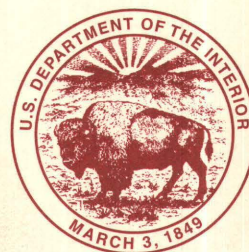Geochemical Signatures of Silver and Gold Deposits, Tonopah 1°×2° Quadrangle, Nevada— Description and Applications to Exploration

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Geochemical Signatures of Silver and Gold Deposits, Tonopah 1°×2° Quadrangle, Nevada—Description and Applications to Exploration

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U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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Geochemical Signatures of Silver and Gold Deposits, Tonopah 1°×2° Quadrangle, Nevada— Description and Applications to Exploration

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ABSTRACT

Geochemical results for 34 elements in 951 samples of altered and mineralized rock samples from mines, prospects, dumps, and drillholes in the Tonopah 1°×2° quadrangle, Nevada, demonstrate a wide range in composition. Although there are large differences in elemental concentrations from sample to sample, within and between deposits, geochemical signatures of grouped data are significantly different for the six geologically defined deposit types in four geologic environments (sedimentary, volcanic, plutonic, and metamorphic). Statistical analysis of grouped data for the six deposit types shows major differences in geochemical associations for silver, gold, and base-metal elements. Multivariate statistical techniques such as discriminant function analysis provide objective comparison and classification of prospect samples relative to known deposits types that have established grade, tonnage, and chemical signature.

Silver and gold have been produced from hundreds of deposits in the Tonopah quadrangle. Historically, the value of silver has exceeded that of gold. Silver-rich oxidized polymetallic deposits yielded important amounts of silver (but not much gold) in the 19th century, but most of the deposits probably were found because they have conspicuous gossans. The deposits are easily recognized by their base-metal-rich geochemical signatures, but the prevailing low price of silver in the 1980's and 1990's makes them less attractive targets than in the past. Gold-dominant deposits, the prime exploration targets of the 1990's, are chiefly in volcanic and sedimentary rock environments. The geochemical signatures of these deposits are subtle, involving fewer elements and lower concentrations than the base-metal-rich silver-bearing deposits. Geochemical detection and discrimination of these deposits is possible but should be complimented by geologic and alteration data.

Chemical trends do not relate in a simple way to local geology within about 1 km of deposits. One of the few empirical trends for deposits of the Tonopah quadrangle is that silver is enriched relative to gold in volcanic- and plutonic-associated deposits localized in or near carbonate rocks. Regional east-west variations for many elements probably reflect geologic processes deep in the crust, or the absence of them. Higher amounts of many mafic elements suggest a source in oceanic rocks (shale or volcanogenic rocks), whereas higher amounts of elements such as silver, lead, and molybdenum, as in eastern parts of the quadrangle, possibly reflect a cratonic source. Ore processes are not defined by the geochemical signatures but do lend support for mechanisms suggested by isotopic and laboratory studies. Polymetallic ore suites, rich in copper, lead, zinc, arsenic, antimony, and bismuth, and of interest for silver, probably are related to deep-seated hydrothermal processes associated with magmatic systems and magmatic volatile elements such as chlorine and sulfur. In contrast, deposits having low content of base metals, and tending to be more valuable for gold than silver, may reflect dominantly near-surface meteoric-dominated waters that probably contained insufficient chloride or bisulfide for base-metal transport.

INTRODUCTION

Gold and silver mining has been important in the history of Nevada since the 1850's and is certain to continue to be important in the future. The earliest prospectors moved eastward from the California goldfields (Ferguson, 1929) but at first were not familiar with silver-bearing veins. With the discovery of the Comstock ores the prospectors learned how to recognize promising silver deposits and soon located rich silver ores at Austin and Eureka. Several deposits in the Tonopah 1°×2° quadrangle (fig. 1) were discovered in the mid-1860's as prospectors moved south. The Bonanza silver camps such as at Belmont and Ione exploited rich, near-surface supergene concentrations of easily mined and milled ore. The panic of 1879 and steadily declining silver prices from 1873 to 1894 forced closure of all mines in the area,

which were also struggling with lower grades, milling complexities, and water problems as they mined deeper into primary ores. A second boom was caused by the discovery of silver-gold ores at Tonopah in 1900. Experience with ores in volcanic rocks at Tonopah led to new discoveries a few years later in districts such as Divide and Round Mountain. Mining of these deposits was sporadic until 1940 when mining came to a halt during World War II. In the 1970's a third burst of exploration activity resulted from rising precious-metal prices following demonetization of gold. Previously known deposits were reevaluated and additional reserves found that permitted open-pit mines to be started in the

Northumberland, Round Mountain, Divide, and Manhattan areas. Exploration activity has fluctuated in the 1980's and 1990's, chiefly in response to gold and silver prices and changes in exploration and mining regulations. Known and potential resources of gold and silver in the Tonopah quadrangle are large and in the future should be competitive with other mining areas in North America.

Prospectors of the past have thoroughly examined all parts of the Tonopah area, learning new tricks from new deposit discoveries but not always utilizing the more sophisticated aspects of geology, geophysics, or geochemistry. Although most of the more obvious near-surface deposits

EXPLANATION

✕ Sediment-hosted deposit

✚ Volcanic-associated low-base-metal deposit

◇ Volcanic-associated high-base-metal deposit

○ Plutonic-associated skarn deposit

□ Plutonic-associated polymetallic replacement deposit

△ Metamorphic vein deposit
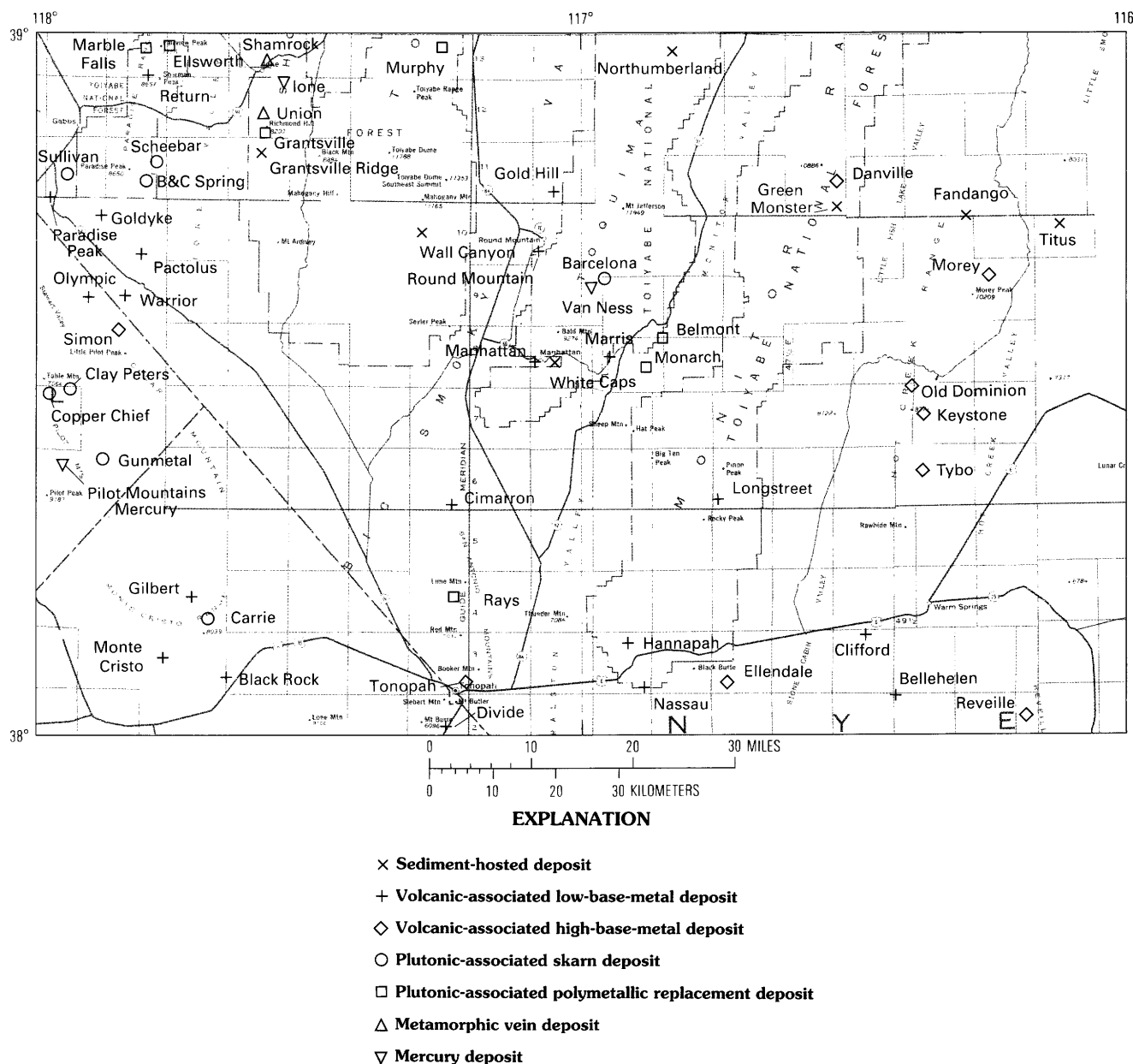
▽ Mercury deposit

Figure 1.   Map showing location of major silver and gold districts, mines, and prospects in the Tonopah 1°×2° quadrangle, Nevada. Modified from Nash (1988a).

probably have been found by those diligent prospectors, new geologic concepts and new geochemical methods may be able to identify deposits in ground previously traversed by prospectors. To that end, the Conterminous United States Mineral Appraisal Program (CUSMAP) was initiated in 1981 to provide modern geologic, geochemical, and geo-physical description and interpretation of rocks and mineral-ized areas in the Tonopah 1°×2° quadrangle. This reconnaissance geochemical study of more than 50 deposits and districts, most having some known production of gold or silver, was designed to provide multielement geochemical description of the deposits to establish geochemical criteria for resource assessment and mineral exploration. Nine hundred and fifty-one samples were chemically analyzed for 34 elements, about 50 samples were examined with a petrographic microscope, and fluid inclusions were studied in 30 samples. Districts or deposits described in this study are shown in figure 1 and on plate 1 and listed in table 1. The regional geochemistry of the Tonopah quadrangle, based on stream-sediment samples, was described earlier (Nash, 1988a), and interpretations in that report relied on many of the deposit signatures described here.

Fieldwork and sampling for this study was done from 1981 to 1985, and a draft manuscript was written in 1985. The report languished while other priorities were addressed for the next 8 years. During those years many of the unre-solved questions from Tonopah project reappeared, during resource assessments of other areas and particularly during study of the Sleeper gold-silver deposit in northwestern Nevada (Nash and others, 1991). Why are some deposits, like Sleeper, rich in gold rather than silver and thus so much more valuable? What are the reasons for the major differ-ences in base-metal concentrations of epithermal deposits? More pragmatically, can geochemical signatures be used to evaluate the grade and tonnage potential of a prospect? Lab-oratory research offers possible answers to the former ques-tions, but field studies are needed for the last. Empirical geologic relations of known deposits offer useful insights to grades and tonnages of deposits (Cox and Singer, 1986; Mosier and others, 1986), but there is a need for complimen-tary geochemical criteria, some of which are described and interpreted here.

SILVER AND GOLD DEPOSITS IN THE TONOPAH QUADRANGLE

A great diversity of ore deposits is present in the Tonopah area, in different settings that vary in age, size, min-eralogy and chemistry. Ore deposits discussed in this report are listed in table 1 and shown on plate 1. They range in age from pre-Tertiary to Holocene, although Pleistocene and Holocene placer deposits are not considered here. Precious-metal deposits are present in metamorphic rocks, such as in the Union district; in sedimentary rocks, such as at Northum-berland; in volcanic rocks, such as in the Tonopah and Morey districts; and associated with plutonic rocks, such as at Belmont and Murphy. Some deposits were mined in mines more than 700 m deep, whereas others could be mined only near the surface where oxidized, and recently a few have been mined by open-pit methods. The Tonopah district is world class in stature and has production of almost $150 mil-lion (Kleinhampl and Ziony, 1984), and several other dis-tricts produced more than $1 million (Belmont, Divide, Gilbert, Manhattan, Northumberland, Reveille, and Union). Almost all deposits in the region contain some silver or gold; in some silver was the major product and in others gold, and in some silver or gold were byproducts.

The deposits can be described on a commodity basis as silver, silver-gold, or gold-silver, depending on the value of the precious metals. Production data (Kral, 1951; Klein-hampl and Ziony, 1984) commonly provides information on individual metal values, but reliable and representative assay data are difficult to find for all districts and deposits. Chang-ing prices for silver and gold, especially since 1973, can give a distorted (minimum) estimate of value. Changing milling and refining technology influenced economics: in the 1800's oxidized (halide) ores of silver were most effectively worked, and prior to about 1910 zinc drew a smelter penalty. Changing mining technology, notably bulk mining in open pits, makes some near-surface deposits of low grade eco-nomic; average grades published for deposits mined by open-pit methods are always lower than for those mined underground, but the reasons are engineering, not geologic. For these and other reasons, commodity classification of deposits, as given in table 1, may not be consistent or reli-able. Several important features to bear in mind include the following: (1) historically, total ounces of silver have tended to be more valuable than gold; (2) geochemically, silver is

Table 1. Classification of deposits in the Tonopah 1°×2° quadrangle discussed in this report.
[Most deposits are shown in figure 1 or on plate 1. Leader (—) indicates no subtype for that deposit type]

Deposit	Type	Subtype	Silver:gold
Athens district	Volcanic associated	Low base metal	Silver<gold
Barcelona district	Pluton associated	Skarn, mercury	Silver>gold
B&C Spring deposit	Pluton associated	Skarn	Byproduct silver
Bellehelen area	Volcanic associated	Low base metal	Silver>gold
Belmont district	Pluton associated	Polymetallic	Silver>>gold
Black Rock prospect	Volcanic associated	Low base metal	Silver>gold?
Carrie mine	Pluton associated	Skarn	Silver>gold
Clay Peters mine	Pluton associated	Skarn	Byproduct silver
Clifford area	Volcanic associated	Low base metal	Silver=gold
Copper Chief	Pluton associated	Skarn	Byproduct silver
Danville district	Volcanic associated	High base metal/polymetallic?	Silver>gold
Divide district	Volcanic associated	Low base metal	Silver.gold
Ellendale district	Volcanic associated	High base metal	Silver>gold
Ellsworth district	Volcanic associated	High base metal?	Silver=gold
Fandango area	Sediment hosted	—	Silver<gold?
Gilbert district	Volcanic associated	Low base metal	Silver<gold
Gold Hill mine	Volcanic associated	Low base metal	Silver<gold
Gold Ledge mine	Metamorphic associated		Silver<gold?
Goldyke district	Volcanic associated	Low base metal	Silver=gold
Grantsville district	Pluton associated	Polymetallic	Silver>>gold
Grantsville Ridge area	Sediment hosted	—	Silver<gold?
Green Monster Canyon area	Sediment hosted	—	Silver<gold
Gunmetal mine	Pluton associated	Skarn	Byproduct silver
Hannapah district	Volcanic associated	Low base metal	Silver=gold
Hasbrouck mine	Volcanic associated	Low base metal	Silver>gold
Ione area	Volcanic associated	Mercury	No data
Keystone mine	Volcanic associated	High base metal	Silver>>gold
Longstreet area	Volcanic associated	Low base metal	Silver=gold
Manhattan district	Volcanic associated	Low base metal	Silver<gold
Marble Falls area	Pluton associated	Polymetallic	Silver>gold

almost always more abundant than gold, but a small amount of gold at more than $300 per ounce (>$8.75 per gram) can be more valuable than a much larger amount of silver; (3) geologically, deposits rich in gold (having silver to gold atomic ratios of less than about 5) are quite rare compared to those rich in silver. During the past 20 years gold prices in excess of $300 per ounce have shifted exploration and mining interest from silver to gold.

CLASSIFICATION AND MODELS OF SILVER-GOLD DEPOSITS

Ore deposit classification systems range from very simple (such as by commodity or by host rock) to complex (such as by tectonic setting or genetic process). In this study a classification scheme was needed to provide a framework for geochemical descriptions and interpretations. The geologic classification proposed by Ferguson (1929) was a major advance for silver-gold deposits in general and for the Tonopah region in particular. This classification utilizes

geologic associations, age, and silver to gold ratios. Nolan (1933) expanded on Ferguson's scheme by adding mineralogical criteria. These descriptive classifications remain useful today, although they do not address the then unrecognized Carlin-type deposits and do not utilize scientific advances in areas such as geochronology and hydrothermal processes.

Several classification systems recently have been proposed. Mineral deposit types are the cornerstone of a Canadian system (Ekstrand, 1984), which emphasizes features of known deposits that are sought in exploration or pondered in research on ore genesis. For instance, in this study it is useful to draw analogies to well-understood examples such as Creede (Colorado)-type deposits or Carlin (Nevada)-type deposits. A similar approach is utilized by Cox and Singer (1986), who organized information for groups of known deposits in a geologic-tectonic framework. These both are very useful classification systems, although economic geologists tend to disagree on assignment of specific deposits to proposed categories, particularly for the common situation of poorly exposed (unmined prospects) or vaguely described deposits.

Table 1. Classification of deposits in the Tonopah 1°×2° quadrangle discussed in this report—Continued.

Deposit	Type	Subtype	Silver:gold
Marris mine	Volcanic associated	Low base metal	Silver<gold
Monarch area	Plutonic	Polymetallic	No data
Monte Cristo area	Volcanic associated	Low base metal	Silver<gold?
Morey district	Volcanic associated	High base metal	Silver>>gold
Murphy mine	Pluton associated	Polymetallic	Silver>gold
Nassau prospect	Volcanic associated	Low base metal	Silver<gold
Northumberland mine	Sediment hosted	—	Silver<gold
Old Dominion mine	Volcanic associated	High base metal	Silver>>gold
OMCO (Olympic) mine	Volcanic associated	Low base metal	Silver=gold?
Paradise Peak mine	Volcanic associated	Low base metal	Silver>gold
Pilot Mountains mercury district	Volcanic assoicated?	High base metal	No data
Rays district	Pluton associated	Polymetallic	Silver>gold
Return mine	Volcanic associated	Low base metal	Silver<gold?
Reveille district	Volcanic associated	High base metal	Silver>>gold
Richmond mine	Metamorphic associated	—	Silver>gold
Round Mountain district	Volcanic associated	Low base metal	Silver<gold
San Antone district	Volcanic associated	Low base metal	Silver<gold
Scheebar mine	Pluton associated	Skarn, mercury	No data
Shamrock mine	Metamorphic associated	—	Silver>gold
Simon mine	Volcanic associated	High base metal/polymetallic?	Silver>>gold
Sullivan mine	Pluton associated	Skarn	Silver<gold
Teton prospect	Sediment hosted	—	Silver<gold
Titus prospect	Sediment hosted	—	Silver=gold?
Tonopah district	Volcanic associated	High base metal	Silver>gold
Tybo district	Volcanic associated	High base metal	Silver>>gold
Union district	Metamorphic associated	—	Silver>gold
Van Ness mine	Pluton associated(?)	Skarn, mercury	No data
Wall Canyon mine	Sediment hosted	—	Silver=gold
Warrior mine	Volcanic associated	Low base metal	Silver<gold
White Caps mine	Sediment hosted	—	Silver<gold

Recent reviews of classification and genesis that emphasize geochemistry and mineralogy provide helpful insights, especially into common ore-forming processes, and a series of symposia in the 1980's, and their proceedings volumes, stimulated discussion of precious-metal deposit classification and genesis. One of the first reviews, by Buchanan (1981), contains a wealth of tabulated information and provocative ideas on the origins of epithermal systems and the importance of boiling. Key contributions were made by Hayba and others (1985), who proposed a twofold system for precious-metal epithermal deposits characterized by adularia-sericite (neutral pH) or by alunite ("acid sulfate," or acid pH). In a variant on this theme White and Hedenquist (1990) termed the two classes "low sulfidation" (reduced sulfur) and "high sulfidation" (oxidized). Recently a subdivision of the adularia-sericite class was proposed (Albino and Margolis, 1991) that is based on major differences in ore mineralogy, chemistry, and silver to gold ratios that are consistent with tendencies in the Tonopah quadrangle. Physical models of precious-metal systems that refine hydrologic and geochemical processes are based on modern geothermal analogs (for example, Henley and Ellis, 1983; Henley, 1985;

Berger and Henley, 1989; Hedenquist, 1991) or computer-aided reaction-path models (for example, Drummond and Ohmoto, 1985; Reed and Spycher, 1985). The present study lacks much of the detailed mineralogical and isotopic data needed to relate directly to many of these geochemical models, but the models serve as analogs for discussion of results later in this report.

In the present study a simple classification system that emphasizes geologic associations (credits to Ferguson and Nolan) was utilized as a framework for geochemical discussion and interpretation. The classification system employs some of the distinctions proposed by Cox and Singer (1986) but is intentionally broad because the quantity and quality of background geologic and mineralogic data for the deposits are highly variable. The classes include:

1. *Sediment-hosted deposits.*—Similar to carbonate-hosted gold-silver deposits (Carlin-type) (model 26a, Cox and Singer, 1986), rocks tending to be impure carbonate rocks and dark shale, commonly highly silicified (jasperoid). Problems in using this class occur where deposits or districts grade into other volcanic or plutonic environments described following.

2. *Volcanic-associated deposits.*—Epithermal deposits in or near volcanic rocks and subvolcanic intrusions. This class encompasses many types distinguished by Cox and Singer (1986) and is problematic where parts of a district or single deposit are present in both volcanic and underlying sedimentary rocks, or where distinction between subvolcanic and small plutonic intrusive rocks is arbitrary. Aspects of volcanic structure have important geochemical and hydrologic consequences (Berger and Henley, 1989; Albino and Margolis, 1991) but will not be used in this classification. For geochemical emphasis, two mineralogical subclasses are utilized:

a. *Low base metal*—Characterized by low sulfide content; generally similar to hot-spring gold-silver deposits (model 25a, Cox and Singer, 1986) (Berger and Singer, 1992).

b. *High base metal.*—Characterized by several percent pyrite and base-metal sulfide minerals (chalcopyrite, galena, sphalerite) and silver-sulfosalt minerals; generally similar to base-metal-rich examples in the Creede-, Comstock-, or Sado-epithermal vein deposits of Cox and Singer (1986) (models 25b, 25c, 25d) (Mosier and others, 1986).

3. *Plutonic-associated deposits.*—In or near plutons or shallow stocks and dikes, sufficiently deep that contemporaneous volcanic rocks are not exposed. This class represents a diverse mix of deposits of many ages and compositions. Most of the deposits are in altered or contact-metamorphosed sedimentary rocks, especially limestone. The following subclasses are utilized:

a. *Polymetallic vein and replacement.*—Deposits in sedimentary rocks, in the vicinity of plutons but lacking obvious contact metamorphism (skarn). Silicification is characteristic alteration, but dolomitization may be unreported. This class is a generalized combination of models 19a and 22c of Cox and Singer (1986). Deposits of this type clearly grade into the skarn type (following) and probably into the volcanic-associated high-base-metal type.

b. *Skarn.*—Deposits near plutons in calcareous metasedimentary rocks that are altered to calc-silicate assemblages containing garnet, actinolite, diopside, or epidote. Some rare examples are endoskarns developed within the intrusive rocks, such as at Victory mine near Gabbs (Kleinhampl and Ziony, 1984), and are not considered here. Deposits have highly variable ore mineralogy and abundance of sulfide minerals, but molybdenite and scheelite are generally present. Deposits in the Tonopah quadrangle could be assigned to a range of models (models 14a, 18a, 18b, Cox and Singer, 1986; gold-skarn, Theodore and others, 1991). This class very clearly grades into others, especially the polymetallic replacement and distal-disseminated types.

4. *Metamorphic-associated deposits.*—Vein deposits in metamorphic rocks and probably related to regional metamorphism. Geology suggests that these deposits should be pre-Tertiary in age, but the age of individual deposits is not always known. Deposits of this class in the Tonopah quadrangle are not well understood but have some features in common with the low-sulfide gold-quartz vein (Mother Lode) deposits (model 36a, Cox and Singer, 1986). Metamorphosed strataform deposits, such as the massive sulfide type, have not been recognized in the Tonopah quadrangle. Reliable distinction of this class relative to some others is difficult where geologic relations are obscure, particularly in the western part of the quadrangle where there are several styles and ages of mineralization.

GEOCHEMICAL STUDIES

SAMPLING

All samples for this study are rock samples collected from natural or mine exposures or from dumps. The samples were collected during brief reconnaissance study of mines and prospects shown on topographic maps. Generally only a few hours were spent at a deposit or cluster of prospects, and no geologic mapping was done, although notes were taken on rock types, structure, and alteration. The field studies were reconnaissance in nature as part of an experiment to determine the efficacy of quickly collected geochemical information for regional resource assessment and exploration. Much more time could be profitably spent on all of the deposits and prospects visited, and I hope that others will carry on the work that is barely started here. I utilized a sampling style that emphasized content of iron oxide, sulfide, or alteration minerals in an attempt to enhance geochemical signatures. No attempt was made in these brief studies to collect unaltered rocks for the purpose of defining background concentration levels because preliminary results demonstrated good geochemical contrast of ore-related elements in mineralized samples relative to unmineralized samples. Also, none of the samples was collected in a manner that allows it to be used as an assay; that is, the samples were purposefully "high-graded." Insofar as possible, the same sampling method was used by one person (Nash) throughout the study area, but in some places suitable materials were very sparse, such as on dumps that had been carefully gone over by many visitors, and for those localities the material analyzed may be of lower tenor. Anyone using the data from this report should be aware that the samples probably are not reproducible, especially those yielding very high values, and also that a few samples are not a good representation of an entire deposit or of the time-space changes in composition within a deposit or district.

SAMPLE PREPARATION AND ANALYSIS

All samples were crushed and then pulverized between ceramic plates to attain a grain size smaller than 100-mesh (0.15 mm). All samples were analyzed for 31 elements using

Table 2. Limits of determination for the spectrographic analysis of rocks based on a 10-mg sample.

Element	Lower limit of determination	Upper limit of determination
Percent		
Calcium (Ca)	0.05	20
Iron (Fe)	0.05	20
Magnesium (Mg)	0.02	10
Titanium (Ti)	0.002	1
Parts per million		
Antimony (Sb)	100	10,000
Arsenic (As)	200	10,000
Barium (Ba)	20	5,000
Beryllium (Be)	1	1,000
Bismuth (Bi)	10	1,000
Boron (B)	10	2,000
Cadmium (Cd)	20	500
Chromium (Cr)	10	5,000
Cobalt (Co)	5	2,000
Copper (Cu)	5	20,000
Gold (Au)	10	500
Lanthanum (La)	20	1,000
Lead (Pb)	10	20,000
Manganese (Mn)	10	5,000
Molybdenum (Mo)	5	2,000
Nickel (Ni)	5	5,000
Niobium (Nb)	20	2,000
Scandium (Sc)	5	100
Silver (Ag)	0.5	5,000
Strontium (Sr)	100	5,000
Thorium (Th)	100	2,000
Tin (Sn)	10	1,000
Tungsten (W)	50	10,000
Vanadium (V)	10	10,000
Yttrium (Y)	10	2,000
Zinc (Zn)	200	10,000
Zirconium (Zr)	10	1,000

a semiquantitative, direct-current arc emission spectrographic method (Grimes and Marranzino, 1968). Limits of determination are summarized in table 2. Spectrographic results were obtained by visual comparison of spectra derived from the sample with spectra obtained standards made of pure oxides and carbonates. Standard concentrations

are geometrically spaced over any given order of magnitude of concentrations as follows: 100, 50, 20, 10, and so forth. Samples whose concentrations are estimated to fall between those values are assigned values of 70, 30, 15, and so forth. The precision of the method is approximately plus or minus one reporting unit at the 83 percent confidence level and plus or minus two reporting units at the 96 percent confidence level (Motooka and Grimes, 1976). Values determined for the major elements (Fe, Mg, Ca, and Ti) are reported in weight percent of the element; all other elements are reported in parts per million (micrograms per gram).

Most samples were also analyzed by a wet-chemical procedure for determination of elements of special interest or elements that have high limits of determination by emission spectrography (such as As, Sb, Zn, and Hg). The wet-chemical methods are summarized in table 3; most utilized atomic absorption spectrometry, but the method for mercury utilized an instrumental technique.

After completion of the analytical work, results were entered into a computer-based system called RASS (rock analysis storage system) that contains both analytical data and descriptive geologic and geographic information for each sample. Parts of the RASS data were retrieved under a slightly different format and manipulated using routines of the STATPAC system (Van Trump and Miesch, 1976). Analytical results for mineralized rock samples used in this study are given in Nash and Siems (1994).

Fluid inclusions in 30 samples were studied using doubly polished plates cut from transparent gangue minerals, chiefly quartz. Fluid inclusions greater than about 4 microns in diameter, and which were not harmed by postdepositional processes such as necking down, were run on a combination heating-freezing stage that uses nitrogen as the heating or cooling medium. The fluid-inclusion studies were made by Lanier Rowan and James Saunders of the U.S. Geological Survey in the laboratory of David Leach. The fluid-inclusion measurements are accurate to better than 1°C, much less than the spread in measurements between adjacent inclusions.

Table 3. Chemical methods used for analysis of rock samples from the Tonopah 1°×2° quadrangle, Nevada.
[Determination limit (in parts per million) is dependent on sample weight. Stated limits imply use of optimum sample weight; higher limits of determination result from use of smaller sample weights]

Element	Analytical method	Limit of determination	Reference
Antimony (Sb)	Atomic absorption	2.0	Modification of Viets (1978).
Arsenic (As)	Atomic absorption	5.0	Modification of Viets (1978).
Bismuth (Bi)	Atomic absorption	1.0	Modification of Viets (1978).
Cadmium (Cd)	Atomic absorption	0.1	Modification of Viets (1978).
Gold (Au)	Atomic absorption	0.05	Thompson and others, (1968).
Mercury (Hg)	Instrumental	0.02	Modification of Vaughn and McCarthy, (1964).
Tellurium (Te)	Atomic absorption	0.2	Modification of Hubert and Lakin (1972).
Thallium (Tl)	Atomic absorption	0.2	Modification of Hubert and Lakin (1972).
Zinc (Zn)	Atomic absorption	5.0	Modification of Viets (1978).

Table 4. Summary of geochemical data for selected sediment-hosted deposits, Tonopah 1°×2° quadrangle, Nevada.
[Deposits are shown in figure 1 or on plate 1 and are listed in table 1. Number in parentheses is number of samples. All values in parts per million except for Fe, which is in percent. G.M., geometric mean; Max., maximum value. Leader (—) indicates no data or not computed]

Element	Fandango (67)		Grantsville Ridge (21)		Green Monster (11)		Northumberland (35)		Wall Canyon (15)		White Caps (19)		All sediment hosted (217)	
	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.
Fe	1.2	>20	1.1	5	0.81	10	1.1	15	2.8	7	6.1	15	1.7	>20
Mn	82	>5,000	110	1,000	60	3,000	140	1,500	740	2,000	610	>5,000	160	>5,000
Ag	0.45	100	0.81	102,000	1.9	30	1.8	70	0.47	3	0.43	2.0	0.87	300
As	200	2,000	66	1,500	160	700	44	7,000	93	1,000	380	10,000	84	>10,000
Au	0.08	0.43	0.10	6	0.04	0.15	0.03	0.43	0.03	0.2	0.33	4.3	0.07	>20
Ba	320	>5,000	220	1,000	880	5,000	2,100	>5,000	270	1,000	130	3,000	344	>5,000
Cu	14	200	11	50	22	70	52	500	38	300	40	100	29	>10,000
Mo	10	150	8.1	70	7.9	30	13	100	4.2	20	18	300	10	300
Pb	16	1,500	14	50	10	30	14	50	27	500	14	30	18	10,000
Sb	45	700	260	2,000	3,120	>10,000	8.4	300	320	>10,000	9.2	200	46	>10,000
Zn	49	10,000	39	1,000	49	1,000	220	3,000	120	1,000	81	700	79	10,000
Hg	0.90	14	4.7	>20	0.80	16	0.64	11	0.13	0.52	1.6	21	1.0	>20
Te	—	—	—	—	0.12	0.60	0.22	8	—	—	—	—	3.6	>20
Tl	2.3	13	—	—	3.1	>15	0.81	5.5	0.32	0.70	—	—	1.7	>20

SEDIMENT-HOSTED DEPOSITS

Calcareous sedimentary rocks host precious-metal deposits in several districts in the Tonopah quadrangle, the most productive of which are Grantsville, Manhattan, and Northumberland. The discovery of rich, oxidized silver ores at Grantsville in 1863 produced the first "rush" in the Tonopah quadrangle. The polymetallic Grantsville deposits, probably related to a Cretaceous stock, are described in a following section. Other sediment-hosted deposits and prospects that show little direct association with igneous activity are described here. The discovery of the world-class gold deposit at Carlin in 1962 brought new attention to sediment-hosted gold deposits and a revival of exploration activity in the Tonopah quadrangle. The present study, which includes most of the known productive or prospective deposits in sedimentary rocks in the Tonopah quadrangle, indicates a range of host-rock character and geochemical signature, but common aspects include the presence of carbonate or impure carbonate rocks, silicification of those rocks, and enrichment in arsenic, antimony, and mercury (table 4); abundances of trace elements such as vanadium and chromium tend to be high in these altered rocks and can be utilized to discern the sedimentary heritage in places where that may be uncertain. Many deposits in sedimentary rocks are spatially associated with volcanic or subvolcanic rocks (as in the Tybo and Gilbert districts) or with plutonic rocks (such as in the Belmont district), and thus they are placed in those categories. Ores in sedimentary rocks clearly are diverse geochemically and geologically and the class boundaries gradational; thus some class assignments are arbitrary.

NORTHUMBERLAND MINE

Paleozoic impure carbonate rocks in the Toquima Range near the northern border of the quadrangle (fig. 1) host the Northumberland gold deposit. Silver was discovered at Northumberland Pass in 1866, and about $36,000 in silver was produced by 1891. Although gold was present, very little was produced (Kleinhampl and Ziony, 1984). In 1936 low-grade gold was discovered, and $1,146,000 in gold was produced from several open pits from 1939 to 1942 when the operation was closed due to World War II. During those years mostly oxidized ore was mined because it was free milling, whereas reduced ores rich in pyrite and arsenic minerals caused milling problems. In the mid-1970's the deposits were reevaluated for renewed bulk mining, and in 1981 Cyprus Mines Corporation began a new era of open-pit mining with about 3,000 tons (2,715 metric tons) per day processed by a heap-leaching operation.

The geology of the Northumberland gold deposits is complex (Kleinhampl and Ziony, 1984). Paleozoic limestone, carbonaceous shaly limestone, and siltstone are juxtaposed by at least four thrust faults, one of which (the Roberts

Mountains thrust fault) transported allocthonous western-facies carbonaceous rocks into the area. A Jurassic pluton intruded these rocks and produced some contact-metamorphic effects in the gold deposits. Cretaceous dikes also are common in the area. Finally, an Oligocene to Miocene volcanic caldron formed northwest of the deposits; the caldera margin, filled by spectacular megabreccias, is a few kilometers to the northwest of the deposits. The time (or times) of gold deposition has not been established but probably is either Cretaceous or middle Tertiary. Alteration associated with the gold consists of silicification, and the prominent iron oxides might be a primary feature, such as at Carlin (Radtke and others, 1980).

Geochemical results for Northumberland (table 4) include seven samples collected by A.R. Radtke from the old pits in 1973 and six samples collected along the County road about 1 km from the deposit. Other samples are from barite prospects 5 km southeast of the mine. The Northumberland samples are notably enriched relative to other deposits of the class in the elements Be, Ba, and Zn, whereas contents of Cu and Pb are low (table 4). Contents of As, Sb, and Hg are variable and, in places, very high. Molybdenum contents are actually higher than those of most of the volcanic-hosted deposits; these high abundances probably are related to carbonaceous shale.

WALL CANYON MINE

The Last Chance or Wall Canyon mine, about 70 km north of Tonopah in the Toiyabe Range (fig. 1), produced about 200 tons (181 metric tons) of antimony metal from stibnite ore between 1915 and 1953 (Kleinhampl and Ziony, 1984). Veins of milky bull quartz rich in stibnite are in dark carbonaceous shale or phyllite and minor interbedded limestone and chert of the Permian(?) Pablo Formation. Minor amounts of tetrahedrite and oxidized copper minerals are present with the stibnite. Wallrock alteration is chiefly silicification. Several thrust faults of different ages have been mapped within a few kilometers of the mine (Kleinhampl and Ziony, 1984), but the stibnite ores are probably much younger than the faults. Altered andesitic dikes are present near the mine, and Tertiary volcanic rocks cap nearby hills. Because of the known antimony at Wall Canyon and the general similarity of the host-rock lithology to that of some Carlin-type gold deposits, the mine area has been explored for disseminated gold deposits. I collected 15 samples within 1 km of the Wall mine, many of which contained visible stibnite or antimony oxide minerals. Not surprisingly, the samples are rich in Sb, but the only other enriched elements are Zn and As. Contents of Ag, Cu, Mo, and Pb (table 4) are relatively low for deposits of this class.

GREEN MONSTER CANYON AREA

Carbonate rocks on the east flank of the Monitor Range about 65 km north of U.S. Highway 6, 5 km south of Danville (fig. 1), contain a small antimony prospect and a zone of silicification (jasperoid) that extends for about 4 km. Altered rocks at Green Monster Canyon are thick-bedded gray limestone characteristic of eastern-facies Paleozoic platform carbonate rocks. The zone of jasperoid generally follows bedding but is influenced by cross faults and is generally more than 10 m thick. The silica is very fine grained and light colored but in places has boxwork textures, possibly molds of leached carbonate or barite, and sprays of stibnite crystals. A few areas contain some copper oxide minerals, but iron oxide minerals are generally sparse. The jasperoid zone has been drilled by several companies during the past 15 years, but no economically significant results have been reported. Eleven outcrop samples of the jasperoid, some containing visible stibnite, are highly enriched in Sb and moderately enriched in As; a few samples contain notable amounts of Ag, Zn, Hg, and Tl. The maximum contents of Ag and Au are 30 and 0.15 ppm, respectively (table 4). This is a large and interesting geochemical anomaly, but it probably contains submarginal amounts of precious metals, judging from these analyses and from failed exploration projects.

TITUS PROSPECT

A large area of silicified limestone is at the Titus prospect in the Pancake Range near Moores Station (fig. 1). Thick-bedded Paleozoic dolomite hosts stibnite veins in brecciated and silicified zones (Kleinhampl and Ziony, 1984). Interestingly, the carbonate rocks are in an isolated block surrounded by, or engulfed in, Tertiary volcanic rocks at the margin of the Hot Creek Valley caldron complex (Ekren and others, 1973). Silicification extends for hundred of meters beyond the stibnite veins. Seven samples from the Titus antimony prospect pits and nearby jasperoids are not very interesting geochemically other than those from the stibnite-bearing pits. Three samples containing stibnite have mean contents of 566 ppm As, 0.07 Au, and <0.5 ppm Ag and no other metals of notable concentration. Jasperoids in the area contain no metals of note other than 2,000 ppm Ba and 15 ppm Mo in one sample. More careful study and sampling of this interesting area of jasperoid at the caldera margin might locate more significant geochemical anomalies.

GRANTSVILLE RIDGE AREA

Yet another large area of jasperoid in carbonate rocks is south of Grantsville on Grantsville Ridge (fig. 1)

(Kleinhampl and Ziony, 1984). The silicification is chiefly along the Shoshone thrust fault that places Upper Triassic carbonate strata of the Luning Formation above younger Triassic and Jurassic carbonate rocks (Silberling, 1959). This zone of jasperoid may be related to some fluorspar deposits at the top of Grantsville Ridge. The fluorspar is in irregular veins as wide as a meter, has fine-grained mammillary texture, and is intergrown with chalcedonic quartz. The fluorspar deposits have the appearance of a hot-springs environment. Similar fluorspar deposits are in carbonate rocks along normal faults at the west edge of the Shoshone Range between Grantsville and Berlin. The fluorspar veins contain little of geochemical interest other than fluorine and about 10–20 ppm Mo, which is not surprising for a fluorine-rich system. No intrusive rocks are reported from Grantsville Ridge (Silberling, 1959).

Samples of jasperoid from the Shoshone thrust fault zone on the southwestern flank of Grantsville Ridge contain notably high contents of W and Hg, as well as As and Sb and some local concentrations of Au (to as much as 6 ppm). Contents of Ag, Cu, Pb, and Zn are generally low (table 4).

TETON PROSPECT

A substantial zone of silicification in carbonate rocks of the Luning Formation in the Cedar Mountains is enriched in arsenic and antimony but no other metals (Nash, Siems, and Hill, 1985) (pl. 1). This jasperoid zone, which I call Teton for the prominent peak, is probably favorable for Carlin-type gold and was drilled in 1982–83, but results were not sufficient to encourage further activity.

FANDANGO AREA

The largest area of jasperoid that I have seen in the Tonopah quadrangle is in a remote part of the Hot Creek Range known as Fandango, about 5 km northwest of Morey (fig. 1). At Fandango, an area about 4 km by 6 km, generally between Six Mile Canyon and Big Cow Canyon, consists of thrust slices of Paleozoic carbonate rocks that are pervasively silicified, particularly in thrust breccia zones (John and others, 1987). Iron oxide minerals, presumably formed from pyrite, are abundant in the siliceous zones. Geochemical sampling by industry has found widespread enrichment in arsenic, antimony, molybdenum, and mercury in the jasperoid (Robert Bennett, Lac Minerals, oral commun., 1984). Some samples of jasperoid collected from outcrop contain more than 1 ppm Au. Studies of this area by the U.S. Geological Survey confirm the abundance of volatile elements (Nash and others, 1986). Analyses of jasperoid (table 4) show enrichment in As, Sb, Hg, and Zn but low Cu and Pb. Molybdenum contents are as high as 70 ppm and average 9.2 ppm. The maximum Ag and Au contents are 1.5 and 0.1

ppm, respectively. Some locally high values for Fe, Pb, and Zn are in samples from one atypical vein-type prospect.

Other areas of jasperoid are in the Hot Creek Range just north of Hot Creek Canyon. Prominent outcrops of jasperoid are on the ridge between Wood Canyon and Hot Creek Canyon at about lat 38°32′30″ N., long 116°22′ W., in what probably is thick-bedded Paleozoic carbonate rock. I did not determine structural controls in this area. Several rotary drillholes have been drilled in these jasperoids during the past 15 or so years. Results for six samples of jasperoid show the following maximum contents: 137 ppm As, 53 ppm Sb, 2.6 ppm Hg, 53 ppm Zn, and 0.5 ppm Au. About 6 km north of Hot Creek Canyon, at about lat 38°34′06″ N., long 116°20′50″ W., just south of Water Canyon, similar Paleozoic carbonate rocks are thoroughly silicified. This light-colored jasperoid contains only minor geochemical enrichments; the maximum enrichment in an element of interest is 15 ppm As.

WHITE CAPS MINE

Limestone-hosted ores rich in arsenic, antimony, mercury, and gold at White Caps mine in the Manhattan district (fig. 1) are distinct from other ore in the district (Ferguson, 1924) but are of uncertain origin. Ferguson noted two periods of ore deposition in the district, one associated with Cretaceous granite plutonism and another with Tertiary volcanism. Deposits in Paleozoic limestone, best known at the White Caps mine, were believed to represent both stages of mineralization. Ferguson observed many features in these deposits that were later found to be important in Carlin-type gold deposits: ore is controlled by thrust and high-angle faults and is characterized by high amounts of arsenic, antimony, and mercury. However, the deposits really are not of the Carlin-type. Ore shipped in 1922 averaged 22 percent As and posed milling problems because gold could not be separated from the arsenic minerals realgar and orpiment. The silver content of the ores was low; the silver to gold ratio was about 0.05. Associated with the gold in limestone is coarse white calcite, fine-grained quartz, fluorite, sericite and another aluminous clay "leverrierite" (kaolinite), and rare adularia. Stibnite was barren of gold. Recent studies by Shawe (1988) confirm Ferguson's work and suggest the possible existence of a Cretaceous skarn-type gold-bearing deposit below White Caps and remobilization during the Miocene into White Caps-type deposits.

Geochemical analyses of White Caps samples, provided by D.R. Shawe, are summarized in table 4. The White Caps-type deposits at Manhattan are characterized by high contents of As, Ba, Mn, Sb, Zn, and Hg and a low silver to gold ratio.
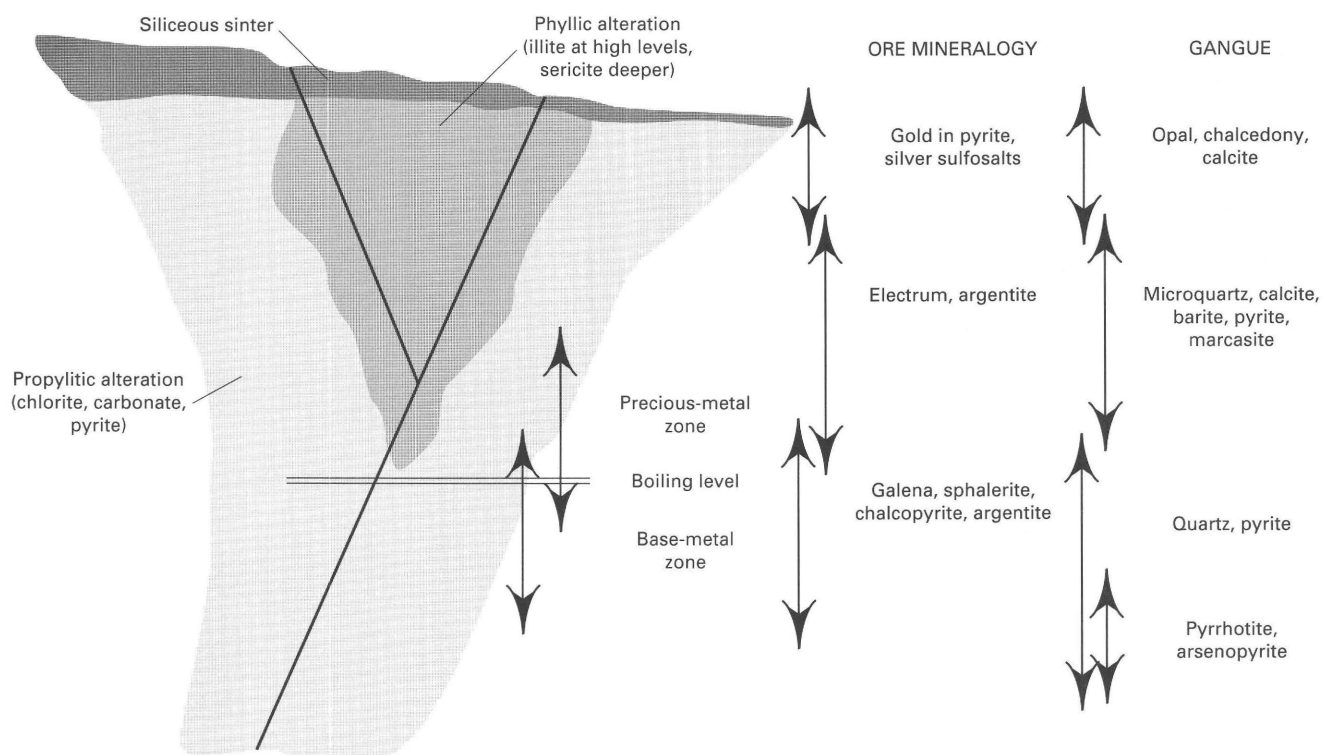
Figure 2. Schematic cross section showing an epithermal adularia-sericite-type silver-gold-base-metal vein system. Modified from Buchanan (1981) and Berger and Eimon (1983).

DEPOSITS ASSOCIATED WITH VOLCANIC ROCKS

Tertiary volcanic rocks are the most common host rocks for silver and gold deposits in the Tonopah quadrangle, and there is increasing evidence (chiefly through geochronologic studies) that many deposits in other host rocks are related to volcanic or subvolcanic processes. As pointed out by Ferguson (1929), the accidental discovery of silver-gold ore at Tonopah in 1900 produced many other discoveries in volcanic rocks as prospectors learned to recognize new features useful as guides to ore. Ferguson (1929) proposed two distinct periods of mineralization in Tertiary volcanic rocks, one of "pre-Esmeralda age, probably Miocene" and the other of "latest upper Miocene or earliest Pliocene age," and he further proposed that the deposits formed during the former period are silver rich, whereas those of the latter period are gold rich. Most of the deposits in volcanic rocks have characteristics of "epithermal" veins as proposed by Lindgren (1933) and more elegantly described by recently developed models of the chemistry and physics of shallow geothermal systems (for example, White, 1981; Heald and others, 1987; Berger and Henley, 1989). A schematic cross section (fig. 2) summarizes commonly observed mineralogical and alteration zones. Most of the deposits are associated with silicic

or argillic alteration, and many of the quartz veins contain some adularia. Most of the deposits in volcanic rocks are characterized mineralogically and geochemically by low contents of sulfide minerals and base metals (table 5), although some contain several percent sulfide minerals and are rich in base metals (hundreds or thousands of parts per million copper, lead, or zinc). In the following discussion, deposits (or districts) are grouped into those containing low and high amounts of visible sulfide or iron oxide minerals replacing sulfide minerals, visible features that are confirmed by chemical analyses. Many of the deposits having high base-metal content exhibit features of the polymetallic vein and replacement subclass, but known associated igneous rocks are volcanic or subvolcanic.

VOLCANIC-ASSOCIATED DEPOSITS HAVING LOW BASE-METAL CONTENT

ROUND MOUNTAIN DISTRICT

The Round Mountain district, a world-class gold-silver deposit, 75 km north of Tonopah (fig. 1), is currently the focus of a giant open-pit mine. Gold was discovered here in 1906, and about $11.5 million worth of ore was produced by 1953, much of which was from placer deposits (Kleinhampl

Table 5. Summary of geochemical data for selected volcanic-associated deposits, Tonopah 1°×2° quadrangle, Nevada.

[Deposits are shown in figure 1 or on plate 1 and are listed in table 1. Number in parentheses is number of samples. All values in parts per million except for Fe, which is in percent. G.M., geometric mean; Max., maximum value. Leader (—) indicates no data or not computed. Deposit types: L, low base metal; H, high base metal]

Element	Bellehelen (7) G.M	Max.	Black Rock (15) G.M	Max.	Clifford (5) G.M	Max.	Divide (85) G.M	Max.	Gilbert (27) G.M	Max.	Goldyke (7) G.M	Max.	Gold Hill (8) G.M	Max.	Hannapah (7) G.M	Max.
Fe	1.2	2	3.2	7	1.7	3.0	1.1	3.0	1.6	15	6.3	15	0.74	10	1.7	5
Mn	120	1,000	630	2,000	57	300	210	>5,000	450	5,000	180	700	65	300	120	2,000
Ag	104	1,000	2.1	10	150	1,000	15	1,500	9.5	100	2.3	70	9.7	150	20	200
As	130	700	620	10,000	740	1,500	36	220	130	700	130	200	160	1,600	490	5,000
Au	1.0	11	0.05	0.55	1.7	120	0.21	15	0.9	15	—	0.43	0.64	100	0.06	0.20
Ba	240	500	1,330	3,000	750	1,000	580	2,000	854	2,000	1,180	2,000	350	1,500	440	2,000
Cu	14	30	33	100	9.4	30	7.9	100	41	1,000	70	200	5.0	20	6.8	15
Mo	38	2,000	5.3	30	7.7	15	8.1	1,500	4.5	150	18	50	5.3	200	10	30
Pb	30	150	17	150	39	300	33	7,000	52	7,000	100	500	12	200	34	200
Sb	40	500	28	200	25	150	6.1	100	12	200	65	300	480	1,500	27	200
Zn	17	80	39	200	16	30	31	2,000	99	700	—	100	22	100	45	200
Hg	0.14	0.38	0.22	1.3	4	14	—	11	—	—	—	—	0.83	7.1	0.12	1.2
Te	—	—	1.1	>15	—	0.1	0.1	0.2	0.2	9	—	8.3	—	—	—	0.1
Tl	1.7	2.9	2.5	6.3	4.5	7	2.4	9.5	1.6	2.8	—	2.5	1.7	3.7	1.3	3.2
Deposit type	L		L		L		L		L		L		L		L	

Element	Hasbrouck (15) G.M	Max.	Manhattan (17) G.M	Max.	Marris (11) G.M	Max.	Nassau (8) G.M	Max.	Paradise Peak (15) G.M	Max.	Round Mountain (14) G.M	Max.	San Antone (9) G.M	Max.	Warrior (18) G.M	Max.
Fe	1.0	2	3.2	7	0.21	1	0.47	7	2.0	15	3.2	10	1.2	3	2.0	10
Mn	133	1,000	145	3,000	47	700	64	300	9.3	50	765	1,000	220	1,000	150	500
Ag	19	1,500	9.6	50	0.28	1	3.2	15	4.5	70	9.6	500	23	70	1.4	20
As	36	500	1,070	15,000	63	150	88	1,500	110	700	1,860	15,000	36	50	140	285
Au	0.86	15	0.7	13	0.05	0.14	0.04	0.15	0.36	31	0.6	15	3.0	50	0.13	15
Ba	900	2,000	130	3,000	600	1,500	290	500	1,670	>5,000	790	3,000	1,190	2,000	390	2,000
Cu	9.5	100	59	5,000	5.4	15	4.4	7	4.6	30	6.3	200	11	50	13	30
Mo	9.0	30	9	20	—	2.5	3.6	15	8.3	50	7.3	70	9.1	50	8.0	20
Pb	21	1,000	12	20	5.7	10	19	100	420	2,000	19	150	19	50	21	50
Sb	8.3	100	14	500	13	100	17	70	200	1,500	14	58	6.7	200	16	100
Zn	18	75	33	700	7.9	100	63	650	—	100	360	3,000	110	200	26	200
Hg	—	—	0.9	21	—	—	0.17	2.7	—	—	—	—	0.23	0.88	4.5	>30
Te	—	0.14	—	—	0.05	0.07	—	—	—	—	—	—	—	0.1	5.1	8.3
Tl	2.3	9.5	—	—	0.32	1.2	0.62	3.1	—	—	—	—	0.89	1.2	0.71	2.5
Deposit type	L		L		L		L		L		L		L		L	

Table 5. Summary of geochemical data for selected volcanic-associated deposits, Tonopah 1°×2° quadrangle, Nevada—Continued.

[Deposits are shown in figure 1 or on plate 1 and are listed in table 1. Number in parentheses is number of samples. All values in parts per million except for Fe, which is in percent. G.M., geometric mean; Max., maximum value. Leader (—) indicates no data or not computed. Deposit types: L, low base metal; H, high base metal]

Element	Monte Cristo (7) G.M	Max.	Ellendale (10) G.M.	Max.	Morey (15) G.M.	Max.	Reveille (14) G.M.	Max.	Tonopah[1] (36) G.M.	Max.	Tybo (70) G.M.	Max.	Simon (17) G.M.	Max.	All volcanic low base metal (279) G.M.	Max.	All volcanic high base metal (139) G.M.	Max.
Fe	2.8	7	3.1	15	3.3	15	3.7	>20	—	—	2.7	>20	8.4	20	1.5	20	2.8	>20
Mn	210	500	720	>5,000	3,650	>5,000	150	>5,000	1,360	14,000	960	>5,000	330	2,000	184	>5,000	530	>5,000
Ag	2.9	10	29.3	500	27	2,000	43	1,000	79	1,750	21	>5,000	9.6	300	7.5	1,500	19	>5,000
As	270	800	110	1,000	440	5,000	630	>10,000	18	348	150	>10,000	310	>10,000	89	>10,000	220	>10,000
Au	0.29	1.1	0.13	1.9	0.42	0.75	0.08	1.0	1.2	23	0.40	7	0.91	>30	0.22	>20	0.30	31
Ba	270	300	840	2,000	240	1,500	110	>5,000	1,150	6,800	180	>5,000	120	1,000	620	>5,000	320	>5,000
Cu	9.6	15	660	>10,000	54	3,000	230	5,000	20	181	57	>10,000	1,990	>10,000	15	>10,000	60	>10,000
Mo	3.6	30	13	300	5.8	30	10	150	4.5	18	5.4	100	6.2	70	7.2	2,000	6.8	300
Pb	14	20	1,220	>10,000	850	>20,000	1,800	>20,000	84	1,400	930	>20,000	130	>20,000	27	7,000	660	>10,000
Sb	53	150	88	10,000	230	>10,000	470	2,000	6.3	160	52	>10,000	100	140	16	10,000	90	>10,000
Zn	21	85	470	5,000	470	>10,000	590	>10,000	41	107	200	>10,000	260	3,000	32	3,000	240	>10,000
Hg	1.9	14	0.41	2.8	5.8	11.5	2.2	14	0.25	3.3	—	—	—	—	2.8	>20	5.0	>20
Te	—	—	—	—	6.8	8.3	0.84	21	—	—	—	—	—	—	0.34	>20	3.4	>20
Tl	2.1	5.6	0.57	1.3	1.7	2.4	2.0	8.8	—	—	2.4	12	—	—	1.7	9.5	2.0	17
Deposit type	L		H		H		H		H		H		H		L		H	

[1]Data from Bonham and Garside (1982).

and Ziony, 1984). East of the town of Round Mountain quartz-heubnerite veins (containing minor tetrahedrite) are in Cretaceous plutonic rocks, and 4 km south of Round Mountain Paleozoic shale and limestone host gold prospects of uncertain age and similar to Carlin-type deposits. Exploration during the 1970's below the historic bonanza veins at Round Mountain defined 10.9 million metric tons of ore averaging 2.1 g/t Au (12 million short tons at 0.062 oz/ton), which allowed the open-pit operation to open. Additional reserves of 159 million metric tons averaging 1.37 g/t Au (175 million tons averaging 0.04 oz/ton) were defined through 1986 (Sander, 1988). Most of the gold and silver is in Oligocene ash-flow tuffs, but some is in Paleozoic rocks. Adularia in the gold-quartz veins yields an age of 25 Ma, only about a million years younger than some of the host volcanic rocks. The deposits are thought to be localized along ring fractures of a caldron complex (Berger and Eimon, 1983) or to be related to extension-related northwest-striking oblique-slip faults and joints that probably predate caldera collapse (Mills and others, 1988). Flat-dipping fractures and hydrothermal breccia are reported to be important local ore controls. Fine-grained silica (some opaline sinter is at shallowest levels), hydromica, and adularia accompany the gold-silver ore. Bulk-mineable ore is somewhat different in character than the near-surface lodes mined earlier (Tingley and Berger, 1985) in that disseminated gold is on sheeted joints and bed-controlled zones of alteration (higher permeability) characterized by potassium feldspar-albite alteration of sanidine that predates silicification (Sander, 1988).

Geochemistry of various parts of the Round Mountain district has been described by Berger and others (Berger and Silberman, 1985; Tingley and Berger, 1985), by Shawe (1988), and by company-supported studies (Mills and others, 1988; Sander, 1988). Geochemical results from a detailed study of a large number of drill-core, mine, and surface samples (Berger and Silberman, 1985) show that Au and Ag are associated with As, Sb, Tl, and F and weakly associated with Mo, W, and Hg. Compared with data for other districts, the data of Berger and Silberman (1985) suggest much higher levels of Tl, but concentrations of other elements are generally similar to other volcanic-associated epithermal deposits characterized by low base-metal concentrations (Cu, Pb, and Zn contents each generally <100 ppm). Berger and Silberman (1985) concluded that pathfinder elements As, Sb, Tl, and Hg, as well as Mo and W, are anomalous in zones enriched in Ag and Au, and that Zn and Cu contents tend to be highest, along with Ag, in zones of manganese enrichment. Concentrations of As, Sb, Tl, and Hg are highest in the structurally high parts of the system. Molybdenum, Bi, and W are enriched above the bonanza veins but not in deeper zones, a common pattern in hot-springs deposits in high-silica volcanic systems (B.R. Berger, written commun., 1993).

Results are similar for samples collected by D.R. Shawe from vein outcrops and old mine workings, summarized in

table 5. These samples were selected because they contained unusual amounts of iron oxide or sulfide minerals (Shawe, oral commun., 1983), a collection technique generally similar to the one I used; thus, these data probably can be reliably compared with results of this study. The 14 samples collected by Shawe at Round Mountain feature relatively high concentrations of Ag, Au, As, Sb, Ba, and Zn, whereas Mn, Cu, Mo, and Pb are not notably concentrated except for a few samples. As a generalization, samples from the upper parts of the Round Mountain system are characterized by low base-metal content.

Mineralized rock exposed at the Gold Hill mine, about 7 km north of Round Mountain, probably is similar to that of the uppermost levels of the epithermal gold-silver system at Round Mountain (B.R. Berger, written commun., 1993). It is in highly silicified rhyolite ash-flow tuff and overlying lacustrine sedimentary rocks. Approximately $1 million in gold was produced from several parallel and branching veins between 1910 and 1941 (Kleinhampl and Ziony, 1984). Open cuts and glory holes provide good exposures of a breccia pipe, hydrothermal breccia, and veins filled by fine-grained, banded chalcedonic silica that have the appearance of very near surface vents. Horizontally layered silica sinter is exposed in a small downfaulted block west of the headframe. Eight samples collected in 1985 show relatively high concentrations of As and Sb (as much as 1,000 ppm and 1,500 ppm, respectively), some high values for Ag and Au (as much as 150 ppm and 63 ppm, respectively), and low concentrations of Fe, Cu (<20 ppm), Pb (<200 ppm), and Zn (<20 ppm). Most of the vein-filling material contains very little iron oxide minerals (after pyrite).

DIVIDE DISTRICT

Silver and gold deposits at Divide, 9 km south of Tonopah on the road to Goldfield (fig. 1), are in a setting very similar to that of the Tonopah deposits. Gold was discovered in 1902, but the real boom at Divide occurred in 1917 when silver-rich veins were encountered by accident in an underground crosscut headed to intercept gold veins. Production between 1911 and 1940 was more than 32,000 ounces (1.1 metric tons) of gold and 2 million ounces (68 metric tons) of silver (Bonham and Garside, 1979). An open-pit mining operation at the site of the former Tonopah Divide mine produced a modest amount of silver and gold in 1982–1984. Geology of the district is much like that of the Tonopah district to the north, but here the Oddie Rhyolite (dome) is the center of mineralization (rather than post-ore at Tonopah), and K/Ar dates of adularia and mica indicate an age of 16.0±0.4 Ma, about 3 m.y. younger than the ores at Tonopah (Bonham and Garside, 1979). Volcanic rocks are argillized and silicified over a broad area, and silicification is particularly intense in silver-gold zones. Silica sinter formed as a hot-spring discharge at the surface at the top of

Hasbrouck Mountain, a useful datum for establishing the shallow level of vein emplacement in the Divide district. The geology of the district is described in detail by Knopf (1921) and Bonham and Garside (1979, 1982), and additional observations and data for 109 samples of ore and altered rocks are reported by Nash, Siems, and Budge (1985a).

Three mineralogical types of ore have been mined in the Divide district (Bonham and Garside, 1979): (1) gold-rich veins of simple mineralogy (pyrite, electrum, minor silver-bearing sulfide minerals, and rare base-metal sulfide minerals); (2) silver-rich lodes (yielding most production) containing sphalerite, argentiferous galena, chalcopyrite, molybdenite, tetrahedrite, and probably other silver-antimony-arsenic sulfosalts; and (3) oxidized silver-rich ores, derived from the silver-rich lodes, containing cerargyrite and other silver halide minerals and notable high amounts of the oxidized molybdenum minerals ferrimolybdite and powellite.

The Hasbrouck Mountain deposit, on the west side of the district, is a prototype, very shallow level, hot-springs deposit associated with abundant silica alteration, layered siliceous sinter, and hydrothermal breccias (Graney, 1987). Early mining at Hasbrouck was in silver-rich veins. Adularia from the disseminated gold-silver zone indicates an age of 16.3 Ma for the mineralization, whereas illite from a gold-breccia yields an age of 15.8 Ma. There is excellent structural, and perhaps K/Ar, evidence for multiple stages of alteration and gold-silver deposition. The subeconomic resource is about 5 million tons (4.5 million metric tons) of rock averaging 0.04 oz/ton (1.4 g/t) Au and 0.7 oz/ton (24 g/t) Ag (Graney, 1987).

Geochemistry of rock samples from the Divide district is summarized in table 5. Relative to most other districts or deposits of the volcanic class, Mn, Ag, and Mo contents are generally high, whereas Fe and Cu contents are low; As, B, Ba, Pb, Sb, Zn, Au, and Tl are rich in some samples. Bismuth and W are rich in a few samples, but data for these elements are not complete. Mercury was not determined, but Bonham and Garside (1982) reported anomalous values of Hg greater than 1 ppm in zones above silver-gold ore; Hg is displaced from the precious-metal zones and does not correlate with Ag, Au, or other metals. Some general zoning trends were observed (Nash, Siems, and Budge, 1985a), although a high sample density is required to document zoning in detail. A zone of molybdenum enrichment in quartz-molybdenite veinlets is at the margin of the rhyolite dome, generally in the rhyolite; this zone does not contain much gold. Near the rhyolite contact on Gold Mountain is a zone of gold-dominant mineralized rock in which Au is associated with Ag, Cu, Pb, As, and Sb and Ag shows similar associations. In samples from the silver-rich silver-gold zone of veins lower on Gold Mountain, and probably deeper under Hasbrouck Mountain, Au is associated with Mo, As, and Sb, whereas Ag is associated with Cu and Sb. The shallowest alteration and silver-gold deposition in the district, Hasbrouck Mountain, is characterized by very low Fe, Cu, Pb, and Zn contents (table 5)

and locally high As, Sb, Bi, and W contents. Geochemical studies of drillhole cuttings (Berger and Silberman, 1985) show that As, Sb, Hg, and Tl are associated with Ag and Au in the central part of the Hasbrouck system and that the concentrations of these elements decrease downward at 30–50 m depth in drillholes.

In the Divide district, silver and gold behave quite independently, unlike the nearby Tonopah district where silver and gold probably are systematically related. Supergene processes at Divide may contribute to the separation of silver and gold, but there probably were primary differences in silver and gold behavior, such as formation at different stages. Molybdenum is more prominent in the Divide deposits than in any other volcanic-associated system in the Tonopah quadrangle; contents are as high as 0.77 percent in upper levels of the Tonopah Divide mine, perhaps reflecting supergene enrichment. In places molybdenum is highly associated with silver and gold, but in other places it is not. Molybdenum enrichment in the Divide district may be analogous to that at Round Mountain, previously described, or may be a different stage relative to gold in the system. A contrasting view (Bonham and Garside, 1979) is that the high base-metal and molybdenum contents reflect an undiscovered porphyry-type molybdenum-copper deposit 1–2 km below the district.

MANHATTAN DISTRICT

The most productive of several environments in the Manhattan district that produced gold-silver ores (Ferguson, 1924) is that of "shallow vein deposits in Cambrian(?) schist." The Manhattan district (fig. 1) also had large production from placer deposits, Cretaceous quartz-sulfide veins, and Cretaceous (or reworked in the Tertiary according to Shawe, 1988) limestone-hosted arsenic-antimony-gold deposits at White Caps. The excellent work of Ferguson (1924) has been supplemented by the more recent studies of D.R. Shawe (1988). The Gold Hill Formation of Cambrian age is the host for many deposits of two types distinguished by Ferguson; some deposits have distinct veinlets of quartz with free gold and, in places, adularia, whereas other deposits are broad zones of low-grade gold having gradational assay boundaries. Adularia from a gold vein in schist yielded a K/Ar age of 16 Ma (Shawe, 1988) that confirms Ferguson's astute observations and inference of a Tertiary age for these deposits. On the basis of age equivalence to volcanic rocks, and the comb quartz-adularia-gold association, I include these deposits in the "volcanic-associated" class. Silver to gold ratios average 0.4 in the schist ores, but nearby deposits in Tertiary rocks contain much more silver and have a silver to gold ratio of about 10. In the mid-1980's two open-pit mines produced gold from deposits in schist (Maddry, 1987); the orebodies were 3.5 million tons (3.1 million metric tons) at 0.036 oz/ton (1.2 g/t) and 2.5 million tons (2.3 million metric tons) at 0.08 oz/ton (2.7 g/t) gold.

The mostly oxidized (weathered) nature of the ore zones possibly explains the presence of coarse gold in fractures.

A general geochemical description of the schist-hosted gold deposits of the Manhattan district is provided by data for 17 samples (table 5) (D.R. Shawe, written commun., 1983; Shawe, 1988). The schist ores are rich in Au, As, and Zn and locally rich in Mn, Cu, Pb, Sb, and Hg. Silver content is relatively low (mean 9.6 ppm) relative to other metals in these samples. Based on careful geologic studies, Shawe (1988) distinguished a low base-metal (Cu-Pb-Zn-As-Sb) signature for the Tertiary gold-rich deposits, in contrast to a Cu-Pb-Zn-Ag signature for Cretaceous veins and an As-Sb-Hg signature for deposits at White Caps.

An interesting area of intensely silicified Tertiary tuff is about 10 km east of Manhattan near the road to Belmont, the site of the Marris pebble mine. The fine-grained siliceous rock was mined for grinding pebbles that were used in the mills at Manhattan, Tonopah, and Goldfield (Ferguson, 1924). The pebbles were known to contain a small amount of gold, worth "not over $2 to the ton" in 1920. The dense silicification has the appearance of a possible siliceous sinter outflow apron from a hot-spring system. I collected 11 samples from the old Marris workings and from some outcrops on the ridge to the west, none of which contained much visible pyrite or limonite. The base-metal contents are very low, but As and Sb are slightly enriched (table 5). Mean values are 0.21 percent Fe, 5.4 ppm Cu, 5.7 ppm Pb, 7.9 ppm Zn, 63 ppm As, and 13 ppm Sb. Six samples contained 0.05–0.14 ppm Au and <1 ppm Ag.

SAN ANTONE DISTRICT

The San Antone district north of Tonopah in the San Antonio Mountains contains several types of precious-metal deposits. The district also contains some large base-metal deposits, including the Hall molybdenum-copper porphyry deposit, associated with 70–66-Ma quartz monzonite stocks (Shaver, 1991). Oxidized parts of lead-rich polymetallic deposits associated with the stocks yielded more than $600,000 in silver from the Liberty and Hall mines, chiefly between 1867 and 1872 and between 1910 and 1912 (Kleinhampl and Ziony, 1984). The primary polymetallic ores, not well described in the old literature, contained galena, pyrite, argentite, tetrahedrite, and presumably other copper-lead-zinc-silver sulfide and sulfosalt minerals. These vein systems were engulfed by the Hall open-pit mining operation and were not studied by me.

The Cimarron camp (San Antone, fig. 1) a few kilometers northeast of the Liberty and Hall mines produced about $15,000 in gold-silver ore in the period 1937–1940 (Kleinhampl and Ziony, 1984). Here several quartz veins are in Tertiary welded tuff adjacent to a dacite porphyry plug (17? Ma) that has vertical flow banding. Although the plug is not silicic, the physical setting is reminiscent of the Divide district. Pyrite or iron oxides after pyrite are sparse, and no

base-metal sulfide minerals were observed. The tuff is silicified and argillized along the quartz veins. Reported silver to gold ratios range from 0.7 to 8. Nine samples, mostly rich in vein quartz, have some very high Au content, high Ba content, and locally high Ag, B, As, and Sb contents. Contents of Cu, Mo, Pb, Zn, As, and Sb are generally low relative to other volcanic-associated deposits. This area probably is a low-sulfur, low-base-metal system.

HANNAPAH DISTRICT

At the south end of the Monitor Range, about 25 km east of Tonopah (fig. 1), a cluster of mines produced a moderate amount of silver and gold from veins in Tertiary welded tuffs. The total production from 1902 to 1935 was about $330,000 (Kleinhampl and Ziony, 1984). Dumps and sparse outcrops show highly argillized and pyritized tuff containing thin veinlets of quartz. Silver is reported to be present chiefly as the sulfantimonide mineral polybasite and as silver halide minerals in the oxidized zone. Gold content is as much as 1.0 oz/ton (34 g/t) and silver as much as 35 oz/ton (1,200 g/t). The deposits are in a major northwest-trending fault zone in silicic tuffs that are in fault contact with younger tuffs dated at 21.6 Ma, but the age of the ore has not been established (Kleinhampl and Ziony, 1984). Rhyolite domes and dikes are present in the district. Although outcrops in this district are not good, I was impressed with the pervasive zone of pyritized tuff (now expressed as iron oxides) and argillic alteration, a zone measuring about 2 km wide by 6 km long. I collected seven samples that emphasize content of pyrite (or iron oxides) and quartz veining. The samples are enriched in Mn, Ag, As, Ba, Sb, and Zn relative to most deposits of this class (table 5). Contents of Cu, Mo, Pb, and Hg are normal or lower than normal for this class; that is, they are not enriched very much.

LONGSTREET AREA

A small group of workings in Longstreet Canyon, about 30 km northeast of Hannapah in the Monitor Range (fig. 1), had a small amount of silver and gold production, probably less than $25,000 (Kleinhampl and Ziony, 1984). The vein deposits are in the tuff of Big Ten Peak (Oligocene?), a thick nonwelded ash-flow tuff within the Big Ten Peak caldera complex (Keith, 1987).

My brief examination of the poorly exposed veins leads me to agree with the description by Kral (1951): "The ore contains Au and silver associated with pyrite and very little quartz* * *The vein is said to average $10 per ton across a 4½ foot width" ($9 per metric ton over 1.4 m). The silver to gold ratio is high, almost 1. In three dump samples, nondescript other than their high content of clay and pyrite, the contents of Ba, Sb, Hg, and Tl are relatively high, and in two

samples the amounts of Ag, As, and Mo are notable; the contents of Cu, Pb, and Zn are low.

BELLEHELEN AND CLIFFORD AREAS

These camps in the Kawich Range (fig. 1) produced chiefly silver from oxidized zones of veins in Tertiary ash-flow tuffs (Kral, 1951; Kleinhampl and Ziony, 1984). A cluster of shafts at Clifford produced as much as $500,000 between 1906 and 1946, and scattered mines at Bellehelen produced at least $216,000 and possibly as much as $500,000 between 1906 and 1935. At both camps workings were chiefly in near-surface zones containing limonite and cerargyrite and electrum, but at depths below about 70 m a few workings encountered sulfide minerals. The deeper ores at Clifford were observed by Ferguson (1917), who reported pyrite and the silver-antimony-sulfur minerals stephanite, pyrargyrite, and proustite. Free gold (electrum) could be panned from the richer ore on the 200-foot level of the Clifford mine. Ore produced in 1930 at Clifford, probably in part from the sulfide zone, averaged 2 oz/ton (69 g/t) Au and 4 oz/ton (137 g/t) Ag (Kral, 1951), but at Bellehelen the ore was chiefly silver and the silver to gold ratio was about 100.

Five samples collected from Clifford were selected as being rich in vein quartz and former pyrite. These samples are rich in Ag, As, Ba, and Sb and very rich in Au (table 5). Contents of Cu, Mo, Pb, and Zn are low.

Seven samples from Bellehelen were selected for their content of vein quartz and iron oxide (but iron oxides are sparse in this district). The Bellehelen samples are rich in Mn, Ag, As, and Mo, and a few samples contain notable amounts of Au (table 5). Contents of Fe, Mn, Cu, Pb, and Zn are low.

GILBERT DISTRICT

West of Tonopah about 45 km, in the Monte Cristo Range (fig. 1), several small mines produced about $105,000, chiefly in gold, during a brief burst of activity in the 1920's (Albers and Stewart, 1972). Despite the relatively small production, the geology and ore deposits of the Gilbert district have some interesting features in common with more productive districts such as Divide and Tonopah (Nash, Siems, and Budge, 1985b). Two types of ore were mined (Ferguson, 1928): gold-silver ore from veins in Tertiary volcanic rocks and adjacent pre-Tertiary rocks and silver-lead ore from supergene-enriched base-metal deposits in skarnlike deposits adjacent to a Jurassic stock. In this section I discuss only the Tertiary ore, dated at 7.9 Ma by K/Ar of vein adularia. Gold is present as native gold, and silver is present as argentite, pyrargyrite, and cerargyrite. The chief alteration near ore is abundant silica, both as vug-filling crystals and as fine-grained banded chalcedony. Twenty-seven samples of mineralized rock and veins from Tertiary rocks near the Gilbert townsite (Nash, Siems, and Budge,

1985b) (table 5) are rich in Mn, Ag, As, Ba, Cu, Pb, Sr, Zn, and Te; some samples contain more than 50 ppm Bi (not all samples were analyzed by the atomic absorption method, and the data for Bi are not complete). The high content of Bi is unusual among this class of deposits.

The Tertiary veins continue on strike into the Ordovician Palmetto Formation at Gilbert, as well as into similar deposits in metasedimentary rocks at South Gilbert. The composition of mineralized samples from Palmetto host rocks is generally similar to that of Tertiary rocks, although As, B, and Sb contents are possibly higher in the metasedimentary-hosted deposits.

BLACK ROCK PROSPECT

An interesting prospect near Black Rock on the south flank of the Monte Cristo Range, about 35 km west of Tonopah (fig. 1), is at the contact of Tertiary welded tuff and the underlying Palmetto Formation. A shaft is shown on the topographic map but, to my knowledge, is not described in the literature. Exploration in the early 1980's consisting of trenching and drilling some rotary holes has tested the property for a bulk-mineable deposit. The geology is similar to that of the Gilbert district, although the stratigraphy of the tuffs is not known and no rhyolite dike or domes were seen near Black Rock. Mineralized rock is in two units: carbonaceous shaly limestone of the Palmetto Formation (as at the prominent Black Rock by U.S. Highway 95), which also contains anomalous amounts of gold, and overlying welded tuffs. The Palmetto is probably silicified, but there is not much visible alteration in these dark rocks. The tuffs show intense white argillic alteration (possibly with some alunite, although not confirmed in the laboratory) and quartz veining and a superimposed brick-red alteration that probably reflects oxidation of pyrite. Fifteen samples were collected from the area of the prospect, many of which were chip samples of altered rock but not with prominent veining that could be used to high grade the sample as was normally done in this reconnaissance; I suspect that the magnitude of chemical enrichments in this suite of samples is not as great as in other deposits because the samples were not taken selectively. The 15 samples (table 5) are relatively rich in Mn, As, B, Ba, Sb, V, and Tl, and some samples are rich in W, Hg, and Te. Contents of Cu, Mo, and Pb are low, but the content of Fe is high. The red hematitic alteration, which may be controlled by a zone of open breccia along faults striking N. 50° W., is enriched in Au, Ag, and As.

ATHENS DISTRICT

Tertiary volcanic rocks on the flanks of the Cedar Mountains and Paradise Range contain several small deposits considered to be in the Athens district. I collected samples from the Warrior and Pactolus mine areas (fig. 1). Several small mines in the Athens district produced a total of

about $72,000 from silver-gold deposits (Kral, 1951; Kleinhampl and Ziony, 1984). The largest mine was the Warrior, which worked chiefly gold in quartz veins. The host rock is argillized and pyritized welded tuff. Quartz-vein material on the Warrior dumps is more massive and thicker than in most deposits of the epithermal class. A dark sulfide mineral, probably galena, was found in some fragments on the Warrior dump, but no other sulfide minerals or copper oxides were evident. Seven kilometers north of the Warrior mine are some small workings called Pactolus. Volcanic rocks at Pactolus are generally similar to those at the Warrior mine and contain fairly intense pyritic-argillic alteration, as well as comb-quartz veins.

Fifteen samples from the Warrior mine and prospects on the hill to the south (table 5) are relatively rich in As and Sb, but other metal contents are not remarkable in comparison with other deposits of this class. Warrior mine is a good example of a deposit that has low base-metal content (Nash, Siems, and Hill, 1985). Results for four samples from Pactolus are similar in their low contents of Cu, Mo, Pb, and Zn; however, the samples show substantial enrichment in Ag, As, and Ba.

OMCO MINE

The Olympic, or OMCO mine, is about 5 km west of the Warrior mine (fig. 1) in generally similar Tertiary rhyolite and trachyte flow rocks lying below lake beds lithologically similar to those of the Esmeralda Formation (Knopf, 1922). The deposit is described as a quartz vein 1–2 m thick that contains no visible gold or other metallic minerals. The vein has an odd bowl-like shape, concave upward, that is thought to be a primary feature rather than produced by faulting or folding (Knopf, 1922). The host rock is silicified and argillized near the vein. Although no ore minerals could be seen, Knopf reasoned that the ore mineral was electrum rich in silver because the bullion was 500 fine. Production was about $700,000, chiefly in the first few years of operation (Knopf, 1922), but greater productivity was hindered by a fire in 1920 and by caving caused by the local earthquake of 1932. Discovery was in 1915, and most production was between 1917 and the early 1920's.

Four samples from dumps at the OMCO mine contain sparse iron oxide minerals and some vein quartz. Barium contents are relatively high, and one sample contains 15 ppm Ag, but most elements are present in low concentrations . No atomic absorption analyses were made for elements such as Au, As, Sb, and Tl. Based on Knopf's description, and these limited geochemical data, the OMCO deposit probably is an epithermal-type deposit that has low content of base metals.

GOLDYKE DISTRICT

The Goldyke or Fairplay district, in the northwest part of the Tonopah quadrangle (fig. 1), contains a variety of

small mines that produced small amounts of precious metals, mercury, and tungsten (Kral, 1951; Kleinhampl and Ziony, 1984). The western part of the district includes some mines that worked gold veins in weakly metamorphosed Mesozoic greenstone; these are discussed in a later section. Vein and skarn deposits of base metals, silver, and tungsten are associated with Cretaceous stocks in the northern part of the district. Tertiary volcanic rocks contain some small gold-silver deposits at Goldyke, which were mined from about 1906 through the 1920's. Gold was the major metal of interest and was recovered from oxidized parts of quartz-pyrite veins, some near rhyolite domes. Seven samples from small mine dumps and prospect pits a few kilometers east of downtown Goldyke (table 5) are generally enriched in Ba and show scattered enrichment in Mn, Ag, B, Bi, Cu, Mo, Pb, Sb, W, and Zn. The local concentrations of Bi and W are unusual for this group of deposits characterized by low content of base metals but are also present in the Divide district.

RETURN MINE

Deposits of several types are in the Ellsworth district, at the north end of the Paradise Range (fig. 1). Several of the deposits, such as the Return mine, are in Tertiary volcanic rocks (John, 1992) and are compositionally distinct from deposits of probable Cretaceous age. Brief descriptions of deposits by Kral (1951) indicate that gold and silver were the main commodities sought in the Ellsworth district, along with some leac-zinc-copper and tungsten, but recorded production from all deposits was small ($37,000 minimum estimate). Deposits are in Permian(?) greenstone, limestone, Cretaceous granite, and Tertiary volcanic rocks. The Return mine, about 4 km west of Ellsworth, probably is one of the larger mines and has substantial dumps, although no production is recorded. Kral (1951, p. 112) described the Return deposit as "principally silver minerals, auriferous pyrite, and tetrahedrite in quartz stringers. Sheared rhyolitic dykes (sic) cutting Triassic(?) meta-volcanics appear to be the favorable ore zones." The Return mine (headframe) is in a valley with poor exposures, but all nearby exposures are argillized welded tuff. Greenstone is exposed about 1 km to the north, probably across a normal fault, and no rock resembling the greenstone is apparent on the dumps. The dumps contain highly argillized tuff that has abundant small comb-quartz veinlets. Iron oxide minerals are sparse, but yellow colors suggestive of sulfate minerals derived from pyrite are fairly abundant. The quartz veinlets and alteration, and the general setting, are reminiscent of the Hannapah district. Data for three carefully picked samples rich in vein quartz indicate the following mean contents for some elements of interest: 69 ppm Ag, 0.4 ppm Au, 600 ppm As, 76 ppm Pb, and 103 ppm Sb. Contents of Bi, Cu, Mo, and Zn are low. The Return deposit fits the general pattern of low-sulfur, low-base-metal, epithermal silver-gold deposits in volcanic host rocks.

PARADISE PEAK MINE

This deposit, 14 km south of Gabbs (fig. 1), was discovered in 1982 by the FMC Corporation and developed into a major open-pit mine by 1985 (John and others, 1991). The deposit was found adjacent to an old mercury mine, under a small hill capped by silicified tuff. The silicified ledges are somewhat brecciated and recemented by fine silica, and some tuff beds are highly altered to white clay and alunite. These alteration zones were trenched some years ago but not recognized as being part of a gold system. I visited the discovery hill briefly in 1983, a short time after the discovery, and collected 16 samples of exposed altered rocks. My strongest impression was that the hill was not particularly unusual in color, form, or alteration. The silicification was more subtle than at hundreds of other places in the Tonopah quadrangle, although the white alteration on the south side of the hill was distinctive to someone with an eye for advanced argillic alteration containing alunite. Orange and red colors from iron oxide minerals were not well developed, which may explain why the property was not discovered sooner.

The geochemical signature, alteration, and ore mineralogy at Paradise Peak are essentially unique in the area, although there are some similarities to the ores at Goldfield (Ashley, 1990). In many ways Paradise Peak should be in a deposit class by itself, but it is included here for convenience. Fifteen samples from outcrop at the top of the FMC deposit are generally enriched in Au, Ba, Bi, Pb, and Sb, and many are enriched locally in Ag, As, Mo, Sn, W, Hg, Te, and Tl (table 5). Contents of Mn and Cu are notably low, especially as compared to Goldfield (alunite)-type deposits. Some of the enrichments in Ba, Bi, Sn, Hg, Te, and Tl are among the highest found in this reconnaissance of precious-metal deposits, yet the samples were not taken in a way that would have caused additional high-grading; if anything, samples from the FMC deposit are more representative chip samples than in many places where dumps and cuts were carefully scrutinized to obtain the richest possible samples. The exposed rocks are very strongly anomalous in many metals. Petrographic study of five thin sections confirms the complete silicification of tuff by multiple stages of very fine grained quartz and chalcedony, as well as the presence of barite. Thin sections also show some intense alteration to be predominantly very fine grained jarosite and lesser light-colored alunite and fine-grained quartz. The sulfate minerals are confirmed by chemical analyses that show as much as 10 weight percent total S in rocks that contain no visible sulfide minerals; the mean content of S in these 15 samples is 4.1 weight percent.

Detailed descriptions of the host rock, structure, hydrothermal alteration, and mineralization at the Paradise Peak open-pit mine are given by John and others (1991). Some of the more distinctive features described are multistage breccias and pervasive hydrothermal leaching associated with alunite alteration. Geochemically, the ore-zone breccias are

unusually rich in Bi (higher than As!), as well as Ag, Au, Ba, Hg, and Sb. Alunite-jarosite-altered rocks are enriched in lead. Deposition of mercury probably followed that of silver and gold. Gold is present as native gold, but silver as cerargyrite and embolite (AgCl-Br) is much more abundant than gold.

The classification of Paradise Peak is much debated. The leaching, powdery silica, and alunite resemble acid sulfate-type deposits at Summitville, Colorado and Goldfield, Nevada (Heald and others, 1987), but other mineralogical features are suggestive of a low-temperature hot-spring deposit (John and others, 1991). Mineralogically and chemically, Paradise Peak is very distinctive in the Tonopah region.

OTHER PROSPECTS

Prospects in silicified volcanic rocks were sampled at several localities in the quadrangle. These prospects are similar in their low contents of visible pyrite or iron oxide minerals after pyrite and their notable fine-grained silica alteration or sinter that may be a near-surface part of a hot-spring system. At the Nassau prospect in the Antelope Range, south of U.S. Highway 6 and about 30 km east of Tonopah, there has been no mining. A large area of silicified tuffs is well exposed, and in places there are horizontally bedded siliceous rocks, probably sinter terrace deposits. Samples of the siliceous alteration and sinter have low base-metal contents, but some As, Sb, and Zn values are high (table 5). Three outcrop samples contain 0.05–0.15 ppm Au. This geochemical signature is very similar to that of the Marris silica-pebble prospect described earlier.

Bedded Tertiary volcaniclastic rocks on the southwestern flank of the Monte Cristo Range are silicified in a large area that was prospected in the early 1980's for bulk-mineable deposits. Seven samples of siliceous alteration, each containing as much limonite as could be selected, have low base-metal contents but are enriched in As, Hg, and Tl (table 5). Outcrop samples have a mean content of 0.29 ppm Au and a high of 1.1 ppm.

VOLCANIC-ASSOCIATED DEPOSITS HAVING HIGH BASE-METAL CONTENT

TONOPAH DISTRICT

The Tonopah district was one of the great precious-metal districts in the United States and had production of about $147 million in silver and gold from 1900 to 1940 (Kleinhampl and Ziony, 1984). Since 1940 there has been minor production and only brief periods of exploration. The deposits were described well by Nolan (1935), which is fortunate because the workings are no longer accessible, a great obstacle to some recent studies (Bonham and Garside,

1979; Kleinhampl and Ziony, 1984). I rely on the work of others to describe Tonopah. Precious-metal veins are chiefly in the 20-Ma Mizpah Trachyte (andesite). Numerous prominent domes and plugs of dacite and rhyolite in the district yielded ages near 16 Ma, and some of these are known to cut ore. Adularia from a silver-gold vein yielded an age of 19.1 Ma (Silberman and others, 1979). The geometry of veins is unusual and remarkable. Individual veins are as wide as 12 m, and the metal values decrease outward into replaced wallrock. The overall geometry of veins in the district is that of a flat bowl or dome having dimensions about 4.5 km by 1.5 km and a productive zone about 100–300 m thick (Nolan, 1935). Silver to gold ratios change systematically from 78 in the center of the district to 111 on the western fringe. Alteration assemblages along the veins are zoned from an inner potassic zone (quartz, sericite, adularia), a middle argillic zone (quartz, sericite, kaolinite), to an outer and pervasive propylitic zone (chlorite in iron-magnesium silicate minerals). The geometry of the ore shell, the unusual faults that have flat dip, and the mineralogy led Nolan to propose doming and ore formation above a buried intrusive body. The chief silver-gold ore minerals were electrum (silver-rich native gold), argentite, and several silver-arsenic-antimony minerals; silver halide minerals and native silver were abundant in the oxidized zone. Sphalerite, galena, and chalcopyrite were reported as abundant, and there was a stage of quartz-heubnerite ($MnWO_4$). Gangue minerals included manganese-rich calcite, barite, albite, and the alteration minerals noted above. Fahley (1979) described fluid-inclusion evidence in ore-stage quartz for temperatures of about 230°C–260°C and multiple periods of boiling. There was some supergene modification of the Tonopah ores but not as much or as economically important as in most districts of the region.

The Tonopah district is included in the high-base-metal subgroup on the basis of reported abundant sphalerite, galena, and chalcopyrite (Bastin and Laney, 1918), but this classification is not obvious in the geochemical data from Bonham and Garside (1982) (table 5). Judging from descriptions of sampling methods and of samples (Bonham and Garside, 1982), their results are lower than would be obtained by my sampling method because they included more altered wallrock. These results show high contents of Ag, Mn, and Ba, moderate contents of Au, Sb, Pb, and Zn, and low content of Cu, expressed qualitatively in relation to compositions of mineralized rocks from other silver-gold deposits in volcanic rocks in the Tonopah quadrangle. For this set of 36 analyses, Ag correlates very highly with Au ($r=0.99$), which is unique for the more than 50 deposits and districts described in this report. For most other deposits and districts, the correlation of Ag and Au is much lower, in part reflecting a greater degree of supergene modification. Both Ag and Au correlate highly with As and Mn, and Ag and Au correlate moderately with Cu, Mo, Pb, and Sb ($r\sim0.5$). In

most other silver-rich deposits, Ag is more strongly associated with Sb and Pb than with As.

REVEILLE DISTRICT

Two camps in the Reveille district, about 95 km east of Tonopah in the southeast corner of the Tonopah quadrangle (fig. 1), produced chiefly silver from oxidized deposits in Paleozoic carbonate and Tertiary volcanic rocks. Discovery was in 1866, just prior to the discovery of the very similar ores at Tybo. Production was at least $500,000, and possibly as much as $1,500,000, chiefly from the New Reveille mines, which were rich in silver, lead, and zinc (Kleinhampl and Ziony, 1984). Antimony as stibnite was mined at the Antimonial mine. Gossan outcrops are prominent in this district and were rich in cerargyrite that was easily milled in the early years of mining. In later years mines worked the deeper sulfide ores, rich in galena and sphalerite. Most recently, in the early 1980's, open-cut mining and heap-leach recovery of silver and gold have been attempted at several sites in the district and probably were foiled by the high base-metal contents of the ores. The deposits are partly in Miocene tuff and may be related to quartz latite dikes and plugs (Kleinhampl and Ziony, 1984, p. 171). The deposits are younger than 30.5-Ma volcanic rocks and probably formed after a 27-Ma tuff but prior to an 18-Ma intrusion. The ores in limestone are particularly similar to the polymetallic vein and replacement class of deposits.

Geochemically, the Reveille deposits are very rich in base metals and Ag. For 14 samples (table 5), the mean values are 200 ppm Ag, 660 ppm Cu, 8,300 ppm Pb, 2,600 ppm Zn, 2,300 ppm As, and 2,900 ppm Sb. Gold values are as high as 1 ppm and average 0.2 ppm in these high-graded samples.

MOREY DISTRICT

This small mining camp in the Hot Creek Range (fig. 1) is a historic producer of silver from ores rich in base metals and in recent years has been the subject of controversy regarding its potential for deposits of molybdenum and tin. About $475,000 of ore was produced from 1866 to 1891 (Kral, 1951; Kleinhampl and Ziony, 1984). Most of the values were in silver, and some in gold and lead (with penalties for zinc). The main camp at the base of the mountain worked veins that contained complex silver-lead-antimony sulfosalt minerals and oxidized derivatives; many rare silver minerals have been identified in the Morey ores (Williams, 1968). The veins are rich in base metals, forming galena, sphalerite, chalcopyrite, jamesonite, and molybdenite. Gangue in the veins is manganese-rich calcite, quartz, and fairly abundant pyrite (where not oxidized), pyrrhotite, and tourmaline. Tin is known to be present in the ores and was explained by Williams (1968) by the discovery of cassiterite. Silver prospects also are present at the top of "Red Mountain," and these also contain notable amounts of tin.

In the past 20 years exploration in the district has focused on disseminated types of molybdenum-copper porphyry and tin porphyry ores. Some of the geologic studies are described in a thesis by Lenzer (1972). Exploration in the late 1960's located a zone of disseminated sulfides west of the main productive part of the district, but a few drillholes into the zone produced no encouraging results (Kleinhampl and Ziony, 1984). The area was known to contain anomalous amounts of molybdenum and is listed as a molybdenum deposit or prospect in several publications. In the mid-1970's several more holes were drilled but gave no encouraging indications of a molybdenum deposit. In 1982 a joint venture tackled the district as a disseminated tin prospect, in part based on the suggestion by Williams (1968) that the silver-tin mineralogy and setting resembled that of the Bolivian tin belt (see Chace, 1947; Sillitoe and others, 1975). Implicit in the exploration models for molybdenum or tin is the presence of a silicic intrusion below Red Mountain. To my knowledge, no such intrusive rock has been identified, either at the surface or in drill core. Red Mountain probably comprises a very thick section (about 2,000 m) of monotonous intracaldera tuff. The tuff is variably altered, pyritized, and locally anomalous in exotic elements such as molybdenum and tin but appears to lack a crucial element, the right kind of porphyry stock at depth. Late intrusive bodies along the caldera margin are not appropriate because they are very little altered; that is, glass is still present. A deep hole drilled in search of disseminated tin, collared at the top of Red Mountain, was shown to me by the claim owner, V.J. Barndt, in 1984. The core displayed abundant quartz-sericite-pyrite alteration of tuff in the upper 300 m, but toward the bottom of the 604-m-deep hole the tuff was generally less altered or cut by fractures containing chloritic alteration. No intrusive rock was encountered.

Samples of ore and mineralized rock, chiefly from dumps in the main lower part of the Morey camp, have some of the highest metal contents of any district sampled in this study. High concentrations of Mn, Ag, As, B, Pb, Sb, Sn, and Zn are the rule, and some samples are rich in Ba, Bi, Cu, and Mo (table 5). The maximum Ag content is 2,000 ppm, and the maximum Au content is 1 ppm. Atomic absorption analysis were run on only a few of the samples and showed low levels of Au, Bi, Te, and Tl. The maximum Hg content in four determinations is 0.08 ppm. The mean content of Sn is 241 ppm, and the maximum is 1,000 ppm! The geochemistry of the Morey ores is uniquely rich in base metals and tin among the volcanic-associated deposits of the Tonopah quadrangle.

TYBO DISTRICT

Silver-rich lead-zinc sulfide ores and oxidized derivatives were mined in Tybo Canyon (fig. 1) from about 1869 to 1936, yielding about $9,500,000 (Kral, 1951; Kleinhampl and Ziony, 1984). This is one of the few camps that reopened

after the crash of 1890, and with the aid of electric pumps veins were worked to a depth of about 400 m. The district is described in detail by Ferguson (1933), the area mapped well by Quinlivan and Rogers (1974), and much useful information provided by V.J. Barndt, a veteran prospector and miner for most of his 80 years. The silver-lead-zinc ores in Tybo Canyon are compositionally similar to areas at Morey and Reveille, but the geologic controls are different from other deposits in this class. The rocks at Tybo are chiefly carbonate rocks, but the ores are predominantly within Tertiary rhyolite dikes. Dreams of finding large replacement bodies in limestone, as at Manhattan (Ferguson, 1924), have not been fulfilled. At Tybo a thick section of Cambrian to Permian(?) sedimentary rocks more than 3,000 m thick is well exposed in spectacular cliffs in the area. Most of the section is composed of Paleozoic carbonate rocks of eastern-facies platform type. An even thicker section of Tertiary volcanic rocks is present in the area, mostly Oligocene lavas and welded tuffs. The structural history of the area is complex and includes several periods of Paleozoic to Tertiary low-angle, normal, and lateral faulting, as well as folding. Several middle Tertiary calderas formed in what is now Hot Creek Valley (Ekren and others, 1973). Structures that contain ore were active at several times, and in the Oligocene the broken ground was intruded by rhyolite dikes that then became the favored host for ore. The ore minerals are galena, sphalerite, chalcopyrite, pyrite, pyrrhotite, and arsenopyrite (Ferguson, 1933); no studies have been made of silver mineralogy. The ore is rich in manganese, mostly as manganese-rich calcite, but some rare manganese minerals are also present. Much of the richest ore was in oxidized zones to depths of 100–200 m; there probably was enrichment of silver during supergene oxidation (Ferguson, 1933). The rhyolite and quartz latite porphyry dikes are pervasively altered to sericite and calcite, but silicification of carbonate rocks in the ore zones is relatively minor. Ferguson (1933) speculated that the lack of ore in carbonate wallrock may have been caused by the sealing effect of pre-mineralization gouge along the faults. Reasons for the unusual selectivity of dikes rather than carbonate rocks as the favored host rock remain puzzles. Ferguson reasoned that the depth of cover over the veins was "not more than a few hundred feet." Lacking an exact age for the mineralization in the Tertiary, I cannot reconstruct the volcanic pile at the time of vein formation. The impressive feature of Tybo is the depth and strike length of the veins. The 2G vein was explored for 760 m at its west end (Tybo mine) and for 100 m at its eastern end (Swarbrick mine), and, although its central part was only weakly mineralized (Ferguson, 1933), the total length of the system may have been about 2,500 m. (The western end of the vein was cut off by a post-mineralization fault.) The 2G vein contained galena and sphalerite at a depth of about 400 m, but the "bottom" of the deposit was a matter of economics and not geology. Presumably, the mineralizing system continued to a considerably greater depth; ore was mined at elevations

about 200 m above the Hale shaft collar, and some of the vein must have been eroded. A vein system more than 2,500 m long and more than 600 m deep resembles some of the large vein systems of the western San Juan Mountains, Colorado (Nash, 1975), not a bonanza-type epithermal system.

Chemical data for 70 samples from Tybo canyon (table 5) show that the ore is rich in Mn, Ag, As, B, Pb, Sb, Sn, and Zn. Some samples are rich in Au (as much as 7 ppm, not representative), Ba, Be, Bi, Cu, Mo, Ni, V, Hg, and Tl. The distinctive features of the Tybo chemistry are the high silver to gold ratios, high base-metal contents (but low Cu), and high contents of Sn and Bi. Samples from the mines at Keystone and Old Dominion (plate 1) 10 km north of Tybo have generally similar compositions. Most samples from the Tybo district contain detectable to high amounts of Sn, as mentioned for Morey. The tin trend may include the entire Hot Creek Range. Tin also is anomalous in the Eureka district to the north (M. Chaffee, oral commun., 1987), and this longitude of Nevada may be a large tin belt.

ELLENDALE DISTRICT

The Ellendale district is south of U.S. Highway 6, about 45 km east of Tonopah (fig. 1). Gold was discovered in 1909 and some very rich gold ore, including visible leaf gold, was produced for about 3 years (Kleinhampl and Ziony, 1984). Total production was at least $166,000, and estimates from area residents are as high as $1 million. Only barite has been produced since 1939, that from the bedded Jumbo deposit in Cambrian or Devonian strata, 6 km east of the Ellendale mine. Precambrian(?) to Tertiary rocks have had a complex structural history of thrusting and intrusion. The major mine in the district, the Ellendale mine, is in Tertiary rhyolite plugs and domes, but mines and prospects also are in Paleozoic carbonate rocks to the south. Calc-silicate alteration and magnetic anomalies suggest a shallow, buried intrusion under the Ellendale mine area (Kleinhampl and Ziony, 1984). Although gold was the most important commodity, the geochemical signature (table 5) is high in base metals, similar to Reveille and other areas known more for silver than gold. Local enrichments in Bi and Mo, as well as Cu, Pb, and Zn, suggest a gradation into a plutonic-associated polymetallic environment, discussed later, which is consistent with the proposed buried pluton. The apparent inconsistency in Au may possibly reflect supergene enrichment that created local pockets of very rich gold having characteristic leaf texture. Anomalous amounts of Sn in several samples suggest that the unusual belt of high tin in the Hot Creek Range continues into this area.

DANVILLE DISTRICT

A relatively small amount of silver was obtained from argentiferous galena veins in Paleozoic rocks at Danville (fig. 1) during sporadic mining from 1866 to 1953

(Kleinhampl and Ziony, 1984). Mineralogy of the veins has not been studied. There were only traces of gold in the ores. Alteration of the thick-bedded gray Paleozoic dolomite along the veins consists of erratic and generally minor amounts of silicification. Tertiary welded tuffs contain notable amounts of limonite where faulted against Paleozoic rocks a few kilometers east of the Danville deposits, and Tertiary rhyolite dikes are present a short distance to the north. These features suggest that the ores might be related to a Tertiary volcanic system, such as at Tybo and other places in the Hot Creek Range about 25 km to the east, but the mineralogy and geology of the Danville deposits also are similar to plutonic-associated polymetallic replacement deposits. Six samples of visibly mineralized rock from the Danville dumps are rich in Mn, Ag, Pb, Sb, and Zn, whereas contents of As, Cu, and Mo are notably low for deposits having prominent oxide gossans.

SIMON MINE

Another polymetallic deposit containing important amounts of silver is at the Simon mine in the Cedar Mountains (fig. 1); its age and origin are not established, but its setting resembles that of the Tybo deposits, and the deposit probably is related to Tertiary subvolcanic processes. The gossan at the Simon mine was discovered in 1879, but it was not until 1919 that exploration below the gossan revealed valuable silver-lead-zinc ore (Knopf, 1922). Two chimneylike deposits are present at Simon; in these steeply dipping replacement zones is limestone of the Luning Formation along the margins of an alaskite porphyry dike. The dike was intruded along a fault that displaces a quartz keratophyre flow (altered rhyolite containing albite) interpreted to be Triassic in age because it was intruded by the dike, which was believed related to the nearby Cretaceous granodiorite stock (Knopf, 1922). The keratophyre resembles middle Tertiary rhyolites of the region rather than the Triassic metavolcanic rocks known farther to the west in the Tonopah quadrangle; the most recent regional geologic map (Whitebread and John, 1992) shows only middle Tertiary volcanic rocks in the Simon area. Primary ore minerals are chiefly galena, sphalerite, pyrite, and arsenopyrite. In the oxidized zone, to a depth of about 70 m, the ore is described as siliceous gossan containing plumbojarosite (lead-iron sulfate, probably containing silver) and some galena and cerusite ($PbSO_4$), but only traces of secondary zinc minerals. The limestone is highly silicified, and the dike is altered to a mixture of fine quartz, sericite, and calcite. The keratophyre is argillized and contains pyrite and arsenopyrite. Unlike Tybo, the altered dike at Simon contains no ore. Production from 1921 to 1927 was about $741,000 to a depth of 305 m (Vanderburg, 1937). Blocked-out ore remaining in 1927 was reported to average 9 percent Pb, 8.5 percent Zn, 2–3 percent Cu, 9 oz/ton (309 g/t) Ag, and 0.04 oz/ton (1.4 g/t) Au.

A glory hole and trenches at the Simon mine contain some good exposures of altered keratophyre and limestone, gossan, and some relict sulfide veinlets. Samples from the Simon mine (table 5) (Nash, Siems, and Hill, 1985) are very rich in Fe, Mn, Ag, As, Cu, Pb, Sb, and Zn, and some are enriched in Au, Bi, Sn, and W. The ore suite resembles that from Tybo and Morey, again with scattered enrichment of gold that apparently is not typical of the ore in general. As at Tybo, the Simon ore had good vertical continuity. The ore mineralogy, chemistry, and vertical continuity suggest formation under conditions that were somewhat hotter and deeper than typical epithermal systems. The Simon mine might better be classified as a polymetallic replacement deposit.

DEPOSITS ASSOCIATED WITH PLUTONIC ROCKS

In the Tonopah quadrangle, silver, and to a much less extent gold, has been mined from polymetallic vein, replacement, and skarn deposits associated with Jurassic to Cretaceous plutons. A schematic cross section (fig. 3) illustrates some of the features. The deposits in calc-silicate rocks containing garnet and diopside are skarn deposits; examples are the Carrie mine in the Gilbert district (Ferguson, 1928), the Gunmetal tungsten skarn in the Pilot Mountains (Grabher, 1984), and the B&C Spring molybdenum deposit in the Paradise Range. In other deposits wallrock alteration is chiefly silicification that in places is obscured by supergene alteration. Some deposits that have high silver contents are the
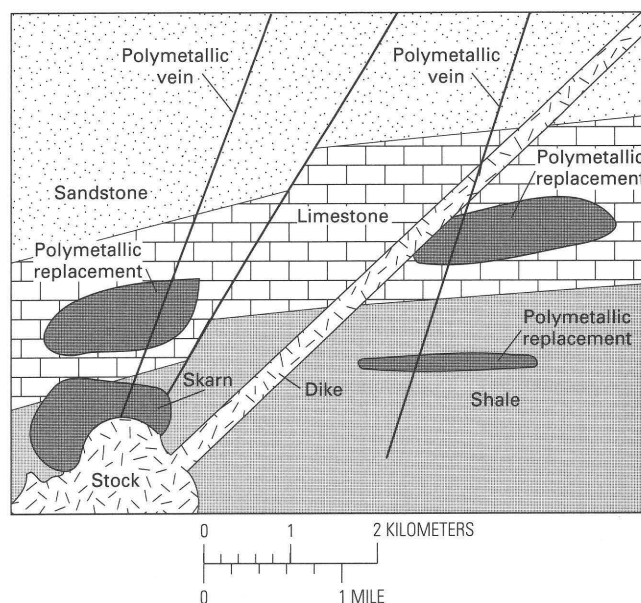

Figure 3. Schematic cross section showing polymetallic vein, replacement, and skarn deposits associated with a stock.

Table 6. Summary of geochemical data for selected plutonic-associated skarn and polymetallic vein and replacement silver-gold deposits, Tonopah 1°×2° quadrangle, Nevada.

[Deposits are shown in figure 1 or on plate 1 and are listed in table 1. Number in parentheses is number of samples. All values in parts per million except for Fe, which is in percent. G.M., geometric mean; Max., maximum value. Leader (—) indicates no data or not computed. Deposit types: SK, skarn; PMR, polymetallic replacement; PMV, polymetallic vein]

Element	Barcelona (8)		Carrie (10)		Clay Peters (30)		Scheebar (10)		Sullivan (14)		Grantsville (22)	
	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.
Fe	1.5	15	3.0	20	8.4	20	0.79	2.0	5.4	15	7.6	>20
Mn	380	>5,000	490	>5,000	330	2,000	290	1,000	270	1,500	880	>5,000
Ag	16	1,500	9.5	2,000	9.6	300	0.37	1.5	5.3	3,000	9.9	3,000
As	180	1,500	190	5,000	310	>10,000	—	<200	39	2,000	180	3,000
Au	0.04	0.40	0.19	1.7	0.91	>50	–	–	1.1	>20	0.27	>20
Ba	470	>5,000	340	2,000	120	1,000	120	>5,000	670	5,000	320	2,000
Cu	280	>10,000	303	>10,000	1,990	>10,000	15	100	3,080	>10,000	390	>10,000
Mo	78	>2,000	37	200	6.2	70	—	<5	11	50	20	300
Pb	66	5,000	180	>20,000	130	>10,000	19	100	17	70	330	>10,000
Sb	67	>10,000	86	10,000	110	143	—	100	110	>10,000	84	500
Zn	580	>10,000	340	5,000	260	3,000	—	<200	170	5,000	690	10,000
Hg	7.6	>14	—	—	—	—	9.4	>100	0.64	5.5	1.1	>20
Te	0.27	>20	0.62	9.3	—	—	—	—	—	—	—	—
Tl	0.81	3.0	0.70	3.4	—	—	—	—	—	—	—	—
Deposit type	SK		SK		SK		SK		SK		PMR	

Element	Murphy (Ophir) (9)		Rays (9)		Belmont (50)		Marble Falls (9)		All polymetallic (151)		All skarn (110)	
	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.	G.M.	Max.
Fe (percent)	4.7	10	3.3	7	1.4	7	9.3	20	2.8	>20	5.0	20
Mn	55	1,500	360	2,000	180	2,000	1,130	>5,000	390	>5,000	340	>5,000
Ag	11	150	27	500	28	5,000	42	1,000	14	5,000	3.3	3,000
As	2,330	3,000	270	1,500	91	700	620	2,000	160	>10,000	140	>10,000
Au	0.22	0.70	0.12	0.80	0.05	0.45	0.06	50	0.15	>20	0.67	>20
Ba	280	500	1,080	>5,000	410	2,000	1,020	>5,000	350	>5,000	280	>5,000
Cu	39	300	180	700	160	>10,000	360	3,000	170	>20,000	810	>10,000
Mo	2.9	10	21	300	16	1,000	24	200	14	>1,000	8.4	500
Pb	830	5,000	1,210	7,000	260	15,000	1,850	>10,000	210	>10,000	44	>10,000
Sb	110	1,000	45	300	41	7,000	24	700	52	>10,000	54	>10,000
Zn	1,940	3,000	1,200	10,000	290	5,000	2,490	>10,000	370	>10,000	220	>10,000
Hg	0.23	0.50	0.63	12	—	—	—	—	4.4	>20	4.6	>20
Te	0.16	0.85	—	0.10	0.52	>20	0.14	0.40	1.3	>20	1.9	>20
Tl	0.07	0.20	0.54	1.5	0.81	3.2	0.79	7.0	1.0	3.4	1.4	3.4
Deposit type	PMR		PMR		PMV		PMV		PMR/PMV		SK	

Clay Peters prospect in the Gabbs Range (Nash, Siems, and Bidge, 1985c), the Fagan prospect in the Cedar Mountains (Nash, Siems, and Hill, 1985), and the Barcelona mine in the Toquima Range (Kleinhampl and Ziony, 1984). Polymetallic vein and replacement deposits are farther from exposed plutonic rocks, and pre-Tertiary sedimentary host rocks do not show obvious metamorphic and high-temperature metasomatic effects. Examples include deposits in the Belmont, Ellsworth, Union (Grantsville), Twin River (Murphy), Rays, and Fairplay (Goldyke) districts. These vein-type and replacement deposits are polymetallic (table 6) but are not proven to be genetically related to plutons (that is, the chronology of ores and plutons are not known in detail) rather than to subvolcanic stocks. The polymetallic deposits share many features with the great Eureka, Nevada, district (Shawe and Nolan, 1989). Compositionally, most of these plutonic-associated deposits are rich in pyrite, galena, sphalerite, and chalcopyrite, but silver can be abundant enough to be a significant byproduct, or silver can be

enriched by supergene processes to be the major commodity. Only in the Sullivan deposit in the Paradise Range is gold more important than silver (Kleinhampl and Ziony, 1984). Many aspects of the geology and geochemistry of these deposits that are probably associated with plutonic rocks are similar to those of base-metal-rich vein deposits associated with volcanic rocks, such as at Reveille, Tybo, and Simon, previously discussed.

POLYMETALLIC VEIN AND REPLACEMENT DEPOSITS

BELMONT DISTRICT

Rich silver ores were mined at Belmont (fig. 1) from Paleozoic rocks adjacent to a large Cretaceous pluton (John, 1987). The sedimentary rocks at Belmont are not highly metamorphosed, and the veins containing silver probably were opened or reopened following metamorphism; thus the

ores probably are not directly related to formation of the exposed granite but formed late during Cretaceous plutonism (Kleinhampl and Ziony, 1984; Nash, Siems, and Budge, 1985d; Shawe, 1988). The Belmont deposits are not easily classified but probably best are included in this class of polymetallic deposits associated with plutonic rocks. As much as $15 million, chiefly as silver, may have been produced between 1865 and 1889. The richest silver zones were above the water table, but variable amounts of primary copper-molybdenum-lead-zinc sulfide and sulfantimonide minerals were present in the deeper parts of a few mines. Massive bull quartz veins are prominent in the deposits, but most of this stage was barren; the pay zone was erratic along the quartz veins and commonly on the hanging-wall side of the vein. Alteration along the veins has not been described and is not prominent megascopically in outcrops. The Belmont ores (Nash, Siems and Budge, 1985d) are notably rich in Ag, As, B, Pb, Sb, and Zn and locally rich in Ba, Bi, Cu, Mo, W, and Te (table 6). Gold was not significant in the ore, and the maximum content of Au in my samples is 0.45 ppm. Supergene processes were important in creating the rich and metallurgically simple silver chloride (cerargyrite) ores, but the primary ores evidently were also rich in silver, as well as many base metals.

GRANTSVILLE DISTRICT

The silver-rich deposits at Grantsville (fig. 1) were discovered in 1863 and yielded about $1.5 million, chiefly before 1890 (Kleinhampl and Ziony, 1984). Host rocks are limestone and calcareous shale of the Triassic Luning Formation (Silberling, 1959). Primary ores were probably chiefly galena, sphalerite, and chalcopyrite and local concentrations of fluorite and scheelite. Silver, the chief commodity, was richest in the oxidized zone to a depth of about 75 m. Gold was not significant. The limonite-rich oxidized ores can be seen today in the pillars of some glory holes. Scheelite was present on the deepest level of the Grantsville mine, and a small amount of tungsten was produced in 1969 (Kleinhampl and Ziony, 1984), but the nature of the tungsten ore has not been described. Union Carbide explored for tungsten in the early 1980's with no success. Silicification of carbonate rocks is evident in some of the workings, but any other hypogene alteration is obscured at the surface by supergene alteration. Ore zones were irregular replacement bodies that followed bedding, contacts, and fractures. The presence of scheelite, fluorite, coarse quartz veins, and abundant base metals at Grantsville suggests that the primary ores formed at higher temperature and greater depth than most of the silver-gold ores in other parts of the area; the general term mesothermal (Guilbert and Park, 1986) is perhaps appropriate for these ores. No intrusive rocks crop out in the Grantsville area, but Silberling (1959) reported that others had seen granitic rocks in the underground mine workings.

I collected samples of rocks from outcrop, mine openings, and dumps from the Grantsville area, all of which are highly oxidized. These samples are notably rich in Ag, B, Bi, Cu, Pb, Zn, As, and Sb (table 6). Some samples show enrichments in Mo and Nb, and W and Sn were detected in one sample. A content of 28 ppm Au was detected in one sample, an apparent contradiction to the lack of mention of byproduct gold at Grantsville. The enrichments in B, Bi, Mo, Nb, and W are reminiscent of skarn deposits elsewhere in the Tonopah quadrangle (Nash, Siems, and Hill, 1985). Samples from Grantsville Ridge, a few kilometers to the southeast, also contain high concentrations of the skarn suite of elements, but no intrusive rocks are known in that area.

MARBLE FALLS AREA

Oxidized polymetallic veins in Marble Falls Canyon, on the west side of Ellsworth district, are locally rich in gold and silver. These deposits in Paleozoic sedimentary rocks and greenstone are probably typical of many that were mined in the Ellsworth district (Kleinhampl and Ziony, 1984) but distinct from those such as Reward that are in Tertiary tuff. No intrusive rocks are exposed in Marble Falls Canyon, but Cretaceous granitic intrusive rocks crop out 2 km to the south and 3 km to the east (John, 1987; Silberling and John, 1989) and thus might be present below the deposits. Mr. L.E. McKinney worked the deposits alone in the mid-1980's and reported that some intervals contained as much as 60 oz/ton (2,050 g/t) Au and 35 oz/ton (1,200 g/t) Ag; his concentrates contained about 10–14 percent Pb. Post-ore faults offset the veins, complicating mining. Host rocks are folded Paleozoic limestone that is faulted against Permian(?) greenstone. White and greasy-gray bull quartz fills the vein with abundant dark-brown iron oxide minerals and remnants of galena. Nine samples from several of the workings at Marble Falls are consistently rich in Pb and Ba (table 6), and many are rich in As, Sb, and Zn. No Bi was detected. Silver contents are as high as 1,000 ppm and average 42 ppm; gold contents are as high as 50 ppm (?) (by emission spectrometry, may not be reproducible because of the small amount of sample burned) and average 0.06 ppm. These are probably mesothermal veins related to a Cretaceous pluton.

MURPHY (OPHIR) MINE

Rich silver ores valued at almost $1 million were produced from the Murphy mine from about 1864 to 1868 from veins or chimneylike deposits in Paleozoic(?) slate and phyllite on the east flank of the Toiyabe Range, 30 km northwest of Round Mountain (fig. 1) (Kral, 1951; Kleinhampl and Ziony, 1984). The ores containing abundant tetrahedrite, stibnite, sphalerite, and ruby silver were oxidized to silver chloride and native silver near the surface. Company reports from the 1860's disagree as to the amount of gold: some said it was minor, but one said it was about 10 percent of the precious-metal content (Kleinhampl and Ziony, 1984). Plutonic

rocks crop out east of the mine (John, 1987) and include a main body of foliated granodiorite (Cretaceous, 100 Ma, scheelite-bearing skarn deposits in border zone), two-mica granite (Cretaceous), and biotite granodiorite (Tertiary, 55 Ma). The age of the Murphy ores is not known, but mapping by Kleinhampl suggests that the ore is related to the older plutonism (dated at 100 Ma by John, 1987). Chemical analyses (table 6) show that the ore is rich in most base metals (Fe, Mn, Pb, Zn, As, Sb) and in Ag, but not very rich in Cu. The lack of extremely high base-metal values may be more a matter of sample selection than a real difference relative to other plutonic-associated polymetallic replacement deposits of the area.

RAYS DISTRICT

A cluster of old workings in the San Antonio Mountains, about 15 km north of Tonopah (fig. 1), is the site of the Rays mining camp. There is very little information on these deposits, but quartz veins in the Ordovician Vinini(?) Formation apparently were worked for gold and silver (Bonham and Garside, 1979). The veins were discovered and worked shortly after 1900. A fault zone about 1 km long hosts the quartz veins, which are 1–2 m wide and were worked by about 10 shafts and prospect pits. Host rocks are dark-colored fine-grained rocks, chiefly argillite, chert, and impure carbonate rocks. No intrusive rocks are shown on the geologic map (Bonham and Garside, 1979), and I saw none on the dumps. Vein-associated alteration is most prominently supergene iron oxide mineral formation, but host rocks also are silicified. The vein strikes N. 55° W. and dips about 75° SW. Several thrust faults are present in the area (Bonham and Garside, 1979), but they probably were not involved with the vein mineralization. Dumps and mine openings do not offer much to sample other than some miscellaneous iron oxide minerals, some white and brown carbonate minerals, and rare copper oxide minerals and galena. Nine samples from Rays (table 6) contain an interesting suite of elements including Ag, Au, As, Ba, Bi, Cu, Mo, Pb, Sn, W, Zn, and Hg. The high contents of Bi, Mo, Sn, W, and base metals are most interesting, although these data probably are not reliable for comparison with results for other deposits in this study because the Rays samples were more carefully picked (high-graded) from the lean dumps.

SKARN DEPOSITS

The high-temperature endmember of plutonic-associated deposits in sedimentary rocks is characterized by calc-silicate contact metamorphic minerals such as garnet, pyroxene, amphibole, and epidote that miners and economic geologists term "skarn" (Guilbert and Park, 1986). Some of these deposits contain enough silver or gold for them to be precious-metal ores or for the silver and gold to be byproducts. In the 19th century some of the skarn deposits were worked for silver if they were oxidized, and in recent years skarn deposits have been recognized as favorable for a distinctive type of low-grade gold ore (Meinert, 1989; Theodore and others, 1991).

BARCELONA DISTRICT

Precious-metals and mercury have been produced by several mines in the Barcelona or Spanish Belt district (fig. 1) from a septum of Paleozoic metasedimentary rocks between two Cretaceous plutons (Kleinhampl and Ziony, 1984; John, 1987; Shawe, 1988). Production was at least $199,000, and possibly another $500,000 of early silver-gold mining went unrecorded. The largest precious-metal mines, the Barcelona and San Pedro, worked veins in metasedimentary rocks (phyllite, spotted schist, and marble) and extensions of the veins in granitic rocks. The granitic rocks are cut by numerous quartz-pyrite veins that have sericite alteration selvages, and molybdenite, chalcopyrite, and scheelite are present in many of the veins and in material on mine dumps. At the south end of the district, the Van Ness and other mines worked cinnabar-stibnite-barite veins in silicified metasedimentary rocks; this type of ore is not obviously part of the contact metasomatism but probably is a later (Tertiary) stage of mineralization similar to that in other mercury deposits adjacent to the Cretaceous plutons of the Toquima Range (Shawe, 1988). The molybdenite veins and scheelite skarns are most clearly relatable to the granite; the silver-gold veins are probably somewhat younger but still related to the Cretaceous plutonism. Alteration associated with copper, molybdenum, and tungsten consists of garnet-epidote skarn and silicification. Eight rock samples from the Barcelona mine dump and adjacent prospects are characterized (table 6) by abundant Ag, As, B, Ba, Cu, Mo, Pb, Zn, Hg, and Te. Beryllium, Bi, Sn, and Tl are abundant locally.

CARRIE MINE

The Carrie mine and adjacent prospects in the Gilbert district (fig. 1) are in an area of Mississippian limestone adjacent to a Jurassic stock (Ferguson, 1928; John, 1987). Some material on mine dumps contains calc-silicate minerals (garnet and actinolite), but much of the alteration is silicification of carbonate rocks. The upper part of the Carrie mine worked oxidized silver-lead ore, probably similar to iron-oxide-rich gossans exposed at nearby prospects. Ten samples from the Carrie mine dump and adjacent prospects (Nash, Siems, and Budge, 1985b) are rich in Fe, Ag, As, Cu, and Sb, and some samples are rich in Bi, Mo, Pb, Zn, and Te (table 6). Compared with Tertiary vein deposits in the Gilbert district, previously described, the Carrie samples are distinctive for their higher contents of Cu, Mo, and Bi and lower contents of Ba, Sr and Au.

GUNMETAL MINE

Important deposits of scheelite are in skarns in Triassic limestone adjacent to a Cretaceous pluton on the east side of the Pilot Mountains (fig. 1) (Grabher, 1984; Stager and Tingley, 1988). Samples of core, from both inside and outside of scheelite-bearing garnetite skarn zones, have a mean content of 8.3 ppm Ag, and Ag contents in skarn are as high as 700 ppm. Silver shows the following correlations: Ag:Pb, 0.87; Ag:Bi, 0.73; Ag:Zn, 0.63; Ag:W, 0.24; Ag:Cu, 0.15, and Ag:Mo, 0.05. Contents of As and Sb are consistently below the limits of detection by the spectrographic method (100 ppm), and no correlations of these elements with silver could be calculated. Silver mineralogy has not been determined, and its paragenetic position cannot be demonstrated, but the correlations of Ag with Pb, Bi, and Zn suggest a later stage of mineralization relative to the formation of tungsten-copper-molybdenum minerals, possibly as an overprinted stage of sulfosalt minerals.

Skarn-type prospects elsewhere in the Pilot Mountains and at the Clay Peters prospect in the adjacent Gabbs Valley Mountains (Nash, Siems, and Budge, 1985c) contain as much as 300 ppm Ag and have a mean content of 226 ppm Ag in 35 samples. In this set of samples Ag correlates highly with As, Bi, and Cu but is independent of Pb. Skarn-type prospects in the Cedar Mountains (Nash, Siems, and Hill, 1985; Stager and Tingley, 1988) contain as much as 300 ppm Ag and have a mean content of 46 ppm Ag in 27 samples. In the Cedar Mountains skarn samples, Ag has high correlations with As, Bi, Cu, and Zn and moderate correlations with Pb and Sb. The molybdenum deposit of UV Industries at B&C Spring in the Paradise Range (fig. 1) is a molybdenum-copper skarn deposit developed in limestone of the Triassic Luning formation and generally rich in garnet and diopside. Silver is a potential byproduct. In 125 samples of drill core from the B&C molybdenum deposit (Nash and Siems, unpub. data), Ag correlates highly with Cu and is independent of Bi and Pb; contents of Sb and As are below the limits of detection by the spectrographic method.

SULLIVAN MINE

The Sullivan mine is a skarnlike deposit that appears to be enriched in gold on the basis of some past production and from this reconnaissance sampling. The Sullivan mine, about 12 km south of Gabbs (fig. 1), is in weakly metamorphosed silty-calcareous rocks of probable Mesozoic age. The host rocks are silicified, but no calc-silicate minerals or skarn are reported or visible in trenches. Some gold was produced from a small mine (Kral, 1951), but more recent trenching and drilling of the deposit has been for a porphyry-type deposit, inferred to be in or above one of the Cretaceous stocks known in the southern part of the Paradise Range (John, 1987). Copper oxide minerals and quartz veinlets are exposed in the trenches. Results from 14 samples (table 6)

indicate Au contents of 130 and 35 ppm in two samples and a mean gold content of 1.1 ppm. The samples are high to very high in Ag, As, Au, Bi, Cu, Sb, Zn, and Hg but not enriched in Mo or Pb. An unusual feature of the chemistry is that Sb is more abundant than As in most of the samples. Although details of the origin of the Sullivan deposit are not clear from available information, it is obvious that the system is large and highly enriched in many elements of interest, most importantly gold.

SCHEEBAR MINE

Substantial workings of the Scheebar mine near Paradise Peak (fig. 1) in marble, quartzite, and phyllite produced a small amount of cinnabar and scheelite (Stager and Tingley, 1988). Intrusive rocks are not exposed, but Cretaceous plutonic rocks are known in the area (John, 1987) and presumably underlie the deposit. Mercury was discovered in 1929 and produced in the 1930's; scheelite was discovered in 1943 and produced in 1954–55. Cinnabar and erratic scheelite are present in veins and disseminations in a white marble bed, probably part of the Luning Formation. Fluorite is present locally, and sulfide minerals are sparse to absent. Analyses of 10 samples (table 6) show very low concentrations of Ag, Cu, Pb, Zn, As, and Sb; only the ore metals Hg and W are enriched. The seemingly unlikely association of high-temperature scheelite and low-temperature cinnabar at Scheebar is not easily explained but may also be present at the San Pedro and Van Ness deposits in the Barcelona district, discussed previously.

In summary, in these skarn deposits silver shows differing metal associations that presumably reflect a variety of mineral residences and possibly different stages or conditions of precipitation. This reconnaissance study indicates that silver can be sufficiently enriched in high-temperature deposits to be a potential byproduct. Data for gold in these skarn deposits are incomplete, but available information suggests that gold is generally not as abundant as silver. Some skarns, however, are enriched in gold, and these are good exploration targets.

DEPOSITS IN METAMORPHIC ROCKS

Several deposits in metamorphic rocks do not fit any classification well. The common denominator for these deposits is their presence in weakly metamorphosed Paleozoic to Mesozoic rocks. The metamorphism is chlorite grade and is regional in character. Two other attributes are abundant quartz in veins, including massive bull quartz in veins a meter or more wide, and a general lack of alteration selvages along the veins. The lack of alteration suggests general equilibrium between ore-forming fluids and country rock, such as in regional metamorphism. The greenschist

metamorphism of these rocks, whether or not an ore-forming process, is of lower grade than that associated with some metamorphic gold-quartz veins in Precambrian greenstone belts (Boyle, 1979) but is of comparable grade to that in many Mother Lode-type (low-sulfide type, Cox and Singer, 1986) districts. Mesozoic or Tertiary plutonic or volcanic rocks are present within a few kilometers of these deposits but are not obviously involved in ore formation. Three examples are in Permian and Triassic clastic and volcaniclastic rocks of the northwest corner of the Tonopah quadrangle at the Richmond, Shamrock, and Gold Ledge mines, and a fourth is in similar greenstone or metadiorite in the Ellsworth district. The geology of these areas is described by Kleinhampl and Ziony (1984). Copper oxide minerals are most conspicuous at these deposits, but precious metals were the economic objective. Production from these mines has not been large; the greatest production was about $107,000 from the Shamrock mine (Kleinhampl and Ziony, 1984).

The Shamrock, Richmond, and Berlin mines, as well as adjacent workings in the Union district (fig. 1), are in metavolcanic rocks and metadiorite of Permian and Triassic age (Kleinhampl and Ziony, 1984). Quartz veins at the Richmond mine are well exposed and a meter or more wide. Narrower bull quartz veins were observed at the Shamrock mine. A gray mineral resembling tetrahedrite was seen in vein quartz at the Richmond mine; tetrahedrite and other silver-copper-antimony minerals are reported to be present in the mines (Kral, 1951). Compared to most deposits in the region, these deposits show relatively little supergene oxidation. Ten samples from the Shamrock mine and vicinity are characterized by high contents of Mn, Ag, As, Ba, B, Cu, Pb, and Sb; Au, Mo, and Zn are rich in a few samples (table 7). Four samples from the Richmond mine are rich in Mn, Ag, Ba, B, Cu, Sb, Zn, and Hg; Au, As, Pb, and Bi are rich in

some samples. The enrichment in B is a distinctive feature of these deposits; however, no mineralogical studies were made to identify the boron mineral (tourmaline?).

The Gold Ledge and adjacent mines are about 10 km south of Gabbs in low hills comprised of Triassic greenstone (Kleinhampl and Ziony, 1984). Exposures are not good but some show quartz veins a few centimeters wide accompanied by copper and iron oxide minerals and minor alteration of greenstone. The deposits apparently were worked for gold. Three samples from the Gold Ledge and adjacent mines are characterized by relatively high contents of Mn, Ag, B, Cu, As, Sb, and Hg; Bi and Sn are locally rich, but Ba, Mo, Pb, and Zn are not notably enriched (table 7).

Other examples of metamorphic gold-silver vein deposits probably are in rocks described as Permian(?) metavolcanic rocks of uncertain stratigraphic assignment in the Ellsworth district (Kral, 1951; Kleinhampl and Ziony, 1984). In reconnaissance of that area I saw some chloritic metavolcanic rocks that contain small prospects. One cluster of crumbled excavations in greenstone about 2 km north of Ellsworth (site) near Big Spring displayed massive bull quartz veining and copper oxide minerals. The general appearance of the poorly exposed mineralized rock was similar to that of the Shamrock and Richmond deposits. Two samples are rich in Cu, As, and Sb but low in Pb and Zn. Of particular interest are contents of greater than 2,000 ppm B and 4 and 12 ppm Bi and high contents of Au and Ag (2.6 and 4.0 ppm Au, 20 and 100 ppm Ag).

These deposits in low-grade metamorphic rocks are quite distinct chemically in their enrichments in boron, bismuth, and tin, as well as base metals. The weak or negligible wallrock alteration at these deposits also is distinctive. The geochemistry of these deposits, only roughly defined in these studies, resembles aspects of the geochemistry of deposits in impure carbonate rocks at Northumberland and

Table 7. Summary of chemical data for selected metamorphic vein deposits, Tonopah 1°×2° quadrangle, Nevada.
[Deposits are shown in figure 1 or on plate 1 and are listed in table 1. Number in parentheses is number of samples. All values in parts per million except for Fe, which is in percent. G.M., geometric mean; Max., maximum value. Leader (—) indicates no data or not computed]

Element	Gold Ledge (3) G.M.	Gold Ledge (3) Max.	Shamrock (10) G.M.	Shamrock (10) Max.	Richmond (4) G.M.	Richmond (4) Max.	All metamorphic veins (21) G.M.	All metamorphic veins (21) Max.
Fe	10.2	15	4.2	10	3.9	10	4.9	15
Mn	670	2,000	560	2,000	740	2,000	620	2,000
Ag	9.3	150	63	1,000	260	1,000	34	1,000
As	220	300	160	285	130	700	180	700
Au	—	0.43	1.0	10	1.5	5.2	1.4	>20
Ba	270	1,000	490	2,000	990	2,000	560	2,000
Cu	3,410	>10,000	260	2,000	2,810	>10,000	510	>10,000
Mo	6.3	10	5.4	500	<5	<5	5.6	500
Pb	34	70	1,130	>10,000	35	500	170	>10,000
Sb	100	150	110	150	1,710	>10,000	170	>10,000
Zn	130	300	160	300	360	2,000	150	2,000
Hg	—	—	—	—	4.6	18	—	18
Te	—	—	—	—	—	—	—	—
Tl	—	—	—	—	—	—	—	—

also aspects of base-metal skarns. Fluid inclusions, described following, are rich in CO_2 in some vein quartz samples and may be diagnostic of metamorphic environment, as suggested by detailed studies elsewhere (Goldfarb and others, 1989).

FLUID-INCLUSION STUDIES

Samples of quartz or other transparent minerals suitable for fluid-inclusion studies were collected where possible during the geochemical fieldwork. The quality of the samples ranged from excellent vuggy quartz from the Gilbert district to milky, sheared quartz from metamorphic veins that proved unworkable in the laboratory. The structural and paragenetic position of the fluid-inclusion samples relative to silver or gold minerals generally could not be established from field relations; I sampled whatever might be suitable for fluid-inclusion studies knowing that the samples would not be specific for the precious-metal stages. Twenty-one samples yielded information on fluid temperatures and compositions (table 8). The laboratory studies were made by Lanier Rowan and James Saunders in the laboratory of David Leach of the U.S. Geological Survey (Saunders and Rowan, 1986). Also included in table 8 are data from nine samples studied in 1968–69 by me and partly described in a previous report (Nash, 1972).

The fluid-inclusion data (table 8) fit the earlier generalizations of Nash (1972) that fluids in epithermal gold-silver deposits had very low salinity, resembling those in modern geothermal systems. The new data suggest chemically distinct fluids in metamorphic environments. The majority of the samples contain fluid inclusions that homogenize in the range 180°C–290°C; homogenization temperatures are minimum estimates of temperatures of formation and require a correction for pressure that can range from as little as 0°C for boiling fluids to more than 100°C for fluids under moderate geologic pressures. Salinities inferred from freezing-point-depression measurements are generally about 1 weight percent NaCl equivalent. For most of the deposits the depth of formation inferred from geology is relatively shallow; thus only a small (<10°C) correction for pressure should be added to the homogenization temperatures. A few samples from the Grantsville district show evidence for somewhat higher salinities of about 3.8–5.8 weight percent NaCl; compared to samples from other environments, such as porphyry copper deposits that have salinities in excess of 30 weight percent NaCl, the salinities of about 5 percent are still quite low, somewhat higher than sea water. The content of CO_2 is low in most of the nonmetamorphic samples, as inferred from the lack of visible liquid CO_2 and the lack of anomalous behavior at temperatures near the critical point of CO_2 (-56°C); however, CO_2 was detected in some inclusions in samples from

Keystone mine, Gilbert district, and in several samples from metamorphic rocks. For the Keystone and Gilbert samples, the CO_2-rich inclusions may be associated with boiling and thus reflect a sample of an effervescing CO_2-rich vapor.

Fluid inclusions in quartz from metamorphic veins and contact zones of plutons (table 8) homogenize in the range 210°C–350°C, and to these temperatures should be added a substantial correction for pressure, possibly from 10°C to more than 100°C. Measured salinities in three samples are not much different from those obtained from veins in sedimentary and volcanic rocks. In several samples CO_2 is abundant, as indicated by the presence of a third liquid phase of liquid CO_2 in the inclusions and by behavior near –56°C. Other skarn-type deposits also show the tendency for high content of CO_2 (Nash and Saunders, unpub. data, 1985). The indications of high CO_2 content in fluid inclusions probably are characteristic of the higher temperature and pressure regimes of metamorphic environments; CO_2- and CH-rich inclusions are characteristic of metamorphic-type fluids elsewhere, such as at Coeur d'Alene, Idaho, and Mother Lode-type mesothermal veins (Goldfarb and others, 1989; Landis and Hofstra, 1991).

These limited fluid-inclusion data are consistent with many published estimates of temperatures of about 180°C to 300°C and low salinities comparable to modern geothermal systems (White, 1981; Hedenquist, 1991). The higher content of CO_2 in some samples from metamorphic environments is consistent with geologic features at those deposits. Other than differences in CO_2, the general composition of the fluids as determined from fluid inclusions is more similar than different among the four deposit environments described in this report. Notably absent is any evidence of compositional differences such as higher salinities for fluids associated with the base-metal-rich deposits.

Boiling, a powerful influence on mineral deposition (Buchanan, 1981; Drummond and Ohmoto, 1985), can be determined from fluid-inclusion studies. Evidence for boiling, deduced from probably contemporaneously trapped liquid-rich and gas-rich inclusions (a matter of judgment, not fact), also is present in several samples, including those from Keystone and Gilbert and one from the Manhattan Consolidated mine near the White Caps mine. Fahley (1979) described evidence for boiling in samples from Tonopah. The fluid-inclusion evidence for the region is mixed; boiling is indicated in some deposits but not in others. However, boiling may not be evident in fluid inclusions if the gas-rich fluid was not trapped (Saunders and Rowan, 1986), and Henley (1985) noted that boiling is virtually inevitable as geothermal water rises to shallow depths; thus boiling is likely on geologic grounds for Tertiary systems of the Tonopah quadrangle. The major effects of boiling on the chemistry of epithermal fluids (Buchanan, 1981; Reed and Spycher, 1985; Hedenquist, 1991) must be considered to have been important in the Tertiary systems of the Tonopah region. Also, boiling conditions, if correctly interpreted from

Table 8. Fluid-inclusion data for some silver-gold-bearing veins in the Tonopah 1°×2° quadrangle, Nevada.
[Locations are shown on plate 1 and are listed in table 1, except for Berlin, which is shown as a town on plate 1. Leader (—) indicates data not available. Homogenization temperature is range of individual measurements in a ±10°C range unless shown as larger range. Salinity is weight percent NaCl]

Sample number	Location	Deposit type	Host	Fluid-inclusion type	Homogenization temperature (°C)	Salinity	Comment
374	Gilbert	Volcanic associated	Quartz	Liquid-rich primary	260–360	–1.2	Boil?
			Quartz	CO_2 rich with liquid CO_2 primary	—	—	—
			Quartz	Liquid-rich secondary	244–327	—	
993	Return	Volcanic associated	Quartz	Liquid-rich primary	252	—	
1273	Clifford	Volcanic associated	Quartz	Liquid-rich primary	241	1.3	
859	San Antone	Volcanic associated	Quartz	Liquid-rich primary	237	0.8	
929	Grantsville	Polymetallic replacement	Quartz	Liquid-rich primary	249	1.7	Mercury deposit with diss. pyrite.
1547	Morey	Volcanic associated	Quartz	Liquid-rich primary	185–226	—	
1287	Ellendale	Volcanic associated	Quartz	Liquid-rich primary	230–267	—	
452	Keystone	Volcanic associated	Quartz	Liquid-rich primary	245	—	
			Quartz	Gas-rich primary	315	—	Boil?
512	Grantsville	Polymetallic replacement	Quartz	Liquid-rich primary	257	—	
514	Grantsville	Polymetallic replacement	Quartz	Liquid-rich secondary	170	3.8	
517	Grantsville	Polymetallic replacement	Quartz	Liquid-rich primary	228	5.8	
920	Grantsville	Polymetallic replacement	Quartz	Liquid-rich primary	208–234	—	
980	Marble Falls	Polymetallic vein	Quartz	Liquid-rich primary/secondary	277–335	2.5–3.7	
931	Richmond	Metamorphic vein	Quartz	Liquid-rich primary	274	—	
935	Richmond	Metamorphic vein	Quartz	Liquid-rich primary	242	—	
1013	Berlin	Metamorphic vein	Quartz	Liquid-rich primary	214	—	
900	Barcelona	Skarn	Quartz	CO_2 rich with liquid CO_2 primary	289	4.8	
1017	Belmont	Polymetallic vein	Quartz	Liquid-rich primary?	254	1.0	
939	Gunmetal	Skarn	Quartz	Liquid-rich primary	247	4.8	
940	Gunmetal	Skarn	Quartz	Liquid-rich primary	231	—	
959	Sullivan	Skarn	Quartz	Liquid-rich primary	299	—	
			Quartz	Gas-rich primary?	350	—	Boil.
N51-68[1]	Nemo mine, Manhattan district	Polymetallic vein	Quartz	Liquid-rich primary	215	5.1	Associated with aplite.
N52-68[1]	Mustang, Manhattan district	Volcanic associated	Fluorite	Liquid-rich primary	220	0.6	
N54-68[1]	Mustang, Manhattan district	Volcanic associated	Fluorite	Liquid-rich primary	210	0.6	Late fluorite.
N56-68[1]	White Caps	Sediment hosted	Calcite	Liquid-rich primary	222	0.4–1.9	Late calcite.
N57-68[1]	Manhattan Consolidated	Volcanic associated	Quartz	Liquid-rich primary	230	0.7	
			Quartz	Gas-rich primary	—	—	Boil.
		Volcanic associated	Fluorite	Liquid-rich primary	200	0.5	Late green fluorite.
		Volcanic associated	Fluorite	Liquid-rich primary	215	0.8	Late white fluorite.
N39-68[1]	Round Mountain	Volcanic associated	Quartz	Liquid-rich primary	260	0.2–1.4	With adularia.
N69-68[1]	Round Mountain	Volcanic associated	Quartz	Liquid-rich primary	250	0.2–1.0	With adularia.
—[2]	Tonopah	Volcanic associated	Quartz, fluorite	Not known	230–260	0.8–2.0	Boiling zones.

[1]From Nash (1972).
[2]From Fahley (1979).

the fluid inclusions, provide an important constraint on pressure and depth regimes, which can be utilized in exploration strategies.

DISCUSSION

In this study, I attempt to define empirical geochemical signatures of silver-gold deposits for use in exploration and resource assessment, with the goal of objectively identifying deposits that are economically important. Understanding the processes responsible for creating the signature and the deposit is a secondary objective. Exploration and resource assessment programs consider the grades and tonnages of deposits being evaluated (Cox and Singer, 1986), but in these programs geochemistry has tended to play a minor role. With the possible exception of assays for silver and gold, it is well known that the magnitude of a geochemical anomaly in outcrop or in stream sediments cannot predict the size or grade of a resource. If geochemical signatures can be used to identify types of precious-metal deposits (having known grade and tonnage attributes), then geochemical studies can provide diagnostic information for assessments. This discussion, with considerable speculation, addresses these issues.

The dataset for this study is not ideal because it suffers from incomplete analyses and from censored values beyond the limits of determination, and equal or better results can be obtained by improved analytical methods of the 1990's. The samples also may not be ideal in size, paragenetic stage, or supergene alteration, but they are typical of materials that can be obtained in reconnaissance, without a drill or an active mine. In my opinion, trends in the data, not specific details, are most informative and can be usefully applied. Unusually high values, such as those cited in tables 4–7 as maximums, are not considered to be representative or reproducible. If the signatures determined in this study are capable of discriminating among deposit types, as discussed following, the technique will be more effective and reliable using more detailed sampling and current (1993) methods of geochemical analysis.

EFFECTIVE SAMPLING AND ANALYTICAL TECHNIQUES

The methods utilized in this study are simple ones that can be used by any exploration or resource geochemist, yet they readily detected strong geochemical signatures for the altered and mineralized rock samples. Sampling of the deposits emphasized collection of pieces containing visible sulfide or oxide minerals or added hydrothermal quartz. In most districts accessible samples at the surface, at mines, or on dumps contained more iron oxide minerals ("limonite") than sulfide minerals; limonite in cracks and boxworks

probably formed by weathering of hypogene sulfide minerals. The logic was that the primary hydrothermal sulfide and silicate minerals have a geochemical suite characteristic of the ore and thus the secondary iron oxides will also be rich in the ore suite because iron-manganese oxide minerals are well-known adsorbers of base metals (Rose and others, 1979). The intent was to high-grade the sites to ensure detection of many metals by routine analytical methods, with no concern for an ore assay (partly because the nature of the field sites precluded representative sampling of possible ore zones). Each analyzed sample contained at least 4–6 small chunks of rock, a modest effort to obtain a composite mixture representative of the selective media, and total sample weight was about 300 g (not very large by engineering standards). No tests were made to determine either the degree of enrichment that this selective sampling produced relative to average altered rocks or the amount of fractionation (enrichment or depletion) of various elements in the weathered samples.

The statistical tests described here suggest that there are major differences in composition between the deposit types studied, differences that are both valid and readily detected at levels above 1 ppm for most elements. I prefer to collect reconnaissance samples in a manner that eases the burden of detection by the chemist, and the methods described above are effective. Most elements were routinely detected by the standard methods of the early 1980's (tables 2, 3) and should be even easier to detect by newer methods that have lower limits of determination. The multielement suites reported by most commercially available inductively coupled plasma-atomic emission spectrometry (ICP) analyses are well suited to studies such as this and are aided by selective dissolution and enhancement routines such as "A–Z" (Motooka, 1988) that have limits of determination for base- and precious-metals well below 1 ppm. Analytical problems, however, will always complicate the geochemical surveys. For example, some elements do not fit well into multielement packages. Tungsten is a potentially useful pathfinder (Berger and Silberman, 1985) and not utilized here because of the high limit of determination of the spectrographic method (50 ppm); improved methods for tungsten are available, but difficulties remain because tungsten is not stable in acids used for ICP analysis. Another problem is lockup of elements in refractory phases such as silica or pyrite that dissolve incompletely in most acids used for sample digestion; methods that analyze the total sample (emission spectrography, X-ray fluorescence, neutron activation) can provide better data for elements such as antimony that can be locked in refractory encapsulating minerals (M. Silberman, oral commun., 1985). Elements having variable mineralogy within alteration zones, such as titanium in ilmenite and rutile, can pose problems in analytical methods such as ICP that are based on acid dissolution (Nash, 1988b).

ELEMENT SUITES AND ASSOCIATIONS

Although silver sometimes is the best guide to silver deposits, or gold to gold deposits, suites of elements are more effective than single elements for characterizing environments and processes. Many techniques can be used to determine element associations that are the basis for defining suites. In this study two statistical techniques, correlation analysis and factor analysis (Davis, 1986), were used. The statistical tests were performed on various subsets of a total database of 951 analyses that were divided, using geologic or chemical criteria, to create the following subsets: (1) sediment-hosted deposits (n=217); and (2) volcanic-associated deposits having low base-metal content (n=279); (3) volcanic-associated deposits having high base-metal content (n=139); (4) plutonic-associated polymetallic vein and replacement deposits (n=151); (5) plutonic-associated skarn deposits (n=110); (6) metamorphic vein deposits (n=21). Also considered were 31 samples from mercury deposits, defined by commodity not geology, from the Pilot Mountains mercury district, Ione area, and Barcelona district (fig. 1, table 1).

For these computations the data for five elements (As, Au, Bi, Sb, and Zn) were selected from results of the two methods used for each sample and combined into a new variable; multivariate statistics run on datasets having incomplete atomic absorption and emission spectrographic results for these elements are inappropriate and misleading. Arsenic, Au, Bi, Sb, and Zn were determined by emission spectrography for all samples, and for highly mineralized samples the results were generally unqualified (within the range of determination, table 2). Weakly mineralized samples were reanalyzed for these elements by atomic absorption to provide valid results if the concentration was below the limit of determination by emission spectrography. Results of the two analyses were compared and the highest of the two reported values selected for statistical studies. Also, variables having relatively few valid (unqualified) determinations (Cd, Nb, Sn, W, and Th determined by emission spectrography) were not used in most statistical tests. The results for Au, Bi, Hg, Te, and Tl were qualified (not detected, not determined) in more than 50 percent of samples in some subsets. Results for these elements were used in computations because of geochemical interest, although the statistical results are not as reliable as those for more complete datasets. Scatter diagrams (x–y plots) were used to corroborate element associations indicated by correlation analysis.

Correlations of Ag and Au with 11 ore-associated elements of interest are summarized in table 9. Regardless of method used (eyeball, plots, multivariate statistics), the associations of elements in the ore environments studied are highly variable among the deposit types. In general, Ag and Au are independent of each other, but they are associated in one type (volcanic low base metal). Silver tends to be associated with a group of base metals (Cu, Pb, Zn) and with Sb, but closer inspection shows that Ag has several different base-metal associations: with Cu in sediment-hosted and volcanic-associated high-base-metal deposits, with Pb and Bi in polymetallic replacement and volcanic-associated high-base-metal deposits, with Pb and Sb in plutonic skarn deposits, with Zn in metamorphic veins, and with Au in volcanic-associated low-base-metal deposits.

In contrast to Ag, Au tends to be relatively independent of other metals. Gold is independent of other metals in two deposit types (polymetallic replacement and metamorphic veins). It is associated with Ag in volcanic-associated low-base-metal deposits, with Bi in sediment-hosted and volcanic-associated high-base-metal deposits, with Sb in mercury deposits, and with Ag, Cu, Zn, and As in plutonic skarn deposits. Gold tends to be independent of other metals in deposits that have low base-metal contents, but it tends to associate with one or more of the elements Cu, Pb, and Zn in deposits that have high base-metal contents. The so-called pathfinder elements (As, Bi, Sb, Hg, Te, Tl) are not closely associated statistically with either Ag or Au in most environments. Mercury is independent of Ag and Au in all deposit types studied, Te is associated with Au in two deposit types (sediment-hosted and volcanic-associated low base metal), and Tl is associated with Au in two deposit types (volcanic-associated high base metal and plutonic). Bismuth is associated with Au in some samples from sediment-hosted, volcanic-associated low-base-metal, and plutonic deposits. Arsenic is associated with Au in sediment-hosted and polymetallic deposits but is not associated with Ag in any deposit type. Antimony is associated with Ag in most deposit types (except volcanic-associated low base metal) but rarely is associated with Au (only polymetallic replacement and plutonic). These associations are determined from correlation coefficients (table 9) and from factor analysis (essentially multivariate correlation analysis) (Davis, 1986).

Factor analysis shows elemental groups or associations similar to those indicated by correlation analysis. Factor analysis was run on the subsets, described above, in order to provide a geologic basis for the analysis and to reduce variance, which is large even in the subsets and required about nine factors to explain at least 70 percent of the geochemical information for the 24 elements in the subset. The following general features were evident (elements in parentheses have lower factor loadings, which indicate weaker associations):

1. For sediment-hosted deposits (n=217), Ag is associated with Cu, and Au is associated with Bi on a separate factor. Iron-Pb-Zn are associated (carried on the same factor), and Sb, As, and Mo are independent of other elements (alone on factors).

2. For volcanic-associated low-base-metal deposits (n=279), Au and Ag are associated; Hg is inverse to Au-Ag. Pb-Zn are associated, as are Sb-Bi, and Cu is independent. Iron is associated with a mafic group of rock-forming elements (Cr, Mg, Ni, V).

Table 9. Correlations of silver, gold, and copper with other elements for seven deposit types, Tonopah 1°×2° quadrangle, Nevada.

[Values shown are correlation coefficients with Ag, Au, and Cu; bold numbers are significant at 95 percent level of confidence. Leader (—) indicates not computed. Values of the correlation coefficient (r) can range from +1 to –1; the larger the number the stronger the positive or negative association. Values of r near 0 indicate independence. The statistical significance of r changes with the number of valid pairs in the analysis (Davis, 1986); r* is the threshold for significance at the 95 percent level of confidence and ranges from 0.13 for 279 sample pairs to 0.43 for 21 pairs. Values of r that are significant are shown in bold type]

Deposit type		Ag	Au	As	Cu	Fe	Mo	Pb	Sb	Zn	Bi	Hg	Te	Tl
Sediment-hosted deposits (n=217)	Ag	—	0.06	0.10	**0.66**	0.12	−0.05	0.10	−0.02	**0.26**	**0.17**	0	0.01	−0.02
(r*>0.12)	Au	0.06	—	0.23	0.01	**0.15**	−0.07	0.10	0.03	−0.01	**0.58**	0	0.01	−0.03
	Cu	**0.66**	0.01	0.03	—	0.11	−0.03	0.05	−0.03	**0.16**	0.10	0	−0.01	−0.02
Volcanic-associated deposits														
Low-base-metal subtype (n=279)	Ag	—	**0.23**	−0.01	**0.22**	−0.05	0.10	0.09	**0.15**	**0.18**	**0.12**	−0.08	−0.05	0.03
(r*>0.12)	Au	**0.23**	—	0.01	0.03	−0.07	0.02	0	0	−0.03	0.01	−0.08	−0.03	−0.03
	Cu	**0.22**	0.09	0.09	—	0	−0.02	**0.23**	**0.25**	**0.16**	**0.51**	−0.14	0.04	−0.13
High-base-metal subtype (n=139)	Ag	—	−0.05	0.03	**0.37**	−0.05	0.08	**0.39**	**0.30**	**0.22**	0.05	0.08	0.15	−0.04
(r*>0.17)	Au	−0.05	—	−0.08	−0.05	−0.09	−0.07	−0.11	−0.02	−0.09	0.16	−0.10	−0.25	0.14
	Cu	**0.37**	−0.05	0	—	0.03	0.04	0.15	0.15	0.19	**0.22**	0.09	0.08	−0.02
Plutonic-associated deposits														
Skarn subtype (n=112) (r*>0.18)	Ag	—	**0.43**	**0.43**	**0.26**	−0.20	−0.08	−0.07	**0.85**	**0.23**	−0.20	−0.15	0.17	−0.17
	Au	**0.43**	—	0.17	**0.31**	0	0.16	0.01	−0.04	**0.35**	−0.04	−0.09	−0.09	−0.12
	Cu	**0.26**	**0.31**	**0.41**	—	0.13	−0.04	−0.11	**0.85**	0.18	−0.34	−0.16	0.09	−0.29
Polymetallic vein and replacement	Ag	—	0.03	−0.03	**0.37**	−0.19	**0.47**	**0.79**	**0.71**	**0.35**	0.11	0.28	0.19	−0.17
subtype (n=110) (r*>0.18)	Au	0.03	—	0.04	−0.01	0.09	0.11	0.01	−0.05	−0.02	0.11	−0.37	−0.02	−0.11
	Cu	**0.37**	−0.01	0.08	—	**0.26**	**0.25**	**0.28**	**0.34**	**0.19**	−0.12	**0.72**	0.05	−0.13
Metamorphic vein deposits (n=21)	Ag	—	0.26	0.37	0.26	**-0.45**	**0.46**	**0.68**	**0.50**	**0.57**	−0.12	0.29	—	—
(r*>0.42)	Au	0.26	—	−0.09	0.08	−0.15	−0.09	0.11	0.24	0.14	−0.08	0.27	—	—
	Cu	0.26	0.08	0.31	—	0.11	−0.07	−0.16	**0.52**	**0.52**	0.33	0.27	—	—
Mercury deposits (n=31) (r*>0.35)	Ag	—	0.03	**0.41**	**0.85**	0.04	0	0.04	**0.35**	−0.03	—	0.28	0.09	0.02
	Au	0.03	—	0.09	0.02	−0.02	0.19	**0.43**	**0.81**	**0.55**	—	**0.52**	−0.32	0.22
	Cu	**0.85**	0.02	**0.35**	—	0.09	−0.07	−0.01	**0.41**	−0.03	—	**0.35**	−0.17	0.01
		Ag	Au	As	Cu	Fe	Mo	Pb	Sb	Zn	Bi	Hg	Te	Tl

3. For volcanic-associated high-base-metal deposits (*n*=139), Ag and Cu are associated (lesser Pb-Sb-Bi), and Au and Bi are associated. Lead is associated with Zn-As-(Fe).

4. For plutonic-associated polymetallic vein and replacement deposits (*n*=151), Ag is associated with Cu-Pb-Sb-Zn, and Au is associated with Ca-Mn. Arsenic is alone (independent) on one factor, as are Bi and Mo.

5. For plutonic-associated skarn deposits (*n*=110), Ag and Au are associated, as are Sb-Bi-Zn. Three other factors carry Pb-(Ag), As, and Mo, indicating they are relatively independent.

6. For metamorphic veins (*n*=21), Ag is associated with Sb-Zn-As-Hg-(Cu), and Au is essentially alone or inverse to other metals including As. Base metals show unusual associations in the metamorphic environment: Pb is associated with Mo, Cu with Zn, and Fe with Co-Bi.

7. For mercury deposits (*n*=31), Ag is associated with Cu-Co-Ni-(As), whereas Au is associated with Sb-Hg. Lead-Zn-Fe are associated on a third factor.

8. The rock-forming elements Ti-Sc-Cr-Ni-V-Zr tend to be on a factor independent of ore metals. Commonly, Mn-Co-Ni-(±Ba-As-Zn) are on a factor together, suggesting an oxidized, supergene assemblage.

9. The volatile elements Hg, Te, and Tl tend to be independent of most ore elements; Hg and Te are associated in several deposit types, and Tl is independent of Te in all types but the plutonic-associated type.

The associations for Ag and Au, outlined in correlation analysis (table 9) and factor analysis, clearly are not the same for all deposit types, especially for elements such as Mo, Cr, or B that are occasionally associated with Ag or Au. There are, however, several recurring associations that stand out as important and these are summarized in table 10. Three types of silver-gold associations are apparent. (1) Silver and Au are present together, independent of base metals or As-Sb-Bi. (2) Silver and Au are independent of each other; Ag is associated with base metals, and Au is associated with As but not other elements. (3) Silver and Au are independent of each

Table 10. Summary of silver and gold associations in six deposit types, Tonopah 1°×2° quadrangle, Nevada.
[Line (a) is base metals or other elements; and line (b) is group Vb elements As, Sb, and Bi. Leader (—) indicates no association evident; query (?) indicates uncertain or limited data]

Deposit type		Silver	Gold
Sediment hosted	a	Base metals	—
	b	Bi?	As
Volcanic, low-base-metal	a	Au	Ag
	b	—	—
Volcanic, high-base-metal	a	Base metals	Ba-Te
	b	As-Sb-Bi	—
Plutonic, skarn	a	Base metals	Base metals
	b	Sb-As	As
Polymetallic replacement	a	Base metals	—
	b	Sb-Bi	Bi?
Metamorphic veins	a	Base metals	B-Ba?-Tl
	b	Sb-Bi	As?

other; Ag is associated with base metals, and Au is associated with one or more of Ba, B, Te, and Tl. There may be some systematic differences in the behavior of group Vb elements (As, Sb, Bi) in these silver-gold deposits.

Silver and Au are mutually associated only in the low-base-metal volcanic deposits. The silver-gold association at Tonopah was noted by Nolan (1933, 1935), who made the judgment from assays and mineralogy. In this deposit type, no other elements have important associations with Ag or Au. In the other deposit types Ag and Au are independent of each other; they likely were deposited at different times or places in the hydrothermal system. In the deposits having independent Ag and Au, Ag is associated chiefly with base metals, notably with Pb and Bi (to the extent that there is reliable data for Bi) and variably with Zn, Cu, or Mo. Silver is associated with Sb in some environments and also with As in one group (volcanic-associated low base metal). The group Vb elements are associated with Ag roughly in proportion to their bulk content in the ores; that is, if As is abundant, then there is a strong As-Ag association. This behavior seems logical but is not necessary because the group Vb elements could precipitate independently of Ag, which actually must be the case because the total of group Vb elements greatly exceeds that of Ag (indicating that the group Vb elements are not stoichiometrically paired with Ag).

COMPOSITIONAL DIFFERENCES BETWEEN DEPOSIT TYPES

Differences in mineralogical and chemical composition were noted earlier in generalized descriptions of individual deposits and districts. The range of compositions within a deposit type and the relative geometric mean values are shown on figure 4 for selected elements. A more rigorous test for differences can be made using the technique of discriminant function analysis (Davis, 1986), which computes a multivariate expression that is most effective for distinguishing two or more groups of samples. Discriminant function analysis is similar to the *F* test, which tests for equality of population variance, but it examines many variates rather than only one parameter (element) describing two groups. The classification of samples according to deposit types, previously described, was the basis for a priori definition of subsets for the tests. The differences in the groups, defined by geology and visible mineralogical and chemical features (such as sulfide or oxide mineral abundances), are confirmed to be significant for many elements.

The large difference in chemistry expected between plutonic-associated and sediment-hosted deposits is confirmed by discriminate function analysis. Most elements that are probably related to mineralizing processes are significantly more abundant in plutonic-associated samples, especially Pb, Hg, Te, Ag, and As (elements having the highest *F* values), whereas Cu, Sb, and Au are not significantly
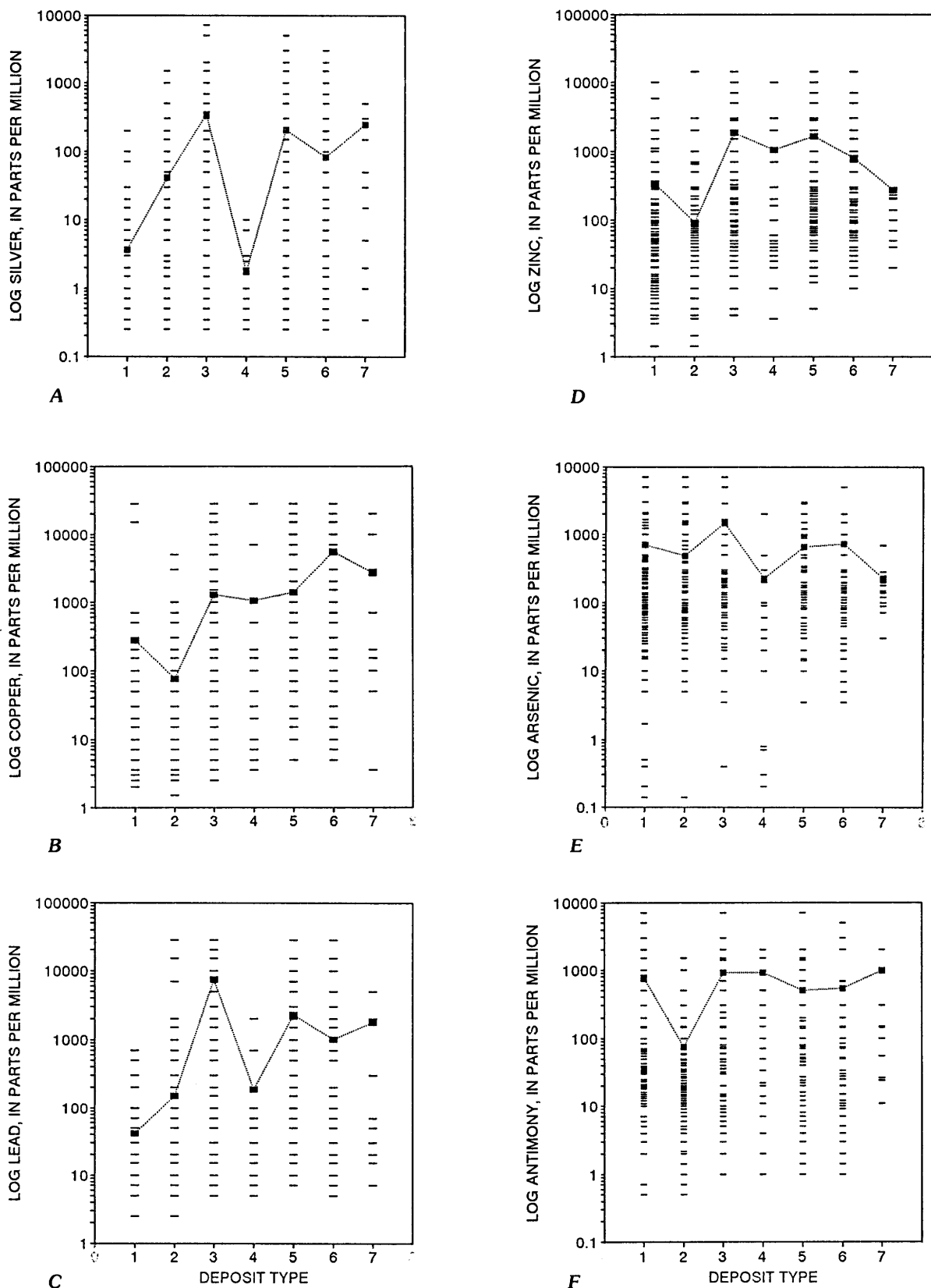
Figure 4.   Graphs showing range in composition of deposit types in the Tonopah 1°×2° quadrangle, Nevada. Solid square indicates geometric mean. Deposit types: 1, sediment hosted; 2, volcanic associated (low base-metal); 3, volcanic associated (high base-metal); 4, mercury; 5, polymetallic vein and replacement; 6, skarn; 7, metamorphic vein. *A*, Silver. *B*, Copper. *C*, Lead. *D*, Zinc. *E*, Arsenic. *F*, Antimony.

different between the two groups. A single variate, the sum of Cu, Pb, and Zn, is most effective at distinguishing the two subsets.

Volcanic-associated deposits (all 418 samples) can be distinguished from plutonic-associated deposits (skarn and polymetallic vein and replacement, $n=261$) by more than 15 elements, most of which are more abundant in the plutonic-associated group. The differences are largest for V, Cu, Bi, Mg, and Fe (higher in plutonic) and for Pb, Sn, and Tl (higher in volcanic). Concentrations of Ba, Sr, Ag, and Au are not significantly different between the two groups.

The large visual difference in composition among volcanic-associated epithermal deposits was tested utilizing subsets defined according to the amount of visible sulfide and oxide minerals: a low-base-metal group $(n=279)$, made up chiefly of silicified and argillized volcanic rocks and veinlets, and a high-base-metal group $(n=139)$, made up of vein and altered rocks containing abundant sulfide and oxide (limonite) minerals. According to discriminant function analysis, there are large and significant differences between these subsets: ore-forming elements (notably Zn, Pb, As, Mn, Fe, Sb, As, and Ag) are more abundant in the high-base-metal subset, whereas only Be is higher in the low-base-metal subset. Copper is significantly higher in the high-base-metal subset but not nearly so much so as Pb, Zn, and Fe. Contents of Mo, Ba, and Au are not significantly different between the two subsets. The attempt to divide volcanic-associated deposits into two groups may be inappropriate if there really is a continuum from low to high base-metal content (Hayba and others, 1985), but I agree with Albino and Margolis (1991) that the two populations are different geologically and geochemically.

Smaller, less visible differences in compositions were also tested using discriminant function analysis. Comparing sediment-hosted $(n=217)$ and volcanic-associated low-base-metal deposits $(n=279)$, the two subsets can be distinguished on the basis of more than 20 elements, most of which are rock forming in character. Not surprisingly, the contents of Ca and Mg are significantly higher in sediment-hosted deposits than in volcanic-hosted deposits, whereas Ti and Zr are higher in volcanic deposits. Less intuitively, Ni, V, and Cr are higher in sediment-hosted deposits than in volcanic-associated low-base-metal deposits; these elements probably are derived from black shale in the Paleozoic rocks. Among the ore-forming elements, Mo, Pb, Cu, and Fe are not significantly different in the two subsets, but Zn, Sb, and Bi are higher in volcanic-associated low-base-metal deposits than in sediment-hosted deposits, and Ag and Hg are higher in volcanic deposits.

Samples of metamorphic-associated deposits are relatively rich in base metals and were collected in western parts of the Tonopah quadrangle that also contain plutonic-associated deposits. According to discriminant function analysis there are not many differences between these two types of deposits, but five elements can be used to

differentiate the two. Concentrations of Ti, Sb, B, Tl, and Zn tend to be higher in metamorphic veins as compared to plutonic-associated deposits; contents of Fe, Ag, As, Au, Cu, and Pb are not significantly different between the two groups.

Problems with classification of polymetallic vein and replacement deposits were described earlier; for example; the apparent overlapping ranges in composition of base-metal-rich deposits (such as the Reveille, Danville, and Tybo districts and Simon mine) that were assigned to the volcanic-associated class and deposits in several problematic districts such as Belmont, Grantsville, Rays, and Marble Falls that were postulated to be pluton associated. Compositional differences and similarities were compared, using the volcanic subset $(n=418)$, a plutonic subset $(n=221)$, and the problem polymetallic subset (Grantsville, Rays, and Marble Falls, $n=40$). The discriminant function analysis, calibrated a priori using results from the best "known" volcanic and plutonic subsets, computes probabilities of classification of "unknown" samples using the discriminant function: 78 percent of the Grantsville samples were classified as volcanic, 80 percent of Rays samples as volcanic, all of the Marble Falls samples as volcanic, and 66 percent of Danville samples as volcanic (the balance in all cases was assigned to plutonic). The discriminant is based chiefly on V, Cu, Tl, Bi, Mg, B, Ni, and Pb, of which all but Tl and Pb are higher in the plutonic-associated "training" subset.

The geochemical classification of mercury deposits relative to other deposit types in the region also is uncertain. In a discriminant function analysis similar to that just described, the classification of 31 samples from mercury deposits was tested relative to volcanic and plutonic training subsets. Samples from the Ione area were classified as chiefly volcanic (85 percent), samples from the Pilot Mountains as chiefly plutonic (79 percent), and samples from the Van Ness mercury mine as volcanic (75 percent). In these districts both volcanic and plutonic associations are plausible, and thus the discriminant-based classification confirms the difficulty of assignment.

Pathfinder elements such as As, Sb, Hg, Te, and Tl are known to be enriched in epithermal systems (Ewers and Keays, 1977; Rose and others, 1979), and zonation of these elements relative to Ag or Au is especially helpful (Berger and Silberman, 1985). Data from this study do not establish zonal pattern but do demonstrate differences in pathfinder element concentrations between deposit types. Discriminant function analysis indicates that As, Hg, Sb, Te, and Tl are significantly higher in the volcanic-associated high-base-metal deposits than in the volcanic-associated low-base-metal deposits. Mercury, Te, Tl, and Sb are significantly higher in the sediment-hosted class than in either class of volcanic-associated deposits, but As is not significantly different. Mercury, Te, and Tl are significantly higher in plutonic-associated skarn and polymetallic deposits relative to volcanic-associated high-base-metal deposits,

whereas As and Sb are significantly higher in the volcanic-associated high-base-metal deposits.

Manganese has been considered to be a guide to some types of epithermal deposits (Hewett and Radtke, 1967), and this study confirms that suggestion in some situations. In general, Mn co-varies with other base-metals (Fe, Cu, Pb, Zn) and with Ag but not with Au. The behavior of Mn is not simple, however. The megascopic mineralogy of samples and statistical tests suggest two endmember situations for manganese: (1) enrichment in hypogene base-metal sulfide minerals, chiefly in volcanic-associated high-base-metal, polymetallic replacement, and plutonic-associated deposits, and (2) enrichment in oxidized "limonitic" fracture fillings and gossanlike deposits in which there is an association with Co, Ni, and Zn but not with Cu and Pb. Curiously, Y is consistently part of this oxidized Mn-Co-Ni assemblage, possibly captured because of its relatively small radius (Goldschmidt, 1958), but I speculate that it might reflect the quadrivalent state of Y (unlike otherwise similar rare earth elements), which would enhance adsorption on manganese-iron oxide minerals. Silver is generally high with Mn in the sulfidic manganese assemblage but erratically enriched in the oxide assemblage. Gold only rarely accompanies Mn.

SPATIAL DIFFERENCES IN DEPOSIT COMPOSITIONS

There are statistically significant differences in deposit compositions when tested for east-west variation. Although not evident in the distribution of deposit types or in their visible compositions, many differences are evident in discriminant function analysis of deposit compositions that are split into east and west subgroups at approximately long 117° W. The differences for 29 elements are summarized in table 11.

The most notable trend is for many elements of mafic affinity to be significantly higher in deposits from the western half of the Tonopah quadrangle. This mafic group includes Bi, Co, Cr, Fe, Sc and Ti; V is higher in volcanic deposits but not in sediment-hosted or plutonic-associated deposits. Copper is higher in most western deposits, Pb tends to be higher in eastern ones, and there is no significant trend for Zn. Arsenic, Hg, and Te tend to be higher in western deposits, whereas Sb and Tl tend to be higher in eastern deposits. Silver is higher in many eastern deposits, whereas Au is higher in western ones. Tin is higher in eastern deposits, chiefly those in the Hot Creek Range. Some elements, such as V and Cu, are not consistently higher in one region, but the trends are surprisingly consistent for many elements in many deposit types.

The basis for these spatial differences is probably complex. The first relationship that comes to mind is that of continental versus oceanic affinity, reflected most clearly in the composition of sedimentary rocks deposited along the continental margin. Another possibility for these differences is deeper sources in plutonic and volcanic magmas, related to the composition of subducted sedimentary rocks and lower continental crust. These matters will be discussed in a later section.

MINERALOGICAL DIFFERENCES

The mineralogy of ore, gangue, and alteration is a diagnostic attribute of most deposit types and rightly emphasized by Hayba and others (1985). Although I did not attempt detailed investigations of mineralogy, numerous macroscopic observations described previously indicate fairly systematic differences between deposit types. Calc-silicate minerals such as garnet, actinolite, diopside or epidote, and magnetite are notable in only the contact-zone (skarn) deposits. Silicification is noted in all the deposit types studied, but the character of silica is variable. Massive, coarse, white to greasy-gray quartz is characteristic of bull quartz in metamorphic veins. Quartz in jasperoidal alteration of clastic rocks is fine grained, rarely vuggy or crystalline enough to sparkle, and commonly is tan to medium brown from entrapped iron oxides. Silicification of carbonate rocks in plutonic-associated or polymetallic deposits such as in the Barcelona and Grantsville districts can closely resemble jasperoid that lacks spatial association with igneous rocks but in places is more coarsely crystalline. Silica in many of the volcanic-associated low-base-metal deposits is uniquely fine grained, light colored, and commonly banded, as emphasized by Buchanan (1981). This fine to opaline silica in many low-base-metal deposits is diagnostic, but it is not present in all of them. It is not present in the high-base-metal volcanic deposits. Carbonate gangue, commonly tan to brown iron-manganese-rich ankerite, is commonly only present in high-base-metal volcanic-associated veins, such as in the Tybo and Morey districts, and in polymetallic veins. Adularia is megascopically visible in many of the volcanic-associated deposits (Divide, Tonopah, Round Mountain, Manhattan, Clifford, San Antone, and Gilbert) and probably is more typical of the low-base-metal variety. Alunite was evident only at the Paradise Peak mine, but fine-grained alunite is not distinctive relative to powdery opal, kaolinite, and other light-colored alteration products and requires X-ray diffraction for reliable determination (John and others, 1991). Phyllic alteration is prominent in Tertiary tuffs but without X-ray study probably is not a diagnostic guide to any deposit type.

Macroscopic or hand-lens mineralogical character of volcanic-associated deposits is diagnostic of the two subtypes proposed here and was the basis for the subdivision before the chemical analyses were returned. In the oxidized zone the concept of leached cappings (Blanchard, 1968; Anderson, 1982) can be applied: boxworks of any type are

Table 11. East-west differences in deposit composition, Tonopah 1°×2° quadrangle, Nevada.
[Deposits are divided into subgroups at approximately long 117° W: W, west; E, east. W and E, significantly higher; w and e, higher but not significant at 95 percent probability. Leader (—) indicates no east-west differences]

Element	Sediment hosted	Plutonic associated	Volcanic, low-base-metal	Volcanic, high-base-metal	All deposits (n=951)
Antimony (Sb)	—	—	E	w	—
Arsenic (As)	W	W	W	w	
Barium (Ba)	E	—	W	W	E
Beryllium (Be)	W	E	—	—	E
Bismuth (Bi)	—	W	E	W	W
Calcium (Ca)	W	W	W	—	W
Chromium (Cr)	W	e	W	W	w
Cobalt (Co)	W	W	—	—	W
Copper (Cu)	W	W	E	w	W
Gold (Au)	W	W	—	W	W
Iron (Fe)	W	W	W	—	W
Lead (Pb)	w	—	e	E	E
Magnesium (Mg)	—	W	W	E	—
Manganese (Mn)	W	W	—	E	E
Mercury (Hg)	W	—	W	—	W
Molybdenum (Mo)	W	E	e		E
Nickel (Ni)	W	—	W	—	—
Scandium (Sc)	W	W	W	W	W
Silver (Ag)	w	E	E	—	E
Strontium (Sr)	—	W	—	W	—
Tellurium (Te)	W	—	W	E	W
Thallium (Tl)	E	W	W	w	E
Tin (Sn)	E	—	E	E	E
Titanium (Ti)	W	—	W	W	W
Vanadium (V)	E	E	W	W	E
Zinc (Zn)	—	—	—	—	—
Zirconium (Zr)	—	—	W	W	W

sparse in low-sulfide (low-base-metal) deposits but are abundant in high-sulfide (high-base-metal) deposits. Copper oxide minerals are not present in the former group of deposits but can be prominent in the latter. In unoxidized samples, if they can be found, sulfide and sulfosalt minerals are prominent in high-base-metal deposits but are essentially absent in low-base-metal deposits; however, low-base-metal deposits may have a distinctive black silica stage of micro-scopic sulfides in microcrystalline silica (Nash and others, 1991). Silica morphology, described above, can be diagnostic, although many low-base-metal deposits (Clifford, Bellehelen, Return, San Antone) contain crystalline, vuggy quartz that is characteristic of high-base-metal deposits. Veins banded at millimeter scale are a diagnostic feature of low-base-metal deposits, recognized years ago by Lindgren in bonanza deposits of the western United States (Lindgren, 1933); these are a favorable sign for good gold values. Depositional processes for silica are well understood, and silica morphology can be related in a general way to temper-ature (Fournier, 1985). Chlorite selvages under quartz-sulfide veinlets are characteristic of many high-base-metal deposits, such as in the Morey district and at Creede, Colorado (Barton and others, 1977), and were not seen in any of the low-base-metal deposits of the Tonopah area (although a few are known elsewhere).

APPLICATIONS TO DRAINAGE GEOCHEMISTRY

The geochemical signatures described here provide guidelines for interpretation of stream-sediment geochemis-try (Nash, 1988a). Many of the characteristic elements show up well in drainage media, especially heavy-mineral concen-trates, and anomalous concentrations can be related to likely deposit types through the use of typical signatures. Epither-mal deposits of low-base-metal content produce very weak signatures in drainage sediments (Nash, 1988a). Because factors such as climate and geomorphology can influence dispersion and deplete or enhance specific elemental con-centrations in various regions (Rose and others, 1979), tests should be made downstream from known deposits to

calibrate the system before routinely applying signatures to new areas.

ORIGINS OF PRECIOUS-METAL SUITES

SOURCES

The general composition of rocks within about 1 km of deposits in the Tonopah quadrangle does not appear to provide an explanation of deposit composition. For epithermal deposits elsewhere, composition of neighboring rock types (reviewed by Buchanan, 1981; Hayba and others, 1985) does not show a consistent relationship with ore composition. Basement composition below quartz-adularia deposits may be a factor in grade, tonnage, and silver to gold ratios (Mosier and others, 1986). Because epithermal ore fluids circulate 2–4 km below the level of ore deposition (Henley and Ellis, 1983; Berger and Henley, 1989) and magma compositions are established at far deeper levels of the crust, deeper parts of the crust must be considered. Tectonic models for

western Nevada provide a framework for estimating possible contributions from rocks in the upper crust.

Pre-Tertiary rocks of the Tonopah quadrangle formed close to the western continental margin. Paleozoic sedimentary rocks typically show facies changes from east to west in the Tonopah quadrangle, from miogeoclinal platform carbonate rocks to eugeoclinal shale and volcanogenic rocks (Stewart, 1980). Middle Jurassic to Early Cretaceous eastward thrusting juxtaposed lithotectonic terranes (Silberling and others, 1987; Silberling, 1991) (fig. 5). The Mesozoic continental margin can be approximated by the initial strontium isopleth of 0.706 in plutonic rocks, which reflects the western (oceanic) limit of sialic Precambrian cratonic rocks (Kistler, 1991). Several of these tectonic breaks or hinges run north-south through the Tonopah quadrangle (fig. 5) and might be reflected in ore compositions.

In a very general manner, the uppermost crust in the eastern part of the Tonopah quadrangle has more limestone (carbonate facies) than the western part. Conversely, the western part has more shale and volcaniclastic rocks than the east. There is no simple east-west variation in ore-type distribution that might reflect this generalization, but east-west variations in composition of deposits of several types do exist, as previously discussed. The concept of an "average" crustal composition obviously is simplistic. For example, even a small amount of a distinctive lithology in the crustal section may be dominant. Although siliciclastic mud rocks are dominant in western-facies terrane, there are carbonate rocks in the western part of the quadrangle and they are important: the Luning Formation is widespread and commonly is favored for ore. As a generalization, the silver- and base-metal-rich variety of volcanic-associated deposits forms relatively close to, or in, carbonate rocks, whether in the east (where such deposits are most numerous) or in the west (such as in the Grantsville district and at the Simon mine). The compositional opposite, volcanic-associated deposits that have low base-metal contents, tends to be distant from carbonate rocks, above pelitic pre-Tertiary rocks. This is not always the case, and clearly there are some carbonate strata below low-base-metal ores.

TRANSPORT

The composition of fluids transporting metals also is a likely factor in explaining ore compositions. Models of metal transport, based on laboratory and geothermal systems, allow compositional estimates to be made (Barnes, 1979; White, 1981; Henley and Ellis, 1983; Wood and others, 1987; Hemley and others, 1992). The debate is chiefly about the roles of chloride and bisulfide complexes; considerable evidence from laboratory experiments indicates that high chloride concentrations allow transport of substantial amounts of base metals. Gold is best transported by bisulfide complexes except under very acidic conditions and high chloride concentrations (Hayashi and Ohmoto,
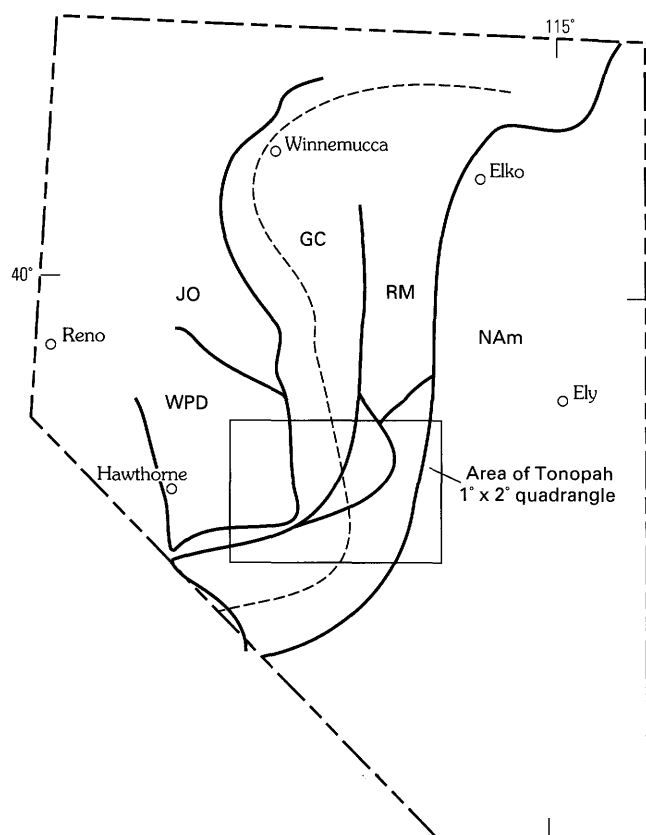

Figure 5. Map showing lithotectonic setting of the Tonopah 1°×2° quadrangle, Nevada. Lithotectonic terranes: GC, Golconda; JO, Jungo; NAm, North American plate; RM, Roberts; WPD, Walker Lake, Paradise subterrane. Solid lines indicate terrane-bounding faults; dashed line is 0.706-initial strontium isopleth. Modified from Silberling and others (1987).

1993), which are not typical of epithermal systems. Epithermal ores elsewhere that have high base-metal contents, such as at Creede, Colorado, and Colqui, Peru, have relatively high salinities of 5–12 weigh percent NaCl equivalent, which possibly explain the base metals (Hayba and others, 1985). Thermodynamic calculations (Henley, 1985) show that high-chloride solutions, and assuming only chloride transport, produce deposits that have high base-metal contents and high silver to gold ratios, whereas low-chloride fluids containing HS^- produce deposits having low silver to gold ratios because of less effective transport of silver and base metals. The limited fluid-inclusion data for deposits in the Tonopah area suggest that fluid chlorinates were generally similar for most of the deposit types. More fluid-inclusion data are needed to determine if the base-metal-rich deposits formed from fluids of higher salinity and how large the difference in salinity might be. It is possible that the low-base-metal deposits formed from very low salinity fluids (<1 weight percent NaCl equivalent), whereas the high-base-metal deposits formed from moderate salinity fluids (3–12 percent) (lower than in porphyry-type deposits).

The other ligand, HS^-, is more difficult to measure in ore deposits, but it can be measured using fluid-inclusion gas analysis (Landis and Hofstra, 1991), or sulfur acitivites can be modeled from mineral compositions in gold deposits (Shikazono and Shimizu, 1987). No information on HS^- is available for deposits from the Tonopah quadrangle. Chemical similarities between the Tonopah volcanic-associated low-base-metal class of deposits and the sediment-hosted class suggest possible analogies to the well-studied Carlin-type deposits (Hofstra and others, 1991; Landis and Hofstra, 1991). In particular, chemical-reaction-path modeling of the mineralogy and fluids in Carlin-type deposits suggests that H_2S is high and chloride is low, a chemical setting that causes transport of gold but not base metals (Hofstra and others, 1991; A.H. Hofstra, written commun., 1993).

MAGMATIC GASES

Recent studies of geothermal systems provide evidence for an important contribution of magmatic gases in the formation of epithermal, as well as deeper and hotter, deposit types that have closer spatial association to plutons (Hedenquist, 1992; Rye and others, 1992). A small amount of a magmatic gas, rich in hydrogen, sulfur, or chlorine, can have a large effect on the chemistry and reactions in geothermal fluids. These gases are not detected in most isotopic analyses because they are easily swamped by an influx of later meteoric fluids, and the sensitivity of the isotopic and gas analyses makes interpretation of as much as 10 percent magmatic component ambiguous (Henley and Ellis, 1983; Berger and Henley, 1989). Magmatic gases play a large role in determining the redox state of fluids, which in turn strongly influences metal transport and deposition. New methods for

analysis of fluid inclusions may provide diagnostic information on aspects such as gas and sulfur contents (Landis and Hofstra, 1991).

The base-metal content of hydrothermal deposits, which is highly variable from type to type in the Tonopah quadrangle and around the world, may mostly reflect the quantity and character of magmatic gases (Margolis and others, 1991; Hedenquist, 1992; Spooner, 1993). The range in composition of epithermal systems was postulated by Margolis and others (1991) to reflect environments that are rich or poor in magmatic volatiles. Volatile-rich systems are rich in many elements including Cu, Pb, Zn, Ag, As, Au, Bi, Te, Sn, and Sb, whereas volatile-poor systems contain minor amounts of base metals but are rich in Au, Ag, Hg, As, Sb, and Se. This generalization probably is appropriate for the geology and chemistry of deposits in the Tonopah quadrangle.

DEPTH

Vertical metal zonation has been noted in many epithermal deposits and is included as an attribute in several geochemical models (fig. 2) (Buchanan, 1981; Silberman and Berger, 1985). Many physical attributes (temperature, pressure, mixing) could contribute to a vertical zonation from Cu-Pb-Zn-(Ag?)-rich zones at depth to Au-Ag-As-Sb-rich zones closer to the surface. Whether empirical or theoretical, the depth model probably is relevant in some districts such as Bodie, California (Silberman and Berger, 1985), but it does not apply to many base-metal-poor deposits that show no evidence for higher copper, lead, and zinc contents below silver-gold ore zones.

The wide range in composition of epithermal ores in the Tonopah quadrangle is not likely a reflection of only depth of formation. Although the depth of formation of individual samples or deposits is not known, and there was no way to collect samples across a vertical range in these deposits, depth is probably much too simple an explanation for observed differences. Samples from the shallowest settings, such as Hasbrouck Mountain in the Divide district, the Nassau prospect, and the Marris mine (estimated from alteration features and paleogeologic reconstruction), do, however, consistently show the simple association of fine-grained silica-Ag-Au-As-Sb-Tl-Hg (low Fe-Cu-Pb-Zn), in keeping with many models of hot-spring-type epithermal deposits that form very close to the surface (Buchanan, 1981; Berger and Silberman, 1985).

DEPOSITION

Several processes that cause mineral deposition can cause selective enrichments of base- or precious-metals (Barnes, 1979; Henley and Ellis, 1983; Spycher and Reed, 1989). For example, boiling at shallow depths can induce major chemical changes (loss of H_2S, oxidation) and the

deposition of adularia, calcite, and gold in preference to sulfide minerals (Cole and Drummond, 1986; Romberger, 1988). There is some evidence for boiling in the fluid-inclusion data for the Tonopah region (table 8), and boiling is likely at many shallow-depth locations in the Tonopah quadrangle, but boiling alone probably cannot explain the widespread difference in base-metal content and silver to gold ratios. Many parameters are involved in boiling (such as initial temperature, depth, Cl and CO_2 contents of the fluid), and many chemical changes occur (most importantly, loss of H_2 and H_2S); thus, consequences for mineral solubilities are complex (Reed and Spycher, 1985; Cole and Drummond, 1986; Morrison and others, 1991; Hayashi and Ohmoto, 1993) and do not permit simple generalizations on metal zoning or metal ratios.

The pH of the depositional environment has a strong effect on the minerals deposited. Several recent reviews (Hayba and others, 1985; Berger and Henley, 1989; White and Hedenquist, 1990) focus on two dominant epithermal environments, acid and neutral. The acid environment, such as at Paradise Peak, Goldfield, and Summitville, is characterized by intense wallrock leaching, alunite and kaolinite deposition, oxidation, and high total sulfur. There is a tendency for some stages to have high base-metal concentrations (especially copper), but other stages such as alunite can be very low in all metals. The neutral environment, such as in the Round Mountain district, is characterized by adularia-sericite, reduced sulfur as pyrite, and a tendency for low base-metal concentrations, but stages of some deposits, such as at Creede or Comstock, can be very rich in base metals (see tabulations by Buchanan, 1981, and Hayba and others, 1985). The large differences in metal content within a deposit type, and within individual deposits, suggest that there is no simple role for fluid pH.

The range of compositions in these precious-metal deposits is so large, and involves so many elements, that a single factor cannot explain the differences. Many processes, operating in sequence, probably were involved. In deeper mesothermal environments adjacent to plutons associated with polymetallic ore suites generally rich in many base metals and some high in silver, magmatic gases probably are important, creating fluids having relatively high chloride content (from a few to more than 20 weight percent NaCl equivalent). In shallower epithermal environments, mixing of deep- and shallow-sourced waters occurs under a wide range of temperatures and structurally controlled permeabilities and results in diverse deposit morphology, alteration, and chemistry (Silberman and Berger, 1985). Some epithermal systems contain magmatic gases, and this magmatic connection may explain the anomalously high base-metal contents of some volcanic-associated deposits (Albino and Margolis, 1991; Hedenquist, 1992). Most shallow-level or very shallow level (<1 km depth) epithermal deposits in volcanic and sedimentary rocks have very low amounts of base metals, regardless of the

composition of nearby source rocks. These deposits probably formed from predominantly meteoric water that lacked ligands such as Cl^- or HS^- for the transport of base metals.

Research directed at these processes could help to improve genetic understanding and thus permit more effective exploration. Hopefully, a cost-effective method, such as fluid-inclusion analysis (Landis and Hofstra, 1991), can be developed that is more definitive than traditional geochemical methods. Geochemistry of altered and mineralized rocks, as discussed here, provides useful empirical guides to deposit types but really does not define genetic processes. Only through analogies with modern geothermal systems and integrated geologic studies that utilize other methods can processes be inferred.

INFERENCES FOR GEOCHEMICAL EXPLORATION AND ASSESSMENT

The precious-metal deposits in several geologic environments described herein produce moderate to very strong geochemical signatures that are not difficult to detect in reconnaissance geochemical studies if the alteration and ore are exposed. Modern multielement analytical techniques are capable of detecting the anomalous metals, without requiring special methods that determine to parts-per-billion levels. Anomalies are enhanced in samples that are visibly enriched in sulfide minerals, silica, or secondary oxide minerals that retain elements of interest. Geochemical interpretation, however, is not simple. Multivariate statistical methods are helpful tools and possibly are more objective than mere qualitative methods. Geologic and mineralogic data greatly aid in characterizing anomalies. Coding of rock lithology, alteration, and vein-filling mineralogy permits sorting of geochemical data and more specific interpretation of ore types.

Geochemists must be careful to avoid overly simplistic interpretations of chemical results. Single elements, especially pathfinders, are particularly quixotic. The pathfinders mercury, tellurium, thallium, arsenic, and antimony tend to be indirectly associated with gold and silver because they generally are deposited in different stages or zones than the precious metals. Examples include arsenic-rich jasperoids above ore, late-stage stibnite-only veins, and late-stage mercury deposition. Pathfinders are probably more reliable for silver than for gold because gold behaves very independently. Arsenic and antimony probably are excellent guides to epithermal systems in general but not to specific deposit types or to gold. The related group Vb element bismuth deserves more attention as an indicator of environment. Bismuth probably is most abundant in plutonic (skarn) environments, but this simple rule is violated by enrichments in a few epithermal systems, such as the acid-sulfate type

(Paradise Peak) (John and others, 1991) and in sinter at Round Mountain (Berger and Silberman, 1985). Similar problems and research opportunities exist for tungsten. Consideration of geology and alteration probably can resolve ambiguities in single-element behavior.

Methods used in this study have application to economic evaluation of prospects in terms of deposit type. Geochemists should be able to assist economic geologists in the assessment of targets according to corporate strategy or resource potential. It is no longer sufficient to seek silver or gold in general: certain ore environments are clearly more likely to produce significant deposits than others. Many of the important producers of the past, such as polymetallic veins, are not viable targets today because of their small size and the predominance of silver over gold. With silver prices languishing below $5 per ounce ($0.15 per gram), silver is generally not an attractive commodity. A target that has even a low probability of being a significant gold deposit of the Sleeper or Round Mountain type is far more important than one that has a high probability for an undesired ore type.

Deposits or prospects having strong Pb-Zn-Sb±(As-Bi) signatures are most likely to be favorable for silver and minor gold. These systems will produce well-developed gossans or oxide coatings on joints, primarily because of their relatively high sulfur content (Blanchard, 1966; Anderson, 1982), and most probably have been tested by prospectors already. These silver-rich systems are not prime exploration targets in the 1990's, but with changing silver values they could become attractive. The high sulfur content of these silver-base-metal systems makes them favorable for supergene enrichment in most semiarid parts of the western United States. With appropriate structure and paleohydrology, a bulk-mineable deposit can form. This multistage upgrading of silver probably occurred at Candelaria, Nevada (Page, 1959; Graybeal and others, 1986), and at other bulk-mineable silver deposits in the western United States. Secondly, these systems have potential for zonation downward into polymetallic replacement deposits, skarn, or porphyry copper-molybdenum deposits. This zonation is seen in the prospects of the San Antone and Grantsville districts and in many classic porphyry districts elsewhere in the western United States; however, depth to the potentially large porphyry deposits is likely to be greater than allowed by current mining scenarios.

Volcanic-associated deposits that have high-base-metal signatures may be difficult to evaluate. As precious-metal prospects, most should be anticipated to have high silver to gold ratios, probably in the range of 50–200 based on past experience (tabulated in Buchanan, 1981). Certainly some of these deposits, such as Tonopah, Nevada, and Guanajuato, Mexico, have very large tonnages and would be exciting discoveries, but those containing little gold and of small tonnage would probably be subeconomic in the 1990's. Among

other problems, the high sulfide and base-metal contents mitigate against cost-effective heap leaching and tend to produce acid mine drainage. The low-base-metal volcanic-associated deposits are more attractive targets because of their generally lower silver to gold ratios, amenability to heap leaching (low sulfide and low base-metal competition for cyanide), and fewer mining and post-mining drainage problems (lower acid generation, lower toxic metal content).

Signatures of deposits that have low contents of base metals are difficult to interpret, yet these are the deposits associated with the most attractive gold deposit types. If the geology and alteration are properly interpreted, then the distinction can be made between sediment-hosted and volcanic-hosted environments. Criteria for sediment-hosted (Carlin-type) deposits are discussed elsewhere (Bagby and Berger, 1985). For the volcanic-associated prospects, there may be problems discriminating between a good prospect of the Round Mountain, Hasbrouck, or Sleeper type that has inherent low contents of base metals and a weakly developed Tybo- or Creede-type prospect. Geologic criteria (Berger and Henley, 1989; Albino and Margolis, 1991) such as volcanic and tectonic setting may help. Alteration character also should help to identify the more promising gold prospects in which fine-grained silica or opal, smectite rather than chlorite, and marcasite rather than pyrite are favorable indications (Nash and others, 1991).

CONCLUSIONS

Geochemical studies of altered and mineralized rock samples from mines, dumps, and prospects in the Tonopah 1°×2° quadrangle, Nevada, document a wide range of concentrations for many ore-associated elements. Although there are large differences from sample to sample and from deposit to deposit, there are enough trends to permit geochemical identification of at least six geologically defined types of deposits. Variability in single elements is sufficiently large that single-element geochemistry is not recommended as a general tool for exploration or resource assessment. Multielement suites, however, can identify deposit types and support geologic evaluation of prospects. If a specific deposit type, having characteristic grade and tonnage attributes, is the subject of the evaluation, the best approach is integrated geologic and geochemical studies that combine interrelated information such as host-rock type, alteration, and structure with multielement chemistry. Multivariate statistical tools such as discriminant function analysis allow objective comparison and classification of prospect samples with known deposits if training datasets can be established.

Geochemical signatures can be used in conjunction with geologic and mineralogic information to classify

prospects by geologic type and attendant grade and tonnage expectation. Deposits characterized by high base-metal content are associated with deposit types noted for silver rather than gold; these deposits were common producers in the past but are not promising targets at times of low silver prices. Sedimentary and volcanic environments noted for high gold to silver ratios, and valuable for gold alone, are characterized by relatively low concentrations of Fe, Mn, Cu, Pb, Zn, As, and Sb. The more subtle signatures of gold deposit types, relative to strong signatures for silver-bearing types, can be difficult to interpret without accompanying geologic and mineralogic information.

The observed wide range in composition of deposits and deposit types is not easily explained. High base-metal contents and silver to gold ratios have been postulated by others to reflect high chloride contents rather than sulfide complexing, but additional factors are likely. Chemical trends do not systematically reflect local geology within about 1 km of deposits. One of the few empirical trends for deposits of the Tonopah quadrangle is that silver tends to be enriched relative to gold in volcanic- and plutonic-associated deposits that are localized in carbonate rocks. Chemical trends probably reflect geologic processes deeper in the crust, or the absence of them, as suggested chiefly by a systematic east-to-west difference in elemental abundances. Higher amounts of a mafic suite of elements in deposits in the western part of the Tonopah quadrangle, including gold and copper, suggest a possible source in oceanic rocks (shales or volcanogenic rocks), whereas higher amounts of silver, lead, and molybdenum in eastern deposits possibly reflect a cratonic source. Processes of ore formation are not defined by the lithogeochemical data, but permissive links to genetic processes are suggested by the geochemical signatures. Polymetallic suites, rich in base metals and of interest for silver, possibly are produced by deep-seated processes associated with magmas and magmatic volatiles including chlorine. Chemically contrasting ores of interest for gold more than silver, and containing minor base metals, may reflect near-surface meteoric-dominated waters that lacked chloride and bisulfide for base-metal transport.

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