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Geology and Stable Isotope Studies of the Carlin Gold Deposit, Nevada

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Abstract

The Carlin gold deposit, largest of the epithermal disseminated replacement-type gold deposits discovered to date in the United States, formed as a result of hydrothermal processes associated with a shallow-seated late Tertiary igneous event. The orebodies formed by the replacement of carbonate minerals, principally calcite, in thin-bedded argillaceous arenaceous dolomitic beds favorable for mineralization within the upper 245+ m of the Roberts Mountains Formation. Early hydrothermal fluids dissolved calcite and deposited quartz. Fluids during the main hydrothermal stage introduced Si, Al, K, Ba, Fe, S, and organic materials, plus Au, As, Sb, Hg, and Tl; quartz and pyrite were deposited, potassium clays formed, and more calcite was dissolved. Sulfides and sulfosalts containing As, Sb, Hg, and Tl, and base metal sulfides of Pb, Zn, and Cu probably formed later in the paragenesis.

The main stage of ore deposition was terminated with the deposition of barite veins and the onset of boiling. The fluids lost H_2O, CO_2, H_2S, and other components, leading to the production of H_2SO_4 in the upper levels of the deposit and to subsequent intense acid leaching and oxidation of rocks and ore near the surface. Within this zone, calcite and large amounts of dolomite were removed, sulfides and organic compounds oxidized, kaolinite and anhydrite formed, and silica was added. After the hydrothermal event, the upper part of the deposit underwent weak oxidation by cooler ground water.

Fluid inclusion evidence indicates that main-stage mineralization temperatures were 175° to 200°C. During later stage acid leaching and vein formation, when boiling was widespread in the hydrothermal fluids, temperatures may have reached as high as 275° to 300°C. The salinity of the fluids increased markedly from about 3 ± 1 equivalent weight percent NaCl during the main stage to as much as 17.4 percent during the later boiling. The salinity as well as the temperatures of fluids during late-stage supergene oxidation were quite low.

Hydrogen and oxygen isotope data indicate that the hydrothermal fluids were highly exchanged meteoric waters of δD -140 to -160 per mil and that $\delta^{18}O$ values increased with boiling from about 3 ± 3 to over 10 per mil. Along some fracture zones the hydrothermal fluids mixed with unexchanged surface water. The $\delta^{18}O$ values of different forms of silica (sedimentary chert, jasperoid, and quartz veinlets) are distinctive, as are different generations of calcite, and may be used as an aid to sort out obscure paragenetic features. Calcite in the favorable facies has undergone extensive recrystalliza-

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tion and isotope exchange near feeder faults. Dolomite in the favorable facies and both calcite and dolomite in unfavorable facies show little recrystallization and exchange.

The $\delta^{34}S$ values of 4.2 to 16.1 per mil for hydrothermal pyrite compare well with values for diagenetic pyrite from the Roberts Mountains Formation and suggest that most of the hydrothermal sulfide sulfur was of sedimentary origin and was derived from the lower Paleozoic section. The $\delta^{34}S$ values for vein barite range from 27.9 to 31.7 per mil. The sulfate sulfur may have been derived from the same source as the sulfide sulfur by equilibrium distribution of sulfur species in the hydrothermal fluid or from disseminated sedimentary barite. The sulfide-sulfate sulfur isotope temperatures are in excellent agreement with fluid inclusion filling temperatures in the late barite veins.

Introduction

THIS paper presents the results of studies on the geology, fluid inclusions, and stable isotope geochemistry of the Carlin deposit, the largest disseminated replacement gold deposit in carbonate rocks discovered to date in the western United States. The deposit is in secs. 13 and 14, T. 35 N., R. 50 E., in the Tuscarora Mountains in northern Eureka County, Nevada (Fig. 1). Since 1965, the Carlin mine has produced over 4 million troy ounces of gold.

The Carlin deposit is the principal example of a group of deposits that have many geologic, mineralogic, and geochemical features in common (Radtke and Dickson, 1974). These deposits are characteristically fine-grained replacements of silty carbonate rocks by silica and minor pyrite, and they contain gold and an associated group of heavy elements, including mercury, arsenic, antimony, and thallium, dispersed in ore and at lower concentrations in altered rocks. The deposits are of middle or late Tertiary age and everywhere are shallow seated. Every deposit is spatially related to strong normal faults, some of which are occupied by preore dikes; some of the normal faults served as conduits for hydrothermal fluids. Apparently the deposits formed by a hydrothermal system that circulated in response to thermal anomalies associated with Tertiary igneous and tectonic activity, possibly without any deeper seated contribution from the igneous rocks. The striking similarities among Carlin-type deposits in the western United States strongly suggest that some general set of processes has operated repeatedly in various places.

Purpose and Methods of Study

The Carlin-type deposits pose a set of questions, including: (1) what was the geologic sequence of events before, during, and after mineralization; (2) what were the physical-chemical environments of ore deposition; (3) what were the ultimate sources of the ore and gangue components.

To provide data to answer these questions, studies were begun in 1967 on the geology and geochemistry of the Carlin gold deposit and the surrounding Lynn mining district. The results summarized in this paper were obtained from a variety of integrated studies. The mine was mapped during open-pit mining from 1968 to 1976 by Radtke and staff geologists of Carlin Gold Mining Company; information on the geology of the mine has been shown by Radtke (1973), regional geology by Radtke (1974; in press) and Evans (1974), and mineralogy of ores, gangue, and vein minerals described in detail by Radtke (in press); samples from surface and pit exposures and drill holes were studied by microscope, X-ray, microprobe, and scanning electron microscope. About 300 samples were analyzed for major elements and more than 600 samples for minor elements. Results of statistical studies of minor element distributions in unoxidized ore were given by Harris and Radtke (1976). The samples used for isotopic analyses for H, O, C, and S were collected at localities with known geographic and geologic positions; a total of 138 isotopic determinations were made on mineral separates and a few whole rocks. Syntheses of the relevant data are in the following sections, together with discussions of the implications on the genesis of the Carlin deposit. Although our conclusions

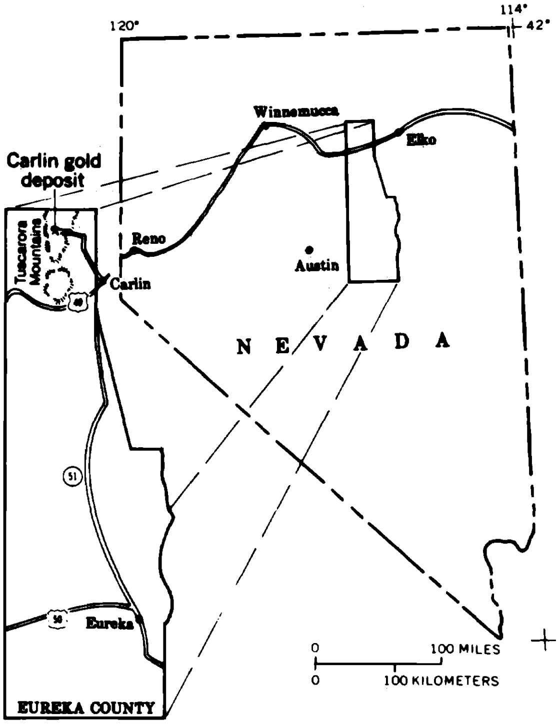

FIG. 1. Index map showing the location of the Carlin gold deposit.

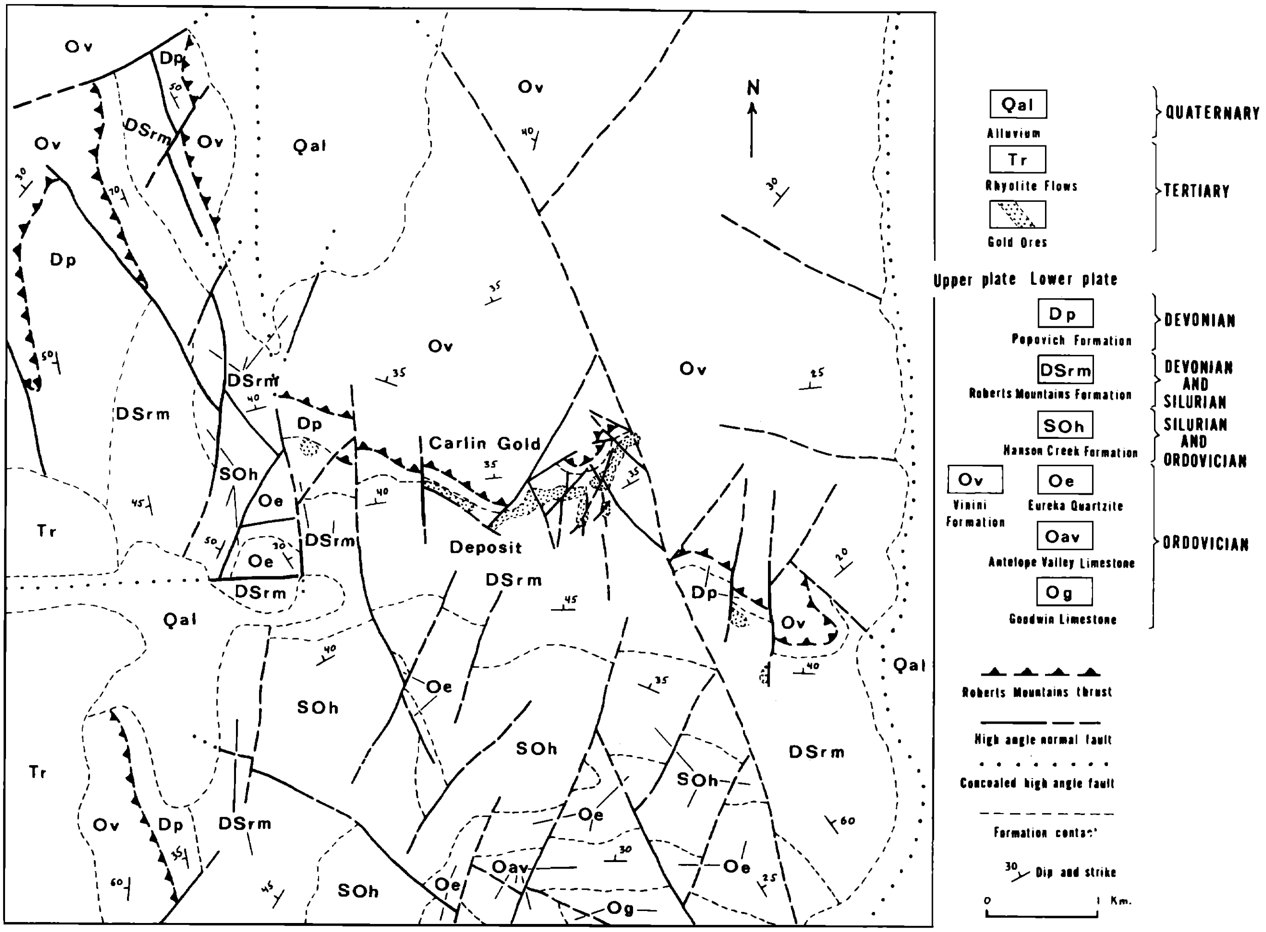

FIG. 2. Geologic map of the northern part of the Lynn window, Lynn mining district (simplified from Radtke, 1974).

apply directly only to the Carlin deposit, it is possible that they hold for other Carlin-type deposits as well. We will, however, reserve discussion of the relation of our conclusions on Carlin to other deposits for a later paper.

Previous Studies

The exploration that led to the discovery of the Carlin deposit was first prompted by Roberts (1960), who proposed that the positions of some mining districts in north-central Nevada were controlled by the Roberts Mountains thrust and that certain areas in lower plate carbonate rocks below the thrust might be favorable for mineralization. Although the positions of most ore deposits including Carlin are not controlled by the thrust fault, exploration was stimulated by the suggestion. Surface mapping, geochemical sampling, and rotary drilling by the Newmont Mining Corporation led to the discovery of the Carlin deposit.

The first complete geologic map and description of the Lynn window was done by Roen (1961). The first general description of the Carlin deposit was given by Hardie (1966). Hausen (1967) and Hausen and Kerr (1968) first described the mineralogy and petrology of shallow oxidized ore. Roberts et al. (1971) attempted to classify hydrothermal gold deposits of north-central Nevada on the bases of age, type of host rock, physical-chemical conditions of ore formation, and mineralogy. Radtke and Dickson (1974) described the collective geologic, mineralogic, and geochemical properties of Carlin-type disseminated gold deposits. Radtke (in press) has prepared an extensive report on the geology of the Carlin deposit.

Data on the mineralogy and chemical composition of primary unoxidized Carlin ores were given by Radtke and Scheiner (1970), Radtke et al. (1972a and b), and Wells and Mullens (1973). Nash (1972) reported from reconnaissance fluid-inclusion studies that disseminated deposits, including Carlin, formed by the action of low (175° ± 25°C) temperature solutions apparently of low salinity. Harris and Radtke (1976) carried out statistical studies on trace element correlations and distributions to evaluate a geochemical model on ore genesis.

Except for data on sulfur isotopes in barite and sulfide minerals given by Dickson et al. (1975a), no previous studies on stable isotopes at Carlin have been done. Rye et al. (1974) presented data on stable isotope and lead isotope studies at the Cortez gold deposit, which has many similarities to Carlin. They concluded that meteoric water was the dominant component of the ore-forming fluid, that most elements were probably derived from the host rocks, that the deposit is Tertiary in age, and that oxidation of the ore took place by normal low-temperature ground water.

Regional Geologic Setting

The regional geology of the northern part of the Lynn mining district and the Lynn window, which includes the Carlin deposit, was given by Radtke (1974) and is shown on the simplified geologic map in Figure 2. Sedimentary rocks exposed in this part of the window are mainly limestone, dolomite, and quartzite of Ordovician to Devonian age, which were deposited under miogeosynclinal conditions and which form part of the eastern or carbonate assemblage (Roberts et al., 1958). These rocks are overlain by the western or siliceous assemblage, a thick sequence composed mainly of interbedded chert and shale, and lesser amounts of sandstone, quartzite, and limestone of Ordovician and Silurian age which were originally deposited in a eugeosynclinal environment in western Nevada. This assemblage was thrust eastward, overriding the eastern assemblage during the Antler orogeny of Late Devonian or Early Mississippian time to form the upper plate of the Roberts Mountains thrust (Merriam and Anderson, 1942; Gilluly, 1954; Roberts, 1966).

Uplift and igneous activity in the form of intrusive stocks and dikes took place during the Late Jurassic or Early Cretaceous time. Additional orogenic movements occurred during Tertiary and Quaternary time. These included basin-and-range faulting, extensive normal faulting within the range, and volcanism.

Sedimentary rocks

The Paleozoic stratigraphy of the lower plate rocks in the vicinity of the Carlin deposit has been described in detail by previous writers, including Roen (1961), Roberts et al. (1967), and Hardie (1966). In the northern part of the Lynn window the oldest exposed rocks are 550+ m of Ordovician limestones of the Pogonip Group. The lower 245+ m of thin-bedded limestone and the overlying 305 m of thick-bedded limestone probably represent the Goodwin Limestone and the Antelope Valley Limestone, respectively (C. Merriam, writ. commun., 1971). The limestone is overlain by 60 to 75 m of sandy dolomite. The dolomite is overlain by 152 to 185 m of the massively bedded, vitreous Eureka Quartzite, followed in turn by 185 to 215 m of dark gray thick-bedded dolomite of the Ordovician Hanson Creek Formation. Above the Hanson Creek Formation is 550 to 600 m of dark gray thin-bedded laminated silty calcareous dolomite and limestone of the Silurian and Devonian Roberts Mountains Formation. The Devonian Popovich Formation, which consists of dark gray thick-bedded limestone interbedded with thin-bedded silty dolomitic limestone, overlies the Roberts Mountains Formation. The Popovich Formation is overlain by the Vinini Formation of Ordovician age with thrust contact. The upper part of the Popovich Formation was truncated by the Roberts Mountains thrust. The thickness of the Popovich Formation that is still preserved ranges from 245 to 275 m in the northwest corner of the Lynn window to only 60 to 90 m in the Carlin mine.

The Vinini Formation of the upper plate of the Roberts Mountains thrust can be divided into two units. The lower unit is 60 to 180 m thick and contains interbedded black chert and siliceous shale with minor amounts of limestone, sandstone, and quartzite. The upper unit is more than 1,520 m thick and contains interbedded shale, chert, and quartzite, plus minor amounts of calcareous sandstone and carbonaceous shale. Chemical and mineralogical data on various rock types in the Vinini Formation were given by Radtke and Scheiner (1970).

Two aspects of the geologic section in the area that could have an important bearing on the genesis and geochemistry of the deposit should be noted: (1) all the Paleozoic units in the area except the Eureka Quartzite contain diagenetic pyrite and organic material; and (2) the Eureka Quartzite is highly shattered, forms topographic highs, and dips northward toward and passes beneath the deposit—this unit could have served as an aquifer for the recharge of ground water and perhaps supplied waters to the hydrothermal system.

Igneous rocks

Intrusive igneous rocks in the northern part of the Lynn district occur as two small stocks and numerous dikes of Late Jurassic to Early Cretaceous age. Radiometric K-Ar age determinations on biotite gave an age of 121 m.y. (Hausen and Kerr, 1968) for the Gold Strike stock located about 1.6 km northeast of the Blue Star deposit or about 4 km north-northwest of the Carlin deposit (Radtke, 1974). A granodiorite dike in the southwest corner of the Carlin main pit was dated at 128 m.y. (M. L. Silberman, written commun., 1972).

The Gold Strike and the North Big Six stocks, located about 4 km north of the Carlin deposit (Radtke, 1974), range from granodiorite to quartz diorite and diorite. Both bodies have been altered hydrothermally and mineralized with minor amounts

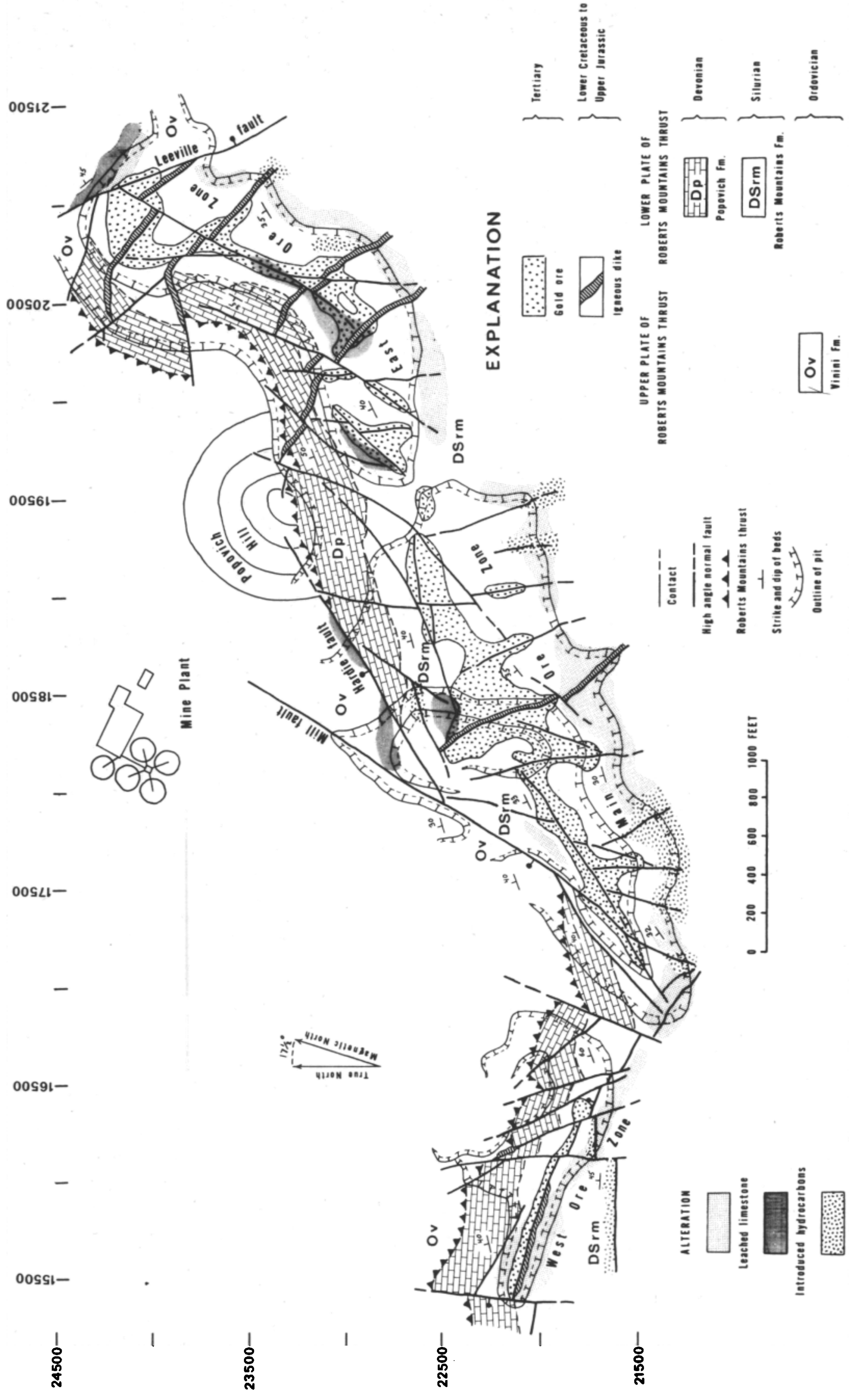

FIG. 3. Geologic map of the Carlin gold deposit (simplified from Radtke, 1973).

of gold in shear zones and fractures. Many dikes in the Lynn district have a similar lithology. They were emplaced in a set of high-angle faults that trend N 45° W to N 45° E.

The dikes at Carlin are Jurassic and (or) Cretaceous in age and were emplaced along northwest-trending high-angle faults. They subsequently were broken by north- to northeast-trending faults (Fig. 3; Radtke, 1973). Most of the dikes have been intensely altered, and locally they have been mineralized by gold-bearing solutions.

Extrusive igneous rocks, consisting of flows of rhyolite and rhyodacite, are well exposed along the west flank of the Tuscarora Mountains (Fig. 2; Radtke, 1974). Excellent petrographic descriptions of these rocks were given by Roen (1961), and K-Ar age determinations on biotites give values of 14 m.y. or Miocene age. This age falls within the youngest pulse of volcanic activity of 13 to 17 m.y. in central Nevada (McKee et al., 1971; Silberman and McKee, 1974), which may have been the heat source for the ore-forming systems.

Regional structures

The Roberts Mountains thrust is the oldest prominent structure in the area. The thrust and numerous high-angle faults which displace it form the northern margin of the Lynn window (Fig. 2). At the Carlin mine the thrust is well exposed in the west pit and along the south and east sides of Popovich Hill.

The Tuscarora anticline, which strikes roughly N 20° to 30° W and plunges 25° to 30° N, formed as the result of uplift, block faulting, and westward tilting of the range. Initial uplift may have taken place during Late Devonian or Early Mississippian time contemporaneous with the Antler Orogeny, and additional uplift associated with intrusive activity occurred during Late Jurassic and Early Cretaceous time.

The Lynn window formed by a combination of processes, including uplift in the core of the Tuscarora anticline, additional uplift with Tertiary block-faulting, and subsequent erosion. Basin-and-range faults occur along the flanks of the Tuscarora Mountains; several faults of this type with northwest and northeast strikes also cut through the range within the Lynn district (Radtke, 1974). No high-angle faults that clearly predate the Roberts Mountains thrust have been recognized.

Structural controls of the Carlin deposit

The Carlin gold deposit is located near the crest of the Tuscarora anticline within an area where high-angle normal faults have broken the range into numerous blocks and produced intense shattering of the lower plate carbonate rocks near the trace of the Roberts Mountains thrust. High-angle normal faults in and near the deposit served as channels for the hydrothermal solutions. The shattered thin-bedded carbonate units in the upper 245 m of the Roberts Mountains Formation were chemically favored and positioned suitably for ore deposition.

Three major high-angle or basin-and-range type faults, referred to as the Mill, Hardie, and Leeville faults, each with several hundred meters of vertical displacement, strongly influenced the development of the structural setting and placed a block of thin-bedded carbonate rock in a structural position favorable for mineralization (Figs. 2 and 3). With the exception of the Hardie fault, none of these large structures apparently served as a channel for the ore solutions, although most of the movement on the structures predated the mineralization.

Most of the known gold orebodies in the Carlin deposit are located within a stratigraphic section 245 m thick at the top of the Roberts Mountains Formation. They occur in several stratigraphic zones that define a northeast trend over a distance of about 2.8 km and are localized by high-angle normal faults. Small amounts of gold ore also occur in thin-bedded carbonate rocks in the basal part of the Popovich Formation and in calcareous shale beds in the Vinini Formation at the northeast end of the east orebody, east of the Leeville fault (Radtke, 1973).

Geochemistry and Mineralogy

Age of mineralization

The Carlin deposit appears to have formed during the late Tertiary as part of a volcanic episode. Although the exact time interval over which the deposit formed cannot be pinpointed, several lines of evidence support a young age.

Radiometric age dating of the rocks has provided gross limits on a maximum age. For example, sericite from the contact between dolomite and altered dike in the main pit yielded a composite K-Ar age of 57 m.y., according to R. L. Akright (writ. commun., 1971). This value is too large since the sample contained large amounts of impurities including apparently original illite from the carbonate rock.

Fluid-inclusion evidence presented later combined with information on boiling point curves (Haas, 1971) suggests that the amount of overburden removed since mineralization has only been about 1,000 to 1,700 feet. Furthermore, away from faults the surface of the lower boundaries of the acid leached zones correspond rather closely to present topography. Evidence will be presented later that most of the acid-leaching and oxidation in the orebodies and surrounding rocks occurred during boiling in the late-stage hydrothermal fluids. The northeast part of the east ore zone crosses the Leeville fault, a typical young basin-and-range fault with apparent middle

Tertiary or younger displacement, showing that the mineralization postdates the movement of this structure. The highly negative δD values of fluids in inclusions in minerals (as discussed in a later section) imply that late Tertiary rather than early Tertiary meteoric water was involved, because as a first aproximation such negative values reflect the colder climate known to have prevailed during the late Tertiary in the western United States.

Orebodies

Most of the orebodies discovered to date at the Carlin deposit occur in three areas, referred to as the west, main, and east ore zones. Although many of the general structural and stratigraphic features are similar in the various zones of gold mineralization, orebodies within each zone show differences in ore controls (Fig. 3; Radtke, 1973) and in chemistry and mineralogy (Harris and Radtke, 1976).

West ore zone: The west ore zone contains a veinlike orebody, continuous for 340 m, which strikes about N 60° W and dips 60° to 70° N; at the southeast end the zone widens into an oval pipelike body that plunges about 70° N. The veinlike part of the orebody is in the hanging-wall side of a high-angle fault, the footwall of which is a highly altered igneous dike cut by barite veinlets. The orebody in the west ore zone is strongly controlled by high-angle normal faults. It contains the largest amounts of barium, the smallest amounts of organic carbon of any of the orebodies, and an apparent lack of visible arsenic, antimony, or mercury sulfides (Harris and Radtke, 1976).

Main ore zone: The main ore zone is made up of several large connected orebodies of widely variable gold content in a zone about 915 m long between the southwest end of the main pit and the southeast side of Popovich Hill (Fig. 3; Radtke, 1973). Most of the ore in the northeast part of the zone is a sheetlike mass up to 30 m thick which strikes about east-west and dips 38° to 40° N, similar in attitude to the host rocks. The position and shape of this orebody reflect strong stratigraphic and structural controls. Particularly important is a set of high-angle faults trending N 45° E to N 45° W, which includes a large dike-filled fault trending northwest through the central part of the main pit.

The southwest part of the main ore zone contains a tabular orebody about 395 m in length and 20 to 30 m thick, which strikes about N 45° E and dips 50° to 70° NW; near the southwest end of the main pit, the orebody steepens in dip, becomes progressively thinner, and pinches out against impermeable gouge-filled faults and breccia zones (Fig. 3; Radtke, 1973). Intersections between numerous north-trending high-angle normal faults and a strong high-angle fault trending N 45° E controlled the deposition of ore in this area.

The main ore zone, which contains about 60 percent of the known gold ore in the deposit, has large tonnages of unoxidized and oxidized ore. The unoxidized ores are characterized by wide variations in the content of silica, pyrite, and organic carbon, and locally, as in the east ore zone, the content of organic carbon reaches 5 percent, due to introduction of hydrocarbons by the hydrothermal fluids (Radtke and Dickson, 1974). Arsenic sulfides and sulfosalts are common in fractures in mineralized carbonate rocks; these minerals and base metal sulfides also occur in deep parts of barite veins in the main ore zone.

East ore zone: The east ore zone begins south of Popovich Hill, continues about 730 m to the northeast, and pinches out in the Vinini Formation east of the Leeville fault (Fig. 3; Radtke, 1973). Most of the ore occurs in an irregular elongate tabular body trending N 20° E and dipping 35° to 45° W, conformable in attitude to the host rocks; near the northeast end, the strike of the orebody swings to east-west, reflecting drag of bedding caused by movement on the Leeville fault before ore deposition. A second orebody occurs at the southwest end of the ore zone, where a thick, continuous pipe-shaped mass of ore 60 m wide at the southwest end narrows to 15 m and plunges 30° NE (Fig. 3; Radtke, 1973).

Shapes and attitudes of both orebodies in the east ore zone reflect an overall stratigraphic control on gold deposition and the influence of feeder faults. Structural controls were provided by two sets of high-angle normal faults. These were (1) an early set striking N 40° to 45° W and (2) a late set striking north-south to N 45° E. Igneous dikes, intruded along at least five of the early northwest-trending faults, were offset by movement on the late set (Fig. 3; Radtke, 1973).

Unoxidized ores in the east ore zone show the largest variations in mineralogy and chemical composition of any ores at Carlin and contain a variety of rare minerals, including frankdicksonite, BaF_2 (Radtke and Brown, 1974); carlinite, Tl_2S (Radtke and Dickson, 1975); christite, $TlHgAsS_3$ (Radtke et al., 1977); weissbergite, $TlSbS_2$ (Dickson and Radtke, 1978), and ellisite, Tl_3AsS_3 (Dickson et al., 1979a); and other thallium-arsenic-antimony-mercury-bearing sulfides and sulfosalt minerals. Other characteristic features include zones heavily enriched in hydrocarbons and, compared to the other ore zones, only small amounts of barite.

Unaltered host rocks

The section of the Roberts Mountains Formation in the Lynn window is described by Mullens (1977) as a "laminated limestone consisting of varying

TABLE 1. Chemical Analyses of Samples of Unaltered Roberts Mountains Formation, Lynn Window, Eureka County, Nevada

Element	Argillaceous arenaceous dolomite, type 1[1]	Arenaceous peloid wackestone, type 2[2]
SiO_2	29.6	12.0
Al_2O_3	3.1	0.72
Fe_2O_3	0.63	0.48
FeO	0.28	0.12
MgO	10.9	0.61
CaO	23.0	47.8
BaO	0.02	0.01
MnO	0.00	0.00
Na_2O	0.00	0.00
K_2O	1.2	0.13
TiO_2	0.11	0.09
P_2O_5	0.32	0.06
$H_2O^{(-)}$	0.19	0.09
$H_2O^{(+)}$	1.0	0.61
CO_2	29.0	38.4
S	0.24	0.05
C (organic)	0.33	0.20
Totals	99.9	101.4

[1] Composite of six samples from three beds located 150 to 200 ft below the top of the formation.

[2] Composite of three samples from three beds located 150 to 175 ft below the top of the formation.

amounts of angular quartz and feldspar silt and very fine sand, silt-sized irregular grains to euhedral rhombs of dolomite, and clay set in an extremely fine-grained calcite matrix. Fresh rock contains pyrite, and specks, films, and coatings of carbonaceous material as well as inclusions of carbonaceous material in the calcite matrix."

The upper 245 m of the formation is composed of two types of interbedded carbonate rocks, similar in physical appearance yet significantly different in composition, texture, fabric, and susceptibility to alteration and mineralization.

The first type, type 1, a favorable host for disseminated gold, is a strongly laminated argillaceous, arenaceous dolomite or limy mudstone. The rock contains 25 to 45 percent dolomite rhombs ranging from 25 to 50 μm, apparently of early diagenetic origin; 20 to 30 percent angular quartz grains, 50 to 100 μm in size; 15 to 20 percent argillaceous material (mainly illite); and 5 to 20 percent fine-grained calcite. Other constituents include 1 to 3 percent chert, possibly of authigenic origin; 0.5 to 1 percent pyrite; 0.3 to 0.8 weight percent organic carbon; and numerous minor accessory minerals including feldspar, zircon, hornblende, monazite, tourmaline, rutile, magnetite, hematite, chalcopyrite, galena, and sphalerite. The origin of these sulfides is not known, but they are not related to hydrothermal activity and may be diagenetic. Illite and the carbonaceous material are commonly admixed and concentrated in fine current-induced laminations, 0.5 to 2 mm thick. This facies has no discrete peloids and, except for common spiculites, contains only small amounts of fossil fragments.

The second type, type 2, is not a favorable host rock, and within the deposit it is fresh or only weakly altered and/or mineralized. This facies is a poorly laminated thin-bedded arenaceous peloid wackestone. Peloids ranging in size from 50 to 300 μm make up 40 to 65 percent of the rock; this facies also contains 10 to 20 percent angular silt to sand-size quartz grains, 1 to 5 percent argillaceous material (principally illite), and a few percent dolomite. Bioclasts, which make up as much as 20 percent of some samples, include fragments of brachiopods, echinoderms, crinoids, and spiculites. Except for a lower content of organic carbon (0.2–0.4 weight percent), minor constituents are similar to those for the other facies. Small amounts of montmorillonite occur in near-surface samples of both types.

Chemical and spectrographic analyses of samples of both facies in the host rocks are given in Tables 1 and 2, and isotopic data are presented in Table 7. Although no data on porosity and permeability of the rocks are currently available, it seems likely that the thin-bedded type 1 rocks have higher porosity and permeability making them suitable for solution

TABLE 2. Spectrographic Analyses of Samples of Unaltered Roberts Mountains Formation, Lynn Window, Eureka County, Nevada

	Element	Argillaceous arenaceous dolomite, type 1[1]	Arenaceous peloid wackestone, type 2[1]
%	Si	10.0	5.0
	Al	2.0	0.5
	Fe	0.5	0.2
	Mg	7.0	0.3
	Ca	>10.0	>10.0
	Na	0.1	0
	K	1.5	0
ppm	Au[3]	0.06	≤0.03
	As[2]	10	<5
	B	10	0
	Ba	200	30
	Cr	50	10
	Cu	10	1.5
	Ga	2	0
	Hg[4]	0.16	0.06
	Mn	30	200
	Ni	20	2
	Sb[2]	4	0.5
	Sc	5	0
	Sr	150	700
	Ti	1,000	200
	V	300	7
	Y	10	20
	Yb	1	1
	Zn[5]	50	<6
	Zr	50	15

[1] Descriptions correspond to those given in Table 1.

[2] Colorimetric and neutron activation analyses.

[3] Neutron activation and atomic absorption analyses.

[4] Leico mercury vapor analysis.

[5] X-ray fluorescence analysis.

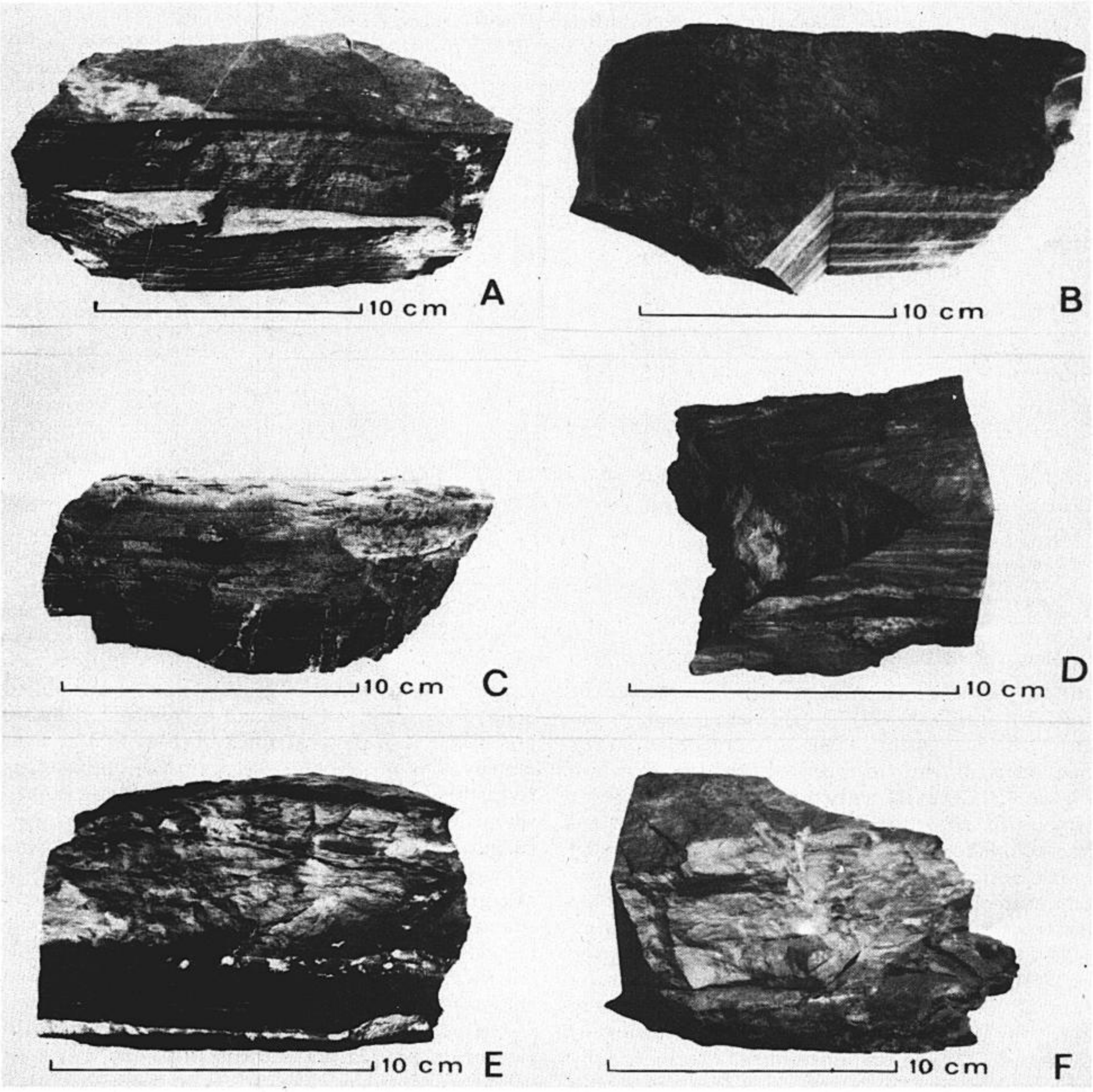

FIG. 4. Carlin ores and host rock: (A) laminated argillaceous arenaceous dolomite (type 1) host rock; (B) normal-type unoxidized ore; (C) siliceous ore showing gradation from weakly silicified (light gray) to heavily silicified (dark gray black); (D) pyritic ore showing pyrite concentrated in light gray zone; (E) arsenical-carbonaceous ore (dark area) partially oxidized (light area); black zones are enriched in hydrocarbons, white seams are mainly realgar and barite; (F) leached oxidized ore.

of interstitial calcite and for introduction of the hydrothermal ore components. The lithologic, chemical, and mineralogic features and the distributions of both facies in the Roberts Mountains Formation are currently under study. The average values for most of the minor elements in unaltered type 1 facies are greater than average values for crustal limestones and less than average values for crustal shales as reported by Turekian and Wedepohl (1961).

Mineralogy and chemistry of the ore

The orebodies at Carlin can be divided into upper oxidized and lower unoxidized zones. The oxidized ores can be further divided into leached and unleached ores. On the basis of mineralogy, chemical composition, and gold associations, the unoxidized ore may be classified into five types which can be easily recognized in the deposit. These are: (1)

TABLE 3. Chemical Analyses of Samples of Various Types of Unoxidized Ores and Oxidized and Leached-Oxidized Ores, Carlin Gold Deposit, Lynn Window, Eureka County, Nevada

Element	Normal[1]	Normal[2]	Siliceous[3]	Pyritic[4]	Carbonaceous[5]	Arsenical[6]	Oxidized[7]	Leached-oxidized[8]
SiO_2	32.6	39.6	95.7	51.9	33.4	42.1	50.9	73.9
Al_2O_3	5.2	6.7	1.6	4.2	3.3	6.0	5.5	12.0
Fe_2O_3	0.69	1.9	0.66	3.3	1.2	1.9	2.0	3.1
FeO	1.0	0.84	0.10	1.1	0.14	0.68	0.12	0.16
MgO	8.0	9.3	0.06	7.3	11.2	9.1	4.9	1.3
CaO	22.1	14.4	0	10.3	18.0	13.1	15.6	0.45
BaO	0.02	0.02	0.05	0.01	0.09	0.08	0.02	0.03
MnO	0.04	0.03	0.21	0.04	0.05	0.04	0.03	0
Na_2O	0.12	0	0	0	0.53	0.03	0.20	0.04
K_2O	1.5	1.7	0.26	1.0	1.1	1.06	1.3	3.5
TiO_2	0.26	0.36	0.03	0.26	0.18	0.30	0.23	0.63
P_2O_5	0.07	0.12	0.07	0.12	1.1	0.25	0.12	0.09
$H_2O^{(-)}$	0.17	0.42	0.10	0.41	0.23	0.39	0.24	1.1
$H_2O^{(+)}$	1.2	1.6	0.82	1.1	1.2	1.8	1.4	3.1
CO_2	26.0	21.6	0.02	15.9	25.6	19.1	16.9	0.04
S (total)	0.72	0.82	0.11	2.8	0.8	2.2	0.2	0.11
C (organic)	0.20	0.31	0.17	0.51	1.9	0.50	0.20	0.05
As	0.02	0.09	0.04	0.02	0.06	1.11	0.15	0.08
Totals	100.0	99.8	100.0	100.3	100.1	100.3	100.0	99.7

[1] Main orebody, 6,300 elevation; Au = 9 ppm.
[2] Main orebody, 6,280 elevation; Au = 18 ppm.
[3] East orebody, 6,320 elevation; Au = 23 ppm.
[4] Main orebody, 6,300 elevayion; Au = 6 ppm.
[5] East orebody, Rotary drill hole P8; Au = 5 ppm.
[6] East orebody, 6,380 elevation; Au = 69 ppm.
[7] Main orebody, 6,330 elevation; Au = 10 ppm.
[8] Main orebody, 6,320 elevation; Au = 50 ppm.

normal, (2) siliceous, (3) pyritic, (4) carbonaceous, and (5) arsenical. These types are not fixed end members, and many kinds of gradations occur. Specimens of various types of ore are shown in Figure 4. Chemical and spectrographic analyses of samples of unoxidized ores and both oxidized and leached oxidized ores are presented in Tables 3 and 4.

The normal type, which accounts for over 60 percent of the known unoxidized ores, closely resembles the fresh host rock in physical appearance. An excellent description of this ore type at Carlin is given by Wells and Mullens (1973). In most samples, from 25 to 50 percent of the original calcite was removed by the hydrothermal fluids; small amounts of pyrite were formed, and fine-grained quartz, together with gold, mercury, thallium, antimony, and arsenic, was also introduced. The average abundances for these elements in this ore type are 8 ppm gold, 25 ppm mercury, ≤50 ppm thallium, 100 ppm antimony, and 400 ppm arsenic. The organic carbon content of about 0.25 to 0.30 weight percent is similar to or slightly higher than that of the fresh host rock. Most of the gold occurs with mercury, antimony, and arsenic as coatings on surfaces and fracture fillings in pyrite grains. Smaller amounts of gold are associated with organic carbon. A very minor amount of metallic gold occurs as small grains locked in quartz. Sulfide minerals other than pyrite are very sparse.

Siliceous ore contains large amounts of introduced silica and very small amounts of remnant dolomite and calcite. In physical appearance as well as mineralogy, this ore type grades from the normal type to jasperoid. The abundances of introduced hydrothermal elements, including gold, vary over wide ranges. Most of the gold occurs on surfaces of fine-grained pyrite locked in quartz, and small amounts of fine-grained metallic gold are dispersed in quartz grains. Stibnite, realgar, and pyrite are the only sulfide minerals recognized to date in this ore type. Siliceous ore accounts for only about 5 percent of the primary unoxidized ore in the deposit.

Pyritic ore makes up about 5 to 10 percent of the known unoxidized ore and contains from 3 to over 10 percent introduced pyrite. Compared to normal ore, pyritic ore has more hydrothermal silica and less calcite (Table 3). Pyrite occurs as: euhedral to subhedral grains, up to 200 μm long, scattered through the rock and concentrated in veinlets, which crosscut bedding; and framboidal clusters of small microspheres, less than 10 μm in diameter, associated with organic material and quartz. The occurrence and origin of authigenic framboidal pyrite in sedimentary rocks has been described in numerous papers, including those by Berner (1969, 1970), Love (1957, 1967), and Love and Amstutz (1966). No framboidal pyrite has been found in the fresh unmineralized host rocks at Carlin. The occurrence of this form of pyrite only in mineralized rocks suggests that it is of hydrothermal origin. Some framboidal pyrite has been coated by gold and other elements, indicating that the framboids formed somewhat earlier than the gold.

The contents of gold, mercury, antimony, and arsenic vary widely in pyritic ore. Gold and mercury occur with carbonaceous material and, together with antimony and arsenic, form coatings on both varieties of pyrite mentioned above (Radtke et al., 1972b). The content of organic carbon varies from about 0.5 to 0.9 weight percent, suggesting some introduction of hydrocarbons. Thin sections of these ores show an increase in hydrocarbons dispersed in the rock matrix. Pyrite is the dominant sulfide mineral, although small sparse grains of realgar, stibnite, sphalerite, galena, molybdenite, and chalcopyrite have been identified by microprobe studies.

The term "carbonaceous ore" has been used commonly as a general term in reference to all unoxidized ores at Carlin and other disseminated gold deposits in carbonate rocks. However, we restrict the term to those ores for which an introduction of hydrocarbons can be documented. Typically these contain from 1 to >5 weight percent organic carbon. Carbonaceous ore is dark gray to black and contains small veinlets and seams of hydrocarbons in addition to the dispersed grains of amorphous carbon, hydrocarbons, and an organic or humic acid described by Radtke and Scheiner (1970). Carbonaceous ore makes up 15 to 20 percent of the unoxidized ore at Carlin.

Carbonaceous ore differs from normal ore in having a higher content of organic carbon. Gold in carbonaceous ore occurs both with carbonaceous material and as coatings on pyrite grains. Mercury, antimony, and arsenic of carbonaceous ore occur similarly to those same elements in pyritic ore. Grains of metallic gold have not been recognized in

TABLE 4. Spectrographic Analyses of Samples of Various Types of Unoxidized Ores, and Oxidized and Leached-Oxidized Ores, Carlin Gold Deposit, Lynn Window, Eureka County, Nevada

Element	Normal[1]	Normal[1]	Siliceous[1]	Pyritic[1]	Carbonaceous[1]	Arsenical[1]	Oxidized[1]	Leached-oxidized[1]
Si (%)[2]	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0
Al	5.0	7.0	0.5	2.0	3.0	5.0	5.0	5.0
Fe	2.0	2.0	0.5	3.0	1.5	2.0	2.0	2.0
Mg	5.0	10.0	0.15	5.0	10.0	7.0	5.0	0.5
Ca	7.0	>10.0	0.03	7.0	>10.0	10.0	10.0	0.2
Na	0.05	0.1	0.03	0.05	0.1	0.07	0.03	0.07
K	1.5	3.0	0	1.5	1.5	2.0	1.5	2.0
Ti	0.2	0.2	0.02	0.1	0.1	0.15	0.15	0.3
P	0	0	0	0	0	2.0	0	0
Mn (ppm)[3]	100	150	7	150	500	150	150	10
Ag	0	0	1	0	2	0	0	0.7
As[4]	154	800	385	180	480	11,000	1,450	790
Au[5]	9	18	23	6	5	69	10	50
B	150	70	7	20	100	30	70	70
Ba	200	200	500	100	500	500	150	300
Co	7	5	0	7	3	3	3	1.5
Cr	70	70	10	30	70	70	50	100
Cu	50	20	70	30	70	50	20	30
Ga	15	15	0	7	7	10	10	20
Hg[6]	25	40	55	25	20	200	35	100
La	50	0	0	50	0	50	70	50
Mo	15	7	5	15	50	10	5	5
Nb	0	7(?)	0	0	0	0	0	10
Ni	50	20	3	70	100	20	20	15
Pb	15	0	0	10	15	0	15	30
Sb[4,7]	<40	150	40	<40	60	115	129	360
Sc	10	15	0	7	7	10	15	15
Sr	150	0	10	100	200	150	100	100
Tl	70	200	0	0	0	150	50	0
V	200	0	70	100	700	70	50	200
W[7]	<20	<20	<20	<20	30	20	<20	<20
Y	20	30	0	15	70	20	30	30
Yb	2	1.5	0	1	3	1.5	3	3
Zn[4]	51	114	6	7	100	<5	163	65
Zr	100	150	20	100	70	150	200	300

[1] Descriptions correspond with those given in Table 3.
[2] Elements Si through P given in weight percent.
[3] Elements Mn through Zr given in parts per million.
[4] X-ray fluorescence analysis.
[5] Atomic absorption analysis.
[6] Leico mercury vapor analysis.
[7] Colorimetric analysis.

this ore type. In addition to pyrite, carbonaceous ore commonly contains other sulfides, including realgar, orpiment, stibnite, lorandite, cinnabar, sphalerite, galena, and carlinite.

Arsenical ore makes up 5 to 10 percent of the known unoxidized ores. It contains large concentrations of arsenic (0.5 to over 10.0 weight percent), most of which is in dispersed grains and veinlets of realgar and orpiment. The arsenic sulfides were deposited late in the paragenesis. They occur in carbonate rocks commonly enriched in hydrocarbons and in the deep parts of barite veins near the bottom of the zone of oxidation and in calcite veinlets in unoxidized ore (Radtke and Dickson, 1974; Dickson and Radtke, 1977; Harris and Radtke, 1976). Aside from arsenic, the major chemical components and mineral phases in most of the arsenical ore correspond closely to those in the normal and carbonaceous ore types.

Gold and mercury in the arsenical ore occur with carbonaceous material and as coatings on the surfaces of pyrite grains dispersed through the carbonate rock and locked in realgar veinlets. Electron microprobe studies of Carlin ores show that small detectable amounts of gold occur in realgar. Gold in some form, either in solid solution or as admixed metallic gold, has been reported in synthetic realgar and orpiment (Dickson et al., 1975b). In addition to gold, arsenic-rich ore generally contains unusually high concentrations of mercury, antimony, and thallium, and a wide variety of sulfide and sulfosalt minerals containing these elements. Excellent descriptions of arsenical ore in other Carlin-type deposits include those of Mercur, Utah (Gilluly, 1932); Manhattan, Nevada (Ferguson, 1924); and Getchell, Nevada (Joralemon, 1951).

Chemical Changes during Mineralization, Acid Leaching, and Oxidation

The major element contents of the Roberts Mountains Formation and the various types of unoxidized ore and the changes in the content of these elements in the rocks as a result of mineralization are shown in Figure 5.

The most notable changes from the unaltered original rocks were the loss of CaO and CO_2 and the introduction of SiO_2. The components Al_2O_3, K_2O, and H_2O^+ increase, reflecting the formation of small amounts of kaolinite and sericite. H_2O^-, the loosely bound or absorbed water, follows closely the trend of Al_2O_3, K_2O, and H_2O^+, revealing the tendency for the surfaces of fine-grained K-containing hydrous aluminous clays to absorb water. The increases of iron and sulfur accord with the formation of pyrite. The increase in BaO content shows that some barium was introduced, apparently as minor amounts of fine-grained barite dispersed throughout the rocks. The disseminated barite may have formed earlier than the barite in the veins. A small amount of TiO_2 was added. Electron microprobe analysis revealed a fine-grained mineral of composition TiO_2 dispersed throughout the matrix in various ore types. The similar content of MgO in both fresh and mineralized rocks is in agreement with mineralogical data, which show that only small amounts of dolomite were dissolved by the hydrothermal fluids and that calcite was removed preferentially to dolomite. Only in areas where the hydrothermal alteration was very intense and siliceous-type ore formed has most of the dolomite as well as all of the calcite been removed. Data for the contents of organic carbon and arsenic, both of which increase in the mineralized rocks, are omitted from Figure 5.

The rocks in much of the upper part of the deposit have been altered visibly. Most of the alteration is due to removal of carbonate from the rocks and the oxidation and removal of pyrite and organic matter. These acid-leached rocks occur in a shallow irregular zone up to 76 m thick. The zone of acid leaching is in the upper beds of the Roberts Mountains Formation and extends horizontally into both the Popovich Formation and the Vinini Formation. The relatively flat-lying acid-leached zone cuts across the dipping mineralized rocks in all three ore zones. Within the upper and lateral parts of the zone, the leaching and oxidation is structurally controlled, with the most intense alteration occurring in rocks along fractures and faults. Remnants of unoxidized and unleached host rocks persist in the Roberts Mountains Formation, particularly in the arenaceous peloid wackestone (type 2 facies) in the acid-leached zone.

The field evidence suggests that acid leaching of calcite and dolomite and most of the strong oxidation occurred simultaneously in the upper part of the deposit. Late post-leaching oxidation, however, which often extends below the leached zone and reaches a depth of 92+ m in the main ore zone, has affected a thicker section of the host rock and ore and is probably going on today.

The highly altered rocks in the acid-leached zone of the deposit are composed mainly of fine-grained quartz and illite, lesser amounts of kaolinite and sericite, minor montmorillonite, some remnant dolomite, small amounts of calcite (depending upon intensity of alteration and location), and scattered remnant iron oxides. Small amounts of remnant anhydrite that formed by reaction between the acid-leaching solution and calcite in the host rock also occur in the leached zone. Probably most of the anhydrite that formed in the upper rocks has been dissolved subsequently by ground water.

Important chemical changes produced in mineral-

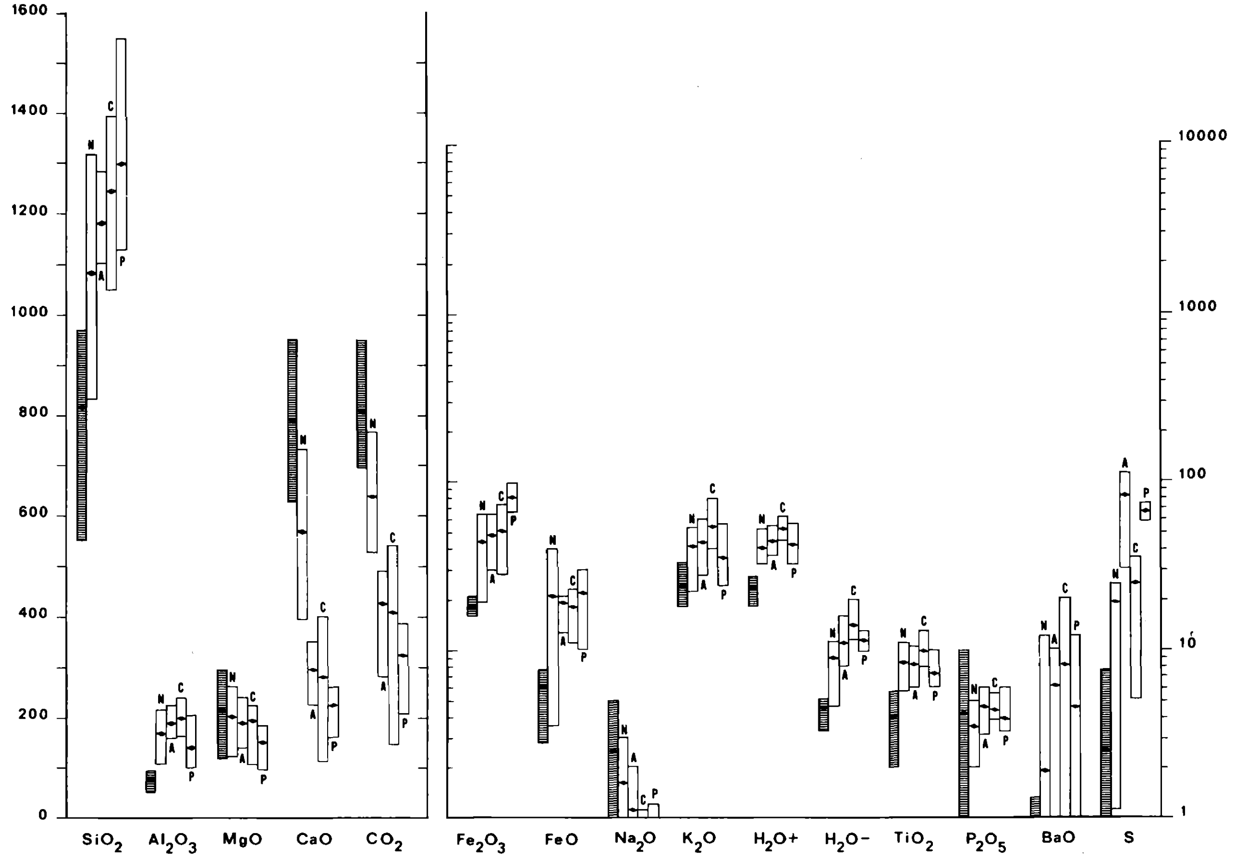

FIG. 5. Chemical changes in dolomitic carbonate rocks of the Roberts Mountains Formation during ore deposition. Vertical bars show ranges and median values (black diamond) of milligrams of the indicated oxide in a cubic centimeter of rock (these values are equal to the weight percent of the oxide times the bulk specific gravity times 10). Petrographic evidence shows that no significant change in volume occurred during alteration. Shaded columns show compositions of unaltered rock and open columns the compositions of various types of unoxidized ore; N = normal ore, A = arsenical ore, C = carbonaceous ore, and P = pyritic ore. Siliceous ore is not shown.

ized rock during late hydrothermal acid leaching and oxidation in the upper part of the ore deposit are summarized by comparing data for normal unoxidized and acid-leached ores in columns 2 and 4 in Figure 6. The very large losses of CaO, MgO, and CO_2 reflect solution of nearly all calcite and much of the dolomite, and an increase in SiO_2 reflects introduction of quartz. The lack of change in K_2O, Al_2O_3, and H_2O^+ contents suggests that no additional potassic alteration occurred during leaching and oxidation in the upper part of the deposit. The decrease in Fe_2O_3 content indicates that iron as well as sulfur was removed during breakdown of pyrite. All changes are in agreement with petrographic evidence. Not shown in Figure 6 is the removal of carbon as organic matter.

Mineralized and unmineralized rocks to a depth of at least 20 m below the leached zone have undergone posthydrothermal supergene oxidation during which they were bleached to light green to tan; they can be distinguished from acid-leached rocks by the color change and relatively unchanged mineral composition. Such rocks also occur in places above the leached zone. In the oxidized but unleached ores and in the leached oxidized ores, small particles of metallic gold, up to about 5 μm in diameter, are scattered through the rock and locked in fine-grained quartz, with lesser amounts associated with secondary iron-oxide minerals and clays. Specimens of oxide gold ore at Carlin are shown in Figure 4. Excellent descriptions and photographs together with chemical analyses of oxide ore were given by Hausen and Kerr (1968).

Comparison of columns 2 and 3 in Figure 6 reveals changes in the chemical composition of mineralized rocks caused by surface-derived water after the close of the hydrothermal activity. The data show that the chemical changes during late supergene oxidation were much less than those during the late hydrothermal leaching. Losses in CaO and CO_2 reflect

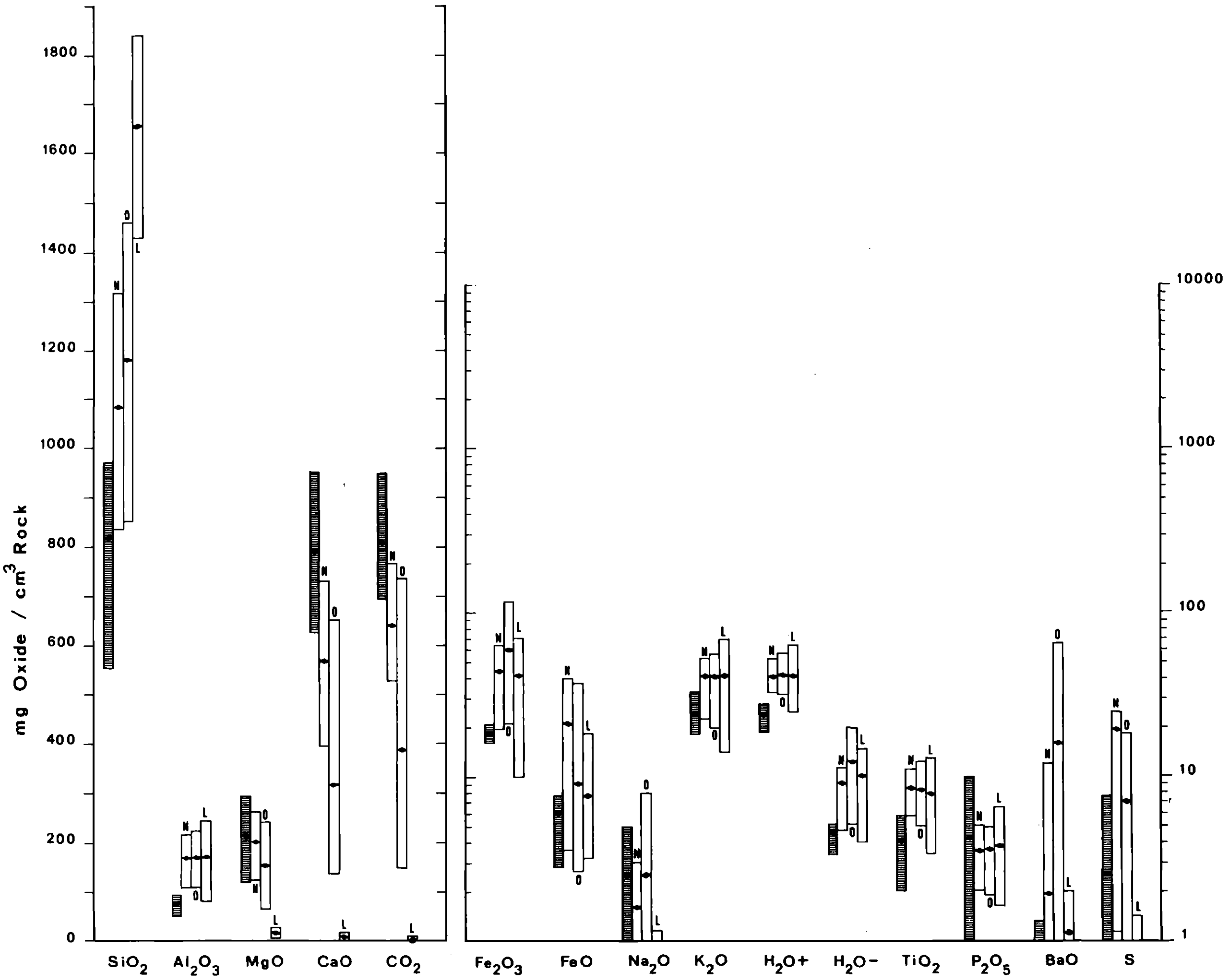

FIG. 6. Chemical changes in dolomitic carbonate rocks of the Roberts Mountains Formation during hydrothermal mineralization, acid-leaching and oxidation of the upper part of the deposit, and late oxidation. Vertical bars show ranges and median values (black diamond) of milligrams of the indicated oxide in a cubic centimeter of rock (these values are equal to the weight percent of the oxide times the bulk specific gravity times 10). Shaded columns show compositions of unaltered rocks and open columns the compositions of normal-type unoxidized ore (N), acid-leached oxidized ore (L), and unleached oxidized ore (O).

the removal of small amounts of calcite; decreases in FeO and S correspond to the oxidation of pyrite and other sulfides. The higher values of SiO_2, suggesting some introduction of late quartz, are compatible with petrographic data showing microveinlets of quartz in some samples; fluid inclusions in this quartz show they formed from low-temperature, low-salinity solutions (discussed in a later section).

Space and Time Relationships

Generalized spatial distributions of important features of the deposit are shown in the cross section of Figure 7. The gross spatial relations of orebodies and altered rocks to structures are similar everywhere in the deposit. Apparently the variability in the orebodies reflects differences of the hydrothermal fluids caused by the complexity of fluid flow paths and by physicochemical responses to boiling above the zone of mineral deposition.

Depicted in Figure 7 with numbers keyed to the figures are:

1. The zone of oxidized acid-leached rocks, the bottom of which locally is parallel to the present topography but extends downward along fractures; this zone contains isolated scattered remnants of unaltered host rock and unoxidized mineralized rock.
2. Areas of oxidized but unleached rocks extending ± 20 m below the leached rocks and also present above the leached rocks; this zone of supergene oxidation actually extends from the surface through and below the leached zone.
3. Disseminated gold orebodies extending to un-

known depths below the oxidized zone and upward into the zones of acid leaching and supergene oxidation.

4. Jasperoid bodies that extend as much as 30 m from faults developed through a vertical distance of about 130 m in the oxidized acid-leached zone; their thickness and lateral extent progressively decrease with depth to nearly zero at the bottom of the zone of acid leaching. The largest bodies tend to occur stratigraphically beneath orebodies, along their lower margins (Fig. 3; Radtke, 1973).

5. Barite veins and veinlets are sporadically distributed throughout the deposit but are most abundant in the main and west ore zones. The barite veins range from paper-thin seams to about 1 m thick. They are most abundant and best developed in the leached zone, and they typically narrow abruptly or terminate at the bottom of the leached zone or in the underlying unleached oxidized zone. Only a few small stringers of barite have been observed to date in the upper 10 to 15 m of the unoxidized zone. Disseminated sphalerite, galena, realgar, orpiment, stibnite, and As-Sb-Tl-Hg-bearing sulfosalt minerals occur in minor amounts in many places in the lower parts of the barite veins.

6. Sparse but geochemically important quartz veinlets up to 1 cm thick occur at deep levels in unoxidized ore, in shallow parts of the oxidized zone, and in silicified carbonate rocks (jasperoid bodies) at the surface. In places quartz pods and seams occur in barite veins.

7. Thin calcite veinlets are sparsely distributed in the unoxidized ore. They are usually absent in the leached zone but are abundant in oxidized rocks immediately above and below the leached zone.

We will develop later the concept that the leached zone was formed by the action of acids generated by oxidation of H_2S given off during late-stage boiling. Part of the leaching took place distinctly after the main-stage mineralization, but the episode may have overlapped deposition of ore at greater depths.

The generalized paragenesis is shown in Figure 8. The fine-grained nature of the ores and the general lack of clearly defined crosscutting relationships between many important geologic features, make difficult a definitive determination of the sequence of events at any locality.

The paragenetic position of the jasperoid bodies is difficult to determine, but they apparently overlapped late hydrothermal stage 2 and acid-leaching alteration stage 3. Some of the carbonaceous compounds and arsenic sulfides in the carbonaceous and arsenical types of ore, respectively, were introduced during the late part of the hydrothermal episode.

Most of the veins and veinlets formed during the acid-leaching stage and continued after the formation of jasperoid bodies. Calcite probably was the last

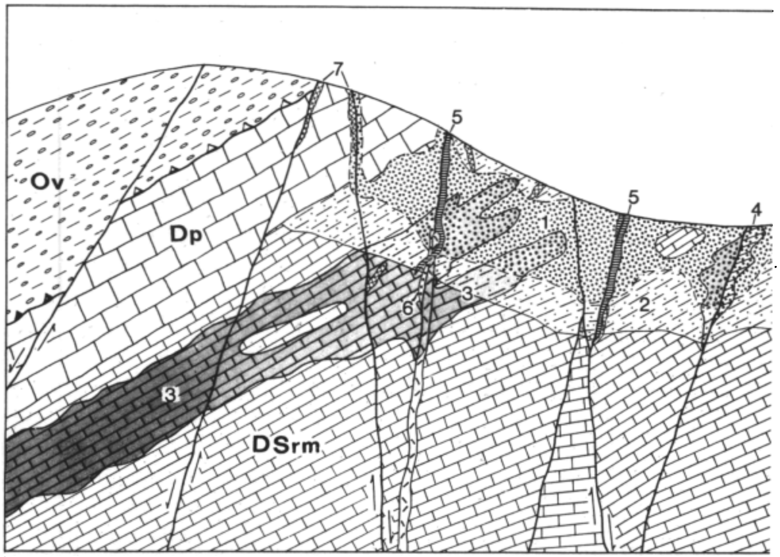

FIG. 7. Schematic north-south cross section through the main ore zone and Popovich Hill showing important geologic features. Lithologic units include Vinini Formation (Ov), Popovich Formation (Dp), and Roberts Mountains Formation (D Srm). 1 = zone of leaching-alteration (small open circles); 2 = zone of late supergene alteration (dots and dashes) extending from surface downward through and below acid-leaching zones; 3 = main ore zone includes lower unoxidized ores (dark gray) and upper oxidized ores (light gray); 4 = jasperoid bodies in solid black dot and line pattern—note igneous dike intruded along fault near center of figure; 5 = barite veins in horizontal bar pattern; 6 = quartz veins in solid black dots; and 7 = calcite veins are shown in cross-hatched pattern.

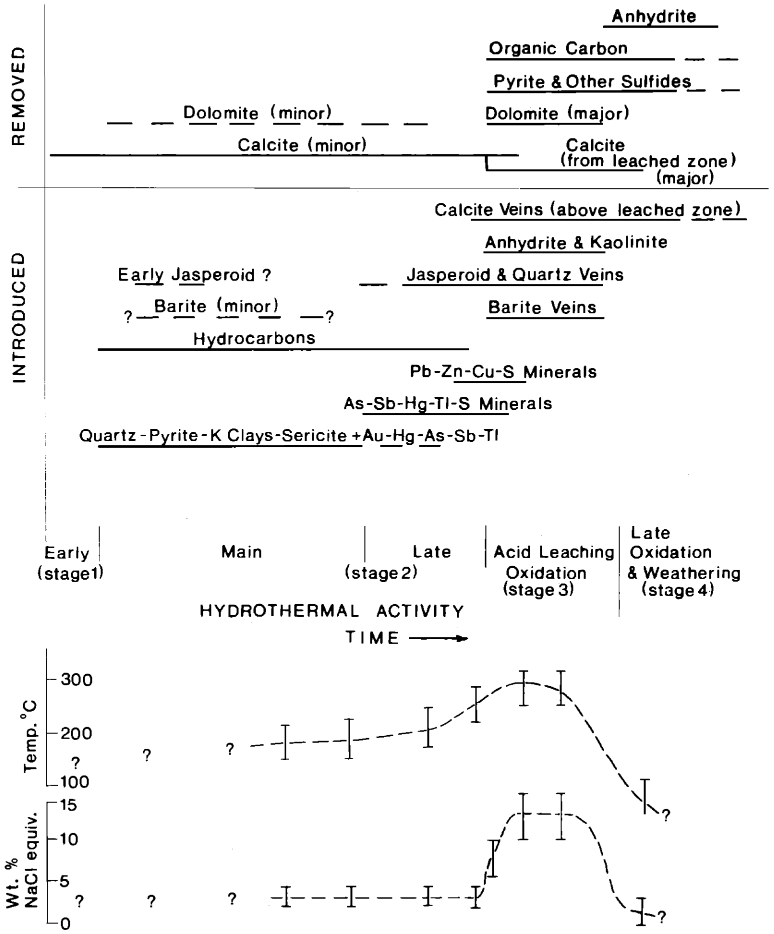

FIG. 8. Paragenesis of the Carlin gold deposit. The acid-leaching and accompanying oxidation (stage 3) were superimposed on the late hydrothermal (stage 2) events in the upper part of the deposit. The extent to which main- and late-stage events including mineralization continued at depth during acid leaching in the upper levels is not known. Also shown are average temperature and salinity trends of hydrothermal fluids as indicated by fluid inclusion data. The curves are highly schematic.

hydrothermally deposited mineral. Some calcite was posthydrothermal, associated with late-stage supergene oxidation. Bodies of jasperoid in places appear to have formed before the late veinlets. The lower part of the oxidized zone below the leached zone was formed by postore processes that are probably still going on.

Fluid Inclusion Studies

Previous studies

The first study of fluid inclusions in Carlin materials was done by Nash (1972) on a few samples of small quartz veinlets and jasperoid bodies which unfortunately did not contain inclusions with satisfactory properties. Based on vapor fractions Nash estimated a homogenization of 175° ± 25°C and suggested that, corrected for pressure, a temperature of 200°C would be reasonable for ore formation. The small size of the inclusions also precluded freezing-stage study of salinity.

John F. Slack (written commun., 1975) examined fluid inclusions in vein gangue minerals from various localities in the deposit. Homogenization temperature data reported by Slack agree well with the extensive new data on the same types of materials and are incorporated with this paper (Table 5). No freezing data on salinity was reported by Slack (pers. commun.) due to the combined effects of inclusion size and limitation of instrument optics. Slack reported the consistent presence of both liquid-rich and vapor-rich inclusions in the same mineral plate and stated "this indicates widespread fluid boiling and the trapping of vapor-rich inclusions along with the boiling curve and explains the anomalously high temperatures of homogenization recorded for many inclusions."

TABLE 5. Temperature and Salinity of Fluid Inclusions in Quartz, Barite, Calcite, Realgar, and Sphalerite, Carlin Gold Deposit, Nevada

Sample no.	Mineral	Stage in paragenesis	Inclusion type	No. inclusions analyzed	Filling temperature (°C)		Salinity % (equiv. wt. % NaCl)	
					Range	Average	Range	Average
Q-1	Quartz	2 (main-stage mineralization)	I	25	164–211	185	2.8–4.6	3.7 ± 0.4
Q-2	Quartz	2 (main or late stage)	I	36	152–214	179	2.7–4.1	3.6 ± 0.4
Q-A	Quartz	Late stage 2 or early stage 3	I	21	204–295	223	3.0–4.3	4.0 ± 0.2
			II	20	248–350	∼310	<1.0	<1.0
			III	3	Not determined		Not determined	
6990-J	Calcite	2 (main or late stage)	I	23	170–218	193	∼2.0–4.0	±3.0
6990-J	Realgar	2 (main or late stage)	I	14	∼180–∼210	∼205	Not determined	
5630-J	Quartz (Jasperoid)	3 (acid-leaching oxidation	I	9	∼185–∼235	∼225	∼6.0–∼10.1	7.5 ± 0.5
			II	>30	Not measurable		Not measurable	
5630-J	Quartz	3 (acid-leaching oxidation)	I	18	198–249	230	5.8–9.3	7.5 ± 0.4
			II	16	216–306	328	<1.0	<1.0
			III	present	Not determined		Not determined	
51-J	Quartz	3 (acid-leaching oxidation)	I	20	245–306	281	12.0–15.1	13.5 ± 0.4
			II	10	285–320	311	<1.0–1.5	<1.0
3512-M	Quartz	3 (acid-leaching oxidation)	I	26	218–298	283	8.9–13.7	10.6 ± 0.5
			II	15	252–330	297	Not determined	
5109-J	Quartz	3 (acid-leaching oxidation	I	20	225–281	268	10.5–15.6	13.4 ± 0.6
			II	16	256–333	294	<1.0–2.0	<1.0
			III	2	Not determined		Not determined	
6967-L	Quartz	3 (acid-leaching oxidation)	I	12	248–270	261	9.4–14.6	12.8 ± 0.4
			I	9	190–217	209	7.1–13.2	11.0 ± 0.4
			II	7	198–305	270	<1.0	<1.0
51-J	Barite	3 (acid-leaching oxidation)	I	29	192–298	268	11.3–17.4	15.1 ± 0.4
			II	12	235–342	290	Not determined	
3512-M	Barite	3 (acid-leaching oxidation)	I	27	232–290	270	9.7–16.1	12.6 ± 0.4
			II	20	260–340	326	Not determined	
5109-J	Barite	3 (acid-leaching oxidation)	I	10	216–263	240	10.3–16.7	13.4 ± 0.4
			I	12	315–338	325		
			II	13	279–365	330	<1.0–1.5	<1.0
6967-L	Barite	3 (acid-leaching oxidation	I	15	224–278	249	Not determined	
			II	12	229–304	273	<1.0	<1.0
51-J	Realgar	3 (acid-leaching oxidation)	I	21	∼200–>210	>210	Not determined	
3512-M	Sphalerite	3 (acid-leaching oxidation)	I	23	266–308	290	9.8–16.2	13.5 ± 0.4
3500A-M	Quartz	4 (supergene oxidation-weathering)	I	15	<70	<70	0.0–1.1	<1.0
73-J	Calcite	4 (supergene oxidation-weathering)	I	28	<70–110	∼80	0.0–2.3	∼1.5

Q-1,	quartz veinlets in fractures in deep unoxidized mineralized carbonaceous dolomitic carbonate rock. Quartz contains dispersed hydrocarbons, and pyrite with coatings of gold, arsenic, antimony, and mercury. 23,000 N; 19,900 E; 6,360 elev.
Q-2,	quartz veinlets along margin and crosscutting igneous dike at base of oxidized zone. Quartz contains minor, partly oxidized pyrite and iron oxides contain gold and associated elements. 23,100 N; 20,250 E; 6,400 elev.
Q-A,	quartz veinlets along margin of igneous dike and in heavily silicified carbonate rock in zone of acid leaching. Quartz contains frankdicksonite and pyrite. 23,800 N; 20,750 E; 6,325 elev.
5630-J,	quartz veinlets intergrown with jasperoid in surface outcrops. 21,910 N; 15,575 E; 6,650 elev.
51-J,	barite seams containing patches of quartz and realgar along fractures in remnant pod of unoxidized carbonaceous carbonate rock near base of acid-leached zone. 22,510 N; 18,400 E, 6,400 elev.
3512-M,	barite vein containing dispersed grains of sphalerite and seams of quartz in center of acid-leached zone. 22,700 N; 18,860 E; 6,580 elev.
5109-J,	barite seams containing dispersed grains of galena and seams of quartz in center of acid-leached zone. 22,550 N; 18,380 E; 6,360 elev.
6967-L,	barite and quartz interlocked in veins near the top of acid-leached zone. 22,200 N; 15,450 E; 6,430 elev.
6990-J,	realgar in calcite veinlets and along fractures in unoxidized carbonaceous dolomitic carbonate rock below oxidized zone. 22,700 N; 19,000 E, 6,220 elev.
73-J,	calcite vein filling fracture in weakly oxidized near-surface carbonate rock above acid-leached zone. 22,580 N; 18,450 E; 6,610 elev.
3500A-M,	quartz patches along fractures in shallow oxidized unleached mineralized carbonate rock. 22,100 N; 18,150 E; 6,460 elev.

Materials and fluid inclusion properties

Doubly polished plates for study of fluid inclusions were prepared from a variety of materials including quartz, barite, calcite, sphalerite, and realgar. Many of these plates were chosen and prepared to permit examination of inclusions in more than one mineral in the same plate. Samples studied include: (1) quartz in patches in unoxidized ores, in veinlets with and without other phases such as pyrite, frankdicksonite, and gold, in unoxidized ores as well as in deep parts of overlying oxidized rocks, intergrown with jasperoid in surface and near-surface acid-leached zones and associated with barite veins in leached zones; (2) barite in veins containing lesser amounts of quartz and scattered concentrations of sphalerite, galena, and realgar and in veins with quartz but lacking sulfide minerals; (3) calcite veinlets in deep unoxidized ores and in shallow oxidized rocks above the acid-leached zone; (4) sphalerite in barite veins; and (5) realgar in calcite veins in deep unoxidized ore, and with barite and quartz in veins in shallow pods of remnant unoxidized carbonaceous rocks near the bottom of the acid-leached zone. These materials cover the paragenesis from the main hydrothermal ore-forming stage (stage 2) through the posthydrothermal oxidation stage (stage 4) (Table 5; Fig. 8).

Determinations of homogenization and freezing temperatures were made by conventional techniques using a modified Chaix Meca heating/liquid N_2 freezing stage at the U. S. Geological Survey in Menlo Park, California. The stage was calibrated using spectrographically analyzed CO_2 fluid inclusions and solutions of known salinity. In the temperature range of 0° to 400°C the stage was calibrated using National Bureau of Standards standards with known melting points.

Minerals studied in most of the plates contained numerous primary, pseudosecondary, and secondary inclusions. Samples of barite, calcite, and some sphalerite contain large numbers of secondary or pseudosecondary inclusions close to or along fractures and cleavage planes. Most of these inclusions are $<20\ \mu$. Except for a few large ($25\ \mu$) secondary inclusions in barite, no homogenization or freezing determinations were made on secondary inclusions and all data reported in Table 5 were collected from primary inclusions or inclusions with properties suggesting they could be either primary or pseudosecondary.

Three types of inclusions were observed during this study and were also reported by J. F. Slack (written commun., 1975).

Type I: This type of fluid inclusion contains a liquid and a vapor phase. The bubble usually makes up 5 to 30 percent of the total volume of the inclusions. This type of inclusion was the most abundant and was present in all mineral plates examined. Measured salinities over all minerals studied range from 0.0 to about 17.0 equivalent weight percent NaCl depending on the type of mineral and the history of the transport solution.

Type II: This type of inclusion also contains a liquid and a vapor phase, but the volume of vapor equals or exceeds that of the liquid phase. In most inclusions the vapor phase makes up 50 to 70 percent of the inclusion volume. Vapor-rich inclusions are present in barite, in some samples of sphalerite and realgar(?), in quartz associated with barite, and in a few quartz veinlets. Some type II inclusions in barite also have vapor bubbles which constitute more than 90 percent of the inclusion volume. In most samples studied type II inclusions homogenize over a wide temperature range and the lowest temperatures in type II inclusions in most samples compare well with average values for type I inclusions in the same sample (Table 5). Measured salinities in most type II inclusions in all types of materials were < 1.0 equivalent weight percent NaCl.

Type III: This inclusion type contains three phases—liquid water, liquid CO_2, and vapor ($H_2O + CO_2$) and is rare in Carlin samples. Nash (1972) reported the presence of type III inclusions in quartz samples; our studies, as well as those by J. F. Slack, confirmed the presence of this rare type of inclusion in two samples of quartz.

No daughter minerals or other phases such as hydrocarbons or iron oxides have been found in any inclusions of any type in Carlin samples.

Main and late hydrothermal stage fluid inclusions

Quartz deposited with pyrite, gold, and associated elements during the main-stage mineralization (stage 2) contains only type I fluid inclusions. Measured homogenization temperatures of these inclusions range from 152° to 214° and average about 182°C (Table 5, samples Q-1 and Q-2). These temperatures agree well with homogenization temperatures in type I inclusions in deep calcite veinlets of 170° to 218°C (Table 5, sample 6990-J). Type I inclusions in realgar crystals in the calcite veinlets have homogenization temperatures of ~180° to >210°C; however, due to behavior of realgar at temperatures above 200°C and optical properties of the mineral, it is difficult to measure precisely these homogenization temperatures. Measured salinities of fluids in type I inclusions in quartz range from 2.7 to 4.6, and for those in calcite from about 2 to 4 equivalent weight percent NaCl (Table 5). No type II vapor-rich inclusions were observed with type I inclusions in any sample of quartz or calcite deposited during stage 2, which suggests that the hydrothermal fluids did not boil at the sample localities during this time of ore deposition. Temperatures of the hydrothermal fluids probably increased with time (Fig. 8) and were greater than 200°C at the onset of boiling.

Acid-leaching oxidation-stage fluid inclusions

A large amount of fluid inclusion data was obtained on minerals deposited during this part of the paragenesis (stage 3) and shows that the hydrothermal fluids increased in temperature and that the salinity increased in response to boiling. Type I fluid inclusions in quartz veinlets, formed at the onset of boiling (late stage 2 or early stage 3), show homogenization temperatures of 204° to 295° and average 223°C (Table 5, sample Q-A). The presence of abundant type II inclusions with generally higher homogenization temperatures indicates that these fluids were boiling. Salinities of 3.0 to 4.3 equivalent weight percent NaCl in type I fluid inclusions were close to those in main stage 2 fluids and suggest that these veinlets, which also contain frankdicksonite, pyrite, and locally, gold, formed early in the boiling episode.

Jasperoid bodies, formed by almost complete replacement of calcite and dolomite in carbonate rocks along high angle faults, contain small type I inclusions. Only a few inclusions were found in plates with satisfactory properties for study and these showed approximate homogenization temperatures of 185° to 235°C. The type II inclusions were too small for study. Narrow white to blue-white quartz veinlets occur locally in the jasperoid, grade into dark gray to black jasperoid, and probably formed as a final stage of the silicification. Type I and type II inclusions occur in these veinlets and homogenization temperatures of type I inclusions in the sample reported in Table 5 (sample 5630-J) with a range of 198° to 249°C and an average of 224°C indicate fluid temperatures above those of the main stage of ore deposition. Nash (1972) reported the presence of liquid CO_2 in type III fluid inclusions in this and other samples, but no temperature or salinity data are available. Salinities in type I inclusions range from 5.8 to 9.3 and average 7.5 ± 0.4 equivalent weight percent NaCl.

Most of the fluid inclusions examined in barite and in intergrown quartz deposited during the period of boiling and acid leaching show homogenization temperatures far above those in minerals formed during stage 2 (Table 5, samples 51-J, 3512-M, 5109-J, and 6967-L). All samples contained type I and a lesser number of type II inclusions with wide ranges of homogenization temperatures. The ranges in homogenization temperatures in type II inclusions overlap those of type I and the lowest homogenization temperatures in type II inclusions generally agree well with averages for type I inclusions. Homogenization temperatures in type I fluid inclusions in sphalerite range from 266° to 308° and average 290°C which agrees well with the average of 283°C for inclusions in coexisting quartz (Table 5, sample 3512-M). Salinities measured for type I inclusions in quartz, barite, and sphalerite range from 8.9 to 15.6, 9.7 to 17.4, and 9.8 to 16.2 equivalent weight percent NaCl, respectively, and are much larger than salinities in stage 2 fluids.

Posthydrothermal oxidation and weathering-stage fluid inclusions

Fluid inclusions in small patches of secondary quartz in unleached oxidized ore show homogenization temperatures of <70°C and salinities of 0.0 to 1.1 equivalent weight percent NaCl (Table 5, sample 3500A-M). These data support the conclusion that silica was added by cool solutions during stage 4 processes. Fluid inclusions in stage 4 calcite veins show homogenization temperatures of <70° to 110°C and salinities of 0.0 to 2.3 equivalent weight percent NaCl (Table 5, sample 73-J). These veins formed by deposition of calcite from low-temperature solutions near or after the close of hydrothermal activity. All inclusions observed in minerals formed during stage 4 are type I. All fluids associated with the close of hydrothermal activity and posthydrothermal processes are of low temperature and low salinity. The generalized temperature and salinity history of the fluids is summarized in Figure 8.

Stable Isotope Studies

The coordinates and elevations of the samples analyzed are included in the tables in this paper; samples can be located on the simplified geologic map (Fig. 3) and the detailed map by Radtke (1973). Some samples were from rotary drill holes; others were from a bench along a line trending at right angles to a major fracture; several suites were collected across benches at places of particular interest. Data were obtained on the hydrogen, oxygen, carbon, and sulfur isotopic compositions of rocks, veins, minerals, and fluid inclusions in samples from the Carlin deposit.

Most of the techniques used in the study have been described by Rye and Sawkins (1974). Appropriate fractionation curves used in calculations are referenced in the tables. Stable isotope data are presented in per mil (‰) deviations from the appropriate standards using standard δ notation. Carbon, oxygen, and sulfur analyses were performed

TABLE 6. The δD Values of Water in Fluid Inclusions of Vein Minerals and of Hydrous Minerals from Dikes

Sample no.	Mineral	Ore zone	Location	Elevation	δD ‰[1]
		Fluid inclusions			
38-J	Barite	Main	21,605 N; 18,650 E	6,610	−140
114-J	Barite	West	22,045 N; 15,815 E	6,530	−149
6967-J	Barite	West	22,300 N; 15,450 E	6,430	−139
5630-JA	Quartz	West	22,870 N; 15,500 E	6,660	−153
Q-1	Quartz	East	23,000 N; 19,900 E	6,360	−153
73-J	Calcite	Main	22,780 N; 18,850 E	6,610	−142
3501-J	Calcite	West	22,225 N; 15,800 E	6,400	−143
		Hydrothermally altered dikes			
23-J	Whole rock Sericite:kaolinite = 1:3	Main	21,765 N; 18,495 E	6,505	−160
5120-J	Whole rock Sericite:kaolinite = 2:1	West	22,195 N; 15,665 E	6,410	−145

[1] Relative to SMOW.

on a modified 6-inch Nuclide 6-60-RMS mass spectrometer. The hydrogen isotope analyses were performed on a mass spectrometer constructed in U.S. Geological Survey facilities with a 3-inch Nuclide 3-60-RMS analyzer tube.

Hydrogen isotope data

Hydrogen isotope compositions of water in fluid inclusions in quartz, barite, and calcite from veins and in the whole-rock samples of highly altered Jurassic and/or Cretaceous dikes were determined by standard techniques. These data were obtained principally to gain information on possible sources of the hydrothermal fluids.

The hydrogen isotope data on fluids from inclusions in the samples of vein minerals studied permit conclusions on main-stage and post-main-stage hydrothermal fluids. These include fluids from inclusions in vein quartz associated with gold and pyrite (sample Q-1) representative of main-stage solutions, fluids from barite samples representative of latest hydrothermal fluids (acid-leaching and oxidation, stage 3), and fluids from calcite from barren veins representative of surface waters or mixtures of surface water and the latest stage hydrothermal fluids.

Many of the fluid inclusions in vein minerals are small and commonly are crowded along healed fractures in a manner typical of secondary or pseudosecondary inclusions. However, most of the fluid recovered for the isotopic determinations was from minute inclusions, densely crowded in milky zones, which have been demonstrated elsewhere to be primary (Rye, 1966). If this holds for Carlin, the δD values of the inclusions fluids are those of the parent fluid.

Hydrous clays of altered host rocks were not separate from sedimentary clays and therefore were unsuitable for isotopic analysis. Whole-rock samples of altered igneous dike rocks were analyzed for δD, giving data on the fluids that altered the dikes. The hydrous dike minerals were almost entirely sericite and kaolinite, which presumably formed at about the same time as the hydrothermal clays in the unoxidized ores during main-stage mineralization.

The δD values of fluids from inclusions and of clays are strongly negative, ranging from −139 to −160 per mil (Table 6). Such low values are consistent with negative δD values of rainwaters during the Tertiary in the Great Basin, indicating that the fluid that deposited the vein minerals and altered minerals in the dikes to clays, was dominantly of meteoric origin. Inasmuch as the times of dike alteration and vein formation spanned the hydrothermal episode, we conclude that the main-stage mineralizing fluids were likewise of meteoric origin. Isotopic studies of the 35-m.y.-old Cortez gold deposit (Wells et al., 1971) led to the same conclusion (Rye et al., 1974). Studies of other epithermal gold deposits of the basin-and-range province have demonstrated the active role of meteoric water as an ore-depositing fluid (O'Neil and Silberman, 1974).

Oxygen isotope data

Materials analyzed for oxygen isotopic composition include calcite, dolomite, and chert from unaltered rocks, remnant calcite and dolomite from mineralized rocks, jasperoid and quartz veinlets from hydrothermally altered rocks, calcite and dolomite from acid-leached and oxidized rocks, and barite and calcite from late veins.

Unaltered host rocks: Samples of unmineralized rock from the Roberts Mountains Formation were collected at several localities within 2 km west and southeast of the Carlin deposit and within the de-

TABLE 7. The $\delta^{18}O$ and $\delta^{13}C$ Values of Calcite and Dolomite in Samples of Unaltered Roberts Mountains Formation

			Calcite		Dolomite			
Sample no.	Facies type[1]	Location	$\delta^{18}O$‰	$\delta^{13}C$‰	$\delta^{18}O$‰	$\delta^{13}C$‰	Calcite/ dolomite	Weight percent CO_2
DSrm-1	1	1 mile SE of deposit	21.2	0.4	22.5	0.2	1.3	29.9
DSrm-3	1	0.75 miles SE of deposit	22.5	0.6	23.0	0.3	0.8	30.5
DSrm-1A	2	1 mile SE of deposit	18.6	0.6	24.1	0.4	16.8	34.3
DSrm-4	2	0.5 miles W of deposit	12.6	−0.1			Very large	36.5
5607-Ja	2	Main pit of Carlin deposit	16.3	0.8			Very large	40.6

In calcite and dolomite columns, all $\delta^{18}O$‰ values are relative to SMOW and all $\delta^{13}C$‰ values are relative to PDB.

[1] Type 1, laminated argillaceous, arenaceous dolomite; type 2, laminated arenaceous, peloid wackestone.

posit for $\delta^{18}O$ analyses of calcite and dolomite (Table 7). Samples were taken of both lithologic types (the arenaceous dolomite, favorable for ore deposition, and the unfavorable arenaceous peloid wackestone). For comparison samples were taken within the deposits of remnant unaltered rock of the Roberts Mountains Formation and overlying Popovich Formation (Tables 7 and 8).

The $\delta^{18}O$ values of calcite in unaltered arenaceous dolomite collected away from the deposit ranged from 21.2 to 22.5 per mil; corresponding values for dolomite were 22.5 and 23.0 per mil. These values are similar to values reported by Rye et al. (1974, table 4) for samples of unaltered Roberts Mountains Formation near the Cortez deposit.

The $\delta^{18}O$ values of calcite in unaltered arenaceous peloid wackestone both within and away from the deposit range from 12.6 to 18.6 per mil; the $\delta^{18}O$ of dolomite in one sample that contained enough dolomite to be separated was 24.0 per mil. The $\delta^{18}O$ values of these rocks are significantly lower than those of the arenaceous dolomite and presumably reflect a difference in diagenetic and/or depositional histories. No differences attributable to hydrothermal alteration were found in the wackestone units.

Seams of sedimentary chert occur throughout the Roberts Mountains Formation; they are abundant and well exposed in the main ore zone. The $\delta^{18}O$ values for chert range from 24.0 to 25.2 per mil, typical of early Paleozoic sedimentary cherts (Knauth and Epstein, 1976); they differ distinctly from the hydrothermal jasperoid and quartz veins in the deposit (Table 9).

Hydrothermally altered and mineralized rocks: The $\delta^{18}O$ values of calcite and dolomite of mineralized and hydrothermally altered rock of the Roberts Mountains Formation from a 900-ft (270-m) vertical drill hole in the east ore zone, collared in the Popovich Formation, and which bottomed about 800 ft (240 m) in the Roberts Mountains Formation, are shown in Table 10. The samples from the upper 150 ft (45 m) were oxidized. Table 10 also

TABLE 8. The $\delta^{18}O$ and $\delta^{13}C$ Values of Calcite and Dolomite in Samples of Unmineralized, Progressively Leached and Oxidized, Roberts Mountains Formation (DSrm) and Popovich Formation (Dp).

			Calcite		Dolomite			
Sample no.	Sample distance from fault (ft)	Description	$\delta^{18}O$‰[1]	$\delta^{13}C$‰[2]	$\delta^{18}O$‰[1]	$\delta^{13}C$‰[2]	Calcite/ dolomite	Weight percent CO_2
5607-Ja	100	Unaltered type 2 DSrm[3]	16.3	0.8			50.6	40.6
6979-La	90	Slightly altered type 2 DSrm[3]	15.7	−0.6			55.9	38.4
5607-Jc	60	Weakly altered type 2 DSrm[3]	13.9	−0.9			17.9	35.3
5607-Jd	40	Moderately altered type 1 DSrm[3]	12.7	−1.9	—[5]	—[5]	2.1	23.5
6979-Lb	20	Strong altered type 1 DSrm[3]	13.4	−1.7	25.2	−0.4	1.4	14.1
5608-Jb	10	Very strongly altered, probably type 1 DSrm[3]			24.3	−0.5	<1.0	9.5
5608-Ja	0	Intensely leached and oxidized DSrm[3]						0.03
6968-L1	10	Unaltered Dp[4]	18.3	0.1	25.9	0.3	1.6	33.3
6968-L2	0	Slightly altered Dp[4]	18.5	0.3	26.0	0.1	1.3	31.4

[1] All $\delta^{18}O$‰ values relative to SMOW.

[2] All $\delta^{13}C$‰ values relative to PDB.

[3] Sample suite from 6300 bench in Main pit.

[4] Sample suite from 6400 bench in West pit.

[5] Lost.

TABLE 9. The $\delta^{18}O$ Values in Samples of Chert, Jasperoid, Quartz Veinlets, and Barite Veins

Sample no.	Ore zone	Location	Elevation	Description	$\delta^{18}O$‰	Calculated $\delta^{18}O$‰ of depositing fluids[1]				
						175°C	200°C	225°C	250°C	275°C
				Chert						
5611-J	Main	21,850 N; 17,450 E	6,325	Black chert seam in moderately leached DSrm[2]	25.2					
3532-M	Main	22,050 N; 17,750 E	6,330	Black chert seam in strongly leached DSrm	25.1					
5608-J	Main	21,650 N; 17,650 E	6,340	Black chert seam in weakly leached DSrm	24.0					
				Jasperoid						
5630-J	West	21,910 N; 15,575 E	6,650	Dense black jasperoid with quartz veinlets in surface outcrop (see below)	16.5	1.4	3.3	4.9		
58-J	West	21,950 N; 15,995 E	6,570	Dense dark gray jasperoid	13.0	−2.1	−0.2	1.4		
6964-Lb	West	21,980 N; 16,025 E	6,430	Silicified limestone with visible remnant bedding; 30 ft from fault	13.3	−1.8	−0.1	1.7		
6964-Lc	West	21,975 N; 16,035 E	6,430	Heavily silicified limestone with faint remnant bedding; 15 ft from fault	14.6	−0.5	1.4	3.0		
6964-Ld	West	21,970 N; 16,045 E	6,430	Massive jasperoid; 5 ft from fault	14.9	−0.2	1.7	3.3		
11-J	Main	21,655 N; 18,540 E	6,545	Brown jasperoid	18.1	3.7	4.9	6.5		
5136-J	Main	21,380 N; 17,045 E	6,465	Red jasperoid	13.8	−1.3	0.6	2.2		
AR-J2	Main	22,195 N; 18,395 E	6,360	Gray-black jasperoid	16.2	1.1	3.0	4.6		
AR-J3	Main	22,225 N; 19,180 E	6,510	Gray-black jasperoid	16.6	1.5	3.4	5.0		
3526-M	East	23,050 N; 22,000 E	6,420	Jasperoid containing minor gold and coarse-grained stibnite	9.3	−5.8	−3.9	−2.3		
6952-Lb1	East	24,075 N; 21,000 E	6,320	Jasperoid with high gold (siliceous-type ore)	15.8	−0.7	2.6	4.2		

TABLE 9—(*Continued*)

Sample no.	Ore zone	Location	Elevation	Description	$\delta^{18}O$‰	Calculated $\delta^{18}O$‰ of depositing fluids[1] 175°C	200°C	225°C	250°C	275°C
				Quartz veinlets						
Q-1	East	23,000 N; 19,900 E	6,360	Quartz veinlets with hydrocarbons, pyrite, gold, and associated elements (main stage 2)	19.1	4.0	5.9			
Q-2	East	23,100 N; 20,250 E	6,400	Quartz veinlets with partially oxidized pyrite, gold, and associated elements (main or late stage 2)	18.5	3.4	5.3			
XI	Main	22,270 N; 18,350 E	6,340	Quartz veinlet with minor sulfides (stage 2)	18.1	3.0	4.9			
Q-A	East	23,800 N; 20,750 E	6,325	Quartz veinlets with pyrite, fluorite, frankdicksonite, and gold (late stage 2 or early stage 3)	21.8		8.6	10.2	11.5	
5630-J	West	21,910 N; 15,575 E	6,650	Quartz veinlets cutting jasperoid in surface outcrop (see above) (stage 3)	20.5		7.3	8.9	10.2	
35-J	Main	21,905 N; 18,455 E	6,430	Quartz with barite vein (stage 3)	19.5		6.3	7.9	9.2	10.3
109-J	Main	22,290 N; 18,600 E	6,505	Quartz veinlet cutting(?) barite vein (see below) (stage 3)	18.6			7.0	8.4	9.4
51-J	Main	22,510 N; 18,400 E	6,400	Quartz patches with realgar in barite vein	20.4				10.1	11.2
3512-M	Main	22,700 N; 18,860 E	6,580	Quartz seams in barite vein	18.8			7.2	8.7	9.6
6967-L	West	22,300 N; 15,450 E	6,430	Quartz interlocked with barite in vein	19.5		6.3	7.9	9.2	10.3
				Barite veins						
38-J	Main	21,605 N; 18,650 E	6,610	Barite vein lacking sulfide	9.6				5.4	6.4
109-J	Main	22,290 N; 18,600 E	6,505	Barite vein with quartz (see above)	12.0				7.8	8.8
3512-M	Main	22,700 N; 18,860 E	6,580	Barite vein with sphalerite	14.2				10.0	11.0
5632-J	Main	22,520 N; 18,260 E	6,300	Barite vein with galena	12.2				8.0	9.0

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[1] Calculated from the curves of Taylor (1974) and Kusakabe and Robinson (1977), from data in Table 5, and probable depositional temperatures. Use of the curve of Clayton et al. (1972) for quartz water fractionations will result in $\delta^{18}O_{H_2O}$ values about 1‰ larger, whereas use of the extrapolated curve of Bottinga and Javoy (1973) will result in $\delta^{18}O_{H_2O}$ values about 1‰ smaller.

[2] DSrm = Roberts Mountains Formation.

TABLE 10. The $\delta^{18}O$ and $\delta^{13}C$ Values of Calcite and Dolomite and Chemical Data on Samples from a Drill Hole through Mineralized Popovich Formation and Roberts Mountains Formation in the East Ore Zone

Depth (ft)	Description	Calcite		Dolomite		Calcite/ dolomite mole ratios	Weight percent			Au oz/ton
		$\delta^{18}O$‰	$\delta^{13}C$‰	$\delta^{18}O$‰	$\delta^{13}C$‰		CO_2	SiO_2	Al_2O_3	
150–160	Oxidized Dp	14.8	−0.8	24.8	0.2	2.8	23.4	33.8	6.6	trace
440–445	Unoxidized DSrm	13.9	−0.2	20.9	1.13	2.8	27.9	23.3	6.5	0.08
500–505	"	18.0	−1.3	24.5	−0.1	1.1	35.6	17.5	1.8	0.01
570–585	"	16.9	−0.3	23.5	0.4	0.12	22.6	31.5	8.8	trace
610–620	"			21.5	0.1	0.15	25.6	33.4	3.3	0.04
690–700	"	15.8	−0.6	?	?	0.23	12.3	57.4	6.2	0.48
865–880	"			19.4	0.4	0.38	3.5	72.3	5.9	0.01

Samples were from rotary drill hole P-8 located at: 24,018 N; 20,233 E. All DSrm samples are arenaceous dolomite (type 1 facies).

includes the contents of Au, CO_2, SiO_2, and Al_2O_3, and the calcite to dolomite mole ratios of the samples. Abundance of calcite diminished strongly with depth and quartz increased. The gold content showed no correlation with the amount of silica present. Most of the rocks from this drill hole contained more than 0.3 weight percent organic carbon. The $\delta^{18}O$ values of calcite in mineralized rock ranged from 13.9 to 18.0 per mil, distinctly lower than $\delta^{18}O$ values of unaltered type 1 facies, indicating that the remnant calcite exchanged oxygen with the ore-forming fluids during recrystallization. Previous work has shown that oxygen isotope exchange in wall-rock carbonates is dependent upon the degree of recrystallization (Pinckney and Rye, 1972). Petrographic examination indicates that calcite in all of the samples has undergone recrystallization.

The $\delta^{18}O$ values of dolomite ranged from 19.4 to 24.5 per mil, suggesting that some dolomite probably also underwent limited recrystallization and isotope exchange. This result agrees with petrographic evidence; dolomite rhombs commonly exhibit corroded borders, and some show peripheries replaced by silica.

Acid-leached and oxidized rocks: The $\delta^{18}O$ values of calcite and dolomite of samples from a stratigraphic interval of the Roberts Mountains Formation from the 6300 level along the northwest boundary of the main ore zone, taken perpendicular to a fault, where the rocks showed progressively less acid-leaching effects away from the fault, are given in Table 8. The sample suite is not ideal because the facies change from type 1 to type 2 rocks. The $\delta^{18}O$ values of dolomite were 24.3 to 25.2 per mil, which are typical of unaltered rocks, and which are in accord with the lack of exchange expected for unrecrystallized dolomite. The $\delta^{18}O$ values of calcite in the altered type 1 and type 2 rocks were 12.7 to 15.7 per mil, which is within the lower part of the range of values observed in unoxidized ore (Table 10).

The $\delta^{18}O$ values of calcite increase progressively from the most intensely leached and oxidized rock at the fault to unaltered rock. Petrographic study indicates that the degree of recrystallization of remnant calcite increases in the most altered rocks near the fault. It is not known if recrystallization and isotope exchange occurred mainly during acid-leaching oxidation or earlier during main-stage mineralization. The $\delta^{18}O$ values of calcite in the leached rocks are within the range of those of calcite in unoxidized ores and indicate that mineralization and acid-leaching oxidation in the upper part of the deposit were a product of isotopically similar fluids or that acid-leaching oxidation was not accompanied by significant isotopic exchange with remnant calcite in the host rock. The average $\delta^{18}O$ of the recrystallized calcite in the host rock is less than the average values for quartz veinlets and jasperoid, indicating that the calcite in the host rocks probably obtained approximate equilibrium with the main-stage hydrothermal fluids at the temperatures of mineralization.

Unleached oxidized rocks: Data presented in Table 11 show the isotopic effects on calcite and dolomite in mineralized parts of the Roberts Mountains Formation during acid-leaching oxidation and late posthydrothermal supergene oxidation. The suite of samples was collected from the main ore zone at approximately the same map locality, at successively higher levels; they included unoxidized ore, oxidized ore, and oxidized acid-leached ore. Calcite had been removed from the acid-leached oxidized samples. The $\delta^{18}O$ of calcite of the unleached, weakly oxidized sample was 15.4 per mil compared to 16.3 per mil for the underlying unoxidized ore, within the range of $\delta^{18}O$ values of unoxidized ore in general (Table 10). The data are consistent with a negligible effect of supergene oxidation on $\delta^{18}O$ values of host rock and ore. Petrographic evidence likewise indicates that little recrystallization or removal of calcite took place during supergene oxidation.

Quartz veinlets: Of the various types of hydrothermal silica at Carlin, only jasperoid and sparsely developed quartz veinlets were suitable for isotopic analyses. The dispersed fine-grained quartz and the tiny seams of quartz in unoxidized ores, unfortunately, could not be separated from quartz of sedimentary origin. The quartz veinlets analyzed included those formed during main- and later-stage mineralization (stage 2) and the acid-leaching oxidation stage (stage 3). The $\delta^{18}O$ values of all veinlets range from 18.1 to 21.8 per mil, with the largest values in those formed during stage 3. The $\delta^{18}O$ values of the quartz veinlets, including those of stage 3 which probably were contemporaneous with much jasperoid, are generally larger and more uniform than the values for the jasperoids. The difference in $\delta^{18}O$ values of the two forms of silica probably reflects the influence of variable water-rock ratios on the $\delta^{18}O$ of the fluids in veinlet and replacement-type processes.

Fluid inclusion data (Table 5) indicate temperatures of 175° to 200°C for stage 2 and up to 250° to 300°C for stage 3 fluids. Calculated $\delta^{18}O$ values of stage 2 fluids that deposited quartz between 175° and 200°C range from 3.0 to 5.9 per mil and those of stage 3 fluids that deposited quartz between 250° and 275°C range from 8.7 to 11.5 per mil (Table 9). The larger $\delta^{18}O$ for stage 3 fluids is consistent with the widespread boiling of the hydrothermal fluids indicated by fluid inclusion evidence.

Jasperoid: The $\delta^{18}O$ values for jasperoid, with one exception, ranged from 13.0 to 18.1 per mil (Table 9). No systematic vertical variations were observed. The $\delta^{18}O$ values of three heavily silicified samples from the west pit collected at the same level, from 5 to 30 ft (2–9 m) away from a fault, regularly decreased. This probably reflects increasing exchange with low $\delta^{18}O$ original carbonate in the host rock.

The $\delta^{18}O$ values of the jasperoids are difficult to interpret because data on their temperatures of formation are sparse. A few suitable fluid inclusions out of hundreds examined in jasperoid samples suggest homogenization temperatures of about 185° to 235°C. These temperatures are reasonable in view of the apparent position of most jasperoids in the paragenesis. Regardless of their depositional temperatures, the $\delta^{18}O$ values of the jasperoids are lower than those of vein quartz and the $\delta^{18}O$ values of hydrothermal fluids in equilibrium with the jasperoids are lower than those of vein quartz at equivalent temperatures (Table 9). This is consistent with smaller water/rock ratios during jasperoid formation than during quartz vein deposition.

All values are compatible with meteoric-water-dominated hydrothermal fluids that were modified to different degrees by exchange with the carbonate host rock. The differences of $\delta^{18}O$ in the jasperoid listed in Table 9 are difficult to interpret in terms of local factors. They may reflect variations in the isotopic composition of water due to mixing of deep and shallow meteoric waters, boiling of fluid, or variations in amounts of exchange with wall rock, or differences in temperature from place to place. One unusually low value, 9.3 per mil, was found in brecciated jasperoid from a prominent fault zone. Presumably near-surface water of low $\delta^{18}O$ content was able to penetrate along the fault.

Barite veins: The $\delta^{18}O$ values determined on four samples of barite from veins from different levels in the upper part of the deposit showed a narrow range, from 9.6 to 14.2 per mil (Table 9). No systematic variations were observed. In contrast to the $\delta^{18}O$ of the jasperoid, the smallest $\delta^{18}O$ values were in barite samples high in the deposit.

The $\delta^{18}O$ values for water in equilibrium with barite were calculated for depositional temperatures of 250° and 275°C, using data of Kusakabe and Robinson (1977). The calculated values, 5.4 to 11.0 per mil, are within the range of calculated $\delta^{18}O$ for fluids from coexisting quartz and the large values are consistent with widespread boiling of fluids during barite deposition.

Calcite veins: Calcite veins and veinlets are abundant in oxidized host rocks and ores in upper levels of the deposit in the Roberts Mountains Formation and in the overlying Popovich Formation; calcite veinlets are very sparse in the acid-leached rocks. Small scattered veinlets and pods of calcite occur

TABLE 11. The $\delta^{18}O$ and $\delta^{13}C$ Values of Calcite and Dolomite in Samples across Interfaces between Unoxidized-Oxidized and Unleached Oxidized-Leached Oxidized Zones in Mineralized Roberts Mountains Formation (DSrm), Main Ore Zone

Sample number	Elevation	Description	Calcite $\delta^{18}O$‰	Calcite $\delta^{13}C$‰	Dolomite $\delta^{18}O$‰	Dolomite $\delta^{13}C$‰	Calcite/ dolomite	Weight percent CO_2
3504-M	6,340	Acid leached-oxidized type 1 DSrm gold ore			24.0	0.3	0	16.0
3505-M	6,300	Unleached weakly oxidized type 1 DSrm gold ore	15.4	0.2	22.1	0.3	1.5	26.0
3506-M	6,280	Unoxidized type 1 DSrm gold ore	16.3	0.9	23.0	0.1	1.0	26.0

Location: 22,500 N; 18,350 E.

TABLE 12. The δ^{18}O and δ^{13}C Values of Calcite in Veins

Sample number	Ore zone	Location	Elevation	Description	δ^{18}O‰[1]	δ^{13}C‰[2]
5116-J	West	22,230 N; 15,790 E	6,460	In altered oxidized ore	10.6	−0.4
3501-M	West	22,225 N; 15,800 E	6,400	Massive vein near DSrm-Dp[3] contact	13.3	−0.6
73-J	Main	22,780 N; 18,850 E	6,610	Vein in Dp	2.5	0.4
AR-C3a	Main	21,575 N; 16,925 E	6,320	Small crystals in vug in oxide ore	5.9	0
6979-La	Main	22,105 N; 17,910 E	6,300	In fracture in oxidized rocks below leached zone	14.8	−0.2
6990-J	Main	22,700 N; 19,000 E	6,220	In fracture in unoxidized ore	12.3	−6.2
AR-C4a	East	23,250 N; 20,200 E	~6,600	In surface outcrop of Dp	22.9	−1.0

[1] All δ^{18}O‰ values relative to SMOW.
[2] All δ^{13}C‰ values relative to PDB.
[3] DSrm = Roberts Mountains Formation, Dp = Popovich Formation.

in upper levels of the underlying unoxidized ore zones.

The δ^{18}O values of samples of vein calcite in shallow oxidized rocks range from 2.5 to 22.9 per mil (Table 12). One sample of veinlet calcite from deep unoxidized mineralized rock had a δ^{18}O value of 12.3 per mil.

Interpretation of the calcite data is complicated by the lack of fluid inclusions suitable for filling temperature measurement. The very large value of 22.9 per mil probably reflects deposition at low temperature (<70°C, Table 5). The very low values of 2.5 and 5.9 per mil observed for calcite from a near-surface vein in the Popovich Formation and from a late vug, respectively, probably reflect deposition from shallow surface water. Most of the intermediate values in Table 12 are within the range of values of remnant recrystallized calcite in mineralized rocks. Possibly some of this vein calcite was derived from host rocks at deep levels during mineralization and was reprecipitated at higher levels because of loss of CO_2 during boiling. Most of the calcite, however, was probably derived from the acid-leached zone.

The calculated δ^{18}O values of the fluids that deposited calcite in the unoxidized mineralized zone, using filling temperatures of 175° to 200°C, range from 0.8 to 2.8 per mil. These values are consistent with the calculated values for exchanged meteoric fluids that deposited some of the jasperoid.

Conclusions from hydrogen and oxygen isotope data

1. The δD values in altered igneous dikes and fluid inclusions in quartz and the δ^{18}O values of main and late stage 2 quartz and jasperoid indicate that the main-stage hydrothermal fluids were highly exchanged meteoric waters with δ^{18}O values which varied through time and space. The variations reflect differences in degree of exchange with host rocks, mixing with local ground waters, different water/rock ratios, and perhaps initial boiling in late stage 2 fluids.

2. The δ^{18}O data of barite and associated stage 3 quartz indicate that the δ^{18}O of the hydrothermal fluids increased during later acid leaching and oxidation in the upper part of the deposit. This increase probably resulted largely from boiling of the fluids.

3. The δ^{18}O values of calcite veins fall into three groups, reflecting different origins of the material. Veins with high δ^{18}O values formed at low temperatures from hydrothermal fluids. Veins with low δ^{18}O values formed from low-temperature ground waters. Calcite veins with intermediate δ^{18}O values were probably formed from calcite dissolved out of carbonate rocks in the acid-leached zone by the hydrothermal fluids and precipitated at higher levels in response to loss of CO_2 during boiling. Some of this calcite may have originated from deeper levels below the acid-leached zone.

4. The degree of isotopic alteration of the carbonate minerals is related to the degree of recrystallization of these minerals in the altered rocks. Carbonate minerals in type 2 facies unfavorable for mineralization are usually unrecrystallized and retain primary δ^{18}O values. In contrast, calcite in the favorable type 1 facies usually shows some recrystallization, and the degree of this and attendant ^{18}O exchange is related to distance from structures which served as solution conduits. Dolomite in type 1 facies is only very weakly recrystallized and shows little attendant isotopic exchange.

5. Most of the recrystallization and isotopic exchange in carbonate minerals in the host rocks apparently took place during main-stage mineralization and prior to leaching and oxidation. Posthydrothermal supergene oxidation had no detectable effect on the δ^{18}O values of either calcite or dolomite in the host rocks.

Carbon isotope data

Host rocks and ores: The $\delta^{13}C$ values of calcite and dolomite of the samples in Tables 7, 8, 10, and 11 are in the range of $\delta^{13}C$ values for unaltered marine carbonates. Inasmuch as the solutions exchanged ^{18}O with recrystallizing calcite and are known from fluid inclusion studies to have contained CO_2, it is reasonable to expect that they likewise would exchange ^{13}C with calcite. The similarity of the $\delta^{13}C$ of recrystallized calcite in altered rocks (in the range of 175°–200°C) to that of calcite in unaltered host rocks probably means that the ^{13}C content in solution was about the same as that of the host rocks, as shown by fractionation curves of Bottinga (1968); that CO_2/CH_4 ratios in the fluids were large; and that much of the carbon in solution was derived from the host rocks.

Calcite veins: The range of $\delta^{13}C$ values for most calcite veinlets is very narrow, −1.0 to 0.4 per mil (Table 12). These values are typical of the $\delta^{13}C$ values observed in altered and unaltered host rocks (Tables 7, 8, 10, and 11).

The interpretation of the $\delta^{13}C$ data is hampered by lack of sufficient temperature data on the calcites. It was previously suggested, however, that the $\delta^{18}O$ data can be used to recognize different generations of calcite. For those calcites precipitated at hydrothermal temperatures (possibly samples 3501M and 6979LA), their carbon was probably derived by solution of calcite from deeper levels of the carbonate rock sequence. For those calcites precipitated at low temperatures such as AR-C4A and probably 73J and AR-C3A (Table 5), the $\delta^{13}C$ values of the carbon in their parent fluids were probably considerably lower than those in the calcites and were probably partly derived from the oxidation of organic matter during the formation of the acid-leached zones in the upper part of the deposit.

The only main-stage carbonate that was analyzed (6990-J, Table 5) has a $\delta^{13}C$ value of −6.2 per mil. The carbon for this calcite was probably also partly derived from organic matter in the host rocks.

Sulfur isotope data

The sulfur isotope compositions of Carlin sulfide and sulfate minerals were determined to obtain data on temperatures of ore deposition, on possible sources of sulfur, and to estimate some chemical parameters during ore deposition (Table 13). Materials analyzed included diagenetic pyrite from the host rocks; hydrothermal pyrite from ore; hydrothermal realgar, stibnite, sphalerite and galena from veins; and barite from veins.

Host rocks: Most of the sulfur in the sedimentary carbonate rocks is in diagenetic pyrite; much smaller amounts are in dispersed barite and carbonaceous material. Host rocks contain as much as 1.0 weight percent diagenetic pyrite and up to 0.8 weight per-

TABLE 13. The $\delta^{34}S$ Values of Diagenetic Pyrite, Hydrothermal Sulfide Minerals, Barite, and Calculated Isotopic Temperatures

Sample number	Ore zone	Location	Elevation	$\delta^{34}S$‰[1]		T°C[2]	T°C[3]
				Barite	Sulfide minerals		
114-J	West	22,045 N; 15,815 E	6,530	29.0			
6960-L	West	22,210 N; 16,790 E	6,505	30.4			
5632-J	Main	22,520 N; 18,260 E	6,300	29.8	6.5 (galena)	300	284
51-J	Main	22,510 N; 18,400 E	6,400	30.3	15.2 (realgar)		
5109-J	Main	22,550 N; 18,380 E	6,360	31.4	5.1 (galena)	270	251
3512-M	Main	22,700 N; 18,860 E	6,580	31.2	10.1 (sphalerite)	300	285
5633-J	Main	22,410 N; 18,260 E	6,260	31.7	10.7 (sphalerite)	305	288
35-J	Main	21,905 N; 18,455 E	6,430	30.6			
38-J	Main	21,605 N; 18,650 E	6,610	29.1			
109-J	Main	22,290 N; 18,600 E	6,505	27.8			
3526-M	East	23,050 N; 20,000 E	6,420		8.7 (stibnite)		
6955-Le	Main	22,440 N; 18,300 E	6,300		4.2 (pyrite in ore)		
6956-Lb	East	23,200 N; 20,600 E	6,360		16.1 (pyrite in ore)		
3523-M	East	23,880 N; 20,650 E	6,300		9.7 (pyrite in mineralized dikes)		
Q-A	East	23,800 N; 20,750 E	6,325		15.4 (pyrite in quartz veinlet)		
DSrm-1		1 mile SE of deposit			11.7 (diagenetic pyrite)		
DSrm-2		3 miles NW of deposit			14.3 (diagenetic pyrite)		

[1] Relative to Cañon Diablo troilite.

[2] Calculated from Ohmoto and Rye (1978).

[3] Calculated from experimental value of +20.0‰ for $\Delta^{34}S$ ($\delta^{34}S_{sulfate} - \delta^{34}S_{sulfide}$) in aqueous solution at 300°C and 1,000 bars, from Sakai and Dickson (1978).

cent organic carbon. The carbonaceous material commonly contains over 10 weight percent sulfur.

Bedded barite, common in lower Paleozoic carbonate rocks in many areas in north-central Nevada, has not been recognized in the vicinity of the Carlin deposit; barite in the carbonate rocks below the deposit is fine grained and dispersed. The amount of barium in these unaltered rocks is about 200 to 300 ppm.

Two $\delta^{34}S$ values for diagenetic pyrite in the Roberts Mountains Formation near the Carlin deposit were 11.7 and 14.3 per mil (Table 13). Rye et al. (1974) reported a value of 11.4 per mil for diagenetic pyrite from unmineralized parts of the Roberts Mountains Formation several kilometers northwest of the deposit. No data are available on the isotopic composition of the sulfur associated with the organic material in the rocks. However, Thode and Monster (1965) reported that H_2S derived from sulfur in organic compounds such as petroleum tends to be 15 ± 5 per mil lower than that of sea-water sulfate. Since the $\delta^{34}S$ of sea-water sulfate during Roberts Mountains sedimentation was probably 25 to 30 per mil (Holser and Kaplan, 1966), the $\delta^{34}S$ of any H_2S derived from the organic material would have been close to and indistinguishable from that of diagenetic pyrite. Attempts to leach SO_4 from unaltered Paleozoic carbonate rocks near the deposit containing minor amounts of disseminated barite were not successful. However, bedded and disseminated barite in early Paleozoic carbonate rocks of Nevada (Rye et al., 1978) have average values of 30 per mil.

Hydrothermal sulfides and barite: The $\delta^{34}S$ data on the disseminated hydrothermal pyrite in most types of gold ore at Carlin must be interpreted carefully, because the ores contain variable amounts of remnant fine-grained diagenetic pyrite, which cannot be separated cleanly from hydrothermal pyrite. However, values of 4.2 and 16.1 per mil (Table 13) were of pyrite from pyritic-type ore, in which over 90 percent of the pyrite was of hydrothermal origin. Other values for hydrothermal pyrite include 9.7 per mil for pyrite from an altered mineralized dike, and 15.4 per mil for pyrite from a small quartz veinlet containing some metallic gold. The range of $\delta^{34}S$ values for the hydrothermal pyrite is consistent with a common sulfur source for both veins and disseminated sulfides.

Barite veins, common in both the west and the main ore zones but sparse in the east ore zone, lack sulfides in most places. However, at deep levels near the bottom of the oxidized rocks in the main and east ore zones, barite veins contain local concentrations of sphalerite, galena, and realgar. Associated with realgar are small amounts of sulfides and sulfosalts of Hg, As, Sb, and Tl (Dickson and Radtke, 1977). Several small barite veins containing minor amounts of stibnite were recognized at the surface before mining (R. B. Fulton, oral commun., 1972).

The $\delta^{34}S$ values of sulfides in the veins range from 5.1 to 15.2 per mil, but in contrast to pyrite values, the $\delta^{34}S$ values in other individual sulfide minerals show little variability. The $\delta^{34}S$ values of barite ranged from 27.8 to 31.7 per mil (Table 13), in keeping with values reported for barite from several other Carlin-type deposits (Dickson et al., 1975a). No significant differences exist in $\delta^{34}S$ values of materials from the main and west ore zones.

Deposition temperatures calculated from $\delta^{34}S$ data on galena-barite and sphalerite-barite mineral pairs, using the data of Rye and Ohmoto (1974), were 270° to 305°C; using recent experimental data of Sakai and Dickson (1978), the calculated temperature range was somewhat lower, 251° to 288°C. These data are in excellent agreement with fluid inclusion temperatures of vein barite and associated quartz and sphalerite. However, this agreement may be fortuitous if, as suggested below, the sulfate-sulfide sulfur isotope relationships were governed by disequilibrium relationships.

Origin of the sulfur: Sulfur in the Carlin deposit occurs dominantly as sulfide in hydrothermal pyrite of the orebodies and subordinately as sulfate, most of which is in barite in veins. Any discussion of the origin of the sulfur in the deposit requires that the $\delta^{34}S$ values be interpreted in terms of the $\delta^{34}S$ of the sulfur in the hydrothermal fluids during deposition of the sulfide minerals. This in turn requires a knowledge of the physical/chemical environment of ore deposition including such variables as temperature, pH, and f_{O_2} of the ore fluids (Ohmoto, 1972). Fluid inclusion data indicate temperatures of 175° to 200°C during main-stage mineralization, rising to 275°C or higher during barite vein formation. The presence of sericite and kaolinite in the unoxidized ores and the dissolution of calcite suggest mildly acid conditions and the presence of hydrocarbon compounds in the country rocks and in the hydrothermal fluids indicates that the oxygen fugacity of the fluids was low enough for the fluids to be H_2S dominant. For H_2S-dominant fluids the $\delta^{34}S$ of sulfur in solution can be deduced from the $\delta^{34}S$ data on pyrite and sphalerite to average about 10 per mil (Ohmoto and Rye, 1979). This value requires a sedimentary source for most of the hydrothermal sulfide sulfur. The range of $\delta^{34}S$ values in the hydrothermal pyrites suggests either mixing of sulfur sources or an isotopically heterogeneous source as would be typical of most sedimentary sources.

The average $\delta^{34}S$ of barite in the veins at Carlin is about 30 per mil. This value agrees closely with values for barites in eight other Carlin-type deposits which range from 27 to 30 per mil (Dickson, Radtke, and Rye, unpub. data) and indicate a sedimentary origin for the sulfate sulfur (Dickson et al., 1975a). The marked similarities of the $\delta^{34}S$ values of sulfate sulfur among these deposits suggest a remarkable common sulfur isotope geochemistry.

The sulfur in the sulfate may have been derived from ~10 per mil sulfide sulfur by high-temperature equilibrium distribution of sulfur species in the hydrothermal fluids (Ohmoto, 1972). The excellent agreement between sulfide-sulfate temperatures (Table 13) and fluid inclusion filling temperatures (Table 5) supports this possibility. However, since the carbonate rocks below the deposit contain significant amounts of organic material, and the hydrothermal fluids in equilibrium with the rocks transported organic material, these fluids would have only low levels of sulfate in solution. If most of the organic material along the deep plumbing system was removed by the beginning of late-stage hydrothermal activity, the f_{O_2} of the fluids would increase permitting transport of sulfate in solution. Unfortunately, no data are available on the deep carbonate rocks directly below the deposit.

As discussed earlier, the $\delta^{34}S$ value of 30 per mil is within the range of values of bedded and disseminated barite widespread in north-central Nevada in the early Paleozoic section (Rye et al., 1978; R. O. Rye, unpub. data), and the value is close to the composition of lower Paleozoic sea-water sulfate (Holser and Kaplan, 1966). It is possible, therefore, that the sulfate sulfur in barite in the deposit was derived from dispersed sedimentary barite in carbonate rocks below the deposit and that its $\delta^{34}S$ was not altered by exchange with sulfide in the hydrothermal system. This would imply that the close agreement between temperatures calculated from sulfide-sulfate pairs in the vein in Table 13 and those measured for fluid inclusions in veins minerals is fortuitous. Disequilibrium is not uncommon in the sulfate sulfur hydrothermal systems at low temperatures (Rye and Ohmoto, 1974). A final solution to the origin of the sulfate sulfur may be resolved from studies of other Carlin-type deposits.

Boiling of the hydrothermal solutions in fractures with silicified walls resulted in the preferential loss of H_2S and the enrichment of SO_4 relative to H_2S in the fluids. This process could separate the sulfur species without changing the isotopic composition of either. The pH of the fluids in fractures during boiling would rise because of loss of H_2S and CO_2. Oxidation of H_2S in turn produced very acid high f_{O_2} waters in the shallow acid-leached zone.

Small amounts of anhydrite occur in rocks near the surface where SO_4 created by oxidation of H_2S reacted with carbonate minerals. Unfortunately, most of the anhydrite had been dissolved by low-temperature ground waters and no samples were found which contained sufficient amounts of anhydrite for isotopic analysis. Since the oxidation of H_2S under near-surface conditions should occur without isotopic fractionation, anhydrite formed in this way should have a $\delta^{34}S$ of about 10 per mil (Schoen and Rye, 1970).

Conclusions from carbon and sulfur isotope data

1. Most of the carbon in the hydrothermal fluids was derived mainly from the solution of host rock carbonates. During acid-leaching oxidation a considerable amount of organic carbon was added to the shallow fluids in the upper part of the deposit.
2. The sulfur in the deposit was derived mostly from sedimentary sulfide in underlying Paleozoic sedimentary rocks. The sulfur in the late barite veins was derived either from sedimentary sulfide or from sedimentary barite, depending upon whether equilibrium or disequilibrium relationships predominated in the hydrothermal system.
3. Boiling of solutions in fractures with silicified walls separated H_2S from solution and concentrated SO_4 relative to H_2S, without changing the isotopic composition of either. The oxidation of the H_2S led to the production of H_2SO_4, the subsequent leaching of carbonate host rocks and ores, and the eventual precipitation of anhydrite in upper levels of the deposit.

Summary

The geologic, chemical, and isotopic data presented in this paper permit a qualitative summary of the processes that produced the Carlin deposit. Figure 9 is a generalized cross section showing gross structural relations and the proposed hydrothermal system for the deposit.

The δD and $\delta^{18}O$ data indicate that the hydrothermal fluids were entirely exchanged meteoric water. Recharge for the hydrothermal system was probably along topographic highs formed by the highly brecciated Eureka Quartzite and along steep faults.

The $\delta^{34}S$ data show that the sulfur in the deposit is of sedimentary origin. Although data are available only for unaltered rocks of the Roberts Mountains Formation, all of the lower Paleozoic carbonate units in the area contain diagenetic pyrite and organic material and probably all these carbonate rocks were potential source rocks for the ore and gangue components in the deposit (Dickson et al., 1978, 1979b). Variations in chemical and mineralogical

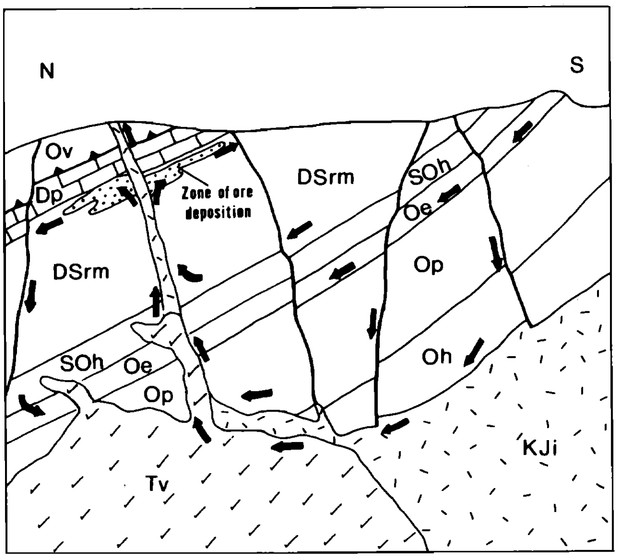

FIG. 9. Hydrothermal system and solution paths (large arrows) inferred for the formation of the Carlin gold deposit. See Figure 2 for explanation of symbols.

compositions of the gold ores in different parts of the deposit could reflect different fluid reservoirs at different levels in the underlying sedimentary section.

The orebodies formed near steep faults by replacement of carbonate minerals, principally calcite, in a favorable facies of thin-bedded argillaceous arenaceous dolomitic beds in the upper part of the Roberts Mountains Formation. Unfavorable facies of pelloidal wackestone within the same stratigraphic interval were not mineralized and only weakly altered.

Early hydrothermal fluids dissolved calcite and deposited quartz. Main-stage fluids introduced Si, Al, K, Ba, Fe, S, and organic materials together with Au, As, Sb, Hg, and Tl; calcite continued to be removed or replaced; and pyrite and K-clays formed. The remnant calcite was extensively recrystallized and exchanged with the ore fluids. Little exchange occurred between host rock dolomite and the ore fluids. Late main-stage fluids introduced sulfide and sulfosalt minerals containing As, Sb, Hg, and Tl, and later fluids introduced base metal sulfide minerals of Pb, Zn, and Cu. Most of the base metal minerals were deposited during the late period of solution boiling and acid alteration. Temperatures and salinities of the fluids during main-stage mineralization were about 175° to 200°C and 3 ± 1 equivalent weight percent NaCl, respectively. The $\delta^{18}O$ of the meteoric water hydrothermal fluids varied depending on local conditions but averaged 3 ± 3 per mil.

The main stage of ore deposition was terminated, at least in the upper part of the deposit, by a rise in temperature of the ore fluids to as much as 275° to 300°C. This resulted in widespread boiling of the fluids and coincided with the formation of barite veins. Boiling of the fluids increased the salinity of the fluids to values as high as 17.4 equivalent weight percent NaCl and $\delta^{18}O$ values over 10 per mil. Loss of H_2S during boiling led to production of H_2SO_4 in the upper part of the deposit and to the subsequent intense acid-leaching and oxidation of ores and surrounding rocks in a zone near the surface. Within this zone, calcite and large amounts of dolomite were removed, sulfides and organic compounds oxidized, kaolinite and anhydrite formed, and silica added. Some of the calcite may have been reprecipitated to form the abundant veinlets above the leached zone. Since the boiling event, the upper part of the ore deposit has continued to undergo weak oxidation and removal of nearly all of the anhydrite by surface waters.

In a future paper we will develop a geochemical model for the formation of the Carlin deposit which will cover experimental studies on the leaching of ore and gangue components from carbonate source rocks, and the transport and deposition of these components. It is clear that the Carlin deposit is an integrated result of hydrothermal processes initiated by heat emanating from igneous intrusives during the late Tertiary. Fluids of meteoric origin received heat from igneous masses, reacted with source rocks at depth, extracted ore and gangue components, and migrated upward along steep faults into near-surface permeable units in the Roberts Mountains Formation.

The occurrence of gold deposits with similar characteristics in numerous places in the western United States and elsewhere in the world indicates that the processes that formed them were not specialized. Thick sections of carbonate rocks like those in the Carlin area have the potential to produce gold deposits wherever underlying igneous activity has developed a hydrothermal system.

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