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Comparative Elemental and Oxygen Isotope Geochemistry of Jasperoid in the Northern Great Basin: Evidence for Distinctive Fluid Evolution in Gold-Producing Hydrothermal Systems

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Abstract

This comparative geochemical study of jasperoid in the northern Great Basin is based on 65 samples from 10 Carlin-type gold deposits and 22 similar but apparently barren hydrothermal systems. Multielement geochemistry coupled with oxygen isotope data indicate that hydrothermal fluids in barren and mineralized systems evolved in different ways, and that there are fundamental geochemical differences among the various gold-producing deposits of the area.

Much of the variation in the jasperoid geochemical data can be explained in terms of seven abstract end-member components obtained through factor analysis. Three of these components (factors) dominate the results and are related to common products of alteration and mineralization in epithermal systems of the northern Great Basin. Element associations for these factors are: factor 1: TiO_2, Al_2O_3, La, K_2O, Sr, Fe_2O_3, Th; factor 2: Au, Ag, Sb, SiO_2, As, Pb; and factor 3: W, B, V, Zn, Co, Au, CaO, Ni, Mn, Cu.

Samples from barren systems are predominantly associated with high factor 1 loadings, whereas samples from mineralized systems are generally characterized by high loadings of factor 2 and/or factor 3. Factor 1 is related to residual, argillically altered, noncarbonate constituents in original host rocks. Factor 2 is related to hydrothermal silica (jasperoid) and is characterized by many of the so-called pathfinder elements used in Great Basin exploration. Factor 3, although characterized by a transition metal assemblage, is related to syngenetic inclusions of hydrothermal calcite within jasperoidal silica.

High factor 2 loadings are associated with samples from the Windfall and Northumberland deposits but not with samples from other gold-producing systems in the study. Factor 3, on the other hand, is the dominant component in most samples from the Carlin, Gold Quarry, Maggie Creek, Pinson, and Preble deposits. It therefore appears that there are at least two geochemically discernible types of gold deposits in the northern Great Basin. These types are represented in this study by the Windfall deposit (factor 2) at one extreme and by the Gold Quarry deposit (factor 3) at the other. Other deposits, including Alligator Ridge and Tonkin Springs, are intermediate between these extremes. In this study, the hydrothermal geochemistry of the Jerritt Canyon samples is obscured by a chert-related compositional factor.

Jasperoid samples from gold-producing ore deposits have $\delta^{18}O$ values ranging from 3 to 20 per mil, whereas jasperoid samples from analogous barren systems have $\delta^{18}O$ values ranging from 3 to 11 per mil. This indicates that at least some fluids in ore-related hydrothermal systems were relatively ^{18}O rich compared to those in barren systems. Jasperoid samples having high $\delta^{18}O$ values invariably have high factor 3 loadings.

The elemental and isotopic geochemistry of jasperoid samples indicates that hydrothermal fluids in individual gold-producing systems of the northern Great Basin evolved in different ways. It appears that high CO_2 contents were a critical distinguishing feature of deeply circulating fluids in the hydrothermal systems associated with high factor 3 loadings. Within the scope of this study, it therefore appears that the systems located on the Carlin and Getchell trends (mineral belts) must have been relatively CO_2 rich. Fluids in these systems would have been relatively reactive and perhaps more efficient at extracting gold and other metals from

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rocks in fluid exchange reservoirs. Moreover, the generally high ^{18}O character of ore-stage fluids in these systems, as inferred from jasperoid compositions, is indicative of extensive water-rock exchange.

The largest gold deposits in the jasperoid study area appear to have been high CO_2, high ^{18}O systems. The primary source of CO_2 in these systems is uncertain. It does appear, however, that deep crustal structure, rather than the lithologic character of fluid exchange reservoirs, was probably a dominant factor governing the distribution of high CO_2 systems in the northern Great Basin.

Introduction

THIS paper reports on a comparative study of jasperoid geochemistry in Carlin-type gold deposits and in analogous, but apparently gold-poor, hydrothermal systems. Jasperoid is associated to some extent with virtually all of the Carlin-type (sediment-hosted, disseminated-replacement) deposits in the northern Great Basin of the western United States. Because of this association, and because it commonly forms prominent outcrops, jasperoid has been of considerable interest to exploration geologists working in this area.

In this study we have attempted to exploit the widespread occurrence of jasperoid by using it as a medium for making geochemical comparisons between barren and mineralized hydrothermal systems. Jasperoid bodies, as hydrothermal products, should reflect differences in the geochemical nature of the fluids which produced them and should, therefore, offer some insight into the ore-forming processes associated with economic gold deposits. Geochemical data that can be routinely and economically obtained by exploration geologists were used as the basis for this study.

The initial purpose of this investigation was simply to address several related questions:

1. What is the range of geochemical variation, both elemental and isotopic, in jasperoid throughout the northern Great Basin, and what are the genetic implications of this variation?
2. Do oxygen isotope compositions of jasperoid differ significantly among Carlin-type hydrothermal systems, and if so, what factors might have been responsible for such variation?
3. What is the relationship, if any, between the elemental geochemistry and the oxygen isotope composition of jasperoid?
4. Are there systematic geochemical differences, either elemental or isotopic, between jasperoid from hydrothermal systems that generated mineable gold deposits and jasperoid from apparently similar but barren systems?

Answers to these questions should provide some insight into the nature of the geologic and geochemical controls influencing gold distribution in the northern Great Basin.

Previous work

Interest in jasperoid and its relationship to ore deposits is reflected in a growing body of literature that dates back to the last century. Jasperoid bodies have long been recognized as products of hydrothermal activity (e.g., Spurr, 1898; Irving, 1911; Lindgren and Loughlin, 1919). It has only been in the last 30 years, however, that jasperoid geochemistry and its application to mineral exploration have been studied in detail. The origins of this work can be traced to studies on jasperoid in the Tintic and East Tintic mining districts of Utah which were supported by the Bear Creek Mining Company beginning in the mid-1950s (Howd, 1957; Duke, 1959; Duke and Howd, 1959; Bush et al., 1960). These studies were based in part on earlier field work by Lindgren and Loughlin (1919) and Lovering (1949). In a study that typified much of the Bear Creek Mining Company work, Duke (1959) used statistical analysis of textural, mineralogic, and multielement data in an attempt to identify jasperoid masses that were spatially related to ore in the East Tintic district. Howd (1964) later expanded on this work in a taxonomic study of jasperoid samples from over 20 mining districts in Arizona, Nevada, New Mexico, and Utah.

Lovering and Hamilton (1962) used this same general approach (with the addition of rock color data) to evaluate the spatial association of jasperoid bodies and ore in a study which included numerous mining districts throughout the western United States. In subsequent work, geochemical analyses on tellurium and mercury (Lovering et al., 1966) and gold (Lovering et al., 1968) were added to this jasperoid data base. Lovering (1972) incorporated most of these data in an expanded study on the use of jasperoid as a guide to ore, but he did not deal specifically with jasperoid geochemistry in Carlin-type gold deposits. Some of the concepts developed in Lovering's work on jasperoid were later applied by Lovering and Heyl (1974) to silver exploration in the Taylor mining district near Ely, Nevada.

In general, jasperoid geochemistry has received only incidental attention in the literature on Carlin-type systems. Lovering (1962) discussed mechanisms of limestone replacement by silica, and Fournier (1985) summarized the physico-chemical conditions required for jasperoid formation in Carlin-type systems. Neither Lovering (1962) nor Fournier (1985),

however, discussed formational processes in relation to specific analytical data (i.e., jasperoid compositions). Geochemical analyses for jasperoid in Carlin-type deposits of Nevada appear in papers by Erickson et al. (1966) and Hill et al. (1986), but these data are not discussed in relation to formational processes. Sullivan (1984) presented partial geochemical analyses of jasperoid from six fossil hydrothermal systems in Nevada, but he discussed mechanisms of jasperoid formation without attempting to relate processes to compositions. McCarthy et al. (1969) have reported summary trace element data for gold-bearing jasperoid in the Drum Mountains of Utah.

Other studies by Akright et al. (1969), Radtke et al. (1972), and Harris and Radtke (1976) contain extensive data on rocks from the Carlin deposit but do not specifically discuss jasperoid geochemistry. Radtke (1985), however, described siliceous alteration at the Carlin deposit and presented geochemical analyses for silicified carbonate rocks in the deposit. These studies, and others such as those by Marsh (1976) and Ikramuddin et al. (1986), have undoubtedly encouraged the widespread use of As, Sb, Tl, and Hg as pathfinder elements in Great Basin exploration programs. Nelson (1985), however, has pointed out that anomalous concentrations of these elements are common to both barren and mineralized systems and cannot be used to discriminate between them. In another study that included jasperoid analyses, Nelson (1986) suggested that an unspecified source-rock geochemical signature may constitute a more effective, discriminatory exploration tool.

Only a small body of data exists on the oxygen isotope composition of jasperoid in Carlin-type deposits. To date, only the Carlin, Cortez, and Jerritt Canyon deposits have been studied extensively in this regard, although O'Neil and Bailey (1979) have documented oxygen isotope ratios in gold-bearing jasperoid samples from the Drum Mountains in Utah. Radtke et al. (1980) and Radtke (1985) described variations in $\delta^{18}O$ values for jasperoid at the Carlin gold deposit, and Rye (1985) summarized the $\delta^{18}O$ compositions of jasperoid at both the Carlin and Cortez deposits.

Recent fluid inclusion and oxygen isotope studies by Hofstra et al. (1987) and Northrop et al. (1987) at the Jerritt Canyon deposit, and similar studies by Rose and Kuehn (1987) at Carlin, have led to genetic models of ore formation which account for the composition and evolution of hydrothermal fluids in these systems. The relationships between jasperoid paragenesis, $\delta^{18}O$ values, and fluid inclusion compositions observed in these studies provide a working framework within which much of our elemental and isotopic data on jasperoid can be interpreted.

Although Rye (1985) compared $\delta^{18}O$ data from jasperoid at the Carlin and Cortez deposits, the isotopic studies mentioned above are generally deposit-specific rather than comparative, and none speculate on how $\delta^{18}O$ values might vary in other deposits or in related gold-barren systems of the Great Basin province. Beaty (1987), however, noted that $\delta^{18}O$ values associated with jasperoid from a subeconomic gold occurrence in southern Utah were generally lower than those associated with jasperoid from the Carlin deposit (Radtke et al., 1980).

Design and Scope of the Geochemical Study

In this paper the term "jasperoid" is used to denote "an epigenetic siliceous replacement of a previously lithified host rock"—a definition adopted by Lovering (1972, p. 3) based on the original introduction of the term by Spurr (1898). For the purposes of this study, the additional qualifications were imposed that the replacement silica be of hydrothermal origin and that the host rocks be sedimentary (either carbonate or clastic). Furthermore, any sample that contained less than 70 percent SiO_2 or more than 10 percent Al_2O_3 was considered to be only weakly silicified and was not used in the study.

Throughout this paper the terms "mineralized" and "barren" are used to make the general distinction between hydrothermal systems that have formed economically significant Carlin-type gold deposits (at gold prices of $300 to $500 an ounce) and those that have not, or presumably have not. The barren systems discussed in this paper may therefore include systems that are, apparently, only weakly mineralized but that could in some cases prove to be economic upon further testing.

Sample distribution

The investigation of jasperoid geochemistry outlined in this paper was based on 65 samples collected from 32 different localities in the northern Great Basin of Nevada (Fig. 1a). Of these samples, 32 were collected from ten different deposits that have been gold producers (Alligator Ridge, Carlin, Gold Quarry, Jerritt Canyon, Maggie Creek, Northumberland, Pinson, Preble, Tonkin Springs, and Windfall). The other 33 samples were collected from 22 different exploration prospects (many of which have been drill tested) that are considered to be barren systems.

Regional geologic setting

The geographic distribution of jasperoid samples is such that two distinctly different geologic terranes are represented in this study. The trace of the Roberts Mountains thrust roughly divides the jasperoid study area into eastern and western parts (Fig. 1b). The Roberts Mountains thrust approximates the boundary between transitional facies and tectonically juxtaposed eugeoclinical sedimentary rocks on the west and miogeoclinal sedimentary rocks on the east. In northern Nevada, the thrust is nearly coincident with

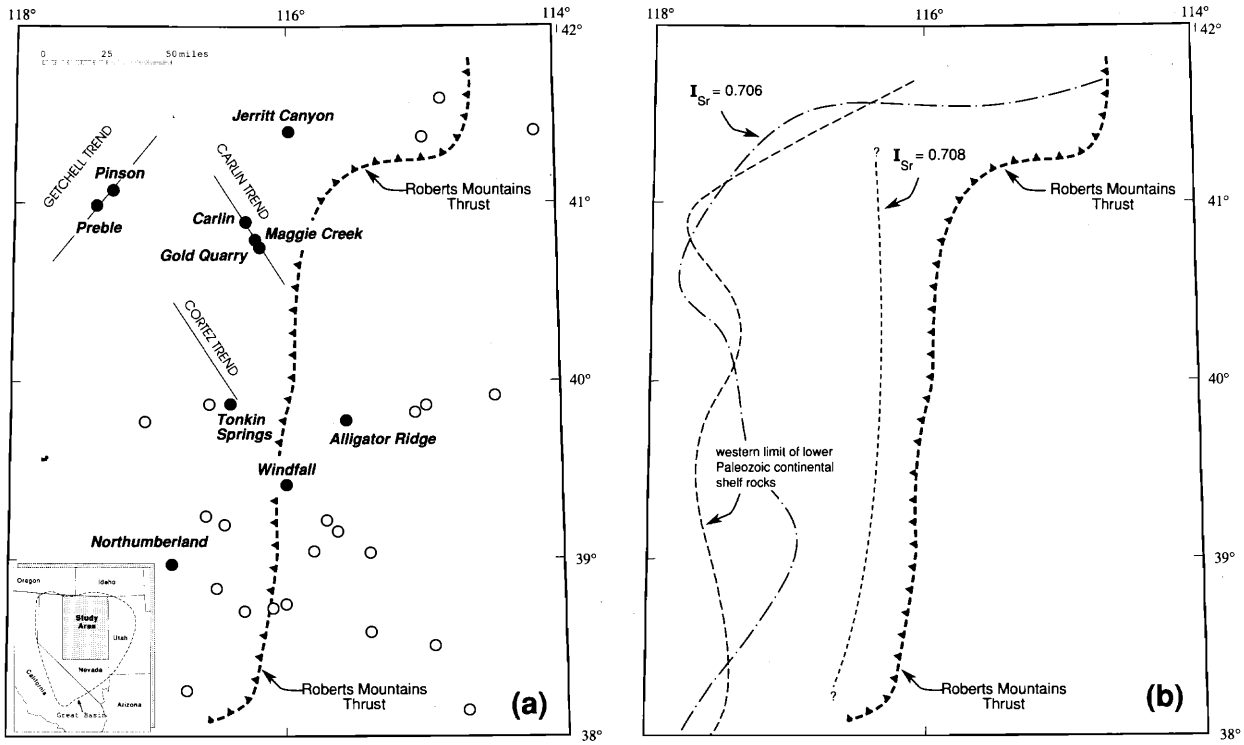

FIG. 1. (a). Map of northeast Nevada showing locations of samples used in jasperoid geochemistry study. Symbols in this figure and all subsequent figures: open circles = samples from barren hydrothermal systems, and solid dots = samples from gold-producing systems. The Carlin, Getchell, and Cortez trends are discussed by Bagby and Berger (1985). Inset map of the southwestern United States shows the approximate limit of the Great Basin physiographic province. (b). Map of northeast Nevada showing the trace of the Roberts Mountains thrust (from Stewart, 1980), the western limit of lower Paleozoic continental shelf rocks (from Speed, 1983), the initial strontium isotope 0.706 (I_{Sr} = 0.706) isopleth (from Speed, 1983), and the initial strontium isotope 0.708 (I_{Sr} = 0.708) isopleth (from Farmer and DePaolo, 1983).

the axis of the Lower Mississippian flysch basin (Stewart, 1980).

Reflecting deeper crustal structure, the trace of the initial $^{87}Sr/^{86}Sr$ = 0.706 isopleth (I_{Sr} = 0.706) is located somewhat west of the Roberts Mountains thrust (Kistler, 1983; Speed, 1983) and is nearly coincident with the western limit of lower Paleozoic continental shelf rocks (Stewart, 1980; Speed, 1983). The I_{Sr} = 0.706 isopleth is considered by some (see Stewart, 1980) to represent the boundary between oceanic and continental lithosphere; however, Farmer and DePaolo (1983) have interpreted the I_{Sr} = 0.708 isopleth, somewhat east of the 0.706 isopleth (Fig. 1b), as the western edge of Precambrian crystalline basement. Based on the Sr and Nd isotope signatures of Mesozoic and Tertiary granites (i.e., granodiorites) in the northern Great Basin, Farmer and DePaolo (1983) suggested that granites west of the Roberts Mountains thrust have a mantle derivation whereas those east of the thrust have a continental derivation. The geologic terranes on the east and west sides of the thrust therefore represent two quite different rock environments—at both shallow and deep levels—within which Tertiary hydrothermal systems would have operated.

In only using samples from northern and eastern Nevada, this investigation focuses on the geologic terranes immediately bordering (on either side) the trace of the Roberts Mountains thrust in the northern Great Basin. The terrane lying between the trace of the thrust on the east and the I_{Sr} = 0.706 isopleth on the west (Fig. 1b) hosts most of the large-tonnage Carlin-type gold deposits in Nevada, the Alligator Ridge deposit being the most notable exception. Although there are many jasperoid occurrences in western Utah, this area is well inboard from the I_{Sr} = 0.708 isopleth and, with the exception of the Mercur deposit, does not contain any large-tonnage Carlin-type gold deposits.

Methodology

Sampling

The jasperoid samples used in this study constitute a diverse sample population. Samples were collected

either as hand specimens or as composite rock chip samples by over a dozen different geologists in the course of mine tours, project work, and regional reconnaissance. All samples were collected either from exposures in open-pit mines or from undisturbed outcrop, although none were collected specifically for the purposes of this investigation. Samples from operating gold mines were generally collected from within or near ore zones, although geochemical zoning with respect to ore was not a primary consideration in sampling. Outcrop samples from undeveloped prospects were typical of those collected in the course of routine exploration work.

Elemental analyses

Multielement data were obtained on all samples through commercial laboratories. Gold was analyzed at Skyline Labs, Inc. (Wheat Ridge, Colorado), by atomic absorption spectrometry using an HBr digestion and a MIBK (methyl isobutyl ketone) extraction. Data on all other elements were obtained by means of inductively coupled argon plasma (ICP) spectrometry at Acme Analytical Laboratories Ltd. (Vancouver, B.C.). The aqua regia digestion used for ICP trace element analyses (not major element oxide analyses) was reported by the laboratory to be only partial for some of the elements used in this study (B, Ba, Mn, and W). Although higher quality data could have been obtained by means of other analytical techniques, we deliberately used data that could be obtained at low cost in the course of routine exploration work.

Oxygen isotope analyses

Oxygen isotope compositions were determined for 19 of the 65 jasperoid samples used in the geochemical investigation. Prior to isotopic analysis, purified quartz fractions were obtained by boiling pulverized jasperoid subsamples in aqua regia. (This procedure does not remove either detrital or diagenetic quartz, nor does it remove certain acid-stable mineral phases such as barite.) Oxygen isotope ratios were measured at the Center for Applied Isotope Studies at the University of Georgia using the fluorine technique (Taylor and Epstein, 1962). The data are reported with respect to SMOW in standard per mil notation; precision is ±0.2 per mil.

Elemental Geochemistry

Summary statistics on the 27 elements used to interpret the jasperoid geochemistry appear in Table 1 (gold analyses reported as <0.01 ppm were assigned values of 0.007 ppm for computational purposes). A complete listing of the analytic data for these elements (plus $\delta^{18}O$) appears in Appendix I.

In this jasperoid study, SiO_2 concentrations range from about 73 to 98 wt percent (Table 1). This variation underscores the fact that, besides hydrothermal quartz, jasperoid samples contain a number of other minerals. These other components could be hydrothermal minerals (or their oxidized products) which formed at the same time as the replacement silica. They might also, however, include minerals related to host-rock lithologies or to hydrothermal events that pre- and/or postdate jasperoid formation. Variation in the analytical data indicates that these components were present in varying proportions throughout the sample population. Because unaltered host rocks were not analyzed to obtain reference compositions for mass balance computations, an evaluation of the geochemical data by means of univariate or bivariate statistical techniques might have produced equivocal, if not misleading, results. Q-mode factor analysis was therefore employed as the primary means of interpreting the elemental geochemical data.

TABLE 1. Summary Statistics for Analytical Data on 65 Northern Great Basin Jasperoid Samples

Variable	Geometric mean	Geometric deviation	Low value	High value
Ag ppm	0.68	5.87	0.10	60.30
Al_2O_3 %	1.46	2.08	0.25	6.77
As ppm	219.66	3.70	7.00	2,953.00
Au ppm	0.20	7.86	<0.01	7.10
B ppm	4.16	2.02	2.00	25.00
Ba ppm	306.68	3.24	17.00	1,696.00
CaO %	0.34	2.97	0.05	6.84
Co ppm	2.90	2.36	1.00	93.00
Cu ppm	15.84	2.56	4.00	776.00
Fe_2O_3 %	1.71	2.40	0.37	16.60
K_2O %	0.27	2.56	0.02	2.11
La ppm	4.51	1.96	2.00	21.00
MgO %	0.13	2.70	0.01	4.63
Mn ppm	63.44	3.05	9.00	1,069.00
Mo ppm	6.84	2.42	1.00	47.00
Na_2O %	0.03	2.13	0.01	0.14
Ni ppm	11.53	2.97	1.00	336.00
P_2O_5 %	0.07	2.76	0.01	1.16
Pb ppm	24.15	5.62	2.00	1,708.00
Sb ppm	86.13	5.01	2.00	2,589.00
SiO_2 %	89.63	1.07	72.85	98.07
Sr ppm	29.36	2.00	6.00	113.00
Th ppm	1.56	1.64	1.00	6.00
TiO_2 %	0.04	3.03	0.01	0.33
V ppm	19.89	4.49	1.00	652.00
W ppm	3.12	4.71	1.00	257.00
Zn ppm	35.18	4.65	1.00	860.00

Raw data are tabulated in Appendix I

Q-mode factor analysis

Q-mode factor analysis is a multivariate statistical technique that can be used to identify simple, underlying relationships in large and complex data bases. The technique can be thought of as a mathematical tool for unmixing geochemical data into: a matrix of end-member components, or factors, responsible for data variation (factor scores), and a matrix of weight-

ing coefficients which reflect the relative importance of these factors in each of the real samples (factor loadings).

In this study, the data for bismuth, cadmium, and uranium were not used because of their relatively low variations. Data for chromium were discarded because of possible contamination from pulverizer plates in some samples. The remaining data were log transformed so that element variation would be independent of concentration. Data for each element were then scaled to a decimal fraction of their range so that relatively abundant variables, such as the major element oxides, would not dominate the results.

Much of the variation in the jasperoid geochemical data can be accounted for in terms of a seven-factor model. The varimax factor scores obtained in evaluating the jasperoid data are presented in Table 2. The factor loadings for jasperoid samples are tabulated in Appendix II. The seven-factor model (Table 2) accounts for over 92 percent of the total sum of squares (commonly, but erroneously, referred to as total variance) in the jasperoid data. Models with more than seven factors had trailing factors which individually accounted for less than 2 percent of the total sum of squares. The factor model is dominated by factors 1, 2, and 3 which together account for over 72 percent of the total sum of squares. In contrast, factor 4 alone accounts for just over 10 percent, whereas factors 5 through 7 together account for less than 10 percent.

An abstract of the factor score matrix in Table 2 is presented in Table 3 where elements with scores above 0.2 are listed in order of decreasing factor score. Synoptic interpretations for each of the seven factors in Table 2 are also listed in Table 3. These interpretations are discussed in the following sections. In general, the factor model reflects common lithologic components associated with jasperoid in Carlin-type deposits: altered and unaltered host-rock constituents, chert, barite, silica, carbonate minerals, and perhaps secondary iron oxide minerals.

Q-mode factor analysis is not based on normal (Gaussian) element distributions and results cannot be interpreted in terms of statistical significance or probability. We have used factor analysis in this study only as means of obtaining some insight into the processes responsible for chemical variability in jasperoid samples. The factor model which appears in Table 2 is just one of many that might have been obtained had a different mix of variables (or samples) been included or had the data been scaled in different ways.

TABLE 2. Varimax Factor Score Matrix, Northern Great Basin Jasperoid

	Factor number						
Variable	1	2	3	4	5	6	7
Ag	−0.060	0.415	0.029	−0.188	−0.083	−0.197	0.222
Al_2O_3	0.408	0.096	−0.086	−0.038	−0.216	0.196	0.007
As	0.109	0.294	0.143	−0.148	0.285	−0.082	−0.090
Au	−0.181	0.473	0.264	−0.055	−0.154	0.005	−0.183
B	0.039	0.096	0.301	−0.047	−0.186	−0.197	−0.162
Ba	0.093	0.118	0.028	0.646	−0.280	−0.065	−0.112
CaO	−0.021	−0.101	0.259	0.186	0.013	0.309	0.020
Co	0.000	−0.076	0.266	0.010	−0.023	0.005	0.085
Cu	−0.001	0.034	0.203	−0.012	−0.055	−0.128	0.201
Fe_2O_3	0.229	−0.073	0.170	−0.074	0.275	−0.106	0.030
K_2O	0.317	0.060	−0.036	−0.025	−0.084	0.282	0.148
La	0.343	−0.133	0.001	0.044	0.261	−0.199	0.044
MgO	0.108	−0.011	0.135	0.042	−0.106	0.252	0.141
Mn	0.062	−0.109	0.243	0.057	−0.008	0.241	0.191
Mo	−0.026	0.133	0.115	0.152	0.501	−0.024	−0.031
Na_2O	0.067	0.199	−0.011	−0.246	0.347	0.534	−0.197
Ni	0.047	−0.050	0.244	0.112	0.026	0.050	0.122
P_2O_5	0.098	0.093	0.130	0.123	0.184	−0.277	−0.077
Pb	0.032	0.270	−0.060	−0.059	−0.013	−0.182	0.512
Sb	0.006	0.385	0.084	0.020	−0.062	0.087	−0.221
SiO_2	0.041	0.343	−0.249	0.429	0.096	0.230	0.252
Sr	0.317	0.026	−0.015	0.284	0.152	−0.158	−0.257
Th	0.205	−0.089	0.186	−0.138	−0.126	−0.011	0.051
TiO_2	0.547	0.085	−0.084	−0.244	−0.250	−0.083	−0.091
V	0.132	−0.065	0.278	0.107	0.064	−0.056	−0.059
W	−0.091	−0.048	0.407	−0.025	−0.167	0.126	−0.150
Zn	0.027	−0.008	0.275	0.016	0.096	0.010	0.450
Percent sum of squares	27.76	25.48	19.39	10.37	2.77	3.71	3.04
Cumulative percent	27.76	53.24	72.63	83.00	85.77	89.48	92.52

TABLE 3. Abstract and Synoptic Interpretation of Factor Score Matrix (from Table 2)

Factor number		Percent sum of squares
	Element association (in order of decreasing factor score)	
1	TiO_2, Al_2O_3, La, K_2O, Sr, Fe_2O_3, Th	27.76
2	Au, Ag, Sb, SiO_2, As, Pb	25.48
3	W, B, V, Zn, Co, Au, CaO, Ni, Mn, Cu	19.39
4	Ba, SiO_2, Sr	10.37
5	Mo, Na_2O, As, Fe_2O_3, La	2.77
6	Na_2O, CaO, K_2O, MgO, Mn, SiO_2	3.71
7	Pb, Zn, SiO_2, Ag, Cu	3.04
	Synoptic interpretations (see text)	
1	Argillically altered noncarbonate residuum	
2	Mineralized hydrothermal silica	
3	Syngenetic hydrothermal calcite inclusions	
4	Barite-quartz and/or chert	
5	Uncertain (secondary iron oxide minerals?)	
6	Unaltered silty limestone (host rock)	
7	Base metal-mineralized silica	

Nevertheless, given our method of scaling the data, the essential character of the jasperoid model, as expressed in factors 1 through 3, reflects fundamental geochemical relationships that are little changed by using various subsets of variables or samples or by retaining different numbers of factors in the model. Minor factors, however, which account for little variation in the data, can be greatly altered by even small changes in these parameters.

Factor interpretation

Factor 1: Because of its high scores for TiO_2, Al_2O_3, K_2O, and Fe_2O_3 (total iron) in Table 2, factor 1 is interpreted as representing residual, noncarbonate constituents from original host rocks (detrital clays, feldspars, and Fe and Ti oxides). Factor 1 might also reflect argillic alteration of residuum silicates and the presence of minerals such as kaolinite, dickite, sericite, montmorillonite, illite, or alunite. The high score for TiO_2 in factor 1 might be explained by the fact that rutile and sphene are minor host-rock constituents at Carlin (Radtke et al., 1972); however, Radtke et al. (1980) have determined that a small amount of TiO_2 was added to altered rocks at the Carlin deposit along with Al_2O_3 and K_2O. Both gold and silver have negative associations with factor 1 (Table 2), and almost all of the samples collected from barren prospects have relatively high factor 1 loadings (Appendix II).

Factor 2: With high scores for Au, Ag, Sb, SiO_2, As, and Pb, factor 2 is much like the epithermal pathfinder assemblage upon which many Great Basin exploration programs have been based. Factor 2 is interpreted simply as an epithermal mineralization factor related to the deposition of hydrothermal silica. In some samples factor 2 could be associated with nondiagenetic quartz veinlets as well as with jasperoidal silica. The slightly negative score for Fe_2O_3 (Table 2) suggests that factor 2 mineralization may have had a relatively weak association with the deposition of iron sulfide minerals.

The five samples with the highest loadings of factor 2 are all from the Windfall deposit (Appendix II), indicating that the alteration-mineralization represented by factor 2 is most clearly expressed in the samples from this locality. Although factor 2 is apparently related to gold mineralization, many barren system samples have factor 2 loadings that are as high or higher than many samples from the Alligator Ridge, Carlin, Gold Quarry, Maggie Creek, Pinson, and Preble deposits (Appendix II). This implies that some other factor (or factors) must also be related to gold mineralization in the northern Great Basin.

Factor 3: Factor 3 is characterized by relatively high scores for tungsten, boron, and most of the transition metals in the study (vanadium, zinc, cobalt, nickel, manganese, and copper—see Tables 2 and 3). Factor 3 also carries a relatively high score for gold and positive (though not especially high) scores for arsenic and antimony (Table 2).

Although trace element constituents dominate factor 3, it is the major element associations that provide the framework for its interpretation. (The relative dominance of trace elements in factor 3 is an artifact of the log-transformation and scaling procedures.) The only major element oxide having a score above 0.2 is CaO; however, scores for both Fe_2O_3 and MgO are above the 0.1 level. The major element oxides associated with silicate minerals, including Al_2O_3, K_2O, Na_2O, and TiO_2, have negative factor 3 scores, and the score for SiO_2 is strongly negative. In light of its major element relationships, factor 3 must be interpreted as a carbonate factor related to the precipitation of hydrothermal calcite, dolomite, and/or ferroan dolomite. High factor 3 loadings might also reflect the presence of scheelite in some samples.

The association of carbonate minerals and transition metals in factor 3 can be interpreted in terms of fluid chemistry and this aspect of the factor will be discussed in a later section. There is, however, an empirical precedent for this association in other gold deposits. Veins and wall-rock alteration in Archean lode gold deposits are commonly characterized by carbonate minerals in association with anomalous concentrations of nickel, copper, zinc, and gold (Kerrich and Fyfe, 1981). A genetic parallel between Carlin-type deposits and Archean lode gold deposits is not implied, but the association between carbonate minerals and transition metals probably occurs in both types of deposits as a result of similar geochemical processes and affinities. Likewise, scheelite commonly

occurs in association with gold in other types of deposits.

It must be emphasized that factor 3 is not considered to be a vein-related factor. Concentrations of CaO and the transition metals are generally low in the jasperoid samples of this study (Table 1), and calcite veins are not mentioned in any of the sample descriptions. The carbonate minerals associated with factor 3 probably formed contemporaneously with jasperoidal silica and are included within it. Petrographic data are not available for samples in this study; however, Sullivan (1984) has described jasperoid from the Rooster Canyon area of central Nevada in which calcite inclusions occur along growth planes in replacement silica. In this study, petrographically similar jasperoid samples probably typify those that have high factor 3 loadings.

The presence of ore-stage carbonate veins in many deposits does, however, indicate that carbonate mineralization can be temporally and spatially associated with gold mineralization in Carlin-type systems. Carbonate veins have been documented in varying degrees of detail at a number of Carlin-type deposits: Carlin (Radtke et al., 1980; Radtke, 1985; Rye, 1985; Bakken and Einaudi, 1986; Madrid and Bagby, 1986), Cortez (Erickson et al., 1966; Rye, 1985), Preble (Bagby and Berger, 1985), Pinson (Kretschmer, 1986), Jerritt Canyon (Tooker, 1985), and Getchell (Joralemon, 1951). Moreover, Madrid and Bagby (1986) documented vein paragenesis at the Carlin, Pinson, Preble, and Bootstrap deposits and described jasperoid-calcite-breccia veins that are zoned with respect to ore in two paragenetic stages. At Carlin, and presumably at other Carlin-type deposits, many of the calcite-bearing veins are related to diagenetic processes that predate hydrothermal activity (Bakken and Einaudi, 1986), whereas others are related to late-stage, postore hydrothermal activity (Radtke et al., 1980; Rye, 1985). Nevertheless, some carbonate veinlets at Carlin appear to be unequivocally associated with ore-producing hydrothermal processes (Bakken and Einaudi, 1986; Madrid and Bagby, 1986).

In this study, the three samples with the highest factor 3 loadings are all from the Gold Quarry deposit (Appendix II), and samples from the Carlin, Maggie Creek, Pinson, and Preble deposits also have relatively high factor 3 loadings. Samples from other gold-producing deposits in the study have generally lower factor 3 loadings, and samples from the Windfall and Northumberland deposits have factor 3 loadings that are lower than those associated with many samples from barren systems.

Factor 4: With relatively high scores for Ba, SiO_2, and Sr, factor 4 is undoubtedly related to barite and quartz. Sample descriptions (coupled with the oxygen isotope data), however, indicate that factor 4 is also related, in some samples at least, to chert—an unreplaced host-rock component present in many Carlin-type deposits of northern Nevada. It may be that chert in the study area is either barium rich or has a common primary association with barite that makes it indistinguishable in the factor model from a jasperoid-barite association (also common at many deposits) or from hydrothermal quartz-barite veinlets. In any case, some (but not all) samples with high factor 4 loadings (Appendix II) probably have a significant chert component, and in a strict sense, should not be considered jasperoid. Two of the three Jerritt Canyon samples in this study have high factor 4 loadings and appear to contain a significant chert-related component.

Factor 5: Factor 5 is the least understood component of the factor model; however, in terms of the sum of squares data, it is also the least important (Table 2). Factor 5 has scores above 0.2 for Mo, Na_2O, As, Fe_2O_3 (total iron), and La—and a score above 0.1 for P_2O_5. It has negative scores (below −0.2) for Ba, TiO_2, and Al_2O_3. Factor 5 might be related to secondary iron oxide minerals, although it is difficult to explain the association with Na_2O in these terms. Still, under oxidizing conditions, Mo, As, and P are mobile as anionic species that are readily scavenged by secondary iron oxide minerals.

Two observations can be made regarding the geologic associations of factor 5. First, factor 5 has moderately high loadings in samples from both the Northumberland and Pinson deposits where intrusive rocks are proximal to ore (Motter and Chapman, 1984; Kretschmer, 1986). Second, the three samples having the highest factor 5 loadings are all from the Hanson Creek Formation. At least one of these samples was collected from the Upper Chert member of the Hanson Creek Formation and chert is present at the Northumberland and Pinson deposits. These observations do not, however, provide an obvious interpretation for factor 5 and may not be particularly relevant. Therefore, for the purposes of this study, factor 5 will be left uninterpreted.

Factor 6: With relatively high scores for Na_2O, CaO, K_2O, MgO, Mn, and SiO_2 (and Al_2O_3), factor 6 is interpreted as an unaltered, silty carbonate, host-rock component. It represents a component of jasperoid samples that, like chert, is unrelated to Tertiary silicification, alteration, or mineralization. Relatively high factor 6 loadings in individual samples mean that loadings for other, hydrothermal-related factors will be concomitantly lower (Appendix II).

Factor 7: The element association of factor 7 is indicative of base metal mineralization, silicification, and perhaps, phyllic (K-rich) alteration as well. Pb, Zn, SiO_2, Ag, and Cu have factor scores above 0.2, and Mn and K_2O have scores above 0.1 (Table 2). The Pb-Zn-Ag-Mn assemblage is typical of manto deposits, such as those of the Pioche district (Gemmill, 1968),

which is located just south of the jasperoid study area, or those of the Eureka district (Nolan, 1962), which is located near the Windfall deposit (Fig. 1a). Manto deposits are generally associated with intermediate composition porphyry intrusions, and in their metal assemblages, are distinctly different from Carlin-type gold deposits. Factor 7 may therefore reflect the overlapping influence of another metallogenic province in the study area. Indeed, the three samples with the highest factor 7 loadings (Appendix II) are from the prospects located in the southernmost part of the study area (Fig. 1a). Geochemically, these prospects may bear more of a similarity to the Taylor silver deposit (in the southeast part of the study area near Ely, Nevada) than to the Carlin gold deposit.

Relationship between the factor model and jasperoid paragenesis

Several components of the jasperoid factor model can be interpreted in terms of the general scheme for jasperoid paragenesis developed by Hofstra et al. (1987) at the Jerritt Canyon deposit and used by Northrop et al. (1987) in developing a model for ore deposition. These studies indicate that jasperoid paragenesis at Jerritt Canyon was related to three major hydrologic events, designated as events I, IIA, and IIB. In brief, fluids related to event I were saline, CH_4-dominated fluids and were the product of an early (Paleozoic) regional metamorphic event. These fluids produced jasperoids and included cherts that considerably predate gold mineralization. Event IIA fluids were the hydrothermal solutions responsible for gold mineralization; these were acidic, CO_2 dominated, and generally less saline than event I fluids. Event IIB fluids were related to the late-stage incursion of more dilute, relatively gas-poor, meteoric waters which eventually flooded the system and signaled the end of gold-mineralizing processes. At Jerritt Canyon, the mixing of event IIA and IIB fluids appears to have been an important ore-forming process. Fluids similar to those of the IIA and IIB events at Jerritt Canyon have been recognized by Rose and Kuehn (1987) at the Carlin deposit.

Factor 4 (Ba, SiO_2, Sr), as discussed above, reflects the presence of chert in some samples and must be related (in these cases) to fluids like those of event I at Jerritt Canyon. Factor 3 (W, B, V, Zn, Co, Au, CaO, Ni, Mn, Cu) is a gold mineralization factor related to hydrothermal calcite; it may therefore reflect ore-stage, CO_2-rich fluids such as those characteristic of event IIA. Factor 2 (Au, Ag, Sb, SiO_2, As, Pb) must also be related to ore-stage (event IIA) fluids; however, these fluids must have been somewhat different from those associated with factor 3—perhaps relatively CO_2 poor. Factor 7 (Pb, Zn, SiO_2, Ag, Cu) may represent yet another type of mineralizing fluid or perhaps mineral deposition from similar fluids in a relatively high-temperature environment.

Factor 1 (TiO_2, Al_2O_3, La, K_2O, Sr, Fe_2O_3, Th) reflects altered host-rock residuum which could have formed in either event IIA fluids or in more dilute, less exchanged fluids such as those associated with event IIB. Factor 1, however, has a negative score for gold (Table 2) and may thus reflect fluids that were at least unrelated, if not antithetical, to gold mineralization. Fluids such as these would be comparable to the relatively unexchanged event IIB fluids of Jerritt Canyon (Hofstra et al., 1987; Northrop et al., 1987). Although fluids of this type must have been present in both the mineralized and barren systems of this study, they must have been relatively dominant in the gold-barren systems.

Factor 6 (Na_2O, CaO, K_2O, MgO, Mn, SiO_2) is related to unreplaced, unaltered host rock and is therefore a factor that is relatively independent of fluid type. Note that factor 6 has a near-neutral factor score for gold (Table 2).

Barren versus mineralized systems

The factor model quantifies relationships among jasperoid samples in terms of components (factors) that reflect the composition and evolution of hydrothermal fluids. Because of this, the factor model provides some insight into the systematics of jasperoid geochemistry in Carlin-type gold deposits and in related but barren epithermal systems.

Factors 2 and 3 are the only factors in the model directly related to gold mineralization (Table 2), yet they are negatively correlated (Appendix II). Because factors 2 and 3 are most strongly associated with individual deposits (Windfall and Gold Quarry, respectively), the negative correlation between them suggests that different types of mineralizing fluids, or perhaps different mineralizing processes, were associated with samples from different localities in this study.

In Figure 2, all of the jasperoid samples are plotted in terms of their loadings for factor 3 against those for factor 2. This diagram clearly shows that samples from barren and mineralized systems are, in general, geochemically distinct and plot in separate areas. Moreover, most samples from specific mineralized systems plot in relatively small, well-defined groups in areas of high factor 2 and/or high factor 3 loadings. All of the mineralized-system samples which do not plot in or near their respective system groups have high loadings of one or more of factors 4 through 7, indicating that they have a significant chert, barite, iron oxide (?), unreplaced silty limestone, and/or base metal component (Tables 2 and 3).

Figure 3 is essentially the same plot as Figure 2 except that samples in which factors 1, 2, and 3 together account for less than two-thirds of the total

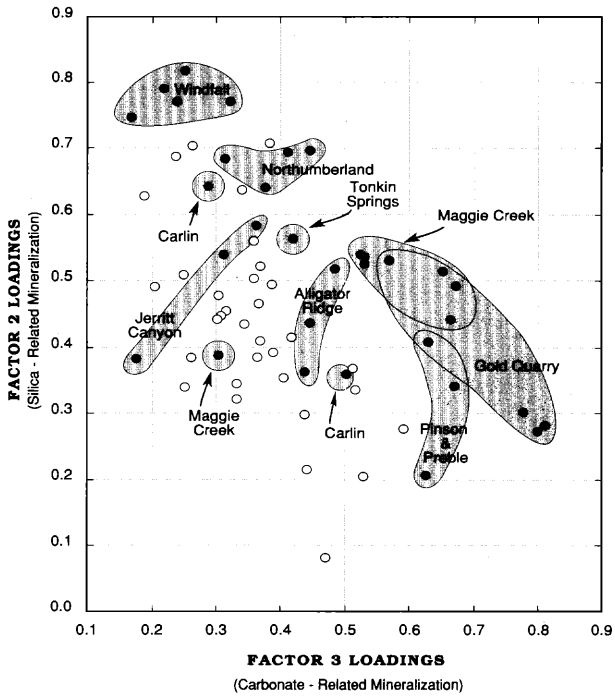

FIG. 2. Factor 3 loadings versus factor 2 loadings for jasperoid samples (Appendix II). Shaded fields contain samples from specified individual gold deposits. Note the clustering of data points for samples from individual localities, and the general separation of samples from barren and productive systems. Symbols as in Figure 1a.

sum of squares have been omitted. Figure 3 therefore considers only those samples in which some combination of the gold-related factors (factors 2 and 3) and/or the argillically altered residuum factor (factor 1) are relatively important. Samples in which any combination of factors 4 through 7 (chert, barite, iron oxide, unreplaced silty limestone, and/or base metal components) are relatively important do not appear in Figure 3. Application of this criterion eliminates all three samples from the Jerritt Canyon deposit, two from the Maggie Creek deposit, and one each from the Alligator Ridge, Carlin, Northumberland, and Windfall deposits; it also eliminates about the same number of samples from barren systems.

For the remaining samples that do plot in Figure 3, it can be inferred that factor 1 is the major component in those samples with relatively low factor 2 and factor 3 loadings (i.e., samples closest to the origin of the axes). Figure 3, therefore, portrays relationships among samples in terms of the three dominant factors in the model, all of which are apparently related to common hydrothermal processes (or fluid types) in Carlin-type systems. Considered in terms of the Jerritt Canyon model for jasperoid paragenesis (Hofstra et al., 1987), Figure 3 portrays relationships among samples that are predominantly the products of event IIA and IIB fluids.

In Figure 3, samples with high factor 1 loadings (those nearest the origin) are characterized by a relatively dominant argillically altered residuum component and relatively weak gold-related mineralization components (factors 2 and 3). Altered noncarbonate residuum would be a component common to jasperoid in both barren and mineralized systems. Factor 1 loadings are, therefore, probably influenced by an interplay among several variables: (1) the amount of noncarbonate material in original host rocks, (2) the degree to which aluminum and potassium were soluble in hydrothermal fluids, and (3) the degree to which elements with high scores of factors 2 and 3 were either not present or not precipitated during jasperoid formation.

If the first two of these variables were roughly comparable in all of the systems studied, it would imply that the factor 1 component (residuum) simply dominates by default in weakly mineralized samples. It may be, however, that factor 1 loadings are generally low in mineralized samples not only because metal-bearing solutions were present but also because aluminum and potassium were inherently more soluble in these solutions.

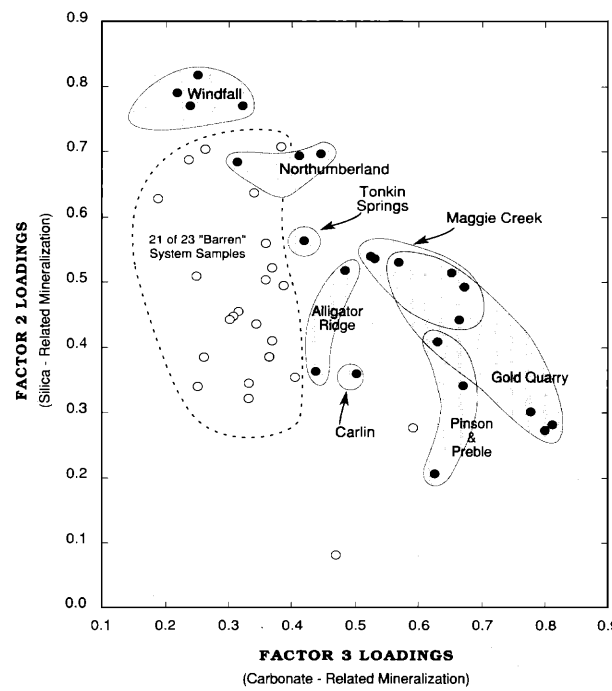

FIG. 3. Factor 3 loadings versus factor 2 loadings for jasperoid samples in which factors 1, 2, and 3 together account for more than two-thirds of the total sum of squares. Note the separations between specific mineralized systems, and between mineralized and barren systems in general. Symbols as in Figure 1a.

Relationships between loadings for the two gold mineralization factors (factors 2 and 3) are roughly similar in samples from individual deposits but are highly variable among samples from different deposits (Appendix II and Fig. 3). This observation suggests that the gold deposits considered in this study form a continuum between two end-member types, with the Windfall deposit (primarily related to factor 2) at one extreme and the Gold Quarry deposit (related to factor 3) at the other. Other deposits appear to be intermediate between these two extremes. The hypothesis that the Windfall and Gold Quarry deposits may represent geochemically distinct deposit types and that their differences are readily apparent in jasperoid geochemistry has far-reaching implications for understanding the genesis of these deposits and for exploration work as well.

The deposit groupings in Figure 3 also suggest that there is a definite regional geologic control governing the relative importance of factors 2 and 3 in jasperoid samples from producing mines (Appendix II and Fig. 1a). Samples with high factor 3 loadings and relatively low factor 2 loadings are from deposits that lie either on the northwest-trending Carlin trend (Carlin, Gold Quarry, and Maggie Creek) or on the nearby northeast-trending lineament commonly referred to as the Getchell trend (Pinson and Preble). The location, geology, and ore deposits of the Carlin and Getchell trends have been discussed by Bagby and Berger (1985). Samples from deposits not on these trends generally have higher factor 2 loadings and lower factor 3 loadings. Samples from the two southernmost deposits in the study, Windfall and Northumberland, have the highest factor 2 loadings. These observations suggest that mineralizing fluids which evolved in hydrothermal systems along the Carlin and Getchell trends were somewhat different from those which evolved in other parts of the northern Great Basin.

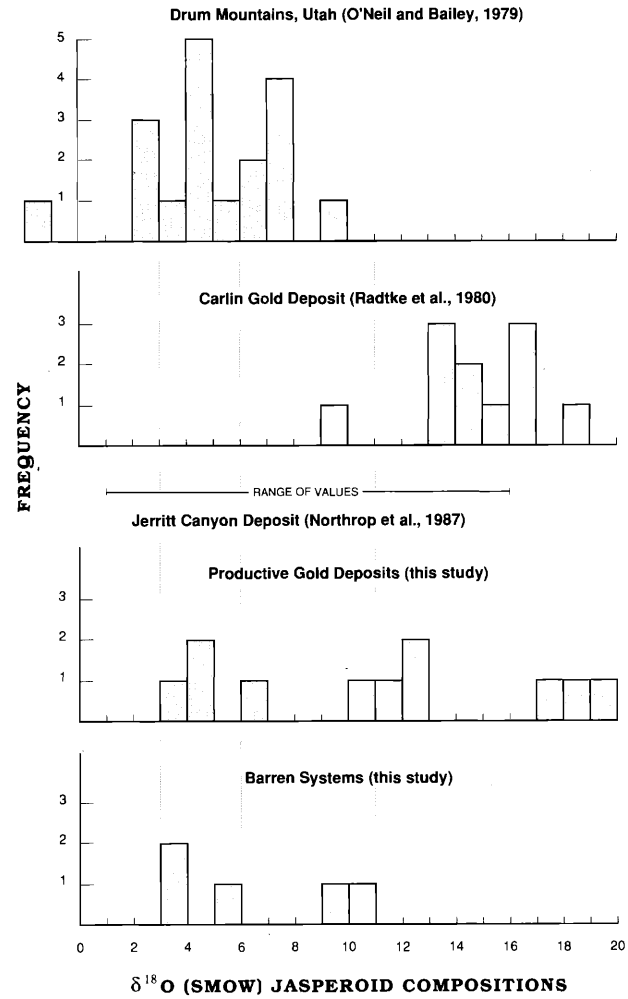

FIG. 4. Frequency distribution plots for $\delta^{18}O$ values in jasperoid from barren and mineralized hydrothermal systems (data from this study; O'Neil and Bailey, 1979; Radtke et al., 1980; Northrop et al., 1987). Note that barren and mineralized systems in this study generally have common lower $\delta^{18}O$ values in the range of 3 to 6 per mil but different upper values. Only gold-mineralized systems have $\delta^{18}O$ values above 11 per mil.

Oxygen Isotope Geochemistry

The 19 jasperoid samples analyzed for oxygen isotope ratios were selected in order to cover a wide range of geochemical variation, as portrayed in Figure 2, and also to obtain a wide geographic distribution. Results of the oxygen isotope analyses are tabulated in Appendix I and are portrayed graphically in Figures 4 and 5.

Results

Jasperoid: Oxygen isotope compositions of jasperoid show extreme variation within individual hydrothermal systems. In 11 jasperoid samples from the Carlin deposit, for example, Radtke et al. (1980) found $\delta^{18}O$ values ranging from 9.3 to 18.1 per mil (Fig. 4). At the Jerritt Canyon deposit, Northrop et al. (1987) measured $\delta^{18}O$ values ranging from 1.1 to 15.2 per mil in (event IIA) jasperoid temporally associated with gold mineralization. In our study, $\delta^{18}O$ values of 4.0 and 19.3 per mil were obtained in samples from the Carlin deposit (Appendix I). In samples from other deposits, $\delta^{18}O$ values of 3.5 and 17.0 per mil were obtained from the Alligator Ridge deposit, 4.5 and 10.8 per mil from the Windfall deposit, and 6.7 to 12.4 per mil on three samples from the Gold Quarry deposit. In the five (nonchert) barren-system samples analyzed for this study, $\delta^{18}O$ values range from 3.7 to 10.3 per mil. For comparison, $\delta^{18}O$ values obtained by O'Neil and Bailey (1979) on 18 jasperoid samples from the Drum Mountains in western Utah range from −1.2 to +9.9 per mil (Fig. 4). Oxygen isotope data

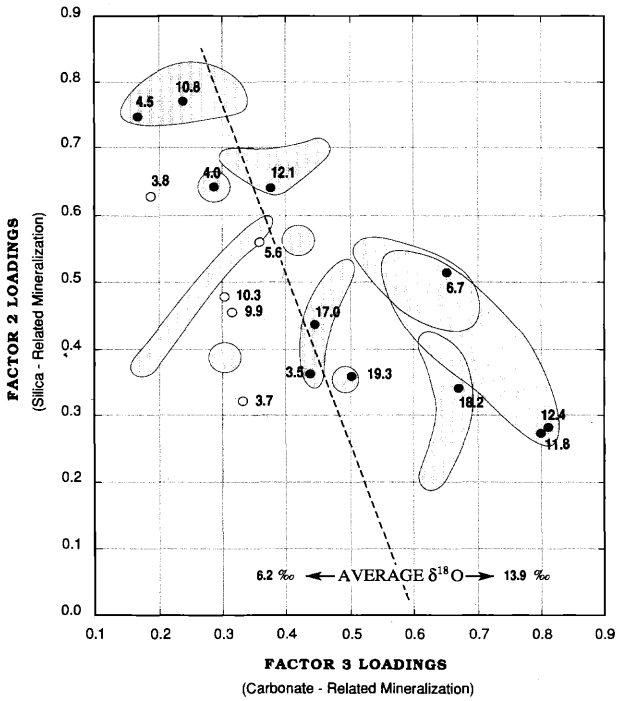

FIG. 5. $\delta^{18}O$ values for jasperoid samples plotted on factor 3 versus factor 2 axes which correspond to Figures 2 and 3. The diagonal dashed line divides samples into two groups having mean $\delta^{18}O$ values which differ by over 7 per mil. This same line roughly separates most samples from barren and mineralized systems. Shaded areas correspond to labeled fields for individual gold deposits as shown in Figure 2. Symbols as in Figure 1a.

in the same general range (4.7, 6.9, 9.9, and 10.3‰) were obtained on jasperoid from a Carlin-type, though subeconomic, gold occurrence in southern Utah known as Bull Valley (referred to in Beaty, 1987).

Jasperoids in most of the systems examined for this study have similar minimum $\delta^{18}O$ values in the range of 3 to 6 per mil (Fig. 4). This common minimum is found in widely separated systems (both mineralized and barren) and in different geologic settings. High ^{18}O jasperoid (11–19‰), on the other hand, appears to be associated only with gold-producing systems and not with barren systems. Based on limited sampling, the Carlin, Alligator Ridge, and Pinson deposits all have jasperoid heavier than 17 per mil, whereas the Northumberland and Gold Quarry deposits have jasperoid at least as heavy as 12 per mil. By contrast, the maximum $\delta^{18}O$ value obtained from a barren-system jasperoid in this study was 10.3 per mil.

Calculated fluids: Based on homogenization temperatures of fluid inclusions, Nash (1972) estimated the temperature of deposition for quartz veinlets at the Cortez deposit to be about 200°C. At the Carlin deposit, Radtke et al. (1980) found homogenization temperatures of 185° to 235°C for fluid inclusions in jasperoid and slightly higher homogenization temperatures for quartz veinlets in jasperoid. These temperature estimates are generally similar to those made by Rye et al. (1974) and Rye (1985) for gold mineralization at the Cortez and Carlin deposits. Because of the petrologic and geochemical similarities among the disseminated-replacement gold deposits of northern Nevada (Tooker, 1985; Tingley and Bonham, 1986), it is reasonable to assume that much of the jasperoid in these deposits formed at about 200°C. It is also assumed, in light of hydrogen isotope studies at the Carlin and Cortez deposits (Rye, 1985), that hydrothermal fluids in all of the systems discussed in this paper were ^{18}O-shifted meteoric waters.

At a temperature of 200°C, low ^{18}O jasperoid (3–6‰) is in equilibrium with water having a $\delta^{18}O$ value ranging from −9 to −6 per mil, whereas high ^{18}O jasperoid (11–19‰) would have formed from fluids having a $\delta^{18}O$ value range of approximately −1 to +7 per mil (Clayton et al., 1972). Modern meteoric ground water in north-central Nevada has a $\delta^{18}O$ value of about −16 per mil (Taylor, 1979), and based on age estimates by Rye (1985), roughly similar values of −17 to −19 per mil are inferred for ground water at the time of ore deposition in the Cortez and Carlin deposits. The $\delta^{18}O$ compositions of some ore-related jasperoid samples (11–19‰) therefore require that meteoric waters in some Carlin-type hydrothermal systems were ^{18}O shifted by at least 16 per mil.

Discussion

Oxygen exchange between meteoric water and high ^{18}O country rock could account for the high $\delta^{18}O$ values (11–19‰) obtained on many jasperoid samples (Rye et al., 1974; Radtke et al., 1980). It follows that varying degrees of water-rock exchange could account for much of the variation in $\delta^{18}O$ values. Low ^{18}O jasperoid (3–6‰) could have formed from fluids that became saturated in silica but either experienced minimal water-rock exchange beyond that or circulated in low ^{18}O exchange reservoirs. High ^{18}O jasperoid (11–19‰), however, must have formed from fluids that experienced extensive water-rock interaction in relatively high ^{18}O exchange reservoirs.

Mixing of evolved high ^{18}O fluids with near-surface low ^{18}O meteoric water could account for some of the variations in $\delta^{18}O$ values, particularly within individual systems. The occurrence of fluid mixing in Carlin-type systems has been inferred from fluid inclusion studies at the Jerritt Canyon deposit (Hofstra et al., 1987; Northrop et al., 1987) and the Carlin deposit (Rose and Kuehn, 1987). Mixing in these systems probably took place where ascending hydrothermal fluids were swamped by ambient ground wa-

ter (either on system margins or in certain structural settings) or during the late-stage collapse of the hydrothermal cell. Radtke et al. (1980) speculated that a relatively low $\delta^{18}O$ value associated with a jasperoid sample from the Carlin deposit (9.3‰; see Fig. 4) might have been related to the incursion of near-surface low ^{18}O water along a fault zone. For the mineralized systems in this study especially, fluid mixing may well account for some of the relatively low $\delta^{18}O$ values (3–6‰) in jasperoid.

Two other factors, temperature variation and fluid boiling, undoubtedly account for some of the variation in jasperoid $\delta^{18}O$ values. The influence of these factors, however, is small compared to that of the water-rock exchange and mixing processes. Temperature variation over the range of 190° to 220°C, for example, would produce jasperoid $\delta^{18}O$ values that varied by only about 2 per mil (Clayton et al., 1972). Similar variation of about 2 per mil (or less) might be expected in jasperoid from Carlin-type systems as a result of the liquid-vapor isotopic fractionation associated with fluid boiling along the hydrostatic pressure gradient (Truesdell et al., 1977).

Comparison with factor model

Relationships between jasperoid samples, as portrayed in Figure 3, suggest that fundamental geochemical differences may exist, not only among individual hydrothermal systems but also between mineralized and barren systems in general. One objective of this investigation was to see if these geochemical differences would be reflected in the oxygen isotope ratios obtained from selected jasperoid samples. A full understanding of the oxygen isotope data, however, depends upon an initial understanding of the nature of the samples analyzed.

Barite and chert are two components of the jasperoid samples that would have survived the treatment with hot aqua regia made prior to oxygen isotope analysis. In many descriptions of the jasperoid samples analyzed for this study, barite is mentioned as an accessory mineral and visual estimates of concentration range from trace amounts to 2 vol percent. Although oxygen in either sedimentary or hydrothermal barite would be isotopically heavy, there is insufficient barite in any of the jasperoid samples to affect substantially the $^{18}O/^{16}O$ mass balance. Chert, however, as reflected in some factor 4 loadings (Appendix II), was probably a significant component of some samples and its presence, as documented in the following section, has obviously affected some of the oxygen isotope analyses.

Specific samples: The two samples from the Jerritt Canyon deposit which were analyzed for oxygen isotope ratios have host-rock lithologies described as cherty, silty limestone. These samples may have been largely composed of primary chert rather than replacement hydrothermal silica. One of these samples has a $\delta^{18}O$ value of 27.1 per mil (Appendix I) which is consistent with those obtained by Radtke et al. (1980) on chert at the Carlin deposit and by Northrop et al. (1987) for chert-related (event I) samples at the Jerritt Canyon deposit. This sample also has an extremely high loading on factor 4 (Appendix II). The other of these Jerritt Canyon samples has a $\delta^{18}O$ value of 17.8 per mil (Appendix I). This sample has a relatively low factor 4 loading but an extremely high factor 6 loading (Appendix II); it may reflect a situation in which a substantial component of unaltered host rock (factor 6) was protected from hydrothermal silica replacement by chert (factor 4).

One barren-system sample collected from the Upper Chert member of the Hanson Creek Formation has a $\delta^{18}O$ value of 21.5 per mil (prospect H, Appendix I). Although this sample has a moderately high factor 4 (chert-barite) loading, it has the highest factor 5 loading in the study (Appendix II). Factor 5, though not well understood, may therefore reflect a rock component that has been preserved by chert in this particular sample.

One sample from the Carlin deposit has a high factor 4 loading (Appendix II) but a $\delta^{18}O$ value of only 4.0 per mil (Appendix I). The host-rock lithology for this sample was not described as cherty and it is therefore likely that a barite-quartz assemblage accounts for the high factor 4 loading in this case. There is also one sample from the Alligator Ridge deposit that has a high factor 4 loading and a fairly high $\delta^{18}O$ value of 17.0 per mil. Chert was not mentioned in the description of host-rock lithology for this sample either; however, barite was noted as an accessory mineral. For this sample, the $\delta^{18}O$ value probably reflects, for the most part at least, the oxygen isotope composition of replacement silica.

General relationships: Figure 5 shows how the oxygen isotope data relate to the elemental geochemistry of jasperoid samples as portrayed in terms of factors 2 and 3. (The three chert-related samples discussed in the previous section are excluded from Figure 5.) $\delta^{18}O$ values above 11 per mil are generally associated with samples that have relatively high factor 2 and/or factor 3 loadings; however, $\delta^{18}O$ values above 17 per mil are associated only with samples that have relatively high factor 3 loadings and relatively low factor 2 loadings. The near-vertical dashed line drawn across Figure 5 further illustrates these general relationships. To the right of this line samples have relatively high factor 3 loadings. The $\delta^{18}O$ values for these seven samples range between 6.7 and 19.3 per mil and have a mean value of 13.9 per mil. The nine samples to the left of this line have $\delta^{18}O$ values ranging from 3.5 to 10.8 per mil and a mean of 6.2

per mil. The low $\delta^{18}O$ values group includes samples with relatively high factor 1 and/or factor 2 loadings.

Relationships between $\delta^{18}O$ values and factor loadings for the nonchert samples are also reflected in the following correlation coefficients (for a population of 16 samples, a correlation of 0.426 is statistically significant at the 0.1 level): $\delta^{18}O$ vs. factor 1 loadings = −0.067, $\delta^{18}O$ vs. factor 2 loadings = −0.370, and $\delta^{18}O$ vs. factor 3 loadings = 0.487. Factor 3 loadings show a fairly strong positive correlation with $\delta^{18}O$ values, whereas factor 2 loadings are negatively correlated with $\delta^{18}O$ values. Moreover, Figure 5 shows that in every case but one (prospect B, see Appendix I), where there are two or more samples from a particular locality, the sample with the higher $\delta^{18}O$ value also has the higher factor 3 loading (Appendices I and II). Loadings for the argillically altered residuum factor (factor 1) are not strongly correlated with $\delta^{18}O$ values.

The implications of Figure 5 and the correlation data are that the hydrothermal processes associated with factor 3 involved considerable water-rock ^{18}O exchange, and that these processes were probably critical to the formation of Carlin-type deposits along the Carlin and Getchell trends. Moreover, relationships between the results of factor analysis and the oxygen isotope data indicate that the elemental geochemistry of jasperoid samples does indeed reflect fundamental properties of the hydrothermal fluids which produced them.

Discussion: Genetic Implications for Carlin-type Deposits

The jasperoid factor model together with the oxygen isotope data indicates that hydrothermal fluids in barren and mineralized systems evolved in different ways. These data also suggest that fluid evolution in hydrothermal systems along the Carlin and Getchell trends may have been somewhat different from that in other gold-producing systems of the northern Great Basin. Chemically, jasperoid samples from specific gold deposits are quite similar to one another, yet, as groups, they are generally distinct from those of other localities (Fig. 3). These relationships suggest that the overall chemistries of the individual systems studied were largely determined before fluids reached the levels at which most of the gold and silica were precipitated from solution. It is therefore inferred that water-rock exchange involving deeply circulating fluids in different geologic settings must have been a critical factor in determining the elemental and isotopic geochemistry of jasperoid in Carlin-type gold deposits of the northern Great Basin.

Fluid evolution in barren systems

Taken together, the elemental and oxygen isotope data indicate that jasperoids from barren systems were the products of relatively unexchanged hydrothermal fluids. Samples from barren systems are generally characterized by relatively high factor 1 (altered residuum) loadings, low factor 2 and factor 3 (gold-related) loadings, and low $\delta^{18}O$ values (Figs. 3 and 5). The factor analysis signature is indicative of processes that could have occurred simply as the result of rock interaction with relatively metal-deficient hydrothermal fluids. The $\delta^{18}O$ data are indicative of hydrothermal fluids that either did not, for some reason, experience significant water-rock exchange, or were diluted by relatively unexchanged, high-level, meteoric water. Although capable of silicifying and argillically altering host rocks, the relatively unexchanged fluids in barren systems did not, evidently, carry sufficient gold to produce mineable deposits. It does not necessarily follow, however, that exchange reservoirs in barren systems were dominated by relatively unreactive rocks, or even by rocks that were relatively low in ^{18}O and gold contents. If this were true, it would be difficult to explain the proximity of many barren and mineralized systems in apparently similar geologic settings.

Fluid evolution in Carlin-type systems

Jasperoid from the Windfall, Northumberland, and Tonkin Springs deposits apparently formed from hydrothermal fluids that were relatively more exchanged than barren-system fluids and that probably carried significantly more gold in solution. These fluids not only silicified and argillized host rocks but also produced small- to medium-sized gold deposits. Samples from these deposits are generally characterized by high factor 2 (Au, Ag, Sb, SiO_2, As, Pb) loadings, low factor 1 and 3 loadings, and low to moderately high $\delta^{18}O$ values (up to 12.1‰).

Based on the oxygen isotope data, it appears that at least some hydrothermal fluids in the Alligator Ridge, Carlin, and Pinson systems experienced extensive oxygen exchange with ^{18}O-rich source rocks. Samples from these deposits, and from the Gold Quarry and Maggie Creek deposits as well, also have relatively high factor 3 (W, B, V, Zn, Co, Au, CaO, Ni, Mn, Cu) loadings—a factor interpreted as being related to jasperoidal inclusions of hydrothermal calcite. It appears, at first, that exchange reservoirs for these hydrothermal systems must have contained source rocks that were relatively reactive, permeable, ^{18}O rich, and metalliferous. It is doubtful, however, that these exchange reservoirs (except for Alligator Ridge) would have differed significantly in bulk composition from those associated with other Carlin-type deposits located west of the Roberts Mountains thrust. It seems unlikely, therefore, that the lithologic character of fluid exchange reservoirs alone could satisfactorily account for the geochemical and isotopic

variation which is associated with the hydrothermal systems considered in this study.

Fluid compositions

It is argued above that the geochemical and isotopic differences among hydrothermal systems in this study cannot be solely attributed to variations in the general character and composition of fluid exchange reservoirs. A possible explanation for these differences may therefore lie in the character of the hydrothermal fluids themselves. The implication of this argument is that circulating meteoric waters must have been influenced by deep-seated crustal processes in such a way as to affect profoundly the manner in which they interacted with rocks in fluid exchange reservoirs.

In this study the geochemical differences among jasperoid samples from the gold-producing deposits are most clearly expressed in terms of their factor 2 and 3 loadings—factors interpreted as being related to the deposition of hydrothermal silica and calcite, respectively. Although these factors appear to have a generally antithetic relationship in Figure 3, in actual hydrothermal systems the precipitation of silica and calcite are by no means mutually exclusive processes and can, in fact, occur simultaneously.

The components represented by factors 2 and 3 are present to some extent in all samples (Appendix II) and the main differences between samples from gold-producing systems are, for the most part, simply differences in the balance between these two end members. Because jasperoid samples from all mineralized systems generally contain anomalous concentrations of the elements associated with factor 2 (i.e., Ag, Sb, As, and SiO_2), most of the variation among these samples can be attributed to the relative importance of the factor 3 (calcite) component in individual cases. If hydrothermal calcite (factor 3) is absent or relatively unimportant in jasperoid from a gold-mineralized system, factor 2 would be the relatively dominant factor. Conversely, factor 3 loadings would increase relative to factor 2 (and other) loadings to the extent that a hydrothermal calcite phase was present as inclusions within jasperoid. In actual jasperoid samples, the calcite-related component represented by factor 3 would always be a very minor constituent compared to the silica-related component represented by factor 2, even in samples with exceptionally high factor 3 loadings.

The one property of hydrothermal fluids most likely to influence the calcite content of jasperoid is CO_2 content. Although calcite solubility is retrograde with respect to temperature, it increases substantially with increases in the partial pressure of CO_2 and salinity (Holland and Malinin, 1979). Deep fluids in most active geothermal systems are near calcite saturation (Ellis, 1970) and it is likely that fluids in Carlin-type hydrothermal systems were as well. Any loss of CO_2 from these solutions, as in the partitioning of gases into a separated vapor phase during boiling, would have resulted in the precipitation of calcite (Mahon et al., 1980). During decompressional boiling, decreasing temperature and increasing silica concentration in residual fluids would have also resulted in the precipitation of silica (Drummond, 1981; Fournier, 1985). Boiling of CO_2-rich fluids could therefore produce a siliceous precipitate that included hydrothermal calcite. Although jasperoid samples with high factor 3 loadings may reflect some variation of this process, it probably could not have occurred simultaneously with the dissolution of carbonate host rocks. Boiling solutions do, however, become calcite undersaturated after some vapor separation (Ellis and Mahon, 1977; Drummond, 1981) and it may well be that jasperoid associated with high factor 3 loadings formed in some sort of an episodic fashion.

It is not the purpose of this paper to discuss fully the mechanisms by which jasperoids with high factor 3 loadings might have formed. Based on discussions by Lovering (1962), Drummond (1981), Sullivan (1984), and Fournier (1985), however, it appears likely that this type of jasperoid probably formed in association with boiling processes. Although jasperoid could have also formed as a result of fluid mixing with cooler meteoric ground water, it is unlikely that calcite-bearing (factor 3) jasperoid would have formed in this process since calcite would have become relatively more soluble in lower temperature mixed fluids. In light of these observations it might be argued that the main difference between jasperoid having high factor 2 or high factor 3 loadings lies simply in the mode of formation—factor 2 related to nonboiling processes and factor 3 related to boiling processes. This argument notwithstanding, jasperoid with high factor 3 loadings would have been more likely to form in hydrothermal systems that had high CO_2 contents.

Calcite is most likely to precipitate from hydrothermal fluids in which CO_2 concentrations are high (Mahon et al., 1980). On the basis of the factor model (Table 2, Fig. 3), it therefore appears that Gold Quarry (primarily associated with factor 3) and other deposits on the Carlin and Getchell trends were relatively high CO_2 systems. Conversely, the Windfall, Northumberland, and Tonkin Springs deposits (primarily associated with factor 2) appear to have been relatively low CO_2 systems. Although it is likely that mineralizing fluids in both the Windfall and Gold Quarry systems were dilute, sodium chloride solutions near saturation with respect to quartz and calcite at 200°C, these solutions may have been quite different with respect to their CO_2 contents.

Although there is no direct evidence to support the contention that Windfall was a relatively low CO_2 system, there are data which indicate that CO_2 was a

prominent constituent of hydrothermal fluids at Carlin. Three-phase, CO_2-H_2O fluid inclusions have been found in rocks from the Carlin deposit by several investigators (Nash, 1972; Radtke et al., 1980; Kuehn and Bodnar, 1984; Pasteris et al., 1986). Moreover, Rose and Kuehn (1987) have suggested (also on the basis of a fluid inclusion study) that deep hydrothermal fluids at Carlin were saturated with CO_2. There is also evidence for high CO_2 contents at the Jerritt Canyon deposit where Hofstra et al. (1987) have found ore-stage fluid inclusions containing up to about 4 mole percent CO_2.

Physical and chemical conditions in high CO_2 hydrothermal systems could have been dramatically different from those in low CO_2 systems. Besides the formation of calcite, CO_2 affects solution pH, the stability of numerous alteration minerals, solution vapor pressures (and therefore depth to first boiling), fluid densities, effective porosities, heat transfer systematics, and bulk hydrology (Mahon et al., 1980). Giggenbach (1981) has suggested that the dominant control on the chemistry of deep single-phase source fluids in New Zealand geothermal systems is a temperature-dependent reaction involving the conversion of primary plagioclase by CO_2 to calcite and clay minerals. Because CO_2 is a relatively reactive gas (Mahon et al., 1980), it seems likely that high CO_2 contents promoted extensive water-rock interaction in the exchange reservoirs of the Carlin and Getchell trend systems, and that this process liberated relatively large quantities of gold and other metals from source rocks in these systems. The reactivity of high CO_2 fluids may thus account for the association of transition metals and calcite as reflected in factor 3 (W, B, V, Zn, Co, Au, CaO, Ni, Mn, Cu).

If Carlin and some of the other large gold-producing systems of the northern Great Basin were indeed relatively CO_2 rich, there may be a significant analogy to be drawn with some of the active geothermal systems in New Zealand. Weissberg (1969) and Weissberg et al. (1979) have reported on ore-grade, gold-bearing, metastibnite precipitates observed in bore hole and hot spring discharges in certain geothermal fields of the Taupo volcanic zone in New Zealand. These precipitates have formed in natural surface discharges at Broadlands (Ohaki Pool) and Waiotapu (Champagne Pool) and have formed in bore hole discharges at Broadlands and the nearby Rotokawa geothermal field. Similar gold-bearing precipitates have not been observed in discharges at the renowned Wairakei geothermal system even though it has been extensively drilled, lies in a similar geologic setting about 20 km from Broadlands, and has source solutions of roughly comparable salinity and temperature to those at Broadlands. It is probably not mere coincidence that Wairakei is a relatively CO_2-poor system, whereas Broadlands, Waiotapu, and Rotokawa are all relatively CO_2-rich systems (Weissberg, 1969; Ellis and Mahon, 1977).

Estimates of CO_2 contents in deep reservoir solutions at Broadlands range as high as 4 to 6 wt percent (Grant, 1977; Sutton and McNabb, 1977), whereas source solutions in the Wairakei system contain only about 0.06 wt percent CO_2 (Mahon et al., 1980). As a result of the difference in CO_2 contents in reservoir fluids, calcite is an abundant alteration mineral at Broadlands but is rarely observed at Wairakei (Ellis, 1979). Although it is beyond the scope of this paper to speculate on reasons for an apparent gold-CO_2 relationship in specific hydrothermal systems, data from the New Zealand geothermal systems suggest that there is at least an empirical basis for drawing such a connection.

Oxygen isotopes: The empirical connection between high factor 3 loadings and high $\delta^{18}O$ values (Fig. 5) suggests that a causal relationship may exist between high CO_2 contents and extreme ^{18}O enrichment in certain hydrothermal solutions. The pronounced ^{18}O shifts associated with these fluids reflect extensive water-rock interaction in high ^{18}O exchange reservoirs. Although the mechanisms involved are uncertain, it appears that increased calcite solubility due to high CO_2 contents (and low pH) must somehow promote the processes of exchange and recrystallization that are necessary to produce significantly ^{18}O-shifted meteoric waters. Likewise, the reactivity of high CO_2 fluids might also promote oxygen exchange with other ^{18}O-rich source rocks such as shale. Calcite is an ^{18}O-rich mineral; however, even in extreme cases, the solubility of calcite alone (i.e., without the processes of exchange and recrystallization) could account for only a minuscule ^{18}O shift in hydrothermal solutions. Nevertheless, it seems doubtful that significant oxygen exchange involving calcite would occur in low CO_2 systems where calcite was relatively insoluble.

Regional geologic controls

Fluids circulating through lithologically similar exchange reservoirs could have attained markedly different chemical (and perhaps oxygen isotope) compositions as a result of different initial CO_2 contents. Although the ultimate source of CO_2 in Great Basin hydrothermal systems is uncertain, high CO_2 solutions could not have evolved in the simple process of circulating hot meteoric water through carbonate-rich rock. At temperatures above 200°C, carbonate minerals are appreciably soluble only in solutions already having high CO_2 contents and/or high salinity and low pH (Holland and Malinin, 1979). For relatively low-salinity hydrothermal fluids, such as those associated with the Carlin deposit (Rose and Kuehn,

1987), some initial CO_2 must have been present in solution at the onset of water-rock interaction in exchange reservoirs. In any case, the high CO_2 concentrations in mineralizing solutions at Jerritt Canyon (Hofstra et al., 1987)—and in some of the New Zealand geothermal systems as well—are far in excess of what could be attributed to calcite solubility alone. Therefore, in the high CO_2 hydrothermal systems, there must have been some source of CO_2 other than carbonate minerals in fluid exchange reservoirs.

Cunningham (1985) noted that the area between the initial strontium isotope 0.706 and 0.708 isopleths (Fig. 1b) hosts many of the major Great Basin gold deposits (including those on the Carlin and Getchell trends). It is unlikely that the bulk chemical compositions of fluid exchange reservoirs in this area differed substantially from place to place, yet many barren hydrothermal systems also occur in this terrane. The fact that many of these barren systems must have had exchange reservoirs that were not significantly different from the one at Carlin must be explained. Conversely, the fact that some significant gold deposits, such as Alligator Ridge and Mercur, lie well to the east of the I_{Sr} = 0.708 isopleth and the Roberts Mountains thrust also requires explanation. Exchange reservoirs for these hydrothermal systems must have been markedly different in character from those at Carlin and other deposits which lie west of the Roberts Mountains thrust, yet these systems produced large-tonnage Carlin-type gold deposits.

These observations argue that the chemical and lithologic characteristics of upper crustal exchange reservoirs were probably of little import in determining the CO_2 contents of deep fluids in convecting Great Basin hydrothermal systems. It appears, therefore, that the factors determining CO_2 contents in these fluids must have been related to a more profound geologic control. We speculate that this control must be related to deep crustal structures which traverse the upper crustal boundary of the Precambrian continental margin. The ultimate source of CO_2 in many Great Basin hydrothermal systems may be related to deep crustal processes such as decarbonation metamorphic reactions (Rose and Kuehn, 1987) or even to subcrustal process such as mantle degassing (Barnes et al., 1984).

Conclusions

Carlin-type gold deposits of the northern Great Basin may include two geochemically and isotopically discernible end members. Our study suggests that these end-member types are primarily distinguished by the degree to which CO_2 played a role in hydrothermal processes. Jasperoids from the Carlin and Getchell trend deposits (Carlin, Gold Quarry, Maggie Creek, Pinson, and Preble) have geochemical and isotopic characteristics which distinguish them from jasperoids in the other gold deposits of this study. It appears that mineralizing fluids in the Carlin and Getchell trend systems were characterized by comparatively high CO_2 contents and by extensive oxygen exchange in source-rock reservoirs. A causal connection between high CO_2 contents and extensive oxygen exchange is suggested by this study but cannot be proven. It does appear, however, that high CO_2 contents may have been a critical factor in the hydrothermal processes associated with formation of the larger Carlin-type deposits. In terms of total contained gold, the Gold Quarry deposit, a high CO_2 system, is almost two orders of magnitude larger than the Windfall deposit, a low CO_2 system.

Application to exploration

Many barren epithermal systems in the northern Great Basin have been drill tested in exploration programs that were based in part on the occurrence and pathfinder geochemistry (i.e., As, Sb, Hg, and Tl content) of jasperoid. Clearly, more cost-effective exploration decisions could be made if the processes responsible for variations in jasperoid geochemistry were better understood. This study shows that these processes can be identified and evaluated through factor analysis of rudimentary geochemical data and the acquisition of oxygen isotope analyses.

The jasperoid factor model provides an overview of geochemical variation in hydrothermal systems of the northern Great Basin. It also provides a means of understanding these systems in terms of paragenetic relationships and fluid evolution. The extent to which this study can currently be applied to exploration may be somewhat limited, however, by its regional, rather than deposit-specific, scope.

At this time, it is not known how loadings associated with factor 2 (Au, Ag, Sb, SiO_2, As, Pb) and factor 3 (W, B, V, Zn, Co, Au, CaO, Ni, Mn, Cu) might be zoned with respect to ore (or with respect to one another) at specific deposits—or to what extent they might occur in truly barren systems. These factors are, however, apparently related to different types of ore-stage hydrothermal solutions and there are definite paragenetic implications associated with factor 1 (TiO_2, Al_2O_3, La, K_2O, Sr, Fe_2O_3, Th) and factor 4 (Ba, SiO_2, Sr) as well. The elemental and isotopic geochemistry of randomly collected samples can therefore provide some insight into the types of fluids involved in jasperoid formation, and into their ore-forming potential.

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APPENDIX I

Analytical Data on Northern

Samples	Ag (ppm)	Al_2O_3 (%)	As (ppm)	Au (ppm)	B (ppm)	Ba (ppm)	CaO (%)	Co (ppm)	Cu (ppm)	Fe_2O_3 (%)	K_2O (%)	La (ppm)
												Part A. Samples from
Alligator Ridge-1	1.0	3.08	296	1.30	16	1,564	0.29	8	18	1.75	0.38	4
Alligator Ridge-2	0.3	1.12	74	0.02	8	890	0.71	2	9	0.49	0.07	2
Alligator Ridge-3	0.1	3.29	123	0.16	17	101	0.19	4	18	4.73	0.76	15
Carlin-1	0.2	1.33	61	0.40	3	1,484	0.19	2	9	0.42	0.26	2
Carlin-2	0.1	4.18	1,655	0.04	8	161	0.15	7	36	8.57	0.75	11
Gold Quarry-1	0.1	0.68	2,953	0.25	13	17	0.50	93	43	16.60	0.08	2
Gold Quarry-2	0.4	0.53	270	0.75	7	1,638	5.09	9	16	2.70	0.12	3
Gold Quarry-3	3.9	0.75	152	7.10	9	1,310	0.31	21	776	1.13	0.08	4
Gold Quarry-4	0.9	1.23	327	0.80	16	298	6.84	15	137	2.56	0.34	3
Gold Quarry-5	7.0	0.42	217	0.55	9	1,258	0.35	4	16	2.22	0.13	6
Jerritt Canyon-1	0.2	1.96	69	0.45	2	55	2.22	1	12	0.94	0.48	2
Jerritt Canyon-2	0.1	0.36	7	0.02	2	588	0.14	1	8	0.38	0.06	3
Jerritt Canyon-3	0.1	0.51	30	0.80	25	738	0.14	1	12	0.37	0.02	3
Maggie Creek-1	1.8	1.36	55	3.60	2	543	0.63	9	14	0.53	0.32	2
Maggie Creek-2	3.5	1.27	370	2.00	11	192	1.15	5	35	1.75	0.34	4
Maggie Creek-3	1.3	2.35	354	3.40	5	1,285	2.52	6	82	1.91	0.68	3
Maggie Creek-4	2.6	1.65	175	5.40	5	1,696	0.19	4	49	1.76	0.34	6
Maggie Creek-5	3.6	0.66	153	0.36	8	1,368	0.14	3	11	2.27	0.05	5
Maggie Creek-6	0.7	1.26	11	0.03	2	1,678	0.78	2	4	0.42	0.22	7
Northumberland-1	3.3	0.95	948	1.30	5	124	0.22	2	14	0.99	0.06	2
Northumberland-2	3.6	0.79	1,528	0.35	2	30	0.08	1	11	1.27	0.12	5
Northumberland-3	13.0	1.07	2,061	7.00	4	246	0.32	2	14	1.48	0.27	5
Northumberland-4	0.8	0.52	468	2.20	2	271	0.32	2	12	1.37	0.17	6
Pinson-1	0.1	0.86	1,735	5.00	7	145	1.19	2	26	3.35	0.12	13
Pinson-2	0.1	2.44	1,450	3.60	17	106	1.03	6	45	4.25	0.45	18
Preble	0.3	1.68	232	0.01	2	262	5.86	4	43	3.27	0.36	5
Tonkin Springs	2.8	1.24	319	0.70	4	247	0.19	2	14	1.11	0.18	4
Windfall-1	3.0	0.79	756	5.40	3	887	0.26	2	27	0.84	0.16	3
Windfall-2	0.8	0.54	103	0.30	2	130	0.23	1	5	0.61	0.06	2
Windfall-3	5.4	0.94	246	1.50	2	822	0.07	2	18	0.71	0.15	2
Windfall-4	5.8	1.47	854	0.90	5	280	0.12	1	5	0.81	0.29	2
Windfall-5	13.2	0.77	790	1.30	3	819	0.10	2	5	0.79	0.07	2
												Part B. Samples from
Prospect A	0.1	2.85	220	0.32	5	566	0.14	2	9	2.15	0.47	5
Prospect B-1	0.7	2.03	21	0.02	2	137	0.28	1	13	0.89	0.36	4
Prospect B-2	0.1	2.90	45	0.02	3	75	0.40	2	4	1.93	0.72	7
Prospect B-3	0.1	1.63	276	0.01	2	621	0.20	3	13	2.25	0.42	4
Prospect B-4	0.6	2.06	95	0.16	2	233	0.20	1	4	0.66	0.54	2
Prospect B-5	1.0	1.96	1,536	0.04	6	135	0.29	3	12	0.88	0.37	5
Prospect B-6	3.1	2.52	576	0.35	2	131	0.21	2	18	1.57	0.69	4
Prospect B-7	39.0	2.51	1,387	4.30	8	95	0.35	2	13	1.98	0.63	4
Prospect C	1.1	2.84	132	0.02	6	1,150	0.27	4	13	1.59	0.88	11
Prospect D	0.1	2.45	187	0.01	3	479	0.19	2	12	2.58	0.44	7
Prospect E	0.1	1.39	107	0.12	2	202	0.42	3	8	1.12	0.38	4
Prospect F	6.7	1.80	472	0.05	12	47	0.78	8	34	13.13	0.54	13
Prospect G-1	0.1	3.39	409	0.04	2	704	0.36	3	4	1.72	0.80	4
Prospect G-2	1.8	1.70	92	0.31	4	521	0.11	1	4	0.75	0.51	2
Prospect H	0.1	0.25	267	<0.01	2	202	0.93	4	10	7.70	0.25	12
Prospect I-1	0.8	2.23	122	0.09	2	161	0.23	3	7	0.86	0.57	8
Prospect I-2	3.9	2.54	91	1.20	2	682	0.32	2	12	1.00	0.52	2
Prospect J	7.7	1.00	210	0.03	2	111	0.08	4	44	2.78	0.47	9
Prospect K	0.1	0.58	23	0.02	4	65	0.77	4	93	0.69	0.21	2
Prospect L-1	0.1	2.63	61	0.03	6	170	0.28	2	10	1.34	0.46	4
Prospect L-2	0.1	3.02	143	0.30	2	265	0.83	5	13	1.72	0.59	4
Prospect M	0.1	0.47	252	0.01	2	1,388	1.74	4	13	8.58	0.06	3
Prospect N	0.3	0.73	1,127	0.01	2	103	2.16	3	12	9.28	0.34	2
Prospect O-1	0.2	4.61	216	<0.01	3	623	0.46	3	12	1.72	0.13	8
Prospect O-2	0.5	3.85	786	0.15	3	140	0.41	1	8	3.23	0.08	21
Prospect P	0.1	6.77	16	0.01	5	673	0.22	11	44	8.22	1.45	20
Prospect Q-1	0.3	1.13	86	0.10	3	1,508	0.35	6	12	2.66	0.20	5
Prospect Q-2	0.1	0.57	573	0.50	5	818	0.66	7	15	2.95	0.18	8
Prospect R	10.3	3.40	375	0.21	6	773	0.14	3	36	2.90	0.62	6
Prospect S	0.1	2.83	338	<0.01	7	65	0.05	1	5	1.48	0.06	3
Prospect T	60.3	1.51	115	0.23	4	17	0.05	1	35	0.69	0.26	2
Prospect U	0.3	5.63	163	0.03	6	313	0.09	2	47	2.53	2.11	16
Prospect V	0.7	3.99	191	0.30	3	260	0.19	1	11	3.38	1.01	6

Great Basin Jasperoid Samples

MgO (%)	Mn (ppm)	Mo (ppm)	Na_2O (%)	Ni (ppm)	P_2O_5 (%)	Pb (ppm)	Sb (ppm)	SiO_2 (%)	Sr (ppm)	Th (ppm)	TiO_2 (%)	V (ppm)	W (ppm)	Zn (ppm)	$\delta^{18}O$ (‰)
mineralized systems															
0.18	96	8	0.05	34	0.08	35	78	90.88	113	2	0.08	18	2	101	
0.12	97	8	0.02	8	0.03	3	48	89.70	41	1	0.01	5	2	20	17.0
0.23	53	11	0.14	15	0.13	44	36	85.52	88	3	0.22	32	2	64	3.5
0.07	18	3	0.03	5	0.02	19	127	91.64	17	1	0.01	3	2	7	4.0
0.11	72	38	0.10	26	0.08	22	130	81.08	23	2	0.23	81	6	117	19.3
0.08	45	15	0.03	336	0.17	31	776	74.64	27	3	0.01	137	257	860	12.4
0.62	1,069	5	0.02	86	0.04	8	466	78.34	25	2	0.01	86	87	357	
0.04	30	7	0.01	9	0.10	88	183	78.54	49	2	0.03	68	11	28	6.7
4.63	265	5	0.02	72	0.07	12	124	72.85	29	5	0.03	143	49	253	11.8
0.15	117	10	0.02	18	0.06	1,448	717	94.24	20	2	0.11	652	98	102	
0.26	24	4	0.04	3	0.02	13	23	91.85	6	1	0.03	8	1	11	17.8
0.03	23	3	0.01	8	0.04	5	10	97.70	21	1	0.01	6	2	3	27.1
0.01	9	7	0.01	7	0.17	6	523	98.07	35	1	0.01	13	1	10	
0.34	347	4	0.04	21	0.12	8	41	95.48	7	1	0.02	42	13	75	
0.66	225	7	0.02	107	0.11	11	532	91.57	13	1	0.03	147	43	452	
1.65	220	7	0.02	50	0.06	15	318	84.55	18	2	0.05	79	45	319	
0.13	68	17	0.02	10	0.06	48	211	88.96	32	3	0.21	81	19	49	
0.07	144	9	0.04	13	0.03	1,271	556	93.80	24	2	0.12	515	106	78	
0.25	73	9	0.03	8	0.04	16	9	94.66	18	1	0.01	14	3	12	
0.10	17	15	0.02	19	0.03	4	197	95.36	17	1	0.01	6	1	114	
0.05	14	33	0.03	6	0.07	4	354	93.29	21	1	0.01	19	1	7	
0.12	35	15	0.05	9	0.22	3	347	93.70	39	1	0.02	28	1	9	
0.05	19	47	0.05	10	0.19	10	382	95.30	25	1	0.01	11	1	28	12.1
0.10	336	12	0.06	16	0.62	2	52	91.40	24	1	0.04	93	103	68	
0.16	689	30	0.04	37	0.48	2	73	88.23	20	2	0.11	218	116	114	18.2
0.15	168	9	0.02	50	0.12	36	28	82.31	76	4	0.02	156	48	199	
0.08	47	2	0.01	6	0.10	6	8	95.66	16	2	0.07	13	3	13	
0.05	12	12	0.03	5	0.30	398	461	93.92	28	1	0.04	3	1	19	
0.13	12	7	0.07	3	0.01	74	57	96.93	14	1	0.01	1	1	7	4.5
0.02	10	4	0.03	4	0.08	1,475	539	94.35	16	2	0.08	2	1	15	
0.07	16	6	0.08	1	0.12	1,614	224	83.20	38	1	0.10	3	1	10	10.8
0.05	52	8	0.06	3	0.28	1,708	484	93.88	7	1	0.03	1	1	9	
barren systems															
0.12	37	4	0.06	8	0.12	34	208	87.62	43	3	0.13	12	2	4	
0.09	70	3	0.06	8	0.03	12	2,589	94.20	70	2	0.06	8	2	10	
0.14	96	2	0.09	4	0.03	9	19	91.69	38	1	0.11	26	2	9	
0.08	44	43	0.06	3	0.02	13	741	92.74	32	1	0.06	33	3	17	10.3
0.08	70	3	0.05	1	0.03	12	1,052	95.38	42	2	0.06	6	1	6	3.8
0.05	69	2	0.04	11	0.09	6	52	94.97	18	2	0.10	9	1	28	
0.16	38	4	0.04	11	0.03	13	16	93.30	23	2	0.08	12	2	49	5.6
0.15	26	5	0.04	7	0.02	18	160	91.80	37	1	0.07	7	2	18	
0.41	46	5	0.02	12	0.06	12	31	89.70	21	3	0.09	67	1	104	
0.04	54	4	0.09	7	0.14	12	16	90.22	76	1	0.10	18	2	6	
0.11	146	40	0.06	19	0.02	8	36	95.03	27	2	0.01	9	3	46	
0.45	959	10	0.08	59	1.16	22	46	75.97	100	6	0.09	151	1	427	
0.22	25	1	0.02	11	0.04	10	1,498	90.90	32	2	0.10	16	2	21	
0.09	23	4	0.02	2	0.06	14	134	89.98	42	1	0.04	5	2	2	
0.06	118	30	0.03	42	0.21	11	40	87.86	58	2	0.01	232	3	179	21.5
0.19	64	4	0.02	13	0.02	9	14	94.56	25	2	0.04	6	2	6	
0.09	60	6	0.01	6	0.06	10	1,358	90.86	31	2	0.01	4	2	1	
0.06	291	4	0.04	11	0.11	1,220	25	93.65	32	2	0.01	14	1	322	
0.25	42	3	0.01	7	0.05	329	19	95.06	7	1	0.01	1	1	420	
0.17	282	17	0.05	17	0.01	47	19	93.23	16	2	0.09	10	1	61	
0.17	66	1	0.04	21	0.03	13	39	91.46	59	1	0.13	17	3	45	
0.09	61	37	0.01	6	0.15	13	2	85.14	101	1	0.02	97	1	24	
0.47	124	7	0.01	4	0.08	5	31	80.28	63	1	0.08	11	1	8	
0.19	18	10	0.01	17	0.06	9	46	89.20	70	2	0.23	14	3	18	3.7
0.08	18	4	0.01	9	0.23	88	174	88.63	84	2	0.15	18	2	68	
0.55	256	11	0.01	103	0.33	13	2	77.61	27	6	0.33	32	1	330	
0.15	200	4	0.01	22	0.05	48	12	88.48	23	1	0.01	53	2	352	
0.07	168	6	0.01	29	0.12	19	10	93.88	53	1	0.01	28	1	147	
0.07	81	4	0.01	10	0.18	7	47	88.42	70	1	0.27	59	2	17	
0.05	40	3	0.01	12	0.01	8	232	93.12	10	1	0.07	2	1	6	
0.05	74	4	0.01	6	0.01	571	79	95.83	9	1	0.04	5	1	137	
0.54	14	7	0.01	11	0.11	75	38	84.21	53	2	0.23	46	1	58	
0.18	31	2	0.01	4	0.08	42	24	83.05	46	1	0.15	47	1	19	9.9

APPENDIX II

Factor Loadings Matrix, Northern Great Basin Jasperoid

Samples	Factor number 1	2	3	4	5	6	7
Part A. Samples from mineralized systems							
Alligator Ridge-1	0.574	0.518	0.485	0.312	0.046	0.112	0.065
Alligator Ridge-2	0.376	0.437	0.445	0.562	0.081	0.229	0.051
Alligator Ridge-3	0.732	0.363	0.437	0.113	0.194	0.131	0.041
Carlin-1	0.342	0.643	0.289	0.498	−0.031	0.302	0.069
Carlin-2	0.688	0.359	0.503	0.086	0.254	0.142	0.063
Gold Quarry-1	0.305	0.283	0.813	0.053	0.223	0.056	0.073
Gold Quarry-2	0.304	0.302	0.778	0.346	0.020	0.214	0.096
Gold Quarry-3	0.356	0.515	0.652	0.287	−0.048	−0.142	0.085
Gold Quarry-4	0.428	0.274	0.800	0.162	−0.044	0.153	0.120
Gold Quarry-5	0.426	0.531	0.569	0.278	0.025	0.015	0.191
Jerritt Canyon-1	0.420	0.540	0.313	0.211	0.085	0.485	0.203
Jerritt Canyon-2	0.322	0.383	0.177	0.784	0.068	0.147	0.152
Jerritt Canyon-3	0.227	0.583	0.362	0.556	0.045	−0.098	−0.098
Maggie Creek-1	0.291	0.525	0.530	0.340	0.001	0.355	0.209
Maggie Creek-2	0.367	0.494	0.672	0.254	0.046	0.175	0.173
Maggie Creek-3	0.441	0.442	0.664	0.279	−0.049	0.219	0.154
Maggie Creek-4	0.550	0.541	0.525	0.264	−0.015	0.044	0.090
Maggie Creek-5	0.442	0.537	0.530	0.260	0.038	0.053	0.147
Maggie Creek-6	0.427	0.389	0.305	0.582	0.124	0.305	0.212
Northumberland-1	0.249	0.698	0.445	0.305	0.207	0.132	0.136
Northumberland-2	0.347	0.684	0.314	0.211	0.431	0.097	0.045
Northumberland-3	0.399	0.694	0.412	0.265	0.247	0.117	−0.015
Northumberland-4	0.325	0.642	0.378	0.369	0.387	0.144	0.052
Pinson-1	0.430	0.408	0.629	0.250	0.261	0.165	−0.031
Pinson-2	0.533	0.342	0.670	0.176	0.179	0.137	0.011
Preble	0.541	0.207	0.626	0.316	0.163	0.168	0.193
Tonkin Springs	0.545	0.563	0.420	0.293	−0.031	0.045	0.170
Windfall-1	0.361	0.771	0.322	0.319	0.138	0.017	0.119
Windfall-2	0.220	0.748	0.169	0.302	0.240	0.365	0.178
Windfall-3	0.400	0.792	0.219	0.222	−0.005	0.026	0.207
Windfall-4	0.476	0.772	0.240	0.091	0.099	0.074	0.069
Windfall-5	0.263	0.818	0.252	0.211	0.124	0.089	0.193
Part B. Samples from barren systems							
Prospect A	0.698	0.505	0.359	0.228	0.060	0.169	−0.027
Prospect B-1	0.618	0.509	0.249	0.283	0.086	0.317	0.067
Prospect B-2	0.741	0.340	0.252	0.212	0.165	0.382	0.076
Prospect B-3	0.565	0.478	0.304	0.354	0.273	0.273	0.037
Prospect B-4	0.566	0.629	0.188	0.270	0.032	0.342	0.025
Prospect B-5	0.643	0.523	0.368	0.184	0.103	0.187	0.134
Prospect B-6	0.614	0.560	0.359	0.166	0.107	0.237	0.212
Prospect B-7	0.495	0.709	0.383	0.107	0.074	0.145	0.083
Prospect C	0.709	0.354	0.406	0.312	0.036	0.105	0.211
Prospect D	0.731	0.385	0.262	0.320	0.233	0.199	0.001
Prospect E	0.441	0.416	0.418	0.378	0.307	0.387	0.161
Prospect F	0.643	0.277	0.592	0.057	0.238	0.044	0.150
Prospect G-1	0.685	0.442	0.303	0.316	−0.035	0.243	0.058
Prospect G-2	0.525	0.688	0.237	0.364	−0.025	0.151	−0.017
Prospect H	0.495	0.205	0.528	0.395	0.462	0.091	0.162
Prospect I-1	0.652	0.448	0.308	0.315	0.086	0.255	0.206
Prospect I-2	0.392	0.638	0.340	0.399	−0.044	0.170	0.049
Prospect J	0.495	0.467	0.367	0.216	0.268	0.075	0.455
Prospect K	0.262	0.392	0.389	0.357	0.058	0.196	0.575
Prospect L-1	0.624	0.385	0.365	0.243	0.131	0.330	0.252
Prospect L-2	0.653	0.411	0.369	0.295	0.023	0.306	0.110
Prospect M	0.469	0.216	0.441	0.553	0.343	−0.017	0.099
Prospect N	0.599	0.298	0.437	0.267	0.216	0.123	0.083
Prospect O-1	0.760	0.322	0.332	0.373	0.073	0.040	0.076

APPENDIX II (*Cont.*)

Samples	Factor number						
	1	2	3	4	5	6	7
Prospect O-2	0.712	0.436	0.344	0.244	0.161	−0.085	0.110
Prospect P	0.773	0.081	0.470	0.214	0.035	0.010	0.244
Prospect Q-1	0.445	0.337	0.516	0.503	0.103	0.095	0.321
Prospect Q-2	0.437	0.368	0.513	0.510	0.227	0.028	0.194
Prospect R	0.679	0.495	0.388	0.283	0.000	−0.052	0.080
Prospect S	0.597	0.492	0.206	0.224	0.028	0.134	0.118
Prospect T	0.338	0.705	0.263	0.049	−0.005	0.055	0.496
Prospect U	0.798	0.346	0.333	0.225	0.047	−0.037	0.185
Prospect V	0.738	0.455	0.317	0.235	0.002	0.020	0.133