

Geology, geochemistry, and geochronology of the Midas epithermal gold system, Nevada

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Abstract

The Midas epithermal system is one of the larger low-sulfidation epithermal vein systems discovered in the western US in recent years, containing in excess of 3 Moz of gold (premining). The deposit is spatially and temporally related to bimodal volcanism in the Northern Nevada Rift; dates on igneous rocks (16-14.7 Ma) bracket the age of high grade veins (15.3 Ma). Hydrothermal alteration at Midas is typical of epithermal systems, comprising proximal potassic through distal propylitic assemblages; in contrast to many epithermal systems, Midas has minimal development of wallrock illite/sericite. Mineral assemblages are clearly zoned on the vein structures that acted as focal planes for fluid upflow. Geochemical zoning patterns also show this zoning. Metals were deposited in open-space veins as the result of boiling of hydrothermal fluids; multiple episodes of crustiform mineral deposition are documented in the vein textures. The major vein minerals include quartz, adularia, calcite, selenides and sulfides, with electrum as the primary ore mineral. REE patterns for vein material are similar to patterns for coeval rhyolites, but distinctly different from patterns of the host rocks. Stable isotope data are consistent with meteoric water as the dominant ore fluid. Combined REE and stable isotope data suggest that fluid from which the main ore-bearing stage of the veins was deposited was slightly lower pH than other stages.

Keywords: *epithermal, Great Basin, Nevada, gold, geochronology, hydrothermal alteration, isotope, REE*

Introduction

The Ken Snyder (Midas) mine exploits the largest known Au-Ag epithermal deposit along the middle Miocene northern Nevada rift (NNR) (Leavitt et al., 2004). Midas is located near the eastern margin of the NNR, a lineament that extends from east-central Nevada to southern Oregon (Fig. 1; Zoback and Thompson, 1978; Zoback et al., 1994; John and Wallace, 2000). The NNR is defined by a strong aeromagnetic anomaly that locally corresponds to an alignment of middle Miocene eruptive centers (John and Wallace, 2000; John et al., 2000) formed during Basin and Range extension at ca. 16 Ma (Zoback et al., 1994; John, 2001; Dickinson, 2002). Drilling in the Midas area has shown that Miocene tuffs, flows and volcanoclastic rocks extend to a depth of at least 1.5 km beneath the present surface with depth to pre-Tertiary basement unknown.

The Midas deposit is hosted by a deeply-eroded section of Miocene volcanic rocks along the eastern margin of the NNR (Emmons, 1910; Wallace, 1993; Goldstrand and Schmidt, 2000). It is a selenide-rich, low-sulfidation, epithermal system, and it belongs to a suite of precious metal occurrences that formed along the NNR between 15.6 and 15.0 Ma (John, 2001; Fig. 1). These systems formed from fluids dominated by meteoric water of near-neutral pH, and have relatively

high Au:Ag ratios, low total base metal contents, high selenide mineral contents, and predominantly reduced sulfur (John et al., 1999; John and Wallace, 2000; John, 2001; John et al., 2003). They are most commonly associated with rhyolite flows and domes in extensional rift environments, although along the NNR examples of both mafic- and felsic-hosted systems exist (John, 2001). Similar temporal associations between low-sulfidation epithermal systems, magmatism and faulting have been observed in rift-related, continental extension, and/or backarc settings elsewhere in the world (Sillitoe and Hedenquist, 2003). As presently known, ore is confined to steeply-dipping, banded quartz-adularia-calcite-precious metal bonanza veins filling north-northwest-striking faults in felsic units and locally contains ore grades greater than 3400 grams per tonne (g/t) of gold. Gold occurs as electrum and is intimately associated with selenide and sulfide minerals, forming dark bands similar to the ginguero ore at Hishikari (e.g., Izawa et al., 1990; Naito, 1993).

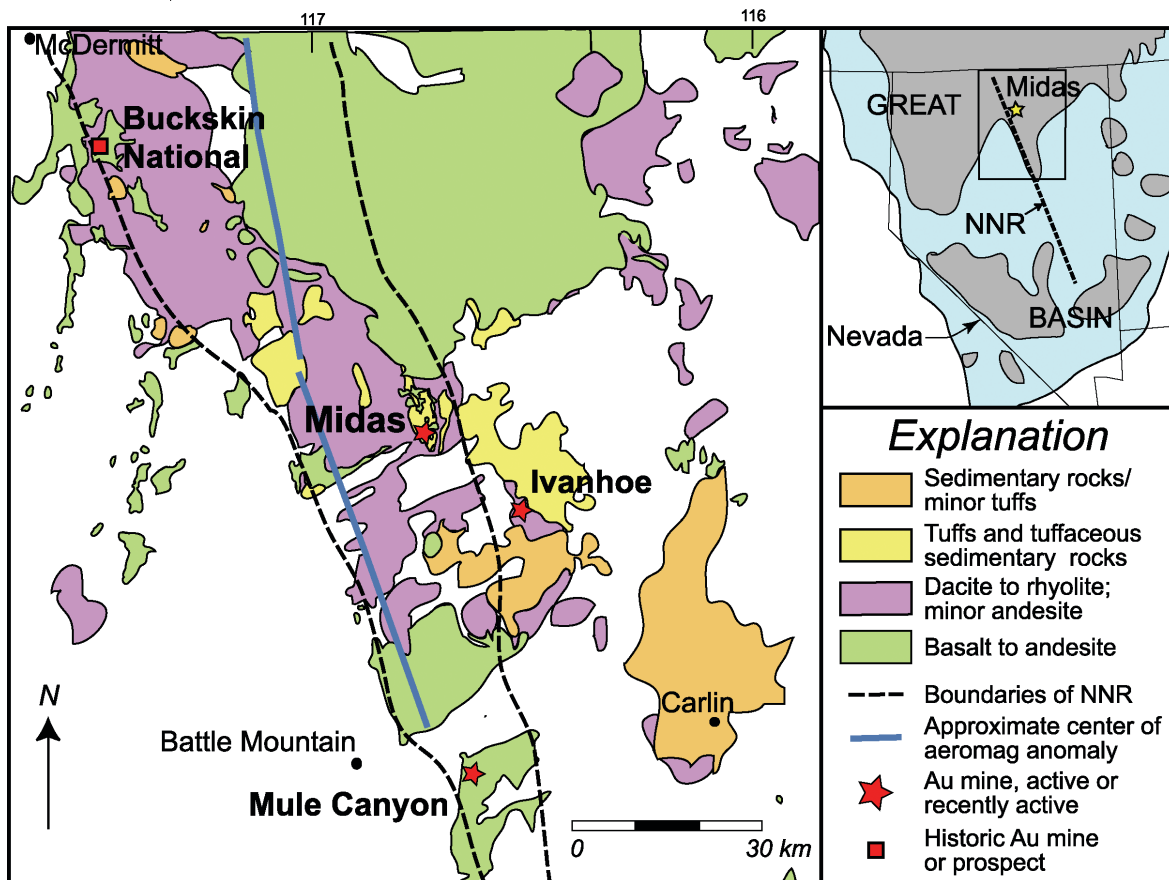


Figure 1. Location and general geology of the northern Nevada rift (NNR). A. Bimodal basalt-rhyolite assemblage (shaded) and axis of NNR. From Leavitt et al. (2004) based on the maps of Christiansen and Yeats (1992), Ludington et al. (1996), and John (2001). B. Approximate locations of volcanic-hosted, low-sulfidation epithermal precious metal occurrences associated with the NNR. Modified from Leavitt et al. (2004).

Geochronology

Newly-determined $^{40}\text{Ar}/^{39}\text{Ar}$ dates from mineralized veins and a volcanic host rock at Midas provide constraints on the timing of volcanism and hydrothermal activity along this part of the northern Nevada rift (Leavitt et al., 2004). An average of new dates for adularia from the Ken Snyder Mine area indicates an age of mineralization of about 15.3 Ma. A $^{40}\text{Ar}/^{39}\text{Ar}$ date for diabase that intrudes the Esmeralda formation (informal name), the youngest ore-bearing unit, yields an age of no more than 16.0 Ma. This date is consistent with ages of early rift-related mafic volcanic flows in the northern Shoshone Range. Constraints on the age of the Esmeralda formation imply that mafic volcanism and basin development had occurred in the Midas area by ~16 Ma. New dates show that sinters and opalized sediments formed on the paleosurface of

the Midas hydrothermal system and that Au-Ag mineralization was coeval with felsic volcanism (Leavitt et al., 2004). Detailed geochronology (Leavitt et al., 2004) indicates that the high-grade Au-Ag veins at Midas were deposited no more than 400 kyr after eruption of the youngest felsic volcanic host rocks, and are only slightly older than overlying fresh tuffs.

In the Midas region, the high-grade Au-Ag veins formed within a period of 300 kyr, although hydrothermal activity may have lasted much longer. By analogy with active low-sulfidation geothermal systems, the estimated precious metal content of veins easily could have been deposited within this time frame. Precision geochronology also shows that high-grade Au-Ag veins were deposited after a change from mafic-dominated bimodal volcanism and basin development to felsic volcanism, faulting, and local uplift. The similar ages of *in situ* rhyolite and mineralization suggest that they are genetically linked and that felsic volcanism and tectonic events led to the formation of high-grade selenium- and Au-Ag-rich bonanza veins in the Midas district (Leavitt et al., 2004).

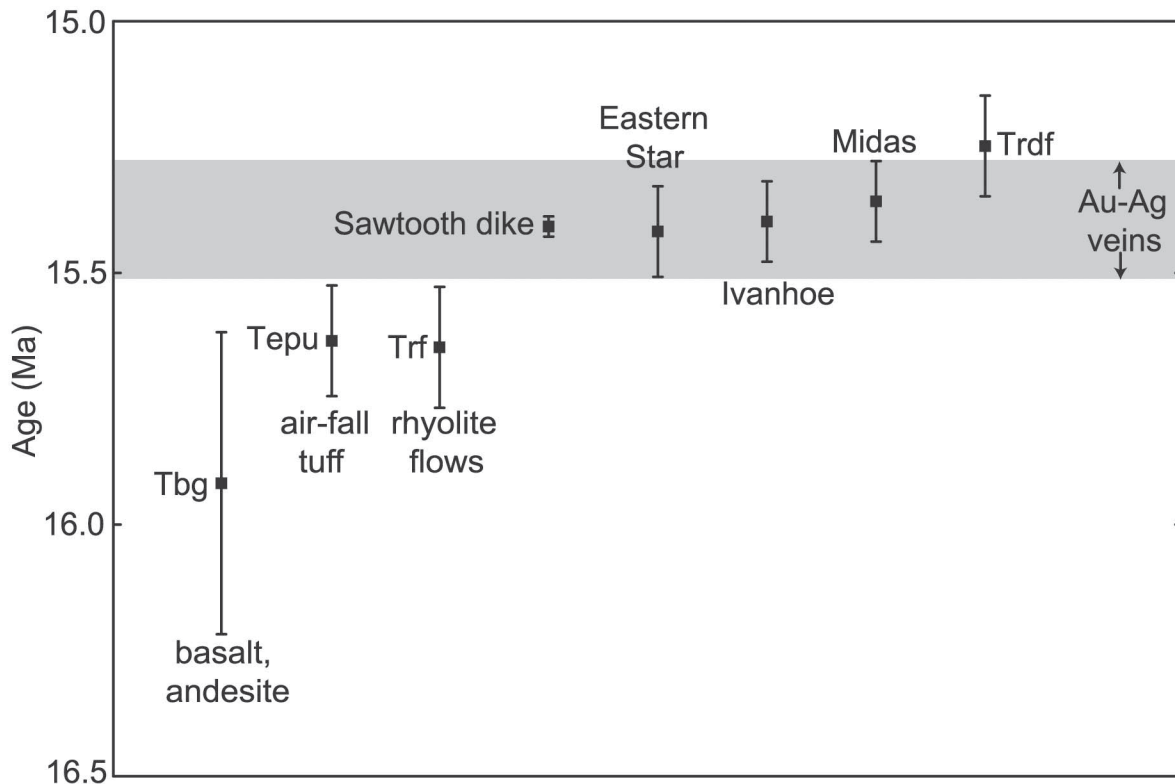


Figure 2. Geochronology of igneous and hydrothermal events in the Midas area. From Leavitt et al., 2004.

Hydrothermal alteration and vein paragenesis

The spatial and temporal distribution of alteration and geochemical anomalies associated with the Midas precious metal deposit is typical of many low-sulfidation epithermal bonanza vein systems and is summarized here from the work of Leavitt (2004) and Leavitt et al. (2005). The main types of alteration include: weak, moderate and intense propylitic; potassic, intense potassic and silicic-potassic; argillic; and silicic. Alteration shows patterns of increasing temperature and water/rock interactions towards the main veins, and with time (Figure 3). Secondary mineral assemblages, textures, and distribution of alteration types have been characterized for mafic and felsic lithologies. Weak propylitic alteration is widespread, common in mafic volcanic rocks, and characterized by an assemblage of calcite-chlorite. Moderate propylitic alteration extends up to 1300 ft (400 m) from the main veins, and is characterized by an assemblage of chlorite-calcite-pyrite-smectite, and an increase in replacement and veining. Mineral assemblages indicate temperatures of ~200-230°C. An epidote isograd (first appearance of epidote) forms

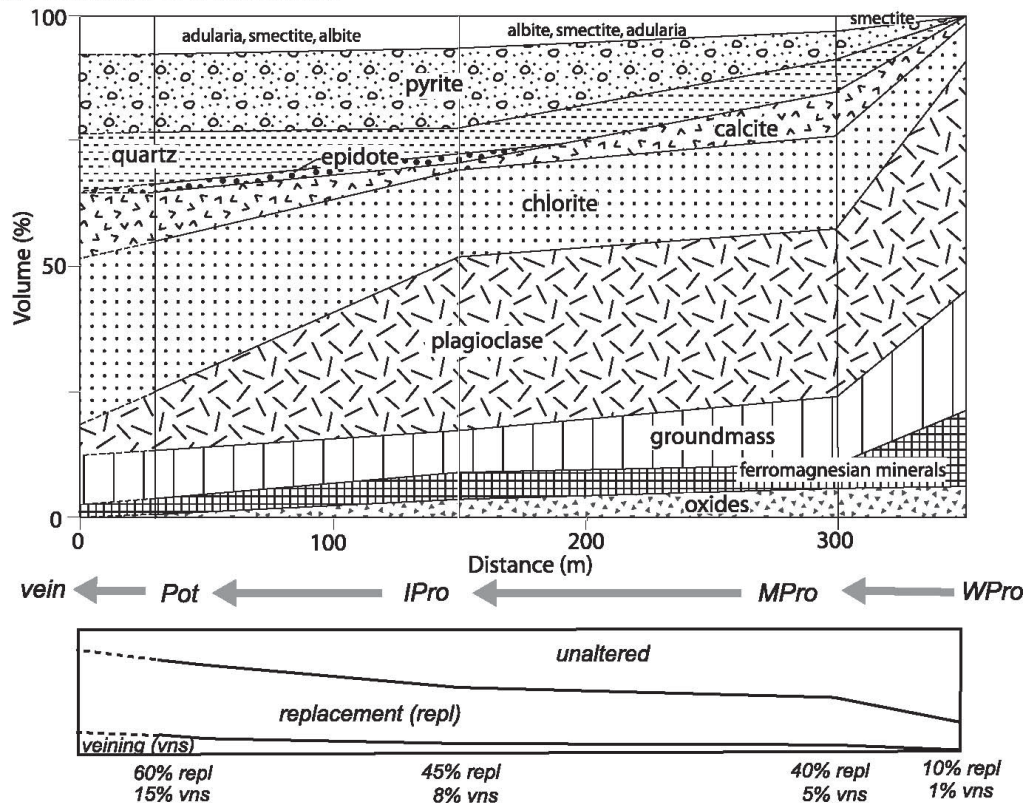
the contact between moderate and intense propylitic alteration, and drapes over the main veins, recording paleoisotherms associated with upflow zones. An assemblage of chlorite-pyrite-epidote-smectite, lesser albite, \pm prehnite in mafic rocks, and adularia in felsic rocks formed at temperatures of $\sim 250^{\circ}\text{C}$. Gains in S, Ag, As, Sb, Hg, Zn, P, H_2O and CO_2 accompanied propylitic alteration. Potassic alteration forms haloes that extend up to 100 ft (30 m) from the main veins and faults. It is characterized by an assemblage of adularia-chlorite-pyrite/marcasite-smectite/illite-quartz, and further increases in replacement and veining. Below $\sim 5,800$ ft elevation (~ 1770 m), epidote and albite are variably present, indicating temperatures similar to those of intense propylitic alteration. Illite is accompanied by Fe-rich chlorite below $\sim 5,500$ ft elevation (~ 1670 m). Within narrow zones of intense potassic alteration, less than 30 ft (10 m) from the main veins, illite/sericite, kaolinite, and feldspars rimmed with adularia accompany the potassic assemblage. Potassically-altered wall rocks of the main veins locally exhibit silica flooding and comprise a narrow zone of silicic-potassic alteration adjacent to the main veins; this alteration likely overlaps the initial stages of emplacement of the main veins. S, P, Ag, Sb, W \pm K, Hg, As, Pb, Zn, and Mo are the main components enriched in mafic and felsic rocks during potassic alteration. Cross-cutting veinlets suggest that weak propylitic to silicic-potassic alteration types reflect a temporal progression with the most pervasive, and highest temperatures of alteration coeval with the onset of the main-stage veins.

The main veins formed in deep-seated faults that provided permeable conduits for fluids. Numerous episodes of boiling produced crustiform ore with alternating bands rich in silica, adularia, bladed calcite, selenides and sulfides. Boiling textures are present over almost the entire vertical extent studied (~ 1600 ft or ~ 500 m), including the present-day surface, and include bladed calcite (commonly replaced by quartz), adularia, and quartz recrystallized from amorphous silica. Late stage, cross-cutting veinlets of clay minerals, pyrite, carbonate, crystalline quartz, and minor sulfates formed during collapse of the system, and downward migration of acidic, cooler fluids. Additional argillic alteration is hosted by subsidiary faults, and permeable volcanoclastic rocks. Both argillic and silicic alteration are common at shallow levels and the present-day surface.

Pathfinder elements typical of epithermal systems, including Hg, As, and Sb, form haloes above ore-grade veins. Enrichment in K occurred with deposition of precious metals, and in overlying haloes along the main ore-bearing faults. The lack of significant enrichment in base metals and depletion in precious metals with depth suggests that only the upper portion of this hydrothermal system has been studied.

The Colorado Grande and Gold Crown veins host the greater part of high-grade Au-Ag ore at the Ken Snyder Mine in north-central Nevada. The veins formed in N- and NW-trending faults that deform a bimodal, basalt-rhyolite series of volcanic host rocks. The veins formed in six main stages. Stage II veins, which comprise the bulk of known mineable reserves, are crustiform, colloform veins composed of alternating dark, metal-rich bands and light, quartz-calcite-adularia-rich bands. The main metal-bearing phases include naumannite, chalcopyrite, electrum, pyrite, sphalerite, and galena, with minor aguilarite, and marcasite. Metal-rich bands are commonly associated with fine-grained, idiomorphic adularia. Bladed and massive calcite are abundant in some bands. Episodes of brecciation occurred between and during main stages; at least two episodes of brecciation and or phreatic activity accompanied emplacement of Stage II bands, disrupting earlier bands and transporting lithic fragments and xenocrysts within bands. Geochemical analyses of trace elements clearly show that Stage II is enriched in precious metals, selenium, and base metals compared to the other stages of veining. Typical pathfinder elements including Hg and As show the greatest enrichment in the latest stages of veining, with variable increases in middle stages of formation. Sb shows enrichment in the middle stages of formation, and depletion in the latest stage of veining.

a. Alteration of Mafic Rocks



b. Alteration of Felsic Rocks

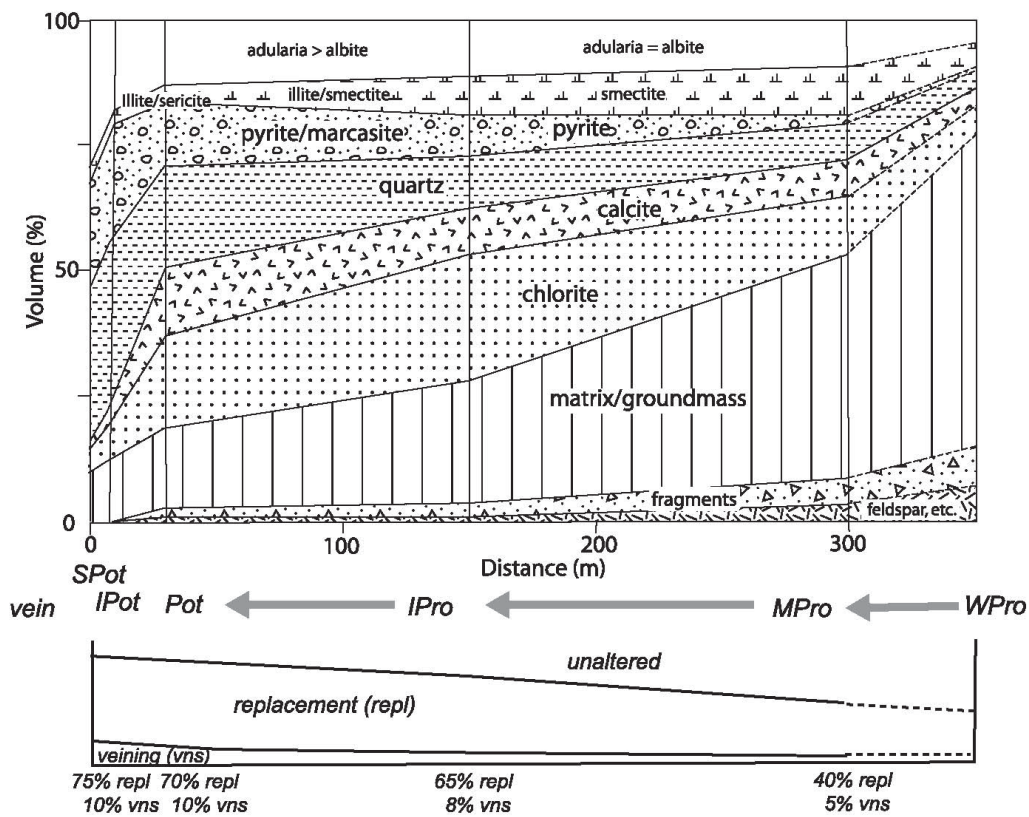


Figure 3. Schematic representation of progressive alteration of a) mafic rocks, and b) felsic rocks. Alteration types shown with spatial reference to main gold veins. Based on petrographic analysis of thin-section samples. Detailed description of alteration types (mineral assemblages) can be found in Leavitt (2004). Abbreviations: WPro = weak propylitic; MPro = moderate propylitic; IPro = intense propylitic; Pot = potassic; IPot = intermediate potassic; SPot = strong potassic.

REE and isotope geochemistry

REE and isotope geochemistry (summarized here from Leavitt, 2004) yield insights into the nature of the ore fluids. Patterns of chondrite-normalized rare earth elements (REEs) for host volcanic rocks show enrichment in light rare earth element (LREE) and depletion in Eu; these patterns appear unaffected by alteration. Patterns for coeval rhyolite are flatter, and do not exhibit an Eu anomaly. Patterns of chondrite-normalized REEs for Stage I, II, IV, and V veins are relatively flat with weak positive Eu anomalies, somewhat similar to patterns of coeval rhyolites, but distinctly different from those of host rocks. Stage III veins, which formed during a widespread episode of brecciation, contain higher concentrations of REEs and immobile elements including Zr and Nb; REE patterns are similar to those of host rocks, and likely reflect the incorporation of lithic fragments. Stage VI veins exhibit patterns more similar to Stage III veins. Normalization of REEs for Stage II through VI veins to Stage I veins, and to coeval rhyolite dikes, shows slight enrichment in Eu in Stage II veins, and in heavy rare earth elements (HREEs) in Stage VI.

The $\delta^{18}\text{O}$ values of quartz from all stages of the veins range from 1.0 to 7.5‰. The $\delta^{18}\text{O}$ values of water in equilibrium with quartz for Stages I through IV at 230°C range from -8 to -4‰, and for Stages V through VI at 140°C from -13 to -9‰. The $\delta^{18}\text{O}$ values of calcite range from 1.2 to 4.9‰ for Stages I through V, and 5.3 to 9.5‰ for Stage VI. The $\delta^{13}\text{C}$ values range from -6 to -1‰. The $\delta^{18}\text{O}$ values of water in equilibrium with calcite for Stages I through IV at 230°C range from -7 to -3‰, and for Stages V through VI at 140°C from -12 to -4‰. The $\delta^{13}\text{C}$ values of CO_2 in equilibrium with calcite for Stages I through IV at 230°C range from -6 to 0‰, and for Stages V through VI at 140°C range from -8 to -6‰.

The REE and isotope signatures of the veins reflect the near-neutral pH of meteoric waters. The combined data indicate that a shift to slightly lower pH accompanied emplacement of Stage II high-grade ore. Latest stage veins were enriched in HREEs that were likely derived from shallow meteoric waters mixed with acidic waters from advanced argillic alteration zones near the paleosurface.

Summary and conclusions

$^{40}\text{Ar}/^{39}\text{Ar}$ ages of host rocks and gold-quartz veins, results of geologic mapping, and several additional isotopic dates for volcanic rocks show that regional high-grade Au-Ag mineralization was coeval with felsic volcanism and faulting. In the Midas region, high-grade Au-Ag veins formed within a period of 300 kyr, no more than 400 kyr after eruption of the youngest volcanic host rocks and only slightly before overlying fresh tuffs. The similar ages of *in situ* rhyolite and mineralization suggest that they are genetically linked and that felsic volcanism and tectonic events led to the formation of high-grade Se- and Au-Ag-rich bonanza veins. The duration of the hydrothermal system, and timing of mineralization relative to volcanic activity are similar to that of other Miocene low-sulfidation epithermal precious metal deposits in the Great Basin (e.g., Conrad and McKee, 1996; Henry et al., 1997; John et al., 2003; Wallace, 2003; Leavitt et al., 2004).

Detailed characterization of alteration mineralogy and geochemical zonation has provided evidence of the pathways of hydrothermal fluid flow, and vectors to ore. Patterns of alteration show that as the hydrothermal system evolved, temperature and water:rock interactions increased toward the main veins. The main types of alteration are similar to those present in other low sulfidation epithermal systems and include from distal to proximal: propylitic, potassic and silicic with a local argillic overprint. Identification of mineral isograds coupled with geologic reconstructions and data from fluid inclusions allowed for determination of the elevation of the paleosurface relative to ore, and recognition of the main paleo-upflow zone for the Colorado Grande (CG) and Gold Crown (GC) veins. Gains and losses in a variety of elements increase in magnitude with increased volumes of replacement and veining. Mercury, As, and Sb are zoned

with respect to the main veins, and increase in abundance above ore. Unlike many epithermal systems, base metals show little increase with depth within the vertical interval studied.

Comparison of chondrite-normalized REE patterns of Midas veins to those of host rocks indicates that most stages of veins do not show a direct correlation and/or inheritance of patterns from host rocks; rather they suggest a possible genetic tie to coeval rhyolite. Stable isotope data for carbonates suggest that the Midas veins were deposited from a parent fluid with a composition of $\delta^{13}\text{C} = -4\text{‰}$, and $\delta^{18}\text{O} = -5\text{‰}$. A decrease in $\delta^{13}\text{C}$ in calcite from Stage I to II may have resulted from a decrease in pH of the parent fluid, or a change to a parent fluid of a different composition. A decrease in pH of the parent fluid may have taken place as the system developed and the buffering capacity of wall rocks along the flow path decreased.

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