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46. Fine Gold Occurrence at Carlin, Nevada

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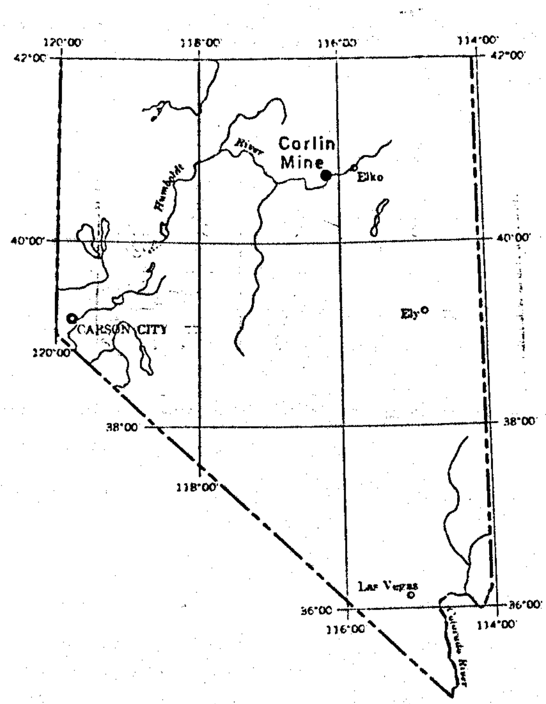

ABSTRACT

Fine colloidal gold near Carlin, Nevada is disseminated in leached carbonate strata of the Roberts Mountains Formation in the Lynn "window" of the Roberts Mountains thrust fault. The ore body is generally stratiform and is more or less conformable to altered beds near the top of the formation, underlying Devonian limestones.

Two sequences of mineralization are recognized: (1) an earlier base metal-barite assemblage related to early Cretaceous intrusives (121 ± 5 m.y.), and (2) a later low temperature Au-As-Hg-Sb assemblage of near surface emplacement. The earlier sequence consisting of sparse galena and sphalerite in barite with anomalous amounts of zinc, lead, nickel and copper, associated with dikes of dacitic composition, is of little economic importance. The later sequence of gold, realgar, cinnabar, and stibnite associated with extensive silicification and argillic alteration of limestone beds, has resulted in important deposits of gold.

Argillic alteration of hydrothermally leached carbonate strata has provided the environment in which the most prominent gold deposition took place. Carbonate minerals in the limestone host rock have been replaced by microcrystalline quartz and chalcedony to form stratiform silica masses and recrystallized lenses of euhedral quartz. Zones of porous silicification are light gray to white, elliptical in shape, and more or less follow bedding. Silicification is bordered by argillic alteration and pyritization. Deposition of gold usually lies in a zonal pattern that encircles chimney areas of silicification.

Ore textures, mineral assemblages, and alteration criteria in the Carlin ore body all favor late stage epithermal mineralization. Gold introduction is attributed to late hydrothermal solutions rising along elliptical conduits controlled by permeability of select horizons in the Roberts Mountains Formation. Precipitation of gold has occurred mostly in illitic clays, organic matter, pyrite, and microcrystalline quartz.

INTRODUCTION

Location

The Carlin mine is located in north central Nevada, in the Lynn Mining District, in northeastern Eureka County, 40 miles northwest of Elko and 20 miles north of Carlin, (Figure 1). Near-surface ore is being mined from an open pit at an elevation of about 6300 feet above sea level in the Tuscarora Mountains. Gold occurs in Silurian rocks along the eastern edge of the Lynn Window of the Roberts Mountain thrust fault. The host rock belongs to the eastern assemblage in the lower plate group of the Silurian Roberts Mountains Formation (Roberts, *et al.* 1958).

Acknowledgments

This paper includes much hitherto unpublished information from the files of Newmont Exploration, Ltd., and has benefitted from correspondence and conversations with many at the Carlin mine, the Danbury laboratory, and the New York offices of Newmont Mining Corporation. In particular we thank R. B. Fulton, Vice President and Manager of Exploration; F. W. McQuiston, Jr., Vice President of Metallurgy; D. J. Christie, Metallurgist; R. D. MacDonald, Director of the Danbury Laboratory; and R. W. Hernlund and W. C. Hellyer.

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Fire assays for gold and silver were provided by H. Treweek of the Carlin mill and G. V. Larsen of the Danbury Laboratory. Chemical analyses were provided by W. Hart and G. V. Larsen under the supervision of J. D. Crozier, Chief Chemist at the Danbury Laboratory. Sample preparation was conducted by L. DeVries and A. Bochnia. Thin and polished sections were prepared by L. DeVries. We thank all for their generous assistance.

We are grateful to T. I. Taylor of the Chemistry Department and to E. Hamburg of the Physical Metallurgy Department at Columbia University for guidance in the use of the electron microscope. We appreciate the cooperation of P. J. M. Ypma and R. J. Holmes in making suggestions and for their critical reading of the manuscript. We thank Mary Hausen for aid in manuscript assembly.

Techniques

X-ray diffraction analyses were performed on a General Electric Diffraction Unit, Model XRD-5, using a wide range goniometer and Ni filtered copper Kα radiation ($\lambda = 1.5418$).

Identification of clay minerals was facilitated by the use of sedimented slides. X-ray diffraction patterns were compared from: (1) untreated samples; (2) glycolated samples; and (3) heated samples taken to 550°C for one hour, in accordance with procedures outlined by Molloy and Kerr (25).

Emission spectographic analyses were obtained from the American Spectrographic laboratories in San Francisco, and from direct use of the Baird spectrograph at Columbia University. X-ray fluorescence analyses were performed semiquantitatively on finely ground Carlin samples by scanning from 10° to 90°, 2θ, on a wide range goniometer, utilizing a General Electric Spectrometer, Model XRD-5.

Differential thermal analyses of Carlin ore samples were run on a Brinkman Differential Thermo-Analyzer, Model DDTA IV. This instrument utilizes a thermocouple-amplifier-recorder arrangement to produce a low noise, high gain, differential thermal curve and temperature tracing on a standard Honeywell chart recorder. Gases given off by differential thermal analyses of carbonaceous and pyritic samples were analyzed by their infrared spectra using a Perkin Elmer Model 21 Infrared Spectrophotometer.

Selected hand specimens were inspected visually under the binocular microscope. Thin and polished sections were examined at higher magnifications by means of a Zeiss Universal Microscope with a split beam light source. Gold in the Carlin ore is finely disseminated through poorly consolidated argillaceous silty rocks that require careful impregnation with epoxy plastic prior to cutting, grinding, and polishing.

Electron micrographs were taken of submicroscopic gold from the main ore body. Microscopic equipment included an RCA electron microscope, model EMU-2B and a Siemens electron microscope.

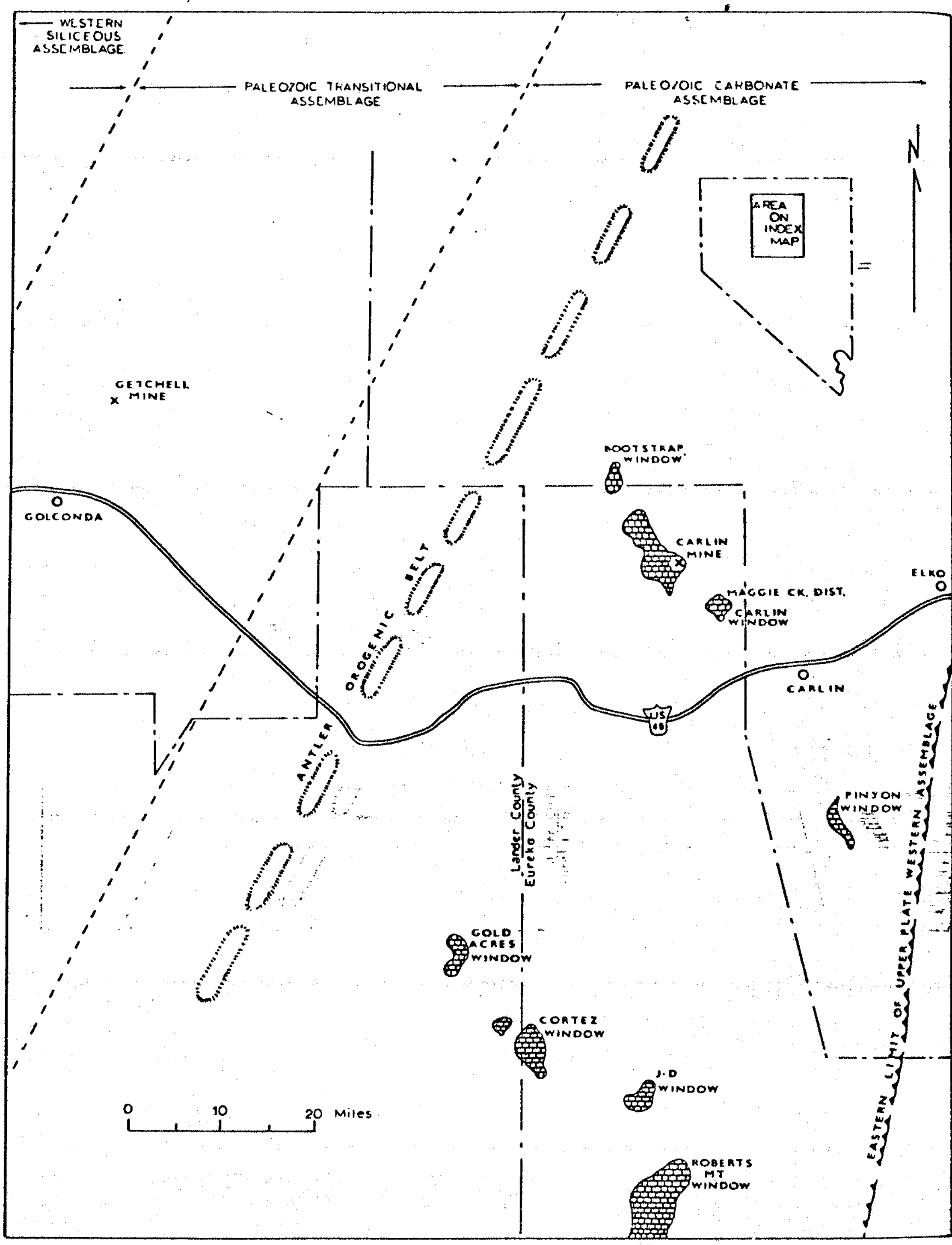

FIG. 1. *Index Map of the Carlin Mine.*

HISTORICAL INFORMATION

Visible gold was discovered in placer deposits in the Lynn district in April, 1907. This was followed by sporadic production from shallow surface and underground workings, mostly from eroded upper plate rocks of the Ordovician Vinini Formation. In lower plate rocks in recent pit operations, visible gold has not been observed.

The Carlin property is operated by the Carlin Gold Mining Company owned by the Newmont Mining Corporation. Exploration was first prompted by a U.S. Geological Survey report by R. J. Roberts (23), describing the alignment of mining districts in north central Nevada. Mapping and claim location were followed by drilling in 1962, with significant gold being found in the third drill hole. Estimated gold reserves in early 1965 were approximately 11 million tons, averaging 0.32 ounces of gold per ton (32).

Construction of a cyanidation mill was started in June, 1964, and gold production commenced in April, 1965.

Mineralogic studies were initiated during the summer of 1964 at the Newmont Research and Development Laboratory in Danbury, Connecticut, in support of metallurgical and geological investigations both at Carlin and Danbury. Several trips were made to the Carlin property in 1965 and 1966.

The Carlin pit was large enough in the late summer of 1966 to expose the altered lower-Paleozoic rocks that serve as a host for mineralization. Although megascopic gold has not been observed in the deposit, alteration features associated with gold content have been inspected in the field and samples collected for detailed laboratory study.

White to light gray, porous, silicified circular to elliptical chimneys, with brown pyritic halos, have been observed near high angle pre-ore faults and in lenses along sedimentary beds. In general, these bleached zones are more or less elongate parallel to bedding, representing zones of high permeability through which solutions apparently migrated upward.

GENERAL GEOLOGY

Regional Features

The Carlin mine is situated near the eastern edge of the Lynn window of the Roberts Mountains thrust fault. According to Roberts *et al.* (21), thrusting is related to the Pre-Carboniferous Antler orogeny and occurred along a regional thrust plane that brought western eugeosynclinal clastic rocks into contact with eastern miogeosynclinal carbonate rocks of correlative age. Roberts presumes a single broad continuous sheet extended over a wide region in North Central Nevada; he has designated this as the Roberts Mountains thrust fault.

Other investigators, however, believe that the fault is not a single thrust sheet but rather that multiple planes of thrusting can be distinguished in intricate thrust slices both in the Seetoya Mountains north of Elko (26) and in the Torquina Range south of Cortez (30).

Nevertheless, the term, Roberts Mountains thrust has been assigned by Roberts *et al.* (21) to faults bordering the Lynn and Carlin windows north of Carlin, Nevada, and, to avoid extended structural analysis beyond the scope of this paper, the name will be retained in this discussion.

The effect of thrust faulting as an ore control feature at the Carlin deposit is limited, but using the distribution of windows in the over-thrust sheet as a guide to loci of mineralization has merit. The Lynn window is typical of other exposures of lower-plate carbonate rocks including the Bootstrap window to the north as well as the Carlin, Pinyon, Gold Acres, Cortez, J-D, and Roberts Mountains windows to the south (Figure 1).

According to Roberts (23), the windows have been formed as the result of erosion of upper-plate rocks near local areas of post-thrust uplift and doming. Roberts further points out that the principal mining districts are located in and around eroded windows of lower-plate carbonate rocks and that the alignment of windows indicates zones of structural weakness along which igneous rocks and related ore-bearing fluids have penetrated. Windows are aligned along zones or belts trending to the northwest. The Carlin gold deposit is situated near the north end of the Lynn-Pinyon belt, which extends from the Pinyon window northward through the Carlin and Lynn windows to the Bootstrap window. The Shoshone-Eureka belt southwest of the Lynn-Pinyon belt trends northwestward from the Eureka window through the J-D, Cortez, Gold Acres, and Goat Ridge windows toward the Golconda and Getchell mines. Lower-plate rocks at the north end of this belt consist of the transitional assemblage that may be difficult to distinguish locally from upper-plate rocks of the western assemblages.

A geochemical association of arsenic, mercury, and antimony with gold has been recognized at several localities including Getchell, Bootstrap, Carlin, and Gold Acres in north-central Nevada (Erickson *et al.* 24,29,37). Anomalous association of arsenic, antimony, tungsten, and mercury with gold in the Cortez window also is reported by Erickson *et al.* (37) south of a major northeast fault in silicified Devonian limestones in the lower plate of the Roberts Mountains fault. Similar metallic assemblages have been reported in hot spring deposits, notably from Steamboat Springs, Washoe County, Nevada.

Structure of the Deposit

The Carlin ore body consists of irregularly stratiform masses of mineralized Roberts Mountains Formation that strike northeast and dip northwest conformably beneath Devonian limestones. The stratigraphy of the district is discussed in the following section, headed "Sedimentary Rocks," and is shown in tabular form in Figure 2.) In plan, the ore body is elongate to the northeast along the strike of the beds, and forms three recognizable mine units (Figures 3, 4): (1) the main ore body, (2) the easterly extension, and (3) the west ore body.

In general, faults are of two types, (1) the older low-angle Roberts Mountains thrust and (2) more or less vertical faults which may intersect the earlier thrust fault. Between are tilted segments of strata. Although the general aspects of the structural pattern are beginning to emerge, the fault structures in the pits are

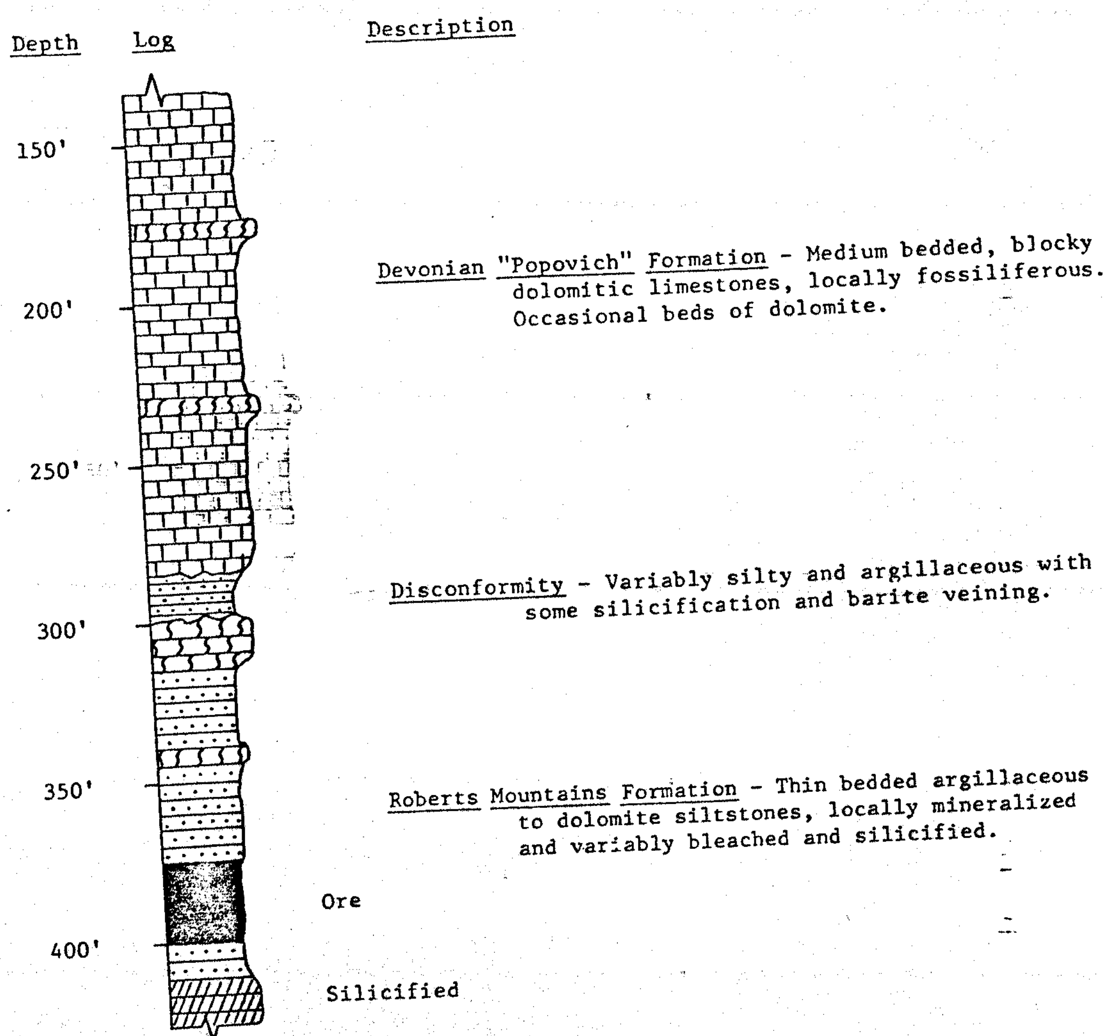

FIG. 2. *Lithologic Log of Drill Hole Based upon X-ray Diffraction.*

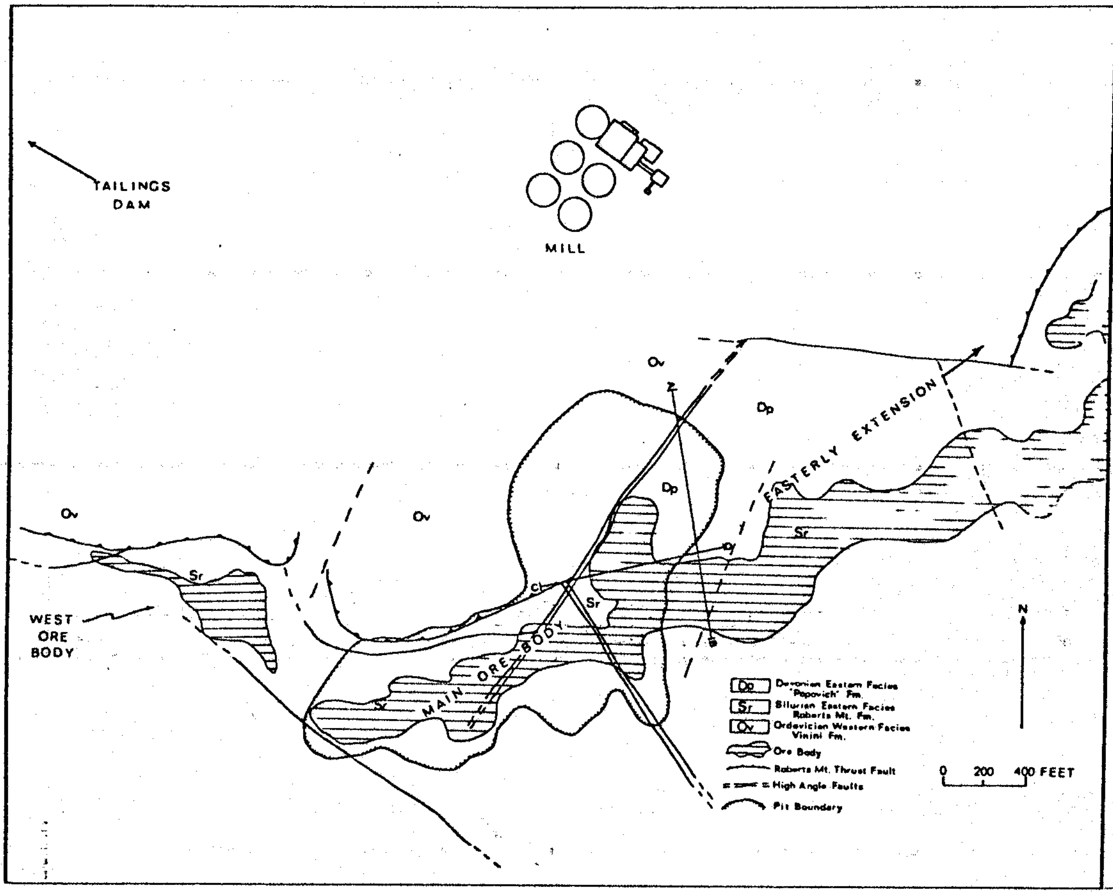

FIG. 3. *Schematic Map of Carlin Mine.*

not yet adequately exposed to complete the structural interpretation.

The west ore body is separated from the main ore body with an intervening northeast-trending vertical fault that marks in places the western boundary of the main ore body (Figures 3, 4). This fault can be followed intermittently along the northwestern edge of the main ore body and to the northeast where it continues to the north of the easterly extension. The Roberts Mountains thrust fault is intersected by the northeast fault along the northwestern edge of the main pit. A considerable vertical displacement of upper plate rocks of the Vinini Formation apparently has occurred along the northeast fault near the point of intersection with the thrust.

A vertical northwest fault is exposed in the east face of the main pit and strikes about N35°W (Figure 3). This fault appears to be pre-mineral and has been intruded locally by a quartz-porphyry dike and barite veins. The dike and adjacent wall rock are highly altered and numerous silicified "chimneys" occur nearby.

A schematic diagram of the east face of the main pit is shown in Figure 5. The Roberts Mountains Formation is overlain by Devonian limestones with the local name "Popovich" Formation (31). The underlying limestones show argillic alteration, silicifications, and mineralization . These beds are slightly off-set by a steep northwest dual fault pattern that has produced slight differences in strike by tilting. The fault pattern is intruded by a quartz-porphyry dike ranging from about 2 to 6 feet wide. Steep dikes of similar composition in the Roberts Mountains Formation extend to discontinuous outcrop northwesterly to the major northeast fault. Upper-plate rocks of the Vinini Formation are exposed on the northwest side of the major northeast fault at the north end of the pit (Figures 3, 4, 5).

The Roberts Mountains thrust fault is projected in the foreground of the sketch, Figure 6. The intersection of the thrust sheet with

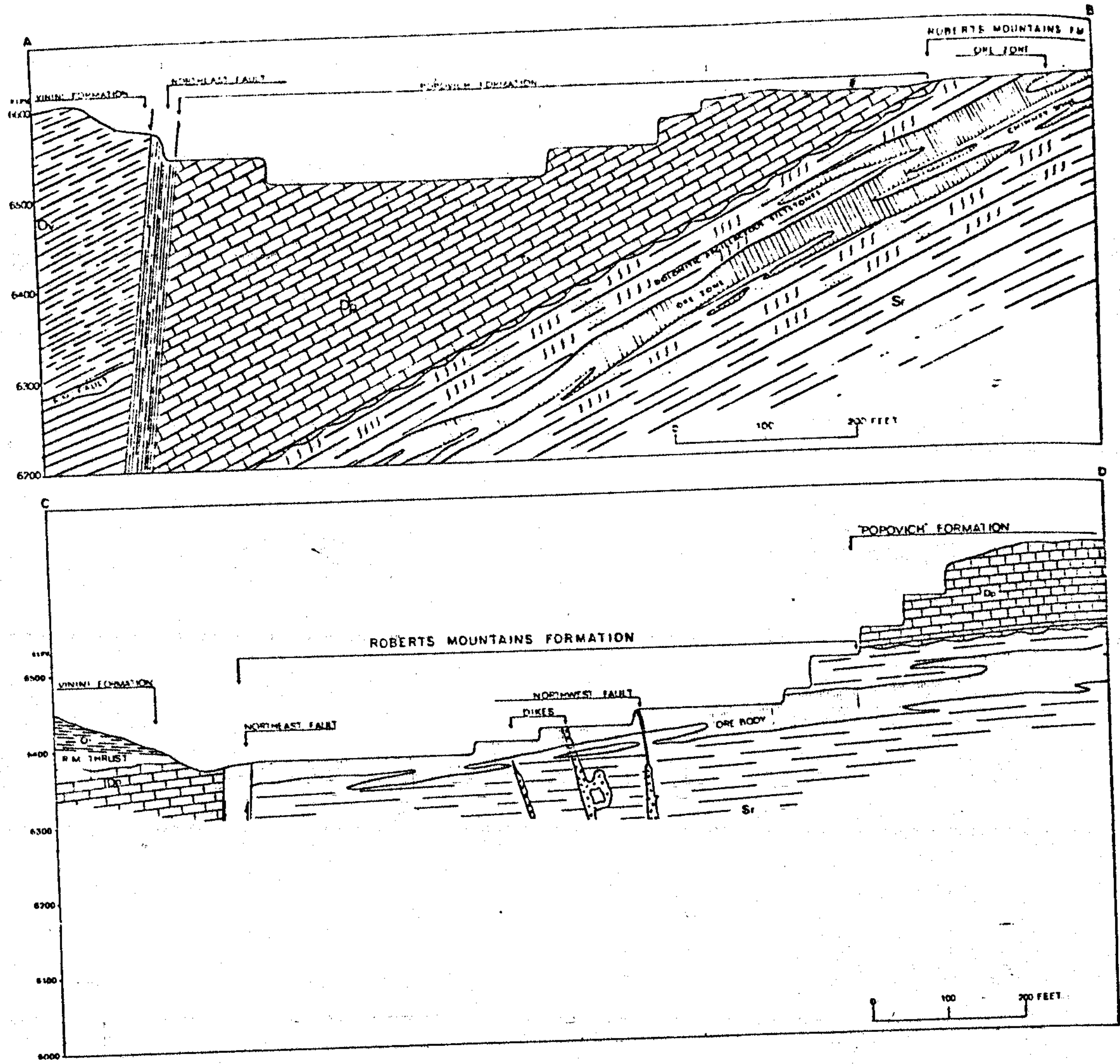

FIG. 4. *Cross Sections of Carlin Ore Body (A-B above, C-D below).*

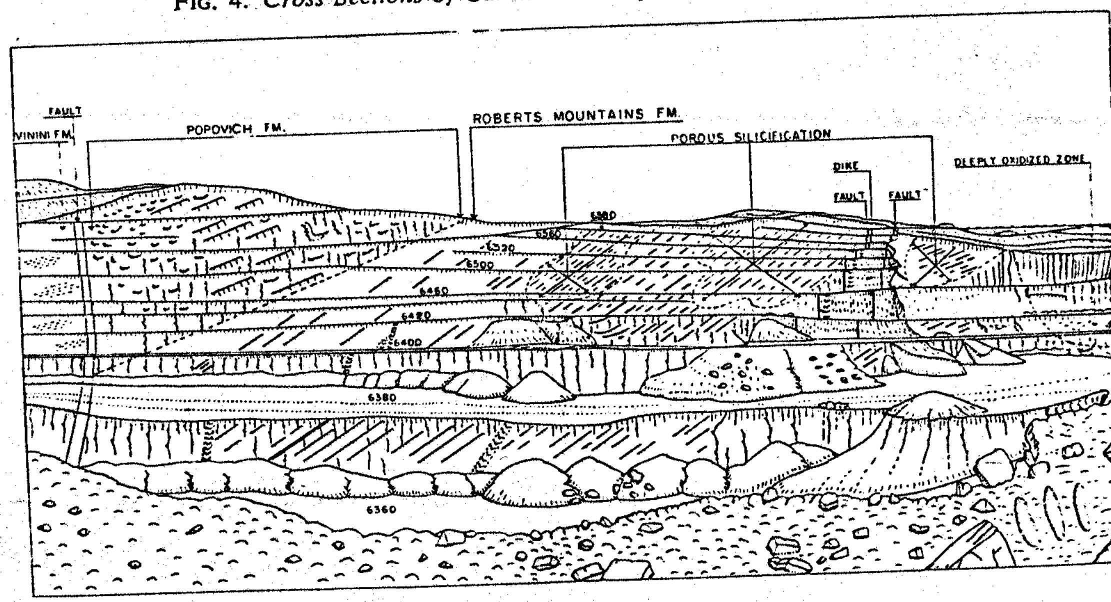

FIG. 5. *Sketch of East Face of Main Ore Body.*

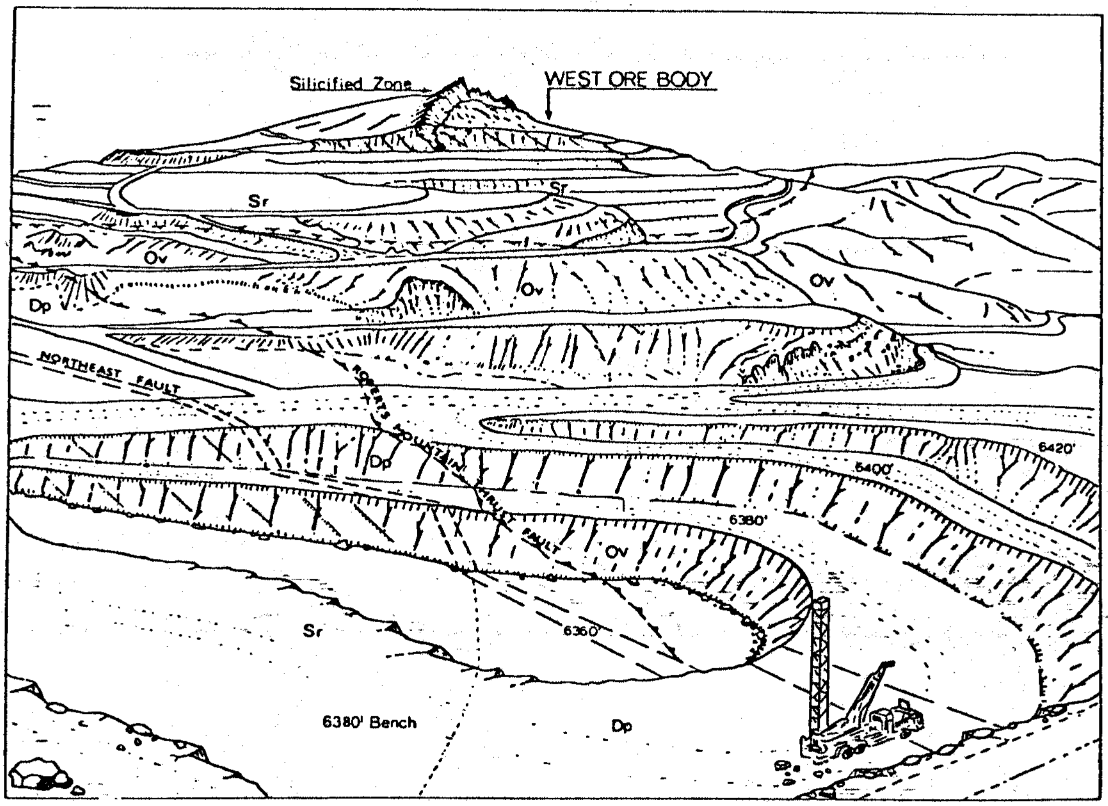

FIG. 6. *Sketch of West Ore Body.*

the vertical northeast fault occurs near this location. In cross-section, the thrust zone consists of about 10 to 20 feet of alternating layers of bleached, brecciated, and iron-stained rock rubble, above which lie nearly horizontal beds of cherts and carbonaceous shales of the Vinini Formation. Sediments immediately below the fault are highly altered beds of the "Popovich" limestone. Argillic alteration is prevalent along the thrust zone.

The thrust zone between the Vinini and Roberts Mountains Formations contains major montmorillonite with lesser illitic clays and quartz. Carbonate minerals are absent from the fault zone and from adjacent units of Vinini and Roberts Mountains beds. Small amounts of alunite were identified locally in the Vinini Formation near the fault.

SEDIMENTARY ROCKS

Roberts Mountain Formation

Platy silty limestones of the lower Silurian Roberts Mountains Formation have been described by Roberts *et al.* (21) from the Lynn and Carlin windows. In addition, unaltered samples of Roberts Mountains Formation were obtained for comparative study from road cuts along Maggie Creek Canyon within the Carlin window about 6 miles southeast of the mine. Two vertical sections were sampled, ranging from 10 to 20 feet thick. Samples consist of medium to hard, dense, dark-gray dolomitic limestone, silty to sandy in composition and thin-bedded. The rock is platy to blocky and closely jointed. Joints are filled locally with calcite. Chert is thin bedded and sparse to absent.

In the pit area, the Roberts Mountains Formation has been altered extensively with local bleaching and iron staining, but bedding features are often preserved, displaying a platy, thin-bedded character. However, carbonate minerals have been largely removed, leaving porous, low-density rocks that range in composition from argillaceous to dolomitic siltstones. Late introduction of chalcedonic silica has resulted locally in silicified seams or lenses that frequently parallel bedding.

On close study, the mineral composition and

TABLE I. Minerologic Composition of Unaltered and Altered Roberts Mountains Carbonate Rocks

Mineral Constituents	Unaltered Roberts Mountain at Maggie Creek 20′ Section Per Cent	Unaltered Roberts Mountain at Maggie Creek 10′ Section Per Cent	Altered Roberts Mountain (Main Ore Body Composite) Per Cent
Calcite	50	40	4
Dolomite	15	10	10
Quartz	20	20	40
Illite	5–10	5–10	10–20
Montmorillonite	5–10	10–20	10–20
Kaolinite	2	2	2–5
Pyrite	tr	tr	tr
Carbonaceous Material	tr	tr	tr

textures of Carlin ore appear to be more closely related to alteration effects than to primary sedimentary composition. However, primary bedding outlines are retained and reflect the general pattern of the original unaltered Roberts Mountains limestone.

The Roberts Mountains Formation as exposed below the thrust fault consists mostly of argillaceous siltstones, with quartz and small to moderate amounts of montmorillonite, illite, and traces of kaolinite. Dolomite and barite increase locally to major proportions. The formation was much higher in carbonate content and lower in silica prior to mineralization (Tables I, II). Calcite is the major component of the unaltered rocks with small to moderate amounts of dolomite. In leaching, most of the calcite was removed, but the dolomite largely remained. Illite, montmorillonite, kaolinite, and detrital quartz were moderately abundant in unaltered rocks. All but montmorillonite were increased by major amounts after calcite was leached by hydrothermal solutions. Original angular grains of quartz are poorly sorted

TABLE II. Chemical Composition of Unaltered and Altered Roberts Mountains Carbonate Rocks

Chemical Composition	Unaltered 20′ Section of Dol. Ls. Maggie Creek Per Cent	Altered Roberts Mountain Main Ore Body Composite Per Cent	Method of Analysis
SiO_2	26.46	69.1[illegible]	Chemical Analysis
Al_2O_3	9.06	11.18	" "
Fe_2O_3	1.47	3.23	" "
CaO	30.96	5.12	" "
MgO	3.98	2.45	" "
K_2O	1.25	1.75	Spectrographic
Na_2O	0.05	<0.01	"
TiO_2	0.2	0.6	"
MnO_2	0.01	0.02	"
BaO	0.015	0.5	"
SrO	0.015	0.015	"
ZnO	<0.005	0.01	"
CuO	0.004	0.008	"
PbO	—	0.003	"
As_2O_5	—	0.25	"
HgO	—	0.01	"
Sb_2O_5	—	0.02	"
NiO	0.003	0.01	"
ZrO_2	0.03	0.04	"
CO_2	Most of remainder		
Au	<0.005 oz/ton	0.49 oz/ton	Fire Assay

and randomly scattered through a dolomitic matrix containing disseminated clays. Individual grains range from 15 to 70 μ in size, and show relatively few inclusions, cavities or strain shadows.

Dolomite rhombs up to 60 μ are randomly distributed through a fine grained carbonate matrix. Small amounts of pyrite and carbonaceous matter in the fresh rock were probably syngenetic but, during alteration, were remobilized locally and redistributed. The dark gray of the unaltered limestone is attributed to carbonaceous matter.

Unaltered Roberts Mountains limestones from Maggie Creek have bulk densities near 2.63, compared with values ranging from 1.95 to 2.40 for ore-bearing replaced samples from the Carlin pit.

"Popovich" Formation

The "Popovich" formation (Devonian) overlies the Roberts Mountains Formation and consists of gray, fossiliferous medium to thin-bedded limestone, locally dolomitic and silty near the base. This, the youngest formation in the area, was named "Popovich," by Hardie (31), after an early prospector in the district. Fossil evidence has dated the "Popovich" formation at the base of the upper Devonian, stratigraphically equivalent to the Devils Gate Limestone. The "Popovich" unconformably overlies the Roberts Mountains Formation, but some movement appears to have occurred along the contact.

The "Popovich" has been altered hydrothermally along its base and along nearby joints and fractures. Altered rock has been leached of its carbonate content and replaced by clay and iron oxide. Altered samples usually are reddish brown, soft, porous, and low in density. Select zones in the "Popovich" have been silicified similarly to the Roberts Mountains, notably near the northeast fault at the north end of the ore body.

Unaltered "Popovich" usually is fine to medium-grained dolomitic limestone similar in composition to the Roberts Mountains but with less silt and clay. The mineralogic and chemical compositions of altered and unaltered "Popovich" are compared in Tables III and IV. Small amounts of carbonaceous matter and pyrite are distributed along bedding planes, resulting in a dark-gray rock. Most samples are also fossiliferous, containing a variety of microfossils that resemble spicules, crinoid stems, and types of foraminifera. Microfossils have been recrystallized and replaced by microcrystalline quartz.

Dolomitic limestones grade into massive dolomite near the base. Samples of altered and unaltered dolomite were analyzed from near the base of the "Popovich" along a road cut north of the east pit (Table IV). A comparison of analyses for the two samples indicates major removal of both dolomite and calcite during alteration. Micropore space in the rock is indicated by low-bulk densities (near 1.60) as compared with 2.75 for nearby unaltered dolomite.

Vinini Formation

The Vinini Formation (middle Ordovician) occurs in upper-plate rocks along the Roberts Mountains thrust fault. This formation consists mostly of thin-bedded siliceous cherts, organic shales, minor quartzites, and lenses of limestone. The bedded cherts and black organic

TABLE III. Minerologic Composition of Unaltered and Altered Samples from the Popovich Formation

Mineral Constituents	Unaltered Popovich Sample No. 1	Unaltered Popovich Sample No. 2	Altered Popovich Sample No. 3
Calcite	45 Per Cent	5 Per Cent	<2 Per Cent
Dolomite	15	60	<2
Quartz	15	20	60
Illite	5–10	2–5	10–20
Montmorillonite	2–5	2–5	5–10
Kaolinite	2–5	<2	2–5
Pyrite	Tr	Tr	—
Carbonaceous Material	Tr	Tr	—

Sample 1 represents an average of analyses for 125' of drill cuttings from Popovich.
Sample 2 is from a dolomite bed near base of Popovich.
Sample 3 is altered material adjacent to Sample 2 of fresh dolomite.

TABLE IV. *Chemical Composition of Unaltered and Altered Samples from the Popovich Formation*

Chemical Constituents	Unaltered Popovich Sample No. 2	Altered Popovich Sample No. 3	Method of Analysis
SiO_2	32.04	81.00	Chemical Analysis
Al_2O_3	10.82	12.34	″ ″
Fe_2O_3	1.90	1.61	″ ″
CaO	18.66	1.40	″ ″
MgO	9.10	0.58	″ ″
K_2O	1.0	<1.0	Spectrographic
Na_2O	0.07	<0.01	″
TiO_2	0.30	0.35	″
MnO_2	0.01	0.03	″
BaO	0.03	0.08	″
SrO_2	0.008	0.008	″
ZnO	0.002	0.003	″
CuO	0.010	0.015	″
PbO	<0.001	0.002	″
As_2O_5	0.01	0.02	″
HgO	<0.01	<0.01	″
Sb_2O_5	<0.01	<0.01	″
NiO	0.003	0.003	″
ZrO_2	0.02	0.02	
CO_2	Most of remainder		
Au	<0.005 oz/ton	0.04 oz/ton	Fire Assay

shales are clearly of the western lithologic assemblage. According to Roberts *et al.* (21), the most complete stratigraphic section of the Vinini Formation can be seen in the Tuscarora Mountains in northern Eureka County. Here the Vinini Formation is locally mineralized, and gold has been mined from small workings, but no large ore bodies have been found. However, near the Carlin pit, traces of gold have been detected in Vinini outcrops.

At Carlin, the Vinini Formation consists of siliceous shales in two groups. An upper unit of undetermined thickness contains moderate to major amounts of well-crystallized illite and small to trace amounts of K-feldspar in addition to major quartz. A lower unit contains major amounts of mixed layered illite-montmorillonite in addition to major quartz. Both Vinini units contain little to no kaolinite and montmorillonite and are separated by a manganese zone of wad containing anomalously high zinc, arsenic, barium, and nickel.

Lithologic Interpretation by X-ray Diffraction Analysis

Numerous samples from across the Carlin ore body have been examined by x-ray diffraction. Analyses are semiquantitative and based on relative intensities of characteristic reflections for major minerals, including quartz, calcite, dolomite, kaolinite, illite, and barite. Measured intensities were compared with intensities calibrated from standard samples. An example is provided by the lithologic section in Figure 2 that was interpreted from x-ray diffraction analyses of cuttings from a drill hole located east of the main ore body.

Estimated percentages have provided a rapid semi-quantitative method for evaluating lithologic trends that otherwise might escape detection by visual methods of logging. Microscopic examination of samples in grain mounts also has been used to supplement x-ray diffraction data in distinguishing fine massive quartz from granular detrital quartz.

Observations drawn from x-ray and microscopic examination of drill cuttings and outcrop samples are summarized below:

(1) Major lithologic types of gold-bearing samples collected across the ore body are: (a) limestones, (b) dolomitic limestones, (c) argillaceous siltstones, and (d) silicified rocks. Samples may be silty, argillaceous, dolomitic, calcareous, siliceous, carbonaceous, pyritic, and baritic in composition. Rock units are gradational with few sharp differences in mineralogic composition.

(2) Calcite has been removed selectively from mineralized zones leaving an altered rock matrix consisting mostly of detrital quartz, clays, and relic dolomite. Illite is the dominant clay mineral associated with mineralization, comprising as much as 50 per cent of some ore samples. Quartz may range from 25 per cent in highly argillized samples to 75 per cent in silicified ore zones. Relic dolomite may range from nil to as much as 40 per cent in a few samples. Calcite is normally sparse but has been enriched locally in some portions of the ore, apparently as a late epigenetic mineral.

(3) Unaltered "Popovich" limestones are highly calcareous (>70 per cent calcite) and low in detrital quartz, except near the base, where dolomite and silty quartz increase significantly. Here, alteration is accompanied by removal of carbonates, mostly calcite, accompanied by argillization and local silicification.

(4) Several different rock units appear in drill cuttings. An upper calcareous unit detected in cuttings from the northeast portion of the ore body apparently is "Popovich" limestone. The underlying Roberts Mountains Formation consists of alternate zones of argillaceous siltstones, dolomites, and chalcedonic strata of highly varied composition. Massive silicified zones may occur locally in altered portions of either formation, accompanied by an increase in quartz. Other differences may be detected by x-ray diffraction, including increases of: (a) kaolinite along altered dikes of porphyry, (b) montmorillonite along fault zones, and (c) barite along veins and replacements.

(5) Gold largely is confined to altered rock units of the Roberts Mountains Formation. Larger amounts occur locally in argillaceous siltstones. In porous light gray chimney-like forms with fine crystalline quartz, gold usually is low. In general, small amounts of gold are disseminated through silicified rocks including chalcedonic lenses, altered dikes, and even occasionally in zones of barite replacement.

(6) In general, argillaceous and dolomitic siltstones are prevalent in ore samples from the main ore body; the rock becomes more dolomitic, chalcedonic, and carbonaceous across the east ore body.

IGNEOUS ROCKS

Igneous rocks examined from the area include quartz porphyry dikes in the pit and a large quartz diorite intrusive exposed about 3 miles to the north.

Quartz Porphyry Dikes

Quartz porphyry dikes that cut the "Popovich" limestone and the Roberts Mountains Formation in the Carlin pit dip steeply northeast and strike northwest, following a system of northwest faults and associated fractures. The dikes range from a few inches to 10 feet in thickness and may differ widely in thickness over short distances. Barite veins and sparse base-metal mineralization appear to be related closely to the dike intrusions, as shown by mutual association along the northwest fault on the east face of the main ore body. Subsequent low-temperature alteration of dikes and wall rock apparently occurred at a much later date associated with gold mineralization.

Borders of most dikes for a distance of about one-half inch on both sides are extremely fine grained and are zones of chilled contact against host rocks. Central zones are more crystalline in thin section but have been replaced completely by secondary clay minerals and quartz. Most samples are porphyritic, containing phenocrysts of embayed quartz and relics of amphiboles and feldspars. Apparent relics of hornblende are euhedral and typically pseudo-hexagonal to rhombic in cross-section (Figure 7). Subhedral phenocrysts of plagioclase have been replaced completely by microcrystalline quartz of chalcedonic texture. Quartz phenocrysts are only slightly altered with the exception of reaction rims along external borders. Reaction rims are attributed to primary processes of interaction between phenocrysts and the cooling magma. Relic groundmass textures range from pilitic along dike margins to intersertal in interior portions. Felty needles of feldspar in the groundmass have undergone pseudomorphic replacement

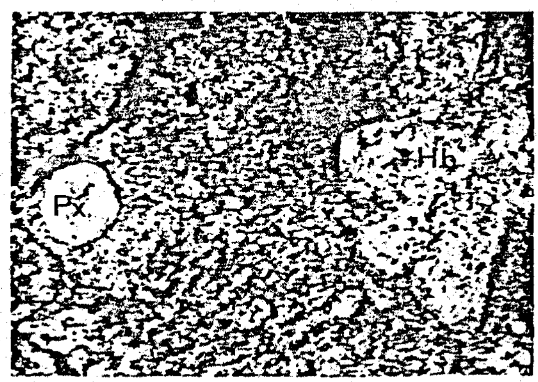

FIG. 7. *Euhedral Outlines of Hornblende (Hb) and Pyroxene (Px) in Altered Dike from Main Pit. ×18, Transmitted light.*

by microcrystalline quartz and kaolinite. Microscopic textures indicate that the dikes were either dacite or quartz latite in composition, but the general field term "quartz porphyry" is used in this paper.

X-ray diffraction analyses of dike samples show major quartz and kaolinite with minor dickite, illite, montmorillonite, and hydrous iron oxides. Feldspars and mafic silicates were not detected. Argillization of dikes and surrounding sediments has resulted from the same processes of alteration since the same assemblages of clay minerals are widely distributed through both.

Gold ore continues into the dikes in the vicinity of ore bodies, but, in places, gold may be essentially absent.

Quartz Diorite

A small plutonic intrusion of quartz diorite is exposed in the Gold Strike claims in section 30 about 3 miles north of the Carlin mine. At the surface, the intrusive is moderately to highly altered and weathered. Nearly fresh cuttings from a drill hole at about 195 to 200 feet depth are gray to dark gray and medium to fine grained in texture. X-ray diffraction scans show major constituents to be plagioclase, mica, hornblende, quartz, and chlorite. Thin sections reveal a hypidiomorphic granular texture consisting mostly of anhedral plagioclase and quartz with moderate amounts of biotite and hornblende. Accessory amounts of sphene were also observed (Figure 8). Potash feldspars were not detected.

Plagioclase, near sodic andesine in composition, is locally sericitized and argillized. Hornblende and biotite are altered partially to chlorite. Pyrite locally is abundant in altered samples and is associated with alteration of feldspars and mafic silicates. In weathered samples, pyrite is oxidized to hydrous iron oxides. Small amounts of gold (0.02 oz/ton) were detected in altered samples.

FIG. 8. *Photomicrograph of Quartz Diorite 4 Miles North of Carlin Mine. Alteration of plagioclase (P) to sericite and clays. Biotite (B) is partially altered to chlorite (C), and late quartz (Q) contains sphene. ×18. Crossed nicols.*

TABLE V. Analytical Data on K/Ar Age Determination of Biotite from Quartz Diorite

Argon Analyses		Potassium Analyses	
Ar^{40*} ppm	0.0333	$K_{(per\ cent)}$	3.53
	0.0315		3.74
Ar^{40*}/Total Ar^{40}	0.775	$K_{Average\ (per\ cent)}$	3.65
	0.860		
Average Ar^{40*}	0.0324	K^{40} ppm	4.44

Ratio

$Ar^{40*}/K^{40*} = 0.0073$

Age = 121(±5) × 10^6 years (middle to early Cretaceous)

An age of 121 ± 5 m.y.) (early Cretaceous) was determined for biotite separated from the intrusive using the K/Ar method. The sample contained less than 10 per cent impurities most of which were hornblende that did not affect the accuracy of the determination. Data were reported by Harold W. Krueger, technical director of Geochron Laboratories, Inc. (Table V). Because of petrographic similarity, the dikes in the Carlin pit may be of the same age. The close proximity and similarity in composition of the quartz diorite and the quartz porphyry dikes suggest a common magmatic source.

The potassium-argon dates of Nevada and Utah intrusives apparently provide reliable ages for the crystallization of these rocks (27). The ages of these intrusives fall broadly into two groups (12–64 m.y. and 93–182 m.y.) with periods of maximum ore genesis believed to coincide in general with periods of igneous activity (33). An age of 121 m.y. for intrusives near the Carlin mine is compatible with determinations from the Cortez mine in northern Eureka County that range from 124 to 150 m.y. A number of intrusives of apparent Cretaceous age are distributed along a northwesterly trend through the Lynn and Bootstrap windows.

BARITE MINERALIZATION

Barite deposits are of widespread occurrence in Nevada (Gianella, 1941) and often are associated with precious and base-metal mineralization. Barite occurs in several places in the Carlin ore body and in the overlying "Popovich" formation. Deposits occur as: (1) veins and irregular replacement bodies in limestones; (2) injections along high-angle faults and dike contacts; and (3) irregular replacements that follow bedding, notably along the disconformity between the "Popovich" formation and the Roberts Mountains. Most of the veins dip steeply and strike northwesterly.

Barite and dike material are associated mutually along a northwest fault exposed in the east face of the main ore body. Most dikes also contain anomalously high barium on chemical analysis. Anomalously high lead, zinc, nickel, and copper are also found both in dikes and barite veins.

Galena and sphalerite have been identified microscopically in barite samples from the main pit. Barite is replaced locally by microcrystalline quartz veinlets that contain finely crystalline pyrite. Realgar, stibnite, and carbonaceous matter have been identified also as late fracture fillings in barite. Galena is altered locally to jordanite, while sphalerite is partially replaced in places, apparently by tennantite. The latter replacements probably occurred at a later age of mineralization, possibly associated with late gold-arsenic solutions.

GOLD DEPOSITS

General Features of the Ore Body

Drilling to date indicates that the Carlin main ore body is an irregular inclined deposit (Figure 4), located near the top of the Roberts Mountains Formation and underlying the "Popovich" formation. Thickness may range from a few feet to nearly 100 feet with gradational assay boundaries. The upper ore boundary occurs just below the "Popovich," ranging stratigraphically from a few feet to a few tens of feet below the contact. The lower contact grades into light gray zones of porous silicification, locally penetrated by dark-gray stratiform, but tapering, chalcedonic masses.

The ore mass follows the inclination of strata and continues downward from the surface until intersected by the northeast fault. In horizontal section, the ore body is elongate, extending to the northeast along strike.

Lithologic Influence on Ore Deposition

Permeable horizons of silty dolomitic limestones in the Roberts Mountains Formation have provided a favorable host environment for mineralizing solutions.

As exposed, nearly 200 feet of uppermost Roberts Mountains strata have been leached and locally silicified, presumably by ascending solutions associated with mineralization. Gold in this interval may range from a few ounces per ton to virtually nil (<0.002 oz/ton). In outcrops, low-grade to barren materials are not readily distinguished from those that are highly mineralized, hence closely spaced samples and numerous assays are required to delineate the ore body.

Mineralized portions of the ore body usually range from replaced argillaceous to dolomitic siltstones that in places may be carbonaceous, calcareous, or silicified. Only a few consistently recognizable rock types may be associated visually with barren rock or ore. Highly bleached, rounded, porous, silicified zones in the Roberts Mountains usually contain negligible amounts of gold. On the other hand, a peculiar spotted rock (Figure 9), that may overlie silicified zones in the deposit often contains significant amounts of gold. "Spots" appear to be initial patches of alteration that form small patches of argillitization parallel to bedding. Seams of argillic alteration in "spotted" rock commonly range from a few tenths of a millimeter to several centimeters thick. Smaller seamlets are usually lenticular in cross section and follow continuous paths along bedding planes or into fractures, resembling "worm borings" (Figure 10). Larger seams of alteration are more continuous in cross section, usually follow bedding planes, and locally are irregular and sinuous in distribution. Spotted features are a light-grayish

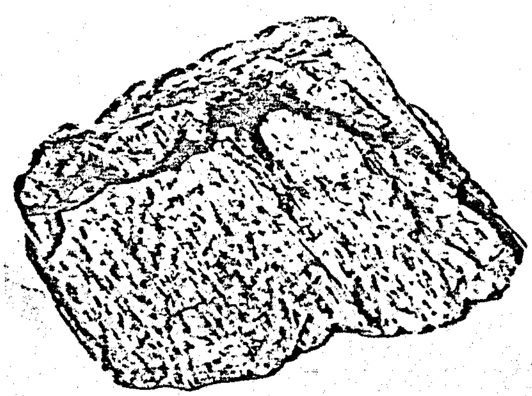

FIG. 9. *"Spotted" Ore Concentrations; in argillic alteration in Roberts Mountains Formation these yield a "spotted rock" often high in gold. From 6400 foot bench, main ore body.*

FIG. 10. *Argillic Alteration Seamlets along Bedding Planes. Bleached seamlets resembled "worm borings" in mineralized Roberts Mountains Formation. From 6400' bench, main ore body.*

alteration in contrast to a residual dark-gray rock matrix in unweathered areas. On weathering "spots" are stained with ferruginous oxide and appear as dark-brown areas in a light-reddish-buff matrix. This type has been observed and sampled from several locations; each location was highly mineralized but was bordered by a major silicified zone. Under the microscope, "spots" reveal clay-mineral orientation. Seamlets of alteration display a fabric of epigenetic clays, mostly illite flakes, that are aligned more or less parallel to bedding. Under crossed nicols, the extinction angles lie on the plane of lineation. Visible gold is detected in the matrix of oriented clay seamlets, whereas no gold has been detected in unoriented clay seamlets.

In a sequence of highly mineralized samples from the 6400-foot bench (Figure 11), a correlation may be established between gold content and the abundance of oriented clay seamlets in the ore. In lower grade samples, e.g., sample No. 9 containing 0.19 oz/ton Au, oriented seamlets are less abundant but occur along multiple bedding planes (Figure 12). In high grade samples, above 2 oz/ton, oriented seamlets interfinger and coalesce into a continuous fabric of oriented clays (Figure 13). Dark reddish brown to opaque matter associated with oriented clay seamlets is amor-

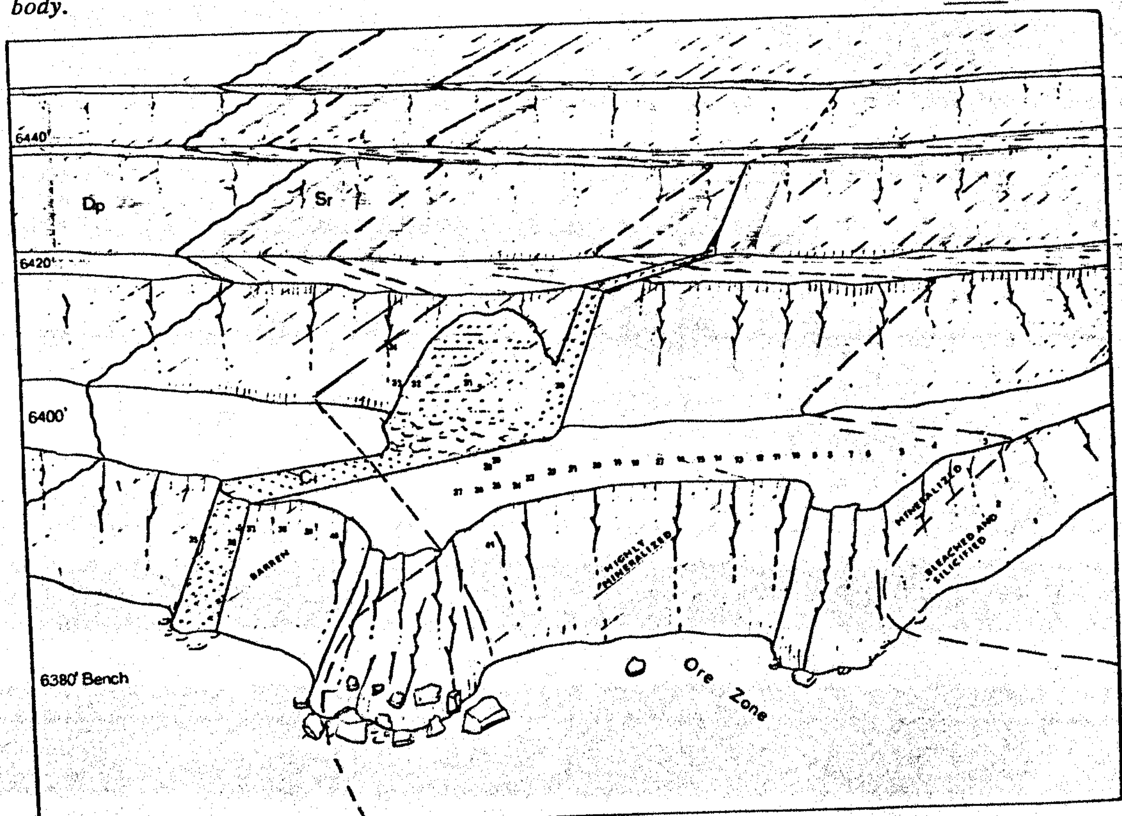

FIG. 11. *Sketch of Ore Zone, showing location of samples taken along 6400-foot bench. The ore zone lies near the top of the Silurian Roberts Mountains (Sr) underlying Devonian "Popovich" (Dp), and is intruded by Cretaceous dike (Ci) along NW fault.*

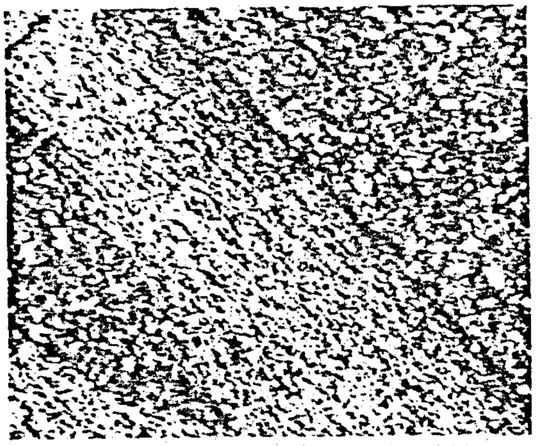

FIG. 12. *Photomicrograph of Argillization Seamlets in Dolomitic Siltstone (Sample No. 9. Figure 12 and Table V), showing oriented clay fabric in contrast to random fabric of surrounding area.* ×*22, partially crossed nicols.*

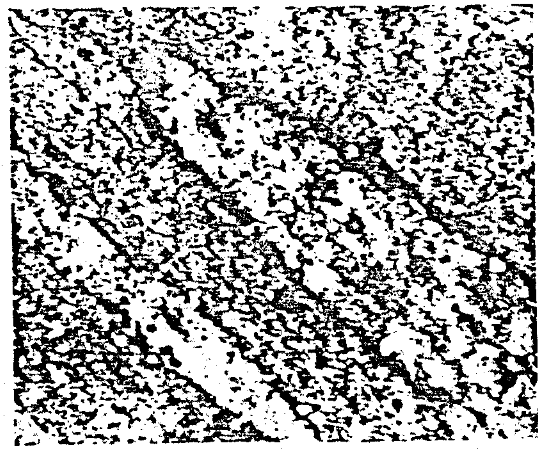

FIG. 13. *"Island Relics" of Unaltered Dolomitic Sandstone in Matrix of Coalescing Alteration Seamlets (Sample No. 5, Figure 12 and Table V).*×*21. partially crossed nicols.*

phous and appears to be a mixture of ferruginous oxides.

Oriented clay seamlets are believed to be epigenetic alteration channels along which gold was introduced as the carbonate was leached from the rock. Carbonate minerals are largely absent in oriented clay seamlets. The lamellar texture of the clay fabric may be explained either by flow orientation from solution movement or by the collapse of local rock structure along zones of carbonate removal. The latter explanation seems more plausible from the view point of rock deformation.

Deposition of gold appears to have occurred in the capillaries of argillaceous siltstones, associated closely with the removal of carbonate along bedding planes. Certain minor differences in lithology have noticeable effects on ore grade (Table VI). Small siltstone-sandstone seams, up to several inches thick, usually are less mineralized than adjacent finer-grained

TABLE VI. Metal Content Across Ore Zone on 6400-foot Bench of the Main Pit, Carlin Ore Body[1]

Rock Type and Sample Numbers (Fig. 21)	Average Fire Assay Au/Oz. Ton	Average Semiquantitative Spectrographic Analyses Per Cent As	Sh	Hg	Zn	Cu	Fe	Ba	Ni	Zr	Sr	Rb
Dolomitic argillaceous siltstone (8, 9, 10, 11, 12, 13, 15, 17, 19, 20, 21, 22, 25, 34, 38, 39, 40, 41)	2.66	0.22	.01	.01	.020	.005	3.0	0.1	.004	.030	.008	.007
Argillaceous siltstone (4, 23, 29)	2.19	0.22	.01	.01	.044	.008	4.7	0.3	.003	.020	.013	.010
Siltstone-sandstone (14, 16, 24, 26)	1.26	0.28	<.01	<.01	.015	.004	4.3	0.4	.002	.026	.005	.005
Calcified argillaceous siltstone	0.84	0.17	<.01	<.01	.01	.003	4.0	0.3	.002	.045	.006	<.005
Silty argillaceous dolomite (1, 5, 7, 27)	0.805	0.12	<.01	<.01	.020	.006	3.0	0.2	.003	.046	.009	.009
Silty calcareous dolomite (18)	0.19	0.12	<.01	.01	.020	.005	3.0	0.1	.004	.030	.008	.007
Altered porphyry dike (30, 31, 32, 36)	0.153	0.59	<.01	<.01	.15	.016	12.5	0.8	.050	.050	.021	<.005
Calcareous siltstone near dike (33 above, 35, 37 below)	0.052	0.09	<.01	<.01	.12	.006	2.8	0.2	.024	.025	.008	.005
Bleached argillaceous siltstone (2, 3)	0.023	0.025	<.01	<.01	<.002	.003	1.25	<.1	.002	.042	.013	<.005

[1] Sample numbers are located on sketch map shown in Figure 12.

TABLE VII. *Dilution of Gold Content by Impregnations of Silica and Calcite*

	Silica Impregnation	Calcite Impregnation
Sample Location	6440-foot Bench (Fig. 22)	6550-foot Bench (Fig. 23)
Au Oz/Ton		
Porous	0.06 oz/ton	0.49 oz/ton
Impregnated	0.03 "	0.20 "
Bulk Density		
Porous	1.91 Sp. G.	2.21 Sp. G.
Impregnated	2.58 "	2.53 "

argillaceous siltstones. Sandy and fossiliferous beds are more permeable, are commonly silicified, and carry lower amounts of gold.

Where quartz porphyry dikes carry gold, they usually are less mineralized than adjacent sediments. An example is provided by a quartz porphyry dike that transects the ore body between the 6380-foot and 6420-foot benches (Figs. 5, and 11). Samples of the dike from the ore zone between the 6400-foot and 6420-foot benches range from 0.003 to 0.48 oz/ton of gold, compared with 0.19 to 5.67 oz/ton in adjacent altered sediments. Samples of the dike, where it intrudes sparsely mineralized sediments between the 6380-foot and the 6400-foot benches, range from nil to 0.002 oz/ton Au, compared with 0.003 to 0.045 oz/ton in adjacent sediments. Gold contents and descriptions of rock units shown in Figure 11 are compared in Table VI.

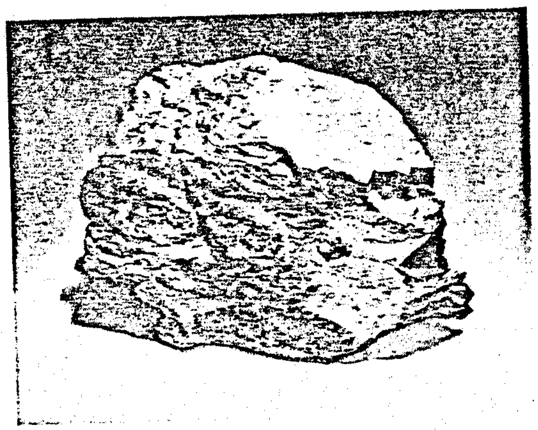

FIG. 14. *Silicified Rock from 6440-foot Bench along East Face of Main Ore Body. Silica has penetrated white permeable beds, resulting in dark gray chalcedonic rock of higher bulk density.*

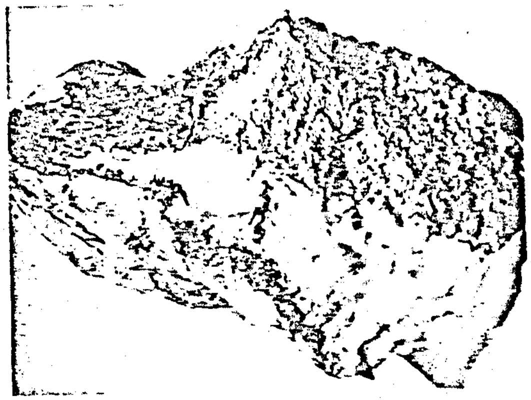

FIG. 15. *Calcite Vein (white) Penetrating Light-Gray Leached Rock. The vein has been accompanied by calcitic permeation of the border rock with a change to dark gray. From 6400' bench along east face of main ore body.*

Ores usually are of lower grade in rocks of chalcedonic or calcareous composition. Apparently microcrystalline quartz and calcite have been added to local rock units after the gold was deposited with dilution of gold values (Table VII). Pore spaces in highly porous siltstones have been filled locally in places with silica (Figure 14) and also with calcite (Figure 15), resulting in slightly lower gold content and higher bulk density. The gold also is more difficult to extract from these ore types.

Relationship of Structure to Gold Deposition

The Roberts Mountains overthrust per se has little apparent structural control over the distribution of ore. The thrust plane undoubtedly has served as a conduit for migrating solutions over a long period but appears of little importance as a site for ore deposition. However, ore concentrations of importance occur adjacent to portions of the northwest faults.

Porous "white" silicification is most prevalent along northwest faults that cut the main and the west ore bodies. Fault zones, however, are sparsely mineralized, carrying quite low amounts of gold. A number of samples of gouge and bleached rock adjacent to northwest and northeast faults have been sampled and analyzed (Table VIII), without finding evidence of significant gold mineralization. Samples of gouge usually contain illite and montmorillonite. Kaolinite and dickite become locally abundant as alteration products of quartz porphyry dikes that intrude high-grade faults in the area.

TABLE VIII. Gold Content in Fault Gouge and Silicified Rocks

Northeast Fault, 6360-foot and 6380-foot Benches, Main Ore Body	
Gouge along fault	<0.005 oz/ton Au
Vinini near fault	0.005 "
Northwest Fault, Top Bench, West Ore Body	
Bleached shear zone in fault	<0.005 oz/ton Au
Argillaceous stiltstone, foot wall of fault	0.02 "
" " hanging wall of fault	0.32 "
Barite in fault	0.05 "
Northwest Fault, 6240-foot Bench, East Face of Main Ore Body	
Barite in fault	0.07 oz/ton Au
Bleached dike in fault	0.19 "

Highly altered fault zones may have served as conduits for mineralizing solutions but have not become significantly mineralized. Gouge from northwest faults usually contains from a trace to 0.05 oz/ton Au.

Original minor fracturing and jointing have been somewhat obscured in the Roberts Mountains Formation by intense argillizing alteration and local silicification. The alteration, as inferred from silicification, is a general permeation and cuts across jointing and fracturing.

The unconformity between the "Popovich" and the Roberts Mountains has been highly silicified and is sparsely mineralized in places. Alteration of the "Popovich" appears to be localized largely along vertical joints. Altered "Popovich" samples usually contain only traces of gold (0.005 to 0.03 oz/ton).

ROLE OF COLLOIDAL GOLD IN ORE FORMATION

Microscopic Gold

Not even specks of gold are visible in Carlin ore to the unaided eye, but with the microscope at 1000x or more, gold from the main ore body may be detected in a variety of argillaceous rocks with a range in carbonate content. Textural associations of gold in the 5 to 0.5 μ range are frequently visible under the microscope, but submicron sizes (0.2–0.5 μ) may be barely resolved at high magnifications, while particles below the limits of resolution are barely visible but can not be resolved. Particles much less than 0.5 μ in diameter must be observed with the electron microscope. Gold often borders detrital quartz grains (Figure 16), and may be included within fractures in detrital quartz or disseminated in matrix clays. Gold particles do not appear to have been transported mechanically.

Larger gold particles (5 to 1 μ) are irregular but generally subrounded to oval in outline. Reflected colors range from pale to deep yellow in polished sections. The low hardness and slight negative relief aid in distinguishing between gold and pyrite. It is estimated that possibly 90 per cent or more of the gold may be submicroscopic (<0.2 μ).

Samples containing gold microscopically visible at high magnifications often show pore spaces where calcite has been selectively removed. Gold is common along friable zones, but impregnation with epoxy plastic is required to retain it in situ during polishing.

Microscopic gold has been observed locally in association with late quartz veinlets in silicified siltstones (Figure 17), and with barite and along external boundaries of pyrite. Oxidation of the pyrite to hematite has liberated smaller inclusions of gold.

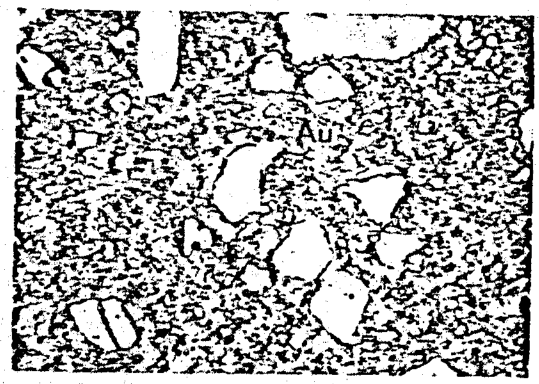

FIG. 16. *Particle of Gold (Au) Attached to Detrital Quartz (Q) Grain. Sample from main ore body. ×900, Incident light.*

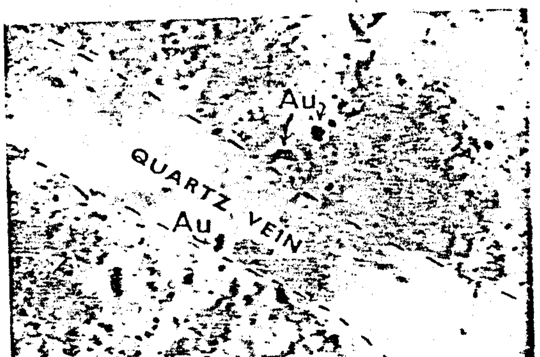

FIG. 17. *Mineralized Quartz Veinlet in Silicified Siltstone. Gold (opaque) is distributed within the veinlet and through the adjacent silicified host rock. ×720, Transmitted light.*

Submicroscopic Gold

The oval outline of the gold particles is preserved in electron micrographs at magnifications up to 120,000× (Figure 18). Individual particles may range down to less than 0.005 μ. Their identification has been confirmed by limited area electron diffraction on clusters of rather high gold concentration. Earlier identifications were made in late 1965 with the assistance of Emil Hamburg, graduate student in Physical Metallurgy, Columbia School of Mines, utilizing a Siemans Electron Microscope.

The fine dimensions of Carlin gold are confirmed by analyses of screen fractions from a high-grade composite sample from the 6400-foot bench (Table IX).

In the analysis, 85.8 per cent of the gold is concentrated in the −400 slimes and decanted slimes where half of the gold is associated with illitic clays.

FIG. 18. *Electron Micrograph of Native Gold Clusters in Clay Matrix.*

TABLE IX. Gold Content in Screen Fractions (6400' Bench)

Screen Fraction	Per Cent of Sample by Wt.	Au Oz/Ton	Per Cent of Total Au
+200 mesh (74 μ)	5.0	2.29	5.9
+400 mesh (28 μ)	14.2	1.13	8.3
−400 slimes (5–28 μ)	43.3	1.57	35.3
Decanted slimes (−5 μ)	37.5	2.58	50.5

Attempts were made to dissolve silicate minerals selectively and leave the gold, using various solvents and fluxes including hydrofluoric acid, caustic soda, borax, sodium carbonate, potassium carbonate, and sodium acid phosphate. Solubility tests were conducted at temperatures ranging from room temperature to about 100°C; fluxing was conducted from 750° to 900°C. In each instance, significant amounts of gold were dissolved along with the silicates. A method was not found to separate colloidal-sized gold from the silicates by physical treatment.

Precipitation of Colloidal-Sized Gold

The mechanics of colloidal gold precipitation have been investigated by many workers, Butler (4); Haycock (7); Smith (13); Stillwell and Edwards (17); W. H. White (14); Van Aubel (9); and Joralemon (19). Most investigators agree that hydrothermal gold is carried in true solution and not as colloidal particles. This conclusion is supported by textural studies of vein gold (14) and solubility studies of metallic gold in alkali sulfide solutions (13).

Precipitation of gold from alkali sulfide solutions may depend on several mechanisms including: (1) sulfide ion concentration; (2) pH of the solution; (3) the temperature and pressure system; and (4) the nature of mineral surfaces for adsorption or nucleation of gold. Metallic gold crystals may be precipitated from alkali sulfide solutions by lowering the sulfide ion concentration (13). The sulfide ion concentration may be lowered by the escape of H_2S under low pressure or by oxidizing the sulfur to sulfates. The latter lowers the pH and enhances precipitation.

Haycock (7) states that submicroscopic gold tends to occur when deposition is contemporaneous with that of the host minerals, whereas, coarser gold tends to form when deposition is later than the host. Essentially contemporaneous deposition would appear to prevail at Carlin. Here various clay minerals, carbonaceous bitumen, pyrite, arsenic sulfides, and silica have accompanied gold deposition. Gold has been adsorbed selectively by, or nucleated onto, surfaces of illitic clays, carbonaceous matter, iron sulfides, and quartz. Submicroscopic colloidal-sized gold may be distributed over a range in particle size from about 0.2 μ down to the size of a gold atom (1.45 Å or 0.000145 μ). Haycock (7) restricts colloidal-sized gold to a limited range between about 6 Å (0.0006 μ), and 75 Å (0.0075 μ). Colloidal-sized, gold, as defined by Haycock, may account for as much as half of the gold in the deposit, as indicated by the optical and electron microscopes and reference to Haycock's grain size curves (7, p. 409). The rapid solubility of the Carlin gold in cyanide solution also indicates the distribution of fine gold through a permeable rock matrix.

Influence of Host-Rock Permeability

The deposition of gold may be regarded as a subsidiary phase in the sequence of leaching and silicification of sedimentary limestones influenced greatly by permeability. More permeable beds served as conduits for solution movement, from which auriferous fluids diffused into minute interstices and tiny fractures of less permeable beds. Gold deposition occurred mostly along the finer capillaries and not along the main avenues of fluid transport. These observations agree with those of a number of investigators including Mawdsley (8), Johnston (11), Pardee and Park (16), W. H. White (14), and Chase (18), who have noted the importance of fine fractures and microcavities in minerals, notably quartz, in admitting gold to a site of emplacement.

The Roberts Mountains limestone with accompanying thin clay streaks becomes readily permeable to ore solutions after the calcium carbonate has been removed. Distribution of gold appears to depend more on micro-permeability than macro-permeable characteristics, Highly permeable silty strata, porous silicified zones, and drusy chalcedonic seams are inherently low in gold compared with nearby argillaceous beds with pore dimensions that are submicroscopic but provide large surface areas.

Gold Deposition in Clay

The association of gold with kaolinite and fine micas has long been noted (3). The possibility exists that, following the precipitation of fine gold from true solution, positive charges on the edges of colloidal particles in the Carlin matrix clay may have attracted the negatively charged colloidal-sized particles of gold. H. van Olphen (28) has reproduced an electron micrograph showing crystals of kaolinite more or less translucent in the electron beam, with small opaque spheres of gold attached to the edges of almost hexagonal flakes of kaolinite. The kaolinite crystals measure about .5 to 1.0 μ while the gold particles measure about .005 to .01 μ.

In discussion, H. van Olphen points out that, in contrast to the large flat surfaces of clay mineral crystals where negative charges prevail, the edges of the crystals expose edges of the layer lattice structure where the charge is positive. Thus, the positive double layer on the edge of the clay crystal flake would attract gold while the flat negative double layers would repel gold. This may account for the absence of gold particles on the flat surfaces of the kaolinite flakes in contrast to the concentration that takes place around the rims of the crystals.

This colloidal phenomenon is of particular interest in view of the natural concentration of gold which appears to take place in the small streamers of clay at Carlin. It would appear that colloidal gold, once precipitated from solution, would be apt to become entrapped by such a mechanism. Thus the positive charges of the mono-layers on the edges of clay crystals may have provided a source of attraction for the gold particles that, in turn, resulted in the concentration of more than normal amounts of gold in the clay.

Organic Material and Fine Gold

Gold and organic material, at times resembling asphaltite, locally are associated in ores from the easterly extension of the main ore body. Also concentrates rich in organic matter show an increase in gold content, and the mutual association of some gold and organic matter is indicated by metallurgical test work. Gold insoluble in cyanide solution has been noted to increase with carbon content, (Table X), although most of the gold readily becomes soluble after the hydrocarbon is removed in roasting.

Organic matter is a known precipitant for gold, and precipitation of gold from cyanide solutions apparently is accomplished by physical adsorption of the gold onto surfaces of some forms of carbon. Such a phenomenon also might be suggested to have occurred between the organic matter in the Roberts Mountains limestone and the ore solutions, except that large sections of organic limestones in

TABLE X. Insoluble Gold Content in Carbonaceous and Pyritic Ores

Locality	Carbon Per Cent	Pyrite Per Cent	Insoluble Gold
Mercur District, Utah[1]			
Oxidized ore	0.105	N.R.	$0.40 $/Ton
Raw Base (Arsenic)	0.358	N.R.	0.90 "
Pyritic base	0.450	N.R.	All but trace "
Carlin Ore Body, Nevada[2]			
Oxidized ore, Main Ore Body	N.D.	0.2	8 per cent of total Au
Pyritic ore, Northeasterly extension	N.D.	20.0	31.6 "
Carbonaceous ore, Northeasterly extension	0.18	1.0	79.7 "
Carbonaceous-pyritic ore, Northeasterly extension	0.45	3.0	87.7 "
Carbonaceous-pyritic ore, Northeasterly extension	0.53	3.0	87.9 "

[1] Association of carbon and insoluble gold in Mercur ores described by B. S. Butler, et al (1920), p. 394.

[2] Investigations into treatments of Carlin refractory gold from metallurgical files of Newmont Explortion Limited, Danbury, Connecticut. It should be noted that refractory carbonaceous and pyritic ores are relatively minor in occurrence in the Carlin ore body, but are worthy of note for comparison with other carbonaceous gold deposits in Nevada and Utah.

the vicinity of Carlin are virtually unmineralized.

The main ore body at the Carlin mine has been partly oxidized by recent weathering, resulting in removal of much of the pyrite and carbon. Some unoxidized ore has been encountered in the main pit that is dark gray to black and deleterious to gold recovery in the mill.

Unweathered limestones of the "Popovich" and Roberts Mountains formations are slightly organic and pyritic through a stratigraphic interval of hundreds of feet. The amount of organic carbon by assay mostly ranges from a few tenths to several per cent. Some redistribution has occurred during periods of mineralization. The migratory nature of organic matter appears upon thin section study. It is such as might result from petroliferous origin. The latter, however, has not been verified by other studies.

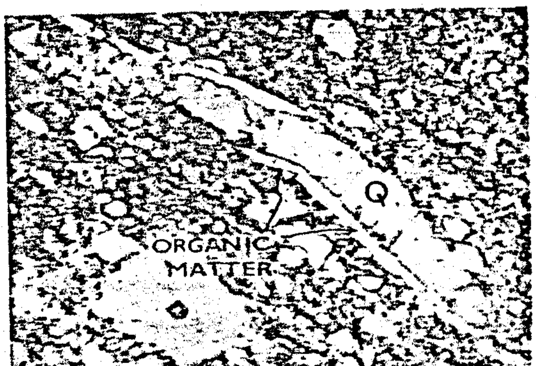

FIG. 19. *Organic Residues, Resembling Asphaltic Bitumen, along Borders of Quartz Veinlet (Q) in Dolomitic Siltstone. Organic matter appears to have been mobilized and emplaced epigenetically after the quartz veinlet. ×110, Incident light.*

The organic matter is medium to dark gray, slightly anistropic in incident light, opaque except on thinnest edges, and takes a poor polish. Bituminous residues have accumulated within a variety of accessible spaces including: (1) passageways along silica veinlets (Figure 19); (2) fractures in sedimentary rocks and in barite veins; (3) bedding planes; and (4) interstitial pores in argillaceous siltstones. Most of the bituminous matter occurs as micron-size disseminations in interstitial clays.

Paragenetic features indicate that much of the bitumen in carbonaceous ore was remobilized and redistributed during and after the introduction of gold and hydrothermal silica. Highly carbonaceous ores appear to have been literally soaked in "petroleum" that subsequently was polymerized in situ by thermal solutions.

Organic matter in the ore is amorphous as indicated by x-ray diffraction patterns, but qualitative estimates of the relative amounts and types of the material can be made by differential thermal analysis. D.T.A. curves were run in air to temperatures as high as 1000°C. Oxidation temperatures were determined and reaction gases examined both for organic matter and pyrite from a number of samples. Pyrite oxidizes exothermally in air between 440° and 575°C, accompanied by the evolution of SO_2. Organic matter begins to oxidize slowly at about 350°C and reaches exothermic maxima at two temperature intervals, near 490° and 570°C, respectively. Strong endothermic reactions near 760° and 850° are attributed to the decomposition of carbonate minerals. The relative amounts of organic matter were roughly estimated in a number of samples from the intensity of oxidation exotherms.

Infrared spectra were found useful in the analysis of gases from differential thermal analyses. Surges of oxidation products such as sulfur dioxide and carbon dioxide may be correlated with oxidation exotherms recorded on D.T.A. charts. However, hydrocarbon absorption bands near 3.5 microns are weak and broad and will require further study.

Individual particles of gold have not been observed in organic matter. Poorly resolved clusters of submicron gold occasionally may appear in dolomitic siltstones of moderate organic content, where the gold is associated with clays or quartz. The textural features in most unoxidized ore samples indicate that organic matter was mobilized and redistributed possibly during mineralization.

Role of Sulfur in Deposition

The importance of sulfur in the transportation and precipitation of metals in hydrothermal systems has been repeatedly investigated. Sulfides of gold, in common with Hg, Bi, Sb, As, and Te, are soluble in dilute aqueous solutions at different temperatures. The solubility of gold and mercury alkali-sulfide solutions was demonstrated long ago (Becker, 1). This was subsequently expanded into the "alkali sulphide theory of gold deposition" by F. Gordon Smith (13), which has gained moderate acceptance. He precipitated native gold from alkali-sulfide solutions.

Since the solubility of gold in aqueous solutions depends on free sulfur and high pH, it follows that precipitation of gold depends on lowering the sulfur content and the pH of the system. Such a mechanism for gold precipitation was proposed by Ransome (2) for the Goldfield deposits, and by Joralemon (19) for the Getchell deposit. The loss of sulfur as H_2S from hot springs is well documented. Discharge gases from Steamboat Springs are principally H_2S, CO_2, nitrogen, and argon (15). According to White (20), hydrogen sulfide is evolved from the water table wherever active thermal systems exist and, under favorable conditions, is oxidized in part to sulfuric acid. He reports a pH of 7.9 for flowing saline water, while sinter only a few inches above the water table may have a pH of less than 2.

Sulfide minerals associated with gold deposition at Carlin include pyrite, stibnite, realgar, and cinnabar. The depth of the water table at the time of mineralization is not known, and only minor amounts of alunite and jarosite have been identified. Some degassing of thermal solutions may have occurred and possibly contributed in places to the supersaturation and ultimate precipitation of gold, arsenic, mercury, antimony, and iron.

METALLIC MINERAL ASSOCIATES OF GOLD

Microscopic particles of gold have been observed in mutual contact with quartz, dolomite, barite, illitic clays, pyrite, and carbonaceous matter. Also a number of metallic minerals occur that have not been observed in mutual contact with gold; cinnabar, native arsenic, realgar, orpiment, and stibnite.

Base metal sulfides and sulfarsenides, including galena, sphalerite, jordanite, and possibly tennantite, have been detected in barite veins and quartz porphyry dikes quite low in gold. Metallic minerals that have been identified within or adjacent to ore zones at the Carlin mine are described in the following sections.

Native Arsenic

Small, nearly spherical inclusions of native arsenic, 2 to 30 μ thick, occur in argillaceous siltstones and barite veins. Arsenic granules occur locally in the interstices between grains in argillaceous siltstones and in solution cavities in barite. Visible gold has been detected in polished mounts spatially associated with native arsenic but not in mutual contact.

Pyrite

Pyrite is distributed throughout portions of unoxidized ore, ranging in concentration mostly from about 0.7 to 3 per cent; occasional samples may contain up to 10 per cent pyrite but are largely limited to the easterly extension of the main ore body. Pyrite crystals range predominantly from one to 20 μ in diameter and occur as minute inclusions in quartz crystals even where ore is highly oxidized. Pyrite is finely disseminated, similarly to gold, but, in some instances, may occur as replacements of microfossils.

In reflected light, pyrite is pale brass yellow and quite hard compared with associated gold. Morphologically, most pyrite crystals have been partially replaced and only occasionally appear as euhedral crystals, displaying pyritohedral and cubic outlines.

Growth rings and inclusions are common in pyrite and most crystals show microfracturing with cavity defects. Some grains are nearly spherical, a shape probably caused by crystal growth under conditions in which particles of colloidal size were precipitated initially, followed by some continued crystal growth directly from solution. Much of the gold appears to be slightly later than the pyrite, occurring along accessible cavities or external defects in the pyrite.

Occasionally gold is barely discernible microscopically as inclusions in pyrite. Such inclusions are liberated from the pyrite by oxidation. Gold may be more easily observed in polished sections of oxidized ores surrounded by hematite, goethite, and amorphous limonite.

X-ray diffraction patterns from flotation concentrates from the east ore body show major pyrite with minor amounts of quartz and clays as contaminants. Arsenopyrite or marcasite were not detected, but significant amounts of arsenic (1 to 2 per cent As) were noted by x-ray fluorescence analyses. Small amounts of copper and zinc (0.01 per cent) were also detected in the pyrite concentrates.

Cinnabar

Small amounts of cinnabar are widely distributed, occurring as spotty disseminations along cavities in silicified beds. Fine, bright red crystals usually may be separated from most ore samples by panning and range from a few microns up to several millimeters long. Reddish brown crystals of cinnabar, up to nearly a centimeter long, were found near the northwest fault on the 6380-foot bench of the main ore body. Traces of schuetteite, $HgSO_4 \cdot 2H_2O$ were identified as occasional coatings on oxidized surfaces of the cinnabar (22). In thin section, crystals of cinnabar appear sparsely distributed in interstitial cavities along zones of porous silicification and occasionally are surrounded by late fillings of calcite.

Arsenic Sulfides

Realgar and orpiment have been identified in the Roberts Mountains and "Popovich" limestones and in mineralized seams of siltstone in the main ore, body. Realgar alters to orpiment and arsenolite, which appear as yellow coatings along exposed surfaces of barite veins and adjacent carbonaceous zones.

The distribution of arsenic in the ore body is somewhat parallel to gold. Higher gold values are usually accompanied by higher arsenic, as indicated by comparison of metal values across a high grade ore zone on the 6400-foot bench (Table VI). Gold content of from about 1 to 5 ounces per ton may be accompanied by from 0.1 to 0.4 per cent As. Some arsenic samples range up to several per cent. Partially oxidized ore in the main pit may contain arsenolite and locally scorodite.

Stibnite

Antimony, like mercury and arsenic, is widely disseminated through the ore body and locally is concentrated in restricted pockets as finely crystalline stibnite. Stibnite crystals are usually highly prismatic and hairlike in appearance. Microscopically, crystals are opaque in transmitted light, light gray to white in reflected light, and strongly anisotropic. Stibnite is usually associated with realgar along silicified portions of barite veins.

Antimony commonly occurs in concentrations from 0.01 to 0.02 per cent in the ore and locally increases to several tenths of a per cent along barite veins mineralized with arsenic.

Galena

Galena occurs sparsely with sphalerite in barite. Polished specimens show triangular pits typical of the cubic cleavage pattern of galena. Galena has been partially replaced by jordanite as the result of reaction with arsenic during mineralization.

Amounts of lead in the ore predominantly range from 0.001 to 0.003 per cent but may increase to nearly 0.01 per cent near quartz porphyry dikes and barite veins in the Roberts Mountains and "Popovich" formations. Sphalerite and galena are reported by R. A. Hardy (10) at Getchell, Nevada.

Sphalerite

Sphalerite is associated with galena in barite replacements. Crystals are highly embayed by barite and microcrystalline quartz. Jordanite is locally associated with quartz veinlets that penetrate sphalerite. Sphalerite is medium gray in incident light and translucent amber yellow in transmitted light.

Alteration of sphalerite to an opaque phase resembling tennantite has occurred along the external boundaries of some crystals.

Jordanite, $Pb_{14}As_7S_{24}$

Borders of galena crystals are rimmed by microcrystalline replacements by jordanite. Jordanite is microcrystalline and similar in reflectance to galena, but the jordanite is anisotropic. At some barite localities, galena has been completely replaced by jordanite. Some pods of jordanite in barite range up to several millimeters across.

Tennantite $(Zn,Cu,Fe)_{12}As_4S_{13}$

An isotropic gray, metallic mineral locally replaces sphalerite in barite veins where mineralized by late arsenic-bearing solutions. This opaque mineral may be zincian tennantite, since the mineral assemblage and chemical environment are compatible. However, as yet insufficient amounts of the mineral have been available for identification.

Secondary Supergene Minerals

Several supergene products have been tentatively identified in weathered portions of the ore; schuetteite, $HgSO_4 \cdot 2HgO$, arsenolite, As_2O_3, carminite, $PbFe_2(AsO_4)_2(OH)_2$, and scorodite, $FeAsO_4 \cdot 2H_2O$. These minerals reflect the association and local reactions of lead, arsenic, mercury, and iron in an oxidizing environment. Oxidation products are usually fine grained and difficult to identify without combined microscopic and x-ray techniques.

Paragenesis of Metallic Minerals

Although only a few of the metallic minerals described from the Carlin ore are found in any one specimen, there is a sufficient overlap of mineral assemblages to permit in outline, a probable sequence of metallic deposition (Figure 20).

Two main sequences of mineralization appear: (1) earlier base metal mineralization associated with barite and Cretaceous intrusives and (2) later low temperature Au-Hg-Sb-As mineralization possibly related to epithermal activity during the Tertiary.

Field and microscopic evidence indicate that cinnabar was deposited after the gold along porous silicified channels of the deposit. Crystals of cinnabar are locally surrounded by late calcite that fills porous interstices of the ore.

The gold has not been noticeably affected by recent weathering. There is no field or laboratory evidence to indicate that supergene redistribution of gold has occurred in significant amounts at the Carlin deposit.

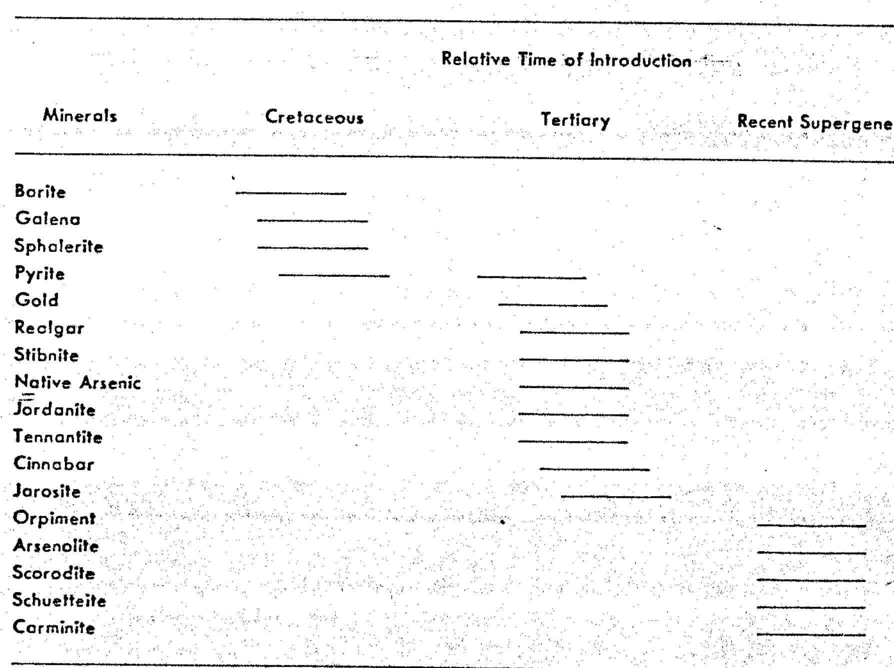

FIG. 20. *Paragenesis of Metallic Minerals in Main Ore Body*

ALTERATION FEATURES

General Description

Among the most striking alteration features exposed in the Carlin pit are rounded white to light-gray areas caused by extensive silicification of the Roberts Mountains Formation along the east face of the main ore body. Areas are elliptical in outline with long axes 20 to 150 feet in length and elongate in the direction of bedding. Ellipses are isolated but occur in broadly spaced clusters shown in at least three pit areas. The elliptical forms may cut directly across bedding and also occur at multiple horizons in the deposit. They appear to represent ancient conduits, perhaps indicative of the direction of flow of late solutions causing silicification through the ore deposit. The conduit areas are low in gold and do not appear to yield ore but may bear a zonal relationship to encircling ore zones. A siliceous-pyritic zone several feet thick frequently becomes brown on oxidation and surrounds the light gray conduits. The downward projection of the conduits is yet to be established.

In general, alteration at Carlin may be described in terms of four processes of replacement which have resulted in textural and compositional changes: (1) decarbonatization, (2) argillitization, (3) silicification, and (4) calcification.

Decarbonatization

Decarbonatization represents the earliest stage of alteration in which carbonate minerals were removed selectively and redistributed. Se-

TABLE XI. *Chemical Composition of Miscellaneous Rock Types at Carlin*

Chemical Constituents	(1) Silicified Roberts Mts. Per Cent	(2) Silicified Roberts Mts. Per Cent	(3) Altered Porphyry Dike Per Cent	(4) Quartz Diorite Per Cent	(5) Altered Quartz Diorite Per Cent	Method of Analysis
SiO_2	91.22	74.14	63.11	59.94	53.46	Wet Chemical
Al_2O_3	6.28	13.52	10.80	13.12	9.90	"
Fe_2O_3	2.26	0.92	11.74	5.58	6.45	"
CaO	0.18	0.64	0.92			"
MgO	0.34	0.85	0.15			"
K_2O	<0.5	5.0	<0.5	6.0	4.0	Spectrographic
Na_2O	<0.05	0.05	<0.05	4.0	2.5	"
TiO_2	0.25	0.7	1.0	0.75	0.85	"
MnO_2	0.02	0.003	0.03	0.08	0.12	"
BaO	0.04	0.1	0.35	0.25	0.25	"
SrO_2	0.005	0.008	0.05	0.08	0.05	"
ZnO	0.002	<0.002	0.4	0.003	0.005	"
CuO	0.015	0.002	0.03	0.020	0.025	"
PbO	<0.001	<0.008	0.003	0.003	0.002	"
As_2O_5	0.04	0.03	0.075	0.01	0.03	"
HgO	<0.01	<0.01	<0.01	<0.01	<0.01	"
Sb_2O_5	0.05	<0.01	<0.01	<0.01	<0.01	"
NiO	0.004	<0.001	0.06	0.005	0.002	"
ZrO_2	0.01	0.08	0.04	0.05	0.05	"
CoO	<0.001	<0.001	0.01	0.003	0.002	"
Cr_2O_3	0.02	0.02	0.15	0.015	0.01	"
V_2O_5	0.06	0.1	0.07	0.04	0.04	"
B_2O_5	0.02	0.12	0.03	<0.01	0.01	"
Y	—	0.007	0.015	0.005	0.005	"
Au	0.005 oz/t	0.015 oz/t	0.05 oz/t	Nil	0.02 oz/t	Fire Assay

(1) Silicified Roberts Mts. from Top Bench of West Ore Body.
(2) Silicified Roberts Mts. from 6460 Bench shown.
(3) Composite sample of altered porphyry dikes from 6380′ and 6400′ Benches of Main Ore Body.
(4) Quartz diorite from drill hole in intrusive 3 miles north of Main Pit.
(5) Altered sample from same drill hole as fresh quartz diorite.

lective removal of calcite by hydrothermal solutions occurred both in the Roberts Mountains and in the overlying "Popovich." Dolomite being less soluble commonly remained as relic rhomb-shaped crystals in a matrix of porous clays.

Calcite and dolomite were removed along a zone subjected to later silicification. There, relic sand grains may be observed distributed through a matrix of porous clays. However, later veinlets of calcite were locally re-introduced into some of the silicified zones. Largely decalcified rocks that include significant amounts of dolomite (5 to 30 per cent) often contain gold in larger amounts.

Fine-grained pyrite is disseminated through most of the altered rock but is not detected along zones of intense silicification. Such zones appear to have been largely stripped of their metal content, including iron, base metals, and gold (Table XI).

Argillization

Argillic alteration apparently accompanied decarbonatization. Illite is the predominant clay mineral, while montmorillonite and kaolinite are less abundant. In most ore samples, clays constitute 20 to 60 per cent of the rock. However, the clay content of the rock prior to alteration is largely a matter of inference. Probably a portion of the clay in altered rocks was derived from original clays, concentrated during the removal of carbonates. However, both recrystallization and direct crystallization of clay minerals occurred during hydrothermal alteration. Recrystallization, at least, and even direct crystallization could account for the major portion of clays in argillized rocks of the Roberts Mountains Formation.

In thin sections of ore samples, illite occurs as finely crystalline clay flakes. Individual clay flakes are submicron in size but lie together in aggregates that show parallel extinction under crossed nicols. Oriented slides have been prepared from clay concentrates and analyzed by x-ray diffraction. X-ray diffraction patterns indicate that the illite is uncommonly well crystallized and usually does not contain interstratified layers of montmorillonite. Montmorillonite normally occurs as a minor but distinct mineral phase in most ore samples and increases locally in the vicinity of quartz porphyry dikes to become a major component within altered dikes and along contacts. Kaolinite also is locally prominent while minor dickite has been identified from altered dike samples along the northwest fault in the main ore body.

Consideration of polytype stabilities of clay mineral structures by Bailey (36), or polymorphs as determined by Güven and Burnham (35), suggests that low-grade metamorphic or hydrothermal illites usually are of the metastable 1Md and 1M structures. These metastable micas crystallize early and may persist indefinitely at low temperatures. Illite as used herein probably includes hydromica (which is often a synonym) and even fine sericite.

Irregularly crenulated and even vein-like clay seams of possible epigenetic origin follow the trend of lineation. Seams are lenticular, ranging from less than a millimeter to a centimeter or more in thickness, and do not show regularly bedded features. Illite is the dominant component forming as much as 80 per cent of some seams. Gold has been found to concentrate in the illite fractions of the rock as indicated by analyses of selected lithologic layers (Figure 21) and by clay concentrates (Table IX). Silicified beds found in portions of the ore body have been depleted in clays that may have been removed or destroyed.

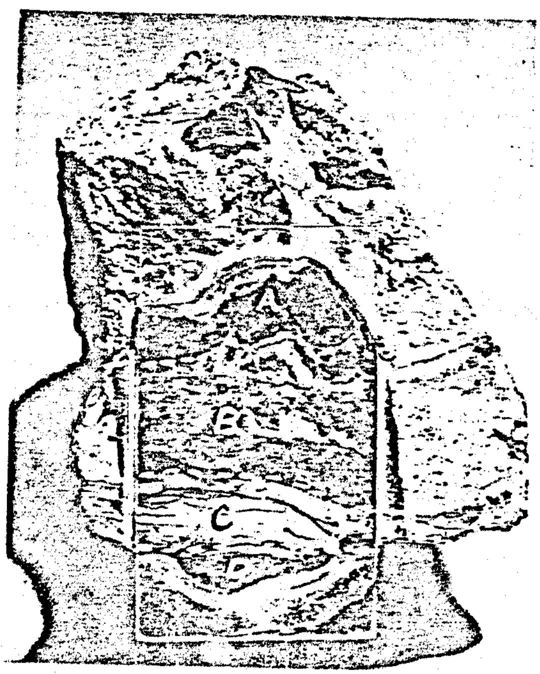

FIG. 21. *Crenulated Clay Seams in Ore, as shown beneath a glass slide. (A) silicified argillaceous siltstone, 1 in. thick, 2.70 oz/ton Au; (B) carbonaceous silty clay, 0.6 in. thick, 2.98 oz/ton Au; (C) white bleached illitic clay seamlet, 0.3 in thick, 3.02 oz/ton Au; and (D) siltstone-sandstone, 0.5 in. thick, 0.82 oz/ton Au.*

Silicification

Silica in several types of field occurrence may be recognized at Carlin: (1) original detrital quartz grains in the Roberts Mountains Formation; (2) thin dark sedimentary chert bands sparsley distributed through the original

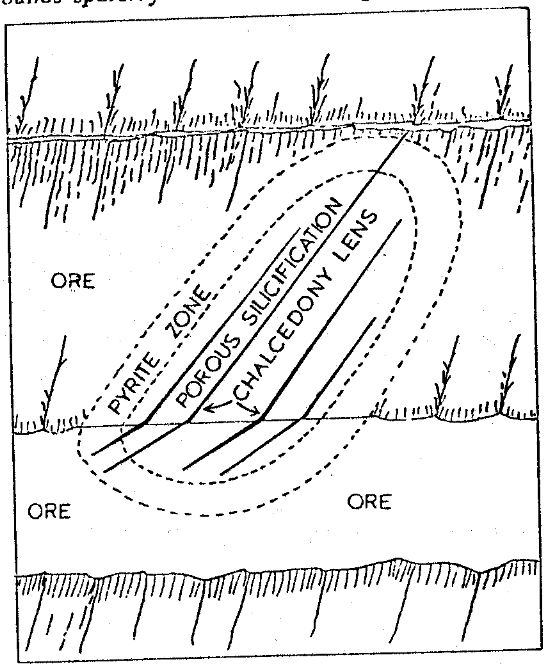

FIG. 22. *Schematic Diagram of a Chimney-like Form in the Main Ore Body. An ellipitical core of porous silicification is cut by more or less parallel chalcedonic lenses and surrounded by a pyrite-bearing zone. Ore surrounds the chimney but the chimney itself is non-ore-bearing.*

FIG. 23. *Close-up View of Chimney Structure, showing dark chalcedonic tongues of drusy silica pinching out upward along bleached beds.*

FIG. 24. *Drusy Dark-Gray Chalcedonic Seam from Close Up of Chimney on 6420-foot Bench.*

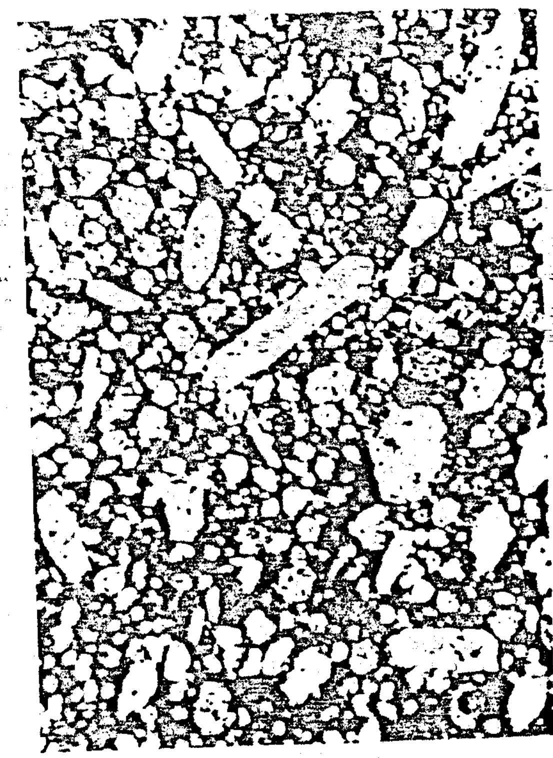

FIG. 25. *Photomicrograph of Recrystallized Siltstone Bed from 6380-foot Bench, showing euhedral doubly terminated crystals of quartz. ×26, partially crossed nicols.*

formation; (3) porous chimney-like ellipsoidal masses of fine recrystallized quartz (Figure 22); (4) chalcedonic tongues of gray silica, porous and drusy to hard and massive, that follow stratification but either pinch out in places or may swell to masses as much as 10 feet thick (Figures 23, 24); (5) recrystallized (often euhedral) quartz in the ore zone (Figure 25); and (6) small white quartz veins possibly accompanying surface induration that probably were formed by supergene recrystallization.

Lenses of cherty silicification in the original strata are thin dark gray and sinous, and intercalated with carbonate (calcite-bearing) strata, as would be expected in a syngenetic origin. Such dense dark-gray lenses of silica consist mostly of microcrystalline quartz and probably persist along less altered stratigraphic horizons in the deposit, locally grading into fine drusy quartz between upper and lower layers of dark-gray chalcedony. In thin sections, the inner zone of drusy silica displays remarkable networks of interconnecting micro-channels ranging from about 30 μ up to a millimeter or more in diameter. The silica framework consists of a mozaic of anhedral microcrystalline quartz that ranges considerably in size and shape. The permeability of the drusy silica to water flow must be high compared to adjacent solid chalcedonic lenses.

Thin sections of finely crystalline silicification show a maze of open channels through a recrystallized framework of quartz crystals. Quartz crystals often display euhedral outlines (Figure 25) and range from about 30 to 100 μ long. Euhedral quartz crystals often are doubly terminated but show little or no tendency to

TABLE XII. Gold Content of Bleached, Silicified, and Related Rock Types in the Roberts Mountains Formation

	Au Oz/Ton
(A) Cross Section Through Light Gray Silicified Zone in Ore Body on 6380-foot Bench near Center of Main Pit (Fig. 64)	
Dol. Arg. Siltstone above "white"[1] zone	0.43
Silicified chalcedonic seam at upper "white" contact	0.08
Arg. siltstone with drusy silica seams in "white" zone	0.03
Silicified chalcedonic seam at lower "white" contact	0.22
Arg. siltstone below "white" zone	0.54
Recrystallized siltstone-sandstone bed below "white" zone	0.03
(B) Altered silicified Zone in Sparsely Mineralized Beds on 6460-foot Bench at North-east End of Main Pit	
Argillaceous siltstone above bleached	0.065
Argillaceous siltstone up-dip from "white" area	0.04
Argillaceous siltstone at contact of "white" area	0.03
Argillaceous siltstone near center of "white" area	0.015
Drusy and chalcedonic silica in "white" area	0.02
Drusy and chalcedonic silica at lower contact of "white" ellipse	0.03
Chalcedonic silica seam below "white" zone	0.14
Argillaceous siltstone below "white" zone	0.055
(C) Silicified Beds Below Ore Zone in West Ore Body	
Silicified outcrop with quartz veins at top of southwest ore body	<0.005
Quartz vein in silicified beds exposed on top bench	<0.005
Chalcedonic silica adjacent to quartz vein	0.02
Footwall adjacent to silicified beds	0.01
Argillaceous siltstones 50′ below silicified zone in footwall	0.02
Argillaceous siltstones 50′ above silicified zone in hanging wall	<0.005
(D) Miscellaneous Silicified Zones in East Face of Main Ore Body	
Silicified Arg. siltstones on 6440-foot bench	<0.002
Buff arg. siltstone above "white" zone on 6440-foot bench	0.005
Chalcedonic silica seams on 6600-foot bench	0.03
Chalcedonic silica in bleached zone on 6420-foot bench	<0.002

[1] "White" refers to ellipsoidal and other masses of finely crystalline silica (Figures 22, 23).

develop comb structures. Cavities in recrystallized siltstones range mostly between 10 and 150 μ. The largest crystals rarely measure as much as several millimeters long.

Clays, carbonates, pyrite, and gold occur in minor amounts as minute inclusions in crystals of quartz. Possibly the gold inclusions in quartz are a final form of sparse precipitation. Interstitial cavities between crystals have been swept clean of residual clays but may be coated or filled locally with later epigenetic minerals, e.g., calcite, montmorillonite, realgar, and cinnabar. Gold usually is sparse in fine crystalline silicification and drusy silica lenses, being confined to minute inclusions in quartz crystals.

Drusy chalcedony (Figure 24) grades sharply into friable recrystallized portions of silicification ellipses that in turn pass transitionally into unsilicified argillaceous siltstones. Argillaceous siltstones adjacent to ellipsoidal zones are variably dolomitic and frequently ore bearing. Ellipses or "chimneys" show intermediate stages of silicification ranging from incipient quartz overgrowths to advanced stages of quartz authigenesis. Interstices are filled largely with leached clays, mostly illite, and the resulting rock is loosely coherent, friable and granular.

Friable white silicified areas are spatially associated and genetically related to lenses of drusy silica (Figure 24). A typical "chimney" observed in the main ore body (Figure 22) displays finger-like projections caused by bleaching solutions. Encircling the "chimney" is a brownish pyrite-bearing zone about 5 feet thick. Gold increases beyond the perimeter of the brownish zone. Another zone of fine crystalline silicification was examined in the east face above the 6400-foot bench, where arcuate upper and lower elliptical boundaries were in the direction of stratification. Numerous "chimneys" are grouped in the silicified areas designated in the east pit face (Figure 5).

Silicification also occurs as siliceous impregnations that both transect or follow bedding. Permeable decarbonatized rocks above the 6440-foot bench along the east face appear literally to have "soaked up" silica that forms irregular pockets of silicification with sharp boundaries (Figure 14). The bulk density of porous, slightly mineralized beds of argillaceous siltstone was increased from 1.90 to 2.58 in silicified pockets adjacent to unsilicified rock. The gold content apparently is greater in unsilicified rock than in silicified rock. This local form of silicification seemingly accompanied early stages of mineralization and diluted the amounts of gold in the ore body.

One large lens of chalcedonic silicification was observed to expand to 10 feet thick from a thin bed in the west ore body. At the surface not far distant, quartz veins, presumably supergene, locally are associated with chalcedonic lenses. White quartz veins exposed along the top of the hill south of the top bench follow the strike and dip of the bedding, but disappear down-dip, grading into dark-gray chalcedonic silica and siliceous impregnations.

The amounts of gold in various bleached and silicified portions of the main ore body are compared in Table XII. In Table XII (A), ore appears in argillic material both above and below the chimney.

Calcification

Carbonate veinlets locally transect silicified zones locally replacing microcrystalline quartz. Chalcedonic to microcrystalline quartz also has been replaced by late calcite introduced along vertical fractures and interstitial vugs or channels. Permeable seams and beds in the ore may be impregnated with late calcite that fills interstices around euhedral quartz veins and permeates adjacent beds.

Decarbonated portions of the main ore body have been re-impregnated locally with calcite to form pseudo-limestones of higher bulk densities and lower amounts of gold. A sample of ore partially impregnated with calcite was separated into calcified and uncalcified fractions. A specific gravity of the uncalcified portion was 2.27 and that in the calcified portion 2.53. Gold, however, decreased from 0.49 to 0.20 oz/ton in the calcified material, possibly as a result of dilution from added carbonates.

ORE GENESIS

The development at Carlin has not yet reached the point at which observations appear adequate to justify comparisons with other gold deposits in the Great Basin area. Thus, only brief reference to selected occurrences concerning which published data are available will be made.

The Carlin deposit appears to show some genetic similarities to the Getchell deposit. It may also be low-temperature epithermal bordering on telethermal (6). Feeders in the Carlin deposit lack many such common epithermal features as crustification, comb structure, and banding and even show some resemblance to siliceous sinters.

Vein development seldom is recognizable, except occasionally in outcrop exposures. Permeable zones and feeders in the deposit often require microscopic examination for detection.

The similarity of the Getchell deposit to quicksilver deposits in the Great Basin has been discussed by Joralemon (19), who also suggests a close genetic relationship to Steamboat Springs.

The Carlin deposit in Nevada, together with Bootstrap and Getchell, and the Mercur deposit in western Utah and others (5), may comprise a genetically similar type, but considerably more study is needed to establish this relationship.

Recent studies of drill cores at Steamboat Springs (34) indicate that hot spring waters deposit small amounts of Hg, Sb, Au, and Ag and hydrothermally alter the rocks through which they flow. The most intense alteration is immediately adjacent to fractures where feldspars, carbonates, and clays are replaced by illite, quartz, and pyrite. This type of alteration also is prevalent at Carlin.

Hydrothermal alteration, coupled with the proven ability of such waters to deposit metals, indicate to Schoen and White (34) that spring waters are similar to some ore-forming fluids. It is well to remember, however, that the late silicification centers at Carlin, the features most suggestive of rising thermal centers, are deficient in gold. The genetic relationship of thermal waters at depth to epithermal ore solutions should receive further study.

Gold mineralization at Carlin is interpreted as epigenetic, of low-temperature origin, and formed under low-pressure conditions perhaps along the deeper roots of thermal spring activity.

CONCLUSIONS

The cumulative evidence at Carlin points strongly to the epigenetic origin of the gold. Among other features, argillic replacement of dolomitic host rock, major deposition of colloidal-sized gold in clay aggregates, chemical changes from rock to ore, nearby igneous activity, and elliptical chimneys of recrystallized silicification, all point to low-temperature epithermal origin. Major stages in the creation of the gold deposits as now found include:

(1) Deposition of the Vinini, Roberts Mountains and "Popovich" formations.

(2) Overthrusting as represented by the Roberts Mountains fault.

(3) Cretaceous igneous invasion and subsequent deformation.

(4) Base-metal emplacement in veins and replacements.

(5) Hydrothermal alteration and gold deposition.

(6) Epithermal silicification.

(7) Supergene action, weathering, and oxidation.

Distribution of gold depends largely upon the permeability of decalcified strata of the Roberts Mountains Formation to ore-forming fluids and precipitation in favorable hosts such as illitic clays, carbonaceous matter, and pyrite. Quite near surface emplacement by the release of H_2S may have contributed to the precipitation of gold, realgar, cinnabar, stibnite, and pyrite.

The fine gold occurrence at Carlin may be grouped along with other deposits at Getchell, Bootstrap, and Manhattan in Nevada, and at Mercur in Utah, as a shallow low-temperature epithermal deposit where vein development is hardly recognizable and ore minerals are finely disseminated in replacement bodies in carbonate sediments.

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