MAGMATIC-HYDROTHERMAL EVOLUTION OF THE TUVATU ALKALIC EPITHERMAL AU-TELLURIDE DEPOSIT, VITI LEVU, FIJI

by
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A thesis submitted to the Faculty and the 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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The Tuvatu deposit is a high-grade alkalic epithermal Au deposit in Fiji that consists of steeply dipping lode veins, flat lying lodes, and breccias hosted in alkalic intrusive and volcanic rocks. This study performed drill core logging of veins and alteration, vein sample petrography, and geochemical microanalysis of biotite, pyrite, and marcasite to reconstruct the evolution of the magmatic-hydrothermal system and to identify the relative timing of Au mineralization. Eight vein types have been identified, including four porphyry-style veins which formed at higher temperatures and larger pressures, and four epithermal-style veins associated with shallow Au mineralization. The two environments were found to be genetically distinct. Secondary hydrothermal and primary magmatic biotite grains were analyzed with an electron microprobe and are found to contain different major element ratios. Hydrothermal biotite at Tuvatu contains element ratios associated with the porphyry environment and high temperature potassic alteration. Quartz in epithermal veins is shown to have textures indicating recrystallization from originally noncrystalline silica, which is interpreted to have deposited through flashing. Ore-stage pyrite and marcasite show distinct enrichments in As. Laser ablation-ICP-MS analysis revealed high As and Au incorporation in a specific stage of arsenic-rich pyrite which contains Au as a lattice-bound ion. This study emphasizes the potential importance of hydrothermal fluid flashing to high-grade Au deposition in the epithermal environment and the contribution of invisible Au in Fe sulfides to the total Au contained in alkalic epithermal deposits.
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Elements

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<td>Al</td>
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<td>As</td>
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<td>F</td>
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<tr>
<td>Pt</td>
<td>platinum</td>
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<tr>
<td>Se</td>
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<tr>
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</tr>
<tr>
<td>Te</td>
<td>tellurium</td>
</tr>
<tr>
<td>Ti</td>
<td>titanium</td>
</tr>
<tr>
<td>Tl</td>
<td>thallium</td>
</tr>
<tr>
<td>V</td>
<td>vanadium</td>
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<tr>
<td>Zn</td>
<td>zinc</td>
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Minerals

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<td>ad</td>
<td>adularia</td>
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<tr>
<td>alt</td>
<td>altaite</td>
</tr>
<tr>
<td>apy</td>
<td>arsenopyrite</td>
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</table>
co    coloradoite
cpy    chalcopyrite
gn    galena
kfs    potassium feldspar
mrc    marcasite
py    pyrite
qz    quartz
rsc    roscelite
sp    sphalerite
wm    white mica

Miscellaneous
km    kilometers
m    meters
cm    centimeters
mm    millimeters
µm    micrometers / microns
EDS    energy-dispersive x-ray spectroscopy
LA-ICP-MS    laser ablation inductively coupled plasma mass spectrometry
nA    nanoamps
BM    epithermal base metal sulfide vein stage
AM    epithermal arsenian marcasite vein stage
QRP    epithermal quartz-roscelite-pyrite vein stage
mq    mosaic-textured quartz
q2    layered quartz
chal    chalcedonic-textured quartz
cq    coarse crystalline quartz
carb    carbonate minerals
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CHAPTER 1
INTRODUCTION

The Pliocene Tuvatu alkali-hosted epithermal deposit is one of the most significant Au deposits in Fiji (Scherbarth and Spry, 2006; Clarke, 2022). Mineralization occurs in narrow high-grade ore zones called lodes over a strike length of almost 900 meters with a vertical extent of more than 500 meters. The lodes consist of steeply dipping narrow veins, shallow dipping flat veins, and irregular breccia bodies that are hosted by an alkali monzonite and to a lesser extent the shoshonitic volcanic rocks in which the monzonite emplaced (Scherbarth and Spry, 2006; Holden et al., 2022). The Tuvatu deposit is currently under development, containing an indicated resource of ~1.0 million metric tons of ore grading 8.48 grams/ton Au for a total of 274,600 ounces Au and an inferred resource of ~1.3 million metric tons of ore at 9.0 grams/ton Au for 384,000 ounces Au at a cut-off of 3 grams/ton Au (Holden et al., 2022).

Tuvatu shares a number of geological characteristics with other alkali-epithermal deposits (Scherbarth and Spry, 2006; Spry and Scherbarth, 2006; Forsythe et al., 2019; Clarke, 2022). Most notably, the low-temperature, epithermal mineralization at Tuvatu overprints earlier high-temperature, biotite-stable hydrothermal alteration of the host alkali monzonite (Scherbarth and Spry, 2006; Clarke, 2022). This is comparable to Cripple Creek in Colorado (Kelley et al., 1998; Jensen and Barton, 2007; Kelley et al., 2020), Ladolam on Lihir island in Papua New Guinea (Moyle et al., 1990; Müller et al., 2002; Carman, 2003; Blackwell et al., 2014), and Porgera in Papua New Guinea (Richards, 1992; Richards and Kerrich, 1993; Richards et al., 1997) where similar relationships have been interpreted to result from telescoping of the evolving magmatic-hydrothermal systems. Previous stable isotope work at Tuvatu is consistent with a model that links the formation of this deposit to magmatic-hydrothermal fluids originating from an alkali igneous source (Scherbarth and Spry, 2006; Forsythe et al., 2019). However, important questions remain as to the relative timing of Au mineralization with respect to the overall evolution of the magmatic-hydrothermal system and the mechanisms that resulted in the development of high-grade ore zones.

This contribution provides a comprehensive review of the geology of the Tuvatu alkali-hosted epithermal deposit that is based on extensive logging of new exploration drill core. Following on previous work by Schmidt (2023), the sequence of different vein types and
associated alteration styles was established through the documentation of crosscutting relationships in core and the use of sample petrography. Microanalytical techniques were employed to identify the mineralogical sequestration of Au and to constrain the paragenetic setting of Au-bearing minerals, which allowed determination of the relative timing of precious metal introduction and deposition. Based on the improved understanding of the vein sequence and paragenetic relationships within the veins, it is shown that precious metal enrichment at Tuvatu occurred entirely during late-stage magmatic-hydrothermal processes, with gold occurring in distinct low-temperature, roscoelite-bearing veins in which native gold is associated with telluride minerals and arsenian pyrite. A model is proposed that links the epithermal precious metal enrichment at Tuvatu to vigorous boiling or flashing of the magmatic-hydrothermal fluids in the near-surface environment.
This chapter summarizes the tectonic setting, regional geology, and deposit geology of Tuvatu and provides a brief summary of the style of mineralization encountered.

2.1 Tectonic Setting

The Fiji Islands (Fiji) encompasses the large islands Viti Levu and Vanua Levu and numerous small surrounding islands. Fiji is located in the southwest Pacific Ocean, 2,700 km east of Australia and 2,000 km north of New Zealand. Together with the Tonga arc and New Hebrides (Vanuatu) arc, the islands of Fiji initially formed at around 35 Ma as part of the Vitiaz arc, the result of subduction of the Pacific plate beneath the Indo-Australian plate. Fiji remained part of the Vitiaz arc from the initiation of subduction until ~10 Ma. Over this period, volcanic rocks erupted on the arc transitioning from tholeiitic to calc-alkaline signature as it matured (Gill, 1987).

The continuous Vitiaz arc underwent fragmentation between 10 and 5.5 Ma caused by the onset of spreading starting to the north of the arc and continuing south to the North Fiji Basin back-arc, the timing of which is the subject of disagreement. Paleomagnetic evidence suggests that the tectonic platform containing the Fiji arc fragment began rapid counterclockwise rotation at 10 Ma (Taylor et al., 2000). However, the oldest ocean crust definitively identified as resulting from back-arc spreading at the North Fiji Basin dates to 5.5 Ma, with inconclusive evidence for older spreading. Additionally, volcanic rocks dating to 10 Ma in Fiji have an arc signature similar to those previously erupted (Gill and Whelan, 1989).

By 5.5 Ma at the latest, the Vitiaz arc had begun fragmentation. At the same time voluminous volcanism occurred along the Vitiaz arc fragments. At ~5.5 Ma, alkalic shoshonitic basalts were erupted in Fiji, which could suggest subduction was stalling at that time (Gill et al., 1984). The rifting of the North Fiji Basin and the shoshonitic volcanism were coeval with a reversal of subduction polarity next to the Vanuatu fragment of the Vitiaz arc. On the Fiji tectonic platform, the rifting axis was parallel to a series of ENE-trending structural lineaments, including the Viti Levu Lineament on Viti Levu and Vanua Levu (Gill and Whelan, 1989).
2.2 Geology of Viti Levu

The late Eocene Yavuna Group of volcanic rocks and interspersed limestones comprises the oldest rocks on the island of Viti Levu, and results from the initiation of arc volcanism. The Yavuna lavas have a tholeiitic to boninitic signature. The trondhjemitic Yavuna stock intruded the Yavuna Group volcanic rocks in the early Oligocene. Following a hiatus in volcanism, the arc volcanic rocks of the late Oligocene Wainimala group were deposited. They unconformably overlay the Yavuna Group on Viti Levu.

Figure 2.1: Geologic setting of the Tuvatu epithermal deposit on the island of Viti Levu, Fiji (modified from Phillips, 1965). The map also shows the locations of other major precious and base metal deposits. The inset displays the regional tectonic setting with interpreted plate boundaries from Bird (2003).
The Wainimala volcanic rocks are interbedded with limestones and include the Nadele volcaniclastic breccia unit, which is exposed near Tuvatu in west-central Viti Levu. The Colo Plutonic suite of gabbros and tonalites intruded the Yavuna and Wainimala groups along the arc axis in the middle Miocene (Wharton et al., 1994). The Wainimala Group is overlain by the Tuva sedimentary group, which occurs in western Viti Levu as the Nadi sedimentary group. In the early Pliocene, alkalic and shoshonitic volcanics erupted on Viti Levu as the Koroimavua and Ba volcanic groups. At 3 Ma active volcanism on Viti Levu ceased, but the island has undergone continued uplift (Hathway, 1993).

2.3 Navilawa Caldera

The Tuvatu deposit is located within a topographic depression surrounded by the Mt. Evans range. The range is formed from the Sabeto Volcanics unit and has been interpreted as the eroded walls of a caldera referred to as the Navilawa caldera (Forsythe et al., 2019). The Sabeto volcanic rocks make up part of the Koroimavua volcanic group on northwestern Viti Levu. The Sabeto Volcanics overlay the Nadele breccia, which is a component of the Wainimala Group. Both units are intruded by the Navilawa Monzonite, which hosts the Tuvatu deposit. The Navilawa Monzonite is exposed in a northeastern-extended oval at the center of the Navilawa caldera. There are two major varieties of the Navilawa Monzonite: a medium-grained equigranular monzonite with plagioclase and alkali feldspar, biotite, and augite, and a porphyritic monzonite with plagioclase and augite phenocrysts, referred to as micromonzonite. The equigranular monzonite is surrounded by, and contains xenoliths of, the micromonzonite (Scherbarth and Spry, 2006). The Navilawa Monzonite is likely the source for the magma that produced the Sabeto Volcanics. Later basaltic and andesitic dikes with a distinct chemical signature and magma source crosscut (A-Izzeddin, 1998).

Samples of Navilawa Monzonite have an alkalic composition due to a high weight percent Na$_2$O and K$_2$O. They also follow a calc-alkalic fractionation trend, supporting the fact that they are at least partially island-arc related. The Navilawa Monzonite shows enrichment in light REEs and depletion in heavy REEs in a similar pattern to the host rocks of the Vatukoula alkalic epithermal Au deposit in Viti Levu, Fiji as well as those of the Porgera alkalic epithermal Au deposit in Papua New Guinea (Scherbarth and Spry, 2006). When plotted on a total-alkali-
silica diagram, the Navilawa Monzonite is compositionally similar to rocks hosting other alkalic epithermal deposits such as Cripple Creek in Colorado, Goonumbla in New South Wales, and Porgera in Papua New Guinea (Holden et al., 2022).

Figure 2.2: Geologic map of the Navilawa Caldera. Lithology dates from Forsythe et al. (2019). Local lithology contacts and regional prospect locations provided by Lion One Metals Limited.
2.4 Deposit Geology

The Tuvatu deposit consists of several principal sets of similarly oriented meter-scale lodes, each of which is comprised of multiple millimeter- to centimeter-scale subparallel anastomosing vein networks. Tuvatu has a surface footprint of about 900 meters north-south by 500 meters east-west and is located in the southwestern corner of the Navilawa caldera. The primary mineralized zone is the area of the steeply dipping Upper Ridges lodes, which strike north in the northern area of the deposit and transition to the “UR splays” with northeast strike in the southern area. The Upper Ridges lodes are spatially extensive, with strike lengths and depth extents between 500 and 600 meters, respectively. The smaller, more shallowly dipping, E-striking Murau and Snake lodes intersect with the Upper Ridges lodes in the north-central area of the deposit. The shallow, narrow, flat-lying SKL lode set is situated at the intersection between the Upper Ridges region (including the GRF and Nasivi lodes) and Murau and Snake region. Informally known as flatmakes, the very-shallowly-dipping stacked SKL veins are interpreted to be well-mineralized “shatter zones” similar to those occurring at lode intersections at the Vatukoula alkalic Au deposit in Tavua, Fiji (Scherbarth and Spry, 2006; Holden et al., 2022).

The southern Upper Ridges splay lodes continue at depth for at least an additional 300 to 400 meters in high grade mineralized structures referred to collectively as the 500 Zone. The 500 Zone lodes have been interpreted as potential feeder structures for the magmatic-hydrothermal system that formed the shallow lodes at Tuvatu (Holden et al., 2022).

The H and Tuvatu lodes are distinct: they are located on the north side of the Coreshed Fault, an unmineralized steeply dipping ESE-striking fault cutting through the Tuvatu deposit. The host rock of the H and Tuvatu lodes has been affected by high-temperature potassic alteration, and the lodes themselves strike northwest in contrast to the rest of the deposit. Also separate from the bulk of Tuvatu are the West lodes (or Plant Site lodes), a 200-meter strike length E-striking lode set situated half a kilometer west of the Murau and Snake lodes (Clarke, 2022; Holden et al., 2022).

The primary host rock for the Tuvatu deposit is an alkalic intrusive: the 4.85 Ma Navilawa Monzonite exposed in the center of the Navilawa caldera. Some of the lodes in the southern part of the deposit such as the Upper Ridges splay lodes are hosted in the 5.5–4.8 Ma Sabeto Volcanics, an eruptive equivalent of the monzonite typically logged as andesite. The
andesite surrounds the monzonite and is exposed on the caldera walls. The 500 Zone is proximal to the monzonite-andesite contact, which strikes northeast. The Navilawa caldera is rimmed by the 32–13 Ma Nadele Breccia, part of the Wainimala Group of arc volcanic rocks predating alkalic magmatism (Forsythe et al., 2019; Holden et al., 2022).

Figure 2.3: Tuvatu consists of sets of narrow lodes including the steeply dipping N-to-NW-striking Upper Ridges lodes (dark blue), E-striking Murau and Snake Lodes (green), and shallowly-dipping SKL lodes (light blue). (A) Tuvatu deposit plan view footprint with lode projections to surface from 150 meters elevation. Contour interval = 20 meters. (B) cross section A-A’ along deposit strike length. West and GRF lodes are not intersected.
Figure 2.4: Underground pictures of lodes at Tuvatu. (A) and (B) photographs of URA-1 lode, part of the Upper Ridges lodes, exposed in the Tuvatu mine adit. (C) H1 lode exposed in the Tuvatu exploration decline. The lode forms part of the NW-SE-trending and steeply dipping HT zone on the north side of the Coreshed fault. The HT zone is notable for the presence of strong potassic alteration and copious secondary biotite. (D) SKL-5 lode in the exploration decline. It is one of the stacked set of narrow and shallow-dipping SKL lodes. These high-grade "flatmakes" occur near the intersection of two principal lode sets, the Upper Ridges lodes (N-S-trending) and the Murau lodes.
CHAPTER 3
METHODS

This study was performed on drill core and field samples from the Tuvatu deposit provided by Lion One Metals Limited in October 2021, as well as drill core and field samples collected by the author from May to August 2022 on site in Fiji. Logging of diamond drill core intervals of interest and vein density analysis logging was performed at the Lion One Tuvatu base camp. During this time, 83 core samples were collected for processing into petrographic thick sections at the Colorado School of Mines and 16 core samples were collected for optical digital photography. Field observations were also made at outcrops in the Navilawa Caldera and in the Lion One Tuvatu exploration decline.

Digital photographs of hand samples were captured using a Keyence VHX-5000 digital optical microscope using high-resolution image stitching.

Petrographic slides and 1-inch round epoxy mounts were imaged using the Colorado School of Mines Minerals and Materials Characterization Facility’s (MMCF) TESCAN MIRA-3 LMH Schottky field emission scanning electron microscope (FE-SEM). Backscattered electron images were captured using a YAG BSE detector with a working distance of 10 mm, accelerating voltage of 20 kV, and beam intensity setting of 11. Mineral chemical analysis via semiquantitative energy-dispersive X-ray spectroscopy was performed using a Bruker XFlash 6|30 silicon drift detector.

Petrographic slides were investigated in transmitted and reflected light using an Olympus BX53 and Nikon Eclipse LLV100Pol. Photomicrographs were captured using a Leica Flexacam C1 camera attached to each microscope.

Biotite major element chemistry data was collected at the University of Colorado Boulder Electron Microprobe Laboratory in the Department of Geological Sciences. A JEOL 8230 Superprobe instrument equipped with an LaB₆ crystal electron gun and five JEOL quantitative wavelength dispersive spectrometers (WDS) was used. The instrument was operated with a 40° takeoff angle, a beam current of 10 nA, and a beam diameter of 2 μm. Count times for all analyses were 30 seconds. Elements analyzed, weight percent detection limits, and mineral standards follow: Si (mean detection limit 0.0193, labradorite), Ti (mean detection limit 0.0251, rutile), Al (mean detection limit 0.0174, almandine garnet), Cr (mean detection limit 0.0191,
chromite), Fe (mean detection limit 0.0254, magnetite), Mn (mean detection limit 0.0239, rhodonite), V (mean detection limit 0.0879, karelianite), Mg (mean detection limit 0.0059, olivine), Ca (mean detection limit 0.0089, labradorite), Na (mean detection limit 0.0082, albite), K (mean detection limit 0.0085, orthoclase), Cl (mean detection limit 0.00840, tugtupite), and F (mean detection limit 0.0979, fluorite).

In-situ laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) on pyrite and marcasite was conducted at the USGS-LTRACE lab in Denver, Colorado. Petrographic slides and 1-inch epoxy round mounts previously imaged with BSE were used. The laser ablation system used was a Photon Machines Analyte G2, and the ICP-MS instrument was an Agilent 8900 quadrupole ICP-MS. Some analyses were conducted as spot analyses with a spot size of 25 µm; the remaining majority were conducted as ablation lines with a spot size of 20 µm. Both had an ablation duration of 30 seconds, a laser repetition rate of 10 Hz, and a laser fluence of 3.5 J/cm² checked with an external meter. Te, As, Se, Au, Pt, and Tl were calibrated using the NIST610 reference glass. Hg was calibrated using the MASS-1 sulfide pressed pellet reference material. All other elements were calibrated using the GSE-1g standard or the GSD-1g glass reference material. Calibration standards were analyzed at the start and end of run and every ~1 hour with a minimum of 6 analyses for the primary calibration materials. Reference glasses BHVO-2g and GSE-1g (when GSD-1g was used as a calibration material) were reported as unknowns to assess accuracy of the results. Full analytical precision (1s) was used. Laser ablation He carrier gas flow rate was 0.60 liters per min and was mixed with Ar carrier gas flowing at 1.05 liters per minute. Useful yield sensitivity was 2,300 cps/ppm for $^{238}$U using the BCR-2g basaltic glass. Data was processed and reduced using the LADR software package by Norris Scientific (Norris and Danyushevsky, 2018). Quantification of pyrite was done using $^{57}$Fe as the internal standard element and all metal cations, except lithophile elements (e.g., Na, Al, Si, etc.), were combined with sulfur (in proportions according to the mineral pyrite) and the sum of the cations plus sulfur was summed to 100% total. Lithophile elements are also included in this analytical total and were combined with oxygen instead of sulfur; these elements typically consisted of <0.5% of the total ablated volume.
CHAPTER 4
VEIN TYPES

This chapter summarizes the macroscopic observations made at Tuvatu permitting classification of veins into different vein types. The chapter also summarizes field work conducted to constrain the abundance of vein types in core.

This study has divided veins observed in drill core at Tuvatu into two groups and eight discrete types. Cross-cutting relationships have been established for the different vein types. Based on the character of the veins and their mineralogical composition, the veins have been classified as porphyry-style veins and epithermal veins.

4.1 Porphyry-Style Veins

A total of four porphyry-style vein types have been distinguished. This includes gray quartz veins, potassium feldspar veins, Cu-sulfide veins, and epidote veins.

Gray Quartz Veins

Porphyry-style gray quartz veins (Figure 4.1A) occur primarily beneath the main Tuvatu deposit within drill core at Tuvatu and are hosted within the Navilawa Monzonite. The veins observed measure 1 cm and less in width and consist of gray to white quartz that is fine-grained. The veins generally display irregular geometry. They form a stockwork of crosscutting veinlets that reopen and truncate one another. The vein walls are nonparallel and display no alteration halo immediately surrounding them, although the monzonite host rock contains both potassium feldspar and chlorite / epidote alteration. The gray quartz veins are interpreted to be equivalent to A veins in porphyry Cu deposits (Gustafson and Hunt, 1975; Monecke et al., 2018).

Potassium Feldspar Veins

Veins of white potassium feldspar and minor intergrown quartz (Figure 4.1B) occur throughout the deposit. These are coarser-grained than the host monzonite and vary in width between 0.5 to 5 centimeters. Nonplanar and nonparallel vein walls sometimes cause small-scale
width changes along the length of the vein. Potassium feldspar veins are often surrounded by a halo of coarse secondary biotite; however, not all potassic alteration zones of the host monzonite are associated with potassium feldspar veins. A crosscutting relationship between gray quartz veins and potassium feldspar veins has not been established.

**Cu-Sulfide Veins**

Cu-sulfide veins occur at Tuvatu within the HT zone and beneath the main Tuvatu deposit. These veins consist of bornite and lesser chalcopyrite and are surrounded by haloes of chlorite/epidote alteration. The veins lack visible quartz. These veins have nonplanar, nonparallel walls and the sulfide minerals form an interlocking texture. These veins are interpreted to be equivalent to C veins in porphyry Cu deposits (Dilles and Einaudi, 1992; Gustafson and Quiroga, 1995).

**Epidote Veins**

Epidote occurs at all elevations at Tuvatu within the host monzonite and Sabeto Volcanics. The epidote exhibits large variations in morphology, with veins and patches of varying dimensions being most common. Below the zones of Au mineralization, epidote occurs with magnetite, and throughout the deposit epidote regularly overprints potassic alteration.
Figure 4.1: Photographs of Tuvatu core samples illustrating porphyry-style vein types. (A) Gray quartz vein from TUDDH-494 at 816.8 meters. (B) Potassium feldspar vein with secondary biotite from TUDDH-565 at 69.8 meters. (C) Cu-sulfide vein hosted in HT zone from TUDDH-481 at 194.7 meters. Bornite is the most abundant Cu sulfide in the vein (D) Patchy epidote vein with minor magnetite overprinting a potassium feldspar vein from TUDDH-494 at 1,248 meters.
4.2 Epithermal-Style Veins

Based on the mineralogy of the veins and the surrounding alteration halos, a total of four epithermal-style veins were distinguished.

*Epithermal Base Metal Sulfide Veins*

Epithermal veins containing abundant base metal sulfides (Figure 4.2A) are the earliest epithermal veins at Tuvatu. These veins vary between 0.5 to 5 cm in thickness and are typically wider than younger epithermal veins. Sphalerite, chalcopyrite, and galena occur together, and all overgrow earlier euhedral pyrite and adularia, which typically occurs along the vein walls. Sphalerite is the most prevalent by volume and occurs as spherical grains and crustiform masses. It displays concentric zoning visible in coarse grains at the hand-sample scale, with colors varying from bright yellow to dark red. Chalcopyrite forms angular subhedral grains or anhedral masses and often contains pyrite inclusions. Galena, the least common of the three, usually occurs as euhedral or subhedral grains. Dark-colored fine-grained quartz typically occurs as a cement.

*Arsenian Marcasite Veins*

Veins containing arsenic-rich marcasite as the primary mineral formed after the base metal sulfide veins and before the epithermal veinlets containing much of the visible Au. The marcasite veins occur as separate veins or can be reopened by the quartz-roscoelite-pyrite veins or the late carbonate veins (Figure 4.2B). Unlike the brightly colored euhedral pyrite in the epithermal base metal sulfide veins, the marcasite is dark colored and typically takes on an anhedral colloidal texture, coating wall rock, earlier sulfides, or breccia clasts. The marcasite can also occur as coarse dark-colored needles.

*Quartz-Roscoelite-Pyrite Veins*

The main Au-bearing vein type at Tuvatu consists of quartz, roscoelite, arsenic-rich pyrite, native gold, and minor telluride minerals. Some quartz-roscoelite-pyrite veins contain small amounts of pyrite which is obscured by the color of roscoelite (Figure 4.2D); others contain much higher volumes of pyrite (Figure 4.2C). Similar to the base metal sulfide veins,
adularia is often observed as coarse crystals on vein walls. Quartz appears in a variety of forms, varying from light blue to translucent gray to areas nearly opaque black in color and from smooth and crystalline to fine-grained and rough in texture. Roscoelite is soft and dark green to black in color, and often occurs as a dark band or strip coating earlier minerals. Within the quartz and roscoelite, arsenian pyrite occurs in blobs, small dendrites, and amoeboid shapes. Visible native gold occurs as grains within roscoelite and/or pyrite in this stage. Telluride minerals are present as well among the opaque phases in this vein type and occur as small grains in contact with native gold and arsenian pyrite. Telluride grains are difficult to distinguish macroscopically. Their presence may be obscured by the apparent “staining” of nearby quartz by roscocelite, which together with fine-grained pyrite creates the macroscopic appearance of some quartz being rough and black colored. This phenomenon which may also hide small gold grains.

Arsenian pyrite is one of the key constituents in the quartz-roscoelite-pyrite veins containing native gold and precious metal tellurides. It occurs both with roscocelite in those veins and overgrows marcasite. Arsenian pyrite is nearly always anhedral and has a dark, rough, and pitted texture. Small volumes are difficult to see macroscopically due to the roscocelite staining effect described above; visible arsenian pyrite is found as a thin (typically <1 mm) coating on early euhedral pyrite, arsenian marcasite, vein wall adularia, and wall rock either at vein edges or on clasts within the vein. Branch-like dendrites and botryoidal clumps of roughly spherical arsenian pyrite extend out from the thin coatings toward the interior of the veins.

**Carbonate Veins**

The latest epithermal veins at Tuvatu consist of carbonate minerals, primarily calcite. These veins contain no other minerals and are not associated with mineralization except by reopening and crosscutting of previously formed epithermal veins (Figure 4.2B). Due to reopening, carbonate veins are often surrounded by earlier alteration assemblages, such as potassium feldspar and secondary biotite. Large volumes of carbonate minerals can be present in reopened veins or breccia infills, but isolated carbonate veinlets are usually less than 1 mm in width.
Figure 4.2: Photographs of Tuvatu core samples illustrating epithermal-style vein types (excluding carbonate veins). Arrows indicate described overprint if present. (A) Base metal sulfide vein with galena, sphalerite, chalcopyrite, and quartz, with later pyrite and quartz overprint. From TUG-149 at 261.0 meters. (B) Marcasite breccia with arsenian marcasite, small amounts of later arsenian pyrite, and carbonate infill. From TUG-144 at 119.11 meters. (C) Pyrite-rich quartz-roscoelite-pyrite vein overprinting early euhedral pyrite. Volcanic host rock. From TUG-141 at 495.4 meters. (D) Quartz and roscoelite rich quartz-roscoelite-pyrite vein overprinting early euhedral pyrite. From TUG-141 at 578.9 meters.
Figure 4.3: Crosscutting relationships in (A) porphyry-style and (B) epithermal-style vein types.
4.3 Vein Density Quantification

Vein densities were quantified to constrain relationships between Au mineralization, vein types, and associated alteration styles. Figure 4.4 shows tallied values of minerals and alteration encountered in each drillhole interval in millimeters of material perpendicular to the vein where the vein crossed the center of the drill core, if applicable.

Potassic alteration with biotite and carbonate veining were ubiquitous all throughout the three drillhole intervals examined. Epidote alteration and veining were relatively rare in shallow elevations but were common in middle elevations and ubiquitous at depth. Base metal sulfide veins were much more common at intermediate depth, and arsenian marcasite veins were less common (Figure 4.4).

Potassic alteration is defined as amount of hydrothermal biotite or potassium feldspar present. Phyllic alteration is defined as a vein selvage of soft clay and white mica alteration. Silicification is defined as a hard quartz vein selvage. Demagnetization is defined as distance from a vein where wall rock is not magnetic, typically implying wall rock magnetite has been replaced by disseminated pyrite.

Figure 4.4: Vein mineral density comparison from three ~100-meter Tuvatu drill hole intervals: TUDDH-570 (72.7 m to 183.4 m downhole), TUDDH-528 (257.97 m to 345.6 m downhole), and TUG-138 (503.4 m to 588.6 m downhole).
Figures 4.5, 4.6, and 4.7 stack up Au sample grades, selected sample pathfinder element analyses (in parts per million), and relevant vein density analyses (in millimeters) from each drillhole interval. Gaps in pathfinder element data indicate no analysis and typically coincide with Au grades below 0.05 ppm. The width of each bar corresponds to the sample length in which is contained the element grades and millimeters of vein material.

In shallow depth intercepts in drillhole TUDDH-570, the presence of Au grades over 5 g/t generally coincides with the presence of quartz-roscobelite-pyrite veins, arsenian marcasite veins, phyllic alteration, wall rock demagnetization, silicification, hydrothermal biotite alteration, and hydrothermal potassium feldspar alteration. The distribution of potassium feldspar veins correlates with the presence of base metal sulfide veins and quartz-roscobelite-pyrite veins. The presence of quartz-roscobelite-pyrite veins matches with higher Au grades, but the highest volumes of each do not necessarily correlate with the highest Au grades. Similarly, peak alteration widths do not match with peak Au grades, nor do peak pathfinder base metal grades match with instances of base metal sulfide veins.

Intermediate depth Au intercepts in TUDDH-528 coincide with the presence of quartz-roscobelite-pyrite veins, base metal sulfide veins, hydrothermal biotite and potassium feldspar alteration, wall rock demagnetization, and silicification. Cu and Pb track very closely with high Au grades, as do the presence of base metal sulfide veins. Quartz-roscobelite-pyrite veins also correlate with Au but sometimes occur in places with no high Au grade. There are expansive areas of hydrothermal potassium feldspar alteration which occur in nonmineralized areas. Epidote, hydrothermal biotite, silicification, phyllic alteration, and wall rock demagnetization all hew closely to one another and the presence of veins and higher Au grades.

In deep intercepts from hole TUG-138, high Au grades occur with quartz-roscobelite-pyrite veins, arsenian marcasite veins, phyllic alteration, silicification, wall rock demagnetization, hydrothermal biotite, and hydrothermal potassium feldspar. Arsenian marcasite vein count closely aligns with high Au grades, whereas many instances of quartz-roscobelite-pyrite veins do not correspond to Au intercepts. Potassium feldspar veins spatially coincide with epidote and hydrothermal biotite. Base metal sulfide veins are relatively rare and do not correspond with high Au, Cu, and Pb grades. High As correlates with the presence of arsenian marcasite and quartz-roscobelite-pyrite veins.
Figure 4.5: Comparison of Au grades, pathfinder ICP analyses, and vein and alteration width measurements from the shallow interval in drillhole TUDDH-570. The interval originated from a shallow-depth drill hole (45 to 110 m below present surface) within the deposit.
Figure 4.6: Comparison of Au grades, concentrations of pathfinder elements, and abundance of vein types and alteration styles width in drillhole TUDDH-528. The interval originated from an intermediate-depth drill hole (250 to 400 m below surface) within the deposit.
Figure 4.7: Comparison of Au grades, concentrations of pathfinder elements, and abundance of vein types and alteration styles in drillhole TUG-138. The interval originated from a deep drill hole (510 to 580 m below surface) within the deposit.
CHAPTER 5
PETROGRAPHIC CHARACTERISTICS OF EPITHERMAL-STYLE VEINS

This chapter describes the petrographic characteristics of the epithermal-style veins occurring at the Tuvatu deposit. Optical microscopy on thin sections was conducted to unravel textural and paragenetic relationships. In addition, BSE imaging of pyrite and marcasite was performed to study compositional zoning.

5.1 Epithermal Base Metal Sulfide Veins

Epithermal base metal sulfide veins are the earliest epithermal veins at Tuvatu. They contain adularia (low-temperature potassium feldspar), bright euhedral pyrite, base metal sulfides, minor sulfosalts and selenides, white mica fans, and quartz.

White adularia is present in two forms in the epithermal base metal sulfide veins, as early subhedral crystals and as later anhedral grains occurring in the matrix of the veins. The early subhedral adularia crystals typically point inward from vein walls and are up to 3 mm in diameter. These angular crystals display simple twinning, crosshatch twinning, or core/rim extinction under crossed polars. The second type of adularia occurs in and around base metal sulfides. It usually lacks clear grain boundaries, although sometimes a prismatic crystal can be observed. Adularia crystals contain easily visible liquid-rich fluid inclusions and mineral inclusions of silicates such as white mica (Figure 5.1A).

Sphalerite is the most common base metal sulfide by volume and often the earliest, although sphalerite, chalcopyrite, and galena are broadly coeval. Its most common color is honey brown; bands or concentric zones of darker red to brown colors are often observed, with no color zonation pattern between veins. Isolated spheres of sphalerite can be up to 8 mm in diameter. Crustiform sphalerite forms as a vein-parallel layer and typically contains color bands. The color banding in crustiform sphalerite is typically localized, truncated, and nonparallel to the growth surface. Concentric zoning in spherical sphalerite grains displays no consistent core-to-rim zoning pattern. Crustiform sphalerite can also display a vein-scale dendrite-like texture in which the mineral fans and branches out towards the inside of the vein and color bands become progressively more tightly packed (Figure 5.1B).
Both chalcopyrite and galena are lower in volume than sphalerite. Chalcopyrite is found with a wide variety of textures and occurs as euhedral or subhedral crystals to anhedral masses or dendrites. It often is heavily included, and small grains are often dendritic or anhedral.

Coarse grains of galena are typically uniform and euhedral. Smaller grains are similar to the texture of chalcopyrite (Figure 5.1C). Where clausthalite occurs, it is associated with medium to fine sub- to anhedral galena grains. Sulfosalts including minor tennantite-tetrahedrite are rarely observed. Fine-grained, red proustite-pyrargyrite grains also occur in areas of abundant galena.

Fans of narrow white mica grains overgrow base metal sulfides in some veins. White mica typically occurs as a single narrow layer less than 1 mm thick from the tip of the fan to the growth surface. The white mica occurrences have fewer and coarser grains than roscoelite and are generally asymmetrical instead of radial (Figure 5.1D).

The properties of quartz found in epithermal base metal veins are very similar to those of the quartz found in quartz-roscoelite-pyrite veins. The former generally contain less quartz than the latter. Quartz occurs as a repeating pattern of textural layers. The first is a relatively thick layer of fine-grained quartz accounting for 50 to 70 percent of quartz in this vein type. This quartz layer exhibits a mosaic texture under crossed polars. Crystals are small, lack regular flat faces, and grain boundaries are often discontinuous and truncated. The second quartz texture layer is very thin and consists of thin layers parallel to the growth surface. The third layer is of varying thickness and consists of one or more colloform bands with a fine needle-like internal texture perpendicular to the growth surface referred to as colloform chalcedonic and chalcedonic moss textures. The fourth and final layer contains relatively coarse subhedral quartz crystals terminating as vugs on the inside of the vein (Figure 5.1D).
Figure 5.1: Photomicrographs of epithermal base metal sulfide veins. (A) Adularia crystals overgrowing wall rock, with opaque phases, quartz, and carbonate minerals. From TUG-144 at 103.8 meters. (B) Banded sphalerite with progressively denser bands that forms part of a dendrite. From TUDDH-595 at 114 meters. (C) Galena and pyrite in reflected light. From TUDDH 207 at 306.16 meters. (D) Sulfides, white mica, mosaic-textured quartz, parallel-layered quartz, and chalcedonic-textured quartz. From TUDDH-565 at 71.2 meters. ad = adularia, chal = chalcedonic-textured quartz, gn = galena, mq = mosaic-textured quartz; py = pyrite, q2 = layered quartz, sp = sphalerite, wm = white mica.
5.2 Arsenian Marcasite Veins

Arsenian marcasite veins are the second epithermal vein type. The only component is arsenian marcasite, although most are found at least with later carbonate infill. The arsenian marcasite occurs as a 1 to 5 mm thick crustiform growth layer on wall rock in veins or breccias. In veins it is typically found only on one vein wall. The arsenian marcasite is dark yellow to brown and not found as euhedral crystals. Under crossed polars, arsenian marcasite displays pink to blue bireflectance colors indicative of its anisotropic nature, which is distinctly different from isotropic pyrite (Figure 5.2A). Arsenian marcasite occurs rarely as coarse needles with a fine arsenopyrite comb coating and infill (Figure 5.2B). This is the only observed mode of occurrence of arsenopyrite by this study at Tuvatu.

Figure 5.2: Photomicrographs of arsenian marcasite veins. (A) Arsenian marcasite with red/white bireflectance under crossed polars overgrowing pyrite. From TUG-144 at 119.11 m. (B) Marcasite needles coated with arsenopyrite combs. From TUDDH-565 at 71.2 m. apy = arsenopyrite, mrc = marcasite, py = pyrite.
5.3 Quartz-Roscoelite-Pyrite Veins

Roscoelite fans, arsenian pyrite, and variably textured quartz make up the quartz-
roscoelite-pyrite veins, which are the principal carrier of native gold. Where mineralized, quartz-
roscoelite-pyrite veins contain abundant grains of native gold and base and precious metal
tellurides.

Roscoelite occurs mostly as radial bunches of dark green needles and less commonly as
an overgrowth strip similar in texture to the white mica in the base metal sulfide veins. Radial
bunches are hosted in quartz with mosaic texture (Figure 5.3C); overgrowths typically occur on
sulfides from previous vein generations (Figure 5.3D, 5.3E). Roscoelite does not occur in quartz
of any of the other two textures. In plane-polarized light, roscoelite varies in color from algae-
green to dark forest green to near black, with darker shade corresponding to higher V content.
This study observed up to 25% weight V in roscoelite in EDS analyses.

Arsenian pyrite occurs as anhedral coatings, botryoidal masses, and occasionally as fine
aggregates. It is pitted and darker colored than the euhedral pyrite found in base metal sulfide
veins. Arsenian pyrite displays no bireflectance under crossed polar reflected light. In most
quartz-roscoelite-pyrite veins, this pyrite appears preferentially as isolated grains with a spherical
or rounded asymmetrical shape within a matrix of quartz and roscoelite (Figure 5.3C, 5.3D); in
veins with higher relative volumes of arsenian pyrite, the mineral takes on a botryoidal form and
acts as a matrix hosting roscoelite, tellurides, and native gold grains (Figure 5.4B).

Quartz in quartz-roscoelite-pyrite veins follows a repeating pattern of textural layers
parallel to the growth surface, which usually consists of the vein wall or minerals from previous
vein stages such as base metal sulfides or arsenian marcasite. The sequence of quartz texture
layers is consistent between veins and matches the sequence in base metal sulfide veins
described above.

Uncommon base and precious metal telluride minerals appear in close association with
roscoelite, native gold grains, and quartz. They are hosted in mosaic-textured quartz layers and
are usually near or in contact with gold grains (Figure 5.3B). Tellurides have a predominantly
anhedral and irregular texture. Both base and precious metal tellurides occur in quartz-roscoelite-
pyrite veins and no patterns were observed in the behaviors, associations, and relative timing of
different telluride minerals.
Native gold grains often have irregular or dendritic shapes and overgrow earlier minerals (Figure 5.3A) or are hosted in quartz (Figure 5.4D), arsenian pyrite (Figure 5.4A, 5.4B), and various combinations of the above (Figure 5.4E). The native gold is found in quartz that contains mosaic texture and is not observed in any other textural band (Figure 5.3, 5.4); it often occurs near or in contact with roscoelite (Figure 5.3F), arsenian pyrite (Figure 5.4B), and telluride minerals (Figure 5.4C). Limited EDS analyses show that the native gold grains are typically about 90% Au or higher, with less than 10% Ag and trace amounts of Te.
Figure 5.3: Photomicrographs of quartz-roscelite-pyrite veins. (A) Galena, pyrite, and dendritic gold. From TUDDH-207 at 307.16 meters. (B) Pyrite, marcasite, native gold, fresh and tarnished altaite, and tarnished coloradoite. From TUDDH-565 at 71.2 meters. (C) Roscoelite bunches, mosaic textured quartz, and pyrite. From TUG-136 at 445.2 meters. (D) Pyrite, roscoelite, and quartz layers in plane polarized and cross polarized light. (E) Pyrite, quartz, and native gold. From TUG-136 at 445.3 meters. (F) Corresponding reflected light image. apy = arsenopyrite, alt = altaite, Au = native gold, co = coloradoite, chal = chalcedonic-textured quartz, cq = crystalline quartz, gn = galena, mrc = marcasite, mq = mosaic quartz, py = pyrite, rsc = roscoelite.
Figure 5.4: Back-scattered electron images Au-mineralized veins. (A) and (B) Arsenian marcasite overprinted by arsenian pyrite, roscoelite, and native gold. from TUG-136 at 446.4 meters. (C) Native gold, altaite, and coloradoite overprinting base metal sulfide vein pyrite. From TUDDH-565 at 71.2 meters. (D) Arsenian pyrite, gold, and quartz overprinting needle-shaped arsenian marcasite and base metal vein pyrite. From TUG-136 at 445.2 meters. (E) Quartz, native gold, and roscoelite overprinting chalcopyrite. From TUG-144 at 104.55 meters. (F) Arsenian pyrite, quartz, and roscoelite overprinting arsenian marcasite. From TUDDH-584W1 at 556.05 meters. apy = arsenopyrite, alt = altaite, Au = native gold, co = coloradoite, gn = galena, mrc = marcasite, py = pyrite, qz = quartz, rsc = roscoelite.
5.4 Carbonate Veins

Carbonate veins are the latest vein type at Tuvatu. They contain calcite, dolomite, ankerite, siderite, and other carbonate minerals, with solid solution between various cations present. Carbonate veins vary in width from <1 mm up to a cm, and carbonate minerals are coarse and crystalline. They crosscut, overprint, and infill all earlier vein types (Figure 5.4).

Figure 5.5: Photomicrographs of carbonate veins. (A) Carbonate vein crosscutting pyrite. From TUG-144 at 104.65 meters. (B) Carbonate minerals filling in an arsenian marcasite vein. From TUG-144 at 117.0 meters. Carb = carbonate minerals, mrc = marcasite, py = pyrite
This chapter summarizes microanalytical work performed on biotite from the Tuvatu deposit. The analysis aimed to unravel compositional differences between primary biotite that forms part of the host monzonite and biotite formed as part of the hydrothermal alteration. In addition, microanalytical results obtained on pyrite and marcasite are presented. These sulfide minerals present in the epithermal-style veins were analyzed to determine whether Au and other epithermal-suite elements are contained in these sulfide minerals, which has potential geometallurgical implications.

6.1 Compositional Analyses of Biotite

The host rocks and mineralized zones of Tuvatu contain a high volume of biotite with variable textures. The Navilawa Monzonite contains magmatic biotite. Biotite associated with potassium feldspar veins (Figure 4.3) occurs proximal to some epithermal veins. Very coarse biotite and host rock pervasively altered to coarse potassium feldspar (Figure 4.11) are ubiquitous in the HT zone (named for the H and Tuvatu lodes; Figure 2.3).

Electron microprobe analyses were conducted to study the composition of the biotite. Of the 194 spot analyses conducted, 111 were of biotite grains visually identified as magmatic and 83 were of biotite grains identified as hydrothermal in origin. Hydrothermal biotite grains have a wide textural range but are coarser and of manifold shapes (Figure 6.11A, B). Magmatic biotite grains are tabular and relatively fine-grained (Figure 6.1 C, D). Multiple spot analyses were conducted in each biotite grain analyzed, with a minimum of one in the grain core and a second in the grain rim.

Table 6.1 shows representative analyses from magmatic and hydrothermal biotite grains. The concentrations of Cr and Ca are close to their respective detection limits. V and Na are present in detectable but small levels and show no significant variation between the two groups (Table 6.1).

Figure 6.2 compares the element contents of primary magmatic and hydrothermal biotite. Magmatic biotite is enriched in Al, Fe, Ti, and water relative to hydrothermal biotite.
Hydrothermal biotite is comparably enriched in Si, Mg, and F. There is no significant variation in V content between hydrothermal and magmatic biotite, nor in Cr, Ca, Na, K, or Cl (Figure 6.2).

Figure 6.3A shows the ratio of Mg to Fe for all analyses. The data falls along an inverse curve. Magmatic biotite analyses have lower Mg/Fe ratios and fall on the lower two thirds of the curve. Hydrothermal biotite analyses have high Mg/Fe ratios and make up the remainder of the curve. There is some overlap at intermediate concentrations.

Hydrothermal biotite contains two to four times the concentration of F when compared to magmatic biotite (Figure 6.3B). Among both groups, F concentration decreases with increasing Fe. Hydrothermal biotite contains slightly less Cl than magmatic biotite (Figure 6.3C). Cl decreases sharply as Mg increases in magmatic biotite and remains mostly level as Mg content continues to increase past 18 to 19 % weight in the hydrothermal biotite.

The overall concentrations of F and Cl in all analyses varies considerably, with F varying between 1 and 4% weight and Cl between 0.02 and 0.16% weight (Figure 6.2).
Figure 6.1: Photomicrographs of biotite. (A) Hydrothermal biotite hosted in potassium feldspar. From TUDDH-481, 40.88 meters. (B) Hand specimen image of HT zone potassic alteration assemblage of coarse ragged secondary biotite, potassium feldspar, and pyrite. From TUDDH-481, 46.75 meters. (C) Plane polarized photomicrograph of magmatic biotite. From TUUDDH-565, 71.0 meters. (D) Crossed polars photomicrograph of magmatic biotite. From TUG-136, 614.6 meters.
Table 6.1: Representative major element analyses of magmatic and hydrothermal biotite.

<table>
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<th>Magmatic</th>
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<td>rim</td>
<td>rim</td>
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<td>14.4</td>
<td>15.1</td>
<td>14.4</td>
</tr>
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<td>&lt;0.0195</td>
<td>&lt;0.0180</td>
<td>&lt;0.0202</td>
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<td>9.64</td>
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<tr>
<td><strong>Cl</strong></td>
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<td><strong>SiO</strong>₂</td>
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<td><strong>F</strong></td>
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<tr>
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</tr>
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Figure 6.2: Major element composition distributions in magmatic and hydrothermal biotite.
Figure 6.3: Major element oxide plots from magmatic and hydrothermal biotite in atoms per formula unit (apfu). (A) Fe/Mg ratios, (B) F/Fe ratios, and (C) Cl/Mg ratios.
6.2 Trace Element Analyses of Pyrite and Marcasite

Inspection of pyrite and marcasite in reflected light microscopy and BSE imaging suggested the presence of pronounced compositional variations within individual grains. EDS analysis suggested that zones of bright BSE contrast contain As levels between 1 and 10% confirming the presence of pronounced compositional zoning. Figure 6.14 shows BSE images of euhedral pyrite from the base metal sulfide vein stage (BM), arsenian marcasite from arsenian marcasite vein stage (AM), and arsenian pyrite from the quartz-roscoelite-pyrite stage (QRP).

Zoning in base metal sulfide vein pyrite is relatively rare. Where present, it occurs as very small isolated As-rich rims along the grain boundaries (Figure 6.4B). Base metal vein pyrite is typically internally homogeneous in BSE. Zoning in arsenian marcasite occurs as both grain boundary parallel narrow zones or thick bands, or as polygonal sectors within grains. Where sector zoning occurs in arsenian marcasite, boundaries between areas of different As content often match with intragranular polygons with unique bireflectance colors (Figure 4.9C). Zoning in arsenian pyrite from quartz-roscoelite-pyrite veins manifests as concentric bands in areas where it has a botryoidal texture (Figure 6.4A) and wavy “brushstrokes” (Figure 6.4B) or numerous densely packed streaky zones (Figure 6.4C) in areas where it has a crustiform or colloform texture.

LA-ICP-MS analyses on all three iron sulfide generations yielded elevated contents of As, Au, and numerous other elements in arsenian pyrite from quartz-roscoelite-pyrite veins (Table 3). In arsenian pyrite, As ranges from 4 to 79,900 ppm (mean: 40,500 ppm; n = 55) and Au ranges from 33 to 2,880 ppm (mean: 991 ppm; n = 55). Arsenian marcasite from the arsenian marcasite vein stage is elevated to a lesser extent in these elements. In arsenian marcasite, As ranges from 4 to 25,000 ppm (mean: 5,310 ppm; n = 35) and Au ranges from 1 to 1,390 ppm (mean: 142 ppm; n = 35). Pyrite from the base metal sulfide vein stage is very low in As and other trace elements. In this pyrite, As ranges from 0.434 to 10,900 ppm (mean: 951 ppm; n = 59) and Au ranges from 0.123 to 105 ppm (mean: 9.48 ppm; n = 59) (Figure 6.5).

As concentrations are the highest among the trace elements detected, analyses elevated in As are typically elevated in other trace elements. Analyses from base metal sulfide vein stage pyrite containing more than 0.1 ppm Au are comparably elevated in Se and Co to other Fe sulfide stages. Arsenian marcasite is elevated in Se and Te to a greater extent than the other Fe
sulfide stages and are more elevated in most elements than base metal sulfide vein pyrite. Arsenian pyrite from quartz-roscoelite-pyrite veins is substantially elevated in As, Au, Cu, Sb, and numerous other elements, typically more so than the two earlier Fe sulfide stages (Figure 6.5).

Figure 6.4: BSE images of pyrite and marcasite grains. (A) AM arsenian marcasite coated in QRP arsenian pyrite. From drillhole TUDDH-526, 464.3 meters. (B) BM pyrite and QRP arsenian pyrite. From drillhole TUDDH-462, 69.42 meters. (C) AM marcasite coated in QRP pyrite. From drillhole TUDDH-528, 268.53 meters. (D) BM pyrite with a small amount of QRP arsenian pyrite. From drillhole TUDDH-545, 128.43 meters. Au detection limit = 0.019 ppm; As detection limit = 0.064 ppm. BM = euhedral pyrite from base metal sulfide vein stage; AM = arsenian marcasite from arsenian marcasite vein stage; QRP = arsenian pyrite from quartz-roscoelite-pyrite vein stage.
Table 6.2: Representative trace element analyses of pyrite and marcasite. Full data are listed in Appendix A. BM = euhedral pyrite from base metal sulfide vein stage; AM = arsenian marcasite from arsenian marcasite vein stage; QRP = arsenian pyrite from quartz-roscocelite-pyrite vein stage.

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<th>767_3</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>&lt;0.147</td>
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<td>29.8</td>
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<td>Ni</td>
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<td>428</td>
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Figure 6.5: Box-and-whisker plots of LA-ICP-MS trace element analyses containing more than 0.1 ppm Au from Fe sulfides. Outliers and far outliers follow the same rules as outlined in Figure 6.2. BM = euhedral pyrite from base metal sulfide vein stage; AM = arsenian marcasite from arsenian marcasite vein stage; QRP = arsenian pyrite from quartz-roscocelite-pyrite vein stage.
In summary, the Au content of Fe sulfides increases with each successive Fe sulfide generation. The majority of high-Au analyses are of the arsenian pyrite found in quartz-roscoelite-pyrite veins. Pyrite from the base metal sulfide vein stage can contain Au but is lower overall than the other two stages. Arsenian marcasite can contain small or large amounts of Au (Figure 6.6A). As content is much more skewed, with quartz-roscoelite-pyrite vein stage pyrite being uniformly As-rich (lending it the “arsenian” descriptor), base metal sulfide vein stage pyrite varying in As content, and arsenian marcasite containing moderately high As but less than quartz-roscoelite-pyrite stage arsenian pyrite (Figure 6.6B).

Figure 6.6: Distributions of analyses of (A) Au content and (B) As content in Fe sulfides. BM = euhedral pyrite from base metal sulfide vein stage; AM = arsenian marcasite from arsenian marcasite vein stage; QRP = arsenian pyrite from quartz-roscoelite-pyrite vein stage.
CHAPTER 7
DISCUSSION

This chapter provides a discussion and interpretation of the field and laboratory data obtained as part of this study, including the developed vein classification, the microscopic investigations, and the major and trace element microanalyses. The data obtained on Tuvatu are compared to other deposits. In addition, implications for exploration at Tuvatu and other alkalic epithermal deposits are discussed.

7.1 Porphyry-Style Veins

This study showed that vein types at Tuvatu can be classified into two broad categories, namely (1) porphyry-style and (2) epithermal-style veins. These two categories of veins have formed at different times during the evolution of the magmatic-hydrothermal system and would have formed at different temperature, pressures, and relative depths below the paleosurface. Veins categorized as porphyry-style occur throughout the Tuvatu deposit but are very common at depth in the deposit. Epithermal veins occur only at shallower elevations but are spatially overlapping with the occurrence of porphyry-style veins.

Porphyry-style gray quartz veins (Figure 4.1A) containing only quartz do not occur at shallow elevations within the deposit. They are texturally distinct from the shallow epithermal quartz-bearing vein types. They contain only gray quartz, vary in width over a hand sample scale, and have nonparallel vein walls. These veins at Tuvatu resemble early A-veins from porphyry Cu deposits as defined by Gustafson and Hunt (1975). The gray quartz veins are surrounded by host rocks that have been affected by potassic alteration, which suggests that they have formed at temperatures exceeding ~500º C (Seedorff et al., 2005). At these high temperatures, the host rocks would have been ductile and no throughgoing fracture network would have been established. The fluids would have been at lithostatic pressures (Monecke et al., 2018).

Porphyry-style potassium feldspar veins (Figure 4.1B) are ubiquitous at all deposit elevations. Previous work reported on the occurrence of hydrothermal potassium feldspar and biotite around epithermal veins at Tuvatu (Scherbarth and Spry, 2006; Schmidt, 2023) and
similar observations have been reported from other alkali epithermal Au deposits, including Cripple Creek (Dye, 2015) and Vatukoula (Kwak, 1990). Potassic alteration is also associated with deep cores of porphyry Cu deposits (Sillitoe, 2010). This study has observed instances of apparent potassium feldspar and biotite alteration haloes surrounding epithermal base metal sulfide veins (Figure 4.2A) and quartz-roscoelite-pyrite veins (Figure 4.2C, 4.2D). It has also observed isolated potassium feldspar veins both at shallow and deep elevations. At shallow elevations potassium feldspar veins occur as isolated planar structures (e.g., Figure 4.1B) and are crosscut by the epithermal veins. At depth they often have a patchy appearance and are overprinted by patchy-textured epidote veins (Figure 4.1D). The HT zone (Figure 2.3) contains pervasive alteration of the Navilawa Monzonite to coarse potassium feldspar and hydrothermal biotite which, due to textural similarity, is interpreted to be a more intense version of the potassic alteration described above (Figure 4.11). This assemblage is crosscut by epithermal veins in the H and Tuvatu lodes (Figure 2.3). Based on these observations, it is concluded here that the potassium feldspar veins and potassic alteration zones are not related to the epithermal veins at Tuvatu and predate the epithermal mineralization.

The porphyry-style Cu sulfide veins (Figure 4.1C) at Tuvatu are interpreted to be analogous to C veins in porphyry Cu deposits, which are veins consisting primarily of Cu sulfides (Dilles and Einaudi, 1992; Gustafson and Quiroga, 1995). The absence of quartz as a gangue in the C veins suggests that these veins in porphyry deposits are formed under conditions of retrograde quartz solubility, which is at ~400 °C at hydrostatic pressure (Monecke et al., 2018). Unlike epithermal base metal sulfide veins, C veins at Tuvatu contain bornite and are associated with chlorite alteration. Sulfide grains in porphyry-style Cu sulfide veins (primarily bornite) are texturally distinct from the base metal sulfides in epithermal base metal sulfide veins. The former contain coarse angular grains (Figure 4.1C) distributed throughout the vein and lack colloform, crustiform, and banded textures. Monzonite-hosted Cu mineralization outcrops at several locations within the core of the Navilawa Caldera. This includes the Kingston mine prospect (Figure 2.2) that contains Cu-bearing oxide or hydroxide minerals and an outcrop of a vein of semi-massive bornite in the Sabeto River. Outcrops at the Central Ridge and Kingston mine prospects show porphyry-style potassic and propylitic alteration (Forsythe et al., 2019).
Epidote veins and patchy epidote alteration zones occur at all elevations in the deposit but are more common at depth (Figure 4.4). They are often found overprinting potassium feldspar veins and zones of potassic alteration. At shallow depth, the epidote is crosscut by epithermal-style veins. The epidote in the monzonite likely formed at temperatures transitional between porphyry and epithermal mineralization under hydrostatic conditions. In porphyry Cu deposits, epidote occurs abundantly in propylitic alteration in the periphery of major upflow zones (Sillitoe, 2010). In the epithermal environment, epidote is stabilized at temperatures exceeding ~250° to 300°C (Browne, 1978; Henley and Ellis, 1983).

### 7.2 Biotite Composition

The EPMA analysis of biotite shows that the secondary hydrothermal biotite that is associated with potassium feldspar in the HT zone as well as that present near porphyry-style potassium feldspar veins is chemically distinct from the primary magmatic biotite contained in the Navilawa Monzonite. Hydrothermal biotite ranges texturally from somewhat fine-grained grains adjacent to porphyry-style potassium feldspar veins to very coarse grained biotite from the HT zone. All hydrothermal biotite shows a consistent pattern of high Mg/Fe ratios (Figure 6.13A), high F and Si content, and low H₂O and Al content (Figure 6.12) relative to magmatic biotite. Both very coarse-grained hydrothermal biotite from potassic alteration zones and fine-grained potassium feldspar vein related hydrothermal biotite show the same chemical composition and patterns.

Studies of biotite composition at porphyry Cu deposits such as Casino in Canada and Bingham as well as Santa Rita in the USA have shown similar compositional differences between magmatic and hydrothermal biotite (Jacobs and Parry, 1979). At Casino, secondary biotite from potassic alteration zones contains higher Mg/Fe ratios and lower Al and Si contents than magmatic biotite (Selby and Nesbitt, 2000). The same patterns hold for numerous other porphyry Cu deposits, with the most reliable factor being higher Mg/Fe ratios in hydrothermal biotite (Parry et al., 1978; Afshooni et al., 2013; Tang et al., 2019).

Previous studies on the chemistry of biotite suggest that halogen concentrations in this mineral can be of genetic significance and have implications for ore-forming processes (Afshooni et al., 2013; Jacobs and Parry, 1979). At Tuvatu, Mg/Cl ratios for hydrothermal biotite
are not distinct from those of magmatic biotite. However, Fe/F ratios differ significantly between the two groups with hydrothermal biotite having much higher F and lower Fe/F ratios. The concentration of F decreases with increasing Fe in hydrothermal biotite (Figure 6.13B), which is a crystal-chemical effect called F-Fe avoidance (Mason, 1992). This suggests that fluids responsible for potassic alteration and formation of hydrothermal biotite were rich in F. Hydrothermal biotite shows the analogous Cl-Mg avoidance effect (Figure 6.13C) with a weaker trend. Magmatic biotite exhibits weak F-Fe avoidance and no Cl-Mg avoidance. This suggests that the hydrothermal fluids responsible for potassic alteration and potassium feldspar veins contained elevated levels of both F and Cl, though it was much richer in F relatively. The intruded magma contained relatively elevated F content compared with Cl, which was not high enough concentration to show the Cl-Mg avoidance effect.

The EMP data on biotite from Tuvatu show that coarse-grained secondary biotite in the HT zone is compositionally indistinguishable from fine-grained hydrothermal biotite occurring in the potassic alteration zones. This confirms that the HT zone is simply a more intense version of the more widespread potassic alteration. This supports the conclusion of Schmidt (2023) that epithermal mineralization at Tuvatu overprints earlier high-temperature porphyry-style potassic alteration. The presence of the more intense potassic alteration of the HT zone at the same elevation as less intense and less pervasive potassic alteration elsewhere in the deposit is potentially explained by the presence of the normal-sense Coreshed Fault (Figure 2.3).

The presence of V in biotite was analyzed to determine its potential as a source of V in roscocelite in quartz-roscocelite-pyrite veins, as well as other V-bearing minerals observed at Tuvatu (Scherbarth and Spry, 2006). V occurs in low but detectable amounts (about 0.1% weight) in both magmatic and hydrothermal biotite, with little variation between the two types (Figure 6.12). Petrographic investigations in this study observed sulfidization of both biotite and magnetite in wall rock around epithermal veins. While the correlation of demagnetization and epithermal veins established in the vein density analysis (Figure 4.5, 4.6, 4.7) suggests that V contained in roscocelite is derived from magnetite, further work is recommended on this subject.
7.3 Epithermal-Style Veins

This study identified four epithermal-style vein types, namely base metal sulfide veins, arsenian marcasite veins, quartz-roscoelite-pyrite veins, and carbonate veins. This expands upon the framework provided by Schmidt (2023) with the addition of arsenian marcasite veins. The epithermal-style veins are host to the Au mineralization at Tuvatu and occur at shallow depths within the deposit overprinting the porphyry-style veins. Epithermal base metal sulfide and quartz-roscoelite-pyrite veins often reopen or crosscut porphyry-style veins, especially potassium feldspar veins.

The shallow, intermediate, and deep elevations at Tuvatu display three different associations between veins, minerals, and sample grades. Roscoelite is a common gangue mineral in alkali epithermal Au deposits (Kwak, 1990; Dye, 2015) and is considered an important indicator of mineralization at Tuvatu (Scherbarth and Spry, 2006; Schmidt, 2023). At the macroscopic scale, roscoelite correlates with high Au grades, but it also appears in areas where Au grades are not high, especially at intermediate depths (Figure 4.5, 4.6, 4.7). At intermediate depths at Tuvatu, base metal enrichment correlates well with the occurrence of epithermal base metal sulfide veins. The intermediate elevation drillhole interval also shows the strongest correlation between base metal and Au grades, as well as between the occurrence of base metal sulfide veins and high-grade Au zones. Alkaline epithermal Au deposits commonly have a base metal sulfide generation that precedes Au mineralization (Kelley et al., 2020). At Tuvatu, this base metal generation is most strongly expressed at the intermediate elevation (Figure 4.6). The paragenetic and spatial relationship between epithermal base metal and quartz-roscoelite-pyrite veins implies a temperature gradient increasing with depth.

In the deep drillhole interval examined, Au shows a somewhat stronger correlation with As and arsenian marcasite than epithermal base metal sulfide veins or quartz-roscoelite-pyrite veins. Quartz-roscoelite-pyrite veins are occasionally observed in areas with no high grade Au. However, many arsenian marcasite veins observed also contain later arsenian pyrite that is the same that occurs in quartz-roscoelite-pyrite veins with low volumes of quartz and roscoelite. Coupled with the fact that arsenian marcasite contains much less Au than pyrite in quartz-roscoelite-pyrite veins (Figure 6.16), this suggests the main Au mineralizing phase – quartz-roscoelite-pyrite veins – expresses itself of multiple styles of mineralization. Veins identified
macroscopically as arsenian marcasite veins could contain an overprint of an arsenian pyrite rich quartz-roscoelite-pyrite vein (e.g., Figure 5.4B).

The shallow drillhole interval examined contains comparably high As (peaks of 2,000-3,000 ppm), but these are not correlated with Au grades, base metal veins, or any epithermal vein occurrences. Deep Au mineralization observed has greater association with arsenian marcasite and As peaks than shallower depths. In general, arsenian marcasite veins were observed more commonly in deeper drillhole intervals throughout Tuvatu. Continued exploration in deeper elevations at Tuvatu will clarify the potential presence of mineralogical zoning with depth: that is, the potential correlation of As grade with arsenian marcasite veins and/or elevated levels of arsenian pyrite in quartz-roscoelite-pyrite veins as opposed to with other As-bearing phases such as tennantite-tetrahedrite. Although a trend has been observed in the holes studied, there is presently not enough data to conclusively state a pattern of increased arsenian marcasite or arsenian pyrite at depth.

7.4 Depositional Mechanism of Epithermal-Style Veins

Macroscopic textures within epithermal base metal sulfide and quartz-roscoelite pyrite veins often feature grain shapes and overgrowth textures suggesting far-from-equilibrium growth conditions. In epithermal base metal sulfide veins, base metal sulfide grains can form vein-scale dendrites, and sphalerite shows evidence of recrystallization and development of colloform bands after deposition. Arsenian marcasite, roscoelite, and arsenian pyrite usually exhibit fine-grained overgrowth textures. Coarse-grained native Au grains observed in drill core sometimes have a branch-like dendritic texture.

Quartz in epithermal base metal sulfide and quartz-roscoelite-pyrite veins has distinct microtextures. The quartz occurs as relatively thick layers having a mosaic texture (Figure 4.8A, 4.8C), which consists of fine interlocking quartz grains with curving and uneven grain boundaries (Zeeck et al., 2021). This layer is the only ore-hosting quartz layer and contains roscoelite, native gold, tellurides, and arsenian pyrite which occur within the quartz matrix (Figure 4.10C). Mosaic quartz is interpreted to be a texture formed due to recrystallization of originally noncrystalline silica. The noncrystalline silica presumably originally consisted of silica microspheres and was gel-like, allowing it to be classified as opal-AG (Taksavasu et al., 2018;
Monecke et al., 2023; Tharalson et al., 2023). In modern geothermal systems, opal-A_g is formed through rapid silica supersaturation, which can be induced by fluid flashing (Monecke et al., 2023). At high magnification, quartz formed from recrystallization of opal-A_g exhibits unique textures. Small doubly-terminated quartz crystals can be observed in the matrix (Figure 7.1A). Roscoelite appears to have grown into a silica matrix instead of into open space due to its relationship with the recrystallized opal-A_g (Figure 7.1B). In addition to layers of mosaic quartz formed from recrystallization of opal-A_g, thin layers of quartz interpreted to be recrystallized from hyalite, also known as opal-A_N are observed. Hyalite commonly forms due to fluid cooling (Flörke et al., 1991). Layers interpreted to have originally consisted of opal-A_N are barren at Tuvatu.

The epithermal base metal sulfide and quartz-roscoelite-pyrite veins at Tuvatu also contain abundant colloform chalcedony and coarse subhedral quartz (Figure 5.2D, 5.3D). The chalcedony is defined by the presence of small fibers that are oriented perpendicular to the opal-A_N growth surfaces. Chalcedony is thought to form through cooling of hydrothermal fluids at

Figure 7.1: High-magnification plane-light photomicrographs of recrystallized opal-A_g and roscoelite. (A) recrystallization of noncrystalline opal-A_g creates doubly-terminated quartz crystals in what is now mosaic quartz. (B) Roscoelite overlapping with recrystallized grain boundaries suggesting growth into silica matrix. (A) and (B) from TUG-136, 445.2 meters.
temperatures <180 °C (Fournier, 1985). The coarse quartz crystals exhibit only primary textures suggestive of original deposition as crystal instead of recrystallization from opal (Dong et al., 1995; Zeeck et al., 2021). Neither layer contains roscoelite or ore minerals.

The presence of ore minerals in the mosaic quartz interpreted to have formed through recrystallization of opal-$\text{A}_G$ has significant genetic implications. Deposition of original opal-$\text{A}_G$ inferred from present day mosaic quartz and the other textural interpretations discussed above are indicative of fluid flashing. Flashing is vigorous and rapid boiling of a hydrothermal fluid due to a sudden pressure drop which vaporizes a high proportion of hydrothermal fluid in a short time and causes supersaturation of silica in the fluid and silica deposition (Taksavasu et al., 2018; Zeeck et al., 2021). The sole occurrence of ore minerals with and inside mosaic quartz at Tuvatu suggests that fluid flashing may be the mechanism for ore deposition. It is envisaged here that silica, roscoelite, pyrite, native gold, and tellurides were deposited via flashing, and the silica later recrystallized to quartz. The dendritic texture of Au grains and other minerals is an indicator of non-equilibrium crystal growth which could be explained by flashing of the ore-forming fluid (Monecke et al., 2023).

The presence of flashing suggests that epithermal-style veining and Au mineralization at Tuvatu occurred at depth and temperature shallower and cooler than porphyry-style alteration and veining. Flashing and deposition of opal-$\text{A}_G$ has been found to occur at 200º to 250º C and vaporstatic (sub-hydrostatic) pressures (Taksavasu et al., 2018). Minerals in epithermal veins with normal crystalline textures such as adularia, euhedral pyrite, chalcedony, and coarse crystalline quartz likely formed during periods of boiling occurring before and between flashing events.

Based on observations in this study, three periods of flashing occurred. Flashing resulted in the formation of the epithermal base metal sulfide veins, the arsenian marcasite veins, and the quartz-roscoelite-pyrite veins. Carbonate veins show no evidence of flashing, and they are the youngest epithermal-style vein stage.
7.5 Sequestration of Gold

Trace element LA-ICP-MS analyses show that pyrite from quartz-roscoelite-pyrite veins is the most elevated in trace elements of the three iron sulfide generations (Figure 6.16). This pyrite is especially rich in As, with typical concentrations between 3% and 6% weight lending it the “arsenian” or “arsenic-rich” descriptor. Marcasite from arsenian marcasite veins averages around 0.5% weight As, and euhedral pyrite from base metal sulfide veins contains very little As.

Pyrite containing As can incorporate a variety of other trace elements including Au, which can occur either as Au nanoparticle inclusions or as a crystal-structure-bound Au cation, both referred to as invisible Au (Deditius et al., 2013). The latter type is capped by a solubility limit in As-rich pyrite which increases with As content. Analyses with Au/As ratios that fall below that limit function contain structure-bound Au. Au/As ratios exceeding this threshold indicate that native gold is present as nanoparticles (Reich et al., 2005).

Most Au contained in analyzed Fe sulfides at Tuvatu is structure-bound. In total, 22 of 239 analyses fall in the Au inclusion field, with the remainder in the solid solution field. Analyses in the inclusion field contain elevated Au content without necessarily containing elevated As content. In the structure-bound field, Au content increases and data points become less scattered as As content increases. Pyrite from the base metal sulfide veins in this field varies in As and Au content but contains relatively low concentrations of both elements, whereas arsenian marcasite and arsenian pyrite from quartz-roscoelite-pyrite veins both track closely to the solubility limit line. Euhedral pyrite from base metal sulfide veins contains the widest spread of Au/As ratios of the three vein types and mostly has the lowest As and Au contents of the three vein types. Arsenian marcasite mostly contains As/Au ratios between about 1:100 and 1:50 with a few lower-As analyses with higher Au/As ratios. It contains intermediate to high As and Au content relative to other vein types. Arsenian pyrite from quartz-roscoelite-pyrite veins mostly contains Au/As ratios between about 1:500 and 1:50 with a few lower-As analyses with higher Au/As ratios (Figure 7.2).
Figure 7.2: Plot of As and Au analyses in pyrite and marcasite from epithermal-style veins at Tuvatu. Only data with Au concentrations plotted. Line is the Au solubility limit for pyrite defined by Reich et al. (2005). BM = pyrite from base metal sulfide veins. AM = arsenian marcasite from arsenian marcasite veins. QRP = pyrite from quartz-roscoelite-pyrite veins.
Arsenian pyrite from quartz-roscoelite-pyrite veins contains the most As of the three generations, and the trace Au incorporated within it occurs almost entirely as structure-bound Au. This aligns with the close association of arsenian pyrite with Au mineralization and suggests that arsenian pyrite in quartz-roscoelite-pyrite veins accounts for some percentage of the total volume of Au contained at Tuvatu. Many alkalic epithermal deposits have one or more similar generations of Au-rich arsenian pyrite or marcasite with substantial variations in the relative amounts of Au contained in pyrite, native gold, or tellurides (Dye, 2015; Pals et al., 2003; Carman, 2003). Figure 7.3 shows Tuvatu Fe sulfide Au/As ratios from the solid solution field plotted with those from other deposits where trace Au in arsenian Fe sulfides is found and limited to values below the solubility curve.

Arsenian pyrite and marcasite containing structure bound Au is known from various deposit types and varies from a minor part of the deposit Au budget to the primary source of Au. High-grade low-sulfidation Au deposits such as Hishikari typically contain mostly free Au (Morishita et al., 2018). Carlin-type Au deposits such as Shuiyindong and Jinfeng contain most or all Au as invisible Au (Liang et al., 2021). Orogenic Au deposits such as Sunrise Dam contain a mixture (Sung et al., 2009), as do alkalic epithermal Au deposits such as Vatukoula (Pals et al., 2003), Cripple Creek (Dye, 2015), and Tuvatu Fe sulfide has broadly similar structure-bound As/Au ratios and correlation slope to Vatukoula, Hishikari, Shuiyindong, and Jinfeng, and contains the same order of magnitude amounts of As and Au as arsenian pyrite from those deposits (Figure 7.3). However, the overall percent of invisible Au in arsenian pyrite and marcasite at these deposits varies with the volume of arsenian Fe sulfide relative to other Au mineralization styles. Vatukoula contains Au mostly as invisible Au in arsenian pyrite, with the small remainder as tellurides and very little native gold (Pals et al., 2003; Börner et al., 2021). Shuiyindong and Jinfeng contain invisible Au in arsenian pyrite as structure-bound cations with no visible/native gold present (Liang et al., 2021). Hishikari contains high grade native gold and electrum mineralization as well as some invisible Au (Morishita et al., 2018).

This study therefore establishes arsenian pyrite, and to a lesser extent arsenian marcasite, as sources of Au in the Tuvatu deposit. Arsenian pyrite contains similar Au content to pyrite at the nearby Vatukoula deposit as well as the low-sulfidation and Carlin-type Au deposits shown, but the varying amounts of native gold, electrum, and Au tellurides at these deposits mean they have differing proportions of total Au budget as invisible Au. The abundance of arsenian pyrite
in quartz-roscoelite-pyrite veins is therefore an important variable in determining the percentage of invisible Au at Tuvatu. Methods for determining this percentage vary from relatively simple calculations using historical average ore grade and an optical estimate of average ore pyrite abundance (Pals et al., 2003) to calculation of invisible Au grades by estimating the volume of different arsenian pyrite generations in a petrographic slide and multiplying the median element concentrations in each generation by a mass value (Dye, 2015). Both methods have high uncertainty; the former relies on historical mining data not available for Tuvatu and mineral abundance values while the latter uses a comparably small sample size and requires assumptions about the geometry of pyrite grains that do not apply to arsenian pyrite in quartz-roscoelite-pyrite veins. No such calculation was performed in this study. However, several conclusions regarding the invisible Au budget at Tuvatu can be drawn.

The presence of native gold and Au tellurides means that not all of the Au is invisible. Coarse visible gold occurrences in drill core correlate with high grades, and micron-scale native gold particles can coexist with arsenian pyrite in quartz-roscoelite-pyrite veins (Figure 5.4A). The overall volume of arsenian pyrite observed has been much greater than that of precious metal tellurides, and the former is likely a more significant source of Au. The amount of invisible Au depends on the volume of arsenian pyrite present in quartz-roscoelite-pyrite veins. As discussed in section 7.3, a vein which macroscopically appears to have only quartz and roscoelite often contains small arsenian pyrite grains, the whole of which appears like rough black quartz. Conversely, a quartz-roscoelite-pyrite vein may appear to contain mostly arsenian pyrite but actually includes roscoelite, quartz, native gold, and tellurides (e.g., Figure 5.4B). This in effect creates both a floor and ceiling of invisible Au to free Au ratio. The volume of grains of native gold observed in drill core and microscopy in this study suggests that the invisible Au budget at Tuvatu is likely much less than that of Vatukoula. Higher proportions of arsenian pyrite will increase invisible Au proportion in a vein. Moreover, Au/As ratios in pyrite at Hishikari were observed to increase with increased sample Au grade (Morishita et al., 2018); this effect, if it occurs at Tuvatu, would increase invisible Au proportion in higher-grade ore zones.
Figure 7.3: Comparison of Fe sulfide Au/As ratios from a variety of Au deposits: Hishikari (low-sulfidation Au, blue); Jinfeng and Shuiyindong (Carlin-type, yellow); Tuvatu (alkalic epithermal Au, purple, this study); Vatukoula (alkalic epithermal Au, green); and Sunrise Dam (orogenic Au, black).

### 7.6 Comparison to Other Alkalic Epithermal Deposits

Alkalic epithermal deposits share a common plate tectonic setting. They form in suprasubduction environments during post-subduction extension above a mantle that has been modified by previous subduction processes (Kelley et al., 2020). Tuvatu is hypothesized to have formed during a period of stalled subduction and reversal to rifting. The deposit is hosted in alkalic intrusive and volcanic rocks. The nearby Vatukoula deposit was formed in the same tectonics setting along the Viti Levu lineament (Anderson and Eaton, 1990). Both deposits are Pliocene in age. Vatukoula is hosted in alkalic volcanic rocks (Anderson and Eaton, 1990; Kwak, 1990). The large-tonnage and high-grade Ladolam deposit in Papua New Guinea is also associated with volcanism associated with post-subduction extension. The Au mineralization (dating to 0.5 Ma) is hosted in arc-related calc-alkalic rocks (Carman, 2003). Cripple Creek in Colorado resulted from back-arc extension and is associated with the intrusion of alkalic rocks and the creation of the Rio Grande rift at around 27 Ma. The Cripple Creek deposit is hosted in
Proterozoic rocks, including the 1.4 Ga Cripple Creek monzonite (Jensen and Barton, 2007; Kadel-Harder et al., 2020).

The epithermal mineralization at Tuvatu overprints earlier porphyry-style veins and associated alteration that have formed earlier in the evolution of the magmatic-hydrothermal system. This relationship may require quick unroofing and erosion or a high rate of uplift as suggested by Schmidt (2023) to allow both hydrothermal events to overprint each other. A similar relationship with early porphyry-style potassic alteration being overprinted by the epithermal mineralization is observed at Ladolam. It has been hypothesized that this is the result of sector collapse of the host volcano, creating a highly juxtaposed telescoping relationship (Carman, 2003, Blackwell et al., 2014). At Vatukoula porphyry-style and epithermal-style alteration have been identified, although the two are concentrated on different sides of the Tavua caldera (Anderson and Eaton, 1990). Cripple Creek contains multiple generations of hydrothermal alteration, including earlier high-temperature potassic alteration and later lower temperature veining and associated wall-rock alteration (Kadel-Harder et al., 2020). The relationships observed at Tuvatu do not appear to be an exception.

Alkaline epithermal deposits are known for high-grade ore zones forming veins and low-grade disseminated ores. Tuvatu primarily contains Au in narrow high-grade veins. In contrast to some of the largest alkaline epithermal deposits, Au mineralization at Tuvatu does not occur in extensive disseminated zones. Mineralization at Cripple Creek, Vatukoula, and Ladolam all include both a high-grade vein style and low-grade disseminated ore style. At Cripple Creek and Vatukoula, the vein ore, which is now mostly mined out, consisted of electrum and a variety of base and precious metal tellurides. The vein ore occurs within the lower-grade disseminated ore, which consists of native Au at Cripple Creek and Au in arsenian pyrite at Vatukoula (Kadel-Harder et al., 2020; Pals et al., 2003). At Ladolam, much of the Au is structurally bound by arsenian pyrite and marcasite in breccias, with later Au-poor epithermal quartz-calcite veins (Carman, 2003).

At Tuvatu, Au mineralization is commonly associated with the occurrence of roscoelite as a gangue mineral. A similar assemblage is observed at Vatukoula, and high Au grades are noted in roscoelite-bearing veins that also contain high concentrations of telluride minerals (Anderson and Eaton, 1990). Roscoelite is also found at Cripple Creek but does not occur in high
concentrations (Jensen and Barton, 2007; Dye 2015). Roscoelite is not an important mineral at other alkali epithermal Au deposits such as Ladolam (Carman, 2003).

The research by Schmidt (2023) as well as the petrographic investigations of this study suggest that Au deposition at Tuvatu was caused by fluid flashing. Rapid flashing of liquid to vapor caused the deposition of silica and resulted in the formation of ore mineral dendrites. Fluid flashing has not previously been discussed as an ore-forming process in alkali epithermal deposits although the flashing has been considered to be the potential cause for ore brecciation at Ladolam (Carman, 2003). A number of recent studies suggest that flashing is more widespread in epithermal deposits than previously recognized (Scott and Watanabe, 1998; Zeeck et al., 2021; Tharalson et al., 2023).

7.7 Fluid Evolution

The variety of vein types described in this study indicates the magmatic-hydrothermal fluid at Tuvatu was evolving in chemistry, temperature, and pressure conditions over time. The following section outlines possible geologic changes and events potentially responsible for this evolution.

The primary division of vein types at Tuvatu is porphyry-style and epithermal-style. The two formation environments require very different pressure and temperature conditions. As discussed above, their close spatial relationship requires a mechanism for changing from the porphyry to the epithermal environment. What this mechanism may have been at Tuvatu has implications for the nature of the magmatic-hydrothermal fluids: namely, whether the porphyry-style and epithermal-style veins formed from one causative intrusion, indicating a telescoped system, or whether two causative intrusions caused the two different vein type groups, indicating overlapping but not telescoping.

In telescoped magmatic-hydrothermal systems, the porphyry and epithermal environments and all associated alteration styles can occur less than 0.5 km from one another vertically. Telescoping involves unroofing and epithermal overprinting of the mineralizing porphyry itself. Telescoping may be caused by quick erosion or collapse of a volcano above the magmatic-hydrothermal system. By contrast, non-telescoped systems have a range of alteration and vein styles spread across multiple km of vertical extent (Sillitoe, 1994).
This study has observed the ubiquitous presence of two vein types categorized as porphyry-style veins at shallow elevations juxtaposed with epithermal-style veins: epidote veins and potassium feldspar veins. However, gray quartz veins and Cu-sulfide veins (inferred to be equivalents of porphyry A veins and C veins, respectively) occur beneath 800 meters of the present-day surface of the deposit. Cu-sulfide veins also occur at shallow elevations in the HT zone, where they are crosscut by epithermal-style veins (the H and Tuvatu lodes), epidote veins, and potassium feldspar veins. The Cu-sulfide veins, and by extension the intense potassic alteration in the HT zone, are likely present at shallow depths due to fault slip along the Coreshed fault or relatively proximity to the porphyry-style causative intrusion. For these two vein type groups to have been created by the same intrusion, a process would need to effect geologically near-instantaneous erosion of at least one km of rock during the life of a single intrusion, which would cool in ~100 ka. As stated above, such a process would be related to either very quick erosion of, or sector collapse of, a volcano.

This study views the latter process as improbable. The Navilawa Caldera topographic feature lacks the size or vertical relief to be considered a volcanic caldera without additional work; it is 4–6 km in diameter and much smaller than the Tavua caldera that hosts the Vatukoula deposit, which is 12–14 km in diameter. The Tavua Caldera has much greater topographic relief on the inside of the depression than the Navilawa Caldera, which slopes more gently and appears that it could be an extension of the ridge of the Sabeto Mountains range to the west. While the former process of quick erosion would be possible, and erosion rates would be enhanced due to the warm and wet climate of Fiji, the rate required would be extremely high.

The other principal evidence against telescoping is rather straightforward: epithermal mineralization does not overprint porphyritic rock with very high-temperature or even late magmatic quartz veins and potassic alteration, as is stated to be an indicator of telescoping by Sillitoe (1994). The overprinting relationship that occurs in the HT zone does not occur in the rest of Tuvatu; moreover, there are no instances of gray quartz veins – A veins – overprinted by epithermal veins. This study expresses fair confidence in two causative intrusions and overlapping of the two environments with a significant gap in time as opposed to a single causative intrusion and telescoping of the two environments.

The higher-temperature porphyry-related fluids are argued above to be generated by an earlier intrusion distinct from the later epithermal-mineralizing intrusion. The porphyry-style
veins show an evolution indicative of cooling and isothermal collapse of the causative intrusion, with the gray quartz veins and Cu-sulfide veins being roughly analogous to porphyry Cu A-veins and C-veins, respectively. The chemistry of this fluid was likely not related to the epithermal-mineralizing fluid which came later.

The chemistry of the mineralizing fluid at Tuvatu evolved over time after the transition from the porphyry to epithermal environment. The mineralogy of each successive vein type indicates cooling took place between flashing events. Minerals contained within the veins also indicate changes in fluid chemistry. The three epithermal Fe sulfide generations – euhedral pyrite from base metal sulfide veins, arsenian marcasite from marcasite veins, and arsenian pyrite from quartz-roscoelite-pyrite veins – serve as indicators of fluid chemistry at their respective times of deposition. Each successive generation increased in As and Au content (as well as other trace elements), with the last containing the most As and Au (Figure 6.6). Most trace element analyses of arsenian pyrite from quartz-roscoelite-pyrite veins had a high As/Au ratio indicating crystal-structure bound Au ions (Figure 7.1); this means that the As and Au content of the fluid is preserved and suggests that the primary mineralizing fluid responsible for creating quartz-roscoelite-pyrite veins was also As rich relative to those responsible for the previous epithermal vein types. The fluids that formed the marcasite contains moderate amounts of As which is evidenced by trace element analyses (Figure 6.6) and the presence of arsenopyrite in a small number of marcasite veins. The fluids that formed the base metal sulfide veins were likely As-poor, due to the relatively small amount of As contained in the pyrite in base metal sulfide veins. As and Au incorporation in pyrite is observed to increase with decreasing temperature, at least from ~500º C to ~200º C (Deditius et al., 2014). The epithermal veins all likely formed at the low end of this range; additionally, all three Fe sulfide generations contain mostly structure-bound invisible Au ions and are close to the solubility limit in pyrite (Figure 7.1). This suggests the increase in Au and As content in pyrite is due mostly to fluid chemistry change – higher Au and As in quartz-roscoelite-pyrite veins – as opposed to increase in trace element incorporation.

7.8 Exploration Implications

As described above, overprinting relationships between the porphyry and epithermal mineralization at Tuvatu appears to be a characteristic common to several alkalic epithermal
deposits. However, it is possible that both styles of mineralization can also occur spatially separated. For this reason, exploration strategies for alkali epithermal deposits should not be built on the assumption that porphyry-style alteration needs to be overprinted by epithermal veins or, likewise, that porphyry-style alteration must be present in epithermal vein zones. It is especially important to note that the occurrence of potassic alteration, which is widely viewed to be an exploration vector in the porphyry environment (Sillitoe, 2010), does not have a direct relationship with the epithermal veining as this style of alteration records a period of fluid flow at much higher temperatures and pressures than those that prevailed during the formation of the epithermal Au mineralization.

Alkali epithermal deposits form low-grade, large-tonnage or high-grade, low-tonnage deposits. Low-grade, large-tonnage deposits are characterized by ore zones containing disseminated ore minerals. This contrasts with the high-grade, low-tonnage deposits in which mineralization is vein-controlled. The nature of the wall-rocks will exert a strong control on the style of mineralization. The Navilawa Monzonite is a highly competent rock and thus hosts primarily vein-controlled mineralization. Other rock types that may exist within the Navilawa caldera such as pyroclastic rocks may have been more permeable allowing the formation of disseminated ores. During brownfields exploration, the presence of high-grade vein-style mineralization should not be the exclusive focus and indicators of a potential low-grade disseminated orebody should be carefully catalogued.

In vein-dominated deposits such as Tuvatu, classification of different vein types is important during exploration to predict grade distribution in drill core. The use of vein classification assists in sample grade estimation prior to geochemical assay, allowing for quick turnaround of exploration decisions. This study provides a blueprint for how vein classification can be developed, tested, and implemented.

The research performed here demonstrates that robust vein classification is possible using macroscopic observations once paragenetic relationships have been constrained through a combination of macroscopic and microscopic techniques. The different vein generations at Tuvatu record the overall evolution of the magmatic-hydrothermal system and generally formed as the system was undergoing a retrograde evolution. The early, high temperature veins are overprinted by later, low-temperature veins. When determining vein sequence, it is of paramount importance to consider these overprinting relationships as many of the veins are composite veins
that have reopened one or multiple times throughout the evolution of the magmatic-hydrothermal system. In developing classification, one needs to work backward from the low-temperature to the high-temperature veins to understand vein paragenesis and focus the study on veins that are apparently not the result of complex overprinting relationships. Vein classification should not be built based on the assumption that all minerals visible in hand specimen form an assemblage as paragenetic relationships can be complex and only visible at the thin section scale.

At Tuvatu, gold is not always sufficiently coarse to be easily visible in core or hand sample. Being able to recognize distinctive gangue minerals such as the roscoelite in quartz-roscoelite-pyrite veins has proven to be a useful proxy, as has distinguishing macroscopically between different Fe sulfide generations. The use of vein classification, once established and tested, also simplifies the core logging process and the logs themselves. It speeds up logging and increases consistency between different logging geologists, enabling construction of a 3D model showing the distribution and density of vein types. The use of vein classification minimizes the need for verbose and repetitive descriptions in core logs.

Understanding structure and vein orientation at Tuvatu and similar deposits is of great importance in exploration. The relative narrowness of both the lodes themselves and the alteration selvages means that the design of drilling campaigns is challenging. Detailed understanding of the subsurface geology is required to allow resource calculation and mine planning. As a next step it would be important to better understand the structural context of the different vein types and to understand differences between stockwork veins, veins that are more throughgoing, and veins forming arrays defining the steeply dipping and shallow lodes.

The observations of this study suggest that Au mineralization is entirely confined to the epithermal-style veins suggesting that mineralization took place in brittle rocks (<400°C). The occurrence of fluid flashing, which involves a drop from hydrostatic to vaporstatic conditions due to the generation of large amounts of vapor, requires interconnectivity of the mineralized veins to surface at the time of mineralization. In some large alkalic epithermal deposits, mineralized fracture networks are connected to backbone veins or breccia zones formed as a result of the hydrothermal eruptions caused by fluid flashing. Discovery and characterization of such root zones is an important goal for exploration in an alkalic epithermal system.
CHAPTER 8
CONCLUSIONS

This chapter summarizes the key findings of this study and provides suggestions for further work at Tuvatu. The findings of this research have implications to the understanding of alkalic epithermal systems and the development of exploration strategies for this deposit type.

8.1 Research Findings

1. The Tuvatu deposit represents a magmatic-hydrothermal system in which early porphyry-style veins and associated alteration hosted by a monzonite have been overprinted by later epithermal-style veins. The overprinting relationships require that these two stages of veining are separate in time and indicates unroofing (e.g., caldera collapse or erosion) and/or uplift occurred between the porphyry and epithermal style veins, as each style was formed at drastically different pressure and temperature conditions. The nature of the Tuvatu deposit is comparable to world-class alkali deposits such as Porgera and Ladolam (Sillitoe, 1994). It has significant implications to exploration as the existence of porphyry-style mineralization near surface cannot be ruled out. This is consistent with the occurrence of monzonite-hosted Cu-rich veinlets in outcrops resembling porphyry deposit stockworks in the vicinity of the Tuvatu deposit.

2. This study adds to the understanding of the vein sequence of the Tuvatu deposit. The proposed classification of different vein types makes a clear distinction between porphyry-related high-temperature veins and epithermal-type veins that have been formed at lower temperatures. This study also shows that Au grades at Tuvatu can be directly correlated with the occurrence of a texturally distinct type of epithermal veins. The different vein types define an overall cooling trend of the magmatic-hydrothermal system. The developed classification scheme has been tested extensively during core logging and can now be applied routinely at Tuvatu.

3. This study highlights the importance of synthesizing observations across scales in the development of vein classifications. Apparently complex paragenetic relationships visible in hand specimen could be resolved at the thin section scale when considering that many of the earlier high-temperature veins have experienced reopening during more recent
episodes of low-temperature fluid flow. Without petrographic work some reopening of
the veins would not be easily recognizable.

4. Fluid flashing is an important mechanism for high-grade Au ore formation in the
epithermal veins. Quartz present in the veins was originally deposited as opal-A_G.
Recrystallization of that noncrystalline silica resulted in the formation of mosaic quartz in
the veins. In addition, recrystallized opal-A_N and chalcedony have been recognized in
epithermal-type veins. Deposition of these silica types is interpreted to be related to the
occurrence of rapid silica supersaturation during fluid flashing. Ore minerals commonly
have dendritic and irregular shapes and are surrounded by the originally noncrystalline
silica matrix. The occurrence of dendritic ore minerals suggests that Au deposition
occurred under far-from-equilibrium conditions during two-phase flow within the veins.
The textural relationships suggest that mineralization coincided with short-lived periods
of fluid flashing induced by a pressure drop within the fracture network. Given the fact
that most veins at Tuvatu are narrow and irregular in shape, potentially providing
throttling points during fluid flashing, the existence of one or multiple major backbone
veins at Tuvatu cannot be ruled out.

5. This study has implications for ge metallurgy. The presence of coarse visible gold in drill
core, even in relatively high volumes, does not preclude Au sequestration into sulfide
minerals in the epithermal veins. This study observes a close coexistence of native gold
with auriferous arsenian pyrite. Although not easily quantifiable, the importance of
structurally bound Au in the arsenian pyrite needs to be better understood to optimize
recovery of a future mine at Tuvatu.

8.2 Recommendations for Future Work

Based on the research conducted, a number of recommendations for future work are
made:

1. There is currently only limited information on the absolute ages of the Tuvatu deposit and
its host rocks. As part of this study, a sample of hydrothermal biotite from the HT zone
has been submitted for Ar/Ar dating to the U.S. Geological Survey, but the results were not obtained in time to be included in this thesis. It is recommended here to conduct a comprehensive geochronological study to better constrain the absolute age of mineralization. This could be potentially achieved by Re/Os dating of some of the sulfide phases contained or additional work on alteration phases. As the host rocks are alkalic in composition, it may prove difficult to separate zircon for U/Pb dating. However, least-altered monzonite and some of the volcanic rocks may contain magmatic biotite or amphiboles suitable for Ar/Ar dating.

2. Previous work has emphasized that the Tuvatu deposit is located within the Navilawa Caldera. However, insufficient geological mapping exists to demonstrate that the topographic depression in which Tuvatu is located indeed represents a caldera. Better understanding of the volcanological and structural setting of Tuvatu may assist in brownfields exploration. However, the dense vegetation and deep soil profile may limit mapping to creeks where outcrops exist.

3. It is recommended here to conduct a comprehensive hyperspectral survey of core to better identify spatial variations in alteration mineralogy and to be able to correlate Au grade with the distribution of alteration minerals. This may provide important insights into the nature of the magmatic-hydrothermal system at Tuvatu.

4. Finally, it is recommended to conduct a detailed survey on the V-bearing minerals associated with the Au-bearing precious metal veins. Previous work has shown that roscoelite occurs together with karelianite, vanadian muscovite, Ti-free nolanite, vanadian rutile, and schreyerite at Tuvatu (Scherbarth and Spry, 2006). An attempt should be made to identify how common these minerals are relative to roscoelite and their distribution within the deposit, and the source of excess V leading to formation of these minerals.

5. The Navilawa Monzonite occurs in two textural variations: an equigranular monzonite and porphyritic micromonzonite. Additional work could determine if there is a relationship between grain size and magmatic biotite composition in the Navilawa Monzonite.


Morishita, Y., Shimada, N., and Shimada, K., 2018, Invisible gold in arsenian pyrite from the high-grade Hishikari gold deposit, Japan: Significance of variation and distribution of Au/As ratios in pyrite: Ore Geology Reviews, v. 95, p. 79–93.


Taksavasu, T., Monecke, T., and Reynolds, T., 2018, Textural characteristics of noncrystalline silica in sinters and quartz veins: Implications for the formation of bonanza veins in low-sulfidation epithermal deposits: Minerals, v. 8, 331.


## APPENDIX A

**SUPPLEMENTAL FILES**

<table>
<thead>
<tr>
<th>File name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample_list.csv</td>
<td>List of samples and thin sections</td>
</tr>
<tr>
<td>Vein_density.csv</td>
<td>Spreadsheet listing vein density data for three drillhole intervals</td>
</tr>
<tr>
<td>Bt_epma.csv</td>
<td>EPMA spot analyses of biotite</td>
</tr>
<tr>
<td>Py_laicpms.csv</td>
<td>LA-ICP-MS trace element analyses of Fe sulfides</td>
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