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Gold General Bibliography

SURVEY PUBLICATIONS ON GOLD AND SILVER.

The following list includes the more important publications by the United States Geological Survey, exclusive of those on Alaska, on precious metals and mining districts. Certain mining camps, while principally copper or lead producers, yield also smaller amounts of gold and silver. Publications on such districts are listed in the bibliographies for copper and for lead and zinc. When two metals are of importance in a particular district, references may be duplicated.

These publications, except those to which a price is affixed, may be obtained free by applying to the Director, United States Geological Survey, Washington, D. C. The priced publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.; the monographs from either the Director of the Survey or the Superintendent of Documents.

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PROCESS MINERALOGY VI:

Applications to Precious Metals Deposits, Industrial Minerals, Coal, Liberation, Mineral Processing, Agglomeration, Metallurgical Products, and Refractories, with Special Emphasis on Cathodoluminescence Microscopy.

Proceedings of a symposium presented in six sessions on Process Mineralogy held during The Metallurgical Society Annual Meeting, New Orleans, Louisiana, March 2-6, 1986.

Edited by

Richard D. Hagni
University of Missouri-Rolla
Department of Geology and Geophysics
Rolla, Missouri

A Publication of The Metallurgical Society, Inc.

CATHODOLUMINESCENT ZONATION IN HYDROTHERMAL DOLOMITE CEMENTS: RELATIONSHIP TO MISSISSIPPI VALLEY-TYPE PB-ZN MINERALIZATION IN SOUTHERN MISSOURI AND NORTHERN ARKANSAS

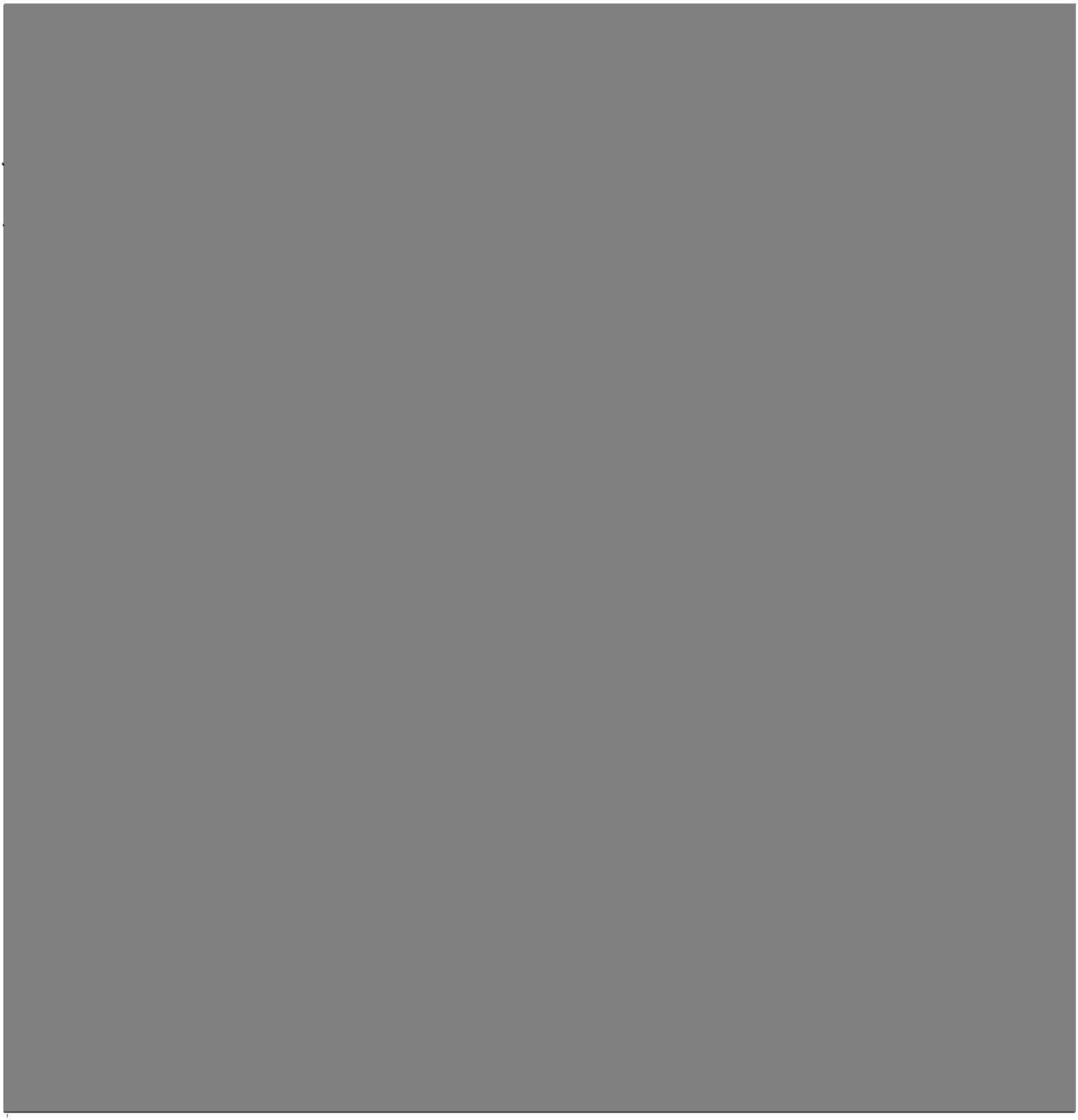
E. Lanier Rowan

U.S. Geological Survey, P.O. Box 25046, Mail Stop 912, Denver, Colorado 80225

Hydrothermal, vug-lining dolomites from mines and drill core in the Viburnum Trend lead district, southeast Missouri, and in drill core from southern Missouri and northern Arkansas, have been examined using cathodoluminescence. A cathodoluminescent (CL) microstratigraphy in the dolomites has provided a time framework to which fluid inclusion measurements have been tied. Equivalent CL zones within microstratigraphies from different locations are interpreted to be time correlative. Local dissolution, much of which is visible only with cathodoluminescence, is associated with sulfide precipitation.

Regionally, the CL microstratigraphy defined in the Viburnum Trend may be traced in dolomite cements for a distance of up to 350 km to the southwest. This observation is consistent with a model in which Mississippi Valley-type lead-zinc mineralization in Missouri and Arkansas is related to regional fluid migration northward from the Arkoma basin.

Geological Society of America Bulletin, v. 99, p. 814–826, 10 figs., 4 tables, December 1987.



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№ 135172

SEDIMENT-HOSTED DISSEMINATED GOLD MINERALIZATION AT JERRITT CANYON, NEVADA. I -- JASPEROIDS AS THE KEY TO THE TIME-SPACE FRAMEWORK

BIRAK, D. J., MANCUSO, T. K., And DAHL, A. R., Freeport McMoRan Gold Co., Elko, NV 89801

The sediment-hosted disseminated gold deposits of the Jerritt Canyon District are world class Carlin-type deposits located in the Independence Mountains about 80 km north of Elko, NV. Gold is hosted in the marine carbonaceous siltstones of the Silurian-Devonian Roberts Mountains and the marine carbonates and cherts of the Ordovician Hanson Creek Formations. These rocks are in the lower plate of the Roberts Mountains thrust and are exposed locally in windows.

Jasperoids (silica-rich epigenetic replacements of chert, dolomitic-limestone and calcareous siltstone) provide a time-space framework for placing gold mineralization in the complex geologic history of the area. They are common throughout the area and are most abundant in the chert-rich units of the Hanson Creek Fm. Where the host-sediments are mineralized the jasperoids may be mineralized. The majority of the jasperoids are roughly tabular, shallowly-dipping stratiform bodies up to tens-of-meters thick that extend hundreds of meters along strike. Additionally, jasperoids are genetically related to faults and fault breccia zones.

Jasperoids and chert record an extensive history of diagenesis, tectonism, metamorphism and hydrothermal activity leading to gold mineralization and dissipation of the hydrothermal system. First, brittle chert-rich beds were repeatedly fractured, preferentially silicified, and cross-cut by numerous randomly oriented quartz veins. These siliceous rocks or early jasperoids were then repeatedly brecciated, silicified, and some were cross-cut by gold mineralization during Tertiary tectonism. Where mineralized, the jasperoids are coarser grained and early formed textural features have been obliterated. The last stage of silicification, consisting of quartz veinlets and drusy quartz crusts on breccia fragments post-dates gold mineralization and extends well beyond the mineralized area.

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№ 135173

SEDIMENT-HOSTED DISSEMINATED GOLD MINERALIZATION AT JERRITT CANYON, NEVADA. II -- JASPEROID PARAGENESIS AND OCCURRENCE OF GOLD

HOFSTRA, A. H., U. S. G. S., MS973, Box 25046, Denver, CO 80225; and
ROWE, W. A. Freeport McMoRan Gold Company, Box 41330, Reno NV 89504.

Previous geochemical studies of sediment-hosted gold deposits lacked precise paragenetic control. This has obscurred geochemical relationships critical to the understanding of these deposits. At Jerritt Canyon, silicified rocks, particularly jasperoids, record the diagenetic, metamorphic, tectonic, and hydrothermal history of the area, including the paragenesis of gold. At least 16 episodes of silica deposition have been distinguished by cross cutting relationships, textural criteria, grain size (GS), cathodoluminescence (CL) color, and accessory mineralogy. These episodes record 3 hydrologic events that developed in response to tectonism: Event I, regional diagenesis/metamorphism (Antler Orogeny); Event IIA, local ore-stage hydrothermal activity (Tertiary deformation); and Event IIB, widespread post-ore hydrothermal activity (Tertiary deformation).

Volumetrically large and widespread Event I silica has 3 forms: recrystallized chert, jasperoid, and milky quartz veinlets. Recrystallized chert has a jigsaw texture (GS 2-25 μm) and jasperoid a xenomorphic texture (GS 5-200 μm). Large veinlets have a granular texture, whereas small veinlets (<0.5 mm wide) adopt textures of the enclosing silica. Brick-red CL colors are diagnostic of Event I silica. Graphite, apatite, and pyrite are diagnostic accessory minerals.

Event IIA jasperoid is volumetrically small and restricted to areas near faults. It cements breccia, replaces host rock, and locally contains ore-grade gold. It has a xenomorphic to reticulate texture (GS 10-400 μm) and rarely a jigsaw texture (GS 2-75 μm). Mottled brick red and blue CL is diagnostic. Hematite pseudomorphs of pyrite and gold are diagnostic accessory minerals. Gold occurs as irregular to spherical 10 to 0.1 μm grains disseminated within quartz and barite. Gold often resides on particles of graphitic carbon and/or hematite, but is not found on or within pyrite.

Colorless, drusy, Event IIB quartz is volumetrically small but widespread, occuppying fractures and breccias developed at the onset and during this event. It contains little gold (≤40 ppb) and has a granular to euhedral texture (GS 5 μm - 10 mm). Banded and sector zoned grains are revealed by strong CL colors of brick red, yellow, lime green, white, gray, blue and black. Diagnostic accessory minerals are stibnite, barite, ± realgar.

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№ 135174

SEDIMENT-HOSTED DISSEMINATED GOLD MINERALIZATION AT JERRITT CANYON, NEVADA. III -- ROLE OF ORGANIC CARBON.

LEVENTHAL, J. S., HOFSTRA, A. H., VULETICH, A. K., U. S. Geological Survey, MS973, Box 25046, Denver, CO. and MANCUSO, T. B., Freeport McMoRan Gold Co., Elko, NV., 89801.

The role of organic matter in the genesis of the Carlin-type deposits has long been questioned. It colors the rocks black, giving them either a shiny, sooty, or mat surface appearance. Companion studies (this abstract volume) have recognized 3 hydrologic events: regional metamorphism (I), hydrothermal gold mineralization (IIA), and post-gold hydrothermal mineralization (IIB). Organic carbon content of unmineralized rock remote from the deposit is <0.1%; whereas, at the deposit it ranges between 0.3 and 5% in both mineralized and unmineralized samples. During Event I, organic matter, now seen as vein fillings and rounded blebs, was introduced into jasperoids and subsequently graphitized. The mature state of the organic matter was determined by Rock-Eval, X-ray diffraction, and laser Raman spectroscopy and agrees with with fluid inclusion temperature data. Several parameters are all consistemt with maturation and migration of normal marine organic matter: bulk $\delta^{13}C_{(organic)}$ values (-27.7 to -30.3) that vary with organic carbon contents, methane/total hydrocarbon ratios of ≈ 15 and the $\delta^{13}C$ values for CH_4 and C_2H_6 in inclusions (-33.7 and -31.4, respectively).

Prior to hydrothermal gold deposition (Event IIA), the organic matter had already been altered to poorly ordered microcrystalline graphite, more mature than anthracite rank coal. Thin-section examination of Event IIA jasperoid shows 10 to 50 µm indigenous sub-angular and rafted particles of poorly ordered graphite. Neither shiny, sooty, or mat black surface appearance nor bulk organic matter content correlates with gold content. Because the organic matter was immobilized as graphite before the gold was introduced, organic matter could not have played a role in the transport of gold.

At Jerritt Canyon the adsorption surface area (m^2/g, determined by BET method) of the rocks is a function of their organic matter content and is not related to the shiny, sooty, or mat black surface appearance. The surface area (organic content) of rocks from mineralized areas is 7 times greater than remote country rock. However, the surface area of mineralized samples does not always correlate with gold content. Gold may have been localized by adsorption and/or reduction on organic matter.

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SEDIMENT-HOSTED DISSEMINATED GOLD MINERALIZATION AT JERRITT CANYON, NEVADA. IV -- FLUID GEOCHEMISTRY

№ 135175

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Fluid inclusions in quartz veins, jasperoid, and barite studied by microthermometry, mass spectrometry, laser Raman spectroscopy, and gas chromatography record changes in compostion, T, and P that characterize 3 hydrologic events. Event I fluids contain ≈10 eq. wt. % NaCl, high CH_4, C_2H_6, H_2, N_2, and CO_2, and small amounts (<1 mole %) of short chain hydrocarbons (HC), H_2S, and Ar. Fluid immiscibility produced variable gas to water ratios. During Event I the fluids evolved from a HC:CO_2 ratio of ≈10 to a HC:CO_2 ratio of ≈1. P-T conditions were 250°-300°C and 1-1.5 kbars.

Event IIA fluids responsible for gold mineralization have a wide range of compositions. At one extreme are 3-10 eq. wt. % NaCl brines with ≈5 mole % gas. CO_2 is the dominant gas (≈4 mole %) with up to 1 mole % of CH_4 and N_2 and typically <0.1 mole % of HC, H_2S, SO_2, and Ar. However, some inclusions contained up to 1 mole % H_2S. At the other extreme are very low salinity (<0.1 eq. wt. % NaCl), low gas (<0.5 mole %) fluids. The observed variation in salinity suggests mixing of two fluids. Minimum trapping conditions for the saline, gas-rich inclusions are 200°-300° C and 0.5-1.0 kbars.

Event IIB fluids contain <0.5 eq. wt. % NaCl and 0.5 to 1.5 mole % gases. CO_2 is the dominant gas with 0.05 to 0.1 mole % of CH_4 and N_2 and <0.02 mole % of H_2S, SO_2, Ar, and HC. CH_4:CO_2 ratios are <0.25. P-T conditions were 200°-250° C and <200 bars.

Gas compositions and P-T conditions of Event I fluids are typical of natural gas generated during metagenesis of carbonaceous sediments; this probably took place during the Antler orogeny. Although gold-bisulfide complexes may have been dominant during Event IIA, the pH (≈4) indicated by dolomite dissolution, high P_{CO_2}, temperature, and salinity suggest that gold may have also been carried as a chloride complex. Our data suggest that gold deposition resulted from mixing of a gold-bearing, chemically reduced, saline brine with an oxidized solution. Regardless of how gold was complexed, mixing of these two fluids would have been an effective mechanism for gold precipitation. The ≈500 bar drop in fluid pressure between Event IIA and IIB may represent a shift from lithostatic to hydrostatic pressures at the same depth. Widespread fracturing and brecciation at the onset of Event IIB allowed meteoric water to flood the system, ending ore deposition. However, these fluids contained enough H_2S (10^{-2} to 10^{-3} mole %) to redistribute gold.

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SEDIMENT-HOSTED DISSEMINATED GOLD MINERALIZATION AT JERRITT CANYON, NEVADA. V -- STABLE ISOTOPE GEOCHEMISTRY AND A MODEL OF ORE DEPOSITION

№ 135176

NORTHROP H. R., RYE, R. O., LANDIS, G. P., LUSTWERK, R., U.S. Geological Survey, MS963, Box 25046, Denver, CO 80225; and JONES, M. B., Freeport McMoRan Gold Co., Elko, NV, 89801

Geologic and geochemical studies of Jerritt Canyon jasperoids in companion abstracts have defined 3 hydrologic events: regional metamorphism (Event I), hydrothermal gold mineralization (Event IIA) and hydrothermal post-gold mineralization (Event IIB). Stable isotope studies constrain the mechanism of gold deposition. Event I jasperoids and included cherts have a narrow range of $\delta^{18}O$ values from about 25 to 28. The $\delta^{18}O$ of Event I quartz veins that cut these jasperoids evolved with time and vary inversely with the CO_2/CH_4 ratio of the parent fluids. Early Event I veins precipitated from CH_4-rich brines and have $\delta^{18}O$ values between about 24 and 26. Late Event I veins have the lowest $\delta^{18}O$ (17.2) and formed from fluids whose $CO_2 \approx CH_4$. Corresponding calculated $\delta^{18}O_{H_2O}$ for Event I quartz fluids decrease with time from about 18 to ≤ 7. Measured δD_{H_2O} of CH_4-rich Event I fluids was -118. Late Event I barite had $\delta^{34}S$-$\delta^{18}O$ values of 29.7 and +12.0 respectively, and may record the most ^{18}O depleted fluid ($\delta^{18}O_{H_2O} \approx 5$) from Event I. In Event IIA jasperoid, textural features a few mm across contain as much as 300 ppm Au. In these samples, log ppm Au (-1.52 to 2.48) varies directly with $\delta^{18}O$ (1.1 to 15.2). $\delta^{34}S$-$\delta^{18}O$ values of Event IIA barite average 29.3 and 11.9 respectively. $\delta^{18}O$ values of granular quartz (Event IIB) range between 9.2 and -1.0; calculated $\delta^{18}O_{H_2O}$ ranges between -3 and -15. δD of Event IIA and IIB waters were -111 and -118, respectively. $\delta^{34}S$-$\delta^{18}O$ of Event IIB barite averages 19.5 and -1.9 respectively. Data from Event I indicate that during Paleozoic regional metamorphism CH_4-rich fluids in a nearly closed system evolved to a more oxidized CH_4+CO_2 fluid in a more open system. Gold mineralization, following Tertiary faulting, resulted from deep (1-3 km) mixing of Au-bearing, isotopically evolved ($\delta^{18}O_{H_2O} \geq +4.6$), slightly acid, Cl-$CO_2$-$H_2S$-rich brines with unexchanged ($\delta^{18}O \leq -9.0$), dilute meteoric water. Au in solution decreased exponentially as a function of the amount of mixing. The onset of Event IIB was marked by a large increase in the areal extent of quartz deposition. Additionally, the fluids in the system went from brine to dilute meteoric-dominated. Gold in a widespread halo (ppb) plus As, Sb, and Hg were deposited during the time this meteoric water flooded the system.

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faults where it cements breccias, replaces host rock, and locally contains ore grade gold. Jasperoid is at one end of the spectrum of alteration types in these rocks. A preliminary study of mineral zonation across an ore zone revealed the sequence quartz, quartz+dolomite, dolomite+calcite, calcite. The bulk of the ore in these deposits is generally in intermediate zones of decarbonation and partial silicification indicating that the hydrothermal fluids were moderately acidic.

The mode of occurrence of gold and mineral paragenesis in this deposit type has long been questioned. This is due to the very small size (<10 microns) and disseminated nature of the gold. However, this study has shown that gold can be located in these samples using a standard petrographic microscope with a high power (125x) objective. The majority of gold observed in jasperoid was found to occur as irregular to equant 0.1 to 5.0 micron blebs disseminated within 100-500 micron jasperoid quartz grains. Gold also is found as inclusions in barite that are disseminated within jasperoid. Another important observation is that pyrite crystals encapsulated within jasperoid quartz grains are partially to completely oxidized to hematite. Within jasperoid quartz grains, gold is occasionally found to reside on particles of graphitic carbon and/or hematite pseudomorphs of pyrite. Using these methods no evidence of gold coprecipitation with pyrite has been observed such as reported by Bakken and others (1987) in ores from the Carlin deposit. The replacement of hydrothermal pyrite by hematite and precipitation of barite during gold deposition indicate that oxidizing fluids were present during ore deposition. Although we have found some evidence of gold adsorption on graphitic carbon, our data show that oxidation was the most important mechanism of gold deposition.

Fluid inclusions in gold stage jasperoid and barite were studied by microthermometry, mass spectrometry, and laser Raman spectroscopy. They have a wide range of salinities (<0.1 to 15 eq. wt. % NaCl) and gas contents (<0.5 to 12 mole %). At one extreme are saline brines (~3-10 eq. wt. % NaCl) with ~5 mole % gas. CO_2 is the dominant gas (~4 mole %) with up to 1 mole % of CH_4 and N_2 and typically <0.1 mole % of short chain hydrocarbons, H_2S, SO_2, and Ar. However, some inclusions contain up to 1.0 mole % H_2S. At the other extreme are very low salinity (<0.1 eq. wt. % NaCl), low gas (<0.5 mole %) fluids with similar gas speciation. CO_2/CH_4 ratios are typically near 100 but range from 5 to 500. Minimum trapping conditions for the saline, gas-rich inclusions were 200-250°C and 0.5 to 1.0 kbars. Fluid inclusion evidence of boiling or fluid immiscibility has not been observed in these samples. These data suggest that two fluids were present during mineralization and that mineralization took place at a depth of a least 1 km and possibly as deep as 5 kms. Figure 2 shows that, at the moderately acid conditions indicated by the alteration assemblage, that the saline, gas-rich fluid containing 0.1 to 1.0 mole % H_2S and 3 to 10 eq. wt. % NaCl was capable of

transporting large amounts of gold as a bisulfide complex and that chloride complexes were less important. It also shows that oxidation is a particularly effective gold precipitation mechanism.

Stable isotope compositions of ore stage minerals provide more difinitive evidence that two fluids were present during gold deposition. The δD_{H2O} value of both fluids was -115 permil and shows that both were derived from meteoric water. The $\delta^{18}O$ values of gold stage jasperoid, ranging from 1 to 15 permil (SMOW), correlate with the salinity of associated fluid inclusions such that isotopically light jasperoid contains fluid inclusions with <1 eq. wt. % NaCl; whereas, isotopically heavy jasperoid contains both low salinity and high salinity, up to 15 eq. wt. % NaCl, fluid inclusions. The data suggest that gold stage jasperoid was deposited from mixtures of high $\delta^{18}O_{H2O}$ fluids of variable salinity and low $\delta^{18}O_{H2O}$ dilute fluids. Mixing is also indicated in isotope data from ore stage barite. $\delta^{18}O$ and $\delta^{34}S$ values of sulfate covary, with $\delta^{18}O$ ranging from 12 to 9 permil and $\delta^{34}S$ ranging from 23 to 28 permil. The heavy sulfate was present in the isotopically exchanged fluid; whereas, the lighter sulfate was derived by oxidation of hydrothermal H_2S or sulfide minerals during mixing with the isotopically unexchanged fluid. This data shows that the fO_2 of the unexchanged fluid was high enough to oxidize sulfide to sulfate. The mineral paragenesis described above provides direct evidence of this. The $\delta^{34}S$ values of gold stage pyrite of 5 to 10 permil are consistent with derivation of sulfur from Paleozoic sedimentary sulfides and/or Tertiary organic matter in basin fill.

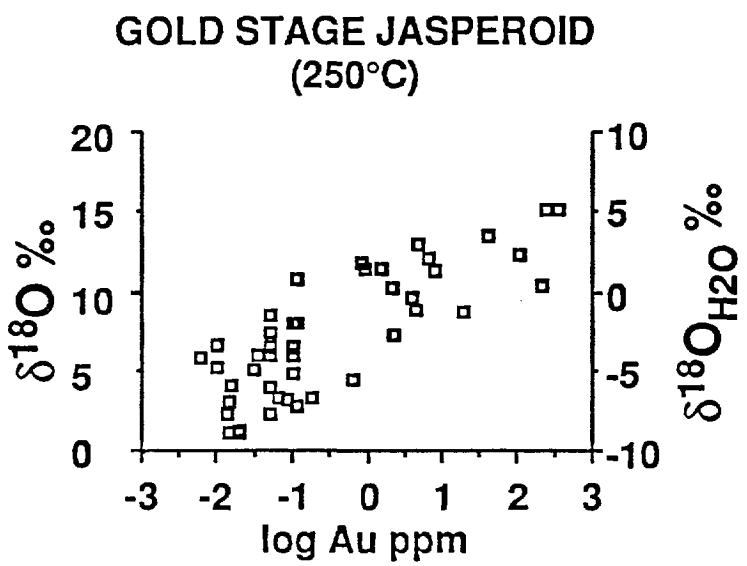

Fig. 3 Plot showing positive log-linear correlation between Au content and $\delta^{18}O$ of gold stage jasperoid.

GOLD '88

ORIGIN OF SEDIMENT-HOSTED DISSEMINATED GOLD DEPOSITS BY FLUID MIXING - EVIDENCE FROM JASPEROIDS IN THE JERRITT CANYON GOLD DISTRICT, NEVADA, U.S.A.

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The Jerritt Canyon gold district, located in the Independence Mountains in north-central Nevada (Fig. 1), contains six sediment-hosted disseminated gold deposits. Since mining began in 1982, the Enfield Bell mine has produced 1.5 million ounces of gold from four of these deposits. There are additional proven reserves of 2.5 million ounces in the district. Ore grade averages 0.184 oz/t (~7.0 g/t) gold. The deposits are low grade, disseminated, epigenetic, stratabound and locally strataform bodies that are typical of Carlin-type deposits occurring throughout north central Nevada (Fig. 1). The deposits are hosted in miogeoclinal, carbonaceous limestones, carbonaceous calcareous silstones and cherts of the Upper Ordovician to Lower Silurian Hanson Creek and Lower Silurian to Lower Devonian Roberts Mountains Formations. These rocks are exposed locally in windows through allochthonous, Ordovician, eugeoclinal, siliceous sedimentary and volcanic rocks that are believed to have been thrust to the east over the younger miogeoclinal rocks in Mississippian time (Roberts et al., 1958) during accretion of an island arc terrain onto the western margin of North America. The gold deposits most often occur immediately below the Roberts Mountains thrust that separates these contrasting lithologies. The deposits are also spatially associated with high angle faults that are thought to be related to Miocene extensional tectonics associated with development of the Basin and Range province in the western U.S. The absolute age of the gold deposits is not known, but the deposits appear to postdate Basin and Range faults in the mine area and therefore may be Miocene or younger in age. Although altered and mineralized intermediate composition dikes and sills can be found in some of the deposits, mineralization has not been directly linked to igneous activity.

Silicified rocks in the Jerritt Canyon district, particularly jasperoids, reveal a complex history of diagenesis, metamorphism, tectonism, and hydrothermal activity, including the paragenesis of gold (Hofstra and Rowe, 1987). Jasperoid is composed predominantly of silica in the form of aphanitic to fine-grained quartz. The term is used to describe epigenetic replacements of previously lithified host rocks as defined by Lovering (1972). The different types and stages of silicified rocks were examined at a variety of scales from field observations of ore zones and mappable units to microscopic observations of thin sections. A variety of techniques were employed to

study these rocks including cathodoluminescence, laser Raman spectroscopy, x-ray diffraction, scanning electron microscopy with energy dispersive x-ray analysis capability, and standard optical petrography. Conclusions presented here are based on petrographic examination of 111 polished thin sections and cathodoluminescence observations on 43 polished thick sections (~100 microns thick) cut from samples collected at 62 sites in the Jerritt Canyon district. On the basis of this work, at least 17 stages of quartz were identified and grouped into two events. Previous work (Hofstra et al., 1987a,b, Northrop et al., 1987 and Leventhal et al.,1987) has shown that the first event is related to regional metamorphism and deformation. Only the second event is attributable to the hydrothermal system that produced the gold deposits.

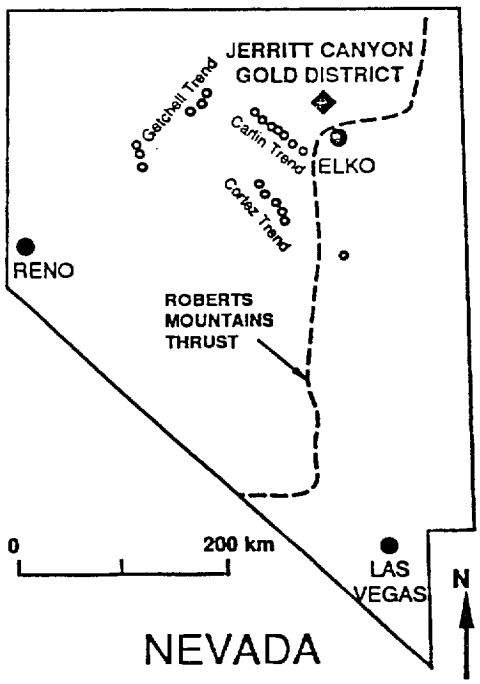

Fig. 1 Location map showing the Roberts Mountains thrust (dashed line) and Jerritt Canyon Gold District (diamond) as well as locations of other Carlin-type deposits in Nevada (circles).

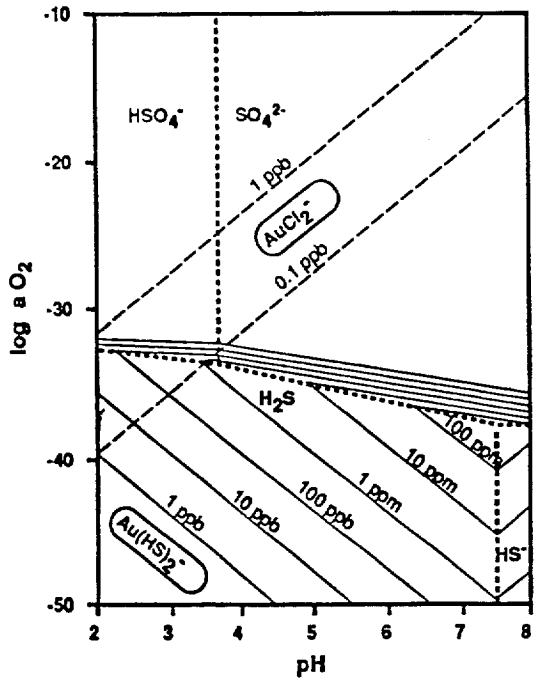

Fig. 2 Calculated oxygen activity -pH diagram for the system Au-NaCl -S-H_2O at 250°C assuming 1 m NaCl and 0.01 m S in aqueous solution. The distribution of aqueous sulfur species is shown by the bold dashed line. The relative solubility of gold bisulfide complexes (solid lines) and gold chloride complexes (dashed lines) are also shown. Adapted from Romberger, 1986.

Jasperoid related to hydrothermal gold mineralization was distinguished from pre- and post-gold stages of silicification by cross-cutting relationships, textural criteria, grain size, cathodoluminescence color and intensity, and accessory mineralogy. Gold stage jasperoid was found to be resticted to areas near high and low angle

To examine the relationship between gold deposition and fluid mixing small (~10 mg) duplicate samples of ore stage jasperoid were separated and analyzed for gold and $\delta^{18}O$. Gold analyses were done by neutron activation analysis and graphite furnace atomic absorbtion spectrophotometry. Figure 3 shows that log ppm gold (-2.22 to +2.54) varies directly with $\delta^{18}O$ (1.1 to 15.2) of quartz in jasperoid. The calculated $\delta^{18}O_{H2O}$ value of the parent fluid at 250°C is also indicated. The $\delta^{18}O_{H2O}$ of the parent fluid decreased from about 5 to -10 permil while the corresponding gold content of the jasperoid deposited from this fluid decreased from about 300 to 0.03 ppm. This is a very important data set. It shows that mineralization occurred at the interface of two fluids. It demonstrates that gold was carried by the $\delta^{18}O$ enriched fluid and that most of the gold precipitated at the onset of mixing with the $\delta^{18}O$ depleted fluid.

The mineral paragenesis, fluid inclusion, geochemical and stable isotope data from ore stage jasperoid combine to show that gold deposition occurred during deep (1-5 km) mixing of two fluids. All of the fluids that we have identified in the hydrothermal system were derived from meteoric water. One fluid was an unexchanged, oxidizing, low salinity, low gas, near neutral fluid that did not exchange much with the wall rocks. The other fluid underwent extensive exchange with wall rocks at low water/rock ratios and elevated temperatures to produce an $\delta^{18}O$ enriched, moderately acid, Cl-CO_2-H_2S-rich brine. This fluid apparently scavenged gold from rocks along fluid flow paths, transporting gold predominantly as a bisulfide complex. During the first increments of mixing with the unexchanged oxidized fluid, small increases in fO2 destroyed the bisulfide ligand, producing large decreases in the solubility of gold (Fig. 2), causing it to precipitate.

A preliminary hypothesis that is consistent with all of our data is that ore fluids were derived from meteoric water that moved through basin fill and circulated to deep levels along major Basin and Range faults where it was heated due to regional high heat flow associated with Basin and Range tectonism. This fluid was focused along major high angle faults in the upwelling part of the system. Ore deposition occurred where the ore fluid encountered oxidizing dilute water descending along the Roberts Mountain thrust. In this model the Roberts Mountains thrust is viewed as a regional freshwater aquifer that allowed cool, dilute waters to descend to great depths and apparently acted as a chemical and possibly as a hydrologic barrier to ascending ore fluids. This model explains the spatial association of the mineral deposits with high angle faults immediately below the thrust at Jerritt Canyon and at many other Carlin-type deposits in western Nevada. If this model is correct, ore deposition was a natural consequence of Basin and Range tectonism and associated high regional thermal gradients. There was probably no need for a specialized heat source.

ACKNOWLEDGEMENTS

This work is a product of cooperative research between the U.S. Geological Survey and Freeport McMoRan Gold Company (F.M.G.C.). We would like to thank the geologists at F.M.G.C.-- Art Dahl, Bill Daly, Tom Doe, Mike Jones, Toby Mancuso and Craig Parkinson -- for their cooperation and thoughtful insights as well as for their excellent detailed mapping that provided a geologic framework within which to constrain samples collected for geochemistry. Detailed studies of jasperoid paragenesis by Win Rowe, also at F.M.G.C., guided our efforts to unravel the jasperoid paragenesis and helped us to identify gold stage jasperoid for which we are extremely grateful. Some of the results presented here are part of A.H.H.'s graduate research at the University of Colorado, Boulder. This research project was initiated by Roy Northrop and many of the ideas and data presented above are based on his work. Roy died on June 24th, 1987 and we have dedicated this report to him.

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Geology and Origin of the Jerritt Canyon Sediment-Hosted Disseminated Gold Deposits, Nevada

Hofstra, A.H., Landis, G.P., Rye, R.O., Birak, D.J.*, Dahl, A.R.*, Daly, W.E.*‡, Jones, M.B.*
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The Jerritt Canyon district is located in the Independence Mountains 80 km northwest of Elko, Nevada. The district contains 8 ore deposits distributed across a 16 by 16 km area. The Enfield Bell mine has produced about 1.5 million ounces of gold from 3 of these deposits and has additional proven reserves of 2.8 million ounces. Ore grade averages 0.142 oz/ton. The deposits are disseminated, epigenetic, stratabound bodies that are hosted in miogeoclinal carbonaceous limestones, carbonaceous calcareous siltstones, and cherts of the Upper Ordovician to Lower Silurian Hanson Creek and Lower Silurian to Lower Devonian Roberts Mountains Formations. These rocks are exposed locally in windows through overlying eugeoclinal, siliceous sedimentary and volcanic rocks of the Ordovician Snow Canyon Formation.

The district has experienced a long and complex structural history with at least 6 episodes of deformation. 1) Early Paleozoic tectonism produced local disconformities between the Roberts Mountains and Hanson Creek Formations. 2) Early Mississippian east-west compression (Antler Orogeny) thrust the older Snow Canyon Formation over the younger Roberts Mountains and Hanson Creek Formations along the Roberts Mountains thrust. Exposures of the thrust in the mine show a wide zone of anastomosing fault strands, tectonic foliation, and rotated blocks. These features are typical of large regional thrusts. 3) North-south compression (Sonoman Orogeny?) produced east-west trending, south verging folds, south-directed thrusting, and related northeast and northwest trending fractures. 4) East-west compression (Laramide? Sevier? Orogeny) produced north-south to northwest trending, large-wavelength, open folds as well as east-west and northeast trending faults and fractures. 5) West-southwest-east-northeast extensional tectonism (~35-10 my) produced northwest trending high-angle faults. 6) West-northwest-east-southeast to east-west directed extension produced Basin-and-Range style block faulting (~10 my - Present) and north-northeast trending, high-angle, normal faults that further dissect the range. The orebodies are most often localized along east-west and northeast trending

high angle faults and along low-angle faults, but also occur in the limbs of east-west trending folds, along northwest trending high-angle faults, and especially at intersections of these features.

Although intrusive rocks are uncommon in the district, three types have been recognized. 1) A small diorite stock (30 by 150 m) that was dry and unreactive with the surrounding carbonate host rocks occurs in the southern part of the district. It is within 150 m of gold mineralization and yet it is unaltered. 2) Several small (<6 m wide) porphyritic andesite dikes that commonly have northwest orientations are sparsely distributed across most of the district and may be contemporaneous with the 14-17 my old northwest trending Northern Nevada Rift. These dikes are propylitically altered to chlorite, smectite, calcite, and pyrite and some of these dikes are mineralized. 3) Porphyritic mafic dikes that were probably emplaced during Basin-and-Range magmatism (<10 my?) occupy north-northeast trending fractures, are unmineralized, propylitically altered, and cross-cut mineralization. The absolute ages of these rocks are currently under investigation.

Detailed mineralogic, petrographic, geochemical, fluid inclusion, and stable isotope studies of jasperoid show that gold deposition was a consequence of the mixing of two meteoric fluids with contrasting water-rock exchange histories. The ore fluid underwent extensive exchange with wallrocks at low water-rock ratios and elevated temperatures to produce an ^{18}O-enriched, moderately acid, Cl-CO_2-H_2S-rich brine. This fluid scavenged gold from rocks along fluid flowpaths and transported it as a bisulfide complex. The other fluid was an oxidizing, very low salinity, near neutral pH fluid that exchanged very little with wallrocks. Jasperoid produced during the mixing of these two fluids shows a direct correlation between $\delta^{18}O$ and log Au concentration. Most of the gold precipitated at the onset of mixing when small increases in fO_2 destroyed the bisulfide ligand. Fluid inclusion data indicate that gold deposition took place at depths greater than 1 km, and possibly as deep as 5 km, at temperatures of 200 to 250°C.

The geologic relations suggest that mineralization took place after deformation that produced east-west, northeast, and northwest trending high-angle faults and before or during Basin-and-Range magmatism and block faulting. At present there is no evidence to indicate that mineralization is related to a localized intrusive heat source. Our current hypothesis is that mineralization is related to extension that

allowed meteoric water to circulate along open faults to great depths where it was heated, due to high regional heat flow, underwent extensive exchange with wallrocks, and scavenged gold. In the upwelling part of the system, the ore fluid was focused along open fracture sytems, especially east-west and northeast trending faults. Gold deposition occurred at sites where the ore fluid encountered oxidizing unexchanged meteoric waters descending along permeable pathways below the Roberts Mountains thrust. The Snow Canyon Formation is rarely mineralized, except within a few feet of mineralizing structures, and apparently acted as a hydrologic barrier to upwelling ore-forming fluids. The deposits in the Jerritt Canyon district share many features with other sediment-hosted disseminated gold deposits in Nevada and the results of this work may have important implications for the origin and age of many of these deposits.

Great Basin Symposium

Genesis of Sediment-Hosted Disseminated Gold Deposits by Fluid Mixing and Sulfidation of Iron in the Host Rocks: Chemical Reaction Path Modeling of Ore Depositional Processes at Jerritt Canyon, Nevada

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Introduction

Sediment-hosted disseminated gold deposits have characteristics that are unique and set them apart from the other types of gold deposits found in the Basin and Range Province. Most important are: (1) alteration patterns (silicification fi dolomitization fi unaltered calcareous host rock, illite stable, ±kaolinite); (2) ore-related mineralogies (micron- to angstrom- sized gold, native arsenic, realgar, orpiment, stibnite, cinnabar, thallium minerals, barite, Au+As-bearing pyrite, base metal sulfides and sulfosalts); and (3) trace element enrichments (Ba 10^2-10^4 ppm, As 10^2-10^4 ppm, Hg 10^{-1}-10^2 ppm, Zn 10^1-10^2 ppm, Pb 10^0-10^1 ppm, Cu 10^0-10^1 ppm, Sb 10^{-1}-10^1 ppm, Au 10^{-2}-10^1 ppm, Tl 10^{-1}-10^1 ppm, Ag 10^{-2}-10^0 ppm, ±W, ±B, ±V, ±Co, ±Ni, ±Mn, jasperoid $d^{18}O_{qtz}$ 0-20‰) (Hofstra and others, 1988a,b, Bagby and Berger, 1985; Bakken et al, 1989; Bakken and Einaudi, 1989; Birak and Hawkins, 1985; Holland et al,1989; Kuehn, 1987; Percival et al, 1988; Radke, 1985; Tooker, 1985). If we are to understand the origin of these deposits we must account for these characteristics. Our approach at Jerritt Canyon has been to conduct detailed geologic, petrographic, isotopic, fluid inclusion temperature, salinity and gas geochemistry studies, as well as geochemical studies of the host rocks, to characterize the hydrothermal fluids and identify ore depositional processes. Chemical reaction path modeling programs were used to simulate these processes and the results compared to the mineral assemblages actually observed in the deposits. Our research on the Jerritt Canyon district indicates that the unique attributes of Carlin-type deposits stem directly from the H_2S-rich composition of the ore forming fluid and from the processes that affected this fluid, namely mixing with cool, dilute, oxidizing groundwater and sulfidation of reactive iron in the host rocks.

Geology

The Jerritt Canyon gold district is located in the Independence Mountains, about 80 km NNW of Elko, Nevada. The district contains about 5 million ounces of gold

distributed among 10 Carlin-type, sediment-hosted, disseminated, gold deposits. Ore grade averages 0.12 oz./ton (4 gm./metric ton). The deposits are restricted to miogeoclinal, carbonaceous limestones, carbonaceous calcareous siltstones and cherts of the Upper Ordovician to Lower Silurian Hanson Creek and Lower Silurian to Lower Devonian Roberts Mountains Formations. These rocks are exposed in windows through allochthonous, eugeoclinal, siliceous, sedimentary and volcanic rocks of the Ordovician Snow Canyon Formation. The gold deposits are located below the Roberts Mountains thrust that separates these contrasting lithologies. The deposits are found in favorable beds along E-W, NE, and NW trending high-angle faults, along thrust faults, and especially at intersections of these features. Although scattered small dikes of intermediate to mafic composition are present in the the district, there is no evidence to link mineralization to igneous activity. Based on geologic arguments the deposits are younger than the youngest compressional deformation in the region (Eocene), and older than basaltic dikes that cross cut mineralization (probably 6-12 Ma).

Two Fluids

Fluid inclusion and stable isotope studies of ore stage jasperoid, barite, sulfides, and calcite show that two distinctly different fluids were present during ore deposition. The ore fluid was a highly evolved meteoric water (dD ª -111‰, $d^{18}O$ ª 5‰), that had a temperature of ª 225°C, salinity of ª 6 eq. wt. % NaCl, and contained ª 2-4 mole % CO_2, ª 0.1 mole % H_2S and < 0.1-1.0 mole % combined of N_2, CH_4, and short-chain hydrocarbons. This fluid obtained its isotopic and chemical composition by circulation through sedimentary rocks, particularly carbonate and shaley sequences, at low water/rock ratios (≤1.0) and elevated temperatures (200°-300°C). The other fluid was unexchanged meteoric water (dD ª -118‰ and $d^{18}O$ ª -16‰), that was cool (< 200°C) and dilute (< 1 eq. wt. % NaCl, < 0.5 mole % CO_2, < 0.01 mole % H_2S and < 0.1 mole % other gases).

It is important to consider how the ore fluid acquired its high H_2S content. $d^{34}S$ values of ore stage pyrite and realgar, of 5 to 10 ‰, are within the range of sulfur in Paleozoic petroleum and sedimentary sulfides in the region. The reduced sulfur in the ore fluid may therefore have been derived from the decomposition of organic matter, hydrolysis of sedimentary pyrite, or desulfidation reactions. These processes would have been promoted by increased heat flow during Basin and Range tectonism or by heating from an as yet unknown concealed intrusive at some other time in the Tertiary.

Fluid Mixing

Our studies have shown that there is a log-linear correlation between the Au content and oxygen isotope composition of gold stage jasperoid. This is conclusive evidence that fluid mixing caused gold deposition. Mixing at the interface of these two fluids caused the $d^{18}O_{H_2O}$ of the resulting fluid to decrease from about +5 to -10 ‰ while the gold content of the jasperoid deposited from this fluid decreased from about 300 to 0.03 ppm. Mixing is also indicated by the isotope data from barite. The $d^{18}O$ and $d^{34}S$ values of sulfate covary, with $d^{18}O$ ranging from 9 to 12 ‰ and $d^{34}S$ ranging from 23 to 28 ‰. The heavy sulfate was present in the ore fluid; whereas, the lighter sulfate was derived by oxidation of H_2S or sulfide minerals during mixing with the isotopically unexchanged meteoric fluid. The f_{O_2} of the unexchanged fluid was sufficient to oxidize sulfide to sulfate. The mixing of these two fluids resulted in cooling, dilution, and oxidation of the ore fluid which destabilized the gold bisulfide complex causing gold to precipitate.

Sulfidation of Iron in the Host Rocks

Gold will also precipitate when the concentration of bisulfide ion in the fluid is decreased by reaction with iron in the host rocks to form pyrite. This process can be documented by measuring the degree of pyritization (DOP) of iron. The DOP determination must be done on fresh unweathered rock and is therefore not generally suitable as a surface exploration tool. DOP is a measure of the fraction of reactive iron in the sample that has been sulfidized; thus, DOP = $Fe_{pyrite}/(Fe_{pyrite} + Fe_{reactive})$. The rock also contains unreactive iron that is not considered in this determination. DOP values for normal marine rocks are typically around 0.5. Unmineralized host rocks from Jerritt Canyon have normal marine values, whereas mineralized samples have DOP values greater than 0.7 and ranging up to 0.95. The enhanced DOP values are due to the reaction of reduced sulfur in the ore fluid with reactive iron in the host rocks. The positive correlation between the DOP and Au or As content of these rocks indicates that this process contributed to ore deposition. This process is shown by the reaction:

$$Au(HS)_2^{-1} + FeO = FeS_2 + Au^\circ + H_2O + e^-$$

where FeO represents reactive iron in the host rocks, gold is reduced and bisulfide is oxidized.

Composition and Speciation of the Ore Fluid

The program SOLVEQ (Reed, 1982 and Spycher and Reed, 1989) was used to calculate the speciation and concentration of metals in solution. The composition and speciation of the ore fluid was calculated based on the measured fluid inclusion temperature, salinity, and gas data and by assuming saturation with various ore minerals

and inferred aquifer minerals. Based on the requirement, from alteration studies, that the fluid be undersaturated with dolomite, and using a CO_2 content of about 2 molal, the pH of the ore fluid was calculated to be ª4.95. At dolomite saturation the pH of the ore fluid is ª5.07 and at calcite saturation it is ª5.19. The oxygen fugacity of the ore fluid was constrained by the sulfur content of the fluid (ª10^{-1} molal) and the narrow stability field of realgar ($\log f_{O_2}$ ª -43.19 to -43.16). The solubility of Au, Ag, Hg, As, Sb, Zn, Cu, Pb, and Fe were constrained by whatever mineral was most stable under the specified pH, f_{O_2}, and total sulfur content of the fluid. The speciation calculations show that sulfide complexing is dominant for Au, Cu, and Pb; roughly equal in importance to chloride complexing for Ag and Zn; whereas iron is dominantly chloride complexed. The HgH_4S_3 complex is about equal in importance to aqueous Hg°. The dominant As species is H_3AsO_3 and the dominant Sb species is $Sb(OH)_3$. The calculations show that the characteristic mineralogy and the low silver and base metal content of Carlin-type deposits is due to the predominance of sulfide complexing over chloride complexing in the ore fluid.

Reaction Path Models of Ore Depositional Processes

The reaction path program CHILLER (Mark Reed, 1982 and Spycher and Reed, 1989) was used to model ore depositional processes. Reaction paths modeling cooling, dilution, and oxidation during mixing of the ore fluid with meteoric water produce ore minerals in amounts that correspond closely to those observed at Jerritt Canyon and at other Carlin-type gold deposits. On a weight basis, realgar is the most abundant mineral, followed by one order of magnitude less cinnabar, two orders of magnitude less gold, sphalerite, ± galena, and three orders of magnitude less pyrite, bornite, ± silver-sulfosalts. Realgar and silver-sulfosalts precipitate only during the first several increments of mixing. Sphalerite is initially more abundant than gold, but then decreases until it is less abundant.

Reaction paths modeling sulfidation of iron show that isothermal reaction of the ore fluid with a calcareous host rock containing 0.25 wt. % reactive iron results in the precipitation of ore grade (ª7 ppm) gold and one order of magnitude less base metal sulfides. An equivalent amount of cinnabar, and one order of magnitude less of silver-sulfosalts precipitate during the first few reaction steps. During the first increments of reaction, the calcareous host rock is silicified and dolomitized until calcite saturation is reached. At this point calcite would have been deposited in veins such as found adjacent to areas of silicified and dolomitized rock. Movement of a reaction front such as this through the calcareous host rocks would have produced the areas of partially silicified and dolomitized rock that are found at the center of many ore bodies. This process is accompanied by a decrease in the volume of the host rock such as documented at Jerritt Canyon (this study) and at Carlin (Bakken and Einaudi, 1989). Deposition of pyrite and

gold continues until the sulfide content of the fluid is depleted. Our data show that the host rocks at Jerritt Canyon contained more than enough reactive iron (0.5-1.0 wt. %) for sulfidation to have been a very effective gold depositional mechanism. Sulfidation readily explains those enigmatic ore zones that occur in apparently unaltered calcareous rocks. It also explains the coprecipitation of gold with pyrite documented by Bakken and others (1989). The disseminated occurrence and small size of the gold in these systems may result from the disseminated occurrence and relatively small amount of reactive iron in the host rocks. Sulfidation of rocks containing large amounts of reactive iron would tend to form narrow high grade ore zones adjacent to fluid conduits. Reaction paths that model the combination of these two processes; (1) **fluid mixing**, with cooling, dilution, and oxidation; and (2) **wallrock reaction**, with sulfidation of reactive iron in the host rock; best explain the alteration zonation, mineralogy, and geochemistry observed at Jerritt Canyon and at other Carlin-type gold deposits.

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