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THE CARLIN GOLD DEPOSIT AS A PRODUCT OF ROCK-WATER INTERACTIONS

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ABSTRACT

The Carlin gold deposit formed at shallow depths from hydrothermal fluids heated by late Tertiary volcanic energy. The fluids ascended from depth along steep faults into permeable thin-bedded carbonate rocks, where they dissolved carbonate minerals, principally calcite, and deposited quartz and pyrite and fine-grained gold. The fluids also introduced Al, K, and Ba, organic materials, plus Hg, As, Sb, and Tl, all closely associated with Au, and the base metals Zn, Pb, and Cu. Late fluids deposited barite and calcite, and minor quartz, in fractures, together with sparse sulfides of Hg, Sb, As, Tl, Pb, Zn, and Cu. Late fluids deposited barite and calcite, and minor quartz, in fractures, together with sparse sulfides of Hg, Sb, As, Tl, Pb, Zn, and Cu. During vein formation the fluids boiled, releasing H₂O vapor, CO₂, and H₂S to the oxygenated ground waters or to the aerated zone above the water table. Atmospherically derived oxygen oxidized H₂S to H₂SO₄. Rocks in the upper part of the ore deposit were strongly leached and oxidized during boiling.

Stable isotope data on fluid inclusions and on vein and rock-forming minerals indicate that the hydrothermal fluid was of meteoric origin, that the introduced sulfur is of sedimentary origin, and that Pb in galena in barite veins is similar to Pb in the host rocks of the Roberts Mountains formation. Temperatures based on $\delta^{34}\text{S}$ fractionation between barite and sulfide minerals ranged from 270-305°C, in contrast to lower temperatures obtained from fluid inclusions in vein barite, calcite, and quartz of 175°C. Sedimentary rocks adjacent to and below the Carlin deposit contain organic carbon compounds, diagenetic pyrite, quartz, illite, calcite and dolomite. They also contain anomalously high levels of Au, Hg, As, Sb, and Tl.

We suggest that the introduced components were leached from Paleozoic sedimentary rocks below the deposit at temperatures above 300°C by mildly saline solutions, migrating as part of a circulating water system set into movement by a buried thermal anomaly. The fluids rose rapidly up steep faults, dropped in temperature and pressure, and became supersaturated with regard to quartz, pyrite, and gold, and undersaturated with regard to calcite. The solutions migrated into host rocks where they formed tabular-shaped orebodies with attitudes similar to those of the sedimentary host rocks. The main-stage mineralization could have been accomplished in 50,000 years, assuming continuous flow. A minimum of about 10⁹ tons of aqueous fluid passed through the rocks during main-stage mineralization. The beginning of vein formation coincided with the onset of boiling. The vein-forming stage perhaps lasted about the same time as main-stage mineralization, but more than 10¹⁰ tons of fluid were involved. Boiling coincided more rapid fluid flow from hotter regions at depth. The vein formation

ceased when the excess pressures of the system were relieved, and cold ground waters were able to reoccupy the fractures. The Carlin deposit is the integrated result of igneous heat, injected into sedimentary rock-fluid systems, dispersed by convective movements of fluids, which dissolved components at high temperatures and deposited them at low temperatures.

INTRODUCTION

The Carlin deposit, largest of the disseminated gold replacement deposits discovered to date in the United States, is located in north-central Nevada (Fig. 1). The deposit has produced over 4 million troy ounces of gold.

Orebodies are tabular and irregular-shaped zones in laminated argillaceous to arenaceous dolomitic limestone from which calcite has been partly dissolved out and into which fine-grained quartz, pyrite, sericite, and kaolinite, and organic materials have been introduced. Gold and mercury are associated with carbonaceous material and pyrite, and arsenic, antimony, and thallium in unknown forms. Shallow parts of most of the orebodies have undergone oxidation and leaching. The oxidation-leaching process dissolved away calcite and converted most of the pyrite and other sulfide minerals to oxide minerals; carbonaceous material was removed, and the gold compounds broken down to micron- to sub-micron-size metallic gold particles.

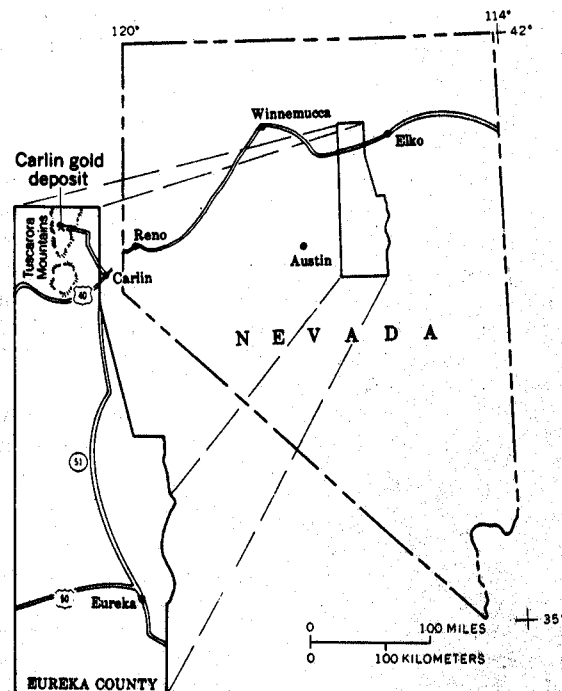


Figure 1. Index map showing the location of the Carlin gold deposit in north-central Nevada, U.S.A.

The Carlin deposit shares a set of characteristic features of the Carlin-type deposits, such as:

- (1) Young age; shallow-seated; occurrence of orebodies in carbonaceous carbonate rocks.
- (2) Orebodies that usually are conformable with or parallel to bedding, extending out from steep faults, some of which contain pre-ore dikes.
- (3) Distinctive geochemical association of Au with Hg, As, Sb, and Tl, which are dispersed in ore and in halos in country rocks.
- (4) Associated Tertiary igneous dikes and flows, and hydrothermal alteration.
- (5) Exceedingly fine-grained ore and gangue minerals.
- (6) Precipitation of hydrocarbon compounds that have been introduced in fluids that moved along the same structures as did the ore-bearing fluids, during and after mineralization.
- (7) Relatively simple rock alteration, mostly silicification and argillation (sericite and kaolinite).
- (8) Near-vertical veinlets of barite and calcite that transect ore and locally contain megascopic Hg, As, Sb, and Tl sulfide and sulfosalt minerals.
- (9) Oxidized and leached upper parts of orebodies that apparently formed during a late stage when H_2S , given off by boiling solutions, was oxidized by atmospherically derived oxygen.
- (10) The presence of pre-ore granitic dikes or stocks and probably masses of granitic rock at depth below the deposit.
- (11) Fluid inclusion data from late veins that indicate depositional temperatures of 175-200°C, comparatively dilute aqueous solutions with dissolved CO_2 , and boiling during the formation of the vein minerals.
- (12) Hydrothermal fluids dominantly of meteoric origin, indicated by highly negative δD values of inclusion fluids and alteration minerals.
- (13) A sedimentary source for sulfur in metallic sulfides and sulfate minerals.
- (14) Lead isotope compositions of galena resembling leads of the underlying Paleozoic terranes.

The geologic features of the Carlin deposit are shown on the composite mine map by Radtke (1973) and regional maps by Evans (1974) and Radtke (1974). Pertinent papers that deal with various aspects of the geology, mineralogy, and geochemistry of the deposit include those by Hardie (1966) Hausen and Kerr (1968), Wells and Mullens (1973), Radtke and Scheiner (1970), Radtke and Dickson (1974), and Radtke, Rye, and Dickson (unpub. manuscript). The Carlin deposit is discussed in detail in a comprehensive report by Radtke, U.S. Geological Survey Professional Paper (in press).

SEDIMENTARY ROCKS

Paleozoic sedimentary rocks exposed within 10 km of the Carlin deposit, below the Roberts Mountains Thrust, range from late Cambrian Hamburg Dolomite to early through late Devonian Popovich formation; those above the thrust belong to the Ordovician to early Silurian Vinini formation (siliceous western assemblage). Limitations of exposure and structural complexities prevent

reconstruction of the entire sedimentary rock sequence that immediately underlies the deposit. Stewart and Poole (1974), in a summary of the stratigraphy of lower Paleozoic and uppermost Precambrian rocks of the western United States, indicated that 8 km of Precambrian and Paleozoic sedimentary rocks originally underlay most of north central Nevada. The nature of the basement on which the sequence rests in Nevada is not well-known; elsewhere crystalline schists and gneisses, and plutonic intrusive rocks crop out or have been found in the subsurface. Thus, the autochthonous sedimentary rocks below the Carlin deposit may be as much as 8 km thick and they probably rest on an ancient crystalline terrane. These sedimentary rocks consist of dominantly clastic rocks, such as quartzites and siltstones in the upper Precambrian and lower Cambrian portions of the section. They pass upward into alternating limestones and dolomites of the middle and upper Cambrian, to dominantly dolomite and quartzite in the Ordovician, dolomite and laminated dolomitic limestone in the Silurian, and limestone in the Devonian.

This sedimentary sequence has been faulted, folded, and intruded by Mesozoic and Cenozoic igneous rocks. The carbonate rocks have been affected by the complex Roberts Mountains overthrusting that placed siliceous rocks of similar age above the carbonates. Deep parts of the sedimentary section probably have also undergone complex thrusting (J. Stewart, oral commun., 1978).

PROVENANCE OF ORE AND GANGUE COMPONENTS

Geological and geochemical data of Radtke, Rye, and Dickson (unpub. manuscript) are in accord with the derivation of much of the constituents from nonmagmatic sources. A contribution by magmatic fluids cannot be ruled out, but if it is present, the magmatic contribution has been modified beyond recognition by mixing with fluids from shallow sources.

The introduction of organic carbon compounds, during and after ore deposition, strongly supports a sedimentary rock source. The organic compounds, which consist of veinlets, seams, and dispersed particles of amorphous carbon, hydrocarbon, and a substance resembling humic acid (Radtke and Scheiner, 1970), occur in the primary unoxidized ores and are especially concentrated in some ores as to form a distinct type referred to as carbonaceous ores. Fresh host rock averages about 0.1% organic carbon and ranges up to about 0.25%. All ores contain some organic carbon at levels in excess of that in the fresh host rock. Carbonaceous ore averages about 2% organic carbon but it ranges up to 5% locally. The organic carbon compounds are concentrated in fault zones, permeable beds, in ore, and in nonmineralized rocks. These compounds occur in intimate associations with the ore suite of minerals in textural relationships that locally imply simultaneous deposition. The fluids that deposited ore at Carlin also transported organic matter derived from sedimentary rocks.

Lead isotopic composition of galena from barite veins that cut the gold ore at Carlin are within the range of leads from the Roberts Mountains formation, but they differ from leads from Cenozoic igneous rocks of Nevada

(B. R. Doe and M. H. Delevaux, U.S. Geol. Survey, written commun., 1968). Doe and Delevaux concluded that possibly all the lead was derived from sedimentary rocks of the Roberts Mountains formation type.

Stable isotopic compositions of selected materials from the Carlin deposit, including fresh, altered, and mineralized rocks, are summarized in Table I. The data are from Radtke, Rye, and Dickson (unpub. manuscript), in which are presented more than 140 isotopic determinations on minerals, altered whole rocks, and inclusion fluids. The isotopic data support a nonmagmatic source for the water, sulfur, and carbon introduced into the deposit.

The δD values of fluids in liquid inclusions and in altered rocks are so strongly negative, -139 to -160‰, that major amounts of meteoric water must have been present during the alteration process and formation of veins. The timing of alteration and vein formation spanned the formation of the ore, hence the main-stage mineralization fluids very probably also were of meteoric origin. The $\delta^{34}S$ values of different sulfides range from 4.2 to 15.2‰, but averages from individual minerals show smaller ranges (Table I). The average value for introduced pyrite is about 11.4‰, close to the average of 13.0‰ for diagenetic pyrite in the Roberts Mountains formation. The

average $\delta^{34}S$ of vein barite is about 30‰, somewhat larger than the value of sedimentary barites of the lower Paleozoic of 24‰ (R. O. Rye, unpub. data).

The vein mineral association at Carlin of barite plus metallic sulfides have $\delta^{34}S$ values appropriate to equilibrium at 250°-305°C, distinctly higher than the depositional temperatures of 175°C indicated from fluid inclusion data. A disequilibrium between SO_4^{2-} and S^{2-} is therefore implied. This perhaps relates to the slowness with which ^{34}S partitions between the species at temperatures less than 300°C (Sakai and Dickson, 1978). The sulfur in the fluids that deposited ore and vein minerals at Carlin may have been derived from sedimentary rocks (Dickson, Radtke, and Rye, 1975) by interaction with aqueous solutions at some temperature above 300°C.

The $\delta^{13}C$ values of hydrothermal and recrystallized wall-rock calcite are close to those of calcite in unaltered carbonate host rocks and indicate that carbon in the ore fluids was derived from the host rocks. The $\delta^{18}O$ of recrystallized calcite, however, shows definite shifts toward larger values as result of exchange with the hydrothermal fluids.

The isotopic evidence, therefore, indicates that meteoric water was involved in the hydrothermal fluids at Carlin and that these fluids contained sedimentary sulfur and host-rock carbon.

TABLE I. SUMMATION OF STABLE ISOTOPE DATA¹

Fresh argillaceous arenaceous dolomite		Hydrothermally altered-mineralized rocks	
$\delta^{34}S$	Material	$\delta^{34}S$	Material
11.4 to 14.3	diagenetic pyrite	4.2 to 16.1	hydrothermal pyrite
		3.1 to 6.5	galena in barite veins
		10.1 to 10.7	sphalerite in barite veins
		15.2	realgar
		27.8 to 31.7	hydrothermal barite
$\delta^{13}C$	Material	$\delta^{13}C$	Material
0.4 to 0.6	calcite in rocks	-1.9 to -1.7	calcite in altered rocks
		-1.3 to +0.9	calcite in mineralized rocks
		-6.2 to +0.4	calcite in veins
0.2 to 0.3	dolomite in rocks	-0.5 to -0.4	dolomite in altered rocks
		-0.1 to +1.13	dolomite in mineralized rocks
δD	Material	δD	Fluid inclusions in
	no data available on host rocks	-149 to -139	hydrothermal barite
		-153	hydrothermal quartz
		-143 to -142	calcite in veins
		-160 to -145	whole rock igneous dike
$\delta^{18}O$	Material	$\delta^{18}O$	Material
21.2 to 22.5	calcite in rocks	12.7 to 13.4	recrystallized calcite in altered rocks
		13.9 to 18.0	recrystallized calcite in mineralized rocks
		2.5 to 22.9	calcite in veins
22.5 to 23.0	dolomite in rocks	24.3 to 25.2	recrystallized dolomite in altered rocks
		19.4 to 24.5	slightly recrystallized dolomite in mineralized rocks

¹Data summarized from Radtke, Rye, and Dickson (unpub. manuscript).

SOURCE BEDS

The isotopic and chemical evidence supports a sedimentary source for much, perhaps all, of the ore and gangue components introduced to the Carlin deposit. The question arises as to which rocks were the most likely sources. As discussed by others, including Krauskopf (1971) and Turekian and Wedepohl (1961), average crustal rocks contain sufficient levels of the needed elements for them to serve as source rocks (Table II). Whether a particular rock type could serve as a source

Table II. Average abundance of selected elements in crustal rocks and argillaceous arenaceous dolomitic limestone facies of the Roberts Mountains formation.

Element ¹	Average values (ppm) ²				Roberts Mountains Fm. ³
	Low calcium granite	Basalt	Shale	Limestone	
Ba	840	330	580	10	240
Sr	100	465	300	610	400
S	300	300	2400	1200	1400
Zn	39	105	19	4	25
Cu	10	87	45	20	14
Pb	19	6	20	9	12
B	10	5	100	20	30
As	1.5	2	13	1	14
Tl	2.3	0.21	1.4	0.0X	0.8
Sb	0.2	0.2	1.5	0.2	3.5
Hg	0.08	0.09	0.4	0.04	0.24
Au	0.004	0.004	0.004	0.004	<0.02

¹Values in ppm

²Turekian and Wedepohl (1961)

³This study

depends on its physical properties, such as porosity and permeability, and the degree of fracturing in the system as much as on its composition.

Evaluation of specific sedimentary units that occur in the vicinity of the Carlin deposit as potential source rocks is made difficult by the scarcity of data on permeability and composition. Thin-bedded carbonate and clastic rocks, which would be easily penetrated by hot flowing waters, are attractive possibilities. Possible source rocks include the clastic beds of upper Precambrian and lower Cambrian, the alternating thin-bedded limestones and argillaceous beds of the Ordovician Pogonip group, and the lower part of the Roberts Mountains formation of middle Silurian age. Compositional data are available on the Roberts Mountains formation only (Table III). The following discussion focuses necessarily on the Roberts Mountains formation, but it should be emphasized that other units mentioned above also are likely possibilities.

The data on rock compositions are from several sources. Data on compositions of more than 260 samples of the Roberts Mountains formation, collected at 38 localities in Nevada by T. Mullens (in press), and analyzed for major and minor elements were available (unpub. Open-file rept., U.S. Geol. Survey, Denver, Colo.). Analyses were made on samples collected by J. Matti, U.S. Geological Survey, Menlo Park, Calif., from seven localities in north-central Nevada, and one suite of 55 samples collected by A. S. Radtke and staff geologists of Carlin Gold Mining Company and Newmont Mining Corporation. Table III summarizes the results for As, Sb, Bi, Tl, Hg, Au, Ba, B, Zn, Cu, Pb, Cd, and S. Figure 2 presents plots of averages and ranges for the elements, together with values for the average crustal shales and carbonate rocks for comparison.

Averages for all elements in Table III and Figure 2 fall above the average values for crustal limestones given by Turekian and Wedepohl (1961). Except for Sb, Au, and Cd, they fall below the values for average crustal shale. Most of the beds in the Roberts Mountains formation contain 20% to 50% noncarbonate matter, mostly clay and silt, with 1 to 2% heavy minerals and minor diagenetic pyrite and organic carbon compounds. Although the contents of minor elements are anomalously high relative to average crustal carbonate rocks, they fall between minor-element contents of average shale and average carbonate rocks in a manner in keeping with the hybrid nature of the Roberts Mountains formation. The rocks of the Roberts Mountains formation have high levels of minor elements and they could have served as sources.

EXPERIMENTAL STUDIES

The probable sedimentary heritage of ore and gangue components in the Carlin deposit led to the design of experiments to test whether the components could be leached from laminated silty carbonaceous dolomitic carbonate rocks such as those of the Roberts Mountains formation.

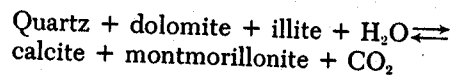
Previous experimental studies support the effectiveness by which ore and gangue constituents can be leached from rocks by aqueous solutions at elevated temperatures.

The pioneering studies by Ellis and his coworkers in New Zealand (Ellis and Mahon, 1964, 1967; Mahon, 1967; Ellis, 1968) demonstrated that ore metals could be solubilized rapidly and in significant quantities from igneous and sedimentary rocks by hot (200°-500°C) aqueous solutions. More recent studies by Bischoff and Dickson (1975) showed similar extraction of Fe, Mn, Cu, and Ni from powdered basalt by seawater at 200°C and 500 bars. Ewers (1977) detected losses of As, Sb, Se, and S in graywacke granules from New Zealand on exposure to aqueous solutions for as much as 449 hours from 100°-500°C. Dickson, Radtke, and Seeley (1977) showed that laminated silty dolomite in the Roberts Mountains formation can give up significant levels of heavy elements at 275°C and 500 bars. Other experimental studies in the Dickson hydrothermal laboratory at Stanford University on the reaction of a series of igneous rocks with H₂O and NaCl-H₂O solutions up to 500°C have confirmed and extended the previous data.

The rock selected for the Carlin source rock experiment study was an argillaceous, arenaceous, dolomitic limestone sample from the basal part of the formation, collected about 2 miles south of the Carlin deposit. The rock contained about 20% dolomite, 25% calcite, 25% illite, 28% quartz, and less than 1% each of diagenetic pyrite, detrital feldspar, and other heavy accessory minerals. The sample also contained about 0.1% organic carbon. The chemical composition of the rock is shown in Table IV.

In preparation for the experiments, the rock was hand ground to -100 mesh in an agate mortar. Fifty grams of powdered rock plus 150 grams of 1% NaCl solution were reacted in Dickson-type gold cell equipment (Dickson, Blount, and Tunell, 1964; Rytuba and Dickson, 1974) for 900 hours at 300°C and 1000 bars. The gold of the cell walls provided excess metallic gold. Internally filtered samples of the solution were withdrawn at regular intervals and analyzed for major and minor components by atomic absorption and emission spectrographic methods. The solution compositions for two replicated experiments after 200 hours of reaction are given in Table V.

The rock reacted rapidly with solution, as follows:



Nearly all of the dolomite and illite decomposed, and the final assemblage was mostly calcite + montmorillonite + quartz + solution. The CO₂ content of the solution during 900 hours rose to about 22,400 ppm, or 0.5 molar in CO₂. The pH of the CO₂-free solution at room conditions initially dropped to about 5.0 at 25 hours but steadied at about 5.3 at 300 hours. The pH calculated for the experimental conditions was slightly acid. About 8 ppm H₂S went into solution. Typically, each element rapidly entered solution to rise to maxima at about 50 hours. Beyond 50 hours, the concentrations slowly dropped. By 200 hours the solution compositions were changing slowly. Gold showed unusual behavior; it rose to 45 ppb at 40 hours and dropped below the detection limit of about 4 ppb by 200 hours.

Gold was present mostly as cell parts and only a tiny fraction was in the rock. Whether the gold that ap-

Table III. Summary of selected minor elements in fresh arenaceous carbonate rocks of the Roberts Mountains formation.

Element	1			2			3			Totals		
	Range	Average	(No. Samples)	Range	Average	(No. Samples)	Range	Average	(No. Samples)	Range	Average	(No. Samples)
As	N.A.	N.A.	--	<1 - 35	16	(40)	3 - 30	12	(31)	1 - 35	14	(71)
Sb	N.A.	N.A.	--	<1 - 10	2.5	(40)	3 - 15	5	(31)	<1 - 15	3.5	(71)
Bi	N.A.	N.A.	--	0.3 - 7	1.2	(55)	0.5 - 5	1.5	(31)	0.3 - 7	1.3	(86)
Tl	N.A.	N.A.	--	<0.7 - 3	0.8	(55)	<0.7 - 1	<1	(31)	<0.7 - 3	0.8±	(86)
Hg	0.01 - 3.0	0.29	(153)	0.01 - 0.45	0.10	(55)	<0.7 - 0.7	<0.7	(31)	0.01 - 3.0	0.24	(239)
Au	<0.02 - 1.0	<0.02	(156)	<0.02 - 0.08	<0.02	(30)	<0.5	<0.5	(31)	<0.02 - 1.0	<0.02	(217)
Ba	<10 - 1500	245	(228)	20 - 500	225	(55)	50 - 700	260	(15)	<10 - 1500	240	(248)
B	2 - 300	32	(231)	<7 - 150	20	(55)	<10 - 125	37	(15)	2 - 300	30	(301)
Zn ^{4/}	<200 - 1000	<200	(216)	3 - 300	28	(55)	3 - 150	22	(31)	3 - 300	25	(86)
Cu	<1 - 70	11	(234)	2 - 50	25	(55)	10 - 58	26	(15)	<1 - 70	14	(304)
Pb	<7 - 100	12	(232)	<7 - 30	10	(55)	N.A.	N.A.	--	<7 - 100	12	(287)
Cd	N.A.	N.A.	--	0.2 - 2.5	0.85	(55)	0.2 - 1.5	0.7	(31)	<0.2 - 2.5	0.8	(86)
S	0.02 - 1.27	0.14	(185)	0.05 - 0.30	0.18	(20)	N.A.	N.A.	--	0.02 - 1.27	0.14	(215)

^{1/}Data from unpublished open-file report by T. Mullens, U.S. Geological Survey, Denver, Colorado. Samples collected by T. Mullens from regional stratigraphic and petrologic studies. Samples showing evidences of alteration and mineralization omitted from data suite.

^{2/}Analyses of samples collected by A. S. Radtke and staff geologists of Carlin Gold Mining Co., A. S. Radtke and F. W. Dickson (unpub. data).

^{3/}Analyses of samples collected by J. Matti, U.S. Geological Survey, Menlo Park, California, from stratigraphic studies in central Nevada.

^{4/}Data from samples collected by Mullens omitted from totals because of poor sensitivity levels in analytical method used.

N.A. = not analyzed or data not available.

peared transiently in solution came from the cell parts, or from the rock cannot be determined. However, Dickson, Radtke, and Seeley (1977) detected gold in NaCl solutions reacted with powdered rocks of the Roberts Mountains formation in a nongold container (Teflon) at 275°C. The miniscule amount of gold in the rock still was sufficiently large to control the level of gold that went into solution. The reaction produced a NaCl-CO₂ solution with: SiO₂, K, Ca, and Ba, at hundreds and tens of ppm levels; As, Mg, B, and Fe at ppm levels; Sb, Sr, Tl, Pb, and Cu at tenths of ppm levels; and Hg at 0.07 ppm. With the exception of Au, all the important ore and gangue elements were dissolved at levels detectable by the analytical methods.

The experimental results support the suitability of rocks of the type found in the Roberts Mountains formation as source rocks for most of the components.

Calculated percentages of the amount of each element extracted from the rock is important in applying the experimental results to the genesis of the deposit. Elements, the levels of which in solution are set by mineral solubilities, such as SiO₂, Ca, Mg, and Fe, show low levels of extraction (less than 1%). Those elements with solution concentrations controlled by exchange reactions (K, Ba, high mineral solubilities (As, B), or by desorption from surfaces and complex-ion formation with sulfur species

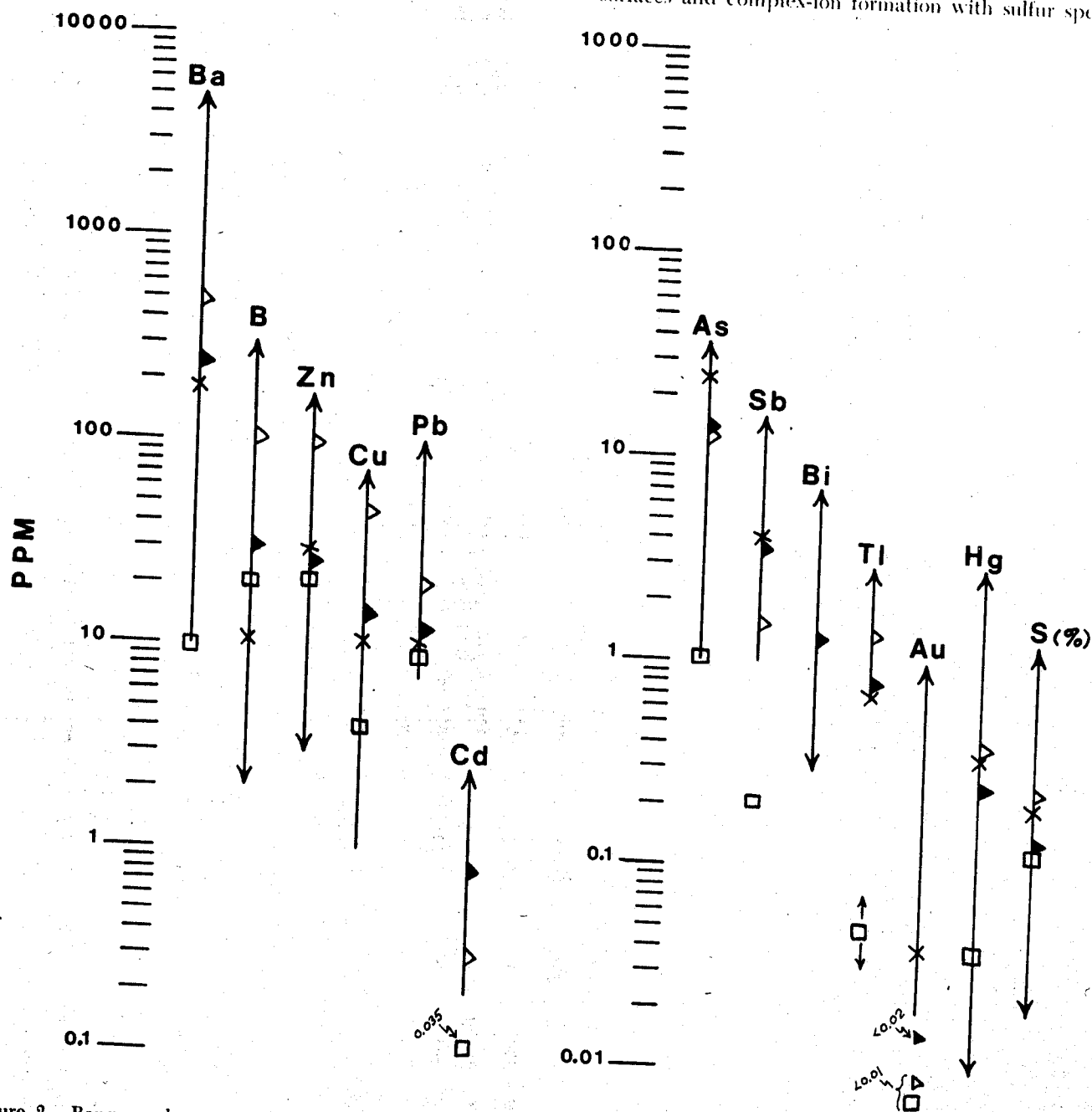


Figure 2. Ranges and averages of selected minor-element contents in samples of fresh Roberts Mountains formation, shown by bars (ranges) and solid triangles (averages). Open triangles and open squares are average values for crustal shales and carbonates (Turekian and Wedepohl, 1961). Arrows represent total ranges; barb omitted where some samples contained the element at less than detection limit. Symbol "X" is average values of the samples of Roberts Mountains formation used in rock-solution experiments. All values are in ppm, except for sulfur, which is in weight %.

Table IV. Chemical composition of sample of Roberts Mountains formation used for rock-water experiments.

Major elements (wt.%)		Minor and trace elements (ppm)	
SiO ₂	41.9	Ag	<0.7
Al ₂ O ₃	4.0	Au	0.04
Fe ₂ O ₃	0.50	As	25
FeO	0.48	B	10
CaO	25.7	Bi	<1
HgO	4.2	Co	<2
BaO	0.02	Cr	50
SrO	0.018	Cu	10
MnO	0.015	Ga	2
Na ₂ O	0.11	Hg	0.38
K ₂ O	0.96	La	10
TiO ₂	0.27	Mo	2
P ₂ O ₅	0.03	Nb	15
H ₂ O ⁺	1.6	Ni	20
H ₂ O ⁻	<0.1	Pb	10
CO ₂	20.2		
S	0.20		
C organic	0.13		
Total	100.3		

(Sb, Hg, Tl(?)) show large levels of extractions, ranging from 20 to 100%. The base-metal sulfides of Pb and Cu, which have low solubilities in reduced, sulfurous solutions that also contain low chloride, were poorly extracted.

The low level of dissolved Au perhaps results from the low experimental temperature of 300°C. Possibly, leaching of gold in nature takes place at 350°C or higher. However, it is more probable that the experimental solution lacked sufficient reduced sulfur to form soluble complex compounds of gold (Rytuba, 1977; Seward, 1973). The initial rise of gold concentration in solution during the experiment probably was a result of the early sharp increase in acidity observed. For the experimental solution to be more realistic, higher concentrations of sulfide sulfur than 7 ppm H₂S would have been necessary. How-

Table V. Solution composition and percent of element extracted from sample of Roberts Mountains formation after 200 hours of reaction with 1 percent NaCl solution at 300°C, 1000 bars and 3:1 solution-rock ratio.

Component	Concentration in ppm	Percent extracted	Component	Concentration in ppm	Percent extracted
Na	4000	--	Sb	0.37	28
SiO ₂	960	0.7	Sr	0.15	0.31
K	520	20	Tl	0.14	60
Ca	150	0.24	Pb	0.14	4.2
Ba	45	75	Cu	0.11	3
As	8.5	100	Hg	0.070	59
Mg	7.6	0.091	Au ^{1/}	<0.004	<10
B	3.6	100			
Fe	2.8	0.12			

¹ Au was at 45 ppb after 75 hours.

ever, very low levels of gold, less than 1 ppb Au, are in hydrothermal waters of New Zealand that are presently depositing ore-grade siliceous sinters (10- > 50 ppm Au) at hot spring outlets (Weissberg, 1969).

The percent extraction values plus knowledge of the size and composition of ores at the Carlin deposit permit calculating the minimum masses of source rock that would be needed to yield each of the elements (Table VI). The calculated masses, in 10⁹ ton units, range from 0.013 for B, to 0.4-0.6 for Pb, As, Tl, and Cu, to 1.29 and 1.77 for Sb and Hg, respectively. The range for volume of the rocks implied, 0.004-0.6 km³ is reasonable. A sedimentary unit, 100 m × 2400 m × 2400 m, with 0.6 km³ volume, would represent only a small fraction of the sedimentary rocks underlying the Carlin deposit. The actual mass of rock required in nature would be much larger because of the probable inefficiency of extraction. However, even a ten-fold larger volume, 6 km³, is reasonable.

The experimental results, therefore, provide some basis for evaluating possible processes that supplied the components to the hydrothermal fluids that produced the Carlin deposit. They are permissive rather than conclusive. They do not prove that closely similar reactions operated in nature. Further experimental studies, using various rock and solution types especially solutions containing reduced sulfur and larger ranges of temperature, pressure, and solution-rock ratios, would enlarge our capabilities to understand the genesis of Carlin-type gold deposits.

Table VI. Volume of carbonate source rock of Roberts Mountains formation required to provide elements introduced at the Carlin deposit.

Element	Average in source rock (mg/kg)	Percent extracted	Average in Carlin deposit (mg/kg)	Amount gained or lost (mg/kg)	Source rock required (10 ⁹ tons)
Ba	240	75	300	+300	0.017
Sr	400	0.3	150	-250	--
S	1400	>1.5	9000	+7600	<0.36
Zn	25	N.A.	150	+125	N.A.
Cu	14	3	40	+26	0.62
Pb	12	4	30	+18	0.38
B	30	100	70	+40	0.013
As	14	100	600	+586	0.42
Tl	0.8	60	30	+29.2	0.61
Sb	3.5	28	130	+126.5	1.29
Hg	0.24	59	25	+24.8	1.77
Au	<0.02	<15	7	+7	23.0

N.A. = Not analyzed or determined

CONCLUSIONS

The geochemical properties of the Carlin deposit are in accord with a sedimentary rock origin for the introduced elements. The compositions of the Roberts Mountains formation and presumably other sedimentary rocks of the Carlin region make them possible source rocks. The experimental studies showed that large fractions of most of the elements needed for the Carlin deposit were given up during reaction with NaCl solution at 300°C and 1000 bars for 200 hours. The Carlin deposit very probably was

formed by a circulating meteoric water system set into motion by heat given off by intrusive igneous material in upper levels of the crust. Where hot fluids at depth passed through permeable source rocks of appropriate composition, ore and gangue components were extracted. The fluids migrated upward into receptive host rocks nearer the surface and deposited the assemblage of quartz, pyrite, gold, and the attendant suite of heavy elements, Hg, As, Sb, and Tl.

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