A petrographic and oxygen isotope study of banded epithermal veins from the Martha Hill Au-Ag Mine, Waihi, New Zealand

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ABSTRACT

Quartz veins from the Martha Hill epithermal gold-silver deposit, Waihi, commonly exhibit crustiform banded textures. Visual differences observed between bands are primarily the result of a 1 to 1500 µm variation in quartz grain size. Quartz band textures are dominated by anhedral interlocking quartz mosaics, commonly associated with minor adularia and sulfide phases; these textures are interpreted to be products of amorphous silica crystallisation. The occurrence of rhombic adularia suggests that prolonged boiling influenced parent fluids. In contrast, the presence of coarsely crystalline bands, made up of subhedral to euhedral quartz grains, infers primary crystal growth from solution; evidenced by the occurrence of growth-zoned quartz within these bands. There is a narrow range of 3.3‰ in $\delta^{18}O_{quartz}$ between maximum and minimum isotopic values for the deposit. Significant overlap in $\delta^{18}O_{quartz}$ values are observed between the Martha and Welcome lodes. However, statistically significant and commonly systematic differences do occur between individual bands analysed in most samples. Temperature fluctuations may be the dominant factor responsible for observed inter-band variation.

KEYWORDS: *Epithermal, gold, quartz veins, crustiform banding, oxygen isotopes*

INTRODUCTION

Banded veins are characteristic of epithermal gold deposits world wide, yet the mechanisms which lead to their formation remain poorly understood. Petrographic and oxygen isotope data from individual bands from the classic, well-studied Martha Hill deposit have been analysed. The recognition and interpretation of observed silica and metal phases, combined with oxygen isotope data has provided useful constraints on processes responsible for banded vein formation at Martha Hill. Few similar integrated studies have been completed, due to the difficulty in working with fine-grained minerals associated with epithermal veins. Studies of this nature include Simmons *et al* (1988), Saunders (1990, 1994), and Matsuhisa *et al* (1994).

GEOLOGIC SETTING AND MINERALISATION

The Martha Hill deposit is an epithermal gold-silver quartz vein system, located in the southeastern sector of a 200 km long metallogenic belt (Figure 1). This belt is associated with Miocene to early Quaternary volcanic rocks of the Coromandel Volcanic Zone (CVZ) (Brathwaite *et al*, 1989; Brathwaite and McKay, 1989). Historic underground mining operations produced 1100 tonnes of bullion (Au/Ag 1:6), making Martha Hill one of the largest epithermal gold-silver deposits in the world (Simmons *et al*, 1992).

Present day open-pit mining is centred on a low-grade stockwork zone, located between the previously mined Martha and Welcome quartz lodes (Figure 2).

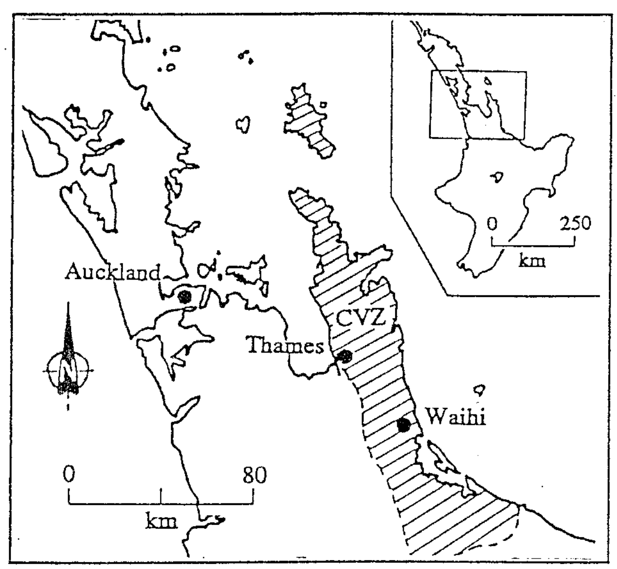

Figure 1 A regional map of Auckland Province with an inset of the North Island, New Zealand.

Initial reserve estimates delineated an open pit mineable reserve of about 7 mt grading approximately 2.8 g of gold/tonne of ore.

The structural geometry of the Martha Hill vein system is characterised by a complex braided pattern, made up of numerous steeply-dipping quartz veins. Vein networks show abundant textural variation, which is attributed to a complex history of incremental extension, brecciation and paleo-hydrologic evolution (Figure 2) (Sibson, 1987; Cargill, 1994).

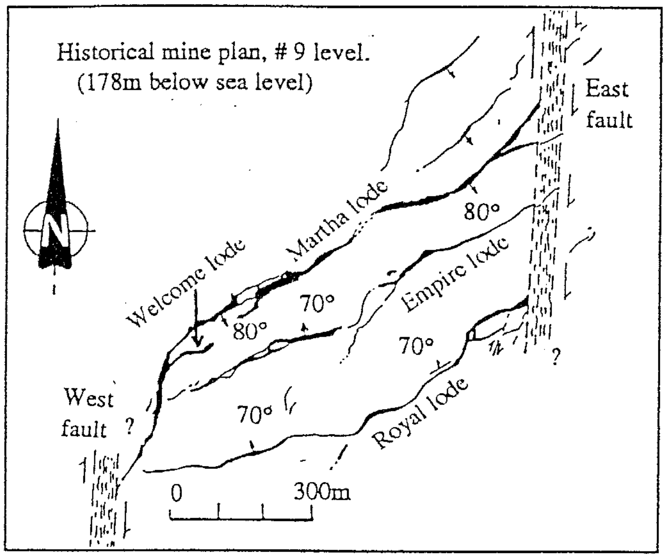

Figure 2 Interpretative map of the Martha Hill lode system, Waihi (after Sibson, 1987).

Veins are composed primarily of quartz (with lesser chalcedony) and minor associated adularia, calcite and inesite. The principal metallic minerals observed include pyrite, chalcopyrite, tetrahedrite, sphalerite and galena. Associated gold-silver bearing minerals include electrum, acanthite and pyrargyrite (Brathwaite *et al*, 1989; Brathwaite and McKay, 1989).

Broad-scale oxygen isotope studies have been carried out on core samples from Martha Hill (Blattner and Brathwaite, 1993). $\delta^{18}O$ values for main lode quartz and calcite range from 6.2-11.2‰ and 2.3-9.4‰ respectively, and show an overall irregular decrease with depth; no clear lateral $\delta^{18}O$ trends have been observed to date. Isotopic geothermometry between calcite and quartz yields a temperature of 250°C, which is consistent with data collected from fluid inclusion studies.

Two types of fluid inclusions have been identified. Type I liquid-rich two phase inclusions are dominant, while type II vapour-rich inclusions are rare (Christie, 1982; Jennings, 1991). Both type I and type II inclusions have homogenisation temperatures in the range of 200°C to 300°C, and have low apparent salinities (< 2 wt % NaCl equiv).

SAMPLE SELECTION AND PETROGRAPHY

We sampled both low and high-grade zones within the present open pit complex. A particular emphasis was placed on banded quartz veins, as individual bands may reflect changes in fluid composition and/or fluid flow regimes though time. Crustiform banded quartz dominates ore zones, and is characterised by sequences of successive planar bands, many of which combine botryoidal, reniform and mamillary forms of fine-grained quartz and lesser chalcedony. Rare calcite is also present, and generally forms anhedral grains which overprint observed silica textures. In hand sample, individual bands are distinguished by their colour and crystallinity. Microscopic examination indicates that a 1 to 1500 μm quartz grain size variation sharply defines visually observed differences in sample band colour and crystallinity. As a general rule, individual bands consist of only one silica textural variety (Figure 3).

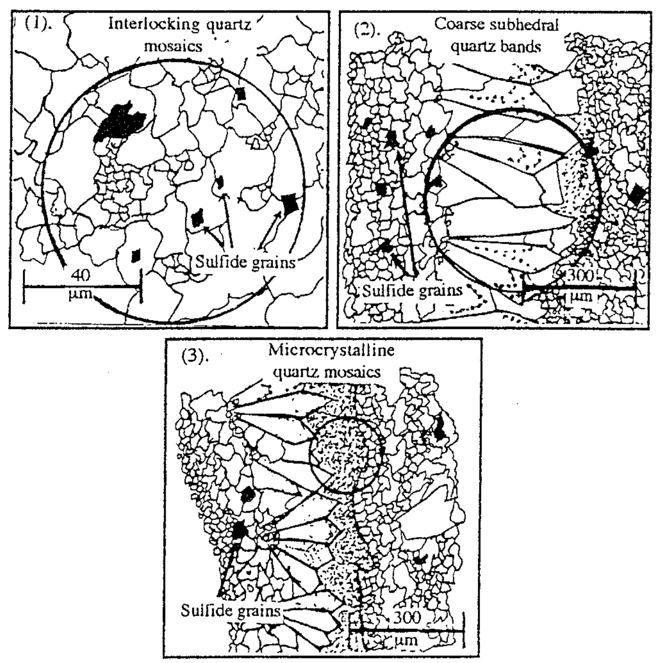

Figure 3 Major silica band textures observed at Martha Hill.

Predominant silica band textures observed are defined below (in order of significance):

(1) Interlocking, fine- to coarse-grained anhedral quartz mosaics. Similar silica textures identified at the Sleeper deposit in Nevada, have been interpreted as amorphous silica crystallisation products (Saunders 1990, 1994).

(2) Coarse grained (50-1500 µm), elongate, subhedral to euhedral quartz bands. Grains commonly contain "V"-shaped fluid inclusion trails.

(3) Microcrystalline quartz mosaics. These fine-grained quartz mosaics are composed of equant quartz grains 0.1 µm in diameter, and commonly exhibit pseudo-sedimentary grain layering.

Crustiform banded vein quartz, which has been split along band surfaces, provides a three dimensional perspective of the vein wall substrate. Such surfaces are characterised by mamillary textures or ripple-like features, often regarded as evidence of the former presence of a colloid (e.g. Saunders, 1990), although fibrous chalcedony can exhibit similar textures (Sanders and Black, 1988). At Martha Hill, these surfaces are commonly coated with kaolinite.

Adularia is also a minor component of most banded samples. Grains are finely dispersed in anhedral quartz mosaics where they form diamonds and rhombs averaging 5 µm in size. Dong and Morrison (1995) also observe fine-grained rhombic adularia-mosaic quartz associations in Australian Paleozoic epithermal deposits. They suggest that formation temperatures around 220°C are responsible for this association, based on extensive fluid inclusion studies. This temperature range is consistent with a 200-300°C temperature window observed for mineralisation at Martha Hill (Christie, 1982).

Sulfide relationships with quartz can be divided into three main groups at Martha Hill (Figure 4).

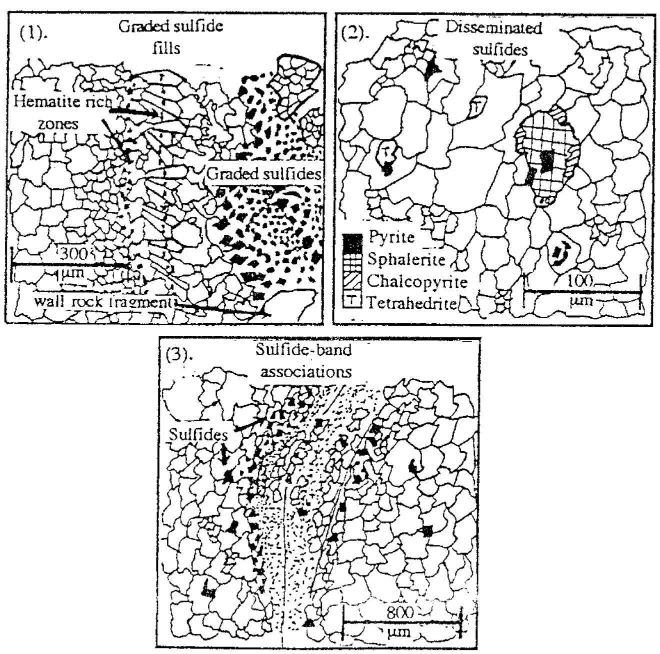

Figure 4 Sulfide-host quartz relationships.

(1) Late-stage sulfide-bearing fills commonly cut crustiform banded zones. These zones commonly exhibit sulfide "flow" textures, dominated by grain size-graded pyrite, sphalerite, and chalcopyrite. Sulfide grains range from 5 to 50 µm in size and are hosted by interlocking anhedral quartz mosaics, characterised by large grain size variation (1-200 µm). Rip-up clasts of wall rock commonly occur and are commonly replaced by secondary quartz and rare hematite.

(2) Fine-grained (5-30 µm) disseminated pyrite, chalcopyrite, tetrahedrite, sphalerite, and chalcopyrite occur in most samples, and are restricted to quartz grain sizes below 50 µm; no apparent association with any specific grain size is observed within this range.

(3) Band specific sulfide occurrences are characterised by pyrite and pyrite-tetrahedrite-chalcopyrite assemblages. Hematite is also commonly band specific and is visually identified by a reddish-brown band colouration in hand sample.

Discussion

Evidence for two main mechanisms of silica deposition are recognised in this study of banded veins at Martha Hill. The presence of coarse (50-1000 µm) subhedral to euhedral growth-zoned bands in banded ore, suggest that a direct fluid-grain precipitative growth mechanism is responsible for these bands. Where anhedral quartz mosaic textures predominate, silica was probably transported to sites of deposition in a colloidal state, forming originally amorphous precipitates (cf. Saunders, 1994). Post-depositional crystallisation of these amorphous progenitors resulted in present quartz mosaic textures and apparently preserved surface features of individual bands. The presence of aqueous colloidal silica suspensions indicate that hydrothermal fluids attained high degrees of silica saturation (Fournier, 1985). Studies by Drummond and Ohmoto (1985) and Fournier (1985) suggest that silica saturation in geothermal environments can be accomplished by rapid fluid cooling, boiling, or interaction with fresh volcanic glass. The occurrence of interstitial rhombic vein adularia, in banded Martha Hill samples, provides strong evidence for the presence of boiling fluids (cf. Browne, 1978). Experimental studies indicate that boiling processes result in coagulation and deposition of colloidal silica in response to increased fluid salinity and pH, as well as decreasing fluid temperature (Drummond and Ohmoto, 1985). Cooling destabilises alumino-hydroxy anions, precipitating adularia and sericite; adularia is preferentially fixed due to higher pH values in accordance with the following reaction:

$$6SiO_{2\,(aq)} + \underset{(Sericite)}{KAl_3Si_3O_{10}(OH)_2} + 2K^+_{(aq)} = \underset{(Adularia)}{3KAlSi_3O_8} + 2H^+_{(aq)}.$$

In active geothermal systems, gold is largely transported as a bisulfide complex (Seward, 1973). Dong and Morrison (1995) suggest that rhombic adularia forms during periods of protracted violent boiling in shallow geothermal environments. Boiling has two competing effects on the solubility of the gold bisulfide complex. Increasing pH due to CO_2 gas loss results in increased gold solubility in the pH range where dissolved H_2S gas dominates over $HS^-_{(aq)}$. However, loss of dissolved H_2S decreases gold solubility. With protracted boiling, H_2S loss effects overcome pH changes, resulting in bisulfide complex destabilisation and resultant precious metal precipitation, according to the reaction (Reed and Spycher, 1985):

$$8Au(HS)^-_{2\,(aq)} + 6H^+ + 4H_2O = 8Au + SO_4^{2-}{}_{(aq)} + 15H_2S_{(g)}$$

Simply stated, the occurrence of rhombic adularia in ore stage samples is not suprising (cf. Dong and Morrison, 1995).

Boiling and subsequent cooling may have also influenced the formation and relative stability of base metal sulfides observed in vein samples, as these phases occur in the presence of ground-mass adularia in banded veins. Similar observations have been made in active geothermal systems such as Broadlands Ohaaki (e.g., Weissburg *et al*, 1979). Experimental studies completed at Broadlands Ohaaki indicate that base metals are transported as chloride and bisulfide complexes, which are destabilised by the effects of boiling (Reed and Spycher, 1985). The occurrence of late stage quartz-sulfide infilling strongly suggests the presence of particulate sulfide suspensions, which moved into open spaces under the influence of gravity, either by settling or in discrete episodic depositional events. A similar sequence of episodic deposition occurs at the Salsigne gold deposit, France (Bouchot and Gros, 1991). These authors interpret observed quartz-sulfide fill textures as a result of rapid deposition, resulting from decompressional boiling in response to a pressure drop initiated by conduit rupturing. Another possibility is a sudden change in fluid chemistry, in response to mixing of fluids of variable composition.

STABLE ISOTOPE INVESTIGATION

Results

A total of 27 samples, taken from well-defined bands in 11 quartz vein samples, have been analysed with respect to their oxygen isotopic compositions. All samples analysed are from open pit Martha and Welcome lode exposures. $\delta^{18}O_{quartz}$ values of all samples are given in Table 1 and shown in figure 5.

Table 1
Martha Hill quartz $\delta^{18}O$ data

CHIP SAMPLE	$\delta^{18}O$ (‰)*	CHIP SAMPLE	$\delta^{18}O$ (‰)*
WGM 1	8.1	WGM 15	8.4
WGM 2	8.4	WGM 16	8.2
WGM 3	9.0	WGM 17	8.8
WGM 4	8.7	WGM 18	7.9
WGM 5	9.6	WGM 19	8.0
WGM 6	8.5	WGM 20	7.1
WGM 7	8.4	WGM 21	8.1
WGM 8	9.6	WGM 22	8.3
WGM 9	8.2	WGM 23	8.1
WGM 10	10.4	WGM 24	9.3
WGM 11	7.6	WGM 25	8.0
WGM 12	8.0	WGM 26	8.2
WGM 13	10.0	WGM 27	8.5
WGM 14	8.7		

* NBS-28 = 9.8‰

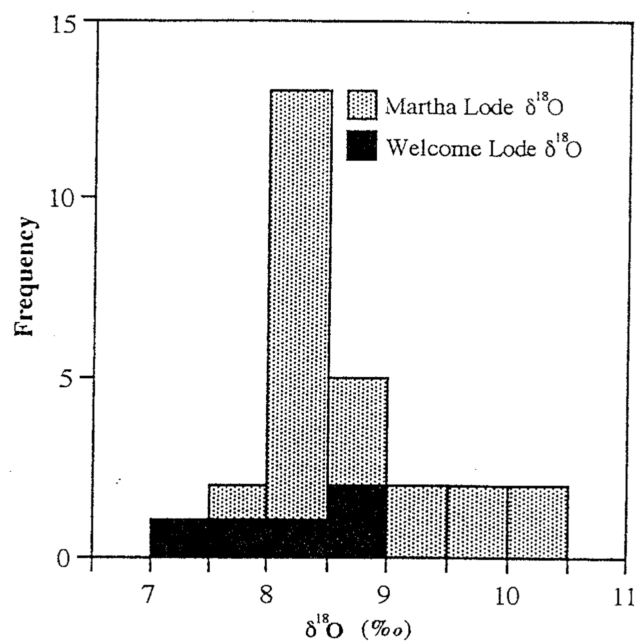

Figure 5 Histogram of Martha Hill $\delta^{18}O$

Discussion

Preliminary results indicate a narrow range of 3.3‰ in $\delta^{18}O$ values for the deposit, and a large overlap in $\delta^{18}O_{quartz}$ values between the Martha and Welcome lodes. Differences occur between individual bands in most samples, yet colour and grain size variations of bands do not correlate with $\delta^{18}O_{quartz}$ values. Separate Martha lode samples show a general systematic increase in $\delta^{18}O_{quartz}$ values away from vein centres toward vein margins (figure 6).

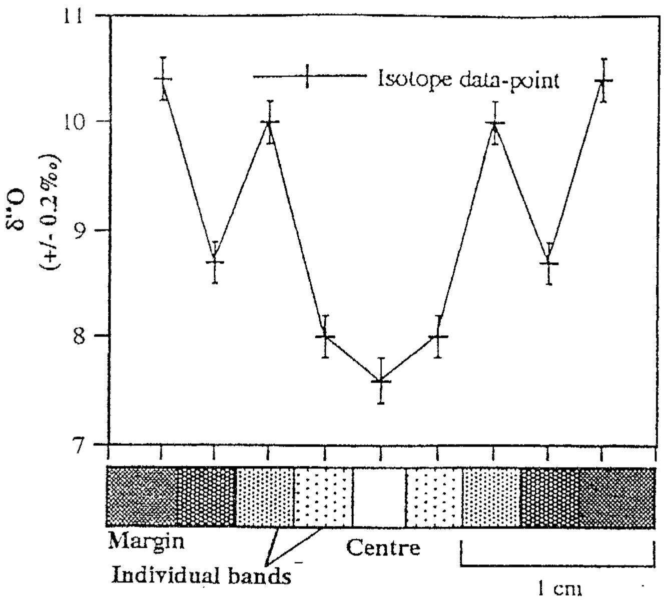

Figure 6 Systematic $\delta^{18}O$ variation across Martha Lode sample CP-1

A variety of factors maybe responsible for these systematic changes and other $\delta^{18}O_{quartz}$ variations.

Boiling and mixing may have influenced $\delta^{18}O_{water}$ compositions, and hence $\delta^{18}O_{quartz}$ values. Evidence for boiling includes the presence of quartz replacement of bladed calcite and interstitial vein adularia (Browne, 1978). Oxygen isotope studies completed at the Golden Cross gold deposit by de Ronde and Blattner (1988), statistically overlap with our data set. The above authors state that the low $\delta^{18}O$ values obtained, indicate that boiling had little quantitative isotopic effect on waters responsible for silica deposition.

Water-rock interaction can also influence oxygen isotope values. Silicate-bearing host rocks and migrating hydrothermal waters can exchange oxygen, reaching an equilibrium state though time; generally, higher degrees of water-rock interaction result in higher $\delta^{18}O$ values (Taylor, 1974). It is unlikely that water-rock interactive effects are responsible for sharp inter-band isotopic variation in this data set, as this would require frequent changes in system fluid source or fluid path through time.

CONCLUSIONS

Individual bands in Martha Hill vein samples are composed primarily of quartz. Visual variations are largely the result of a 1-1500 μm quartz grain size variation, though individual bands dominantly consist of one silica textural type. Observed silica band textures probably formed by two distinct processes. Quartz mosaic textures dominate, representing amorphous silica recrystallisation products. boiling played a role in their formation. Boiling is known to destabilise base and precious metal complexes; consequently, it is not suprising that adularia-bearing quartz mosaic bands contain most of the observed metal-bearing phases in this study. Coarse, growth-zoned, subhedral to euhedral grain bands suggest a mechanism of direct fluid-grain interaction and resultant incremental crystal growth; such bands are devoid of sulfides.

Petrographic studies of banded vein samples have been combined with an oxygen isotope investigation. Preliminary calculations suggest that temperature fluctuations are primarily responsible for inter-band isotopic variation, although the relative significance of water-rock interaction, boiling, and mixing processes is difficult to access.

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