Paragenetic and fluid inclusion study of the Midas low-sulfidation epithermal Au/Ag deposit, Elko County, Nevada

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ABSTRACT

The Midas Mine exploits a mid-Miocene low-sulfidation epithermal Au-Ag deposit. Primary ore minerals in this system are electrum and naumannite, Ag₂Se. Naumannite commonly exhibits partial replacement by the base-metal sulfides pyrite, chalcopyrite, sphalerite, and galena. A later stage of mineralization, best shown in the Discovery and Gold Crown Hanging Wall veins, shows naumannite to be the main ore phase precipitated, with replacement of the naumannite by electrum and base-metal sulfides. One hundred eighty-seven primary, pseudosecondary, and secondary liquid-rich fluid inclusions in 23 samples from 23 locations in the mine homogenize between 83.6°C and 324.8°C and have salinities less than 1.7 wt. % NaCl equiv.; however, a single sample has inclusions up to 13.73 wt. % NaCl equiv. Carbon-dioxide inclusions were observed in a single sample and had final melting temperatures from -57.7°C to -57.1°C, with an average at -57.4°C and homogenization temperatures between -3.5°C and 11.5°C, with an average of 4.7°C, indicating nearly pure CO₂ with densities similar to the water in the aqueous inclusions. The textural relationships of the ore and gangue phases indicate that the ore precipitated into open spaces between two sides of a developing vein and the ore precipitated late in the banding sequence. Therefore, ore phases are the result of precipitation of the first band more proximal to the host rock than the band in which they are physically located. Comparison of fluid-inclusion data with Carlin trend mines (due to spatial correlation) indicates the trapping temperatures are similar, though the fluids at Midas have much lower salinities than Carlin trend fluids. The fluids at Midas are very similar in both trapping temperatures and salinities to other epithermal systems around the world.

INTRODUCTION

Objective

The Midas (formerly Ken Snyder) Mine exploits a lowsulfidation epithermal Au-Ag deposit in the northern Nevada Rift (Goldstrand and Schmidt, 2000; Leavitt, 2004; Leavitt et al., 2004). The Midas deposit was discovered in 1994 and is currently owned by Newmont Mining Corporation. Exploration revealed pre-production reserves of 2.7 million tons of ore grading 1.115 oz (34.67 g) gold and 12.82 oz (398.70 g) silver per ton at year-end 1998. A cut-off grade of 0.250 oz (7.775 g) per ton was used to calculate both silver and gold reserves (Goldstrand and Schmidt, 2000; Leavitt, 2004; Leavitt et al., 2004).

No comprehensive deposit-scale fluid inclusion studies have been conducted at Midas. Here we investigate spatial variability in the temperature and salinity of the fluid(s) responsible for the ore. Paragenesis of the reflecting and transparent phases was also studied to determine which fluid inclusions relate to ore precipitation.

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GEOLOGIC SETTING

The Midas deposit is located in the Snowstorm Mountains of the northern Nevada rift (NNR) (Fig. 1; Stewart et al., 1975; Blakely and Jachens, 1991; Goldstrand and Schmidt, 2000; John et al., 2000; Rhys, 2002; Leavitt, 2004; Leavitt, et al., 2004). Host rocks in the mine area are a series of approximately 16 Ma alternating felsic tuffs and flows with interbedded lacustrine sediments (Blair, 1991; Wallace, 1993; Goldstrand and Schmidt, 2000; Rhys, 2002; Leavitt et al., 2004; Leavitt, 2004). The host rocks are divided into five distinct lithological units: the June Belle, Elko Prince, and Esmeralda formations, a finely crystalline gabbroic sill, and a coarsely crystalline gabbroic sill. Other undifferentiated mafic dikes and thin sills are present throughout the district. Of the five described units, three are known to host ore-bearing veins: the June Belle, the Elko Prince, and the Esmeralda (Goldstrand and Schmidt, 2000; Rhys, 2002; Leavitt et al., 2004; Leavitt, 2004). A very brief description of the mine geology is given below; a more detailed description of each formation and their relationships can be found in Goldstrand and Schmidt (2000).



Figure 1. Location map of the Midas deposit (from Goldstrand and Schmidt, 2000).

A lower tuff unit underlies the host rock pile and is below current mining levels. The lowest host rock formation is the June Belle, a tuff containing lithic clasts and plagioclase and sanidine phenocrysts. The next two formations are the Elko Prince and the Esmeralda, both of which are composed of alternating tuffs and lacustrine sediments. Elsewhere in the district these formations are overlain by a series of rhyolites; however, erosion has removed the rhyolites from the mine property, leaving rocks of the Esmeralda and Elko Prince formations, along with some mafic units, exposed at the surface. Mafic rocks are present as intrusives on the mine property; flows are present elsewhere in the district. The mafic rocks tend to be micro- to finely-crystalline, with at least one coarsely-crystalline sill present; strongly altered plagioclase phenocrysts are abundant.

Alteration in the host rocks is ubiquitous on the mine property and is dominantly propylitic alteration composed of chlorite, calcite, and epidote with minor pyrite (Goldstrand and Schmidt, 2000; Leavitt, 2004; Leavitt et al., 2004, this study). Silicification is related to vein formation and generally extends up to 1 m into the wall rock locally from the veins. Near-surface supergene oxidation penetrates 15 to 30 m below the current surface.

Leavitt et al. (2004) determined the age of mineralization to be 15.38 Ma (40 Ar/ 39 Ar), spanning <300 kyr, with the hydrothermal system possibly lasting as long as 600 kyr. This is 400 kyr after deposition of the youngest host rocks, and the veins are only slightly older than the overlying red rhyolites (15.23 Ma).

The ore at Midas is hosted in a series of banded quartzadularia-calcite veins (Fig. 2) with minor base-metal sulfides. The veins occupy steeply-dipping (~75°NE) to vertical preto syn-mineralization left-lateral strike-slip faults that strike roughly N30°W to N60°W (330° to 300°). The main vein is the Colorado Grande and several smaller veins are hosted by extensional splays off of the Colorado Grande vein.

Vein morphology is highly variable throughout the mine from a narrow (<10 cm) structure dominated by a zone of gouge, clays, with minimal quartz, and little to no banding, to veins approximately 10 m wide with well developed quartz/ adularia/calcite banding originating on the host rock contact and progressing towards the vein center. The morphology of the veins can change dramatically over a span of a few meters, typically less than five. The veins can significantly widen or pinch out from one level to the next above or below, and from one underground mine face to the next (J. Marma and M. Robinson, pers. comm.). Thus, though spectacular examples of ore-bearing banded veins are relatively common in the mine, it is virtually impossible to trace a single band of ore/gangue from one level to the next above/below or from one underground mine face to the next. The total number of bands is highly variable, and ranges from zero where the vein is present only as a slip surface, to more than 15 bands exposed in some faces (Fig. 2).

The well-developed veins show variability in their centers. Banding may persist to the center of the vein, or the center of the vein may be filled with more poorly banded or completely un-banded quartz and/or calcite. Calcite can fill the center of the veins as either blades or a more texturally massive aggregate of intergrown fine crystals. The center of the vein may also be filled with a quartz-, calcite- or quartz/ calcite-cemented breccia containing clasts of host rock and/or banded vein material as angular fragments of variable size (one to tens of cm) (Fig. 2). The Colorado Grande vein is generally completely filled by quartz and calcite; however the major Figure 2. Underground vein exposure of the Gold Crown and Colorado Grande veins. The two veins are ~4 m wide in the large photograph, and the contact between them is the dark black band of ore phases and basemetal sulfides (red arrows). Hammer for scale, ~16 cm wide. Additional black bands, most easily discerned in inset photo, are also ore phases and base-metal sulfides. Clasts in Gold Crown vein are host rock and banded vein material including ore/ base-metal sulfide bands.



extensional veins such as the Gold Crown vein commonly have open spaces and vugs remaining in the center (Rhys, 2002). These vugs commonly have euhedral "dog-tooth" scalenohedrons of calcite growing perpendicular to the vein walls.

The gangue is dominated by quartz, calcite and adularia with minor base-metal sulfides. Major ore minerals in the veins are electrum (Au-Ag alloy) and naumannite (Ag₂Se). Other Au and Ag bearing phases reported in the veins include aguilarite (Ag₄SeS), fischesserite (Ag₃AuSe), and eucairite (AgCuSe). Several base-metal sulfides and selenides have also been reported: pyrite, chalcopyrite, galena, sphalerite, clausthalite (PbSe), berzelianite (Cu_{2-x}Se) and eskebornite (CuFeSe₂) (Cleverly, 1997; Goldstrand and Schmidt, 2000; Leavitt, 2004). Of the diverse group of minerals reported in the district, the only phases encountered as part of this study were quartz, calcite, adularia, electrum, naumannite, pyrite, chalcopyrite, galena, and sphalerite.

FLUID-INCLUSION STUDIES

White (1985) reported formation temperatures from 175° to 200°C. However, the source of the original data and method by which the temperatures were either measured or estimated is unknown (Blair, 1991), so caution should be used in accepting these data at face value. Blair (1991) reports inclusion data from nine sections: homogenization temperatures range from 192° to 314°C, with a mode of approximately 240°C; salinities are between 0.18 and 1.05 wt. % NaCl equiv., and average 0.6 wt. % NaCl equiv. As part of an unpublished company report, Simpson and Mauk (2001) studied secondary inclusions from 12 vein samples. Homogenization temperatures ranged from 199° to 266°C with an average at 227°C. Salinities are low, always less than 2.9 wt. % NaCl equiv., with typical salinities less than 0.9 wt. % NaCl equiv.

METHODS

Samples were chosen to cross multiple bands of quartz and adularia and thus to represent pre-ore-, ore-, and postore-stage banding. Where variability in the vein warranted, multiple samples were collected to constrain the temporal variability at a single location.

Due to similarities in the characteristics of the reflected light phases, electron probe and SEM analysis was initially used to discern different phases, and for subsequent comparison with reflecting phases from other thin sections and samples. Analyses were done using an accelerating voltage of 20 keV. K α lines were used for analysis of Fe, Cu, Zn, and S; L α lines were used for Ag and Se, and M α lines were used for Au and Pb. The standardless analysis feature of the SEM, employing a matrix correction, was used to determine element concentrations for unknown reflecting phases and metal ratios for electrum. Most samples analyzed with the SEM were not carbon coated (electron probe analysis required a carbon coat) due to the conductive nature and disparate chemistry of the phases of interest.

To determine the accuracy of the standardless analysis feature of the SEM, a Au/Ag standard (NIST, then NBS, SRM 481) was analyzed without a carbon coat under operating conditions similar to those used to analyze Midas samples. The standard consists of 6 wires with Au:Ag wt. % ratios ranging from Au₁₀₀:Ag₀ to Au₀:Ag₁₀₀ in 20-wt.-% increments. A minimum of 10 spots were analyzed per wire, the concentrations of Au and Ag were calculated by the standardless analysis feature of the SEM for each spot, and the data averaged for each wire. The averages were then compared to the accepted value for each wire and indicate that the standardless analysis measurements are accurate to $\pm 1\%$ of the concentration of the element over the range of Au:Ag ratios encountered in this study.

Fluid inclusions were analyzed using a Linkam THMSG600 fluid inclusion analysis stage coupled to an Olympus BX60 microscope using either a 40x or 100x objective, depending on the size of the inclusion. To minimize metastable-phase behavior, all measurements were made while heating the chip, none were made while cooling.

RESULTS

Gangue phases

Quartz and adularia are generally very difficult to distinguish optically due to small grain size and the thicker-thannormal thin sections prepared to increase the fluid inclusion populations. These two factors result in stacked grains in the thin sections. Where fine-grained, adularia is most easily distinguished from quartz using SEM analyses, and indicates that the adularia can form bands very similar to the quartz. Quartz and adularia dominantly form bands defined by a gradual increase in grain size, from ~5 μ m, (rarely ~1 μ m to sub- μ m) to ~30 to 40 μ m, with new bands starting at a sharp contact between the relatively coarse-grained material and the new very fine-grained material.

The bands occasionally grow very coarse subhedral to euhedral quartz crystals, up to ~4 mm, growing perpendicular to the banding surface. The crystals do not gradually coarsen to this size; there is a sharp step from the 30-40 μ m grains of the quartz banding to the coarse ~4 mm long euhedral crystals growing perpendicular to the banding surface. The coarse prismatic euhedral crystals generally grow on the last anhedral (30-40 μ m) crystals of a band. Where these very coarse crystals are present, the ore is not. Adularia generally does not grow coarser than ~30 to 40 μ m, and has only been observed coarser than ~500 μ m in a few samples. Later stages in the two largest veins commonly show calcite (which may itself show faint banding) filling in the center.

Calcite forms a significant component of the gangue mineralogy of the vein system and can be divided into two groups: vein-filling, and fracture-filling. The vein-filling calcite has a bladed texture; individual crystals can be up to 10 mm long, with an aspect ratio up to or greater than 10:1; it has multiple forms (Fig 3): lattice, parallel (Etoh et al., 2002), modified lattice, and parallel lattice. This calcite is variably replaced by quartz and fluorite as nearly cryptocrystalline grains and as distinct grains up to ~40 μ m across. In many cases, bladed calcite shows quartz crystals growing orthogonal to the large flat side of the blade (Fig. 3E), with the interstitial spaces variably filled in by fine-grained masses of anhedral quartz. A sample from the deepest part of the mine contains bladed calcite that shows no "armoring" by quartz, nor does it necessarily show interstitial quartz grains in the calcite matrix.

Fracture-filling calcite is anhedral, massive, and takes the shape of the fracture or veinlet it is filling. Grain size is determined by the fracture, and it is not observed with a bladed texture.





Figure 3. Bladed calcite textures observed in the Midas deposit (modified from Etoh et al., 2002). Bladed calcite in E has euhedral quartz up to 1 mm long growing off blades into open spaces remaining between calcite blades. Sample in photograph is \sim 4 cm by \sim 7 cm.

Calcite rarely hosts ore. When it does, the calcite forms bands \sim 1 cm wide that are easily discernible in hand sample but become indistinct in thin section. The calcite banding does not appear to be based on either cyclical or average grain-size variations, but is defined by a relatively smooth curviplanar surface with new calcite crystals growing off the surface, denoting distinct precipitation events. These calcite crystals tend to be anhedral, equant (dominant) to bladed (minor) texture, with irregular grain boundaries that can be indistinct. Sub-40 μ m inclusions of dominantly adularia and minor quartz are common in the calcite proximal to the ore. Near the bottom of the mined extent of the Gold Crown Hanging Wall vein, the ore is again hosted by quartz that is texturally similar to that found in the Colorado Grande and Gold Crown veins.

Fluorite is rare in the mine, and in this study was not observed above the 5125-foot elevation level (the highest level is at approximately 5650 feet elevation). It is massive in hand sample, but transmitted light microscopy indicates that the fluorite is finely crystalline, dominantly subhedral, though anhedral and euhedral crystals have been observed. Grain sizes range up to ~800 μ m, most are less than 300 μ m. Fluorite is interpreted to be late, as it has been observed replacing bladed calcite as well as filling void spaces interstitial to the original blades of calcite. Fluorite may also contain inclusions of calcite (dominant) and quartz (minor). Fluid inclusions are rare, and small (<-10 μ m).

Sulfides are dominantly anhedral and are associated with the electrum and naumannite. Textures of the sulfides and selenides indicate that the sulfides are replacing the naumannite. SEM analysis on several un-coated samples indicates the sulfides are, with the exception of galena, near endmember sulfides with no selenium detected. Galena has been shown to contain a few wt. % Se, though as noted above, the analyses for this study are not quantitative. SEM analysis of pyrite, chalcopyrite, and sphalerite has not revealed Se; this may indicate the Se concentration is merely below detection levels for an uncoated sample. Replacement of the naumannite varies from sample to sample, but is always dominated by either pyrite or chalcopyrite, sub-equal amounts of each have not been observed. Sphalerite and galena, where they do appear, are minor constituents.

Ore phases

The only ore phases encountered as part of this study were electrum and naumannite (Ag₂Se), though the naumannite, based on SEM standardless analysis of uncoated samples, contains up to ~20 mol % Ag₂S. Ore phases tend to form both monophase grains of naumannite, or electrum, as well as polyphase grains composed of electrum + naumannite with replacement of the naumannite by pyrite/chalcopyrite \pm sphalerite \pm galena. Ore phases outcrop on the polished surface of the thin section in irregular anhedral masses up to 1 mm across, though most are less than 500 µm, and merge together within the thin section to form irregular masses that in underground mine face and hand sample appear as a solid black band (Fig. 2). These bands are up to ~10 mm wide and may be traced anywhere from several cm to the entire vertical exposure of the face.

Electrum is a uniform bright yellow-gold color, and standardless SEM analyses generally yield consistent Au:Ag ratios of ~40:60 to ~60:40, with a single sample having a Au: Ag ratio of approximately 20:80. Electrum is present dominantly in polyphase reflecting grains, both as cores surrounded by naumannite and base-metal sulfides, and on the edge of the grain with ~30 to 60% of the electrum's perimeter in contact with other reflecting phases (Fig 4A). Lesser amounts are present as monophase grains within the transparent gangue phases. Electrum is anhedral, and tends to have a globular or blobby habit, with a wide variety of grain sizes ranging from ~10 μ m to ~500 μ m.

Naumannite generally occurs as isolated anhedral irregular-shaped masses in the thin sections. Outcrops of naumannite at the surface show a highly variable size, ranging from less than 10 μ m up to ~1 mm, though most outcrops are less than ~500 μ m. Grains of naumannite are occasionally grown around euhedral quartz crystals and are surrounded by anhedral quartz. Naumannite grains occasionally (due to relative abundances of nuamannite and electrum), are in contact with or surrounding electrum.

Replacement textures between naumannite and electrum, and between electrum and base-metal sulfides, are not evident in the Colorado Grande, Gold Crown, and Snow White veins (Fig. 4). Reflected-light petrography shows electrum replacing naumannite in samples from two small veins that splay off the Colorado Grande vein: the Gold Crown Hanging Wall and Discovery veins. Where electrum is replacing naumannite, replacement textures are very distinctive, and electrum is the coarsest observed, up to 750 μ m (Fig. 4C).

Electrum and naumannite precipitate as anhedral irregular-shaped grains visible under transmitted light as opaque masses; these masses outcrop on the surface of a thin (thick) section as anhedral irregular shaped-grains that are smaller than the masses seen with transmitted light. The electrum and naumannite associated with a particular vein-filling episode did not precipitate into residual porosity among the vein silicates in the band in which they are hosted. Only rarely are euhedral crystals of quartz (Fig. 4C) immediately adjacent to the ore phases, these are likely xenocrysts. The gangue phases adjacent and distal to the ore are anhedral and indistinguishable in any particular ore-bearing band from the gangue in a non ore-bearing band. Quartz does occasionally grow into vugs wholly contained in a band; however these vugs do not contain ore phases. A sample from the Gold Crown vein shows adularia growing radially off of the anhedral masses of electrum and naumannite.



Figure 4. Reflected light photomicrographs of naumannite replacement by base-metal sulfides (A, B, and C), and electrum (C only). Galena in A is present as ~5-10 μ m inclusions in naumannite. Abbreviations: nau, naumannite; py, pyrite; cpy, chalcopyrite; gn, galena; el, electrum; sph, sphalerite; and qtz, quartz. Note naumannite growing around euhedral quartz crystal in the lower right corner of C.

The major ore-bearing bands are located in the outer portions of the veins (Fig. 2; Goldstrand and Schmidt, 2000; Rhys, 2002; Leavitt et al., 2004; Leavitt, 2004; this study). Detailed petrography as part of this study indicates that typically one to several bands of guartz adjacent to the host rock are un-mineralized. Ore mineralization generally has a pattern of relatively low concentration of ore phases at their first appearance, typically one to two bands, followed by very concentrated ore phases in the next one to few bands, in turn followed by one to several bands of relatively low concentrations of ore phases. Ore phases are rare between the main ore-bearing bands and the center of the vein. When the ore phases are more proximal to the vein center than the major ore bands, they tend to be circular to ovoid (approximately 2:1 aspect ratio), with lesser amounts as irregular-shaped, isolated grains less than 100 µm across.

Fluid inclusions

Roedder's (1984) fluid inclusion classification scheme was used to group inclusions into primary, pseudosecondary, or secondary categories. Most inclusions measured as part of this study were primary; however in a few samples pseudosecondary or secondary inclusions were used. Inclusions were generally rounded, equant to 2:1 elongate, with a lesser number having a highly irregular shape. Measurable inclusions ranged from 2 to approximately 50 μ m, but were dominantly <10 μ m, and were liquid-rich biphase, liquid-vapor, inclusions with a liquid:vapor (volume percent) ratio typically 85:15; no daughter salts were observed in these inclusions.

A single sample from the Colorado Grande vein (Midas 55) contained both liquid-rich biphase aqueous inclusions, and inclusions composed of 50% to 70% solid and the remainder filled with CO_2 . The solid phase in the CO_2 inclusions occupies one entire end of the fluid inclusion, and generally has an irregular edge where it contacts the liquid CO_2 . Notably, this is also the only sample locale that shows truly cryptocrystal-line quartz as colloform banding.

Due to the shallow depths of the hydrothermal system, pressure corrections would be small (1-5°C for hydrostatic loads, and 7-20°C for lithostatic loads) and have therefore not been made – the actual homogenization temperatures will be discussed here.

Homogenization temperatures (T_h) range from 83.6°C to 324.8°C with most ore-precipitation-stage inclusions homogenizing between 190° and 260°C (Fig 5A). Pre-ore and post-ore inclusions, as well as those hosted by calcite, tend to homogenize at lower temperatures than the ore-stage inclusions and inclusions hosted in quartz and adularia. However, there is considerable overlap in the homogenization temperature ranges for all stages of vein formation and phases that host the inclusions. All inclusions homogenized to the liquid phase by shrinkage of the vapor bubble. Fluid inclusions in a single adularia crystal from ~5580 feet elevation in the Colorado Grande vein, just to the north of the Colorado



Figure 5. Histogram of data for all fluid inclusions measured as part of this study. (A) Homogenization temperatures. Large peak in homogenization temperatures between 190°C and 260°C represents the major ore-precipitation events throughout the mine. Ore did precipitate at higher and lower temperatures however. Inclusions not hosted by quartz, and not associated with an ore-precipitation event, generally homogenize at lower temperatures than quartz-hosted ore-precipitation fluid inclusions. (B) Final ice-melt temperatures. All inclusions with T_m values below -1°C and several with T_m values between -1° and -0.5°C come from a single sample from the north end of the mine.

Grande and Gold Crown vein intersection, homogenized at 307.5°C and 324.8°C, approximately 30 to 50°C higher than the rest of the samples analyzed. There was not conclusive evidence in the thin section that this crystal was in place, it may be a xenocryst recording unrelated fluids.

Final ice-melt temperatures (T_m) are uniformly between -1°C and 0.0°C, excluding the Midas 55 sample, with most T_m values between -0.5°C and 0.0°C (Fig. 5B). Final ice-melt temperatures within a single crystal are generally homogenous, though different generations of inclusions as well as inclusions in different crystals in the same sample can have slightly different T_m values. The melting of actual ice crystals was only observed in a single inclusion; therefore, most T_m data was collected by observing when the vapor bubble returned to an undeformed state. In some cases the vapor bubble was completely crushed by ice formation, and did not reform on thawing, negating the possibility of collecting T_m data from these inclusions. The problem of vapor bubbles being crushed and not reforming dominantly occurred in calcite and, occasionally, in quartz-hosted fluid inclusions.

A single sample from the Colorado Grande vein contained CO_2 + solid inclusions in quartz along with aqueous inclusions. Both were present as primary inclusions, with some crystals also preserving pseudosecondary aqueous inclusions in quartz. The CO₂ had melting points from -57.7°C to -57.1°C, with an average of -57.4°C. Homogenization temperatures ranged from -3.5°C to 11.5°C, with an average of 4.7°C.

DISCUSSION

Fluid inclusions

 T_h values vary spatially throughout the mine. The highest T_h values occurred in the Colorado Grande vein south of the intersection of the Colorado Grande and Gold Crown veins and in the deepest part of the mine, suggesting this is the fluid source for the vein system. In general, the T_h decreases with increasing distance from this point; however the trend is not absolute. Though they do show a little variation, there is no clear trend to the T_m data either, with higher T_m values (less saline water) closer to the fluid source than lower T_m values (more saline water).

The distribution of T_h and T_m values suggests multiple fluid pulses were responsible for precipitating the ore in localized zones within each vein. The number of bands present in any location is determined by the overlap of multiple zones of precipitation, giving rise to spectacular underground exposures (Fig. 2). If a single fluid pulse was responsible for the ore, there would likely be a clear distribution and trend to the homogenization temperatures. In this scenario, the highest homogenization temperatures would be associated with the point the fluids entered the vein system, and homogenization temperatures would decrease with increasing distance from this point.

Banding events at or very near the intersection of two veins could have formed bands in both veins contemporaneously. As noted above, if each banding and ore precipitation event was ubiquitous in the vein system, the vein morphology would likely be fairly uniform throughout the deposit and not show as much variability as what is commonly observed. That is, the veins would likely be uniform in width, texture, and number of bands throughout the deposit.

Evidence for boiling fluids

Bladed calcite (Fig. 3) and bladed quartz were observed in many localities throughout the mine. These localities encompass the vertical and horizontal extent from which analyzed samples of banded vein material were derived. Occasionally, stringer veins in the host rock proximal to the main veins contained bladed calcite/quartz; however, relatively few samples of stringers were studied, and these were from areas where a sample of banded vein material was not obtainable. The presence of bladed calcite, bladed quartz, or bladed calcite armored by bladed quartz is interpreted here to be the result of boiling fluids (Keith and Muffler, 1978; Etoh et al., 2002).

Most samples studied contained populations of what appear to be monophase inclusions that exhibited no visible change on heating or cooling. These are interpreted to be vapor-rich inclusions, and the lack of observable changes on heating or cooling is due to the low density of the vapor trapped (necessary to coexist with a high-density liquid) and the small size of the inclusions.

The presence of co-existing liquid-rich and vapor-rich fluid inclusions combined with bladed calcite, quartz-armored bladed calcite, and bladed quartz suggests the fluids boiled in the vein system that became the Midas deposit.

Ore paragenesis

The textural relationship between electrum and naumannite – electrum grains partially to completely rimmed by naumannite - suggests the electrum precipitated first, followed by the naumannite, but both ore phases may precipitate contemporaneously. There are three possible times, relative to adjacent gangue phase precipitation, that the ore can precipitate: (1) before, (2) during, or (3) after. (1) Precipitation before the gangue would allow the ore to precipitate rapidly into the anhedral irregularly shaped masses observed in this study. However, the ore phases would quickly be covered/ armored by gangue phases that would likely cut the ore off from the majority of the fluids still flowing through the system. This would allow the anhedral grain shape, and may allow the coarse grain sizes of the ore to develop, but any replacement would have to occur either before the gangue precipitated, possibly a very short time span, or be the result of later fluid flow along grain boundaries.

(2) The ore may precipitate at the same time as the enclosing gangue. If the ore and the gangue are precipitating at the same time, the ore would likely be disseminated throughout the band as fine particles. The ore was not observed disseminated throughout an entire band, though rare to occasional fine particles were observed disseminated in the center fill of the vein. Thus if the ore phases had started as fine, disseminated particles, recrystallization and diffusion of the ore into the observed larger grains concentrated in coarse masses would be necessary.

(3) Ore phases precipitated after the gangue phases precipitated from a particular fluid pulse. Ore precipitation after gangue precipitation for a particular band would allow the ore to grow into any open spaces left at the vein center, and the lack of crystals in the vein center would allow the ore to grow to the large grains, relative to the gangue phases, observed. Euhedral guartz xenocrysts are commonly trapped against or in the ore phases. These crystals tend to be ~300 to 500 μ m across, and up to ~2 mm long, similar in size to those pictured armoring bladed calcite (Fig. 3E). Additionally, there would still be open spaces left at the center of the vein for fluid flow that could cause replacement of naumannite by base-metal sulfides \pm electrum. Precipitation of the ore after the gangue phases would allow the physical and chemical changes as a result of boiling to concentrate the dissolved ore metals in the fluid until they are saturated enough to precipitate as well. Concentrating dissolved metals by boiling could also account for the presence of unmineralized bands. Unmineralized bands could thus be the result of dissolved metal concentrations low enough that the amount of boiling the fluid experienced could not concentrate the metals enough to cause ore precipitation.

Based on the above considerations, we believe the veins formed in the following manner:

The Midas fault system is saturated with a metal-bearing hydrothermal fluid at pressures greater than hydrostatic. A tectonic event (earthquake) fractures the lithocap on the vein system and movement along the fault plane causes irregular, disconnected, open spaces to form. The earthquake also causes fault-valves to form, which allow the hydrothermal fluid pressure to drop causing boiling and precipitation of the ore and gangue (Sibson, 1987, 2001, and references therein). Boiling of the hydrothermal fluid at depth results in rapid nucleation and precipitation of the now supersaturated guartzadularia gangue. Nucleation was initially so rapid that grain sizes remained below 10 µm, but as the degree of supersaturation decreased, growth rates were more in line with nucleation rates and the gangue grain size increased, typically to 30-40 µm. Changes in the fluid chemistry accompanying the pressure drop and the silicate gangue precipitation eventually caused the ore minerals to become saturated and either electrum (Gold Crown and Colorado Grande) or naumannite (Gold Crown Hanging Wall and Discovery) formed first (Fig. 6A [page after next page]).

Continued crystallization and fluid evolution generally resulted in naumannite (Ag₂Se) precipitating on or around earlier formed electrum or, in other areas of the mine, electrum replacing and precipitating around pre-existing naumannite. In most samples there is textural evidence that the last hypogene event (in a particular cycle) was the late replacement by, with likely additional precipitation of, the base-metal sulfides pyrite and chalcopyrite with minor amounts of sphalerite and/or galena. A specific sample will exhibit this late sulfide replacement as dominantly pyrite or chalcopyrite – they are never present in sub-equal amounts. Precipitation of gangue

minerals, likely silicates, higher in the fault system eventually recaps the veins, allowing pressures and temperatures to increase and temporarily stopping precipitation.

A subsequent fault movement could begin the process again possibly in the same location in the vein system. This latest dilation may occur either in the center of the previously (partially) filled vein or, as evidenced by brecciated, banded vein material in exposures underground, at some other weak zone in the vein. In cases where the second opening coincides with the previously incompletely filled vein, the rapidly precipitated quartz and adularia would fill in amongst the coarse sulfides and selenides of the earlier event (Fig. 6B-H).

This sequence of faulting, fluid-pressure reduction, gangue-phase precipitation, ore-phase precipitation, replacement of ore phases, and capping by gangue precipitation higher in the system (though replacement of the ore phases would likely continue during and after formation of the cap) can repeat itself numerous times. Veins have been observed underground (Fig. 2) that have more than 15 individual bands, and it is likely that each band records an individual pulse of fluid through that portion of the vein system.

COMPARISON TO OTHER DEPOSITS

Carlin trend mines

Carlin trend mines are located in northern Nevada and formed 42 to 30 Ma (Hofstra and Cline, 2000), significantly older than the formation of the Midas deposit at the north end of the Carlin trend. Despite this age difference T_h values determined as part of this study correlate well with deposits on the Carlin trend. Several Carlin trend deposits, e.g. Betze-Post (Lamb, 1995; Lubben, 2004), Meikle (Lamb, 1995; Emsbo et al., 2003), Betze and Carlin (Groff et al., 2002), Carlin (Radtke et al., 1980), Lone Tree Complex (Kamali, 1996; Young, 1999), Trenton Canyon (Young, 1999), and North Peak (Young, 1999), have homogenization temperatures between 100°C to 350°C, and salinities between 1.1 and 14 (most <10) wt. % NaCl equiv. The similarities between the Carlin trend fluids and the Midas fluids suggests the fluids responsible for the mineralization at Midas and along the Carlin trend had similar thermal, but not temporal, histories. The much lower salinities of the Midas deposit fluids likely indicate the fluids there had a larger freshwater component than the Carlin trend fluids.

Epithermal systems

Epithermal systems form from low temperature (120-460°C), low salinity (<2.6 wt. % NaCl equiv.) fluid (Cooke and Simmons, 2000). Midas fluids correlate well with this range. However, a few samples homogenized below this range, and a single sample did show significantly more saline fluids. There is also good correlation with other epithermal systems in the region, e.g.: Dixie Claims, Midas District,

NV (Ioannou and Spooner, 2000), Tuscarora, NV (Castor et al., 2003), and Round Mountain, NV (Sander and Einaudi, 1990), and around the world, e.g. El Peñon, Chile (Warren et al., 2004), Koryu, Hokkaido, Japan (Shimizu et al., 1998), and Golden Cross, Waihi, New Zealand (de Ronde and Blattner, 1988). The outlier is the Midas 55 sample, which contains high-salinity (for the Midas deposit) and low-salinity fluids as well as CO_2 inclusions.

CONCLUSIONS

The fluid inclusion and paragenetic data for the Midas deposit obtained as part of this study, by itself and combined with previous studies of Midas, the Carlin trend, and other epithermal mines around the world, leads to several conclusions:

(1) Fluids boiled in the system. The presence of liquid- and vapor-rich fluid inclusions along with bladed calcite, bladed quartz, and quartz armoring bladed calcite indicates the fluids responsible for the ore at Midas boiled.

(2) Multiple pulses of fluid precipitated the ore in the veins at different times, and each band corresponds to a single faulting and precipitation event in the vein system. Ore precipitation and quartz banding were localized events within the vein system. The formation of each band was centered on the location of a rupture or opening of the fault system. The distinction between mineralized and unmineralized bands is the result of the ability of boiling to concentrate dissolved metals enough to precipitate as ore phases.

(3) Ore phases were precipitated late in the banding event, forming anhedral irregular masses growing into open spaces in the middle of the vein. The next band to form in the vein filled in these irregular open spaces left between and around the earlier formed ore phases.

(4) Homogenization temperatures at Midas (~15 to 14 Ma) are indistinguishable from those along the Carlin trend (~42 to 30 Ma). Final ice-melt temperatures are much warmer (dominantly between -1° C and 0° C) than on the Carlin trend, indicating the fluids had a larger freshwater component than the fluids responsible for Carlin trend mineralization. Homogenization and final ice-melt temperatures of inclusions at Midas are largely indistinguishable from those of many epithermal ore deposits around the world.

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between the two sides of the vein is completely arbitrary. (A) First stage of vein formation. Initial quartz crystals start very fine grained and coarsen as crystallization proceeds. Ore minerals precipitate after the gangue has precipitated and trap or grow around euhedral quartz xenocrysts. Note the open space left around and between the ore minerals. This open space allows continued fluid flow in the vein system to replace some of the naumannite with, and cause additional precipitation of, base-metal sulfides. (B) Second stage of vein formation. Open spaces left between and around ore minerals from the first band have been filled in by fine grained anhedral quartz from the second band. This gives the illusion that the ore is associated with the second band, rather than the first. (C) and (D) Third stage of vein growth. Again, quartz coarsens as crystallization of a particular band progresses. In this stage, ore minerals did not precipitate, however, in D, gangue precipitation proceeded to form euhedral quartz crystals growing into open spaces remaining between sides of the vein. (E) and (F) Closure of the vein by bladed calcite growing between the anhedral or euhedral quartz of the last band. Note, there is a great deal of open space left between and around each individual blade of calcite (see Fig. 3). (G) and (H) Armoring of the bladed calcite by euhedral quartz crystals growing on the large flat sides of the blades, not the narrow edges. As discussed in the text, the closure of the vein by bladed calcite armored by euhedral quartz is merely one possibility. There is great variability in the centerfill of the vein.



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