intrusions are what is believed to have caused the economic mineralization that we see today (Figure 36).

When looking at the structural geology of the Helen Zone area, we see many faults and fractures that would have aided the transport of fluids in depositing Au and other precious metals (Figure 37). The Helen Zone is located along the northwest nose of the gently southeast plunging Cove anticline. The late Eocene intrusions are found cross-cutting many southwest-northeast striking, northwest dipping normal faults (Figure 38). The location of faults and fractures present appear to have played a significant role in controlling the deposition of mineralized fluids at the McCoy-Cove and Helen Zone areas (Johnston, 2008).

Helen Zone Geochemistry

Carlin-type Au deposits are emplaced by a late bisulfide fluid complex that has the capability to mobilize Au in solution (Odell et al., 2014). This Au-bisulfide complex \([\text{Au(HS)}_2^-]\) is accompanied by sulfur-rich hydrothermal fluids and mobilizes at <350°C around a neutral pH with concentrations of reduced sulfur between \(10^{-3}\) and \(10^{-2}\) mol/kg \(\text{H}_2\text{S}\) (Hannington and Scott, 1989). Au will remain in solution until \(~200^\circ\text{C}\) and then precipitation will occur from the oxidation of \(\text{H}_2\text{S}\) (Hannington and Scott, 1989). Fluid mixing and oxidation of the ore fluid causes the Au-bisulfide complex to be destroyed, allowing for the deposition of Au into the host carbonate rocks (Hofstra et al., 1991). As Au is mobilized and travels through faults and fractures, instantaneous drops in pressure and/or temperature can also cause Au to drop out of solution (Odell et al., 2014). When looking at differences between vein and grain mineral phases, we see that sulfides carry the highest concentrations of Au (Table 3). Because Au remains in \([\text{Au(HS)}_2^-]\) solutions until \(~200^\circ\text{C}\) and the fact that sulfide vein temperatures were found
Figure 36. Geologic model displaying prograde and retrograde mineralization. (A) Early-middle Eocene cross-section of McCoy-Cove looking NW. (B) Phase 1 intrusions and sub-economic mineralization at McCoy-Cove. (C) Phase 2 intrusions and economic mineralization at McCoy-Cove. (D) Pre-mining cross section for McCoy-Cove. Taken from Johnston et al. (2008).
Figure 37. Geologic map displaying the structural geology of the McCoy-Cove-Helen Zone areas. Taken from Johnston et al. (2008).
Figure 38. Geologic cross-section displaying stratigraphic units and northeast striking normal faults of the McCoy-Cove-Helen Zone areas. Taken from Odell et al. (2014).
to be deposited around 200°-430°C with salinities as high as ~35 eq. wt. %., it makes sense that sulfides would be the main host for higher grades of Au. Fluids produced by late Eocene intrusions most likely mobilized Au in solution at temperatures <350°C and would have continued to permeate through the Cove northeast-southwest striking normal and deeper thrust faults. As the mineralized fluids are being transported further away from the source, a trend of decreasing salinity and temperature would most likely occur, allowing for the desirable precipitation of Au to take place at temperatures <200°C and at high sulfidation and oxidation states. When this retrograde ore-bearing hydrothermal fluid comes into contact with Home Station dolostone and Favret limestone, Au drops out of the Au-bisulfide solution and deposits simultaneously as decarbonatization of the host carbonate rocks takes place (Odell et al., 2014).

Pt is an ion that should form strong bisulfide complexes that we similarly would see with Au (Mountain and Wood, 1988). When looking at the data we see high concentrations of Pt in sulfide vein and grain phases (Tables 2 and 3). Pt is mobilized in chloride and hydroxide complexes at >300°C, but at ~300°C a switch is made and Pt is mobilized in solution as a Pt-bisulfide \([\text{Pt(HS)}_4^{2-}]\) complex (Mountain and Wood, 1988). Because bisulfide complexes are very dependent on temperature and pressure, any drop in these phases will cause Pt to drop out of solution. Pressure drops could cause boiling of the fluids which in return would force a loss in H\textsubscript{2}S, creating a preferred environment for Pt to precipitate out of the ore-bearing fluids (Mountain and Wood, 1988). Because Au and Pt are mobilized in bisulfide complexes at similar temperatures (~200°-350°C), it would make sense that these elements would be deposited at similar timings and in similar vein-types. This coincides with what was found in this study, where sulfide vein and grain types are found to contain similar concentrations of high grade Au and Pt (Table 3).
Carbonate veins, in addition to sulfide veins, contain high grades of Au (Table 3). Carbonate veins show a consistent pattern that can be directly related to Ag (Figures 31 and 32). Any time a line scan was taken across a carbonate vein, data was reported to contain on average 0.98 wt. % Ag throughout all twenty vein samples. Ag trends in calcite veins can be attributed to the fact that both minerals precipitate out of solution around similar Eh-pH values (Figure 39). Ag is transported in solution by chloride complexes $[\text{AgCl}_2^-]$ and $[\text{AgCl}_3^{2-}]$ at near neutral pH and doesn’t disassociate until later hydrothermal processes take place at lower temperatures (Sheng et al., 1997). In sedimentary disseminated formations like the Helen Zone, Ag will precipitate out of hydrothermal solutions around weak-alkaline conditions (Sheng et al., 1997). These are the same conditions where calcite vein-types start to mineralize out of ore-bearing fluids.

Quartz veins were studied in this research and only four veins were identified. Deposition of precious metals is typically found absent in quartz and is due to argillic alteration (Sillitoe, 1995). Because many of the samples at the Helen Zone have undergone extreme alteration, quartz veins may have not withstood the harsh environment, causing a weaker presence of quartz veins in samples from the area. Au and other precious metals studied in this research were identified to have much lower concentrations in quartz vein-types than sulfide and carbonate vein-types (Table 3). Carlin-type Au found in the Helen Zone preferred to drop out of solution with predominantly sulfide and some carbonate vein-types rather than quartz veins due to elevated sulfidation and oxidation states.

Three sphalerite grains were identified in this study. Two of these sphalerite grains were on average $\sim$200 µm in size and one grain of sphalerite was found to be $\sim$2-4 µm in size (Table 2). Line scans over these grains provided averaged metal values that consisted of 4.35 wt. % Au, 0.91 wt. % Ag, 1.21 wt. % Pt, and 0.40 wt. % As (Table 3). These concentrations of Au are unusually high and may be attributed to the fact that
Figure 39. Eh-pH diagram showing silver phases (Ag-Cl-S-O-H) in comparison to calcite phases (Ca-C-O-H). Note that both [metal] silver and calcite share similar Eh and pH values. Taken and modified from Brookins (1988).
these sphalerites contained trace amounts of Fe (<3 wt. %). It was reported that greater concentrations of Fe found in sphalerites directly correlate to poorer concentrations of Au (Hannington and Scott, 1989). That is, Au has a higher affinity for Fe deficient sphalerites. Experimental work was done where pressure was kept stable at ~1 kbar by Barton and Toulmin (1966), Scott and Barnes (1971), and Czamanske (1974). Recorded in their work, at a constant pH, contours of Au solubility are nearly parallel with contours of mole percent FeS in sphalerite (Figure 40). This supports the idea that Au rich hydrothermal fluids at elevated sulfidation states will prefer to drop out of solution with Fe deficient sphalerite (Hannington and Scott, 1989). This information agrees with the data found in this study and explains why Fe deficient sphalerite grains have a higher affinity for disseminated Au.

When looking at all vein-types studied for this research, every vein falls under the category of containing high grades of Au (Tables 2 and 3). The requirement to label samples as high grade Au is equivalent to >0.0031 wt. % whereas low grade Au is equivalent to <0.0001 wt. % (Pires et al., 2016). Some of the samples, when compared to Premier Gold Mines, Ltd, do not necessarily agree with Au grade determination (Table 1). This could be attributed to the fact that geochemical assays provided by Premier Gold Mines, Ltd considered many more elements in addition to analyzing bulk whole rock data. Analyses for this research only took into account thirty elements which can be found in the appendix. In addition, many of the line scans that were taken during this research do not cover the entire rock sample, only ~438 µm per scan. When performing these line scans, it is important to note that emphasis was put on gathering data for vein-types rather than whole rock data; therefore most of the data would have been collected adjacent to veins rather than further away from veins.
Figure 40. Comparison of sphalerite composition with contours of gold-bisulfide fluid complexes \([\text{Au(HS)}_2^-\), which are denoted by dashed lines. Bold solid contours indicate mole % FeS and light solid contours indicate other Fe sulfides that coexist with sphalerite. Note that as Fe becomes more deficient in sphalerite, gold-bisulfide concentrations increase. Taken from Hannington and Scott (1989).
CHAPTER V
CONCLUSIONS

The microscopic veining that occurs in the Helen Zone carries higher grades of gold and other precious metals than does the surrounding gangue of host carbonate and igneous rock types. Petrographic analyses of veining for this study included carbonate, sulfide, and silicate veining which are thought to have been emplaced during one of two pulses of mineralization that occurred ~41.5 and ~39 Ma during the late Eocene. The goal of this study was to identify the following: (1) paragenesis of microscopic veining by using relative dating techniques which includes cross-cutting relationships and the rule of inclusions; and (2) identification of carbonate, sulfide, and silicate vein-types that retained a higher percentage of Au and other precious metals including Ag and Pt.

Geochemical data recorded from the SEM-EDAX shows that sulfide veins contain the highest average concentrations of Au (0.80 wt. %) and Pt (0.87 wt. %). Carbonate veins were found hosting the greatest concentrations of Ag (0.98 wt. %). Silicate veins retained the lowest concentration of precious metals in terms of weight percent, but still carried high grades of Au (0.52 wt. %).

When comparing different stages of veining it was discovered that carbonate, sulfide, and silicate veins did not appear to occur at a specific time, but certain vein-types did show a general pattern. The conclusion was drawn that sulfide veins are typically older than carbonate veins which in turn are older than silicate veins. It was also determined that many carbonate veins cross-cut other carbonate veins. This indicates that carbonate veins may have been asynchronous. Relative dating techniques were insufficient in
terms of finalizing an answer on the origin of vein-type mineralization. This discrepancy suggests that methods of absolute dating need to be performed on veins and dikes that cross-cut each other for future work in order to come to a conclusion on the origin of economic mineralization that occurred during the late Eocene.
REFERENCES


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APPENDIX A

SEM-EDAX RESULTS

SEM-EDAX line scan data tables are available for download or CD only.
APPENDIX B
SEM-EDAX LINE SCANS

The following figures are correlated (metals to vein-type elements) for each sample that was analyzed in this study. Initial figures relate to precious metal percents and As. Elements are displayed by the following colors and shapes: gold diamonds represent gold (Au), red squares represent silver (Ag), teal triangles represent platinum (Pt), and purple circles represent arsenic (As). Subsequent figures relate to vein-type elements. Elements are displayed by the following colors and shapes: blue diamonds represent sulfur (S), red squares represent iron (Fe), green triangles represent silica (Si), and purple circles represent calcium (Ca). High concentrations of Fe and S would indicate pyrite (sulfide) veins, high concentrations of Ca would indicate calcite (carbonate) veins, and high concentrations of Si would indicate quartz (silicate) veins.
SEM-EDAX Line Scan of Sample AX-16 1281 (Line I)

Metals
SEM-EDAX Line Scan of Sample AX-16 1281 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-16 1775 (Line 1)

Metals
SEM-EDAX Line Scan of Sample AX-16 1775 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-16 1847.5 (Line 3)

Metals

Point

Weight Percent

0 50 100 150 200 250 300 350 400

0.1
1.1
2.1
3.1
4.1
5.1
6.1
7.1
8.1

0.1
1.1
2.1
3.1
4.1
5.1
6.1
7.1
8.1

0 50 100 150 200 250 300 350 400

Point
SEM-EDAX Line Scan of Sample AX-16 1847.5 (Line 3)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-16 1914 (Line 1)

Metals

![Graph showing weight percent vs. point for SEM-EDAX Line Scan of Sample AX-16 1914 (Line 1).]
SEM-EDAX Line Scan of Sample AX-16 1914 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-21 1580 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-21 1591 (Line 1)

Metals
SEM-EDAX Line Scan of Sample AX-21 1591 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-21 1601 (Line 1)

Vein-type Elements

Weight Percent

Point
SEM-EDAX Line Scan of Sample AX-26 1182 (Line 1)

Metals

Weight Percent

Point
SEM-EDAX Line Scan of Sample AX-26 1182 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-35 1795 (Line 2)

Metals

![Graph showing metal concentrations across sample points.](image-url)
SEM-EDAX Line Scan of Sample AX-35 1795 (Line 2)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-39 2104a (Line 1)

Metals
SEM-EDAX Line Scan of Sample AX-39 2104a (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-41 1536 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-41 1888 (Line 1)

Metals
SEM-EDAX Line Scan of Sample AX-41 1888 (Line 1)

Vein-type Elements
SEM-EDAX Line Scan of Sample AX-41 1958 (Line 7)

Metals

![Graph showing SEM-EDAX Line Scan of Sample AX-41 1958 (Line 7)]
SEM-EDAX Line Scan of Sample AX-41 1958 (Line 7)

Vein-type Elements

[Graph showing weight percent vs. point along a line scan]
SEM-EDAX Line Scan of Sample AX-41 1963 (Line 1)

Metals
SEM-EDAX Line Scan of Sample AX-42 2118 (Line 1)

Metals

Weight Percent

Point