Distribution of Gold and Other Metals in Silicified Rocks of the Goldfield Mining District, Nevada

GEOLOGICAL SURVEY PROFESSIONAL PAPER 843-B

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By R. P. ASHLEY *and* W. J. KEITH

GEOLOGY AND GEOCHEMISTRY OF THE GOLDFIELD MINING DISTRICT, NEVADA

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Exploration and geochemistry of the Goldfield mining district, Nevada
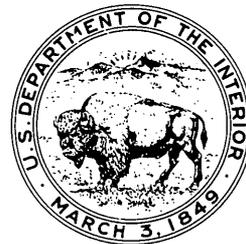
UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

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[Plates are in pocket]

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"There are few gold districts that are not indebted to some man's blind good fortune. This has been well illustrated at Goldfield, and the brief but eventful history of the district teaches that surprises may be in store for one who presumes to say with assurance what ground is ore bearing and what ground is not."—F. L. Ransome, 1909.

DISTRIBUTION OF GOLD AND OTHER METALS IN SILICIFIED ROCKS OF THE GOLDFIELD MINING DISTRICT, NEVADA

By R. P. Ashley and W. J. Keith

ABSTRACT

More than 40 km^2 of hydrothermally altered Tertiary volcanic rocks are exposed near Goldfield, Nev. The gold deposits of the Goldfield mining district were found within or near a few silicified zones in the western and northern parts of this altered area. Samples from some of the productive silicified zones and from hundreds of similar but unproductive silicified zones that appear throughout the remainder of the altered area were analyzed for gold, silver, lead, bismuth, mercury, arsenic, copper, molybdenum, and iron. Scattered samples containing anomalous amounts of gold, silver, lead, bismuth, mercury, or arsenic are found mainly in the productive western and northern parts of the altered area. Anomalous concentrations of gold and silver found in samples from some unproductive silicified zones are similar to concentrations found in samples from nearby productive zones. A third anomalous area includes Preble Mountain, located 5.6 km east of Goldfield, and extends eastward from Preble Mountain for 3.2 km. This anomalous area has not yet produced ore.

Correlation analysis of gold, silver, lead, bismuth, mercury, arsenic, copper, molybdenum, and iron data for all samples, including both background and anomalous concentrations, reveals two associations of elements. The first, gold-silver-lead-bismuth-arsenic-copper, represents a relict hypogene association preserved in spite of oxidation. The distribution of mercury shows similarities with gold, silver, lead, bismuth, and arsenic, but mercury also occurs in many samples from parts of the area in which other elements of this association are relatively scarce. The second association, arsenic-copper-molybdenum-iron, is a supergene association produced during oxidation when varying amounts of these metals were mobilized and precipitated with limonite. Supergene leaching and precipitation with limonite does not significantly affect the hypogene distribution of arsenic but probably does affect the distribution of copper and probably dominates the distribution of molybdenum.

INTRODUCTION

The bonanza gold ores of the Goldfield mining district, one of the principal gold-producing districts of western Nevada, came from zones or ledges of silicified rock. Although the principal ore bodies were found in a 1.3-km^2 area immediately northeast of the town of Goldfield, silicified zones crop out through a 40-km^2 area underlain by hydrothermally altered Tertiary volcanic rocks (fig. 1). An additional 8-km^2 of altered volcanic rocks lies immediately to the east, in Northern Nellis Air Force Bombing and Gunnery Range, but is excluded from this study. Mines found in the altered

area outside the main productive ground near Goldfield account for only a few percent of total production. This report describes a study of the distribution of gold, silver, lead, bismuth, mercury, arsenic, copper, and molybdenum in silicified zones throughout the hydrothermally altered area. The silicified rock samples show anomalous amounts of gold and silver and less commonly lead, bismuth, mercury, and arsenic in two areas that include most of the known deposits and in a third area that has no productive mines. The distributions of mercury, copper, and molybdenum differ significantly from those of gold and silver and probably reflect different conditions of hypogene deposition for mercury and different behavior during oxidation for copper and molybdenum.

Previous investigations of the Goldfield district, many of them conducted during the most productive years (1906–18), consider mainly the general and economic geology of the area (Ransome, 1909, 1910a, b; Locke, 1912a, b; Searls, 1948). More recent geologic investigations consider the geochronology and geochemistry of the district and offer new interpretations of the geologic setting of the deposits (Albers and Cornwall, 1968; Albers and Kleinhampl, 1970; Ashley, 1972, 1973, 1974, 1975; Silberman and Ashley, 1970; Ashley and Albers, 1969, 1975; Ashley and Keith, 1973a). The geochemical maps included in this report have been released as a series of Miscellaneous Field Studies maps (Ashley and Keith, 1973b–i).

In chapter A of this professional paper series, Ashley and Albers (1975) studied the distribution of arsenic, bismuth, copper, gold, lead, mercury, molybdenum, silver, zinc, and several other elements near some ore bodies in the main productive area. That study showed that gold, silver, lead, and mercury are little affected by supergene processes and therefore show relict hypogene dispersion patterns. The same is probably true for bismuth, although most samples did not have amounts of bismuth detectable by the analytical method used. Arsenic, copper, molybdenum, and zinc are increasingly
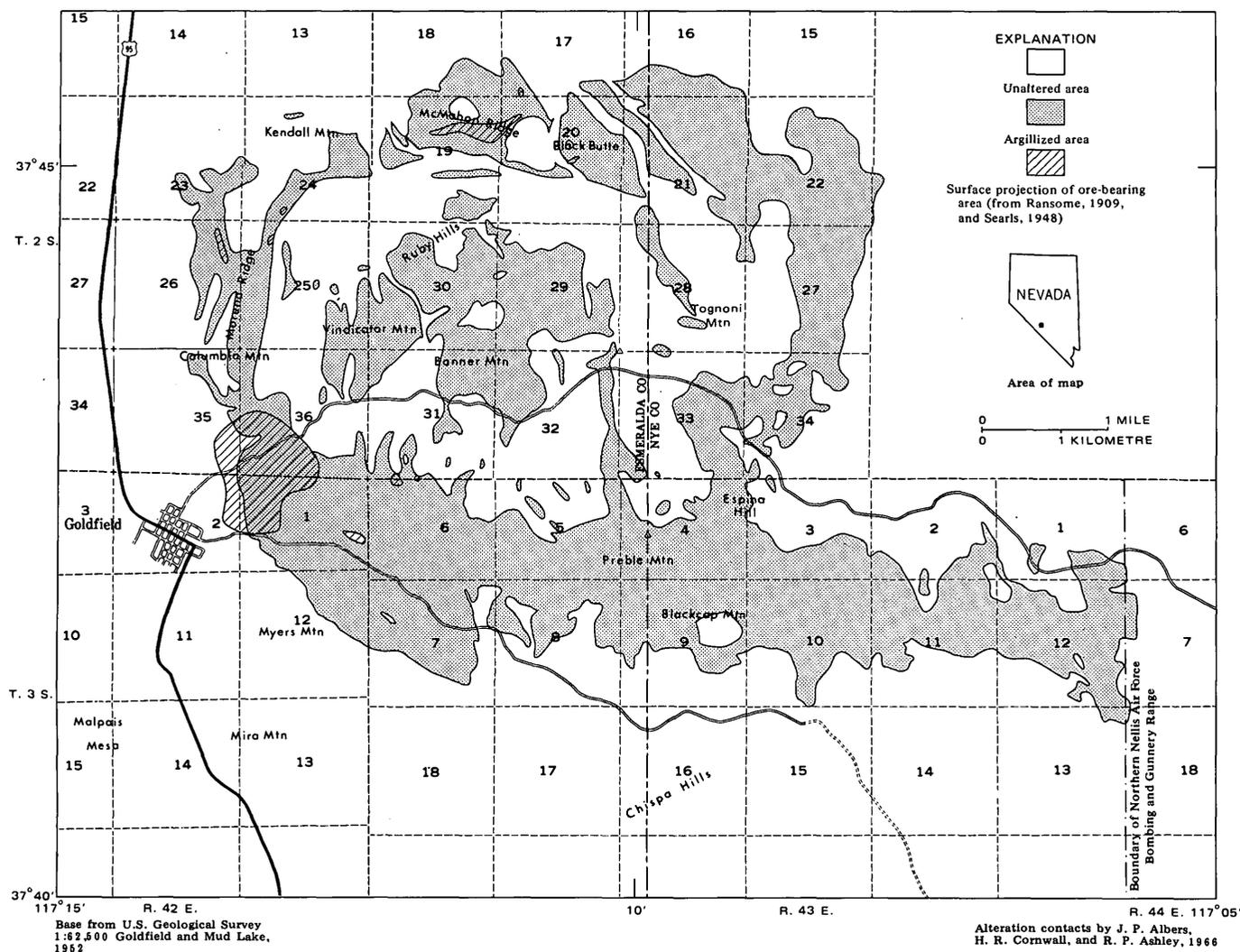
FIGURE 1.—Map of Goldfield and vicinity showing areas of hydrothermal alteration and ore deposits.

strongly redistributed during supergene alteration, but none of these four elements shows well-defined supergene halos. This report considers the distribution of all these elements except zinc in silicified zones throughout the Goldfield altered area. Zinc was omitted because the earlier study showed that it probably owes its distribution in oxidized rocks entirely to supergene processes.

Samples for this study were collected from 1966 through 1972. J. S. Kier, T. D. Palmer, and Duncan Foley assisted at various times in collecting the samples. We appreciate the cooperation of many property owners in the Goldfield mining district, particularly R. L. Minnis and P. R. Burkett, and Davis-Goldfield Mining Corporation.

HISTORY OF DEVELOPMENT AND PRODUCTION

The Goldfield mining district has produced more than 4.2 million ounces of gold, 1.5 million ounces of silver, and 7.7 million pounds of copper since its discovery in

1902. The last recorded production was in 1961. Ransome (1909) gives a concise account of the discovery of the district and of mining in the early years. Some later developments are described by Locke (1912a) and Searls (1948), but no comprehensive account of later mining developments is available.

Gold was discovered in the Goldfield altered area late in 1902, ending a period of unsuccessful prospecting that probably began as early as the 1870's. The first discovery was float gold found on Columbia Mountain. The initial lode discovery, made soon after, was 3 km north of the present Goldfield townsite on or near the Sandstorm-Kendall vein. The rich main district immediately northeast of the Goldfield townsite was discovered in 1903. Development of this area was very rapid, with annual gold production rising from about 3,400 ounces in 1903 to a maximum of about 539,000 ounces in 1910 (U.S. Geological Survey, 1903–10). Development and exploitation in the early stages were

carried out mainly by lessees. Most of the mines of the main district were combined as the Goldfield Consolidated Mines Company late in 1906. Production steadily declined after 1910 as mining progressed to deeper levels. In 1918 Goldfield Consolidated Mines opened their holdings to leasing, and subsequent production was accomplished mainly by lessees. During the 1930's, production included much gold reprocessed from mill tailings.

GEOLOGIC SETTING

Goldfield is the site of a late Oligocene and early Miocene volcanic center composed of trachyandesite, rhyodacite, quartz latite, and rhyolite flows and tuffs (Ransome, 1909; Albers and Cornwall, 1968; Ashley, 1974, 1975). Underlying pre-Tertiary rocks consist of siliceous shales, argillites, and limestones of the Ordovician Palmetto Formation extensively intruded by Jurassic quartz monzonite. The Palmetto Formation and quartz monzonite appear at the surface only in a few inliers in the western part of the area. A preliminary detailed geologic map (Ashley, 1975) includes the geologic information used in this report (fig. 2). This study is concerned with the prealteration units; the postalteration units generally occur around the periphery of the altered area.

The oldest Tertiary rocks are rhyolite and quartz latite flows, ash flows, and air-fall tuffs of Oligocene age (about 30 m.y. old; see Ashley, 1973). Stratigraphic units composing this group of rocks include the Vindicator Rhyolite (rhyolite welded ash-flow tuff and a rhyolite flow), Kendall Tuff (quartz latite tuff), unnamed latite of Ransome (1909; quartz latite flow), and the Sandstorm Formation. The Sandstorm Formation, defined by Albers and Stewart (1972), includes the Morena Rhyolite (rhyolite ash-flow tuff) and the Sandstorm Rhyolite (rhyolite flow and air-fall tuff) of former usage (Ransome, 1909). These silicic volcanic rocks are overlain unconformably by lavas and tuffs dominantly of intermediate composition erupted in early Miocene time (20–22 m.y. ago). The early Miocene volcanic sequence begins with the Milltown Andesite, which includes trachyandesite, rhyodacite, and quartz latite flows and tuffs. A porphyritic rhyodacite (unnamed dacite of Ransome) intrudes and overlies the Milltown Andesite, forming flow-dome complexes. The Milltown Andesite and porphyritic rhyodacite are overlain by tuff of Chispa Hills (unnamed dacite vitrophyre of Ransome), a rhyodacite ash-flow tuff, and the Chispa Andesite, a trachyandesite flow, on the south side of the area, by andesite-rhyodacite breccia and the Espina Breccia in the southeastern part of the area, and by rhyolite of Wildhorse Spring in the northeastern part of the area. The andesite-rhyodacite breccia is a locally very coarse breccia sheet, composed of debris from the Milltown Andesite and porphyritic rhyodacite. The Espina Breccia is locally bedded rhyolite lapilli tuff and tuff breccia, in places very coarse. The tuff of Chispa Hills-Chispa Andesite section, andesite-rhyodacite breccia, Espina Breccia, and rhyolite of Wildhorse Spring are not in contact, so their age relations cannot be determined with certainty. The andesite-rhyodacite breccia is probably the oldest because it does not appear to include debris from any of the other postporphyritic rhyodacite units. The Chispa Andesite and rhyolite of Wildhorse Spring are probably the youngest because, unlike all the other units described above, they are not hydrothermally altered.

Premineralization structural development of the Goldfield volcanic center involved at least two, and possibly three, major structural events (Ashley, 1972). The first inferred event was formation of a ring fracture bounding a small caldera or incipient caldera. This caldera or incipient caldera probably formed during extrusion of the earliest ash flow, found in the Oligocene Vindicator Rhyolite. Although covered by the early Miocene volcanic rocks, the trace of the ring fracture is inferred from the positions of known volcanic vents and intrusive centers. Vents and intrusive centers for various units occur at Black Butte, about 1.5 km southeast of Black Butte, Tognoni Mountain, just north of Espina Hill (Espina Breccia), Preble Mountain, in the main production area, and just northwest of Columbia Mountain (fig. 1). The trace of the ring fracture can be followed from Columbia Mountain north toward Kendall Mountain and then east through McMahon Ridge as a belt of fractures and hydrothermal alteration in the overlying Miocene volcanic rocks.

Most of the faults shown in figure 2 formed during the period of early Miocene volcanism, just before mineralization occurred; this faulting was the second major structural event. The north-northeast-trending faults on Vindicator and Banner Mountains dip to the east, and the intervening fault blocks dip to the west at complementary angles. These faults are thus shingle faults bounding rotated blocks formed in response to west-northwest to east-southeast horizontal distension of the area. Faults in the arcuate belt extending from Columbia Mountain northward and then eastward through McMahon Ridge were formed at the same time and presumably are the result of renewed movement along the inferred ring fracture zone in the subjacent Oligocene and pre-Tertiary rocks.

A conspicuous fracture zone trends S. 80° E. away from the main productive area and extends tangentially away from the ring fracture zone and the area with shingle faults. Although the altered fractures that compose this fracture zone are apparently contemporaneous with the shingle faults and faults of

EXPLANATION

Younger rocks and alluvium	Espina Breccia	Porphyritic rhyodacite
Rhyolite of Wildhorse Spring	Tuff of Chispa Hills	Milltown Andesite
Chispa Andesite	Andesite-rhyodacite breccia	Sandstorm Formation, quartz latite, Kendall Tuff, and Vindicator Rhyolite

Quartz monzonite (Jurassic) and Palmetto Formation (Ordovician)

Contact

Fault
Dashed where approximately located

FIGURE 2.—Generalized geologic map of the Goldfield mining district. Modified from Ashley, 1975.

Columbia Mountain and Morena Ridge that overlie the inferred ring fracture zone, stratigraphic relations of some of the early Miocene units suggest that movement may have begun before horizontal distension occurred. The zone probably is not older than the ring fracture itself, and depending on interpretation of its origin, it may or may not be considered the result of a third major structural event.

HYDROTHERMAL ALTERATION

Faults, fractures, and permeable beds throughout the 40-km^2 altered area are symmetrically enveloped by three successive hydrothermal alteration zones, each ranging in width from several centimetres to more than 100 m. Silicified rocks adjacent to the faults and fractures are surrounded by illite-kaolinite-bearing argillized rocks, which in turn are surrounded by montmorillonite-bearing argillized rocks. Previous work by Harvey and Vitaliano (1964) and Ashley and Albers (1975) provided the data on these zones given in the description below. X-ray diffraction and thin-section study of 254 samples of altered rock collected throughout the altered area from all three alteration zones verified that alteration mineralogy is consistent

across the area. Many rocks outside the montmoril-lonite-bearing zone are propylitized, but propylitiza-tion does not seem to be symmetrical around fractures and may have occurred earlier than the hydrothermal alteration that produced the three zones described above. Here, as in an earlier report (Ashley and Keith, 1973a), propylitized rocks are not distinguished from fresh rocks.

In this report, the term "illite" refers to a group of clay minerals having $d_{(001)}$ approximately equal to 9.9A that do not expand when treated with ethylene glycol. These micas include both 1 M and 2 M polymorphs. The term "kaolinite," as used here, includes any member of the kaolinite group except halloysite (kaolinite, nacrite, dickite), and the term "montmorillonite" refers to a group of expandable clay minerals having $d_{(001)}$ approximately equal to 14.7 to 15.5A in air-dried samples.

The most intensely altered rocks make up silicified zones composed mainly of fine-grained (0.002–0.02 mm) light- to dark-gray quartz. These zones are generally tabular and delineate the fractures or permeable beds that conducted hydrothermal solutions. They form scattered craggy outcrops throughout the altered area and have sharp contacts with the surrounding argillized rocks (fig. 3). Most silicified rocks contain as much as 30 percent alunite and kaolinite; both minerals preferen-tially replace former feldspar phenocrysts or glassy fragments. Some silicified rocks contain pyrophyllite with or without alunite, diaspore, or kaolinite. Alunite is locally most abundant in rhyolitic rocks, which are the most potassium-rich rocks in the area.

Some silicified zones are brecciated; usually the brecciated part of each zone is approximately longitudi-nal and medial, with planar boundaries roughly parallel to the walls of the zone. Brecciation of the silicified zones is especially common in the area between the main district and Preble Mountain.

Argillized rocks adjoining the silicified zones have the mineral assemblage quartz-illite-kaolinite. These rocks typically are moderately hard and moderately well exposed, and appear bleached or stained by limonite to pastel reds, purples, or yellow browns as a result of oxidation of pyrite. Adularia appears locally in the most intensely altered part of this subzone, and opal is an important constituent locally. These rocks form the illite-kaolinite subzone of the argillized zone of Harvey and Vitaliano (1964). At a distance equal to at least several times the width of the nearest silicified zone, the illite-kaolinite-bearing argillized rocks grade into the montmorillonite-bearing argillized rocks that form the third alteration zone.

The montmorillonite-bearing rocks are soft and poorly exposed, forming residual soils. They are
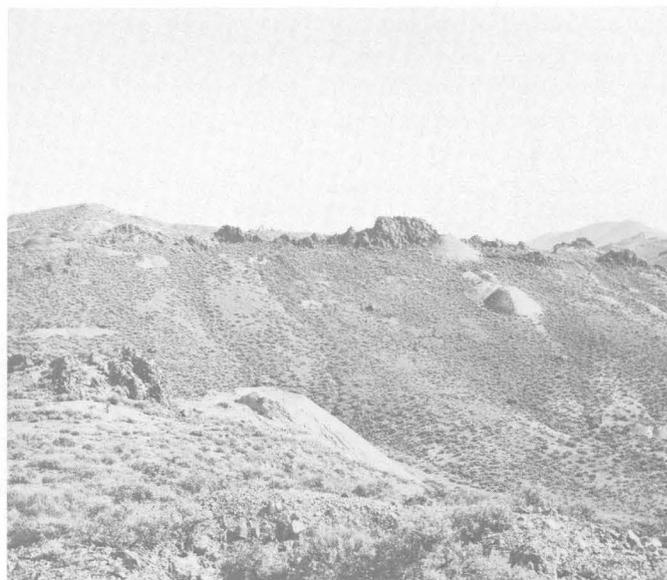
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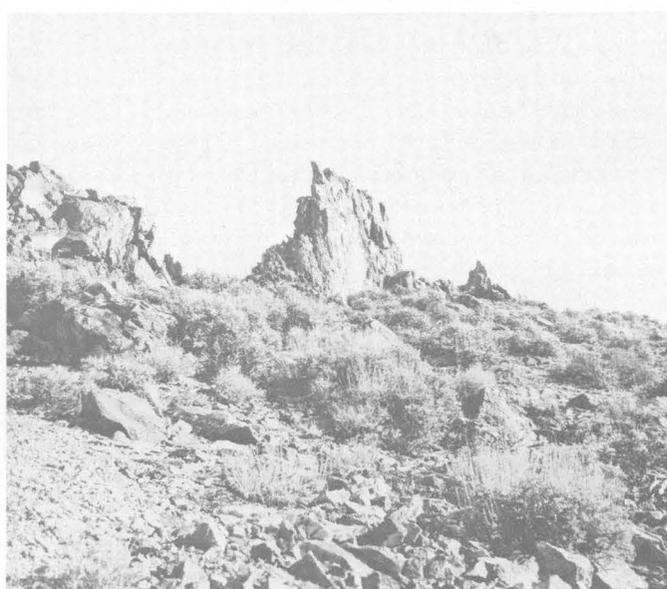
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FIGURE 3.—Silicified zones, Goldfield mining district. A, Silicified zones forming typical craggy outcrops, vicinity of Blue Bull, Commonwealth, and Simmerone mines, 3 km east-northeast of Goldfield townsite. Argillized rocks form slopes surrounding silicified zones. View to southwest. B, Closeup view of a silicified zone in same area as A. Rib in center is about 2.5 m high.

bleached white or stained shades of brown or yellow by limonite or jarosite. Supergene jarosite, in particular, seems to be common in these rocks and gives them a distinctive pale-yellow color at many localities. Vein-lets of supergene gypsum that disintegrate to form a surface lag of crystal fragments are also characteristic of this alteration zone. These rocks are composed of quartz, montmorillonite, kaolinite, and illite, with various amounts of relict plagioclase. They form the

montmorillonite subzone of the argillized zone of Harvey and Vitaliano (1964). Where we use the term "argillized rocks" without qualification, we refer to both montmorillonite and illite-kaolinite alteration zones.

Propylitized rocks are widespread in the Goldfield district and probably predominate over fresh rocks in those areas shown in figure 1 as being unaltered. They do not, however, show symmetrical patterns relative to the zones described above. Indeed, at some localities montmorillonite-bearing rocks appear to terminate against unaltered rather than propylitized rocks. Propylitization seems to have taken place earlier than the hydrothermal alteration that produced the three zones described above. It may represent the first phase of the same hydrothermal activity that produced the silicified and argillized zones and finally the ore deposits, or it may represent alteration that accompanied the emplacement of various Oligocene and lower Miocene volcanic units. Mineral assemblages in propylitized rocks vary between units, and may include diagenetic or deuteric alteration phases.

The depth of thorough oxidation is generally at least 10 m throughout the altered area, and oxidation extends along fractures to depths of at least 300 m. In the oxidized altered rocks limonite replaces former pyrite, but otherwise unoxidized and oxidized altered rocks have the same silicate and sulfate mineral assemblages, indicating that hypogene mineral assemblages have not been affected notably by supergene alteration. Unoxidized altered rock remains at the surface only within massive parts of a few silicified zones; several centimetres of oxidized rock must be broken away from the surface of the outcrop to expose such material. None of the samples of silicified rock collected for geochemical study are unoxidized. Supergene veinlets of halloysite, kaolinite, alunite, and chalcedonic quartz occur locally in and around silicified zones; these were avoided in geochemical sampling.

Much of the pyrite in unoxidized rocks replaces former mafic minerals. Iron content remained about the same during hydrothermal alteration, except where the silicified rocks were fractured or brecciated during the later stages of alteration and quartz, pyrite, and locally other sulfides filled the open spaces (Ashley and Albers, 1975). During oxidation in the Goldfield altered area, iron was partly leached. The iron remaining in the oxidized zone was transported some distance and precipitated as limonite. As in many other areas of oxidized sulfide-bearing rocks, significant amounts of arsenic, copper, and molybdenum were also taken into solution in supergene waters and precipitated with the limonite (Hawkes and Webb, 1962; Ashley and Albers, 1975).

GEOCHEMICAL SAMPLING AND ANALYTICAL PROCEDURES

GEOCHEMICAL SAMPLES

Investigations in the main productive part of the district showed that anomalous concentrations of gold, silver, lead, bismuth, mercury, and at some localities arsenic are restricted to the silicified zones that hosted the known ore bodies (Ashley and Albers, 1975); the anomalies are actually low-grade hypogene aureoles surrounding the ore bodies. Thus sampling was confined to silicified zones.

For this study we collected 1,337 samples from silicified zones; 323 were collected on a 500-foot grid (see Ashley and Keith, 1973a, for further details), and the remaining 1,014 were collected at randomly spaced localities. At each sample locality we collected the most limonite-rich material available in an attempt to detect anomalous amounts of arsenic, copper, and molybdenum, in addition to anomalous amounts of gold, silver, lead, bismuth, or mercury. Silicified zones bearing little limonite, however, were also sampled because many samples containing appreciable gold, silver, lead, bismuth, or mercury, collected from the main productive part of the district, had little limonite (Ashley and Albers, 1975). Individual samples were collected by removing 1–2 kg of material from a 0.1- to 0.5-m^2 area on the outcrop surface, usually as a composite chip sample (several pieces) but sometimes as a grab sample (one piece).

ANALYTICAL METHODS

Gold was determined by an atomic absorption method, utilizing for some of the samples a hot hydrobromic acid extraction from 2-gram analytical portions (Huffman and others, 1967) or, for most of the samples, a cold hydrobromic acid extraction from 10-gram analytical portions (Thompson and others, 1968). The former method has a sensitivity of 0.1 ppm, and the latter method a sensitivity of 0.02 ppm. Arsenic was determined by the Gutzeit colorimetric method (Ward and others, 1963, p. 38–44), and mercury was determined by an atomic absorption method (Vaughn and McCarthy, 1964; Vaughn, 1967). All other elements, including silver, lead, bismuth, copper, and molybdenum, were determined by six-step semiquantitative spectrographic analysis (Grimes and Marranzino, 1968). Most of the analyses were done by Field Services Section, Branch of Exploration Research, U.S. Geological Survey. Some were done by Analytical Laboratories Branch, U.S. Geological Survey, in Denver, Colo.

STATISTICAL METHODS

Statistical data from chemical analyses of silicified rock samples are presented in table 1. All computations were done by computer using the U.S. Geological Survey STATPAC system. We converted all analytical data to log percent, and then calculated logarithmic means and logarithmic standard deviations and their antilogarithms, which are geometric means and deviations. Use of the log transformation in geochemistry is discussed by Miesch (1967) and Ashley and Albers (1975). For all the elements some data are censored, that is, some samples contain concentrations less than the lower detection limit or greater than the upper detection limit. To account for these censored data, the logarithmic means and standard deviations were adjusted by Cohen's method (Cohen, 1959, 1961). Means and deviations are not given for elements for which more than 50 percent of the data falls below the lower detection limit because the average amounts of these elements are probably less than the detection limit. Histograms and frequency tables were computed for each element, and bivariate frequency distributions and correlation coefficients were calculated for element pairs in the total data set. Log-probability plots were prepared from the frequency tables. The computation and use of correlation coefficients are discussed in a later section.

THRESHOLD CONCENTRATIONS

We define threshold concentrations for each element by methods similar to those of Lepeltier (1969). For elements where 50 percent or more of the data are above the lower detection limit (lead, mercury, arsenic, copper, and molybdenum), the geometric mean plus the geometric deviation squared (the logarithmic mean plus twice the logarithmic standard deviation) is the threshold concentration. Thus analytical determinations greater than or equal to two deviations above the logarithmic mean (2.3 percent of the population in a log-normal distribution) are considered anomalous (table 2), and all other determinations are considered background.

Because we are interested merely in classifying data as anomalous or otherwise, for simplicity we refer to all determinations below the threshold concentration as "background." This differs somewhat from Lepeltier's (1969) usage, in which "background" for an element is

TABLE 1.—*Statistical data for grid samples (323 silicified rocks) and total data set (1,337 silicified rocks)*

[--, not calculated]

Element	Detection limit(s), log percent (ppm)	Percent samples outside detection limit(s)	Logarithmic mean, X_L, log percent	Logarithmic standard deviation, S_L, log percent	Cohen's mean, μ_L, log percent	Cohen's standard deviation, σ_L, log percent	Geometric mean, ppm, percent for Fe	Geometric deviation
			323 silicified rocks					
Au	−5.70(0.02) −5.00(0.1)	80	----	----	----	----	----	----
Ag	[1]−4.42(0.5) −4.08(1)	84	----	----	----	----	----	----
Pb	−3.08(10)	16	−2.4	0.5	−2.5	0.6	30	4.0
Bi	−3.08(10)	94	----	----	----	----	----	----
Hg	−6.00(0.01)	[2]0.7	−4.7	0.4	−4.7	0.4	0.2	2.8
As	−3.00(10)	[3]28	−2.6	0.4	−2.8	0.5	20	3.0
Cu	−3.75(2) −3.42(5)	13	−2.8	0.6	−3.0	0.7	10	4.8
Mo	−3.75(2)	41	−3.2	0.4	−3.6	0.6	2	4.2
Fe	----	0	0.5	0.4	----	----	3	2.8
			1,337 silicified rocks					
Au	−5.70(0.02) −5.00(0.1)	64	----	----	----	----	----	----
Ag	−4.42(0.5) −4.08(1)	[4]77	----	----	----	----	----	----
Pb	−3.08(10)	21	−2.3	0.5	−2.6	0.7	30	4.8
Bi	−3.08(10)	93	----	----	----	----	----	----
Hg	−6.00(0.01)	[5]1.4	−4.8	0.5	−4.8	0.6	0.2	3.6
As	−3.00(10)	[6]33	−2.5	0.4	−2.8	0.5	20	3.5
Cu	−3.75(2) −3.42(5)	6.1	−2.7	0.5	−2.7	0.5	20	3.5
Mo	−3.75(2)	52	----	----	----	----	----	----
Fe	1.25(15%)	[7]3.7	0.5	0.5	0.5	0.5	3	3.2

[1]Ppm figure is near the midpoint of a range of concentrations equal to $\sqrt[2]{10}$. The log percent figure is the lower boundary for the same range. Applies only to Ag, Pb, Bi, Cu, Mo, and Fe, obtained by six-step semiquantitative spectrographic analysis.
[2]Data for 303 samples.
[3]Data for 320 samples.

[4]Data for 1,336 samples.
[5]Data for 1,307 samples.
[6]Data for 1,331 samples.
[7]Represents percentage of samples above upper, rather than below lower, detection limit.

the median value. Hawkes and Webb (1962) use the term "background range" to refer to all concentrations that are not anomalous and use "background" to refer to a mean or median value. For those who prefer this strict definition of the term "background," table 1 includes the appropriate information. Our usage of "background" and "threshold" accords with definitions given by Andrews-Jones (1968).

Our method of determining threshold concentration differs from Lepeltier's method mainly in that we use computed logarithmic means and standard deviations adjusted by Cohen's method, rather than using unadjusted logarithmic means and standard deviations obtained graphically. Analytical determinations between one and two deviations above the logarithmic mean are also distinguished on the geochemical maps and are referred to as "high background" concentrations. For gold, silver, and bismuth, where more than 50 percent of the data are below the lower detection limit, we consider the top 2.3 percent of the data (all data greater than or equal to the 97.7 percentile) anomalous. For these three elements we have designated as "high background" concentrations greater than or equal to the 84 percentile and less than the 97.7 percentile. The 84 percentile and the 97.7 percentile are equavalent to one and two deviations, respectively, above the logarithmic mean (50 percentile) for a log-normal distribution. The log-probability plots of figure 4 were used to determine the values at the 84 and 97.7 percentiles for each element with more than 50 percent censored data (see Lepeltier, 1969). Table 2 summarizes the background and threshold concentrations calculated. The ranges of anomalous and "high background" concentrations shown in table 2 are adjusted to coincide with the analytical reporting intervals used by U.S. Geological Survey laboratories; these calculations form the boundaries for the three ranges of data shown on the geochemical maps in the next section of the report.

The threshold concentrations of table 2 are based on analytical data for the 323 samples collected at those intersection points of a randomly positioned 500-ft grid that fell on silicified zones (Ashley and Keith, 1973a). This group of samples was used because sampling localities are evenly distributed throughout the altered area. Although we could have calculated threshold concentrations using all the 1,337 samples collected, sampling density varies from place to place, so areas unusually rich or poor in some elements could be represented disproportionately, resulting in threshold concentrations too low or too high for the altered area as a whole.

Histograms (not shown) and log-probability plots (fig. 4) for seven of the eight elements considered in the 323 silicified samples show unimodal distributions without

TABLE 2.—*Threshold concentrations for Au, Ag, Pb, Bi, Hg, As, Cu, and Mo, determined from 323 silicified rocks*

[$\hat{\mu}_L$ = Cohen's mean (logarithmic), $\hat{\sigma}_L$ = Cohen's standard deviation (logarithmic)]

	Statistical data, (ppm)		Threshold concentrations (ppm)[1]	Range of high background concentrations (ppm)
Au	84 percentile	.03	0.45	0.03–0.44
	97.7 percentile	.45		
Ag	84 percentile	.5	3	.5–2
	97.7 percentile	2		
Pb	$\hat{\mu}_L$	30	500	150–300
	$\hat{\mu}_L+1\hat{\sigma}_L$	100		
	$\hat{\mu}_L+2\hat{\sigma}_L$	500		
Bi	94.4 percentile	10	20	10–15
	97.7 percentile	20		
Hg	$\hat{\mu}_L$	.19	1.6	.54–1.5
	$\hat{\mu}_L+1\hat{\sigma}_L$	.54		
	$\hat{\mu}_L+2\hat{\sigma}_L$	1.5		
As	$\hat{\mu}_L$	20	160	60–150
	$\hat{\mu}_L+1\hat{\sigma}_L$	50		
	$\hat{\mu}_L+2\hat{\sigma}_L$	150		
Cu	$\hat{\mu}_L$	10	300	50–200
	$\hat{\mu}_L+1\hat{\sigma}_L$	50		
	$\hat{\mu}_L+2\hat{\sigma}_L$	200		
Mo	$\hat{\mu}_L$	3	50	15–30
	$\hat{\mu}_L+1\hat{\sigma}_L$	10		
	$\hat{\mu}_L+2\hat{\sigma}_L$	40		

[1]Threshold concentration is lowest concentration considered anomalous. All lower concentrations are considered background.

breaks that could be significant in terms of metallization. Lepeltier (1969) and Wedow and Ericksen (1971) determined threshold concentrations by fitting lines to the data for a given element plotted on log-probability paper. If an excess of high analytical determinations exists, indicating that the log-frequency distribution has an abnormally long upper tail, two lines are necessary to fit the data, and the point at which these lines intersect is the threshold concentration. If data for an element form a bimodal frequency distribution, three lines may be required to fit the data, and the threshold concentration is at the midpoint of the middle line. Only the plot for mercury shows a significant excess of high determinations; this plot yields a threshold concentration of 1.4 ppm, little different from the 1.5 ppm in table 2. Thus analytical determinations for all the metals except mercury and possibly copper seem to be from single, approximately log-normally distributed populations. For these elements, all samples are metallized to some degree, and our threshold concentration is an arbitrary cutoff; samples yielding analytical determinations above this cutoff we consider metallized strongly enough to be noteworthy. Even for mercury, the excess of high determinations is small, so the arbitrarily determined threshold is used.

DISTRIBUTION OF ELEMENTS IN SILICIFIED ROCKS

GOLD, SILVER, AND LEAD

Most samples containing anomalous amounts of gold and silver and many samples containing anomalous
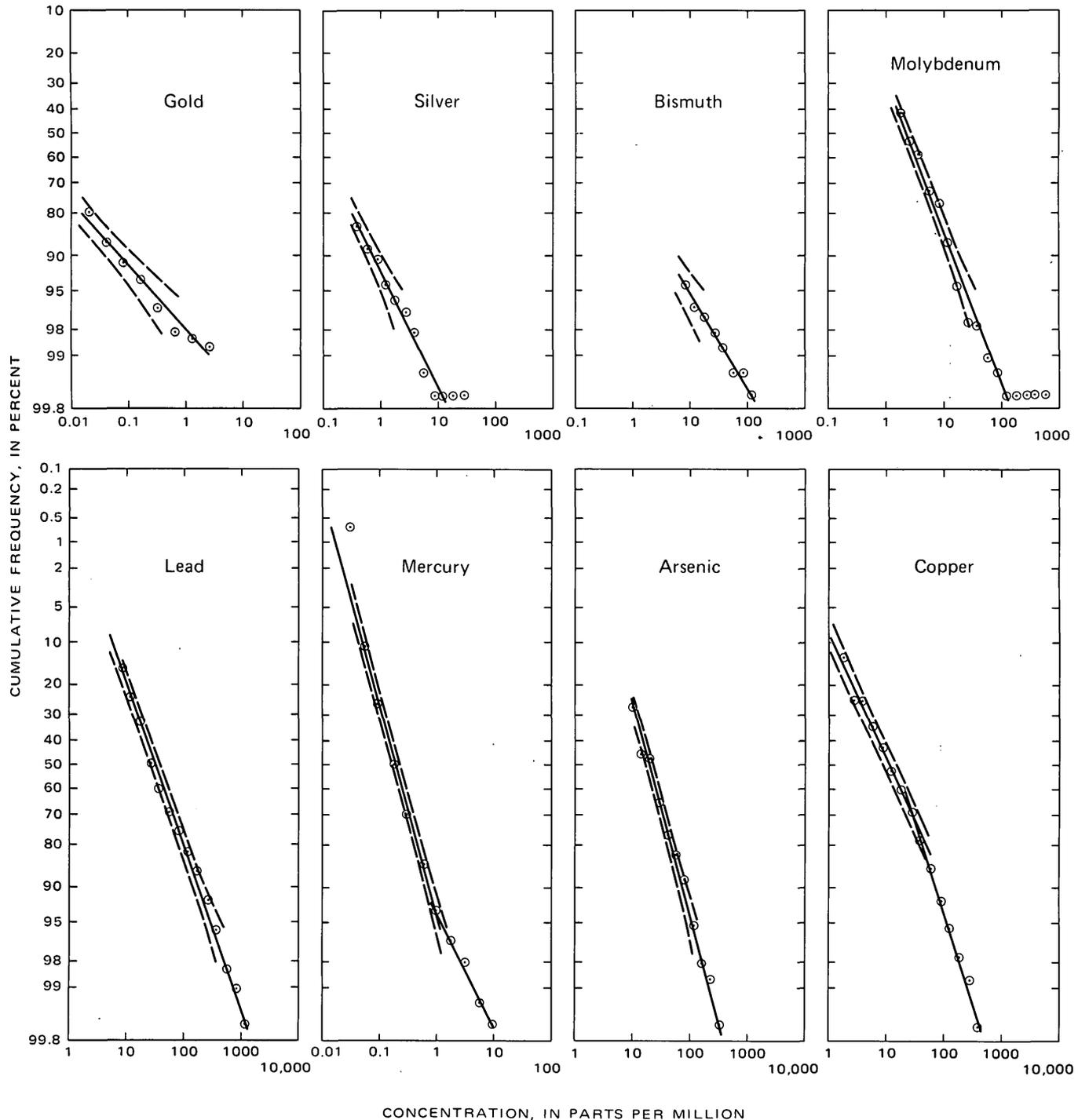
FIGURE 4.—Log-probability plots for gold, silver, bismuth, lead, molybdenum, mercury, arsenic, and copper in 323 silicified rocks. Each data point shows cumulative frequency at the lower end of each class interval. Dashed lines show 95 percent confidence limits for the straight line fit to the data points.

amounts of lead were collected in the arcuate belt around the west and north sides of the district; this belt lies above an inferred ring fracture zone. The western part of the main productive area, where the largest veins come nearest the surface, was poorly sampled owing mainly to extensive ground disturbance related to mining. Veins to the north and northeast of the main productive area, in secs. 24 and 26, T. 2S., R. 42 E., and secs. 17, 19, and 20, T. 2 S., R. 43 E. (pls. 1–3) show many anomalous concentrations of gold and silver and a few of lead. Except for the 50- and 80-ppm values from pillars left in a vein termed the "flat vein" on the south side of

Black Butte (near the center of sec. 20, T. 2 S., R. 43 E.), anomalous amounts of gold and silver in the productive veins are not notably higher than amounts from nearby nonproductive veins that show anomalous values.

Silver, although it does not show a pattern identical to that of gold, is distributed similarly. Silver is of particular interest in the northern part of the area because ores of the Sandstorm and Kendall mines (NE cor. sec. 26, T. 2 S., R. 42 E.) as well as ores from the several mines on McMahon Ridge and Black Butte, were, characterized by Au-Ag ratios that were low relative to ores from the main district (Ransome, 1909, p. 171–173, 250; J. K. Turner, 1934, unpub. report on Great Bend mine). The overall Au-Ag ratio was about 3:1 for ores mined from the main district from 1906 through 1918 (U.S. Geological Survey, 1883–1924), the most productive period, whereas assays cited by Ransome for the McMahon Ridge–Black Butte area and by Turner for ore shipments from the Great Bend mine on McMahon Ridge have Au-Ag ratios ranging from about 2:1 to about 1:60. In this study 179 samples contained detectable amounts of both gold and silver. The highest Au-Ag ratio is 7.6:1, but most samples have ratios less than 1:1. The ratios shown by our samples do not vary with location within the altered area.

Many anomalous gold, lead, and silver concentrations also appear at Preble Mountain at the corner common to secs. 4, 5, 8, and 9, T. 3 S., R. 43 E., and some scattered anomalous concentrations of these elements also occur in a belt extending east from Preble Mountain through secs. 4 and 9, 3 and 10, and into sec. 11, T. 3 S., R. 43 E. (pls. 1–3). Many samples with high background contents of gold appear even farther to the east.

Boundaries of the three anomalous areas shown on plates 1 through 8 are drawn around contiguous groups of samples containing anomalous amounts of gold, silver, or lead. Some nearby samples containing anomalous amounts of bismuth, arsenic, or mercury are included. Parts of the altered area with few or no anomalous gold concentrations are not designated as anomalous, even if they contain anomalous amounts of other metals.

Some of the anomalous samples from Preble Mountain differ from the silicified rock samples generally collected for this study. The large silicified zones capping Preble Mountain and many of the smaller zones in the belt extending 3 km to the east are locally fractured and brecciated, with aggregates of alunite and jarosite, instead of the usual limonite, filling the open spaces. Some of the alunite and jarosite in these aggregates may have formed contemporaneously, but nearly pure alunite was deposited first, and nearly pure jarosite last.

Although many of the anomalous samples from the Preble Mountain area shown on plates 1 through 8 contain alunite and jarosite, many other anomalous samples, some from the same localities, do not. Eleven of the 12 samples with anomalous silver from the Preble Mountain area are alunite-jarosite-bearing samples, but only 19 of the 44 samples with anomalous lead and three of the 10 samples with anomalous gold contain alunite-jarosite. At 29 localities data are available for both alunite-jarosite-bearing and alunite-jarosite-free silicified rock samples. At one of these localities, high background gold occurs in the wallrock as well as in the breccia cemented with alunite and jarosite; at some localities wallrock has high background amounts of gold, but the alunite-jarosite-bearing material does not (table 3). Thus, even though a relatively large proportion of the alunite-jarosite-bearing samples from the Preble Mountain area have anomalous amounts of silver and lead and three samples have anomalous amounts of gold, the Preble Mountain area would show a similar distribution of anomalous and high-background samples if only limonite-bearing silicified rocks had been collected. At the localities where both types of samples were collected, the value shown on the geochemical maps (pls. 1–8) is the higher of the two.

The common occurrence of anomalous metal concentrations in both alunite-jarosite-bearing samples and their adjacent silicified host rocks is not surprising because the alunite-jarosite aggregates are probably of hypogene origin. Because alunite was deposited first and was followed by jarosite, it is likely that Eh (oxidation-reduction potential) gradually increased while the breccias were being filled and that progressively more Fe^{+2} was oxidized to Fe^{+3}. The environment of deposition was probably hypogene, as opposed to supergene for limonite breccia fillings, because high Eh, with Fe^{+3} the dominant ion, should have prevailed throughout deposition if the environment were supergene. Contemporaneous or nearly contemporaneous deposition of relatively pure alunite and jarosite under any conditions, however, is difficult to explain in light of experimental work by Brophy, Scott, and Snellgrove (1962), who synthesized minerals of intermediate composition in the alunite-jarosite series. If the alunite-jarosite aggregates are indeed of hypogene origin, they must have formed late in the period of hydrothermal activity, as did sulfides, sulfosalts, and native gold in the main productive part of the district, where these ore minerals commonly filled brecciated parts of silicified zones.

The anomalous area at Preble Mountain does not include known ore bodies, as do the anomalous areas on the west and north sides of the district, but its structural setting is similar in two respects. First, Preble Mountain itself lies above the inferred ring fracture

TABLE 3.—*Analytical data for pairs of samples from a single locality. First sample listed is brecciated silicified rock bearing alunite and jarosite; second sample listed is silicified rock free of alunite and jarosite collected at same outcrop. Amounts of Au, Ag, Pb, Bi, Hg, As, Cu, and Mo in parts per million, and Fe in percent*

[L, less than detection limit; N, not detected; G, greater than value shown. Detection limit is under element name]

	Au (0.02)	Ag (0.5)	Pb (10)	Bi (10)	Hg (0.01)	As (10)	Cu (2)	Mo (5)	Fe
DY389	L	N	15	N	0.06	30	30	7	1
DY388	L	N	L	N	0.11	L	30	N	15
DY407	L	.7	500	N	0.02	20	20	N	3
DY406	L	.5	700	L	0.02	30	30	N	3
DY411	L	N	200	N	0.03	30	15	15	10
DY413	L	N	100	N	L	10	50	N	7
DY419	L	N	1,500	N	0.02	L	15	N	0.5
DY420	.30	N	30	N	0.01	L	15	N	20
DY421	L	N	70	N	0.02	40	15	N	7
DY422	L	N	70	N	0.04	10	10	10	5
DY424	.04	N	500	N	0.01	10	7	300	10
DY423	L	N	700	N	0.02	30	100	20	7
DY429	L	N	7,000	N	0.02	10	L	L	0.7
DY430	L	N	10	N	0.03	30	15	15	1.5
DY434	L	1.5	150	N	L	150	20	20	7
DY433	L	L	300	N	0.01	100	15	15	3
DY436	.02	10	10,000	L	0.01	100	7	5	3
DY437	.06	N	300	30	0.01	30	15	70	3
DY438	L	L	500	N	0.02	10	10	15	5
DY439	L	N	300	N	0.01	10	50	7	3
DY450	.04	N	200	N	0.02	L	50	20	10
DY449	.08	N	150	N	L	30	30	20	10
DY455	L	N	1,500	30	0.20	60	15	20	7
DY454	L	N	700	N	0.22	20	20	30	10
DY464	.06	N	200	N	0.12	40	20	15	7
DY463	.02	N	70	N	0.10	40	30	N	5
DY527	L	N	150	N	0.15	60	30	15	7
DY526	.3	1	200	N	0.60	300	30	10	5
DY531	L	N	70	L	0.16	30	15	L	3
DY532	L	N	20	30	0.13	30	30	30	10
DY534	.04	0.7	500	N	0.50	L	15	15	3
DY535	.02	2	20	N	0.50	60	70	10	3
DY681	L	N	100	N	3.0	10	15	N	10
DY680	L	1	100	N	1.0	10	30	N	3
DY690	L	0.5	100	N	0.16	10	15	N	7
DY691	.06	N	L	300	0.24	L	15	N	10
DY695	L	N	30	N	1.5	300	70	15	10
DY694	L	N	50	N	0.38	80	20	15	15
DY699	.02	N	150	10	0.60	10	20	N	7
DY698	L	N	50	N	0.50	10	50	N	3
DY708	L	N	700	N	0.22	L	15	N	0.3
DY707	L	N	500	N	0.08	60	15	15	3
DY710	L	0.7	70	N	0.18	L	70	15	3
DY709	L	N	70	N	0.08	L	70	15	7
DY729	L	N	10	N	0.13	20	30	N	1
DY728	L	0.5	20	N	0.05	10	30	N	7
DY733	L	1	100	N	0.11	100	20	N	1.5
DY732	L	N	200	N	0.08	10	15	7	2
DY739	.02	N	30	N	0.08	10	10	N	7
DY740	L	N	50	N	0.05	10	15	L	7
DY742	L	N	150	N	0.01	L	10	N	0.1
DY741	L	N	N	N	0.14	L	15	7	3
DY757	L	N	10	N	0.70	100	20	N	7
DY756	L	N	N	N	0.45	60	15	N	7
DW767	L	N	20	N	0.04	30	20	N(2)	7
DW768	L	N	10	N	0.07	80	50	N(2)	G(10)
DW770	0.02	N	30	N	0.11	40	2	3	0.7
DW769	L	N	20	N	0.26	600	50	100	10

zone, and second, the fracture zone that extends S 80° E. from the main productive area also passes through the anomalous area at Preble Mountain.

BISMUTH, MERCURY, AND ARSENIC

Most samples with anomalous bismuth, mercury, or arsenic are from the same parts of the altered area that show anomalous gold, silver, and lead, but the distribution of these elements differs in some ways from that of gold, silver, and lead. For example, a group of samples with anomalous bismuth occurs in the NW¼ sec. 10, T. 3 S., R. 43 E. (pl. 4) and a group of samples

with anomalous mercury in the NW¼ sec. 9, T. 3 S., R. 43 E. (pl. 5).

Scattered samples containing anomalous amounts of bismuth appear in the vicinity of Vindicator Mountain (NW¼ sec. 31, S½ sec. 30, T. 2 S., R. 43 E.) and Banner Mountain (NE¼ sec. 31, SW¼ sec. 29, T. 2 S., R. 43 E.); several samples here have both anomalous bismuth and lead, and one sample has anomalous silver as well. Anomalous gold accompanies anomalous bismuth and lead in only one sample, and only three other samples contain anomalous silver. Because gold and silver-rich samples are lacking, it is uncertain whether the samples from the Vindicator and Banner Mountain areas containing anomalous bismuth and lead belong to relict hypogene aureoles of undiscovered gold-silver deposits. Similar anomalous samples along the west and north sides of the district are more likely to be parts of hypogene aureoles because samples with anomalous gold and silver concentrations are found nearby.

A considerable number of samples with anomalous mercury appear in sec. 12, T. 3 S., R. 43 E., and some appear in secs. 1, 2, 11, T. 3 S., R. 43 E., and secs. 21, 22, 27, and 28, T. 2 S., R. 43 E. These samples do not fall within the areas previously delineated by samples with anomalous gold, silver, and lead, but they most likely reflect hypogene mercury deposition (see Ashley and Albers, 1975). The sample with anomalous mercury located in the west-central part of sec. 22, T. 2 S., R. 43 E. is near the occurrence of cinnabar described by Ransome (1909, p. 113). Anomalous mercury occurs mainly, but not entirely, in parts of the altered area where silicified rocks do not contain pyrophyllite. Inasmuch as pyrophyllite forms at temperatures over 300°C in a quartz-saturated system at 1 kbar pressure (Thompson, 1970; Reed and Hemley, 1966), mercury shows a preference for parts of the area where maximum temperatures were relatively low. This accords with indications that mercury is mobile in hydrothermal systems at temperatures above 250°C and possibly at temperatures as low as 150°C (White, 1967), although hydrothermal solutions responsible for silicification at Goldfield were probably somewhat more acid than those thought to produce mercury deposits (Hemley and others, 1969).

The character of the frequency distribution for mercury data suggests that anomalous amounts of mercury may be the result of hypogene processes more complex than those responsible for anomalous amounts of the other elements. Mercury is the only element discussed here whose log-probability plot shows an excess of high analytical determinations. Frequency distributions that depart from log-normal typically result from sampling a heterogeneous population. Since the samples here are similar in other respects, a likely

cause of the heteogeneity is that hypogene processes responsible for mercury deposition were more complex at the sites yielding relatively mercury-rich samples.

The distribution pattern for arsenic (pl. 6) is fairly similar to those for lead and bismuth (pls. 3, 4); most anomalous samples come from the areas containing anomalous amounts of gold, silver, and lead, and scattered anomalous samples were found in the Vindicator and Banner Mountain areas as well. Except for the Preble Mountain area, however, samples with anomalous arsenic are scarce relative to samples with anomalous gold and silver.

COPPER

The distribution of copper (pl. 7) shows few similarities to the distribution of gold, silver, lead, bismuth, mercury, and arsenic. If the distribution pattern of copper were similar to those of the other elements, it has since been modified by oxidation. The copper distribution pattern is at least partly the result of supergene processes.

Only 11 samples with anomalous copper appear on plate 7, and these are found mainly near Vindicator and Banner Mountains. Copper concentrations at high background levels are scattered rather evenly throughout the entire altered area. Four of the Vindicator Mountain and Banner Mountain samples also contain anomalous amounts of lead, one contains anomalous bismuth, and one contains anomalous arsenic. The one sample with anomalous copper in the Preble Mountain area is particularly rich in alunite and jarosite.

Both the anomalous and high background samples are relatively rich in limonite minerals; iron content averages 8 percent for both anomalous and high background samples compared with 3 percent for both the 323 silicified rocks and the total data set. The copper in relatively copper-rich silicified rocks must have been at least partly redistributed during oxidation to achieve this association. The copper data also suggest that samples relatively enriched in copper during hypogene mineralization lost copper during supergene leaching.

The seemingly high threshold concentration for copper, which eliminates all but a few determinations as anomalous, results from the shape of the frequency distribution for copper in the 323 silicified rock samples (fig. 5). The distribution is broad and flat from the analytical detection threshold (2 ppm for most of the samples, 5 ppm for some samples) to about 50 ppm. Frequencies for class intervals above 50 ppm drop off rather abruptly, giving the frequency distribution a rather small upper tail. The log-probability plot for copper (fig. 4) also shows a break in slope at 30–50 ppm. This broad flat frequency distribution has a relatively large standard deviation, so that few determinations
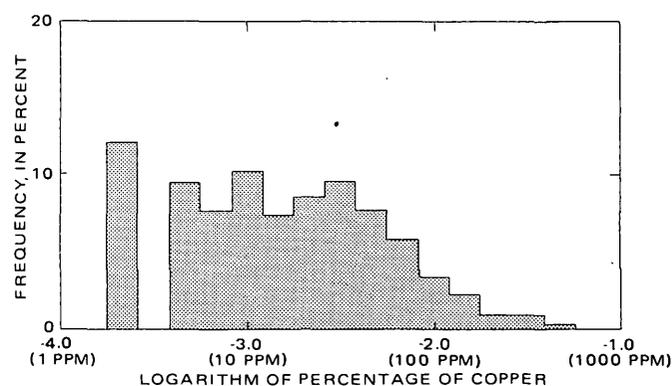

FIGURE 5.—Copper content of 323 silicified rock samples.

exceed twice this value, and therefore the map shows few anomalous samples. A histogram (not shown) plotted for all 1,337 samples collected is similar to that for the 323 grid samples.

Few samples have a relatively large amount of copper probably because of preferential leaching of copper from copper-rich samples during supergene oxidation throughout the area (previously documented by Ashley and Albers, 1975, and Ashley and Keith, 1973a). Geologic relations of postmineralization units suggest that rocks from the central part of the area (Vindicator and Banner Mountains) may have been exposed to supergene conditions for a shorter period of time than rocks nearer the edges of the altered area, which may explain why the few anomalous values are found in the central part of the area (see Ashley and Keith, 1973a). Less intense leaching could also result from lower pyrite content relative to minor amounts of hypogene copper sulfides present in the altered rocks before oxidation. Before alteration, the silicic volcanic rocks and quartz monzonite of the central part of the area contained little iron, and probably little was introduced during alteration. (See section on "Hydrothermal Alteration.") Relatively small amounts of pyrite would yield smaller amounts of acid capable of leaching copper during oxidation and smaller amounts of limonite to coprecipitate copper.

MOLYBDENUM

Although the distribution pattern of molybdenum (pl. 8) differs from that of copper (pl. 7), the main features of the molybdenum pattern are probably also the result of supergene processes. Except for the large number of samples with anomalous molybdenum from the Preble Mountain area (pl. 8), the distribution of molybdenum is different from that of gold, silver, or lead. Anomalous concentrations appear between Preble Mountain and the main productive part of the district in secs. 5, and 6, T. 3 S., R. 43 E., and sec. 1, T. 3S., R. 42 E., a feature not

seen in any of the geochemical patterns described previously. The few other anomalous values are scattered throughout the altered area.

Most of the samples with anomalous molybdenum are typical silicified rocks, but all are brecciated, with limonite coating and cementing the silicified rock breccia fragments. Only five samples with anomalous molybdenum in the Preble Mountain area are from alunite-jarosite-bearing rocks. Although many samples collected for this study were brecciated and cemented with limonite minerals, samples with anomalous molybdenum concentrations are particularly rich in limonite, with an average iron content of 9 percent. Samples with high background concentrations of molybdenum, although more evenly distributed throughout the altered area, are also rich in limonite, with an average iron content of 10 percent, which is about the same as that of the anomalous samples. Relatively large concentrations of molybdenum thus appear in limonite-rich samples, as is true for copper, in accordance with earlier findings (Ashley and Albers, 1975). The molybdenum anomaly between the main productive area and Preble Mountain appears to be the result of heavy sampling of limonite-rich silicified rocks; brecciation of silicified zones is especially common in this part of the area, and abundant limonite cements the breccias. Consequently, molybdenum distribution is probably mainly the result of supergene leaching and precipitation with limonite.

ASSOCIATIONS BETWEEN GOLD, SILVER, LEAD, BISMUTH, MERCURY, ARSENIC, COPPER, MOLYBDENUM, AND IRON

Correlation coefficients provide a means of investigating geochemical relations between the eight elements described above. Figure 6 presents correlation coefficients calculated using data for the 1,337 samples that make up the geochemical maps (pls. 1–8). We calculated Spearman nonparametric (rank) correlation coefficients, which are best suited to the data (Flanagan, 1957; Lovering, 1963). For each pair of elements to be compared, only samples having analytical values within detection limits for both elements were used. In accord with procedures adopted in an earlier study (Ashley and Albers, 1975), positive and negative correlation coefficients significant at the 95 percent confidence level are considered geologically meaningful, and correlation coefficients significant at the 99 percent level indicate a strong geological association. It is important to keep in mind that the correlation coefficients compare many more samples than those showing anomalous amounts of an element; for each element pair yielding a correlation coefficient, samples are included that have metal contents ranging down to

CORRELATION COEFFICIENTS

	Au	Ag	Pb	Bi	Hg	As	Cu	Mo	Fe
Au		0.39	0.14	0.25	0.07	0.12	0.20	0.00	0.02
Ag	179		0.00	0.35	0.15	0.16	0.14	-0.02	-0.12
Pb	376	262		0.22	-0.20	0.04	0.10	0.15	-0.05
Bi	53	50	86		-0.06	0.37	-0.13	0.37	0.36
Hg	468	295	1020	91		0.08	0.05	-0.07	-0.06
As	323	239	742	78	868		0.12	0.20	0.11
Cu	464	296	997	90	1211	845		0.25	0.18
Mo	236	148	527	49	612	481	614		0.37
Fe	462	302	1023	90	1240	856	1207	620	

NUMBER OF DATA PAIRS

| Symbol	Meaning
0.04	Correlation coefficient not significant at 95 percent confidence level.
-0.15	Negative correlation coefficient significant at 95 percent confidence level but not at 99 percent confidence level.
0.15	Positive correlation coefficient significant at 95 percent confidence level but not at 99 percent confidence level.
-0.30	Negative correlation coefficient significant at 99 percent confidence level.
0.30	Positive correlation coefficient significant at 99 percent coefficient level.

FIGURE 6.—Spearman correlation matrix for total data set (1,337 samples).

their lower detection limits. Although discussion centers on the correlation coefficients, the data used in computing the coefficients were also examined by means of bivariate frequency tables; only the bivariate frequency table for gold and copper is included (fig. 7).

Silver, lead, bismuth, arsenic, and copper correlate positively with gold, that is, their respective concentrations tend to vary together. The strong gold-lead correlation was revealed in previous work in the main district (Ashley and Albers, 1975). In that area silver was probably introduced early in the ore paragenesis, whereas gold was introduced late, and these two elements were found to vary almost independently. The strong gold-silver correlation found in this study, however, suggests that throughout much of the area excluding the main district, gold and silver probably were introduced together. The strong gold-silver and

gold-lead correlations and weaker but significant gold-bismuth and gold-arsenic correlations accord with the close coincidence of gold, silver, and lead anomalies and approximate coincidence of bismuth and arsenic anomalies with gold anomalies. For this group of elements, the areal distributions of relatively high and low concentrations in background samples are also similar. The lack of a gold-mercury correlation, on the other hand, accords with the differing areal distribution patterns of gold and mercury.

The strong gold-copper correlation, which does not accord with the gold and copper areal distribution patterns, exists mainly because gold and copper concentrations vary directly in samples that contain only background amounts of both of these elements (see bivariate frequency distribution, fig. 7). Appreciable amounts of copper in these samples are presumably residual copper not mobilized during oxidation. Thus samples containing less than 50 ppm copper have lost relatively little copper during oxidation, relative to samples that contain more than 50 ppm copper (see figs. 4, 5, and discussion in previous section). A difference in hypogene mineralogy between copper-rich and copper-poor samples may be the underlying cause of the difference in supergene behavior. The existence of the copper-gold correlation suggests that prior to oxidation, parts of the area with anomalous gold concentrations probably had larger copper concentrations.
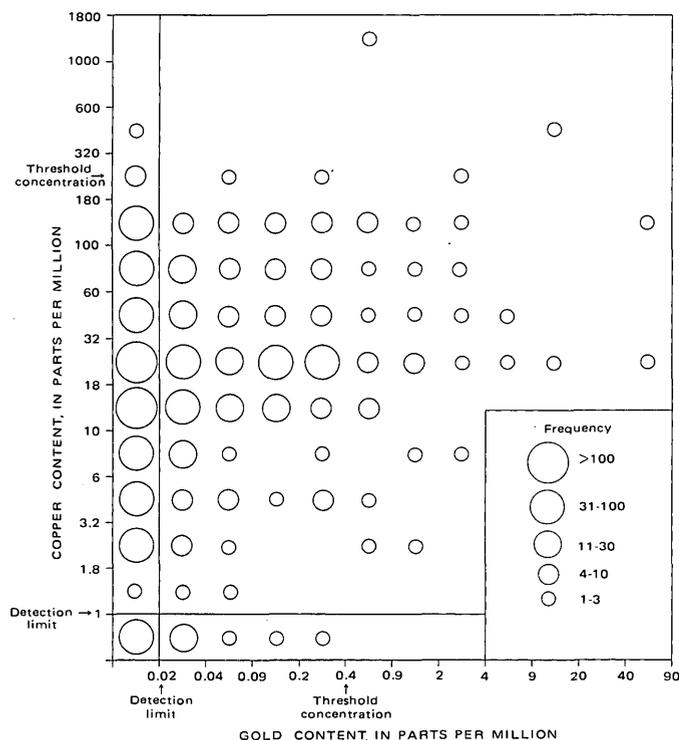

FIGURE 7.—Bivariate frequency distribution of gold and copper.

The elements that correlate with gold also show many correlations with one another. Silver correlates strongly with bismuth, arsenic, and copper. Lead correlates with bismuth and copper, and bismuth with arsenic. That mercury shows associations with few of the elements that correlate with gold is not surprising considering that anomalous concentrations of mercury occur in parts of the altered area where few samples show anomalous amounts of gold, silver, lead, bismuth, or arsenic (pl. 5). In the main productive part of the district, mercury correlates with gold and is similarly distributed in silicified rocks (Ashley and Albers, 1975). This relation probably holds for the anomalous areas on the west and north sides of the district, even though it does not hold for the altered area as a whole (see earlier section on mercury.).

Whether or not a given element in oxidized altered rocks at Goldfield is correlated with iron provides a measure of its supergene mobility. Much iron has been removed from the Goldfield altered rocks during supergene alteration, but a considerable amount was merely redistributed, having been precipitated in the oxidized zone as limonite. Other elements that have been leached during oxidation and that tend to precipitate with limonite (arsenic, copper, and molybdenum) correlate with iron and are intercorrelated (see Ashley and Albers, 1975, for further discussion). Bismuth correlates with iron, molybdenum, and arsenic, but not with copper. Furthermore, the average amount of iron in samples containing detectable amounts of bismuth is little different from the average for all 1,337 silicified rock samples. Thus bismuth and iron vary directly in samples that are not particularly rich in limonite, so whether bismuth is concentrated in limonite is questionable. Because copper and arsenic are included in both the Au-Ag-Pb-Bi-As-Cu and the As-Cu-Mo-Fe associations, the copper-arsenic correlation presumably results from both hypogene and supergene associations. The bismuth-iron correlation has not been previously observed in Goldfield altered rocks and cannot as yet be explained. Iron does not correlate with gold, silver, and lead, which show low supergene mobility. The lead-molybdenum correlation may be due to the formation of small amounts of wulfenite in the oxidized zone.

INTERPRETATION OF ANOMALOUS AREAS

Three anomalous areas were outlined mainly on the basis of anomalous gold and silver values but considering lead, bismuth, arsenic, and mercury as well (see pl. 9), and these areas were referred to in describing geochemical distribution patterns for silicified rocks in the Goldfield altered area (pls. 1–8). The first area extends from the main productive part of the district

northward through Columbia Mountain (NE¼ sec. 35, and NW¼ sec. 36, T. 2 S., R. 42 E.) and Morena Ridge to SE¼ sec. 23 and SW¼ sec. 24, T. 2 S., R. 42 E. It includes the vein mined at the Sandstorm and Kendall mines and minor production along the Columbia Mountain fault at the Adams and Conqueror mines. The second area extends from the west end of McMahon Ridge, in sec. 19, through Black Butte, in the center of sec. 20, T. 2 S., R. 43 E., and includes the silicified zones in the SW¼ sec. 17, T. 2 S., R. 43 E. The third area extends from the west side of Preble Mountain (SE¼ sec. 5 and NE¼ sec. 8, T. 3 S., R. 43 E.) eastward to W½ sec. 11, T. 3 S., R. 43 E.

Our sampling unavoidably adds little new information on the main productive part of the district, which has been very thoroughly and intensively explored (Ransome, 1909; Searls, 1948; Paul Billingsley, P. R. Murphy, and L. K. Wilson, unpub. data, 1935–38). Sampling over the apex of the main vein system was hampered by extensive ground disturbance from mining activity, so we cannot compare its geochemical expression to geochemical features elsewhere in the altered area. Our evaluation of the main productive part of the district is limited also by postmineralization Siebert tuff and alluvium, which cover the west side of the productive area (fig. 2). Additional production within the main district is largely a problem of evaluating remaining low-grade ore and developing a feasible scheme for mining it.

The ground from Columbia Mountain northward to secs. 23 and 24, T. 2 S., R. 42 E., has mostly been nonproductive, but gold, silver, and lead concentrations found in many nonproductive veins are similar to those found in surface outcrops of the productive Sandstorm-Kendall vein (see Ransome, 1909, p. 235–238, for description). The initial lode discovery was in the vicinity of the Sandstorm mine (see section entitled "History," and Ransome, 1909), which is one of the most strikingly anomalous areas seen in plates 1 and 2. Columbia Mountain has been explored by means of several tunnels, the longest being the Columbia Mountain east tunnel, over 250 m long. The group of silicified zones immediately east of the Sandstorm mine, on the border between secs. 25 and 26, T. 2 S., R. 42 E., has been explored only by means of three shafts, probably none deeper than 45 m (Ransome, 1909, p. 138–141). The large silicified zone in the NW¼ sec. 25, T. 2 S., R. 42 E., has been extensively trenched at the surface, and the Adams mine, immediately to the east of this zone, probably explored subsurface parts of this same vein or vein system. Minor production is reported from the Adams mine (Ransome, 1909, p. 239). The southernmost silicified outcrops in sec. 24, T. 2 S., R. 42 E., where designated an ore-bearing area on plates 1

through 9, make up the Conqueror mine, also a minor producer (Ransome, 1909, p. 238–239). Other silicified zones in SW¼ sec. 24 and SE¼ sec. 23, T. 2 S., R. 42 E., have been little explored.

Most silicified zones showing anomalous amounts of metals in the McMahon Ridge–Black Butte area (secs. 19, 20, and SW¼ sec. 17, T. 2 S., R. 43 E.) have been well explored (Ransome, 1909, p. 246–251). Several poorly explored unmined veins or groups of veins, however, show amounts of gold and silver comparable to those in the productive areas. The group of silicified zones in the SW¼ sec. 17 is particularly notable. Other interesting occurrences include a single vein on the north side of McMahon Ridge in the north-central part of sec. 19, and several scattered veins to the west, north, and east of Black Butte in sec. 20.

The anomalous area extending eastward from Preble Mountain is the only one of the three anomalous areas in the Goldfield district that has no past production. It has several features not seen in the other two areas. Hydrothermal alteration along the fracture zone trending N. 80° W.–S. 80° E. and passing through Preble Mountain forms a belt of argillized and silicified rocks about 1.5 km wide (fig. 1), whereas the arcuate belt of argillized and silicified rocks extending from the main district to Black Butte is less than half as wide in most places. Drilling information (Utah Internat. Corp., unpub. data, 1969) shows that the vertical extent of alunitic alteration in the vicinity of Preble Mountain is at least 760 m, whereas in and near the main district, it is no greater than about 300–450 m because most mine dump samples from depths greater than 300 m bear diaspore and pyrophyllite but no alunite (depth determined by comparing sample lithology with distribution of rock units shown on mine maps).

The silicified mass forming the top of Preble Mountain is another feature unique to the Preble Mountain anomalous area. This silicified cap partly replaces rhyodacite flow breccia but mostly replaces massive rhyodacite and trachyandesite. The geometry and vertical extent of this mass below the level of prospect tunnels on the flanks of Preble Mountain are not known. Large areas of silicification that appear elsewhere within the altered area generally prove to be low-dipping silicified zones; most are the result of silicification along permeable beds, mainly coarse volcanic breccia layers (most of the zones in secs. 11 and 12, T. 3 S., R. 43 E., and sec. 27, T. 2 S., R. 43 E., formed along such permeable beds). Much less commonly, low-dipping silicified zones formed along low-dipping fractures (for example, the flat vein of Black Butte). The Preble Mountain silicified mass does not appear to follow either permeable beds or low-dipping fault planes.

Alunite-jarosite aggregates cementing brecciated parts of the large silicified mass and other silicified zones are also unique to the Preble Mountain anomalous area. Although alunite veins, some hypogene and some more likely supergene, occur elsewhere in the Goldfield altered area (Ashley and Keith, 1973j; Jensen and others, 1971), only the alunite-jarosite veins of Preble Mountain contain anomalous amounts of all the elements studied here.

The most optimistic interpretation of these geologic features and the geochemical data is that the Preble Mountain anomalous area represents a hypogene halo over metallized zones within the large volume of intensely altered rock present. The alunite-jarosite occurrences, which fill brecciated parts of silicified zones in much the same way that metal sulfides, sulfosalts, and gold do in the main district, may give way to breccia fillings composed of ore-grade sulfide minerals at depth, although because the alunite and jarosite are probably hypogene, this depth can be independent of depth of oxidation.

SUMMARY

Three anomalous areas are shown based on geochemical maps for gold, silver, lead, bismuth, mercury, and arsenic in silicified zones. Both mined and some unmined veins show similar anomalous amounts of gold and silver in two of the three areas. The third area, located at Preble Mountain, has no past production. It has several features not seen elsewhere in the altered area, including great areal extent and depth of hydrothermal alteration characterized by silicified zones bearing alunite, the presence of an extraordinarily large silicified mass forming the top of Preble Mountain, and the occurrence of coarse alunite-jarosite aggregates filling brecciated parts of the silicified zones.

The facts that geochemical maps for gold, silver, lead, bismuth, and arsenic all show similar distribution patterns and that data for most pairs of elements from this group have significant positive correlation coefficients indicate similar hypogene distribution of these elements. The distribution pattern for mercury shows similarities to these five elements, but anomalous amounts of mercury also occur in the northeastern and southeastern parts of the area, which yield few samples with anomalous gold, silver, lead, bismuth, and arsenic. Mercury, furthermore, shows positive correlations with only two of the above five elements, indicating that it was deposited in the silicified zones under somewhat different conditions. Unlike other elements investigated, the frequency distribution for mercury data shows an excess of high values, which suggests that hypogene deposition of mercury was a more complex process than it was for gold, silver, and lead. Arsenic

shows a positive correlation with iron, but residual arsenic predominates over arsenic transported and precipitated with limonite.

Copper shows a much different areal distribution pattern than the previous six elements, owing mainly to supergene leaching. Copper in background amounts, however, correlates positively with four of the six elements above, including gold. Copper correlates positively with iron and is particularly abundant in limonite-rich samples. In low-copper samples, much copper is residual; in high-copper samples, significant amounts of copper have been leached, and significant amounts of the copper mobilized have been precipitated with limonite. Before oxidation anomalous amounts of copper may have accompanied anomalous amounts of gold, silver, and lead in the three anomalous areas.

Molybdenum, which shows a distribution pattern different from all the other elements, is strongly concentrated in limonite-rich samples, obscuring its hypogene distribution and relations with other elements.

REFERENCES CITED

Albers, J. P., and Cornwall, H. R., 1968, A revised interpretation of the stratigraphy and structure of the Goldfield district, Esmeralda and Nye Counties, Nevada [abs.]: Geol. Soc. America Spec. Paper 101, p. 285.

Albers, J. P., and Kleinhampl, F. J., 1970, Spatial relation of mineral deposits to Tertiary volcanic centers in Nevada, in Geological Survey research 1970: U.S. Geol. Survey Prof. Paper 700–C, p. C1–C10.

Albers, J. P., and Stewart, J. H., 1972, Geology and mineral deposits of Esmeralda County, Nevada: Nevada Bur. Mines and Geology Bull. 78, 80 p.

Andrews-Jones, D. A., 1968, The application of geochemical techniques to mineral exploration: Colorado School Mines Mineral Industries Bull., v. 11, no. 6, 31 p.

Ashley, R. P., 1972, Premineralization structural history of the Goldfield volcanic center, Nevada [abs.]: Econ. Geology, v. 67, p. 1002.

———1973, Fission-track ages for premineralization volcanic and plutonic rocks of the Goldfield mining district, Esmeralda and Nye Counties, Nevada: Isochron/West, no. 8, p. 25–29.

———1974, Goldfield mining district, in Guidebook to the geology of four Tertiary volcanic centers in central Nevada: Nevada Bur. Mines and Geology Rept. 19, p. 49–66.

———1975, Preliminary geologic map of the Goldfield mining district, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF-682.

Ashley, R.P., and Albers, J. P., 1969, Elements associated with gold in the oxidized zone at Goldfield, Nevada [abs.]: Geol. Soc. America Spec. Paper 121, p. 480.

———1975, Distribution of gold and other ore-related elements near ore bodies in the oxidized zone at Goldfield, Nevada: U.S. Geol. Survey Prof. Paper 843–A, 48 p.

Ashley, R. P., and Keith, W. J., 1973a, Geochemistry of the altered area at Goldfield, Nevada, including anomalous and background values for gold and other metals: U.S. Geol. Survey open-file report, 117 p.

———1973b, Geochemical map showing distribution and abundance of arsenic in silicified rocks, Goldfield mining district, Esmeralda

and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–472.

———1973c, Geochemical map showing distribution and abundance of bismuth in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–473.

———1973d, Geochemical map showing distribution and abundance of copper in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–474.

———1973e, Geochemical map showing distribution and abundance of gold in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–475.

———1973f, Geochemical map showing distribution and abundance of lead in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–476.

———1973g, Geochemical map showing distribution and abundance of mercury in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–477.

———1973h, Geochemical map showing distribution and abundance of molybdenum in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–478.

———1973i, Geochemical map showing distribution and abundance of silver in silicified rocks, Goldfield mining district, Esmeralda and Nye Counties, Nevada: U.S. Geol. Survey Misc. Field Studies Map MF–479.

———1973j, Occurrences of alunite in hydrothermally altered rocks and ores at Goldfield, Nevada [abs.]: Geol. Soc. America Abstracts with Programs, v. 5, no. 1, p. 6.

Bropy, G. P., Scott, E. S., and Snellgrove, R. A., 1962, Sulfate studies II—Solid solution between alunite and jarosite: Am. Mineralogist, v. 47, p. 112–126.

Cohen, A. C., Jr., 1959, Simplified estimators for the normal distribution when samples are singly censored or truncated: Technometrics, v. 1, no. 3, p. 217–237.

———1961, Tables for maximum likelihood estimates; singly truncated and singly censored samples: Technometrics, v. 3, no. 4, p. 535–541.

Flanagan, F. J., 1957, Semi-quantitative spectrographic analysis and rank correlation in geochemistry: Geochim. et Cosmochim. Acta, v. 12, p. 315–322.

Grimes, D. J., and Marranzino, A. P., 1968, Direct-current arc and alternating-current spark emission spectrographic field methods for the semiquantitative analysis of geologic materials: U.S. Geol. Survey Circ. 591, 6 p.

Harvey, R. D., and Vitaliano, C. J., 1964, Wall-rock alteration in the Goldfield district, Nevada: Jour. Geology, v. 72, p. 564–579.

Hawkes, H. E., and Webb, J. S., 1962, Geochemistry in mineral exploration: New York, Harper and Row, 415 p.

Hemley J. J., Hostetler, P. B., Gude, A. J., and Mountjoy, W. T., 1969, Some stability relations of alunite: Econ. Geology, v. 64, p. 599–612.

Huffman, Claude, Jr., Mensik, J. D., and Riley, L. B., 1967, Determination of gold in geologic materials by solvent extraction and atomic-absorption spectrometry: U.S. Geol. Survey Circ. 544, 6 p.

Jensen, M. L., Ashley, R. P., and Albers, J. P., 1971, Primary and secondary sulfates at Goldfield, Nevada: Econ. Geology, v. 66, p. 618–626.

Lepeltier, Claude, 1969, A simplified statistical treatment of geochemical data by graphical representation: Econ. Geology, v. 64, p. 538–550.

Locke, Augustus, 1912a, The ore deposits of Goldfield—I: Eng. and Mining Jour., v. 94, no. 17, p. 797–802.

———1912b, The ore deposits of Goldfield—II: Eng. and Mining Jour., v. 94, no. 18, p. 843–849.

Lovering, T. G., 1963, Use of nonparametric statistical tests in the interpretation of geological data: Soc. Mining Engineers Trans., v. 226, no. 2, p. 137–140.

Miesch, A. T., 1967, Methods of computation for estimating geochemical abundance: U.S. Geol. Survey Prof. Paper 574–B, 15 p.

Ransome, F. L., 1909, Geology and ore deposits of Goldfield, Nevada: U.S. Geol. Survey Prof. Paper 66, 258 p.

———1910a, Geology and ore deposits of the Goldfield district, Nevada. Part I—Geology: Econ. Geology, v. 5, p. 301–311.

———1910b, Geology and ore deposits of the Goldfield district, Nevada. Part II—Mines and mining: Econ. Geology, v. 5, p. 438–470.

Reed, B. L., and Hemley, J. J., 1966, Occurrence of pyrophyllite in the Kekiktuk Conglomerate, Brooks Range, northeastern Alaska, in Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550–C, p. C162–C166.

Searls, Fred, Jr., 1948, A contribution to the published information on the geology and ore deposits of Goldfield, Nevada: Nevada Univ. Bull., v. 42, no 5 (Geology and Mining Ser. 48), 24 p.

Silberman, M. L., and Ashley, R. P., 1970, Age of ore deposition at Goldfield, Nevada, from potassium-argon dating of alunite: Econ. Geology, v. 65, p. 352–354.

Thompson, A. B., 1970, A note on the kaolinite-pyrophyllite equilibrium: Am. Jour. Sci., v. 268, p. 454–458.

Thompson, C. E., Nakagawa, H. M., and VanSickle, G. H., 1968, Rapid analysis for gold in geologic materials, in Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–B, p. B130–B132.

U.S. Geological Survey, 1883–1924, Mineral resources of the United States [annual volumes, 1882–1923]: Washington, U.S. Govt. Printing Office.

Vaughn, W. W., 1967, A simple mercury vapor detector for geochemical prospecting: U.S. Geol. Survey Circ. 540, 8 p.

Vaughn, W. W., and McCarthy, J. H., Jr., 1964, An instrumental technique for determination of submicrogram concentrations of mercury in soils, rocks, and gas, in Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501–D, p. D123–D127.

Ward, F. N., Lakin, H. W., Canney, F. C., and others, 1963, Analytical methods used in geochemical exploration by the U.S. Geological Survey: U.S. Geol. Survey Bull. 1152, 100 p.

Wedow, Helmuth, Jr., and Ericksen, G. E., 1971, Log-probability graphs of geochemical data and their use in exploration [abs.]: Econ. Geology, v. 66, p. 1270.

White, D. E., 1967, Mercury and base-metal deposits with associated thermal and mineral waters, [Chap.] 13 in Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart, and Winston, p. 575–631.