

Application of gas analysis of jasperoid inclusion fluids to exploration for micron gold deposits

J.R. Graney, S.E. Kesler and H.D. Jones

Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48019, USA

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ABSTRACT

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Quadrupole mass spectrometric analyses of inclusion gases in jasperoid from the Carlin and Standard sediment-hosted micron gold deposits in Nevada show that mineralized areas exhibit better correlations between H₂O-CO₂ and H₂O-N₂, higher H₂S/CO₂ and higher O₂ ratios than do jasperoids from unmineralized areas. N₂ and Ar in all jasperoids are strongly correlated, with an average ratio near that of air-saturated meteoric water. Speciation and reaction progress calculations show that fluids with high H₂S/CO₂ ratios, such as are associated with mineralization in these deposits, would carry more gold than fluids with lower H₂S/CO₂ ratios. These calculations confirm that boiling would be a more efficient depositional mechanism than cooling or mixing of the ore fluid with groundwater. Although poor optical resolution makes it impossible to determine whether the jasperoids contain distinct liquid-rich and gas-rich fluid inclusions, the strong H₂O-CO₂ and H₂O-N₂ correlations in mineralized areas could be of that origin. Thus, jasperoids associated with mineralization could be recognized by high H₂S:CO₂ ratios, which reflect a strong gold-carrying capacity for the fluid, and strong H₂O-CO₂ and H₂O-N₂ correlations, which probably reflect gold deposition by boiling.

INTRODUCTION

Exploration for sediment-hosted micron gold deposits usually includes detailed sampling and analysis of jasperoid, a distinctive form of silica that replaces carbonate host rocks in and around these deposits (Lovering, 1972). Because jasperoid is commonly the most prominent outcropping rock in sediment-hosted micron gold deposits and because it is also found in other types of hydrothermal systems, considerable attention has been given to the possibility of discriminating between jasperoids from barren and mineralized micron gold systems. Most of these studies have concentrated on trace-element and isotopic characteristics (Holland et al., 1988; Nelson, 1990). Haynes and Kesler (1988) noted that fluid inclusion gas geochemistry could have some advantages in evaluation of jasperoids because the inclusion gases should be

more homogeneously distributed than gold and other metals. Their study showed that the average content of N_2 and CO in jasperoids from mineralized systems was greater than that in jasperoids from barren areas, and that CO_2 and CO contents of inclusion fluids in the central parts of mineralized systems were lower than on the periphery of the systems.

Inclusion gas compositions determined by Haynes and Kesler (1988) were obtained by gas chromatography, which was not sensitive enough to detect H_2S , an important constituent of hydrothermal systems and one of the key complexing ligands for Au (Seward, 1973; Shenberger and Barnes, 1989). In this report, we provide new analyses, obtained by quadrupole mass spectrometry, for sample suites from the Carlin and Standard mine areas. In addition to the gases determined by Haynes and Kesler (1988), this more sensitive method provides data for H_2S , C_2H_6 , C_3H_8 and Ar. As discussed below, the results show that elevated $H_2S:CO_2$ ratios appear to correlate with gold mineralization, an association that would be predicted from available experimental data on gold solubilities.

SAMPLE PREPARATION AND ANALYSIS

Samples analyzed in this study were obtained from the suite used by Haynes and Kesler (1988). These samples consisted of $-18 +60$ mesh jasperoid grains that had been cleaned of carbonate minerals by boiling in aqua regia. Whereas the original analyses were obtained using thermal decrepitation of inclusions in 1-g grain composites, the analyses presented here were obtained on gases released by crushing approximately 20 jasperoid grains, weighing about 10 mg. The samples were crushed under vacuum in a modified Nupro valve and the liberated gases were passed directly into the quadrupole source, which is enclosed for greater sensitivity. Path length and conduit diameter on the crushing inlet system were specifically designed to minimize absorption of gases onto surfaces without losing vacuum conductance (Jones and Kesler, 1991).

Gases released from the inclusions were analyzed with a VG SXP600 quadrupole mass spectrometer using an enclosed electron source operated at 50 mV. Data were collected by monitoring 16 user-specified masses, which permits simultaneous analysis of 11 gases, including H_2O , CO_2 , CO, CH_4 , C_2H_6 , C_3H_8 , H_2 , N_2 , Ar, H_2S and SO_2 (Jones and Kesler, 1991). During each analysis, the instrument collected data for all 16 masses in a cycle period of one second or less. Analyses were carried out by monitoring all masses through about 40 cycles prior to crushing to obtain a background level and by continuing to monitor all masses after the sample was crushed, until all masses returned to background levels, a period that commonly took 1 to 2 minutes. Total response for each mass for the entire gas sample was obtained by integrating under the response-time curve for each mass from the time of crush-

ing to the time the signal returned to background level. This total response for each mass was converted to mole fraction for the 11 gases of interest using a matrix-inversion calculation that takes into account fragmentation patterns and relative sensitivities (to N_2) that were determined in our laboratory for each gas of interest. The most difficult measurement of this type was estimation of the relative response of H_2O to N_2 , since mixtures of known quantities of these two gases are difficult to prepare.

CHARACTERISTICS OF INCLUSION FLUIDS IN JASPEROID

Jasperoid used in this study was collected from outcrops in and around the Carlin and Standard deposits (locations shown by Haynes, 1984). Breccia and other textures indicative of multiple hydrothermal stages are relatively common in these jasperoids. Even jasperoids that lack these textures show color variations that might also reflect several generations of fluids. Analyses of different colored grains from individual jasperoid samples yielded different inclusion gas compositions, further suggesting that many jasperoid samples contained more than one type of fluid inclusion. Optical study designed to clarify the types and mutual relations of these fluid inclusions were greatly complicated by the small size of both jasperoid grains and their contained fluid inclusions (Haynes and Kesler, 1988).

To further investigate the site of fluids in jasperoids, Haynes and Kesler (1988) carried out gas chromatographic step heating analyses, in which gases from several jasperoids were released and analyzed at $100^\circ C$ intervals between 100 and $700^\circ C$. These tests showed that jasperoids released a CH_4 - CO_2 - CO -rich fluid between 300 and $400^\circ C$, which was interpreted to come from decrepitated fluid inclusions, and an H_2O -rich fluid at temperatures in the 600+ range, which could have been from grain boundary sites. Similar measurements were carried out in this study using a heating apparatus connected directly to the quadrupole and employing continuous monitoring of gas release patterns. Use of this heating technique on samples from most hydrothermal deposits commonly results in a pulsed response reflecting the decrepitation of individual fluid inclusions or groups of inclusions (Jones and Kesler, 1991). This pulsed response was not observed during heating tests on jasperoid samples. Instead, broad decrepitation plateaus were observed, with maxima at temperature ranges of 200– $325^\circ C$, and occasionally at 450– $600^\circ C$. This suggests that fluid inclusions in jasperoid are too small to be detected individually by their decrepitation products, even at the rapid scanning rates employed in our analyses. The temperature range at which gases were released in the quadrupole analyses is slightly lower than that observed in the step-heating tests, probably because of the “real-time” nature of the quadrupole tests compared to the large intervals used in the earlier gas chromatographic step-heating tests.

In view of the difficulty in liberating only inclusion-hosted fluids by thermal decrepitation indicated by these tests, we released fluids for analysis in this study by crushing. This method avoids the problem caused by release of non-inclusion fluids during heating tests and, because the analysis is performed as gases are released from the inclusions, the possibility of reactions that would change gas species is also greatly limited. For most gases, there is limited correlation between gas abundances determined for splits of the same crushed sample by the two methods, suggesting that these two potential problems could be important. The most systematic difference observed between the two data sets is for CO₂. Gases released by decrepitation reported much more CO₂ than those released by crushing, a difference that could reflect generation and release of CO₂ from remnant organic matter in the jasperoid.

GEOLOGY OF THE STUDY AREAS

The *Carlin* mine, one of the worlds largest sediment-hosted micron gold deposits, produced 14 million tons of ore with an average grade of 0.33 opt Au between 1965 and 1984 (Bonham, 1988). Mineralization at Carlin is developed in the upper part of the Upper Silurian-Late Devonian Roberts Mountains Formation, a thin-bedded laminated silty dolomite and dolomitic limestone (Radtke, 1985). The Devonian Popovich Formation, which overlies the Roberts Mountains Formation, consists of a massive to thin-bedded limestone that is believed to be the youngest member of the lower plate rocks. The Roberts Mountains thrust separates lower plate rocks from interbedded chert, shale, and quartzite with sandstone and thin-bedded limestone lenses in the overlying Ordovician Vinini Formation. Although mineralization and jasperoid are hosted by all of these rocks, ore is best developed in slightly silicified rocks of the Roberts Mountains and Popovich Formations. The jasperoid occurs as high angle fault fillings and as bedding replacements near faults. In this study, jasperoids were chosen from all three formations and were grouped into Upper Plate (Vinini Formation-J509-J517, Table 1), Lower Plate near ore (Roberts Mountains - J501-J508, Table 1), and Lower Plate away from ore (Roberts Mountains Formation - J518-J522, Table 1) (see Haynes and Kesler, 1988 for sample locations and geologic relations).

Standard, which is considerably smaller than Carlin, consists of two open pits that produced 750,000 tons of ore averaging 0.08 ppt Au between 1939 and 1948 (Ronkos, 1986). Mineralization occurs in silicified shaley limestone of the Early Triassic Prida Formation, which also includes less altered massive fossiliferous limestone containing mafic flows and feeder dikes. The Prida is overlain by massive limestone of the mid-Late Triassic Natchez Pass Formation, which in turn is overlain by phyllitic shale of the Late Triassic Grass Valley Formation. Dark grey to black jasperoid has replaced limestone of the Prida and Natchez Pass Formations near thrust contacts with the Grass

TABLE I

Fluid gas composition of jasperoid samples from the Carlin and Standard sediment-hosted micron gold deposits as determined by quadrupole mass spectrometry. All values reported in mole percent. Sample locations are shown in Haynes and Kesler (1988)

	H ₂ O	CO ₂	CO	CH ₄	C ₂ H ₆	C ₃ H ₈	N ₂	O ₂	Ar	H ₂ S
<i>Standard analyses</i>										
J3011X	98.40	0.47	0.144	0.083	0.000	0.029	0.725	0.066	0.022	0.033
J3021X	98.36	0.70	0.174	0.095	0.000	0.025	0.518	0.049	0.017	0.030
J3031X	98.85	0.36	0.073	0.064	0.000	0.019	0.583	0.011	0.012	0.011
J3041X	97.93	0.53	0.178	0.101	0.002	0.018	1.146	0.042	0.028	0.015
J3051X	97.04	1.21	0.282	0.120	0.055	0.010	1.212	0.002	0.030	0.017
J3061X	98.52	0.48	0.173	0.055	0.000	0.025	0.591	0.086	0.019	0.024
J3071X	96.15	0.66	0.123	0.091	0.000	0.028	2.548	0.326	0.052	0.013
J3081X	96.07	1.11	0.375	0.142	0.000	0.035	2.138	0.050	0.040	0.019
J3091X	99.38	0.27	0.069	0.057	0.002	0.026	0.123	0.025	0.007	0.021
J3111X	99.25	0.36	0.034	0.041	0.000	0.014	0.266	0.000	0.008	0.013
J3121X	99.12	0.48	0.000	0.062	0.017	0.009	0.296	0.000	0.010	0.000
J3181X	95.92	2.01	0.349	0.179	0.000	0.035	1.383	0.047	0.034	0.023
J3191X	99.47	0.29	0.070	0.062	0.003	0.028	0.029	0.000	0.008	0.012
J3192X	97.87	1.41	0.146	0.099	0.000	0.018	0.424	0.000	0.013	0.018
J3201X	98.77	0.57	0.085	0.081	0.006	0.013	0.428	0.000	0.010	0.017
J3211X	98.51	0.86	0.089	0.072	0.000	0.011	0.439	0.000	0.011	0.004
J3221X	97.52	0.98	0.202	0.099	0.000	0.033	0.945	0.150	0.026	0.024
J3231X	99.49	0.13	0.056	0.034	0.000	0.021	0.257	0.000	0.007	0.005
J3241X	97.81	0.52	0.166	0.099	0.000	0.034	1.242	0.058	0.027	0.019
J3251X	97.21	0.50	0.145	0.081	0.000	0.045	1.701	0.239	0.034	0.029
J3261X	96.16	0.84	0.165	0.153	0.002	0.033	2.553	0.001	0.054	0.020
<i>Carlin analyses</i>										
J5011X	99.59	0.15	0.077	0.038	0.006	0.011	0.096	0.000	0.005	0.014
J5031X	88.22	8.35	0.813	0.511	0.044	0.018	1.959	0.019	0.022	0.023
J5051X	95.63	1.38	0.397	0.613	0.083	0.000	1.772	0.079	0.000	0.025
J5061X	98.58	0.58	0.216	0.081	0.000	0.023	0.468	0.013	0.021	0.011
J5071X	97.35	1.12	0.187	0.248	0.011	0.018	0.978	0.018	0.022	0.015
J5081X	98.60	0.63	0.152	0.132	0.004	0.015	0.439	0.000	0.009	0.002
J5091X	98.86	0.53	0.105	0.092	0.000	0.012	0.274	0.092	0.007	0.009
J5101X	97.13	0.98	0.277	0.106	0.030	0.000	1.273	0.183	0.000	0.013
J5111X	95.74	0.00	0.000	0.000	0.000	0.041	3.669	0.456	0.042	0.029
J5121X	92.21	4.06	0.402	1.133	0.000	0.033	1.708	0.410	0.029	0.007
J5131X	86.64	8.09	1.633	1.310	0.058	0.000	1.641	0.588	0.000	0.022
J5141X	92.62	1.39	0.243	0.561	0.000	0.021	4.146	0.060	0.082	0.019
J5151X	95.30	0.77	0.190	0.254	0.000	0.027	3.248	0.147	0.040	0.014
J5161X	97.41	0.29	0.182	0.115	0.000	0.026	1.823	0.091	0.030	0.019
J5171X	94.30	3.65	0.338	0.632	0.000	0.023	0.808	0.213	0.019	0.010
J5181X	79.46	15.87	0.171	4.446	0.001	0.024	0.000	0.000	0.010	0.009
J5191X	99.36	0.12	0.049	0.014	0.000	0.011	0.169	0.259	0.007	0.007
J5201X	96.62	1.64	0.284	0.218	0.023	0.014	1.082	0.073	0.021	0.013
J5211X	99.37	0.40	0.050	0.077	0.009	0.026	0.054	0.000	0.005	0.005
J5221X	95.81	2.05	0.268	0.217	0.000	0.021	1.386	0.194	0.030	0.011

Valley Formation. In this study, the jasperoids were analyzed from both formations (in Table 1, J301, 302, 306, 307, 309 and 325 represent Prida jasperoids, the remainder replace Natchez Pass rocks).

INTERPRETATION OF FLUID INCLUSION GAS COMPOSITION

Abundances and correlations of fluid inclusion gases

CO_2 and N_2 , the most abundant non- H_2O gases in the inclusion fluids, can be divided into groups that show different degrees of correlation with H_2O (Fig. 1). At Carlin, for instance, CO_2 and N_2 from jasperoid in the Roberts Mountains Formation show a strong linear correlation with H_2O , whereas they do not in jasperoid from the Vinini Formation. As might be expected from these correlations, CO_2 and N_2 contents correlate well for Roberts Mountains jasperoids, but show essentially no correlation for samples from the Vinini Formation. At Standard, jasperoid from the Prida Formation shows a better H_2O -gas correlation than jasperoid from the Natchez Pass Formation. CO_2 - N_2 correlations are poor to moderately good for jasperoids from both formations.

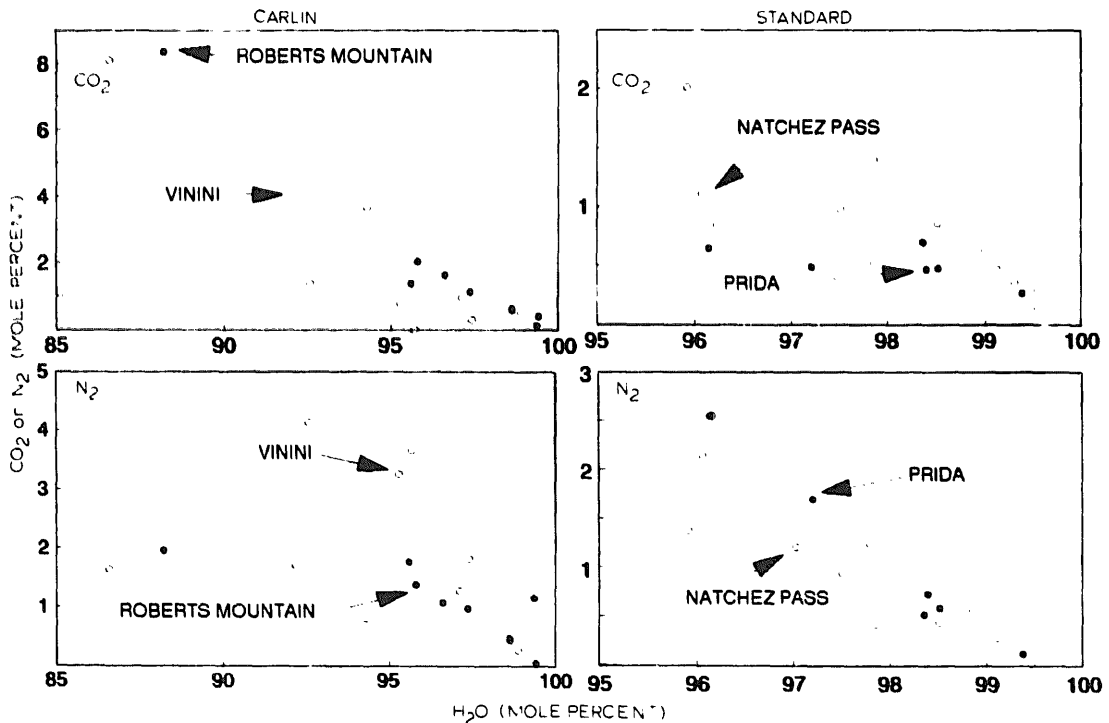


Fig. 1. CO_2 and N_2 versus H_2O correlation diagrams for jasperoid fluid analyses from Carlin and Standard. Formations hosting the jasperoid are denoted by different symbols, with the ore-hosting formation at each deposit shown with filled circles. Note the ore-hosting formation in both deposits displays stronger linear correlations than barren formations.

Both sample groups showing a good gas-H₂O correlation are from jasperoid in and around areas of mineralization. The simplest interpretation of these observations is that the jasperoids near ore contain separate liquid-rich and gas-rich inclusions that mixed during crushing and analysis, and that the gas-rich inclusions formed by boiling during jasperoid (and possibly ore) deposition. Although we have not been able to confirm the presence of separate gas-rich fluid inclusions in these jasperoids by either optical or analytical methods, calculations discussed below suggest that many of the jasperoid fluid inclusion gas compositions would boil at pressures typical of sediment-hosted micron gold deposits, and that boiling was the most effective mechanism of gold deposition. We can estimate the composition of a possible gas-phase by extending the H₂O-gas correlations for each sample group to intersect the gas axis at 0% H₂O. This procedure yields an "H₂O-free gas composition" (in mole%) of 60% CO₂, 35% N₂, and 5% other gases for Roberts Mountains jasperoids, and 70% N₂, 20% CO₂, and 10% other gases for Prida-hosted jasperoids at Standard.

The other pattern that is most apparent in the analytical data is the relation between CO₂ and H₂S in samples that show a H₂O-gas correlation. Note in Figure 2 that mineralized jasperoid samples in both areas have higher H₂S:CO₂ ratios than do jasperoids from barren areas. Whereas samples from the Vinini Formation and parts of the Roberts Mountains Formation that are far from mineralization cover a large range of compositions, Roberts Mountains samples with high H₂S:CO₂ ratios come almost entirely from the mineralized area. These elevated H₂S abundances in mineralized areas probably reflect the fact that H₂S is an important complexing agent for Au (Seward, 1973; Shenberger and Barnes, 1988).

H₂S and O₂ contents of the inclusion gases show generally similar relations (Fig. 3). Note that jasperoid samples from in and around known ore zones have lower O₂ contents than jasperoids from surrounding areas. At Carlin unfavorable jasperoid is clearly indicated by its high O₂ content. The pattern at Standard is more complicated but, with only one exception, ore-related jasperoids are low in O₂, although samples distal from mineralization are also relatively low in O₂. In both areas, ore-related jasperoids appear to exhibit a positive correlation between H₂S and O₂, which results in some ore-related jasperoids with relatively high levels of both H₂S and O₂. The significance of these relations is uncertain, largely because the amounts of O₂ found in these inclusions far exceeds the amount that is thermodynamically stable in these fluids at either ore-forming temperatures or present sample temperatures. Kesler et al. (1991) have suggested that some O₂ in fluid inclusion gases is formed by dissociation of thiosulfate and other metastable sulfur-oxygen species, but these amounts exceed the levels that should be generated by this process. The high O₂ contents might reflect O₂-rich groundwater into which the mineralizing fluids flowed and which surrounded the ore zone. This is an

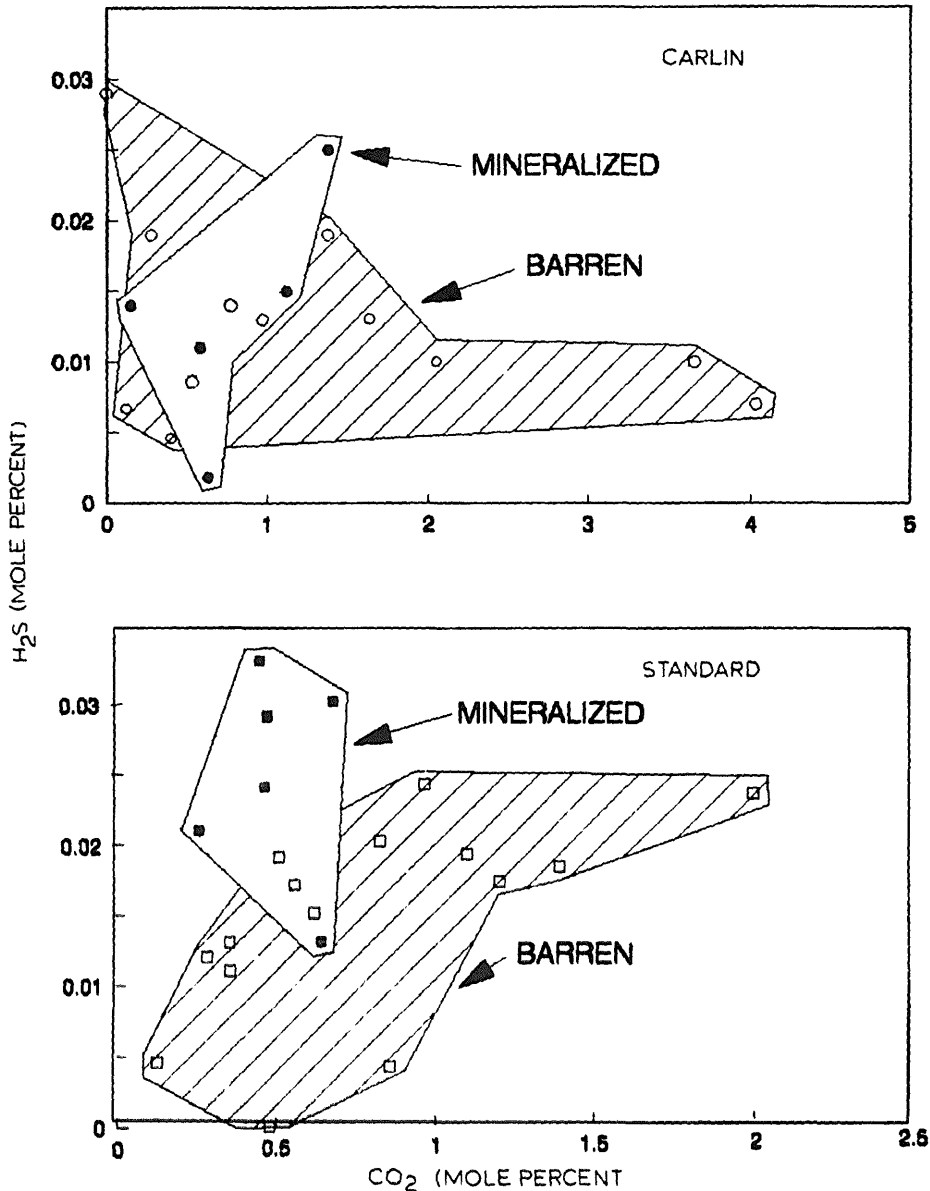


Fig. 2. H₂S versus CO₂ correlation diagrams for jasperoid analyses from Standard and Carlin. The jasperoids from mined areas (labeled mineralized on diagrams) display higher H₂O:CO₂ ratios than jasperoids away from mineralization (labeled barren on diagrams).

attractive possibility from an exploration standpoint, since centers of mineralization could be delineated on the basis of O₂ in fluid inclusions.

N₂:Ar plots for jasperoids from Carlin and Standard also display strong positive correlations (Fig. 4). Although the correlation for Standard is better defined, both correlations indicate that the fluid had N₂:Ar ratios relatively close to the air-saturated meteoric water N₂:Ar ratio of 38, which is consistent with the conclusion that waters in these deposits were derived largely from meteoric recharge (Radtke, 1985). It is interesting to note that many of

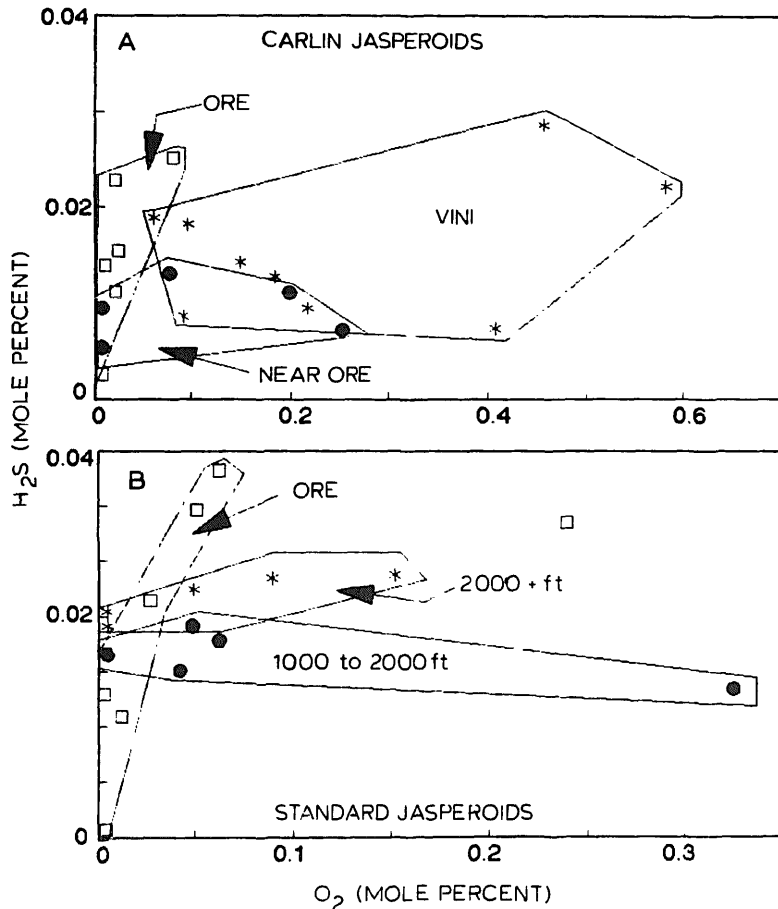


Fig. 3. Relation between O_2 and H_2S contents of fluid inclusions in jasperoid from Carlin (A) and Standard (B). The fields labeled *ORE* in the two diagrams include samples from within and around the mine area (North Pit at Standard). Other samples at Carlin are divided into those from the Roberts Mountain (*NEAR ORE*) and those from the Vinini Formation. At Standard, other samples are divided into those between 1000 and 2000 ft from the North Pit and those more than 2000 ft from the pit.

these samples are enriched in both Ar and N_2 above values typical of meteoric water. The simplest process by which to achieve such an enrichment is boiling and subsequent condensation because both N_2 and Ar will be partitioned strongly into the vapor phase during early stages of boiling. The tendency of the N_2 :Ar ratio in both districts to trend toward values greater than 38 at high N_2 contents probably results from addition of N_2 from degradation of organic matter or alteration of ammonium-bearing silicates (Kydd and Levinson, 1986).

An apparent relation between inclusion composition and host-rock chemistry complicates interpretation of the patterns discussed above. Thus, variations in inclusion composition attributed here to variations within the mineralizing system could reflect chemical interaction between the mineralizing

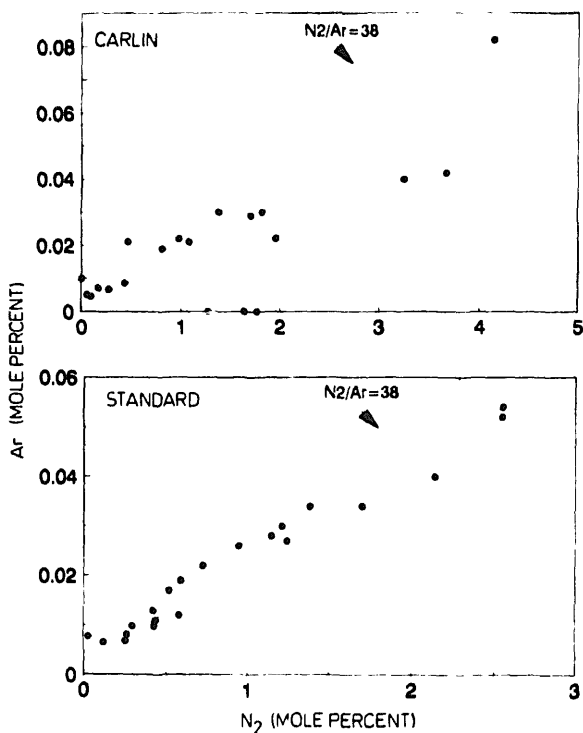


Fig. 4. Ar versus N_2 correlation diagrams for jasperoid analyses from Standard and Carlin. Both data sets display deviation from the air-saturated meteoric water N_2 :Ar ratio of 38 above 1 mole% N_2 .

fluid and its host rock. This is particularly true for the Standard data, where all of the samples with high H_2S and low CO_2 are in the Prida Formation. Similarly, Natchez Pass samples exhibit higher N_2 and CH_4 contents than Prida jasperoids. Although it is likely that interaction between hydrothermal solutions and host rocks will affect fluid gas chemistry, the fact that the entire range of H_2S : CO_2 ratios is seen in jasperoid samples from the Roberts Mountains Formation suggests that such host rock effects can be overridden by fluid chemistry in areas with high water:rock ratios. Support for this interpretation is seen in the fact that hydrocarbons other than methane show little difference between formations or with proximity to mineralization (Table 1).

Relation between gas analyses and gold-depositing mechanisms

An indication of the possible importance of the high H_2S : CO_2 ratios indicated by our gas analyses of the mineralizing fluid can be obtained by comparing gold solubilities in hydrothermal fluids with a range of gas compositions. Because no cation and anion analyses for the mineralizing fluid at Carlin or Standard are available, we have used compositional data for geothermal fluid at Roosevelt, Utah (Capuano and Cole, 1982), supplemented by metal

concentrations (other than Au) from Broadlands, New Zealand, geothermal water compositions (Spycher and Reed, 1989), to approximate the mineralizing fluid in these deposits (Table 2). This fluid was constrained by the program CHILLER (Reed and Spycher, 1985) to equilibrium with quartz, carbonate, pyrite, and muscovite under deep reservoir conditions such as prevail at Roosevelt (270°C, pH=6.0) and which probably prevailed at depth in the sediment-hosted micron gold-depositing systems. By varying the concentrations of H₂S and CO₂ in this fluid and equilibrating it with gold, it was possible to determine the maximum amount of gold that can be carried by mineralizing solutions of this type over a wide range of gas compositions. Results of these calculations, which are compared in Figure 5 to gas compositions of the Carlin and Standard jasperoids, show that fluids with relatively high H₂S:CO₂ ratios, such as found at Carlin and Standard, can indeed dissolve more Au and could be more effective mineralizing solutions.

Although fluids with high H₂S and low CO₂ contents, which our gas analy-

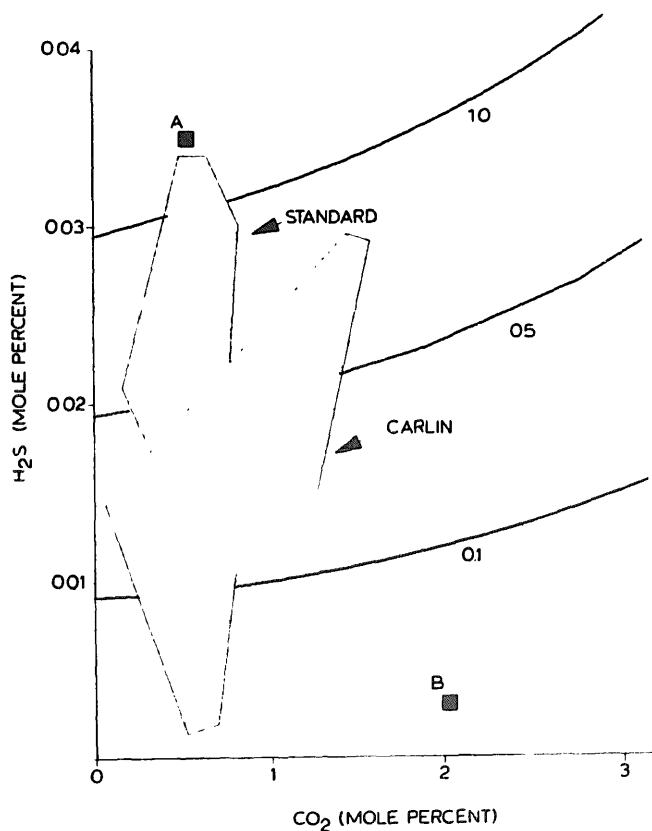


Fig. 5. Variation in solubility of Au (contours in ppm) in fluid composition shown in Table 2, but with variable amounts of H₂S and CO₂ (as shown by axes). Fields show range of H₂S and CO₂ concentrations in Carlin and Standard ore-related jasperoids. Note that both mineralized areas contain jasperoid fluid compositions in regions of high gold solubility. Labeled data points A and B refer to high-H₂S/low-CO₂ and low-H₂S/high-CO₂ fluid compositions, respectively, referred to in the gold deposition models depicted in Figs. 6 and 7.

TABLE 2

Composition of the fluid used to calculate gold solubilities and depositional processes as described in the text. Major ion data from Capuano and Cole (1982); metal data from Spycher and Reed (1989)

	mg/l		ppm
Na ⁺	1800	As ³⁺	3.92
K ⁺	329	Sb ³⁺	0.28
SiO ₂	547	Hg ²⁺	0.0008
Ca ²⁺	12	Fe ²⁺	0.222
Mg ²⁺	0.26	Cu ²⁺	0.007
Al ³⁺	0.12	Zn ²⁺	0.001
Cl ⁻	2990	Pb ²⁺	0.002
SO ₄ ²⁻	5.5	Ag ²⁺	0.008

sis suggest are associated most closely with mineralization, might be capable of dissolving the most gold, they might not deposit it most efficiently. This possibility was tested by further CHILLER calculations comparing gold that would be deposited by either an H₂S-rich fluid (0.035 mole% H₂S, 0.50 mole% CO₂) or an H₂S-poor fluid (0.0029 mole% H₂S, 2.016 mole% CO₂) that cooled, boiled, or mixed with groundwater. These two solutions, which are shown on Figure 5 as points A and B, represent the range of gas compositions observed in the jasperoid analyses and cover the range of calculated gold solubilities. For all calculations, temperature was decreased steadily from 270 to 180°C. Boiling was carried out under both conditions in which the gas remains in contact with fluid and those in which the gas is allowed to escape. Mixing was simulated by addition of pure water at 120°C. Results of these calculations, which are depicted in Figures 6 and 7, show clearly that the high H₂S-low CO₂ fluid can deposit more gold. Note that boiling deposits more gold than cooling or mixing, and boiling with gas escape was essentially 100% efficient at 270°C. Although actual efficiency of deposition via cooling or mixing is slightly higher in the low H₂S models (by a factor of at most 2), the high H₂S solution (12 times more H₂S than the low H₂S solution) carries 140 times more gold, and therefore is a much more important source of gold.

Although the suggestion from these calculations, that boiling is an important depositional mechanism in these deposits, cannot be evaluated directly because of the poor optical characteristics of jasperoid, our gas analyses provide support for this possibility. Saturation pressures (pressures necessary to prevent boiling) calculated using the program SOLMINEQ.88 (Kharaka et al., 1988) and treating N₂ as CH₄, range from 80 to 800 bars for the Carlin jasperoid analyses and from 88 to 500 bars for the Standard jasperoid analyses. Interpretation of these pressures in terms of depths of mineralization requires knowledge of the types of pressure under which the jasperoids formed, estimates of which range from hydrostatic to lithostatic (Rose and Kuehn, 1987;

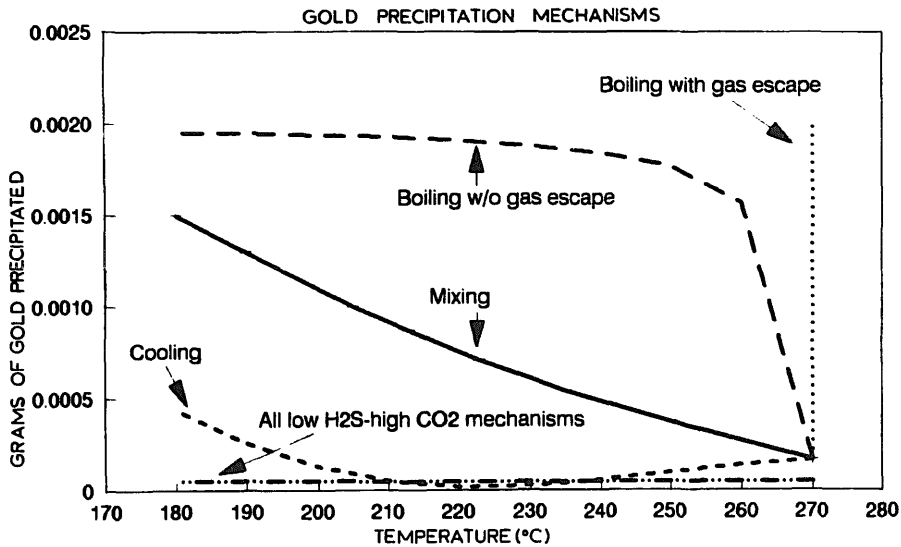


Fig. 6. Grams of gold precipitated versus temperature drop (from 270 to 180°C) for cooling, mixing, and boiling depositional mechanisms. The amount of gold deposited in the low-H₂S/high-CO₂ simulations is significantly less than that in high-H₂S/low-CO₂ simulations. Dissolution of some gold during the high-H₂S/low-CO₂ cooling simulation reflects maximum gold solubility at 220°C for this fluid composition.

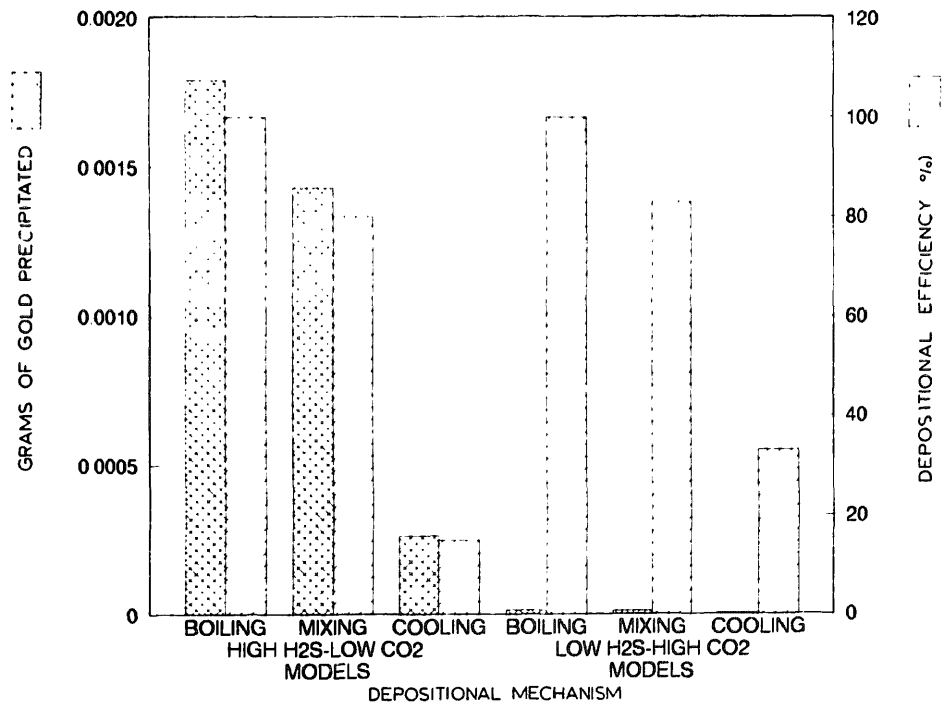


Fig. 7. Total grams of gold precipitated and depositional efficiency of various gold precipitating mechanisms from 270 to 180°C for high-H₂S/low-CO₂ and low-H₂S/high-CO₂ fluids. The amount of gold precipitated from gold-saturated solutions (depositional efficiency) approaches 100% in both modelled fluid compositions for boiling simulations, whereas mixing and cooling simulations were less efficient. Although cooling of low-H₂S/high-CO₂ fluids is more efficient than high-H₂S/low-CO₂ fluids the high-H₂S fluids has 140 times more gold-carrying capacity.

Nesbitt, 1988). Pressures greater than hydrostatic, which resulted from *in situ* hydrocarbon generation, are widespread at present in sedimentary rocks typical of those in which the jasperoids formed (Bradley, 1975; Fertl, 1975; Spencer, 1987). Such overpressures would have been increased further by silica flooding of the rock during jasperoid formation. Hunt (1990) has shown that overpressured fluids in sedimentary rocks are hosted by isolated compartments that rupture periodically causing pressure to fluctuate between hydrostatic and higher values. If this situation prevailed during formation of the jasperoids, the low saturation pressures observed in the jasperoid sample suite could represent hydrostatic conditions corresponding to depths of 1–2 km. Saturation pressures for lithostatic pressures at equivalent depths would be 300–600 bars, somewhat less than those calculated for the gas-rich samples.

Thus, it is likely that the gas-rich samples in Table 1 represent jasperoids that contain separate liquid-rich and gas-rich inclusions, which could have formed by boiling. This interpretation is consistent with the suggestion by Rose and Kuehn (1987) that phase separation accompanied ore deposition at Carlin. In view of the well established correlation between boiling and gold deposition (Reed and Spycher, 1985; Drummond and Ohmoto, 1985), the presence of this correlation could be an important way of recognizing jasperoids in which boiling has taken place and which could be associated with mineralization.

Although the actual cause of such boiling must remain speculative, boiling could be related to silicification of the host carbonate rocks. Carbonate dissolution, which precedes jasperoid formation in deposits of this type, would release large amounts of CO_2 . As this CO_2 accumulated in the environment, it would gradually dilute the incoming solution, causing it to evolve to lower $\text{H}_2\text{S}:\text{CO}_2$ ratios. The results of this process would be two-fold. Firstly, we would expect to find an interior zone of high- H_2S /low- CO_2 fluids, representing the in-coming fluid. Secondly, continuing accumulation of CO_2 could cause the fluid pressure of the solution to exceed confining pressure, thus causing boiling of the system. Trapping of gas-rich fluid inclusions that resulted from this boiling would probably produce erratic gas compositions, including some analyses with gas contents that exceed even prevailing lithostatic saturation pressure. Thus, jasperoids with high- H_2S :low- CO_2 ratios and variable CO_2 contents could be important keys in recognizing hydrothermal systems more likely to host gold mineralization.

CONCLUSIONS

Analyses of fluid inclusion gases in jasperoid from the Carlin and Standard sediment-hosted gold deposits in Nevada shows that jasperoids from mineralized areas exhibit: (1) better $\text{H}_2\text{O}-\text{CO}_2$ and $\text{H}_2\text{O}-\text{N}_2$ correlations, and (2) higher $\text{H}_2\text{S}:\text{CO}_2$ ratios, than do jasperoids away from mineralization. N_2 and

Ar in all jasperoids are closely correlated, with an average ratio near the air-saturated meteoric water ratio of 38, supporting the possibility that these fluids were derived from meteoric water. Speciation and reaction progress calculations show that mineralizing fluids with high H₂S:CO₂ ratios would dissolve and deposit more gold, and that boiling would be a more efficient depositional mechanism than cooling or mixing of the ore fluid with groundwater. Although poor optical quality makes it impossible to determine whether the jasperoids contain liquid-rich and gas-rich fluid inclusions, the close H₂O-CO₂ and H₂O-N₂ correlations noted above are most simply interpreted to be of that origin. Thus, jasperoids associated with mineralization could be recognized by high H₂S:CO₂ ratios and strong correlations between H₂O and other gases.

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