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Distinguishing generations of quartz and a distinct gas signature of deep high-grade Carlin-type gold mineralization using quadrupole mass spectrometry

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ABSTRACT

Carlin-type gold deposits in north-central Nevada occur in a region that was the locus of igneous and/or hydrothermal activity over time and the overprinting of silicification associated with metamorphism, base metal mineralization, barren jasperoid, and post-ore alteration hinders exploration efforts. Therefore, the potential to distinguish unrelated generations of quartz using the results of quadrupole mass spectrometer (QMS) gas analyses was evaluated for the Getchell trend, and compared to results from the Goldstrike property in the Carlin trend and a Carlin-type gold occurrence in the Huijiabao trend, China.

The results of fluid inclusion petrography, QMS analyses, and interpretation of gas data using N_2–Ar–He ternary diagrams and CO_2/CH_4 vs. N_2/Ar plots indicate that different generations of quartz in the Getchell trend were deposited by hydrothermal fluids having distinct characteristics. Metamorphic quartz containing one-phase CH_4 and halite-bearing liquid–water dominant vapor-poor inclusions has the highest gas content (37.6 mol%) and highest N_2/Ar values (3250), which are suggestive of an evolved magmatic fluid. Pre-ore and quartz–base metal veins contain CO_2-bearing inclusions. Base metal veins have N_2/Ar values ≥675 and a positive correlation between H_2S/Ar vs. N_2/Ar that is suggestive of a magmatic fluid. Carlin-type quartz contains liquid-dominant vapor-poor inclusions and is characterized by total gas contents > 10 mol% and N_2/Ar values > 300 that are suggestive of mixed crustal–meteoric–magmatic fluid sources. Post-ore quartz and barren jasperoid formed from mixtures of gas-poor meteoric water and crustal fluids.

Samples of deep high-grade mineralization from the Goldstrike property have total gas contents up to 10.5 mol% and N_2/Ar values > 300. Fluid sources include crustal, meteoric, and magmatic. Gas data from the Goldstrike property, Turquoise Ridge deposit, and metamorphic quartz of the Getchell trend plot near the N_2 apex of N_2–Ar–He diagrams, which is indicative of a magmatic fluid end member.

Carlin-type mineralization in the Huijiabao trend is unique because fluids were CH_4-rich and there is a correlation between CH_4 and hydrocarbons. Gas analyses commonly record < 1 mol% total gas for evolved (crustal) and organic fluids. Fluid inclusions in post-ore quartz and barren jasperoid are also gas poor, but CO_2 is the dominant gas specie.

Together, the results show that fluid inclusion gases can be used to distinguish different generations of quartz in mining districts with complex origins.

1. Introduction

Since discovery of the Carlin mine in Nevada in the 1960 s, exploration for Carlin-type deposits has been hindered by two factors. The first is that fundamental differences exist in published genetic models for Carlin-type deposits. Previous studies have proposed that these deposits formed by the circulation of meteoric water and the source of Au was amagmatic (Ilchik and Barton, 1997; Emsbo et al., 2003). A connection to epizonal intrusions that contributed heat and metals in the formation of Carlin-type deposits was proposed by Sillitoe and Bonham (1990) and Johnston and Ressel (2004). In contrast, models by Cline et al. (2005) and Muntean et al. (2011) involve asthenospheric upwelling related to a change in the subduction of the Farallon Plate; deep crustal metamorphism and melting of lithospheric mantle; and ascending melts that potentially exsolved an Au and Cu-enriched vapor phase.

The second factor complicating exploration for Carlin-type deposits is the complex tectonic history that north-central Nevada experienced

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beginning in the Proterozoic (Tosdal et al., 2000). Different deformational events created a network of high- and low-angle faults that served as the plumbing system for Carlin-type gold deposits. However, this established network of faults and basement structures was reactivated over time, which resulted in the overprinting of different types of mineralization (Hofstra and Cline, 2000). Mining districts in north-central Nevada can contain base metal skarn-type deposits associated with Jurassic–Cretaceous stocks (Arehart et al.,1993; Hitchborn et al., 1996; Groff et al., 1997); porphyry Cu–Mo mineralization related to Cretaceous stocks (Barton, 1990); Eocene Carlin-type, skarn, and porphyry deposits (Theodore et al., 1973; Johnston et al., 2008); and Miocene Au–Ag epithermal deposits (John and Wallace, 2000). Ordovician–Devonian host rocks also contain massive sulfide and SEDEX deposits (Coats and Stephens, 1968; Bloomstein et al., 1991; Emsbo et al., 2003; Large et al., 2011) that could serve as metal sources.

As silicification and/or quartz veining are common in each mineralizing event, the ability to distinguish Carlin-type quartz from unrelated generations of quartz would be a valuable exploration tool. Quadrupole mass spectrometer analyses are used in the present study to determine if fluid inclusions in different generations of quartz have distinct gas compositions, with results from the Getchell trend serving as a case study. Data from metamorphic quartz and pre-ore quartz veins, base metal mineralization, barren jasperoid, and post-ore quartz veins are compared with samples from the Getchell and Twin Creeks Carlin-type gold deposits. For comparison, samples of deep high-grade mineralization from the Goldstrike property on the Carlin trend (Bettles, 2002) and samples from a gold occurrence on the Huijiabao trend in southwest Guizhou province, China (Su et al., 2008; Tan et al., 2015) were analyzed.

2. Geology and mineralization

2.1. North-central Nevada

Geologic events that created the complex structure in north-central Nevada began with the accretion of Paleoproterozoic terranes to the Archean Wyoming Craton (Foster et al., 2006). Rifting of the Laurentian supercontinent at 1–1.3 and 0.6–0.9 Ga created an important structural fabric in basement rocks and resulted in the deposition of a westward thickening wedge of Neoproterozoic and Cambrian rocks (Stewart, 1972; Karlstrom, et al., 1999; Timmons et al., 2001). Crustal shortening during the Late Devonian to Early Mississippian Antler Orogeny was accommodated by the Roberts Mountains thrust fault, which placed nonreactive fine-grained siliciclastic rocks (of low inherent permeability) over a permeable carbonate stratigraphy (Roberts, 1966). Thrust faulting during the Early Triassic Sonoma Orogeny emplaced the Golconda Allocthon (Dickinson, 2006).

By the Middle Triassic, eastward-dipping subduction began along the western margin of North America manifest by back-arc volcanic–plutonic complexes and emplacement of I-type granitoids in north-central Nevada (Barton, 1990). As subduction continued and flattened, magmatism ceased (Burchfiel et al., 1992). Rollback of the Farallon Plate caused crustal extension and significant calc-alkaline magmatism at ~42 Ma, which culminated in the Oligocene–Miocene (Seedorff, 1991).

Carlin-type gold deposits occur primarily in lower plate rocks of the Roberts Mountains thrust fault. In the Getchell trend (Fig. 1), ore at the Getchell and Twin Creeks mines is hosted by shale, chert, and basalt of the Ordovician Valmy Formation; interbedded shale and limestone of the Ordovician Comus Formation; and intercalated sandstone, phyllitic shale, and limestone of the Cambrian Preble Formation (Madrid, 1987). In the Carlin trend (Fig. 1), deep high-grade ore at the Goldstrike property (e.g., Meikle and Deep Post) is hosted by Devonian oolitic, fossiliferous limestone of the Bootstrap Formation and laminated muddy limestone and debris-flow breccias of the Popovich Formation (Armstrong et al., 1998; Griffin, 2000).

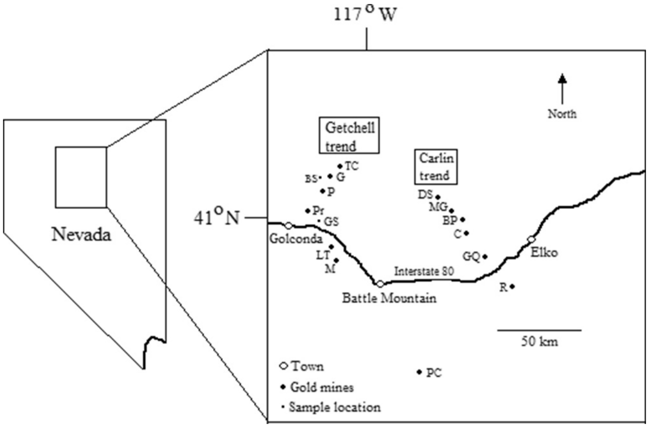

Fig. 1. Location map of the Carlin and Getchell trends, Nevada with sample locations at Berma Summit (quartz–base metal mineralization) and Iron Point (barren jasperoid). Abbreviations: BP = Betze–Post, BS = Berma Summit, C = Carlin, DS = Dee and Storm, G = Getchell, GC = Gold Quarry, IP = Iron Point, LT = Lone Tree, M = Marigold, MG = Meikle and Griffin, P = Pinson, PC = Pipeline and Cortez, PR = Preble, R = Rain, and TC = Twin Creeks.

General characteristics of nearly all deposits are an ore stage including decarbonation, argillization, silicification, and gold deposition by sulfidation (Hofstra and Cline, 2000). Gold occurs in arsenian rims on preexisting pyrite crystals or as fine-grained anhedral pyrite that is a few microns in size (Cline, 2001). Ore fluids had temperatures of ~ 180–240 °C, salinities of 2–3 wt% NaCl equiv., contained low concentrations of CO_2, and there is no evidence of fluid immiscibility (Hofstra and Cline, 2000). In the Getchell trend, gold mineralization occurred in the Eocene based on ages of 42–38 Ma for late-stage adularia–galkhaite–fluorite (Groff et al., 1997; Hofstra et al., 2000; Tretbar et al., 2000). In the Carlin trend, Eocene dikes are both pre and post ore (Ressel and Henry, 2006). Overall, the close temporal and spatial association of Carlin-type gold deposits with centers of Eocene igneous activity on the Carlin and Battle Mountain–Eureka trends suggests a genetic link (Muntean et al., 2011).

2.2. Guizhou province, China

Carlin-type gold deposits in southwestern Guizhou province, China (Fig. 2a) occur at the intersection of the Yangtze Craton and western extension of the Youjiang fold belt of the south China system (Hu et al., 2002). The Youjiang Basin was affected by four episodes of tectonism that include initial rifting, orogenic compression, lateral transpression, and lithospheric extension (Chen et al., 2011). The timing of Carlin-type gold mineralization in the Huijiabao trend is constrained by Sm–Nd ages of ~ 135 Ma on late ore-stage calcite veinlets containing realgar and orpiment (Su et al., 2009), and a Re–Os age of ~ 235 Ma on ore stage arsenopyrite (Chen et al., 2015a).

Host rocks of Carlin-type deposits are primarily Late Permian–Triassic limestone and calcareous clastic sedimentary units (Fig. 2b; Tan et al., 2015a). The Late Permian Longtan Formation is divided into three units: 1) a lower argillite, 2) a silty argillite intercalated with bioclastic limestone and coal seams, and 3) an upper calcareous siltstone, sandstone, argillite, and bioclastic limestone. Gold is preferentially hosted by units 1 and 2, and lower grade mineralization occurs in an unconformity separating massive bioclastic limestone of the Middle Permian Maokou Formation and unit 1 of the Longtan Formation. Rocks along the unconformity are brecciated due to reactivation as a thrust fault.

Ore mineralogy and alteration are similar to Carlin-type deposits in Nevada, although native gold is often present (Su et al., 2008). Four stages of pyrite are recognized as: 1) diagenetic framboidal pyrite in black mudstone, 2) coarse-grain subhedral–euhedral pyrite clusters spatially associated with organic material, 3) hydrothermal coarse-