THE ROLE OF FLASHING IN THE FORMATION OF HIGH-GRADE, LOW-SULFIDATION EPITHERMAL DEPOSITS: A CASE STUDY FROM THE OMU CAMP IN HOKKAIDO, JAPAN

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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ABSTRACT

The Miocene low-sulfidation epithermal Hokuryu and Omui deposits of the Omui camp in northeastern Hokkaido, Japan, are small past-producers of high-grade Au and Ag ores. The quartz textures and distribution of ore minerals within vein samples were studied to identify the processes that resulted in the bonanza-grade precious metal enrichment in these deposits. Correlative microscopy involving optical microscopy, cathodoluminescence microscopy, and scanning electron microscopy was employed. The research shows that vein quartz exhibits a wide range of textures that represent primary growth patterns. In addition, textures indicative of recrystallization of silica precursor phases and replacement of other vein minerals were recognized. In the high-grade vein samples, which are crustiform or brecciated in hand specimen, ore minerals almost exclusively occur within distinct dark gray to black quartz bands. These bands alternate with barren, white to light gray quartz suggesting that ore deposition was episodic. The bands hosting the ore are colloform and composed of mosaic quartz. High-magnification microscopy reveals the presence of densely packed relic microspheres providing evidence that the mosaic quartz formed through recrystallization of a non-crystalline silica precursor phase. The ore minerals occur interstitially to the densely packed microspheres indicating that ore deposition was contemporaneous to the agglomeration of the microspheres. These colloform bands with relic microsphere textures are interpreted to have formed through rapid silica and ore mineral deposition within the veins at high temperatures, presumably involving temporary flashing of the hydrothermal system. Limited fluid inclusion data suggests that silica deposition occurred at a temperature of over 245-250°C implying that flashing occurred to a depth of over 400 m below the paleosurface. The ore-hosting colloform bands composed of agglomerated microspheres are texturally distinct from barren, colloform bands containing fibrous chalcedonic quartz bands formed at lower temperatures. The findings of this study are consistent with models linking the high-grade precious metal enrichment in low-sulfidation epithermal veins to episodic flashing of the hydrothermal system and have significant implications to the design of exploration strategies for bonanza-grade low sulfidation epithermal vein deposits.
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CHAPTER 1

THE ROLE OF FLASHING IN THE FORMATION OF HIGH-GRADE, LOW-SULFIDATION EPITHERMAL DEPOSITS: A CASE STUDY FROM THE OMU CAMP IN HOKKAIDO, JAPAN

1.1 Introduction

The Miocene low-sulfidation epithermal deposits of the Omu camp in the Kitami region of northeast Hokkaido, Japan, represent small past-producers of high-grade Au and Ag ores (Watanabe, 1995). Located in the back-arc region of the present Kuril volcanic arc front, the Kitami region is one of Japan’s major epithermal provinces. Historic precious metal production in the area yielded a total of ~2.9 Moz Au and ~44.7 Moz Ag (Watanabe, 1995), with minor past production of base metals and mercury (Maeda, 1997).

High-grade ore in the low-sulfidation epithermal deposits of the Omu camp is confined to crustiform banded and brecciated quartz veins. Within the ore samples, precious metal mineralization occurs in dark gray to black quartz bands, referred to as ginguro bands (cf. Takeuchi and Shikazono, 1984; Matsuhisa and Aoki, 1994; Shimizu et al., 1998; Faure et al., 2002; Leavitt et al., 2004; Sanematsu et al., 2006; Camprubí and Albinson, 2007; Shimizu, 2014). These high-grade ginguro bands alternate with barren quartz bands suggesting that precious metal enrichment was episodic. The reasons for the episodic nature of the ore-forming processes are currently not well understood in the deposits of the Omu camp and comparable low-sulfidation epithermal deposits worldwide. Previous research at the Sleeper deposit in Nevada and McLaughlin in California suggests that gold in ginguro bands can occur as dendrites that are intergrown with fine-grained colloform quartz formed through recrystallization from a gel-like, non-crystalline silica precursor phase (Saunders, 1990, 1994, 2012; Saunders and Schoenly, 1995; Sherlock and Lehrman, 1995; Saunders et al., 2011). Moncada et al. (2012) and Shimizu (2014) proposed that rapid deposition of the non-crystalline precursor may occur as a result of flashing of the ore-forming hydrothermal system.

The present contribution reports on a study carried out to determine the processes that resulted
in the formation of ginguro bands in high-grade vein material from the Omu camp. Quartz textures in the
vein samples were studied through a combination of optical microscopy, optical cathodoluminescence
microscopy, and fluid inclusion petrography. The study of the ore mineralogy using reflected light
microscopy and field-emission scanning electron microscopy showed that the ore minerals primarily occur
only in two of the texturally distinct types of quartz. Ore minerals are present in colloform quartz consisting
of relic microspheres initially composed of a non-crystalline silica precursor phase and in bands of
microcrystalline and mosaic quartz, which are interpreted to have formed as a result of more intense
recrystallization of the non-crystalline silica precursor phase. Textural and fluid inclusion evidence
suggests that the formation of these ginguro bands is caused by the rapid deposition of silica and ore
minerals at high temperatures, which is consistent with models linking the formation of bonanza-grade
precious metal grades in low-sulfidation epithermal deposits to the occurrence of short episodes of fluid
flashing.

1.2 Geological Setting

Subduction of the Pacific plate along the eastern margins of the Eurasian and Okhotsk plates was
initiated in the Eocene resulting in the development of the Northeast Japan and Kuril arcs (Jackson et al.,
1975). Back-arc extension during the Oligocene to middle Miocene caused the formation of the Japan,
Yamato, and Kuril basins (Kimura and Tamaki, 1986). During the early to middle Miocene, the Eurasian
and Okhotsk plates collided. This collision is recorded by the deposition of coarse clastic rocks in the
Kitami region of northern Hokkaido and a hiatus in volcanic activity along the Kuril arc (Watanabe, 1995).

Back-arc extension in the Kitami region of northern Hokkaido occurred since the middle to late
Miocene. Volcanism, mainly comprised of andesite and rhyolite with minor amounts of basalt and dacite,
occurred along N-S structural trends in the eastern Omu-Kamikawa and western Monbetsu-Rubeshibe
zones, shown in Figure 1.1 on page 5 (Watanabe 1995, 1996). Volcanism commenced at around 14 Ma
in the northern part of both zones and gradually migrated to the south with back-arc volcanism occurring
until 9 Ma in the Omu-Kamikawa zone and 6 Ma in the Monbetsu-Rubeshibe zone. In the Omu-Kamikawa
zone, felsic volcanic rocks overlie basaltic andesites and are in turn overlain by andesite. Rhyolite lavas
predominate in the north whereas welded deposits of dacitic composition are abundant in the south. In
the Monbetsu-Rubeshibe zone felsic lavas and pyroclastic rocks overly andesitic deposits. At 6 Ma,
bimodal volcanism in the back-arc was terminated, with most of the subsequent Pliocene to Quaternary volcanism only occurring near the present arc front (Watanabe 1995, 1996).

Middle to late Miocene hydrothermal activity in the Kitami region was closely associated with felsic volcanism in the back-arc of the Kuril arc. Hydrothermal activity resulted in the formation of a large number of low-sulfidation epithermal deposits, most of which are vein-type deposits although disseminated-type ores are also present. The ore zones are typically located near or within felsic intrusions and lavas, although some of the mercury deposits also occur in sedimentary basement rocks (Watanabe 1995, 1996). The ages of the epithermal deposits closely follow the volcanic activity and shifted over time from north to south. Individual deposits yielded K-Ar ages from adularia ranging from 14.3±0.3 to 4.51±0.62 Ma (Watanabe 1995, Maeda, 1997).

1.3 Geology of the Omu Camp

The Omu camp was mapped in 1966 by the Geological Survey of Hokkaido providing the foundation for the present understanding of the local geological setting of the low-sulfidation epithermal deposits, shown in Figure 1.2 on page 6 (Suzuki et al., 1966). Mapping showed that basement rocks locally outcrop in the northwestern part of the Omu camp (Suzuki et al., 1966). These rocks belong to the Mesozoic Hidaka Supergroup, which forms part of the N-trending Hidaka-Tokoro metamorphic belt transecting much of central and northern Hokkaido (Okada, 1982; Watanabe and Iwata, 1987). In the study area, the Hidaka Supergroup comprises primarily slate with thin intercalated sandstone beds.

The oldest Miocene rocks in the Omu camp form part of the 14.3±1.0 Ma (Watanabe, 1995) Kamiômu Formation. This formation crops out extensively in the southern part of the camp where it is composed of sandstone, shale, breccia, tuff, and minor conglomerate that have a N-S strike and dip shallowly (10–20°) to the east (Suzuki et al., 1966). The Kamiômu Formation is overlain by plagioclase-phric basaltic andesite of the Nakahoronai Lava, which has been dated at 12.9±0.5 Ma (Watanabe et al., 1991). The slightly younger Motoineppu Lava yielded an age of 12.0±0.9 Ma (Koshimizu and Kim, 1987). This lava is of dacitic to rhyolitic composition and contains quartz, plagioclase, and biotite phenocrysts (Takanashi et al., 2012). It represents the main host of low-sulfidation epithermal deposits in the Omu camp (Figure 1.2; Suzuki et al., 1966). The augite-hypersthene-phric Inashibetsu Lava crops out extensively in the southern part the camp (Suzuki et al., 1966) and has been dated at 9.8±0.5 Ma
Augite-hypersthene-phyric andesite of the Miocene (Watanabe, 1995) Maru-yama Lava comprises coherent and breccia facies that are mostly exposed in the western and southern parts of the camp.

Sandstone, shale, and tuff of the Pliocene Onishi Formation occur in the southeast. Augite-hypersthene-phyric andesite of the Kamiômu Lava represents the youngest Pliocene deposits in the area. Pleistocene augite-hypersthene-phyric andesite of the Numa-dake Lava occurs only in the northwestern part of the Omu camp. Pleistocene and Holocene cover rocks include terrace and floodplain deposits (Suzuki et al., 1966).

The Hokuryu deposit was the most significant mine in the Omu camp (Figure 1.2). Discovered in 1918, the mine produced a total of ~300,000 metric tons of ore for an estimated ~68,000 oz Au and ~370,000 oz Ag between 1928 and 1943. High-grade ores were recovered from a NE-striking vein zone over a strike length of 320 m and down dip for over 160 m. The Omui deposit in the eastern part of the camp was discovered in 1919 following earlier placer gold recovery in the area. Mining from 1920 to 1921 yielded 762 metric tons of ore grading 28.5 g/t Au and 562 g/t Ag. From 1925 to 1928 a total of 22,300 metric tons of ore were extracted for a total of ~12,400 oz Au and ~280,000 oz Ag. Minor artisanal mining was conducted in 1933. The major E-W-striking quartz vein at Omui, the so-called Honpi vein, was exploited over a strike length of 120 m from four working levels of a 70 m deep shaft. The old workings are today collapsed to surface. Additional minor production in the Omu camp is reported to have occurred at the Sakinyama and Omu occurrences (Figure 1.2). Ongoing exploration efforts in the Omu camp mostly focus on the Omui area (Irving Resources, press releases January 22 and February 22, 2018).

A large sinter terrace, referred to as the Otoineppu sinter, is located northwest of the town of Omu (Figure 1.2). The sinter crops out over a strike length of at least 1 km and forms a small ridge that is up to 10 m in height, paralleling a major NE-trending fault. A sulfide-bearing sample from the base of the outcrop area returned 14.6 g/t Au and 50.8 g/t Ag with 676 ppm As, 1,675 ppm Sb, 93 ppm Se, and >100 ppm Hg (Irving Resources, press release September 21, 2017). Artisanal mining of the Otoineppu sinter is conducted locally as the material is widely used for landscaping in the Omu area.
Figure 1.1 Geological setting of low-sulfidation epithermal deposits in the Kitami region of northeastern Hokkaido. Deposits occur in the Omu-Kamikawa and Monbetsu-Rubeshibe extensional zones (based on the 1:50,000 and 1:200,000 geological map series of the Geological Survey of Japan).
Figure 1.2 Geologic map of the Omu camp (modified from Suzuki et al., 1966).
1.4 Materials and Methods

The present study is based on the sampling of epithermal vein material in the Omu camp. Sampling was conducted in 2016 and 2017 at the historic Omui and Hokuryu mines. A total of 19 samples were taken from both vein float and host rock outcrop (Table 1.1 beginning on page 8). The samples collected were cut perpendicular to the vein walls, and representative billets were obtained to study the vein textures. Thick (80 µm) polished sections were prepared for petrographic and fluid inclusion analysis.

The thick sections were initially studied by optical microscopy in transmitted light using an Olympus BX51 microscope. Quartz textures present in the samples were classified using the nomenclature proposed by Adams (1920), Bobis (1994), Dong et al. (1995), Moncada et al. (2012), and Shimizu (2014). The relative abundances of the different quartz textures were estimated visually in the different samples. Following the transmitted light microscopy, the samples were examined in reflected light to identify the ore minerals. Point counting was conducted along traverses to quantify the proportion of ore minerals hosted by the different quartz textures.

Selected sections were carbon coated to study the different quartz textures by optical CL microscopy. An HC5-LM hot cathode CL microscope by Lumic Special Microscopes, Germany, was used and operated at 14 kV and a current density of ca. 10 µA mm$^{-2}$ (Neuser, 1995). CL images were captured with a high sensitivity, double-stage Peltier cooled Kappa DX40C CCD camera. Acquisition times of CL images of quartz typically ranged from 8 to 10 seconds.

Fluid inclusion petrographic investigations were performed on the thick sections using the Olympus BX51 microscope. Microthermometric investigations were performed on fluid inclusion assemblages hosted by quartz following the procedures described by Goldstein and Reynolds (1994). The microthermometric measurements were conducted using a FLUID INC.-adapted U.S. Geological Survey gas-flow heating and freezing stage. The accuracy of the heating method was approximately ± 2°C at 200°C while freezing temperatures were accurate to ± 0.5°C.

The ore mineralogy of the vein samples was studied using a TESCAN MIRA3 LMH Schottky field emission-scanning electron microscope (FE-SEM) equipped with a single-crystal YAG backscatter electron (BSE) detector. Imaging was performed at a working distance of 10 mm and an accelerating voltage of 15 kV. Semiquantitative chemical analyses of minerals were performed by energy-dispersive X-
ray spectroscopy (EDS) using an attached Bruker XFlash 6/30 silicon drift detector.

The samples were then analyzed using automated scanning electron microscopy at the Colorado School of Mines to determine their mineralogy. The samples were loaded into the TESCAN-VEGA-3 Model LMU VP-SEM platform and the analysis was initiated using the control program TIMA3.

Four energy dispersive X-ray (EDX) spectrometers acquired spectra with a beam stepping interval (i.e., spacing between acquisition points) of 30 µm, an accelerating voltage of 25 keV, and a beam intensity of 14. Interactions between the beam and the sample were modeled through Monte Carlo simulation. The EDX spectra were compared with spectra held in a look-up table allowing an assignment to be made of a composition at each acquisition point. The assignment makes no distinction between mineral species and amorphous grains of similar composition. Results were output by the TIMA software as a spreadsheet giving the area percent of each composition in the look-up table. This procedure allows a compositional map to be generated. Composition assignments were grouped appropriately.

Table 1.1 List of Samples Investigated in This Study

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<tr>
<th>Sample</th>
<th>Easting (mE)</th>
<th>Northing (mN)</th>
<th>Au (ppm)</th>
<th>Ag (ppm)</th>
<th>Description</th>
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<td>16OM-002</td>
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<td>4933130</td>
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<tr>
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<td>480</td>
<td>9660</td>
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<td>4933998</td>
<td>56.0</td>
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<td>Vein float from Hokuryu</td>
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</table>

Note: Easting and Northing are UTM Zone 54T.
1.5 Macroscopic Vein Textures

Figure 1.3 on page 10 shows vein samples from the Omu camp exhibiting low precious metal grades are typically massive and consist of pink to white and gray massive quartz (Figure 1.3a and b). These samples are usually entirely massive but could also show vugs filled by druzy quartz. Thick section microscopy shows that ore minerals may be present in these samples in fine-grained amber-colored quartz that cannot be identified in hand specimen.

Many of the bonanza-grade samples from the Omu camp are characterized by crustiform banded veins consisting of successive, narrow bands of quartz with individual bands having different colors, textures, grain sizes, and thickness (Figure 1.3c and d). The bands are typically subparallel and range from about 1 to 5 mm in thickness. The bands are white to dark gray and black, with many being yellowish, slightly pink, or tan. The vein samples are symmetrical with mirroring bands being developed from both sides of the vein or asymmetrical having no mirroring quartz bands. Centerlines in symmetrical vein samples may be distinctly vuggy. The crustiform veins contain abundant colloform bands consisting of fine-grained quartz. The outer surfaces of the colloform bands point towards the vein center and exhibit spherical, botryoidal, or mammillary shapes. Microscopic observations suggest that darker gray or black colloform bands characterize the ginguro ore containing abundant precious metal minerals. In contrast, light colored white, light gray, or pink colloform bands lack ore minerals. Bands of quartz replacing bladed calcite occur in some of the samples (Figure 1.3d).

Brecciated vein material can contain high precious metal grades (Figure 1.3e and f), especially in one prominent outcrop of breccia at the Honpi vein of the Omui deposit. At this location, high-grade breccias are composed of small banded clasts of quartz that range from several millimeters to centimeters in size (Figure 1.3f). The clasts are tan, dark gray or black and are sub-rounded or sub-angular. In addition to vein fragments, wall rock clasts are locally present. The cement surrounding the clasts is commonly lighter in color and often appears milky white and banded, having a cockade texture in hand specimen. Vugs are common and are usually filled either with druzy quartz or clay minerals. Bladed calcite that is replaced by quartz is sometimes present in the vugs and the matrix between the clasts.
Figure 1.3 Representative vein samples from the Omu camp. a. and b. Massive vein samples containing low precious metal grades. c. and d. Crustiform vein samples containing high precious metal grades. e. and f. Brecciated vein samples containing high precious metal grades. Scale bars are 2 cm.
1.6 Gangue Mineralogy and Microscopic Quartz Textures

Based on optical microscopy, a total of 16 distinct quartz textures could be identified in the vein samples from the Omu camp. The characteristics of the different textures are summarized in Table 1.2 beginning on page 30 and briefly described below. The classification of these textures closely followed Dong et al. (1995), with some modifications. Most notably, the study of the samples from the Omu camp allowed for the identification of three distinct types of colloform quartz, which were not recognized by previous workers.

1.6.1 Primary textures

The primary growth textures in the samples from the Omu camp formed through the growth of quartz or deposition of silica within open space. Primary textures identified include comb quartz, zonal quartz, microspherical colloform quartz, chalcedonic colloform quartz, and moss quartz.

Comb texture is formed by groups of elongate, parallel or subparallel quartz crystals. Comb textures were observed in all samples from both deposits in the Omu camp. Comb quartz typically has a fairly uniform grain size within individual bands, ranging from 0.25–1 mm in size. The comb quartz either has euhedral terminations when it grows into cavities of open space or may suture together in a pattern resembling the teeth of a comb. Sometimes comb quartz is overgrown by other types of quartz. The quartz crystals commonly are perpendicular to the vein walls and occur in the center of symmetric veins. In crossed-polarized light, comb texture stands out as the euhedral crystals have different extinction angles and appear to (Figure 1.5a on page 14). In plane-polarized light, the comb texture can sometimes be identified based on the outlines of the crystals and the presence of euhedral terminations (Figure 1.5b). In most samples, bands of comb quartz occur directly on top of bands of mosaic quartz. Optical CL microscopy showed that comb quartz is zoned and displays both a bright, long-lived yellow CL emission and a short-lived, dark blue CL emission (Figure 1.5c).

Zonal quartz was only observed in one sample from the Omui deposit. The texture is defined by the occurrence of euhedral quartz crystals that show alternating translucent and clear zones that are parallel to the crystal faces. The translucent zones are rich in fluid and mineral inclusions whereas the clear zones are devoid of inclusions. The quartz crystals can be up to 200 μm in length. Zonal quartz can
be easily recognized in plane-polarized light (Figure 1.5d) and shows a uniform extinction under cross-polarized light as the translucent and clear zones do not differ in orientation (Figure 1.5e). Optical CL shows that the zonal grains have a short-lived dark blue core that changes in color to dark red-brown during continued electron bombardment. The core is surrounded by growth zones that have a yellow CL (Figure 1.5f). The intensity of the yellow emission decreases with time. Some of the zonal quartz grains host primary fluid inclusion assemblages with individual inclusions having regular shapes and consistent liquid to vapor ratios (Figure 1.4a). In the case of one crystal, the zones are crosscut by a secondary trail of fluid inclusions having a consistent liquid to vapor ratio (Figure 1.4b). Due to the large vapor bubble, indicating a relatively high temperature of entrapment, this assemblage of four inclusions was selected for microthermometric work. Homogenization to the liquid occurred at 245° to 255°C.

Figure 1.4 Microphotographs of fluid inclusions present in vein samples from Omu. a. High-magnification plane-polarized light image showing primary liquid-rich inclusions that are regularly shaped and have consistent liquid-to-vapor ratios. These inclusions are located with a zonal quartz grain. b. High-magnification plane-polarized light image of a zonal quartz grain containing a secondary fluid inclusion assemblage that crosscuts the crystal. This assemblage consists of regularly-shaped, liquid-rich fluid inclusions with consistent liquid-to-vapor ratios.

Microspherical colloform quartz is a common texture identified in the sample suite from the Omu camp in samples with high precious metal grades such as the brecciated vein sample from the Honpi vein at the Omui mine. The microspherical colloform bands have spherical, botryoidal, reniform, or mammillarly surfaces pointing towards the vein center. In plane-polarized light the quartz bands alternate in color from light to dark tan (Figure 1.5g). In cross-polarized light, the microspherical colloform texture is composed of
cryptocrystalline quartz (Figure 1.5h). At high magnifications, microspheres having sizes <5 µm can be recognized in plane-polarized light (Figure 1.5i). The microspheres may form globular aggregates that can reach up to 20–50 µm in size. The microspheres are variably fused together. In some areas, the microspheres can be readily recognized whereas in others they are fused to form massive quartz containing a high proportion of micron-sized cavities. The cavities can show sickle-like shapes outlining the relic microspheres. The proportion of voids in the microspherical colloform quartz is typically high, giving the quartz a dark grey to brown color in transmitted light. The microspherical colloform quartz commonly transitions into mosaic quartz. Globular aggregates may control the location of the interpenetrating grain boundaries in the mosaic quartz. Optical CL microscopy showed that the microspherical colloform quartz is dark brown to black. This colloform quartz type lacks fluid inclusions.

Chalcedonic colloform quartz has been recognized in most of the samples from the Omu camp. The chalcedonic colloform quartz bands are texturally similar to the microspherical colloform bands and are typified by spherical, botryoidal, reniform, or mammillary surfaces pointing towards the vein center (Figure 1.6a on page 15). However, at high magnification, this type of quartz is composed of chalcedony fibers. The arrays of approximately parallel fibers are oriented perpendicular to the colloform bands. Where tested, the chalcedony fibers are length-fast. Alternating bands of chalcedonic fibers have variable thicknesses ranging up to 100 µm. Under crossed-polarized light, the chalcedonic colloform quartz shows radial or flamboyant extinction patterns (Figure 1.6b). The chalcedonic colloform quartz exhibits a bright yellow CL emission that decreases in intensity over time. The bands of fibrous quartz lack fluid inclusions.

Chalcedonic moss quartz is defined by groups of spheres that consist of quartz having a turbid appearance. This texture was recognized in most samples from the Omu camp. The spheres tend to cluster together giving them the appearance of organic moss. Under plane and cross-polarized light, the spherical aggregates show internal concentric or radiating patterns (Figure 1.6c and d). Fibrous quartz crystals comprise the outer moss texture. The spherical aggregates are up to 60 µm in diameter. Sometimes two or more spheres form larger aggregates that are coated by concentric bands of chalcedonic colloform quartz. Similar to the chalcedonic colloform texture, moss quartz exhibits a radial or flamboyant extinction pattern and has a bright yellow CL signature.
Figure 1.5 Microphotographs of primary quartz textures present in vein samples from the Omu camp. 

a. Low-magnification cross-polarized light image showing “teeth-like” comb quartz growing from opposite sides of the vein and interlocking in the center. 

b. Low-magnification plane-polarized light image of euhedral comb quartz where faint outlines of individual quartz grains can be seen. 

c. Low-magnification CL image of comb quartz showing alternating zones of blue and yellow spectral emissions. 

d. Low-magnification plane-polarized light image of a zonal quartz grain surrounded by crystalline colloform texture. 

e. Low-magnification cross-polarized light image showing unified extinction throughout zonal quartz grain. 

f. Low-magnification CL image which shows the dark brown inner core and yellow rims of the zonal quartz grain. 

g. Low-magnification plane-polarized image showing translucent microspherical...
colloform quartz band with opaque bands and clasts of ore minerals. h. Low-magnification cross-polarized light image of colloform banding which is comprised of microcrystalline quartz. i. High-magnification image of translucent colloform band consisting of microspheres and opaque material containing ore minerals.

Figure 1.6 Microphotographs of primary quartz textures present in vein samples from Omu. a. Low-magnification plane-polarized light image of layered chalcedonic colloform quartz bands. b. Low-magnification cross-polarized light image showing the radial or flamboyant extinction pattern of chalcedonic colloform bands. c. High-magnification plane-polarized light image showing spheres of chalcedonic moss with both an inner and outer rim. d. High-magnification cross-polarized light image showing the radial or flamboyant extinction pattern of moss spheres surrounded by mosaic quartz.

1.6.2 Recrystallization textures

The vein samples from the Omu camp contain a range of textures that formed through recrystallization of primary textures, and transitions with primary textures can be observed. Recrystallization textures present in the samples include mosaic, flamboyant, feathery, and ghost-sphere textures as previously described in detail by Dong et al. (1995) and Moncada et al. (2012). In addition, a
type of colloform banding, referred to as crystalline colloform quartz, was recognized that was not previously described by these authors.

Mosaic quartz is the most common recrystallization texture and has been recognized in all of the Omu samples. This texture is characterized by equigranular quartz grains that have highly irregular and interlocking grain boundaries. The grain boundaries are not visible under plane-polarized light allowing this texture to be only recognized under crossed polars (Figure 1.7a on page 17). Different degrees of development of mosaic texture have been identified confirming that this texture results from recrystallization. In samples that show an advanced stage of recrystallization, the boundaries of the mosaic quartz are dark and well-defined. In samples that underwent less intense recrystallization, the boundaries of adjacent mosaic quartz grains are not well defined leading to a mottled appearance. In some samples, parallel bands of mosaic quartz occur that vary in grain size, ranging from microcrystalline to coarse-grained (~200 µm) quartz. The coarse-grained texture often hosts crystalline moss and ghost-sphere textures. In many of the samples investigated, mosaic textures can be noted in colloform quartz bands. Textural evidence suggests that all three different types of colloform quartz can recrystallize to mosaic quartz. This texture has a dark blue CL signature.

Flamboyant quartz occurs as infill in open spaces in samples from the Omui deposit. The quartz crystals contain chalcedonic crystal fibers, suggesting that this texture formed as a result of the recrystallization of chalcedony (Figure 1.7b). The quartz forms rounded crystals and irregularly shaped crystal aggregates that show a flamboyant extinction pattern in crossed-polarized light (Figure 1.7c). The flamboyant quartz is not unlike the chalcedonic textures which also show flamboyant extinction patterns, except that the flamboyant quartz does not form spherical, botryoidal, reniform, or mammillary bands. Like the chalcedonic textures, flamboyant quartz has a bright yellow CL emission that fades over time.

Feathery quartz has been recognized in samples from the Hokuryu and Omui deposits. In plane-polarized light, the texture is comprised of light-colored, translucent quartz that does not have distinct grain boundaries (Figure 1.7d). This texture is formed by quartz crystals that have a splintery or feathery appearance only visible under crossed-polarized light (Figure 1.7e). The texture is best developed in the rims of larger quartz crystals that have a clear euhedral core. In some cases, the feathery appearance is caused by the presence of impurities. Feathery quartz typically has a bright yellow optical CL that
decreases in intensity over time. The splintery or feathery rims on euhedral quartz crystals show fine colloform banding in CL suggesting that this texture formed as a result of recrystallization of chalcedonic quartz as chalcedony shows a similar CL response. Colloform bands are seen to overlap grain boundaries between quartz crystals (Figure 1.7f).

![Microphotographs of recrystallized quartz textures present in vein samples from Omu.](image)

**Figure 1.7** Microphotographs of recrystallized quartz textures present in vein samples from Omu. a. Low-magnification cross-polarized light image showing mosaic quartz bands grading from coarse-grained to microcrystalline with remnant colloform shapes. b. High-magnification plane-polarized light image of flamboyant texture present in both chalcedonic moss and within an individual recrystallized grain. c. High-magnification cross-polarized light image of flamboyant extinction pattern with mosaic quartz infill. d. Low-magnification plane-polarized light image of translucent quartz. Individual quartz grains can be seen in cross-polarized light. e. Low-magnification cross-polarized image showing euhedral quartz grains with feathery extinction pattern. f. Low-magnification CL image of colloform banding present in euhedral quartz and overlapping grain boundaries.

Crystalline colloform quartz is the third type of colloform texture recognized in the samples from the Omu camp. Each band consists of a string of blocky quartz grains that have outer curved grain
boundaries. The bands are up to 10 µm wide and are composed of quartz grains that are clear in plane-polarized light and lack fluid and mineral inclusions (Figure 1.8a on page 19). In crossed-polarized light, the blocky quartz grains show a uniform extinction (Figure 1.8b). However, a large number of fluid inclusions occur along the grain boundaries between neighboring quartz bands (Figure 1.9 on page 20). These inclusions are highly irregular in shape and have inconsistent liquid to vapor ratios suggesting that they have experience necking after nucleation of a vapor bubble. The textural evidence indicates that the abundant fluid inclusions occurring along the grain boundaries have migrated out from the center of the bands during the formation of the blocky quartz crystals, making the crystalline colloform quartz a recrystallization texture. Locally, the crystalline colloform quartz transitions into mosaic quartz. This texture has a dark blue CL signature which fades quickly and is similar to other recrystallization textures in the Omu samples.

Crystalline moss quartz is the second type of moss quartz identified in samples from the Omu camp. The texture is defined by the presence of inclusions of impurities which form boundaries around clear quartz crystals, visible under plane-polarized light (Figure 1.8c and e). In some spheres it is possible to discern traces of chalcedonic fibers which have migrated out during recrystallization. In cross-polarized light the spheres show a varying degree of recrystallization to mosaic quartz which is higher in the interior of the sphere and lessens moving outward to the rims (Figure 1.8d and f). This texture has a dark blue CL signature similar to the crystalline colloform texture.

Ghost-sphere quartz has been identified in one sample from the Omui deposit. It is defined by the occurrence of ghost spheres, which range from 25–50 µm in size (Figure 1.8g), that occur within larger quartz crystals, seen best in cross-polarized light (Figure 1.8h). The ghost spheres are texturally similar to both chalcedonic and crystalline moss quartz and are interpreted to represent a product of further recrystallization from these quartz types. The spheres are outlined by the presence of impurities within the recrystallized quartz crystals (Figure 1.8i). Ghost-sphere quartz has a similar CL signature to the crystalline moss quartz. Locally, the ghost-sphere texture transitions into mosaic quartz which involved removal of the impurities and the re-shaping of the boundaries of the quartz grains to become interpenetrating.
Figure 1.8 Microphotographs of recrystallized quartz textures present in vein samples from the Omu camp. 

a. High-magnification plane-polarized light image of crystalline colloform quartz bands surrounding and overlapping zonal quartz grain. 
b. High-magnification cross-polarized light image which shows the individual translucent quartz grains which compose the crystalline colloform bands. 
c. Low-magnification plane-polarized light image of several crystalline moss spheres. 
d. Low-magnification cross-polarized light image showing the mosaic extinction pattern of the crystalline moss spheres. 
e. High-magnification plane-polarized light image of an individual crystalline moss sphere showing concentric rims created by impurities. 
f. High-magnification cross-polarized light image showing variations in the extinction pattern between the interior sphere which exhibits mosaic texture and out rim which is less recrystallized. 
g. Low-
magnification plane-polarized light image of ghost spheres. h. Low-magnification cross-polarized light image of ghost spheres within quartz grains. i. High-magnification plane-polarized light image of ghost spheres which are highlighted by rims of impurities; similar to crystalline moss texture. j. High-magnification cross-polarized light image of ghost spheres enclosed within individual quartz crystals.

Figure 1.9 High-magnification plane-polarized light microphotograph of irregularly-shaped fluid inclusions with inconsistent liquid-to-vapor ratios that form boundaries between individual quartz bands within the crystalline colloform quartz texture.

1.6.3 Replacement textures

Based on textural evidence and previously studied by Dong et al. (1995), Etoh et al. (2002), and Moncada et al. (2012), four distinct types of quartz textures were identified in the samples from the Omu camp that formed as a result of replacement of bladed calcite. Lattice-bladed, ghost-bladed, parallel-bladed, and radiating-bladed quartz can be distinguished by the orientation of the blades. In addition, saccharoidal quartz occurs, which likely also formed as a result of calcite replacement (Dong et al., 1995).

Lattice-bladed quartz is composed of tabular blades having a random orientation that are separated by polygonal cavities that are partly filled by comb quartz crystals (Figure 1.10a on page 22). Each 200–500 µm large blade is composed of multiple seams of quartz crystals. In cross-polarized light the quartz has a mottled appearance (Figure 1.10b). Replacement appears to have occurred from the outside of the blades inwards. Optical CL microscopy showed that the outer seams in the blades typically have a short-lived dark blue CL that fades to a dark red to brown CL over time (Figure 1.10c). The comb quartz infilling the polygonal cavity have euhedral crystal terminations that point towards the center of the cavities. The comb quartz has a yellow CL emission and typically shows fine oscillatory growth banding.
Ghost-bladed quartz is characterized by the faint presence of blades that are located within a fine-grained quartz matrix (Figure 1.10d). The blades are composed of quartz grains that have grain sizes and shapes differing from the surrounding matrix or are typified by the abundant presence of impurities. The blades can be of variable orientation within the quartz matrix and may intersect, but lack cavities between the blades. Under cross-polarized light, the ghost-bladed texture commonly is made of mosaic quartz (Figure 1.10e). The CL signature of this texture is similar to that of the lattice-bladed quartz in that it is dark blue and fades quickly.

Parallel-bladed quartz consists of dense arrays of blades that are parallel to each other (Figure 1.10f). The blades range from 200–500 µm in size and consist of rectangular or prismatic crystals. In some cases, the blades are poorly defined and can be mostly recognized based on variations in the abundance of inclusions between adjacent blades. In crossed-polarized light, quartz in the blades can be recrystallized to mosaic quartz (Figure 1.10g). The CL signature of parallel-bladed texture is similar to that of the ghost and lattice-bladed quartz in that it is dark blue and fades quickly. However, the central backbone of the blade sometimes consists of quartz showing a bright yellow CL that becomes darker over time.

Radiating-bladed quartz is composed of dense arrays of blades that are arranged in a radial pattern originating from a single point (Figure 1.10h). The texture is identical to pseudo-acicular quartz described by Dong et al. (1995) and Moncada et al. (2012). Radiating-bladed quartz has been recognized in two samples from Omui and Hokuryu. The radiating blades are defined by linear arrangements of fine-grained quartz that may be intergrown with adularia. In some cases, the blades are poorly defined and can only be distinguished from neighboring blades based on grain size differences and the presence of impurities. Individual blades can be up to ~500 µm in length. Under cross-polarized light, the quartz in the blades is commonly recrystallized into mosaic quartz (Figure 1.10i). Optical CL showed that this texture has a bright blue signature that fades quickly, only a few spots of yellow CL dot the backbone of the blade.

Saccharoidal quartz was identified in two samples from the Omui deposit. The sugary appearance of this texture is caused by the presence of elongate quartz crystals, some doubly-terminated, that are randomly distributed in a matrix of smaller quartz crystal. The elongate quartz grains
Figure 1.10 Microphotographs of replacement quartz textures present in vein samples from the Omu camp. a. Low-magnification plane-polarized light image of translucent quartz blades intersecting in a lattice-structure with euhedral quartz grains in-filling the cavities between the blades. b. Low-magnification cross-polarized light image of blades and euhedral quartz in-fill with mosaic texture. c. Low-magnification CL image showing the bright yellow CL signature of the in-fill euhedral quartz and the dark CL signature of the quartz blades. d. Low-magnification plane-polarized light image of ghost-bladed texture comprised of intersecting blades defined by impurities e. Low-magnification cross-polarized light image of mosaic quartz between ghost blades. f. Low-magnification plane-polarized light image of parallel-bladed texture. g. Low-magnification cross-polarized light image showing extinction pattern of blocky quartz that has
replaced the calcite blades. h. Low-magnification plane-polarized light image showing fine translucent seams that separate radiating blades of quartz. i. Low-magnification cross-polarized light image showing mosaic quartz replacement material separated by seams of bladed texture. j. Low-magnification cross-polarized light image of saccharoidal texture made up of “mesh-like” quartz.

range up to ca. 100 µm in length. In places, the crystals are aligned forming a crude mesh or network. The saccharoidal texture can only be identified in cross-polarized light (Figure 1.10j). Where present, the texture covers relatively large areas in thick section. Similar to other replacement textures, saccharoidal quartz has a dark blue CL signature that darkens quickly over time.

1.6.4 Adularia

Based on optical and automated scanning electron microscopy the location of adularia was determined for three vein samples from the Omu camp. Adularia (potassium feldspar) was found to be co-located with replacement bladed textures and mosaic quartz. It is not located within significantly mineralized bands but instead found in bands without significant amounts of ore minerals. Sample 16OM-012 from the Honpi vein at Omui contains 1.0 volume % Ag minerals and no adularia (Figure 1.11a on page 24). Sample 16OM-021 from Omui contains 0.5 volume % Ag minerals and no adularia (Figure 1.11b). Sample 16OM-093 from Hokuryu contains 1.2 volume % adularia and no measurable Au or Ag minerals (Figure 1.11c).

1.7 Ore Minerals and Ore Mineral Textures

In the bonanza-type vein samples from the Omu camp, ore minerals primarily occur in the ginguro bands. In transmitted light, the opaque to slightly translucent ore minerals are finely distributed throughout these quartz bands (Figure 1.12a on page 26). Of the ore mineral grains analyzed by EDS on the scanning electron microscope, ~80 % of grains were Ag minerals and 20 % Au minerals.

The Ag minerals include Ag-Se-S and Ag-Sb-S phases. Compositionally, the Ag-Se-S phases occur in a solid solution between aguilarite (Ag4SeS) and acanthite (Ag2S). Pyrargyrite (Ag3SbS3) represents the most common Ag-Sb-S phase. Aguilarite and acanthite are opaque in transmitted light, whereas pyrargyrite has a deep red color. Aguilarite and acanthite are usually massive, irregularly-shaped, and can be intergrown with each other. The grains typically range from 20 to 120 µm in size. Both aguilarite and acanthite are light gray in reflected light, very weakly anisotropic, and sometimes with
Figure 1.11 Microphotographs of ore minerals and adularia (K-fsp) in vein samples from the Omu camp. a. Back-scattered electron image showing the location of ore minerals (white) in vein sample 16OM-012 from the Honpi vein at Omui. This sample does not contain adularia. b. Back-scattered electron image showing the location of ore minerals in vein sample 16OM-021 from Omui. Adularia is also absent from this sample. c. Back-scattered electron image showing the location of potassium feldspar in pink. This is vein sample 16OM-093 from Hokuryu. d. Scanned image of thick section from sample 16OM-012. Ore minerals are present in dark colored clasts. e. Scanned image of thick section from sample 16OM-021 showing both brecciation and colloform banding. f. Scanned image of thick section from sample 16OM-093 showing colloform banding.
a greenish cast. Pyrargyrite is bluish gray in reflected light, and although it is a strongly anisotropic mineral, the carmine red internal reflections mask this property. The Ag-Se-S and Ag-Sb-S phases have a low reflectance with a metallic or adamantine luster.

Electrum represents the principal Au host in the bonanza-type samples from the Omu camp. In transmitted light, electrum is opaque. The grains range from 15 to 40µm in size and are either aggregated or disseminated. Electrum grains in the ginguro bands often appear spongy and have irregularly-shaped grain boundaries. In aggregate, electrum forms pseudo-dendritic masses and is found within the interstitial space between the relic microspheres in microspherical colloform quartz (Figure 1.12b and c). These electrum grains are small but form a complex network, often with the Ag-Se-S and Ag-Sb-S phases. In reflected light, the electrum is bright golden yellow and lightens in color depending on the silver content. The electrum has a very high reflectance and is easily distinguished from the Ag-Se-S and Ag-Sb-S phases using the SEM (Figure 1.12d). The electrum is predominately Ag-rich with semiquantitative EDS analyses on six spots yielding an average composition of 46.6 wt.% Au and 53.4 wt.% Ag.

To quantify the relationship between the ore minerals and quartz textures, thick sections from 15 samples were investigated. Transects were drawn across each slide, approximately perpendicular to the vein walls, to include as many different quartz textures as possible. Subsequently, point counting was conducted along the transects, with the texture of the host quartz being noted for each ore mineral grain occurring along the transects. All ore minerals were included within an envelope of ~8 mm along the transects, which corresponds to the diameter of the reflected light spot using the 5x objective on the optical microscope used. Complexly intergrown grains were treated as a single occurrence during point counting. In total, the textural locations of 760 ore mineral grains were determined. Of those, 70 percent were located within microspherical colloform quartz, and 30 percent were located in mosaic quartz. Ore minerals were not recognized in any of the other quartz textures occurring in the samples (Figure 1.13 on page 27).
Figure 1.12 Microphotographs of ore minerals present in microspherical colloform banding in a bonanza-type sample from the Honpi vein at the Omui deposit (sample 16OM-012). a. Low-magnification plane-polarized light image showing that the sample consists of essentially opaque bands and clasts surrounded by translucent colloform quartz band. At high magnification, microspheres can be observed in the nearly opaque material and the translucent colloform bands. b. High-magnification image of the contact between an almost opaque band of quartz containing a high proportion of ore minerals and a translucent colloform band containing only few ore mineral grains. The ore minerals occur in the interstitial space between microspherical colloform quartz resembling dendrites. c. High-magnification image of a similar contact between the nearly opaque colloform material and the translucent colloform banding. Ore minerals form small flame-like dendrites within the framework of microspherical quartz. d. Back-scattered electron image showing the occurrence of an electrum grain and an Ag-Se-S phase. As only grains intersecting the surface of the thick section are imaged, the dendrite-like appearance of the ore minerals is not apparent.
Figure 1.13 Histogram showing the number of ore mineral grains located in the different quartz textures in samples from the Omu camp. In total, the textural settings were determined for 760 grains located along transects across 14 thick sections. The quartz textures are sorted by decreasing abundance along the transects. The figure illustrates that ore minerals are only present in microspherical colloform and mosaic quartz, which form the ginguro bands in the bonanza-type samples.

1.8 Discussion

1.8.1 Origin of Quartz Textures

Vein textures in low-sulfidation epithermal deposits can be primary or may have formed as a result of recrystallization and replacement processes (Bobis, 1994; Dong et al., 1995; Etoh et al., 2002; Moncada et al., 2012). Primary textures are formed through growth of quartz crystals into open space or direct precipitation of silica from hydrothermal solutions. Recrystallization textures form through the transition from a metastable silica precursor to thermodynamically stable quartz. Replacement textures are partial or complete pseudomorphs of earlier formed gangue minerals such as calcite and adularia by quartz. Table 1.2 beginning on page 30 provides an overview of the 16 different quartz textures observed at the Hokuryu and Omui deposits of the Omu camp and their interpreted mechanisms of formation.

Previous workers have emphasized that colloform textures (Rogers, 1917) in low-sulfidation
epithermal deposits are of primary origin (Bobis, 1994; Dong et al., 1995; Sherlock and Lehrman, 1995; Moncada et al., 2012; Taksavasu et al., 2018). Colloform textures present in the vein samples of the Omu camp were carefully investigated here, and three different types could be distinguished based on optical microscopy and optical CL investigations, only two of which are interpreted to be primary textures. Previous authors have not made a distinction between the three different types of colloform banding.

The first type of colloform banding, referred to as microspherical colloform texture, is typified by the presence of relic microspheres or globular aggregates of fused microspheres. This type of colloform banding has been previously recognized by Sherlock and Lehrman (1995) at the McLaughlin deposit in California and by Taksavasu et al. (2018) at Buckskin National in Nevada. As described below, the microspheres in the colloform banding are interpreted to have been originally composed of non-crystalline silica that directly deposited from the hydrothermal solutions. In crossed-polarized light, the microspherical colloform bands in the samples from the Omu camp consist of microcrystalline quartz, suggesting that the non-crystalline silica precursor phase to these bands has entirely recrystallized to quartz subsequent to deposition. The microcrystalline quartz shows a dark brown to black CL emission. Locally, the transition between microcrystalline quartz and mosaic quartz can be observed in crossed-polarized light indicating that continued textural maturation results in the formation of increasingly larger quartz grains having interpenetrating grain boundaries. The recrystallized coarse grains commonly follow the shape of the original globular aggregates.

The second type of colloform banding, referred to as chalcedonic colloform banding, consists of microcrystalline fibrous quartz. This type of banding is common in crustiform veins from low-sulfidation epithermal deposits (Sander and Black, 1988; Bobis, 1994; Dong et al., 1995). The texture consists of rhythmic bands composed of radiating quartz fibers that are oriented perpendicular to the substrate on which the bands have developed, which includes euhedral quartz crystals. The outermost bands form botryoidal surfaces in open space, suggesting that the colloform band represents a primary texture formed from a hydrothermal solution. The microcrystalline fibers in the chalcedonic colloform banding consist of quartz crystals that are predominantly length-fast with their crystallographic c-axes being oriented perpendicular to the long axes of the fibers (cf. Miche et al., 1984). The fibrous nature of the quartz can be readily identified at high magnification and is texturally distinct from the microspherical
colloform texture. In addition, the chalcedonic colloform banding is characterized by a bright yellow CL response. Flamboyant extinction patterns are common in this type of colloform banding, as described by Sander and Black (1988) and Dong et al. (1995). The chalcedony in the colloform banding can also recrystallize to mosaic quartz. In crossed-polarized light, the mosaic quartz is composed of coarse grains that have interpenetrating grain boundaries although relic fibers may still be recognized in plane-polarized light.

The third type of colloform texture, referred to as crystalline colloform texture, is defined by the presence of bands of inclusion-poor quartz. Abundant, irregularly shaped fluid inclusions with inconsistent liquid to vapor inclusions occur along the grain boundaries between adjacent grains of inclusion-poor quartz. In cross-polarized light, the bands of inclusion-poor quartz are composed of curved blocks of quartz grains. The spatial arrangement of the fluid inclusions suggests that the quartz grains have formed through a process of recrystallization whereby the fluid inclusions migrated to the grain boundaries. The texture is interpreted to have formed as a result of recrystallization of chalcedonic fibers as relic quartz fibers have been identified in the samples investigated. The crystalline colloform texture has a dark brown CL response. In places, the crystalline colloform texture transitions into mosaic quartz defined by coarse quartz grains with interpenetrating grain boundaries.

Lovering (1972) proposed that mosaic quartz forms through recrystallization of colloform quartz. The results of this study show that coarse-grained mosaic quartz forms through the recrystallization of all three types of colloform banding. In some cases, transitions from the preexisting colloform banding can be observed, including relic microspheres or fibrous quartz. However, in intensely recrystallized mosaic quartz, precursor textures cannot be identified based on optical microscopy. The observation that mosaic quartz in low-sulfidation veins may form from different precursor textures may explain why some bands of mosaic quartz contain ore minerals while others are barren (Saunders, 1990; 1994).

1.8.2 Deposition of Non-Crystalline Silica during Vein Formation

The textural evidence suggests that the colloform bands containing ore minerals in the vein samples from the Hokuryu and Omui deposit in the Omu camp were originally composed of 1–5 μm microspheres and globular aggregates consisting of fused microspheres. The textures observed are similar to those documented at McLaughlin in California (Sherlock and Lehrman, 1995) and Buckskin
### Table 1.2 Interpretation of Quartz Textures Observed in the Vein Samples from the Omu Camp

<table>
<thead>
<tr>
<th>Texture</th>
<th>Interpretation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary textures</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comb</td>
<td>Growth of quartz crystals into open space; euhedral crystal terminations</td>
<td>Adams (1920), Bobis (1994), Dong et al. (1995), Moncada et al. (2012)</td>
</tr>
<tr>
<td>Zonal</td>
<td>Euohedral quartz crystals with primary zoning patterns grown in open space</td>
<td>Dong et al. (1995), Moncada et al. (2012)</td>
</tr>
<tr>
<td>Microspherical colloform</td>
<td>Formed as a result of non-crystalline silica deposition during flashing; non-crystalline silica is recrystallized to microcrystalline quartz without significant textural changes</td>
<td>Sherlock and Lehrman (1995), Taksavasu et al. (2018), this study</td>
</tr>
<tr>
<td>Chalcedonic colloform</td>
<td>Formed as a result of growth of bands of chalcedonic fibers at temperatures below ~180°C</td>
<td>Rogers (1917), Fournier (1985), Sander and Black (1988), Bobis (1994), Dong et al. (1995), Moncada et al. (2012), this study</td>
</tr>
<tr>
<td><strong>Recrystallization textures</strong></td>
<td></td>
<td></td>
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<tr>
<td>Mosaic</td>
<td>Forms as a recrystallization product of a range of precursor textures, including all three types of colloform quartz; mosaic quartz appears to be the texturally most stable arrangement of quartz grains in the low-sulfidation environment</td>
<td>Lovering (1972), Saunders (1990), Dong et al. (1995), Camprubí and Albinson (2007), Moncada et al. (2012), this study</td>
</tr>
<tr>
<td>Flamboyant</td>
<td>Rounded quartz crystals or irregularly shaped aggregates formed through recrystallization of chalcedony</td>
<td>Adams (1920), Sander and Black (1988), Dong et al. (1995), Moncada et al. (2012)</td>
</tr>
<tr>
<td>Feathery</td>
<td>Recrystallization of small quartz grains that may have formed as an overgrowth on larger quartz crystals; recrystallization may have occurred preserving the approximate crystallographic continuity with the host quartz crystal; optical CL response suggests that feathery texture may at least in part form as a product of recrystallization from chalcedony</td>
<td>Adams (1920), Sander and Black (1988), Bobis (1994), Dong et al. (1995), Moncada et al. (2012), this study</td>
</tr>
</tbody>
</table>
Table 1.2 Continued

<table>
<thead>
<tr>
<th>Texture</th>
<th>Interpretation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recrystallization textures</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystalline colloform</td>
<td>Recrystallization of a precursor caused migration of fluid inclusions to the grain boundaries; as relic crystal fibers were identified in the samples studied, this texture likely formed through recrystallization of the chalcedonic colloform texture</td>
<td>This study</td>
</tr>
<tr>
<td>Crystalline moss</td>
<td>Presence of relic crystal fibers and distribution of fluid inclusions suggests that this texture formed through recrystallization of the chalcedonic moss texture</td>
<td>This study</td>
</tr>
<tr>
<td>Ghost-sphere</td>
<td>Distribution of fluid inclusions suggests that the ghost spheres formed through recrystallization of chalcedonic moss texture; euhedral quartz surrounding ghost spheres may also represent a product of recrystallization</td>
<td>Dong et al. (1995), Moncada et al. (2012)</td>
</tr>
<tr>
<td><strong>Replacement textures</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lattice-bladed</td>
<td>Quartz replacement of calcite blades forming a house-of-cards structure in which calcite blades intersect each other, forming cavities</td>
<td>Morgan (1925), Bobis (1994), Dong et al. (1995), Etoh et al. (2002), Moncada et al. (2012)</td>
</tr>
<tr>
<td>Ghost-bladed</td>
<td>Quartz replacement of bladed calcite hosted in a matrix of granular calcite in which calcite blades intersect but without forming cavities</td>
<td>Bobis (1994), Dong et al. (1995)</td>
</tr>
<tr>
<td>Parallel-bladed</td>
<td>Quartz replacement of bladed calcite, each having only a slightly different orientation</td>
<td>Bobis (1994), Dong et al. (1995), Etoh et al. (2002)</td>
</tr>
<tr>
<td>Radiating-bladed</td>
<td>Quartz replacement of radiating arrays of calcite crystals</td>
<td>Dong et al. (1995), Moncada et al. (2012)</td>
</tr>
<tr>
<td>Saccharoidal</td>
<td>Forms as quartz replaces massive granular calcite</td>
<td>Lovering (1972), Dong et al. (1995)</td>
</tr>
</tbody>
</table>

National in Nevada (Taksavasu et al., 2018).

Taksavasu et al. (2018) proposed that microspherical colloform quartz from the Buckskin National deposit in Nevada was originally composed of a non-crystalline silica precursor phase. These authors compared the microtextures in the low-sulfidation epithermal veins to textures of modern silica sinters from the Wairakei geothermal field in New Zealand. X-ray diffraction analysis showed that the silica sinter is composed of opal-A. The sinter consists of alternating layers of variably compacted silicified filamentous microbes encased by chains of fused silica microspheres. Textural relationships described
are similar to those of sinters in geothermal systems worldwide (Jones et al., 1997; Herdianita et al., 2000; Campbell et al., 2002; Guidry and Chafetz, 2003; Lynne and Campbell, 2004; Rodgers et al., 2004; Fernandez-Turiel et al., 2005).

Saunders (1990, 1994) suggested that the ore-mineral-bearing colloform opal-A bands in low-sulfidation epithermal veins were gel-like at the time of deposition. He documented textures reminiscent of sedimentary ripple marks at the Sleeper deposit in Nevada, indicating hydraulic shaping of the material during vein formation or gravity-induced sagging of the soft silica. In addition, rip-up silica clasts were observed that were transported along the veins and deposited in pockets (Saunders, 1990, 1994). Saunders (1994) also described a texture, subsequently referred to as the sluice-box texture (Saunders et al., 2008, 2011), in which ore minerals intermixed with silica were deposited around protrusions of the vein walls forming a thin layer over the tops of the protrusion and a thick deposit on the leeward side. Sluice-box textures have also been recognized at Hollister in Nevada (Saunders et al., 2008, 2011; Unger, 2008), Koryu in Japan (Shimizu, 2014), Republic in Washington (Saunders et al., 2011), and Silver City in Idaho (Aseto, 2012).

The non-crystalline silica precursor to the ore-mineral-bearing colloform quartz bands may have been similar in nature to gel-like silica deposits recovered after a hydrothermal eruption at Porkchop Geyser in Yellowstone in 1989 (Fournier et al., 1991; Keith, 1992). Blocks ejected by the eruption were coated by a siliceous gel-like material that was up to one-centimeter-thick and showed botryoidal textures. Within several days of the eruption, the gelatinous material hardened and became no longer pliable (Fournier et al., 1991; Keith, 1992).

Studies on silica sinters (Herdianita et al., 2000; Campbell et al., 2001; Lynne and Campbell, 2004; Rodgers et al., 2004; Lynne et al., 2005, 2007) and siliceous sediments (Mitzutani, 1970; Murata and Nakata, 1974; Murata et al., 1977; Mustoe, 2005) have shown that opal-A is thermodynamically unstable and matures over time. The maturation process involves the transformation into thermodynamically more stable paracrystalline opal-CT, which in turn recrystallizes into opal-C and then into microcrystalline quartz. Investigations by Saunders (1990) showed that silica in colloform bands in bonanza-grade samples from the Sleeper deposit in Nevada are virtually isotropic and XRD investigations confirmed the presence of opal-CT. This suggests that silica in the vein material from this low-sulfidation
epithermal deposit has not been fully transformed to quartz. In contrast, recrystallization has been completed at the deposit of the Omu camp, as the vein samples are entirely composed of anisotropic quartz. Laboratory studies have demonstrated that the transformation from opal-A to quartz may occur within days to months under hydrothermal conditions (Ernst and Calvert, 1969; Mitzutani, 1970; Bettermann and Liebau, 1975; Oehler, 1976). The degree of maturation of opal-A originally present in low-sulfidation epithermal veins perhaps relates to the evolution of the hydrothermal system following silica deposition.

1.8.3 Relationships between Gangue Mineral Textures and Precious Metal Minerals

To quantify the relationship between quartz textures and ore minerals, point counting was conducted along traverses across thick sections of vein sample while recording the textural nature of the quartz hosting each ore mineral grain identified (Figure 1.13). The counts showed that ore minerals are present only in the microspherical colloform quartz and in mosaic quartz. No ore mineral grains were found in any of the other quartz textures.

The finding is consistent with previous studies establishing that ore minerals in low-sulfidation epithermal veins are typically hosted by colloform quartz bands, although the different types of colloform banding distinguished here were not previously recognized. Moncada et al. (2012) studied gangue mineral textures in 855 samples from the Veta Madre in the Guanajuato region of Mexico. They identified a range of textures indicative of boiling, including colloform quartz, plumose, feathery or flamboyant quartz, and bladed calcite replaced by quartz. They showed that colloform quartz is the most important indicator of mineralization. An average grade of 1.1 g/t Au and 178.8 g/t Ag was recorded in samples containing colloform quartz whereas samples without colloform quartz only averaged 0.2 g/t Au and 17.2 g/t Ag (Moncada et al., 2012). Shimizu (2014) studied bonanza-grade samples from the Koryu deposit in Japan and showed that both colloform and mosaic quartz are hosts to ore minerals. Detailed petrographic investigations by Saunders (1990, 1994) on the Sleeper deposit in Nevada also showed that ore minerals occur in colloform quartz bands. However, he noted that the colloform quartz in the bonanza-type veins at Sleeper is composed of alternating gold-rich and barren bands, confirming the finding of this study that not all types of colloform banding are host to ore minerals. At McLaughlin in California, Sherlock and Lehrman (1995) showed that gold occurs as dendrites in colloform bands consisting of compacted silica
microspheres. A detailed petrographic study on vein material from Khan Krum in Bulgaria revealed that electrum dendrites in this deposit also primarily occur in colloform quartz bands (Marinova et al., 2014).

Contemporaneous deposition of ore minerals and the non-crystalline silica in the microspherical colloform bands is also suggested by the delicate intergrowth relationships observed in the samples from the Omu camp. The ore minerals occur in the interstitial space between the microspheres and must have grown at the time of microsphere deposition. Similar relationships have been documented by Lindgren (1915) as well as Saunders et al. (2008, 2011) and Saunders (2012) from the National and Buckskin National deposits in Nevada, respectively. At these deposits, native gold and naumannite form dendrites that point towards the center of the veins and are supported by a framework of non-crystalline silica. Similarly, electrum at the Sleeper deposit in Nevada and McLaughlin in California forms dendrites within a non-crystalline silica matrix (Saunders, 1990, 1994; Sherlock and Lehrman, 1995).

1.8.4 Evidence for Flashing During Ore Formation

Deposition of the non-crystalline silica that originally formed the microspherical colloform banding in the deposits of the Omu camp required a high degree of silica supersaturation in the hydrothermal fluids. Fournier (1985) showed that silica supersaturation is most likely related to fluid immiscibility in the epithermal environment.

Moncada et al. (2012) suggested that two end-member types of fluid immiscibility can be distinguished that differ in the intensity of vapor production. During gentle boiling, a small amount of hydrothermal liquid is converted to vapor as the ascending hydrothermal liquid intersects the liquid plus vapor coexistence boundary. The small amount of vapor produced this way is buoyant and rises through the fracture network. The remaining liquid continues to ascent producing small amounts of vapor. During violent boiling, referred to as flashing, vapor is generated due to near-instantaneous vaporization of a large amount of hydrothermal liquid (Scott and Watanabe, 1998; Moncada et al., 2012). Flashing may occur in response to a seismic event or dike-induced faulting (Rowland and Simmons, 2012). Propagation of vaporstatic conditions in the fracture or fault will cause any liquid present at depth or within the surrounding wall rock to flash to vapor (Henley and Hughes, 2000). This means that while the onset of flashing occurred around 400 m depth, flashing could have propagated downward as far as the structure was continuously open – as well as upwards to surface. Vaporization during fluid flashing could cause
widespread hydrothermal brecciation, potentially explaining the observation that the highest-grade samples from the Omu camp are brecciated.

Flashing of the hydrothermal liquids would result in the near-instantaneous deposition of non-crystalline silica as silica solubility in the vapor phase is significantly lower than in the liquid (Monecke et al., 2018). Deposition of non-crystalline silica may be concomitant to the formation of the precious metal minerals because flashing results in the preferential partitioning of H$_2$S into the vapor phase, reducing the amount of H$_2$S in solution in the coexisting liquid, which in turn destabilizes the gold bisulfide complexes (Brown, 1986). This process of metal deposition is observed in modern geothermal systems where sharp decreases in pressure occur on back-pressure plates in surface pipes of geothermal power plants (Brown, 1986). Theoretical considerations by Sanchez-Alfaro et al. (2016) also indicate that flashing is an effective mechanism of gold precipitation.

Although gentle boiling may also result in silica supersaturation in hydrothermal liquids, this process is not able to explain the observation that ore minerals only occur in the microspherical colloform bands and its recrystallized equivalents. In the samples from the Omu camp, ore minerals are not directly intergrown with other quartz textures indicative of boiling (cf. Moncada et al., 2012) and the ore minerals do not occur together with bladed calcite, quartz replacing the carbonate minerals, or adularia. In modern and ancient geothermal systems, bladed calcite forms from boiling solutions through exsolation of CO$_2$ (Simmons and Christenson, 1994; Etoh et al., 2002). The gas loss associated with boiling can also cause a shift in the stability from illite to adularia, explaining why adularia represents an indicator mineral for boiling in many epithermal deposits (Browne and Ellis, 1970; Hedenquist, 1990; Dong and Morrison, 1995; Moncada et al., 2017).

The reconnaissance fluid inclusion work conducted as part of the present study provides constraints on the depth at which flashing must have occurred at the Omui deposit in the Omu camp. An euhedral, zoned quartz crystal in a barren band intergrown with microspherical colloform quartz containing ore was found to be crosscut by a secondary trail of liquid-rich fluid inclusions showing consistent liquid to vapor ratios. Inclusions in this assemblage homogenized to the liquid phase over a temperature range of 245º to 255ºC. Assuming cold hydrostatic conditions, hydrothermal liquids with this homogenization temperature can only be entrapped at a minimum depth of 370 to 430 m in the pure H$_2$O
system. The NE-trending fault hosting the mineralization at Omui must have been a major structure to open from surface and to a depth of at least ~400 m during the episodic flashing events recorded by the microspherical colloform bands.

1.8.5 Implications for Deposit Model

The occurrence of phase separation has long been recognized as an important process controlling gold deposition in many low-sulfidation epithermal deposits (Kamilli and Ohmoto, 1977; Drummond and Ohmoto, 1985; Hedenquist et al., 2000; Simmons and Browne, 2000; Simmons et al., 2005; Moncada et al., 2012, 2017). However, the results of this study emphasize that while boiling is an important prerequisite for deposit formation, it is the intensity of vapor production that is a key control. Only near instantaneous vaporization of large amounts of liquid results in bonanza-type precious metal grades in low-sulfidation epithermal veins such as those of the Omui camp.

Flashing of the hydrothermal liquids may occur to variable depths below the water table. As a consequence, near instantaneous vaporization will occur for hydrothermal liquids having different maximum temperatures. The boiling-point-to-depth-curve dictates the maximum temperature the hydrothermal liquids can have at different depth. Assuming cold hydrostatic conditions in the pure H$_2$O system, flashing to 100 m below surface would tap into a reservoir having a maximum temperature of 180°C. Hydrothermal liquids at that temperature probably lost much of the gold they were originally carrying at depth as a result of cooling, gentle boiling, or both. In contrast, flashing to 500 m below the water table will cause near instantaneous vaporization of liquids having temperatures of up to 265°C. As the gold content of the liquid phase at this temperature is much higher than at low temperatures, deep flashing could result in more gold precipitation than shallow flashing. The relationship between temperature and gold solubility in hydrothermal solutions is well established based on thermodynamic constraints, experimental data, and analyses of geothermal liquids (Giggenbach, 1992; Stefánsson and Seward, 2004; Pope et al., 2005; Simmons and Brown, 2007; Sanchez-Alfaro et al., 2016).

During the flashing event, the hydrothermal liquids are converted to vapor causing rapid supersaturation of silica and gold in the remaining liquid, which results in near instantaneous deposition. However, as flashing represents a highly dynamic process, silica and gold may be transported upward mechanically by the vapor stream and deposit along the vein walls above the maximum depth of flashing.
Saunders (1990, 1994) proposed that silica and gold form colloidal particles and these may be transported upward by the hydraulic action of the vapor. Deposition of the colloidal particles from the vapor stream may be influenced by a range of processes ranging from changes in the hydraulic regime to surface processes between deposits on the vein walls and colloids still transported in the fluid. Perhaps the relative build-up of precious metal minerals is more effective than that of silica colloids, explaining selective precious metal enrichment in the ginguro bands (Saunders, 1990, 1994).

The findings of this study suggest that the depth of the ore zone below the water table cannot be readily predicted. Deep flashing is required to allow vaporization of gold-laden solutions that have not been previously experienced significant gold deposition as a result of cooling or gentle boiling. The bonanza grades may occur at the depth at which flashing occurred. In case flashing occurred only to a certain depth, a sharp cut-off of gold-grade with depth would be expected. However, due to the upward transport of colloidal particles and deposition along the vein walls, a similarly sharp drop-off in grade may not occur upwards. Figure 1.14 on page 38 shows that bonanza-type precious metal enrichment in low-sulfidation epithermal deposits indeed occurs over a comparably wide range of depths below the water table.

1.8.6 Quartz Textures as a Guide in Mineral Exploration

During exploration at Omu, bonanza-type vein material can be identified in float and outcrop based on the presence of macroscopically identifiable ginguro bands. Careful microscopic work confirmed that ore minerals are exclusively hosted in microspherical colloform quartz and mosaic quartz that represents its recrystallized equivalent. The textural evidence suggests that the ore minerals were co-precipitated with a non-crystalline silica precursor in these bands, and that deposition of ore minerals and the silica occurred as a result of extreme supersaturation during flashing of the hydrothermal system. In the samples investigated, ore minerals were never associated with quartz textures interpreted to form as a result of a gentle boiling system (Moncada et al., 2012). Thus, systems that may have undergone episodic flashing can be distinguished from gentle boiling or non-boiling systems based on the presence of microspherical colloform quartz.

Fluid inclusion studies are widely used in exploration for low-sulfidation epithermal deposits to determine the level of erosion with respect to the paleowater table. This information is used in targeting as
Thermodynamic constraints suggest that >90% percent of gold in gentle boiling liquids deposits over a temperature range of 260°C to 180°C (Simmons and Browne, 2000), which corresponds to a depth of ~470 to 100 m at cold hydrostatic conditions in the pure H₂O system. The results of the present study suggest that great care must be taken using this approach in exploration. The microspherical colloform bands in the vein samples from the Omu camp lack fluid inclusions that could be used for microthermometric work. The study of fluid inclusions hosted by quartz in the barren bands may be misleading, especially if only the largest and most easily recognizable inclusion assemblages are studied. Microthermometric data obtained on these fluid inclusions do not constrain the conditions of ore formation but provide information on the nature of the hydrothermal system during periods of fluid flow that are not associated with significant precious metal deposition.

The optical CL investigations on vein material from the Omu camp suggest that this technique which has been widely used in the study of growth and alteration patterns in quartz (Götze et al., 2001; Frelinger et al., 2015; Monecke et al., 2018) may potentially also be used to differentiate quartz types in low-sulfidation epithermal deposits. The microspherical colloform quartz shows a dark brown to black CL
emission. In the samples investigated, the cores of zonal quartz crystals as well as some mosaic quartz are characterized by short-lived blue CL emission that rapidly fades to a dull brown to red-brown color. In contrast, outer parts of zonal quartz crystals, flamboyant, and chalcedonic colloform quartz shows a bright yellow CL response that becomes darker during continued electron bombardment. The observations on the vein material from the Omu camp suggest that optical CL may be used as a rapid screening tool to distinguish quartz types.

The optical CL microscopy on the samples from the Omu camp revealed that the different types of colloform banding show different CL responses, highlighting the fact that the microspherical colloform quartz bands and the chalcedonic colloform quartz bands have not formed by the same processes. Similar observations have been recorded from the Asachinskoe deposit in Kamchatka. At this deposit, colloform quartz intergrown with ore minerals shows a dull red-brown CL while the late colloform quartz infilling cavities has a bright yellow CL emission (Takahashi et al., 2008). As chalcedony forms at temperatures <180°C (Fourier, 1985), the yellow CL emission may be indicative of a low temperature of formation. This result is consistent with a recent study by Götze et al. (2015) demonstrating that quartz with yellow CL forms through rapid precipitation in reduced, low-temperature hydrothermal solutions.

1.9 Conclusions

Low-sulfidation epithermal quartz veins from the Hokuryu and Omui deposits in the Omu camp of Hokkaido exhibit a wide range of macroscopic and microscopic quartz textures. Crustiform and brecciated veins can contain bonanza-type precious metal grades whereas massive quartz veins typically only show low precious metal grades. Ore minerals in high-grade samples occur in gray to black quartz bands, referred to as ginguro bands, suggesting that ore deposition was episodic during quartz vein formation. The ginguro bands are composed of colloform quartz exhibiting a mosaic texture in crossed-polarized light. Careful petrographic investigations revealed the presence of relic microspheres within the colloform quartz bands. These microspheres are interpreted to have been originally composed of a non-crystalline, presumably gel-like silica precursor that later recrystallized to mosaic quartz. Ore minerals show delicate intergrowth relationships with the quartz and commonly infill the space between the relic microspheres or form dendrites supported by a framework of silica microspheres. The non-crystalline silica precursor and the ore minerals are interpreted to have formed through rapid deposition during flashing of the
hydrothermal liquids at depths ranging to over 400 m below the paleosurface.

The conclusion of the present study that fluid flashing can form bonanza-type low-sulfidation epithermal veins has significant exploration implications. Previous models emphasized the role of ‘gentle’ boiling as a mechanism of gold precipitation, implying that the location of bonanza-type ore zones can be predicted based on the depth of the onset of boiling, as constrained by the presence of bladed calcite or fluid inclusion petrography. However, if flashing represents the principal process responsible for the formation of bonanza-type precious metal enrichment, the ore zones could develop at a more variable depth range. Ore could form at the depth at which vaporization of a large volume of liquid occurs, especially at several hundreds of meters below the paleosurface where gold concentrations in solution are high. As colloidal gold can be transported within the rapidly rising vapor stream, gold deposition is also possible above the depth of flashing.

This study shows that macroscopic and microscopic vein textures may provide useful criteria in exploration as the occurrence of colloform quartz banding showing relic microsphere textures and mosaic quartz formed through recrystallization may be indicative for the occurrence of flashing. Other types of quartz bands, including colloform bands composed of fibrous chalcedony, are barren. Although the study of textures in barren quartz bands located between the ginguro ore may provide valuable information on the evolution of the hydrothermal system, it is important to note that they formed at times when little or no ore was deposited. Care must be taken in the interpretation of fluid inclusion data as the fluid inclusion inventory of quartz in these bands does not record the ore-forming conditions. The colloform quartz bands containing relic microspheres may lack fluid inclusions suitable for microthermometric studies.
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