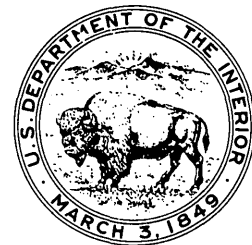# Statistical Study of Selected Trace Elements with Reference to Geology and Genesis of the Carlin Gold Deposit, Nevada

By MICHAEL HARRIS *and* ARTHUR S. RADTKE

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GEOLOGICAL SURVEY

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STATISTICAL STUDY OF SELECTED TRACE ELEMENTS WITH REFERENCE TO GEOLOGY AND GENESIS OF THE CARLIN GOLD DEPOSIT, NEVADA

By MICHAEL HARRIS and ARTHUR S. RADTKE

ABSTRACT

Linear regression and discriminant analyses techniques were applied to gold, mercury, arsenic, antimony, barium, copper, molybdenum, lead, zinc, boron, tellurium, selenium, and tungsten analyses from drill holes into unoxidized gold ore at the Carlin gold mine near Carlin, Nev. The statistical treatments employed were used to judge proposed hypotheses on the origin and geochemical paragenesis of this disseminated gold deposit.

The West, Main, and East ore bodies of the Carlin deposit are in the upper 265+ m (869 ft) of the Silurian and Early Devonian Roberts Mountains Formation in the northeast corner of the Lynn window near the crest of a large northwest-plunging anticline. The intensely deformed carbonate host rocks are in an area containing many intersecting high-angle faults and breccia zones that were the principal channelways for the ore solutions. The major faulting and igneous activity in the mine area took place before the ore formed.

The ore solutions dissolved calcite out of the limestone host rock and introduced silica, pyrite, gold, and various other elements. The initial calcite removal created permeable sections that were to be the more receptive sites for ore deposition. Most of the gold and mercury precipitated during this phase is either associated with organic materials or occurs together with arsenic and antimony as coatings on pyrite grains. A subsequent mineralization (possibly a later stage of the same mineralization) precipitated arsenic, antimony, and mercury sulfides followed by the deposition of copper, lead, zinc, and molybdenum sulfides and an overlapping formation of barite veins. The two sulfide stages and the barite veins were deposited independently of the gold. Geologic relations and statistical comparisons showed that the barite veins were formed after the gold deposition and are either associated with arsenic and (or) antimony sulfides, base-metal sulfides, or have no associated sulfides. Many analyses of barite veins performed to date have shown no detectable amounts of gold.

The linear correlation coefficients between element pairs and suites may or may not reflect the direct cause and effect relations of the mineralization sequence since it is most probable that many parameters controlled their precipitation. However, most of the correlations found agreed with geological observations, and some correlations revealed subtle geochemical relations that had not been previously recognized. The gold, mercury, arsenic, antimony suite of metals in the West ore body conformed quite well to the proposed linear model with an almost 80 percent reduction in variance and linear correlation coefficients as high as 0.87. We believe that the West ore body most closely approximates original conditions of the earliest mineralization phase. This opinion is substantiated by the scarcity of late arsenic, antimony, and mercury sulfides, by the lower organic carbon content, and by the simpler structural setting of this ore body.

The distribution and interrelation of gold, mercury, arsenic, and antimony between and in the three ore bodies were compared by stepwise discriminant analyses. The results of these tests consistently showed the West ore body to be significantly different from the other two. The mean values in the Main ore body tended to be much more similar to the West ore body than to the East. The polarity of the element values in the West ore body from the other areas is in direct accord with the proposed mineral paragenesis model in which the late mercury, arsenic, and antimony sulfide mineralization occurred only in the vicinity of the Main and East ore bodies.

Gold and mercury values showed high correlations in all of the areas tested. These correlations support the hypotheses that (1) gold and mercury were both transported in the same ore solution and were contemporaneously precipitated in response to similar influences, and (2) more than 90 percent of the investigated occurrences of both elements are either associated with various organic materials or occur together on the surfaces of pyrite grains.

Statistical analysis of a gold, barium, copper, molybdenum, lead, zinc suite in the West ore body gave results consistent with the proposed paragenetic model. The highest correlations were between the base metals, followed roughly by these elements to barium, and finally very low or not significant correlations of gold to barium and to the base metals. Gold was found to be negatively correlated to barium over the entire deposit; this relation reflects their paragenetic separation. Discriminant analysis techniques employed for this suite reconfirmed that statistically meaningful geochemical differences exist between the three ore bodies. Mean values in the Main ore body were similar to the mean values in its neighbor bodies, whereas the mean values of the two peripheral areas were fairly polarized toward their own means.

Linear regression analyses of gold with the independent variables boron, tellurium, selenium, tungsten suite show that data for these elements fit a linear model poorly. The only significant correlation found was between gold and tellurium; this correlation is strongest in the East ore body and becomes progressively weaker through the Main and West ore bodies. The mode of tellurium occurrence has not been firmly established, but tellurium and possibly selenium could be present in hydrothermal pyrite or could coat pyrite grains together with gold, mercury, arsenic, and antimony. Discriminant analyses of this suite again showed the West ore body to be significantly different from the other two.

There are still a multitude of unanswered questions concerning the genesis of the Carlin deposit. The significant standard deviations found make it somewhat hazardous to draw exact conclusions from the statistical findings alone. However, the statistical methods employed were very useful in establishing guidelines to interpret data and were also valuable in lending support to theories on the ore genesis.

1

INTRODUCTION

During the course of the geologic and geochemical study of the Carlin gold deposit, which began in 1968, a large amount of chemical data has been gathered on the host rocks and gold ores. Although most of these data were summarized in a paper by Radtke, Heropoulos, Fabbi, Scheiner, and Essington (1972), none of the data had been treated statistically. This paper presents the results of a statistical study made by Harris (1974), of certain minor elements in the unoxidized gold ores, together with basic geologic, mineralogic, and geochemical information provided by Radtke. Statistical data are applied to evaluate certain aspects of the chemical model of the Carlin deposit. Only analyses of samples of primary unoxidized ore were used, as it is likely that highly variable supergene oxidation processes would produce complicated elemental distribution patterns different from those produced by the original hydrothermal conditions.

Standard stepwise regression analyses, incorporating computer treatments shown in Dixon (1964), were used to determine correlations between the important elements and the dependence of the gold content on the presence of these other elements. Linear correlations were emphasized in order to establish direct correspondences between the elements involved.

Ahrens (1954), Lepeltier (1969), and Miesch (1967) gave reasons for treating geochemical data by using the lognormal equivalents of the numerical values found by analysis. We decided against using this approach for two main reasons: (1) Many of the analyzed values for some elements were reported as zero, so that by definition no log value could be assigned. We considered adding a constant, such as $+1$, to all the values, but so far we are unconvinced that it would be statistically valid to add $+1$ to zero and also add $+1$ to a very large number in the same population; (2) An attempt to use logs on some of the more receptive populations did produce more accurate predictor equations and more dramatic correlations, but the relative magnitudes of the latter remained unchanged from the order given in this text. Since the main purpose was to use statistical correlations to delineate geochemical associations, we felt justified in relying on linear functions.

All data used in this study were obtained from various types of analyses of composite samples representing 1.53-m (5-ft) intersections in rotary drill holes that penetrated mineralized carbonate rocks below the zone of oxidation. The drill holes were made at 15.3-m (50-ft) intervals at the intersections of north-south and east-west gridlines and represent development drilling carried out to establish the volume and grade of ore throughout the entire deposit. In order to assure coverage of the entire deposit, individual drill holes used for geochemical studies were selected from combined geologic and drill location maps. For each of the 96 holes chosen, assay and lithologic logs were used to help select representative materials from the top, middle, and bottom of each ore zone to achieve a complete three-dimensional sampling of the entire unoxidized part of the ore deposit. In general at least two samples were chosen from each hole.

Elements included in the study, methods of analyses, total number of samples analyzed, and the number of samples containing detectable amounts of each element are given in table 1. All analyses were performed in various laboratory facilities of the U.S. Geological Survey in Menlo Park, Calif., and Denver, Colo., as well as at the U.S. Bureau of Mines Experimental Station in Reno, Nev.

TABLE 1.—*Data on elements studied and analytical procedures*

[Spectrographic results are reported to the nearest number in the series 1.5, 1.0, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1; analytical error is approximately one standard deviation at plus or minus one reporting interval]

Element	Methods of analysis	Number of Samples		Analytical precision (percent)
		Analyzed	Containing detectable amounts	
Au	Fire assay	292	292	2–50
	Atomic absorption	292	292	2–50
Hg	Instrumental meter	239	230	10–50
As	X-ray fluorescence	80	80	3–10
	Colorimetric	159	159	10–100
Sb	X-ray fluorescence	80	80	3–10
	Colorimetric	159	159	10–100
Ba	Spectrographic	292	281	
	X-ray fluorescence	80	80	3–10
Cu	Spectrographic	292	292	
Mo	Spectrographic	292	198	
Pb	Spectrographic	292	274	
Zn	Atomic absorption	212	176	2–50
	X-ray fluorescence	80	80	3–10
B	Spectrographic	288	286	
W	Colorimetric	288	168	25–100
Se	Colorimetric	288	145	20–100
Te	Atomic absorption	288	89	5–100

FIGURE 1.—The location of the Carlin gold deposit in north-central Nevada.

Statistics and Geology, Stanford University, generously criticized the preliminary statistical work, for which we are very appreciative.

GEOLOGIC SETTING

The Carlin gold deposit, the largest of the disseminated replacement-type gold deposits found to date, is located about 64 km northwest of the town of Elko in north-central Nevada (fig. 1). Carlin Gold Mining Co., a wholly owned subsidiary of Newmont Mining Corp., operates the mine, which currently produces about 2,000 tons of ore per day from three open pits.

General information on the deposit has been presented in papers by Hardie (1966), Hausen and Kerr (1968), and Radtke and Scheiner (1970). A detailed geologic map of the deposit was published by Radtke (1973) and additional information on the structural and stratigraphic setting was included on a regional map of the Lynn mining district (Radtke, 1974). For the purpose of this paper, a simplified map of the deposit (after Radtke, 1973) is shown as figure 2.

Most of the Carlin ore bodies are in the upper 265 + m of the Silurian and Early Devonian Roberts Mountains Formation, which is overlain by the Devonian Popovich Formation (Akright and others, 1969). The Popovich Formation, composed of 80–120 m of alternating thick- and thin-bedded silty limestone, is truncated above by the Roberts Mountains thrust and is overlain by interbedded shale, chert, and limestone of the Ordovician Vinini Formation.

Host rocks for the Carlin deposit, together with other rocks of the lower plate, are exposed in the Tuscarora Range. In the central part of the Tuscarora Range uplift, folding, and high-angle faulting accelerated erosion and removal of the upper plate rocks to form the Lynn window. The Carlin deposit is located in the northeast corner of the Lynn window near the crest of a large northwest-plunging anticline where carbonate host rocks have undergone intense faulting and brecciation.

Within the mine area, high-angle faults and breccia zones served as main channelways for ore solutions and as structural controls for ore deposition. Radtke (1973) showed three sets of high-angle faults including an early east-west-trending set, a later north- to northwest-trending set, and a subsequent northeast-trending set. The presence of Late Jurassic or Early Cretaceous granodiorite dikes along several northwest-trending faults and one east-west fault indicate that these faults predate the dikes; in many areas the dikes are offset by northeast-trending faults confirming the later age of these structures. These relations plus the intense hydrothermal alteration of the dikes and the distribution of the ore, strongly suggest that the dikes and most of the faulting predate the ore formation (Radtke, 1973) and that the hydrothermal ore solutions were channeled along preexisting faults.

GENESIS OF THE ORES

The ore bodies at the Carlin deposit were formed where hydrothermal solutions moving along fault and breccia zones penetrated outward into thin-bedded argillaceous carbonate rocks of the Roberts Mountains Formation. Reactions between the ore solution and the host rock composed mainly of calcite, dolomite, illite, and quartz, dissolved the calcite, deposited hydrothermal silica and pyrite, and introduced gold and various other elements (Radtke and Scheiner, 1970). A generalized sequence for the hydrothermal development of the Carlin ores is shown in figure 3.

Petrographic examination of host rocks and ores indicates that the initial penetration of the hydrothermal fluids resulted in the removal of calcite causing a marked increase in permeability of the rocks. This permeability, in turn, had a strong influence on the de-

EXPLANATION

Upper Jurassic and Lower Cretaceous

Gold ore

Includes both oxidized and un-oxidized ore. Most unoxidized ore is not exposed

Granodiorite dike

Unconformity

UPPER PLATE OF ROBERTS MOUNTAINS THRUST

Silurian and Lower Devonian

Ov

Vinini Formation

Predominantly tan to gray, thin-bedded, interlayered siliceous shale, chert, and limestone

LOWER PLATE OF ROBERTS MOUNTAINS THRUST

Dp

Popovich Formation

Dark-gray, medium- to thick-bedded siliceous dolomitic limestone.

DEVONIAN

DSrm

Roberts Mountains Formation

Medium-gray, thin-bedded, siliceous, dolomitic limestone

SILURIAN AND DEVONIAN

ORDOVICIAN

TERTIARY

JURASSIC AND CRETACEOUS

Contact

Roberts Mountains thrust

High-angle normal fault

40

Strike and dip of beds

Outline of pit

Solid line denotes top of pit wall; dashed line denotes toe of pit wall.

Mine

17½°

TRUE NORTH   MAGNETIC NORTH

Ov

Dp   40

West   DSrm

ore   45

body   60

DSrm

Dp

30   DSrm

Ov

45

40

33

Dp   40

DSrm

Main   30

DSrm   32   DSrm

FIGURE 2.—Simplified geologic map

plant

Popovich
Hill

Ov

DSrm

Dp

Ov

DSrm

Dp

ore

body

East

DSrm

DSrm

Ov

DSrm

Dp

body

Ov

Ov

ore

| 0 | 200 | 400 | 600 | 800 | 1000 FEET |

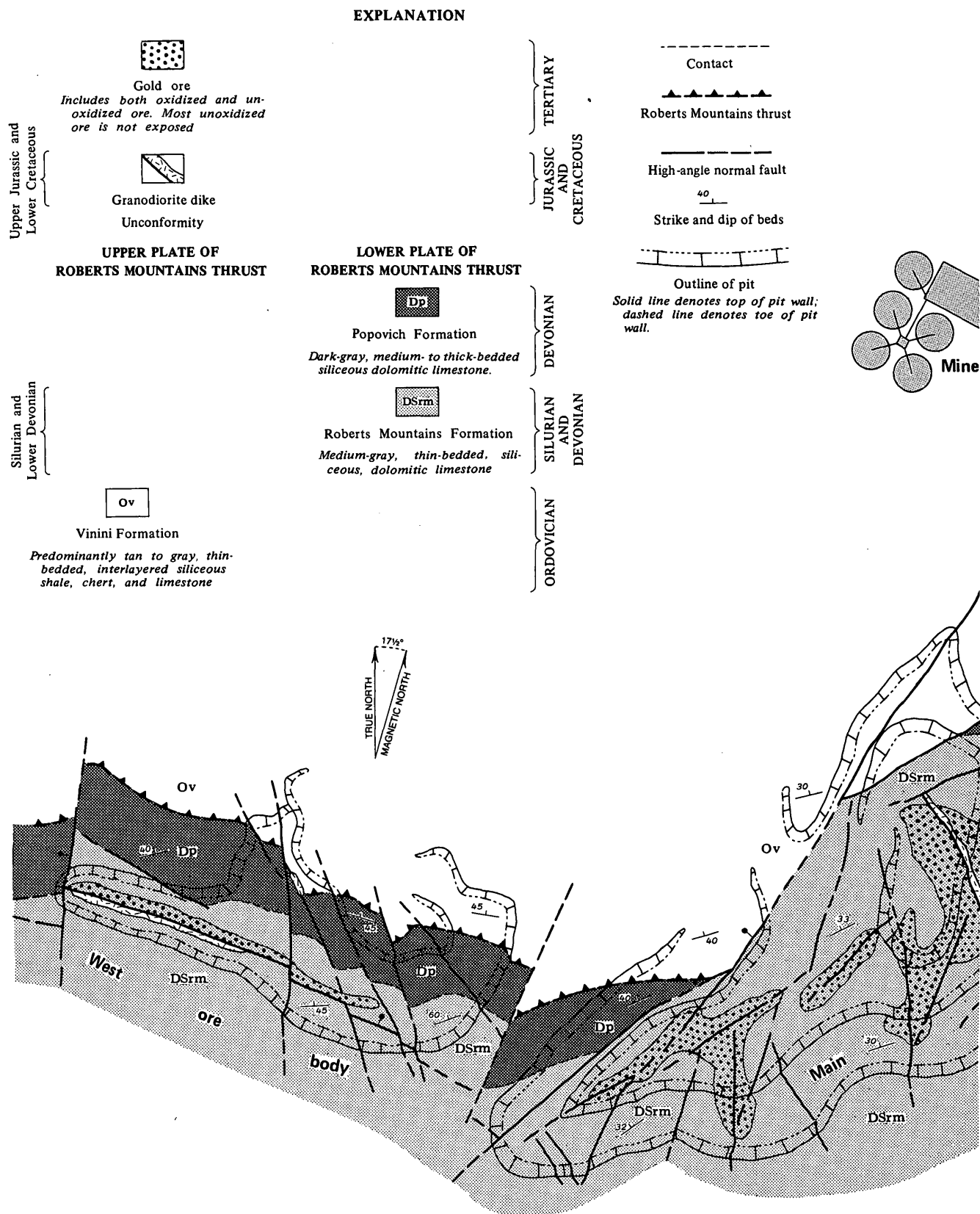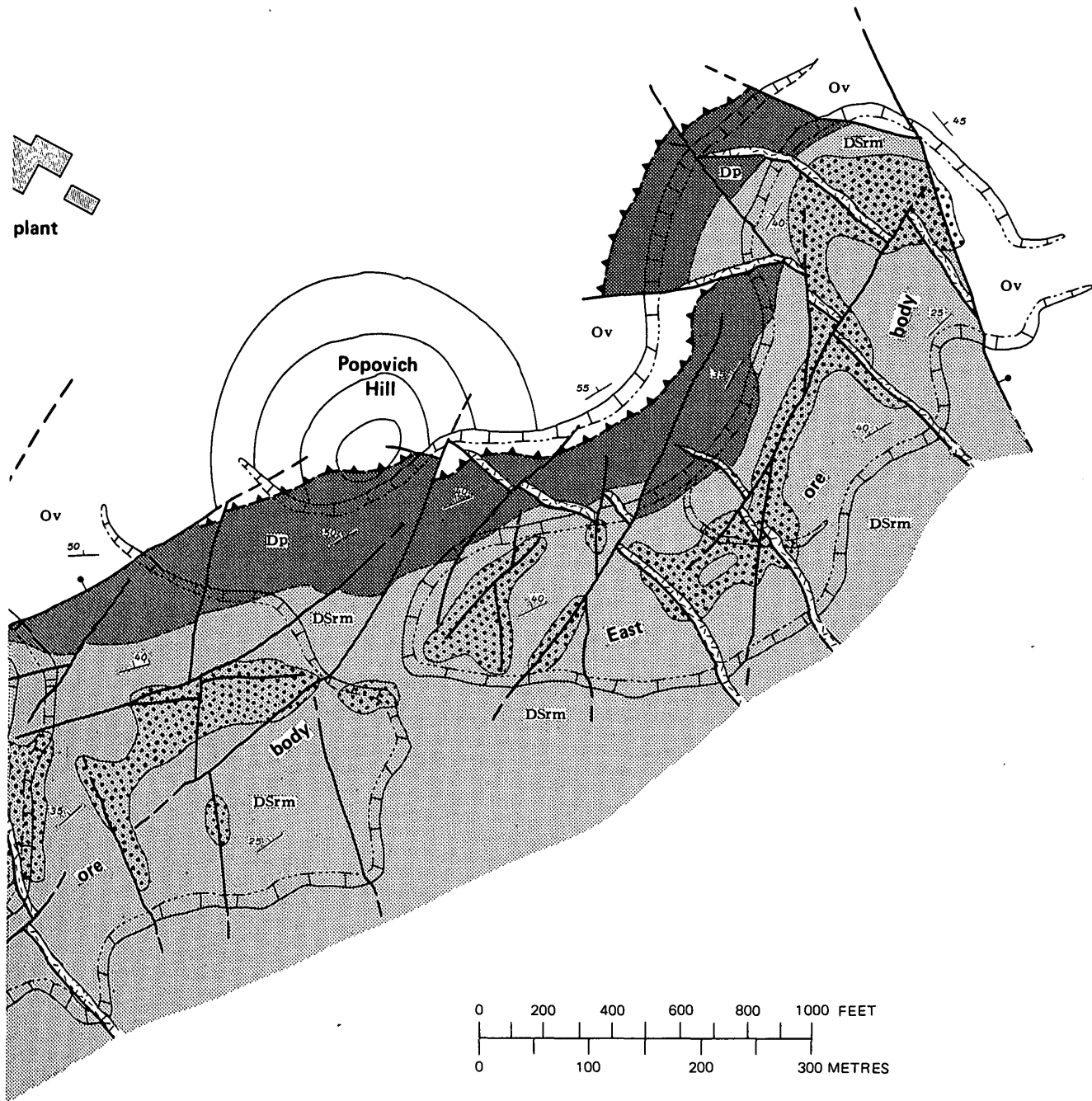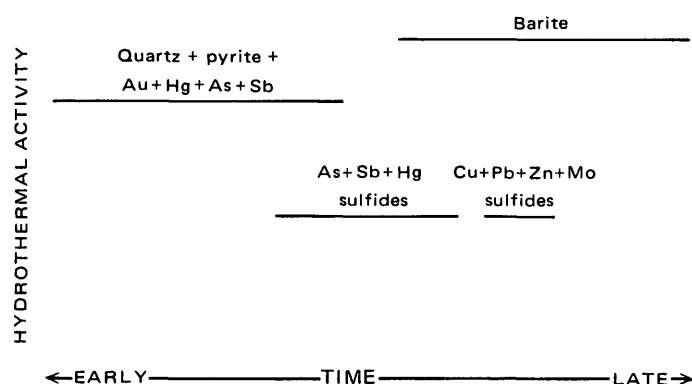| 0 | 100 | 200 | 300 METRES |

of the Carlin gold deposit.

FIGURE 3.—Mineralization paragenesis at the Carlin gold deposit.

velopment of zones favorable for the movement of later ore-bearing solutions.

The main period of gold deposition followed as the ore solution removed additional amounts of calcite and small amounts of dolomite, and deposited silica, pyrite, arsenic, antimony, mercury, and gold. Most of the gold and mercury deposited from the solution during this phase either is associated with organic materials or, along with arsenic and antimony, occurs as coatings on pyrite grains (Radtke, Taylor, and Christ, 1972).

On the basis of electron microprobe studies, Radtke, Taylor, and Christ (1972) distinguished four major modes of gold occurrences in the unoxidized ore: (1) as scattered particles along the rims of amorphous carbon grains, (2) as rather homogeneously distributed particles in other kinds of carbon compounds, or as gold-organic compounds, (3) as coating on pyrite surfaces along with arsenic, antimony, and mercury, and (4) rarely as free native particles. They found the mercury in the unoxidized ore to occur in three principal ways: (1) in association with carbonaceous matter, (2) as a coating on pyrite grains, and (3) as fine-grained cinnabar.

Any mechanism postulated to explain the transport of gold must be compatible with properties of a hydrothermal solution that carried mercury, arsenic, antimony, and quartz. Helgeson and Garrels (1968) used thermodynamic evidence to argue for gold transport as the aurous chloride species, $AuCl_2^-$, in acid ore solutions. Later Radtke and Scheiner (1970) attempted to use this model to explain many of the observed chemical and mineralogical features of the Carlin deposit. Weissberg (1970) suggested that gold could be transported in alkaline sulfide solutions, and Seward (1973) showed that neutral to slightly acidic solutions containing HS^- ion would be capable of moving gold under geologically feasible conditions.

Recent work by Rytuba and Dickson (1974) indicates that in a reducing environment, the chloride ion is not effective in transporting gold. Their experimental studies also suggest that at elevated temperatures in a $NaCl-H_2O$ solution reacted with pyrite and quartz, gold is in solution as a gold-sulfide complex, presumably $Au(HS)_2^-$.

Arsenic and antimony sulfides and silica are transportable in neutral aqueous solutions lacking excess sulfur or chloride ions (Dickson and Tunnell, 1968; Weissberg and others, 1966; Kennedy, 1950). However, so far as is known, mercury sulfide is extremely insoluble in any naturally occurring solutions other than slightly alkaline (pH 8 to 9) solutions containing dissolved sulfur (Dickson and Tunnell, 1968). Taking into account the restrictions imposed on the nature of an ore solution capable of simultaneous transport of gold, sulfides of mercury, arsenic, and antimony, and silica, it is reasonable to conclude that the hydrothermal solution responsible for developing the main stage of the Carlin ores was weakly alkaline and contained excess dissolved sulfur.

Although quartz veinlets are very uncommon at Carlin, a few containing small amounts of pyrite, gold, fluorite, and frankdicksonite have been found. Frankdicksonite, BaF_2, was found and described as a new mineral by Radtke and Brown (1974).

Locally the ore solution was trapped in open fractures, and sulfide minerals of arsenic, antimony, and mercury were formed. Important minerals containing these elements are orpiment, realgar, stibnite, and cinnabar. An apparent segregation exists between sulfides or arsenic and stibnite. In areas where orpiment and realgar are concentrated, only very small amounts of stibnite are present and antimony may substitute for arsenic in the structure of orpiment (Radtke, Taylor, and Heropoulos, 1974). In contrast, stibnite is concentrated in places that are deficient in arsenic sulfides.

The position of barite in the paragenesis of the deposit has been a subject of much speculation and uncertainty. Hardie (1966) initially concluded that barite occurrences have no correlation with the presence of gold in the mine area. Hausen and Kerr (1968) regarded the barite, together with the sphalerite, galena, and part of the pyrite, as forming in the Cretaceous, but the gold and other minerals forming in the Tertiary. Radtke and Scheiner (1970) suggested that barite was transported in and deposited from the gold-bearing hydrothermal solution, thus making the formation of barite veins and the deposition of gold roughly contemporaneous. Detailed geologic mapping suggests that most of the barite veins formed after the main phase of gold deposition and are either associated with arsenic sulfides or base-metal sulfides or are barren and deficient in sulfides (fig. 3). Results of stable isotope studies and considerations of the chemical model for ore genesis at Carlin support the

fact that barite formed late in the paragenetic sequence (Dickson and others, 1975).

Laboratory studies have shown that small amounts of various sulfide minerals of copper, molybdenum, lead, and zinc occur both in the mineralized limestones and locally in barite veins. These four elements show no association with gold either on the surfaces of pyrite grains or chemically combined with carbonaceous materials. They apparently occur only in the form of discrete sulfide minerals that formed late in the hydrothermal episode after gold deposition. Small grains of scheelite randomly scattered through the mineralized limestones account for the tungsten in the ores. Boron occurs in the clay minerals. The form in which the low amounts of selenium and tellurium occur has not been determined.

An important unresolved problem at Carlin is the paragenetic relation of the mineralization with respect to time. The locus of the mineralizing activity varied with time not only in its intensity and chemistry but also in space. For example, mercury, one of the most volatile elements, can be transported aqueously as Hg^{++}, Hg_2^{++}, or $Hg°$ but only as $Hg°$ and $HgCl_2$, in a gaseous phase. Silica and gold (so far as is known) can only be transported in solution and not as a vapor. Thus, to find an expression for the volatility of the elements in the rocks penetrated by mercury, it is necessary to examine the distribution pattern of mercury not associated with gold (that is, mercury not introduced in the aqueous phase). Unfortunately, we could not find a feasible way to do this as almost all samples contained detectable amounts of both elements.

The time distribution of the hydrothermal activity seems to fall into three rather broad categories covering early, intermediate, and late stages. This report deals with the unoxidized ores presumably derived from the early and perhaps part of the intermediate stages. However, much of the oxidized zone may have formed from processes for which these early stages are responsible rather than exclusively from a secondary supergene weathering by downward percolating meteoric waters, although these certainly did have an effect. The dominantly aqueous, ascending, early mineralization phase most probably ranged in temperature from a quite low value to the maximum value achieved. If boiling were induced, H_2S vapor that would be generated would stream upward and become oxidized to H_2SO_4. This phase would cause the overlying rocks to be leached and altered. The liquors derived from this process would then descend, adding sulfate to the subsurface waters and acidifying them, causing the deposition of the late sulfide-bearing sulfate and carbonate veins. It is also possible that descending meteoric waters during this stage were superheated and charged with volatiles, and

the waters thus also rose and joined in the oxidation action.

GEOLOGY OF THE ORE BODIES

The Carlin gold deposit is made up of three separate yet structurally and stratigraphically related ore bodies, each of which contains anomalous concentrations of the 13 elements studied statistically. The general shape and dimensions of the West, Main, and East ore bodies are shown in figure 2.

The West ore body is almost veinlike in form, strikes roughly east-west, dips steeply to the north, and follows the hanging-wall side of a normal fault with the same attitude (fig. 2). This ore body has strong structural controls, contains the smallest amounts of organic carbon of any of the ore bodies, and lacks visible concentrations of arsenic, antimony, and mercury sulfides.

The Main ore body is actually a northeast-trending zone roughly 915 m long within which the gold content varies widely. This zone contains numerous individual ore bodies, the positions of which are related to sets of north- and northeast-trending normal faults. In the northeast part of the Main ore body, stratigraphic control becomes more dominant; individual ore bodies up to 60 m thick with attitudes similar to the host rocks dip about 30°–33° to the north under Popovich Hill (fig. 2).

The Main ore body is characterized by large amounts of unoxidized ores of widely varying silica and pyrite content. The organic carbon content, which is not uniform, ranges from about 0.1–0.8 weight percent. Sulfide minerals of arsenic, antimony, and mercury, and barite veins, some of which have associated base-metal sulfides, are locally abundant.

The East ore body is a general term used to describe a gold-bearing zone made up of many individual ore bodies that occur within a stratigraphic interval of 100–150 m near, but not at the top of, the Roberts Mountains Formation. Northeast-striking faults and earlier, dike-filled, northwest-trending faults provide primary structural controls (fig. 2), and downdip to the west the East ore body may join the Main ore body under Popovich Hill.

Primary unoxidized ores in the East ore body exhibit extremely wide variations in the contents of organic carbon, silica, and pyrite. The organic carbon content usually ranges from 0.5–1.0, and locally it is as high as 8.0 weight percent. Sulfide minerals are common, especially realgar and orpiment, and the element thallium, not included in the present study, has been found in amounts up to several tenths of a percent by weight.

STATISTICAL ANALYSIS OF GOLD, MERCURY, ARSENIC, AND ANTIMONY

Several workers, including Akright, Radtke, and Grimes (1969), Joralemon (1951), Radtke, Dickson, and Rytuba (1974), Wells, Stoiser, and Elliott (1969), and Wrucke and Armbrustmacher (1975), have established that gold, mercury, arsenic, and antimony are ubiquitous constituents of disseminated replacement-type gold deposits. The general levels of concentration of these elements at the Carlin deposit are established by comparing the abundance of each element in mineralized rocks with that in normal carbonate rocks in general and the Carlin host rocks in particular (table 2).

Statistical studies were carried out by stepwise linear regression analysis to determine the linear relations of these four elements and to examine how closely related the three elements are to gold by determining the statistical dependence of gold values on the values for the other three elements. Data used were taken from analyses of 239 samples from 96 rotary drill holes throughout the mine area. The data, in parts per million, had the following characteristics:

Element	Mean	Standard deviation
Au	7.2	9.9
Hg	23	38
As	507	549
Sb	126	282

Since these mean values are so much greater than those in similar unmineralized rocks near the deposit, we concluded that these elements were introduced and were not original in situ constituents of the Roberts Mountains Formation. The gold value of 7.2 ppm is lower than values usually cited for Carlin ores because it includes only unoxidized mineralized rocks ·and excludes certain areas of higher grade oxide ores and also because it includes large tonnages of mineralized rocks of lower grade now considered to be ore at gold prices of $140 to $160 per ounce.

TABLE 2.—*Abundance of gold, mercury, arsenic, and antimony in fresh limestones and unmineralized carbonate host rocks and unoxidized gold ores at the Carlin deposit*
[All values in parts per million. N, not determined; X, order of magnitude estimate]

Element	Fresh carbonate rocks[1]	Fresh carbonate rocks[2]	Carbonate host rocks, Carlin deposit[3]		Mineralized carbonate rocks, Carlin deposit[4]	
	Average	Average	Average	Median	Average	Median
Au	0.00X	0.005–0.009	<0.02	<0.02	11	10
Hg	0.00	0.07	0.08	0.07	25	30
As	1.	2.5±1.0?	4(?)	N	480	360
Sb	0.2	0.2±0.1?	0.8	0.5	130	90

[1]Abundance in carbonate rocks in the Earth's crust (Turekian and Wedepohl, 1961).
[2]Abundance in carbonate rocks (Graf, 1960).
[3]Values for fresh unmineralized Roberts Mountains Formation (Radtke and others, 1972; Radtke, unpublished data).
[4]Values for unoxidized mineralized Roberts Mountains Formation (Radtke and others, 1972).

Krumbein (1959) suggested that it is reasonable to make the assumption that independent variables (mercury, arsenic, and (or) antimony in this study) that show the strongest mathematical correlation to the dependent variable gold also have the strongest physical relation to the phenomenon being studied. Obviously, many factors besides the ones used influenced the deposition of gold. However, as an indication of association, linear correlation coefficients may be valuable even though the variables compared may or may not be related by simple cause and effect. The nature of any relation is expressed by a correlation coefficient that ranges from -1 (perfect negative correlation) through 0 (absolutely no correlation) to $+1$ (perfect positive correlation).

The least-squares method finds a linear function that minimizes the sum of the squared deviations between observed gold values (Y_i) and the calculated gold values ($\hat{Y}_i$),

where

$$\hat{Y}_i = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + \ldots + a_\eta x_\eta$$

where a_1, a_2, ... a_η are the least-squares coefficients associated with x_1, x_2, ... x_η independent variables, and

$a_0 = Y$ intercept.

This method will minimize: $\Sigma(\hat{Y}_i - Y_i)^2$.

The percent reduction in variance due to a linear model (R^2) is given by:

$$R^2 = 1 - \frac{\Sigma(\hat{Y}_i - Y_i)^2}{\Sigma(Y_i - \overline{Y})^2}$$

where $\overline{Y}$ is the average of all gold values.

Comparison of the four elements showed them to have the following linear correlation coefficients over the entire deposit:

(1) Au to Hg:0.44
(2) As to Hg:0.32
(3) Au to As:0.26
(4) As to Sb:0.22
(5) Au to Sb:0.11
(6) Hg to Sb:0.07

Upon reviewing the results of these correlations, we found that by eliminating approximately 1 percent of the samples from the entire population, much better correlations could be obtained. The eliminated samples were those that had created the greatest amount of variance from the proposed linear models. Scatter plots of these new populations with the anomalous values deleted are shown in figure 4. Inspection of the aberrant samples showed that some contained highly anomalous values, usually of mercury or arsenic, that probably

FIGURE 4.—Direct scatter plots of gold, mercury, arsenic, and antimony in unoxidized Carlin ores. Plots are: A, Au to Hg; B, Au to As; C, Au to Sb; D, Hg to As; E, Hg to Sb; F, Sb to As.

The following symbols represent ties of more than one point occurring at the same coordinates:

Symbol	Number of points	Symbol	Number of points	Symbol	Number of points
2	2	8	8	E	14
3	3	9	9	F	15
4	4	A	10	G	16
5	5	B	11	H	17
6	6	C	12	I	18
7	7	D	13	/	>18
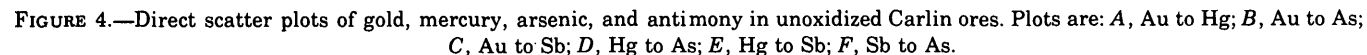
were due to pieces of cinnabar, realgar, or orpiment. Most of them contained combinations of values that were incompatible with the proposed function. The means found for this revised data set do not differ significantly from the means for the original data, but the standard deviations were reduced for most samples.

When the revised set of data was treated as one population over the entire area of the deposit, the results obtained in parts per million were:

Element	Mean	Standard deviation
Au	6.6	8.9
Hg	21	22
As	502	515
Sb	123	185

and the linear correlation coefficients were:

(1) Au to Hg:0.55
(2) As to Hg:0.27
(3) Au to As:0.27

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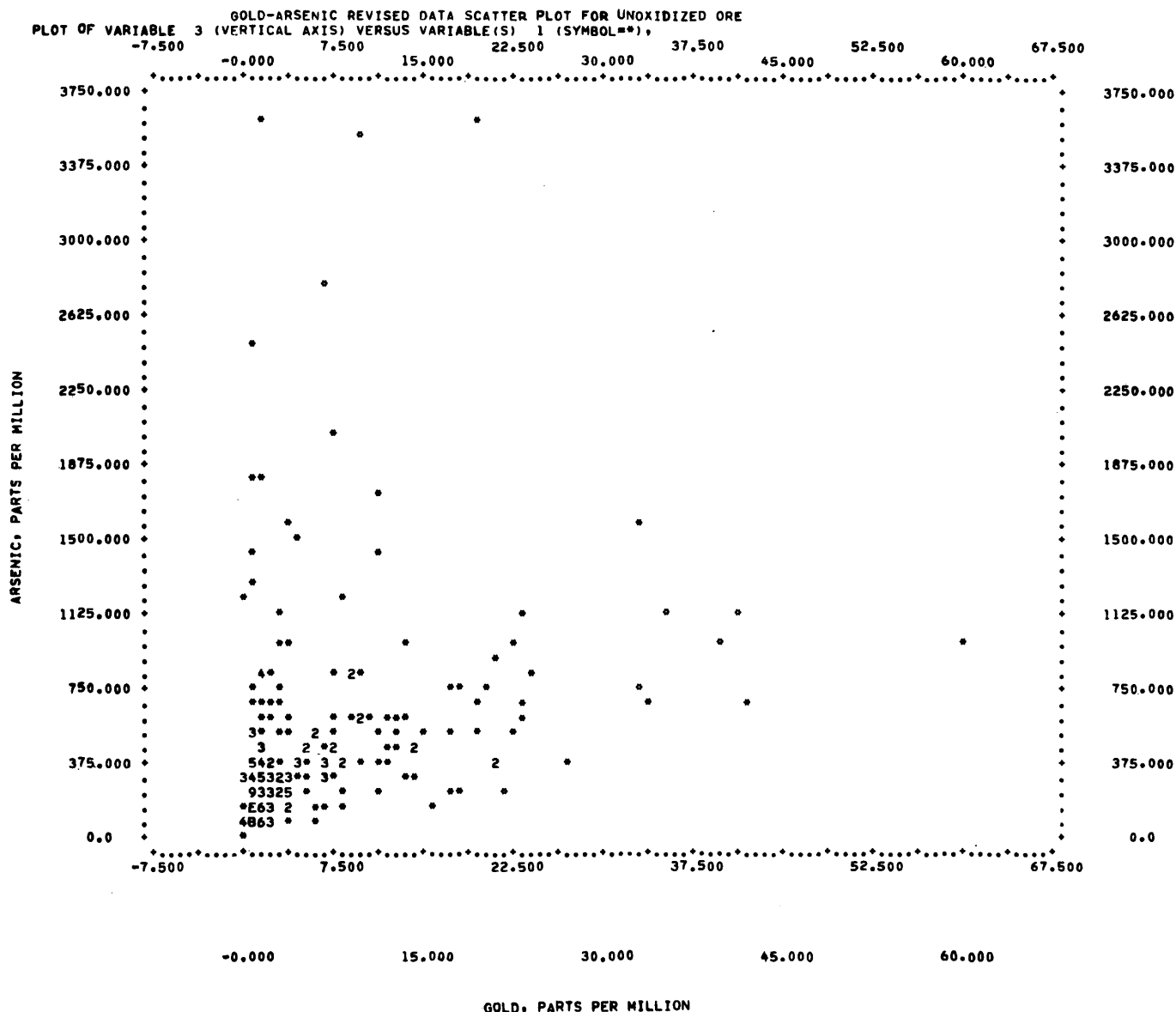
FIGURE 4.—Continued. Explanation on page 9.

(4) As to Sb:0.22
(5) Au to Sb:0.12
(6) Hg to Sb:0.05

The revised means and standard deviations for each of the three ore bodies are summarized in table 3, and linear correlation coefficients for each pair of elements in each ore body are shown in table 4.

These correlation coefficients (R) are strictly applicable only to the data used in the computations. It is our hope that they reflect the correlation coefficients (ρ) of the true population of these elements in the ore bodies at Carlin. We want to establish whether the range of values within which ρ falls includes zero, in which case the correlation is not significant at the 95-percent-confidence level.

It is modeled that $\frac{1}{2} \ln (1+R/1-R)$ can be considered to have an approximately normal distribution with a standard deviation of $1/\sqrt{\eta-3}$. Hence, the 95-percent-confidence interval for ρ is:

$$\frac{1}{2} \ln \frac{1+R}{1-R} - \frac{1.96}{\sqrt{\eta-3}} < \frac{1}{2} \ln \frac{1+\rho}{1-\rho}$$

$$< \frac{1}{2} \ln \frac{1+R}{1-R} + \frac{1.96}{\sqrt{\eta-3}}$$

where η = number of samples.

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GOLD-ANTIMONY REVISED DATA SCATTER PLOT FOR UNOXIDIZED ORE
PLOT OF VARIABLE 4 (VERTICAL AXIS) VERSUS VARIABLE(S) 1 (SYMBOL=*),

FIGURE 4.—Continued. Explanation on page 9.

TABLE 3.—*Mean values and standard deviations for gold, mercury, arsenic, and antimony in the West, Main, and East ore bodies at the Carlin gold deposit*

[All values in parts per million]

Element	West ore body		Main ore body		East ore body	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Au	7.5	8.4	6.5	8.2	6.4	9.4
Hg	22	20	20	25	21	21
As	222	220	490	540	590	580
Sb	52	40	106	76	155	382

TABLE 4.—*Linear correlation coefficients between gold, mercury, arsenic, and antimony for the West, Main, and East ore bodies at the Carlin gold deposit*

West ore body		Main ore body		East ore body	
Element pair	Correlation coefficient	Element pair	Correlation coefficient	Element pair	Correlation coefficient
Sb to As	0.87	Au to Hg	0.62	Au to Hg	0.48
Au to Sb	.85	Au to Sb	.62	Au to As	.23
Au to As	.81	Sb to As	.47	As to Hg	.19
Au to Hg	.68	As to Hg	.41	As to Sb	.19
Sb to Hg	.56	Sb to Hg	.40	Au to Sb	.08
As to Hg	.54	Au to As	.34	Sb to Hg	.00

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MERCURY-ARSENIC REVISED DATA SCATTER PLOT FOR UNOXIDIZED ORE
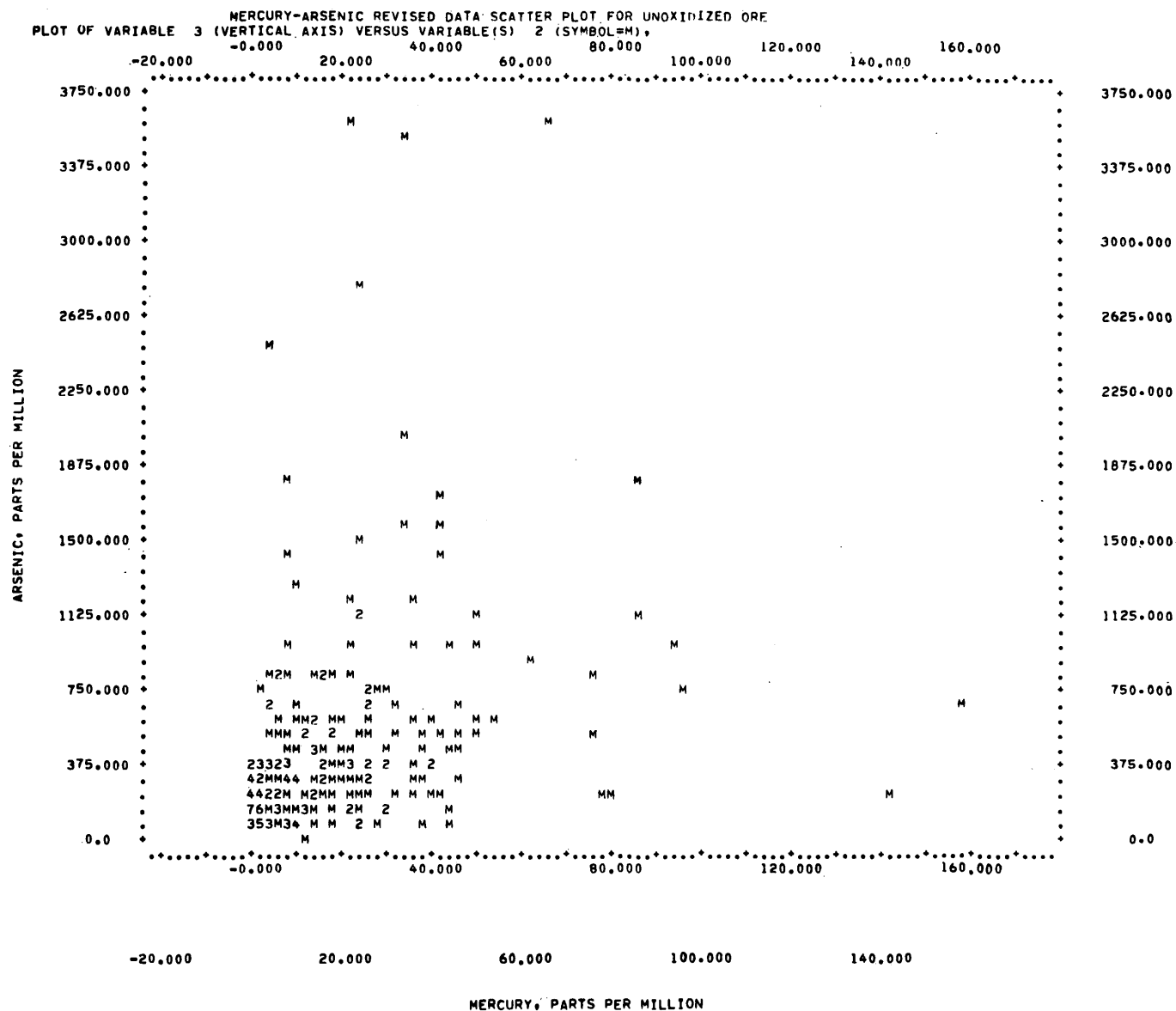
FIGURE 4.—Continued. Explanation on page 9.

1.96 is obtained from the normal distribution tables so that there is a 95-percent probability that ρ lies between the two limits.

The correlation coefficients calculated at the 95-percent-confidence level were:

Sb to As, R=0.87	Au to Hg, R=0.68
$0.77 < \rho < 0.93$	$0.46 < \rho < 0.82$
Au to Sb, R=0.85	Sb to Hg, R=0.56
$0.72 < \rho < 0.92$	$0.30 < \rho < 0.75$
Au to As, R=0.81	As to Hg, R=0.54
$0.66 < \rho < 0.90$	$0.26 < \rho < 0.73$

The least-squares predictor equations for the mean gold content may be computed by the following three functions with all the independent variables entered in parts per million:

(A) West ore body:
$$E(Au) = -2.22959 + 0.11746 \ (Hg) + 0.00833 \ (As) + 0.10364 \ (Sb)$$

(B) Main ore body:
$$E(Au) = -1.20076 + 0.14972 \ (Hg) - 0.00105 \ (As) + 0.04956 \ (Sb)$$

(C) East ore body:
$$E(Au) = 0.79597 + 0.19946 \ (Hg) + 0.00203 \ (As) + 0.00132 \ (Sb)$$

The percent reductions in variance due to a linear model [$R^2 = 1 - \Sigma$ (sample gold values-computed gold

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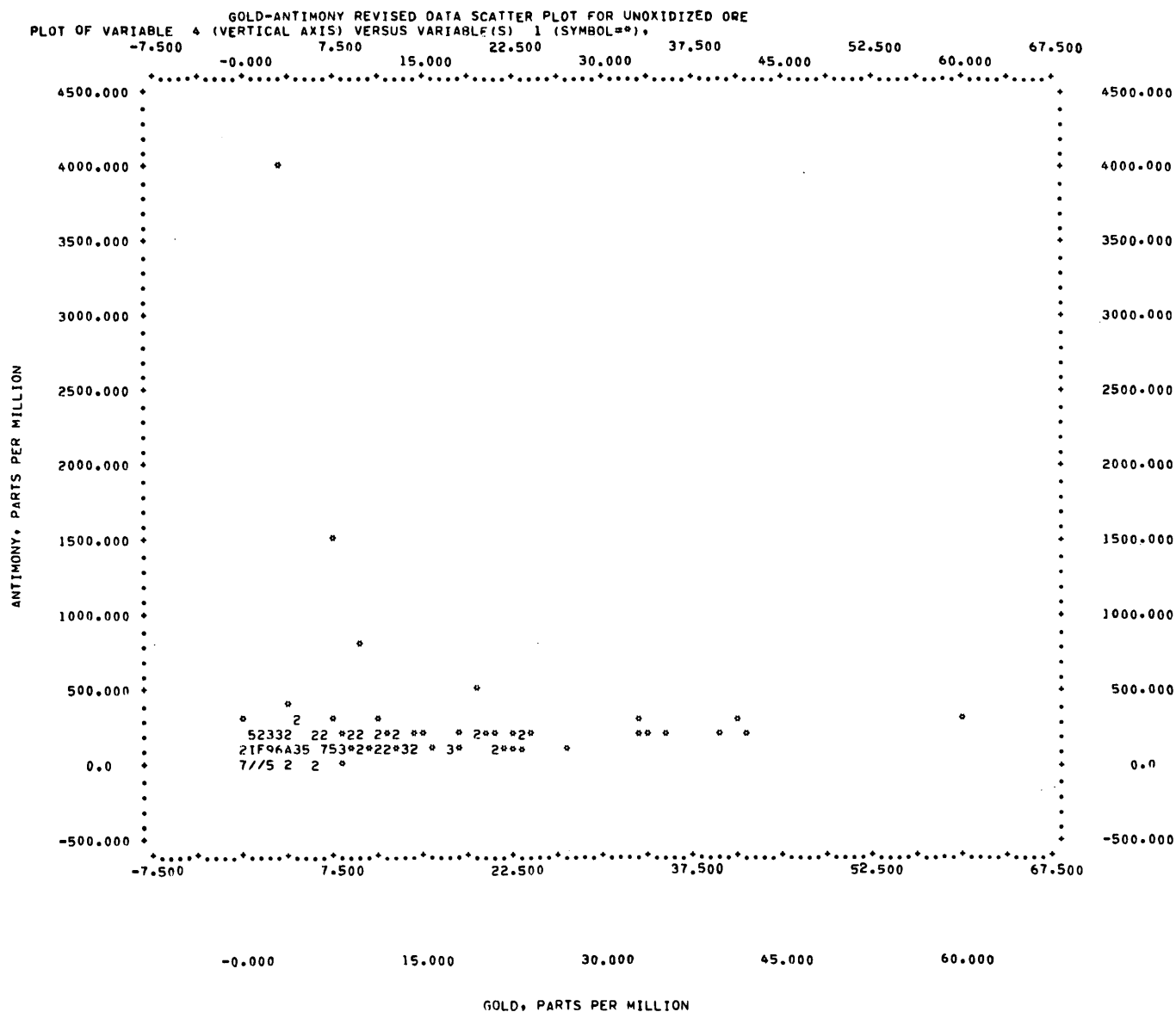MERCURY-ANTIMONY REVISED DATA SCATTER PLOT FOR UNOXIDIZED ORE
PLOT OF VARIABLE 4 (VERTICAL AXIS) VERSUS VARIABLE(S) 2 (SYMBOL=M),

MERCURY, PARTS PER MILLION
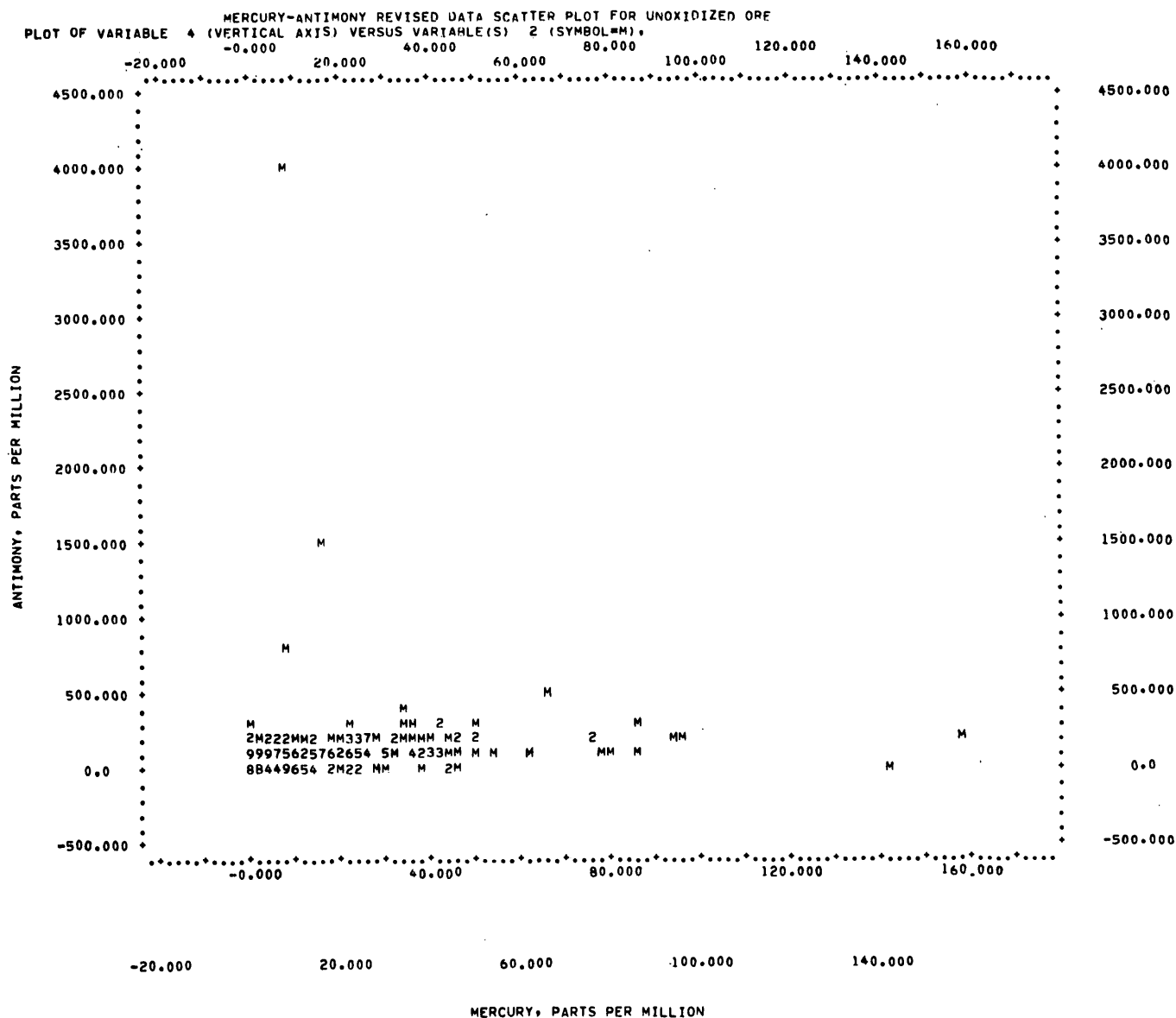
FIGURE 4.—Continued. Explanation on page 9.

values)^2/Σ(sample gold values-mean gold values)^2] using these functions are: (A) West ore body—79.22 percent, (B) Main ore body—54.90 percent, (C) East ore body—25.01 percent. A linear model fits the West ore body quite well.

The standard error of prediction (SE) of using these three variables to predict the mean gold value is determined by

$$SE = (\text{Mean square of residuals})^{1/2}$$

$$= \left[\frac{\Sigma_{i=1}^{\eta}(\text{Sample Au value} - \text{computed Au value})^2}{(\text{number of samples} - \text{number of variables} - 1)} \right]^{1/2}$$

where η is the number of samples and i=1 is the first sample considered.

The standard errors found in the above linear functions (A, B, and C) are (A) West ore body=3.9 ppm, (B) Main ore body=5.6 ppm, and (C) East ore body=8.2 ppm.

The multiple correlation coefficients, defined as the square root of the percent reduction in variance and used as a measure of the adequacy of the different values in predicting the mean gold value (Krumbein and Graybill, 1965), were found to be

West ore body	Main ore body	East ore body
As:0.89	As:0.74	Sb:0.50
Hg:0.88	Sb:0.74	As:0.50
Sb:0.85	Hg:0.62	Hg:0.48

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ANTIMONY-ARSENIC REVISED DATA SCATTER PLOT FOR UNOXIDIZED ORE
PLOT OF VARIABLE   3 (VERTICAL AXIS) VERSUS VARIABLE(S)   4 (SYMBOL=S),

ANTIMONY, PARTS PER MILLION
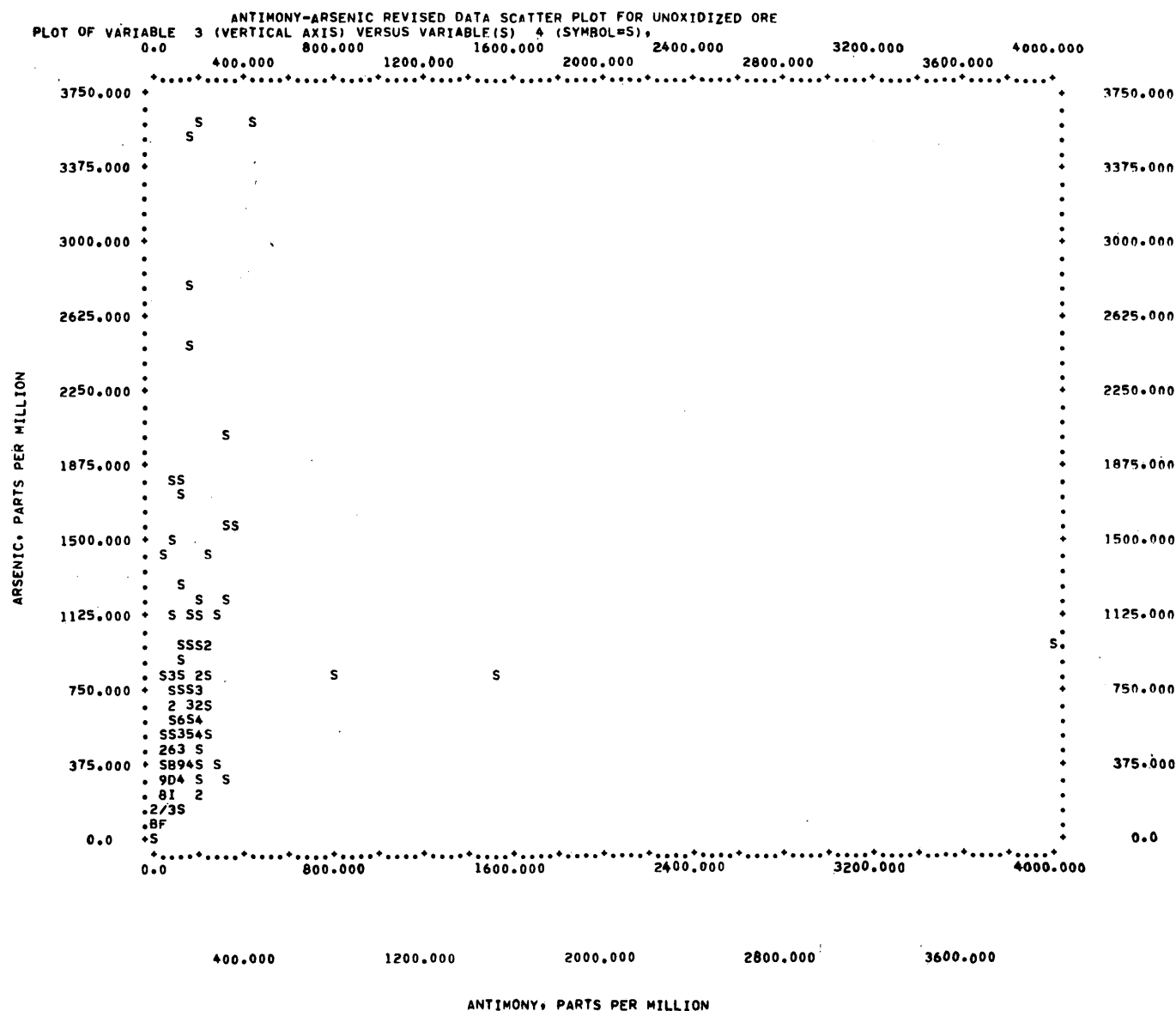
FIGURE 4.—Continued. Explanation on page 9.

By using the linear model with the revised data from the entire deposit, the variance is decreased by 31.8 percent with mercury accounting for 93.8 percent of the reduction. The least-squares equation is:

$$E(Au) = 1.21723 + 0.20225\,(Hg)$$
$$+ 0.00186\,(As) + 0.00209\,(Sb).$$

The standard error of estimate is 7.35 ppm. Multiple correlation coefficients for the variables in the equation are:

Hg:0.55, As:0.56, and Sb:0.56.

Some interesting relationships appear when correlations are compared to the mean values in the three ore bodies. Gold content is fairly constant between the three areas, but the arsenic content is much lower in the West ore body than in the other two. However, the correlation between the gold and arsenic is fairly high (0.81) in the West ore body, whereas the correlations in the Main and East ore bodies (0.34 and 0.23, respectively) show much less dependence of one on the other. Graf (1960) reported that carbonate rocks normally contain only 1 or 2 ppm of arsenic unless there is an abundance of carbonaceous material, iron oxides, or sulfides present. Information derived from samples of the fresh unmineralized Roberts Mountains Formation around Carlin (Radtke, Heropoulos, Fabbi, Scheiner, and Essington, 1972) indicates that this observation holds true here. They

reported that although only 2 out of 15 samples had detectable amounts of arsenic (10 ppm), some rocks contained as much as 0.5 percent syngenetic pyrite and as much as 1 percent organic carbon.

The very high Au:As correlation may be partly explained in the following three ways:

(1) Gold and arsenic appear to have been coprecipitated on the surface of pyrite grains.

(2) The Main and East ore bodies are characterized by an apparent late buildup of arsenic as evidenced by the presence of arsenic sulfides in these two areas.

(3) The host rocks for the West ore body contain relatively small amounts of the carbonaceous materials that tend to induce precipitation of gold and mercury, but not arsenic, elsewhere in the deposit. Consequently, the deposition of gold as well as arsenic in this area was apparently more responsive to physicochemical factors such as fluctuations in the compositions of the invading solutions and (or) changes in pH, temperature, and pressure than in other areas. The West ore body probably formed under a more uniform set of chemical conditions that existed during the earlier part of the mineralizing sequence. Since the late arsenic, antimony, mercury sulfide stage is lacking in this area, the high Au:As correlation in the West ore body suggests that deposition of gold and arsenic in early stages of mineralization occurred under similar physicochemical conditions.

The content of antimony is also very much lower in the West ore body than in the other two. The correlation between antimony and arsenic is much higher in the West ore body (0.87) than in the Main and East ore bodies (which have values of 0.47 and 0.19, respectively). The relation of antimony to gold shows a similar trend. In the West ore body, where antimony has its lowest mean value, the correlation is strongest, whereas in the East ore body, which has the highest mean antimony value, the correlation is very weak.

The poor As:Sb correlation in the East ore body is explained by the presence of antimony as late-formed and unevenly distributed pods of stibnite, whereas arsenic occurs as random scatterings of arsenic sulfides. Mineralogical studies show that there is almost no correlation between the occurrences of the antimony and arsenic sulfides within the Main and East ore bodies. In rocks that contain realgar and (or) orpiment, there is usually little stibnite, concentrations of which are almost invariably marked by the absence of arsenic sulfides. This observation was confirmed by the values of the correlation coefficients. The low correlations between gold and antimony and gold and arsenic in the Main and East ore bodies may be explained by the higher content of organic carbon in these areas that removed large amounts of gold and mercury from the

hydrothermal solutions. The correlations between gold and mercury are the strongest correlations between any element pairs in carbonaceous areas. The stronger gold to mercury correlation also reflects their coeval deposition on the surface of pyrite grains.

Within the host rocks of the West ore body, that had less carbon to fix gold and mercury, a simple paragenesis developed in which gold, mercury, arsenic, and antimony were all deposited together in response to physicochemical conditions that changed in a consistent direction. Relations between elements in the West ore body are those that occurred in the presence of limited or small amounts of organic carbon. In the Main and East ore bodies, larger amounts of organic carbon caused early deposition of gold and mercury, thus the paragenesis was complicated by depleting the ore fluid in these elements and leaving significant amounts of arsenic and antimony to be deposited in a later depositional stage.

Distributions and relations of these four elements between the three ore bodies were compared by stepwise discriminant analysis. Discriminant analysis makes linear combinations of the four quantitative variables to produce two (number of qualitative variables, that is, the three ore bodies, minus one) pseudovariables called the canonical variables. These are chosen so as to: (1) minimize the squared distance from a sample point to the plot of the mean of its respective ore body on a graph with the canonical variables as axes; and (2) maximize the separations of the pits; that is, maximize the distance between the plots of the pit means. The canonical variables thus produce two optimum linear functions (L_1 and L_2) from the original four variables so that when the samples from each site are evaluated with these functions, they are best separated from the samples of the other areas. Consequently, when the data points are plotted in a L_1, L_2 graph, the three sites have the greatest mutual separation.

Listed below are the values found for each element in terms of percentages of samples nearest to the different ore body means, that is, the values are percentages of samples taken from the vertically listed ore bodies whose mean values are closest to the mean of the horizontally listed ore bodies. It is important to note that arsenic values would be included in the second step, gold and arsenic would be included in the third step, and all values are used in the computations for the final step below.

Step 1, Arsenic:

	East	Main	West
East	41.13	20.16	38.71
Main	27.14	20.0	52.86
West	5.4	8.11	86.49

Step 2, gold and arsenic:

	East	Main	West
East ----------------	30.64	42.74	26.62
Main----------------	20.0	30.0	50.0
West ----------------	0.0	8.11	91.89

Step 3, antimony, gold, and arsenic:

	East	Main	West
East ----------------	32.26	43.55	24.19
Main----------------	21.43	31.43	47.14
West ----------------	0.0	8.11	91.89

Step 4, mercury, antimony, gold, and arsenic:

	East	Main	West
East ----------------	34.68	37.10	28.22
Main----------------	20.0	42.86	37.14
West ----------------	0.0	10.81	89.19

When various combinations of the elements were compared between the ore bodies in this fashion, the West ore body consistently showed the greatest polarization. That is, values of arsenic, gold and arsenic together, antimony, gold and arsenic together, and mercury, antimony, gold and arsenic together in the West ore body were always much closer to the mean value in that ore body than to the mean values in the other two ore bodies. These values also reflect the much higher correlations between elements in the gold, mercury, arsenic, antimony suite in the West ore body. Values for these suites of elements in the Main ore body tend to be much more similar to the West ore body than to the East ore body.

Strong polarization of the West ore body is probably due also to the relation of the mean values (given earlier) where, except for gold and mercury that show little variation between the three areas, the values in the West ore body are drastically lower. This reflects the different chemical conditions originally present in this area, which were previously described.

The polarity of the element values in the West ore body support the proposed mineral paragenesis model (fig. 3) in which the late mercury, antimony, and arsenic sulfide mineralization occurred only in the Main and East ore bodies.

The relatively high correlation between gold and mercury found for the entire deposit was probably caused by two conditions: (1) gold and mercury were both transported in the same ore solution and were removed from that solution simultaneously in response to similar influences; and (2) more than 90 percent of the occurrences of both elements either are associated with various organic materials or occur together on the surfaces of pyrite grains; the occurrences reflect a similar depositional process for both elements. Both of these conditions represent deposition on fine-grained materials that are fairly evenly distributed throughout the volume of mineralized rocks in the entire deposit. The removal of gold and mercury from solution probably reflects the extraction capability of various solids on complexes of these metals in highly supersaturated solutions, and this extraction capability led to their precipitation in fairly constant proportions. The processes responsible for the deposition of gold and mercury in highly carbonaceous rocks were probably not the same as those leading to the precipitation of arsenic and (or) antimony.

STATISTICAL ANALYSIS OF GOLD, BARIUM, COPPER, MOLYBDENUM, LEAD, AND ZINC

The fact that anomalous amounts of barium, copper, molybdenum, lead, and zinc occur in areas of disseminated gold mineralization has been pointed out by Akright, Radtke, and Grimes (1969); Radtke, Heropoulos, Fabbi, Scheiner, and Essington (1972); and Wrucke and Armbrustmacher (1975). Comparison of data for normal limestones and unmineralized host rocks with mineralized rocks (table 5) shows that, except for barium, these elements are concentrated from about 4 to 10 times in the ores. The content of barium is slightly increased in the mineralized unoxidized ores. These concentration factors are significantly less than the general range of 100 to 500 times for gold, mercury, arsenic, and antimony (table 2).

Data from analyses of 292 1.53-m (5-ft) composite samples taken from 96 rotary drill holes in unoxidized gold-bearing rocks were used to find the correlations between gold, barium, copper, molybdenum, lead, and zinc. A stepwise linear-regression analysis was performed to find the dependence of gold on the other five elements throughout the entire deposit, and then it was done for each of the three ore bodies individually. Then the elements were compared between the ore bodies by means of a stepwise discriminant analysis. The data, in parts per million, had the following characteristics taken over the three ore bodies:

Element	Mean	Standard deviation
Au --------------------	7.3	10
Ba --------------------	400	200
Cu --------------------	33	15
Mo --------------------	5.9	6.9
Pb --------------------	30	99
Zn --------------------	165	665

These mean values compare well with those reported for Carlin ores cited in table 5. The lower computed mean value for gold was explained previously in this report. The difference in zinc values is not significant in view of the large standard deviation.

Linear correlation coefficients found over the entire deposit are, in decending order:

(1) Au to Zn:0.20   (5) Zn to Cu:0.07

(2) Cu to Mo:0.19   (6) Au to Mo:0.06

(3) Au to Cu:0.17   (7) Au to Ba:−0.06

(4) Cu to Ba:−0.08   (8) Pb to Mo:−0.05

(9) Pb to Ba:0.05

(10) Au to Pb:−0.05

(11) Pb to Zn:0.04

(12) Mo to Ba:0.03

(13) Pb to Cu:−0.02

(14) Zn to Ba:0.01

(15) Zn to Mo:−0.01

All correlations between these elements are weak. The weaknesses may in part be attributed to the fact that many of these elements were analyzed by semiquantitative spectrographic analysis rather than by the more precise methods used for the previous suite of elements.

TABLE 5.—*Abundance of gold, barium, copper, molybdenum, lead, and zinc in fresh limestones and unmineralized carbonate host rocks and unoxidized gold ores at the Carlin deposit*

[All values in parts per million. N, not determined or calculated; X, order of magnitude estimate]

Element	Fresh carbonate rocks[1] Average	Fresh carbonate rocks[2] Average	Carbonate host rocks, Carlin deposit[3] Average	Carbonate host rocks, Carlin deposit[3] Median	Mineralized carbonate rocks, Carlin deposit[4] Average	Mineralized carbonate rocks, Carlin deposit[4] Median
Au	0.00X	0.005–0.009	<0.02	<0.02	11	10
Ba	10	150±110	250	280	400	500
Cu	4	14±9	9	15	35	30
Mo	0.4	1.1±0.7?	<2	<2	7	5
Pb	9	8±4	3	N	30	20
Zn	20	26±5	14	11	185	120

[1] Abundance in carbonate rocks in the Earth's crust (Turekian and Wedepohl, 1961).
[2] Abundance in carbonate rocks (Graf, 1960).
[3] Values for fresh unmineralized Roberts Mountains Formation (Radtke and others, 1972; Radtke, unpublished data).
[4] Values for unoxidized mineralized Roberts Mountains Formation (Radtke and others, 1972; Radtke, unpublished data).

Irregularities in the barium and associated base-metal distributions were predictable from geologic occurrences of the mineral phases involved. Small amounts of barium occurs as barite that is scattered through the mineralized carbonate rocks. Most of the barite, however, is concentrated in late veins that follow faults and fracture zones in the upper oxidized parts of the ore bodies. The erratic distribution and irregular shapes of the barite veins, only some of which contain sulfide minerals, account for local high anomalies in these elements. Genesis of barite in the Carlin ores was discussed in detail by Dickson, Radtke, and Rye (1975).

Detailed electron microprobe studies of Carlin ores (Radtke and others, 1972), including analyses of pyrite grains and carbonaceous materials known to contain gold and mercury, showed that copper, molybdenum, lead, and zinc do not occur in this association. These four elements do occur, however, as discrete sulfides locally concentrated in barite veins and erratically scattered through mineralized rocks. This distribution of these base-metal sulfides tends to produce insignificant correlations between these four elements.

Because the three ore bodies at Carlin are known to possess different geologic and mineralogic characteristics, the correlations between the six elements were examined for each individual ore body. Mean values and standard deviations for gold, barium, copper, molybdenum, lead, and zinc in each ore body are given in table

TABLE 6.—*Mean values and standard deviations for gold, barium, copper, molybdenum, lead, and zinc in the West, Main, and East ore bodies at the Carlin gold deposit*

[All values in parts per million]

Element	West ore body Mean	West ore body Standard deviation	Main ore body Mean	Main ore body Standard deviation	East ore body Mean	East ore body Standard deviation
Au	8.6	10	6.9	8.9	7.2	11
Ba	650	330	500	200	300	100
Cu	25	13	36	18	33	13
Mo	6.2	9.3	7.3	6.1	5.0	6.3
Pb	26	51	49	175	20	19
Zn	7	72	193	197	177	890

6. Linear correlation coefficients for gold, barium, copper, molybdenum, lead, and zinc within each ore body, listed in descending order, are shown in table 7.

Correlation coefficients show that for the Main and East ore bodies most of the correlations between pairs of these six elements are very low. Only in the West ore body do the correlation coefficients show any consistent relations predictable from the geochemical paragenetic model. Correlations between pairs of base metals and between zinc and barium are relatively uniform and strong compared to those between the other base metals to barium, gold to the base metals, and gold to barium. These correlations reflect the fact that the base metals were deposited during a stage in the hydrothermal paragenesis separate from that of gold, and that although some barite formed as base metals were deposited, most of the barite was deposited later in the paragenesis (Dickson, and others, 1975).

That the West ore body is best represented by a linear model is entirely consistent with the following known geologic facts: the West ore body has the most simple structural setting of the three ore bodies; the mineralization in this area included the entire hydrothermal sequence except for the late, postgold, mercury-

TABLE 7.—*Linear correlation coefficients between gold, barium, copper, molybdenum, lead, and zinc for the West, Main, and East ore bodies at the Carlin gold deposit*

West ore body Element pair	West ore body Correlation coefficient	Main ore body Element pair	Main ore body Correlation coefficient	East ore body Element pair	East ore body Correlation coefficient
Pb to Cu	0.56	Au to Cu	0.27	Pb to Ba	0.27
Zn to Pb	.49	Zn to Ba	.17	Au to Zn	.26
Zn to Cu	.40	Mo to Cu	.16	Pb to Cu	.18
Zn to Mo	.31	Pb to Cu	−.15	Mo to Cu	.17
Cu to Mo	.28	Pb to Mo	−.14	Au to Mo	.16
Zn to Ba	.28	Au to Zn	.12	Au to Cu	.15
Cu to Ba	−.23	Zn to Pb	.11	Zn to Pb	.09
Au to Zn	−.20	Zn to Cu	.10	Zn to Cu	.06
Au to Ba	−.17	Mo to Ba	−.09	Pb to Mo	.05
Au to Mo	−.15	Au to Pb	−.08	Zn to Mo	−.03
Pb to Au	−.14	Zn to Mo	.07	Zn to Ba	−.02
Au to Cu	.13	Cu to Ba	−.05	Au to Ba	−.01
Pb to Ba	.10	Au to Ba	−.04	Au to Pb	.00
Pb to Mo	−.09	Au to Mo	.03	Cu to Ba	.00
Mo to Ba	−.07	Pb to Ba	.01	Mo to Ba	.00

arsenic-antimony sulfide stage; and the West ore body has a much lower and more uniform content of organic carbon, creating simpler overall geochemical conditions as described in the preceding section.

The correlation between gold and barium as determined for the entire deposit and also for each separate ore body was the only consistently negative value; this fact indicates that the amount of gold in the ore is inversely correlated with the content of barium. Barite veins generally contain no detectable amounts of gold, and the correlations show that within the mineralized carbonate rocks the areas of higher gold content would contain the smallest amounts of barite. All these facts further support the idea that most of the barite formed during a different stage in the paragenesis from the deposition of gold.

The least-squares predictor equation for the average gold content over the entire deposit with the independent variables in parts per million is:

$$E(Au) = 3.79151 - 0.00002(Ba) + 0.09556 (Cu)$$
$$+ 0.03908 (Mo) + 0.00529 (Pb) + 0.0029 (Zn).$$

The percent reduction in variance from this linear model using only zinc values is 3.99 percent; using zinc and copper values 6.31 percent; zinc, copper and lead values 6.62 percent; zinc, copper, lead and barium values 6.81 percent; and for the full model 6.88 percent. Thus, the copper values improve the prediction using only zinc by 2.32 percent, the lead values reduce the variance by only an additional 0.31 percent, barium by 0.19 percent, and molybdenum by 0.07 percent. The standard error of prediction of this equation is ±9.7 ppm gold.

Statistical analyses carried out to predict the mean gold value in each individual ore body using these four base metals and barium gave only slightly better reductions in variance. These values are for the West ore body 8.20 percent, the Main ore body 8.75 percent, and the East ore body 11.09 percent.

The multiple correlation coefficients of these elements are:

West ore body	Main ore body	East ore body
Ba:0.43	Mo:0.30	Ba:0.33
Mo:0.43	Ba:0.29	Pb:0.33
Pb:0.35	Pb:0.29	Cu:0.33
Cu:0.30	Zn:0.29	Mo:0.31
Zn:0.20	Cu:0.27	Zn:0.26

The equally low multiple correlations found for all these elements reflect the very limited value they have in predicting the average gold content. This conclusion is consistent with the paragenetic model proposed previously.

The distribution and relations of these six elements between the three ore bodies were compared by stepwise discriminant analysis. The values found are summarized subsequently. The figures are percentages of samples taken from the vertically listed ore bodies whose mean values are closest to the mean of the horizontally listed ore bodies with each step also involving the variables in the preceding step(s).

Step 1, copper:

	East	Main	West
East ----------------	75.38	13.85	10.77
Main ----------------	43.05	33.33	23.61
West ----------------	32.5	10.0	57.5

Step 2, barium and copper:

	East	Main	West
East ----------------	74.61	13.85	11.54
Main ----------------	36.11	33.33	30.55
West ----------------	30.0	10.0	60.0

Step 3, molybdenum, barium and copper:

	East	Main	West
East ----------------	60.0	26.92	13.08
Main ----------------	27.78	40.28	31.94
West ----------------	22.5	17.5	60.0

Step 4, lead, molybdenum, barium, and copper:

	East	Main	West
East ----------------	61.54	16.15	22.31
Main ----------------	25.0	44.44	30.56
West ----------------	32.5	12.5	55.0

Step 5, gold, lead, molybdenum, barium, and copper:

	East	Main	West
East ----------------	63.85	20.0	16.15
Main ----------------	22.22	45.83	31.95
West ----------------	27.5	15.0	57.5

Step 6, zinc, gold, lead, molybdenum, barium, and copper:

	East	Main	West
East ----------------	63.85	20.0	16.15
Main ----------------	22.22	47.22	30.55
West ----------------	25.0	15.0	60.0

Discrimination analysis using all the variables (step 6 above) shows that values differed less from the mean of their own ore body than from those of the other two. This result reaffirms the need to analyze the data separately for each ore body. Values in the Main ore body were very similar to the ore bodies on either side, whereas values in the peripheral areas were much more polarized towards their own means. These values compare with the mean values in the Main ore body which were highest for zinc, lead, molybdenum, and copper but lowest for gold.

STATISTICAL ANALYSIS OF GOLD, BORON, TELLURIUM, SELENIUM, AND TUNGSTEN

Boron and tungsten are present in highly anomalous concentrations in Carlin ores compared with their normal abundances in carbonate rocks. Tellurium and selenium are present in low abundance in both the ores and the host rocks, although selenium is enriched in mineralized rocks. Published data on the abundances of these four elements in primary unoxidized Carlin ores, the fresh carbonate host rocks, together with other average values in carbonate rocks are given in table 8.

TABLE 8.—*Abundance of gold, boron, tellurium, selenium, and tungsten in fresh limestones and unmineralized carbonate host rocks and unoxidized gold ores at the Carlin deposit*

[All values in parts per million. N, not determined or not given; X, order of magnitude estimate]

Element	Fresh carbonate rocks[1] Average	Fresh carbonate rocks[2] Average	Carbonate host rocks		Mineralized carbonate rocks	
			Carlin deposit[3] Average	Median	Carlin deposit[4] Average	Median
Au _____	0.00X	0.005–0.009	<0.02	<0.02	11	10
B _____	20	12±8	15	15	70	70
Te _____	N	N	<.2	<.2	<.2	<.2
Se _____	0.08	0.1–1?	<1	<1	2	N
W _____	0.6	0.5?	N	N	18	N

[1]Abundance in carbonate rocks in the Earth's crust (Turekian and Wedepohl, 1961).
[2]Abundance in carbonate rocks (Graf, 1960).
[3]Values for fresh unmineralized Roberts Mountains Formation (Radtke and others, 1972; Radtke, unpublished data).
[4]Values for unoxidized mineralized Roberts Mountains Formation (Radtke and others, 1972; Radtke, unpublished data).

Data used to establish correlations between gold, boron, tellurium, selenium, and tungsten come from analyses of 288 composite samples selected from 94 rotary drill holes in unoxidized mineralized carbonate rocks. The data were treated statistically by stepwise linear-regression analyses to examine correlations throughout the entire deposit as well as within each individual ore body. Stepwise discriminant analysis was also used to compare the mean values of the elements between the three ore bodies.

The data, in parts per million, averaged over the entire deposit have the following characteristics:

Element	Mean	Standard deviation
Au _____	7.4	10
B_____	79	53
Te _____	.02	.08
Se _____	1.5	2.3
W_____	12	44

With the exception of gold, as discussed earlier, the mean values for the elements correspond well to those given in table 8. Values for selenium of 1.5 ppm and tungsten of 12 ppm probably are better than queried values for these elements reported by Radtke, Heropoulos, Fabbi, Scheiner, and Essington (1972), and the tellurium value of 0.02 ppm refines the figure of <0.2 ppm given in table 8.

Linear correlation coefficients between these five elements for the entire deposit are, in descending order:

(1) Au to Te:0.37   (6) Au to W:0.03
(2) B to Te:0.08   (7) B to Se:0.02
(3) W to Te:−0.07   (8) Au to B:−0.02
(4) W to Se:0.04   (9) B to W:0.01
(5) Au to Se:−0.04   (10) Se to Te:−0.01

Among all these pairs of elements, only the ratio of gold to tellurium is significant and even that correlation is much weaker than many others in the Carlin deposit. The very low correlations reflect the fact that the data fit

a linear model poorly:

$$E(Au)=6.76239-0.00808(B)$$
$$+46.84856(Te)-0.15657(Se)+0.01276(W)$$

when the standard error of estimate is ±9.4 ppm gold. The percent reduction in variance due to this function is only 13.95 percent with tellurium providing 95.63 percent of this reduction.

Correlations between these five elements were assessed within each of the three ore bodies. Mean values and standard deviations for each element within each ore body are shown in table 9, and linear correlation coefficients for element pairs for the three ore bodies are given in table 10.

Examination of the correlation coefficients within each individual ore body shows that the only significant correlation is between gold and tellurium and that this is strongest in the East ore body and becomes progressively weaker through the Main and West ore bodies.

Detailed electron microprobe studies and spectrographic analysis of mineral separates show that tungsten occurs in small discrete grains of scheelite, and boron is concentrated in clay minerals. The form of the tellurium and selenium has not been established. We believe that small amounts of these elements could be present in hydrothermal pyrite or could occur together with the gold, mercury, arsenic, and antimony coatings on surfaces of pyrite grains.

Multiple correlation coefficients for boron, tellurium,

TABLE 9.—*Mean values and standard deviations for gold, boron, tellurium, selenium, and tungsten in the West, Main, and East ore bodies at the Carlin gold deposit*

[All values in parts per million]

Element	West ore body		Main ore body		East ore body	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Au _____	8.8	9.8	6.9	9.0	7.2	10
B _____	54	17	85	55	84	56
Te _____	.0	.0	.04	.1	.02	.07
Se _____	1.5	1.7	.9	2.2	1.8	2.5
W _____	9.7	9.9	17	43	10	50

TABLE 10.—*Linear correlation coefficients between gold, boron, tellurium, selenium, and tungsten for the West Main, and East ore bodies at the Carlin gold deposit*

West ore body		Main ore body		East ore body	
Element pair	Correlation coefficient	Element pair	Correlation coefficient	Element pair	Correlation coefficient
Au to B _____	0.25	Au to Te _____	0.34	Au to Te _____	0.50
Au to Se _____	−.15	Au to Se _____	−.13	W to Se _____	.12
W to Se _____	−.13	Au to B _____	.09	W to Te _____	−.07
Se to B _____	−.12	W to Te _____	−.09	B to Te _____	.06
Au to W _____	−.04	W to Se _____	−.09	Au to B _____	−.06
W to B _____	.02	Se to Te _____	.08	Se to Te _____	−.06
W to Te _____	.0	Au to W _____	.08	B to Se _____	.04
Se to Te _____	.0	B to W _____	− .06	B to W _____	.04
Au to Te _____	.0	B to Te _____	.03	Au to W _____	.02
B to Te _____	.0	B to Se _____	.02	Au to Se _____	.02

selenium, and tungsten in each ore body are:

West ore body	Main ore body	East ore body
W:0.29	B:0.39	Se:0.51
Se:0.28	W:0.38	W:0.51
B:0.25	Se:0.37	B:0.51
Te:____	Te:0.33	Te:0.50

Although the multiple correlation coefficients are stronger in the East ore body than in the West and Main ore bodies, they are too low to be useful in predicting the average gold content.

Results of discriminant analyses performed to evaluate the distribution of the five elements between the three ore bodies are shown below. The values are the percent of samples taken from the vertically listed ore bodies that are closest to the mean of the horizontally listed ore bodies.

Step 1, boron:

	East	Main	West
East _____	53.6	26.4	20.0
Main _____	36.11	41.67	22.22
West _____	35.9	0.0	64.1

Step 2, tellurium and boron:

	East	Main	West
East _____	24.8	14.4	60.8
Main _____	31.94	18.06	50.0
West _____	0.0	0.0	100.0

Step 3, selenium, tellurium, and boron:

	East	Main	West
East _____	28.8	48.0	23.2
Main _____	12.5	63.89	23.61
West _____	5.13	23.08	71.79

Step 4, gold, selenium, tellurium, and boron:

	East	Main	West
East _____	24.8	46.4	28.8
Main _____	12.5	65.28	22.22
West _____	10.26	15.38	74.36

Step 5, tungsten, gold, selenium, tellurium, and boron:

	East	Main	West
East _____	26.4	41.6	32.0
Main _____	12.5	62.5	25.0
West _____	10.26	15.38	74.36

These analyses again showed the West ore body to be significantly different from the other two ore bodies; the abundances of these elements in samples within the West ore body are consistently strongly polarized toward the mean values for that ore body. Any cause and effect relation between the statistical data and the paragenetic sequence can be much better understood when more information is available on the forms or occurrences of tellurium, selenium, boron, and tungsten in these ores.

REFERENCES CITED

Ahrens, L. H., 1954, The lognormal distribution of elements, I: Geochim. et Cosmochim. Acta, v. 5, p. 49–73.

Akright, R. L., Radtke, A. S., and Grimes, D. J., 1969, Minor elements as guides to gold in the Roberts Mountains Formation, Carlin gold mine, Eureka County, Nevada, in Canney, F. C., and others, eds., Proc. Internat. Geochem. Explor. Symposium, 1968: Colorado School of Mines Quart., v. 64, no. 1, p. 49–66.

Dickson, F. W., Radtke, A. S., and Rye, R. O., 1975, Implications of the occurrence of barium minerals and sulfur isotopic compositions of barite on late-stage processes in Carlin-type gold deposits: Geol. Soc. America, Abs. with Programs, v. 7, no. 5, p. 604–605.

Dickson, F. W., and Tunnell, George, 1968, Mercury and antimony deposits associated with active hot springs in the western United States, in Ridge, J. D., ed., Ore deposits of the United States 1933–1967, Graton-Sales, v. 2: New York, Am. Inst. Mining, Metall. and Petroleum Engineers, Inc., p. 1673–1701.

Dixon, W. J., 1964, Biomedical computer programs: Los Angeles, Univ. California, Dept. Preventive Medicine and Public Health, School of Medicine, 585 p.

Graf, D. L., 1960, Geochemistry of carbonate sediments and sedimentary carbonate rocks—Pt. 3, Minor element distribution: Illinois Geol. Survey Div. Circ. 301, 71 p.

Hardie, B. S., 1966, Carlin gold mine, Lynn district, Nevada: Nevada Bur. Mines Rept. 13, Pt. A, p. 73–83.

Harris, M., 1974, Statistical treatment of selected trace elements in unoxidized gold ores of the Carlin gold deposit, Nevada: Stanford Univ., Stanford, Calif., Dept. of Applied Earth Sciences, M.S. thesis, 66 p.

Hausen, D. M., and Kerr, P. E., 1968, Fine gold occurrence at Carlin, Nevada, in Ridge, J. D., ed., Ore deposits of the United States 1933–1967, Graton-Sales, v. 1: New York, Am. Inst. Mining, Metall. and Petroleum Engineers, Inc., p. 908–940.

Helgeson, H. C., and Garrels, R. M., 1968, Hydrothermal transport and deposition of gold: Econ. Geology, v. 63, no. 6, p. 622–635.

Joralemon, Peter, 1951, The occurrence of gold at the Getchell mine, Nevada: Econ. Geology, v. 46, no. 3, p. 267–310.

Kennedy, G. C., 1950, A portion of the system silica-water: Econ. Geology, v. 45, p. 629–653.

Krumbein, W. C., 1959, The "sorting out" of geologic variables illustrated by regression analysis of factors controlling beach firmness: Jour. Sed. Petrology, v. 29, no. 4, p. 575–587.

Krumbein, W. C., and Graybill, F. A., 1965, An introduction to statistical models in geology: New York, McGraw-Hill Co., 475 p.

Lepeltier, Claude, 1969, A simplified statistical treatment of geochemical data by graphical representation: Econ. Geology, v. 64, no. 5, p. 538–550.

Miesch, A. T., 1967, Methods of computation for estimating geochemical abundance: U.S. Geol. Survey Prof. Paper 574–B, p. B1–B14.

Radtke, A. S., 1973, Preliminary geologic map of the Carlin gold mine, Eureka County, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–537, scale 1:4,800.

———1974, Preliminary geologic map of the area of the Carlin and Blue Star gold deposits, Eureka County, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–552, scale 1:12,000.

Radtke, A. S., and Brown, G. E., 1974, Frandicksonite, BaF2, a new mineral from Nevada: Am. Mineralogist, v. 59, nos. 9–10, p. 885–888.

Radtke, A. S., Dickson, F. W., and Rytuba, J., 1974, Genesis of disseminated gold deposits of the Carlin type: Geol. Soc. America, Abs. with Programs, v. 6, no. 3, p. 239–240.

Radtke, A. S., Heropoulos, C., Fabbi, B. P., Scheiner, B. J., and Essington, G. M., 1972, Data on major and minor elements in host rocks and ores, Carlin gold deposit, Nevada: Econ. Geology, v. 67, no. 7, p. 975–978.

Radtke, A. S., and Scheiner, B. J., 1970, Studies of hydrothermal gold deposition (I)—Carlin gold deposit, Nevada: The role of car-

bonaceous materials in gold deposition: Econ. Geology, v. 64, no. 2, p. 87–102.

Radtke, A. S., Taylor, C. M., and Christ, C. L., 1972, Chemical distribution of gold and mercury at the Carlin deposit, Nevada [abs.]: Econ. Geology, v. 67, no. 7, p. 1009.

Radtke, A. S., Taylor, C. M., and Heropoulos, C., 1974, Antimony-bearing orpiment, Carlin gold deposit, Nevada: U.S. Geol. Survey Jour. Research, v. 1, no. 1, p. 85–87.

Rytuba, J. J., and Dickson, F. W., 1974, Reaction of pyrite+pyrrhotite+quartz+gold with $NaCl–H_2O$ solutions, 300–500°C, 500–1,500 bars, and genetic implications [abs.]: Internat. Assoc. Genesis Ore Deposits, 4th Symposium, Varna, Bulgaria, 1974, p. 312–313.

Seward, T. M., 1973, Thio complexes of gold and the transport of gold in hydrothermal ore solutions: Geochim. et Cosmochim. Acta, v. 37, p. 379–399.

Turekian, K. K., and Wedepohl, K. H., 1961, Distribution of the elements in some major units of the earth's crust: Geol. Soc. America Bull., v. 72, no. 2, p. 175–192.

Weissberg, B. G., 1970, Solubility of gold in hydrothermal alkaline sulfide solutions: Econ. Geology, v. 65, p. 551–556.

Weissberg, B. G., Dickson, F. W., and Tunnell, George, 1966, Solubility of orpiment (As_2S_3) in Na_2S-H_2O at 50–200°C and 100–1,500 bars, with geological implications: Geochim. et Cosmochim. Acta, v. 30, p. 815–827.

Wells, J. D., Stoiser, L. R., and Elliott, J. E., 1969, Geology and geochemistry of the Cortez gold deposit, Nevada: Econ. Geology, v. 64, no. 5, p. 526–537.

Wrucke, C. T., and Armbrustmacher, T. J., 1975, Geochemical and geologic relations of gold and other elements at the Gold Acres open-pit mine, Lander County, Nevada: U.S. Geol. Survey Prof. Paper 860, 27 p.