

U.S. GEOLOGICAL SURVEY CIRCULAR 975



**The Conterminous United States  
Mineral Assessment Program:  
Background Information to  
Accompany Folio of Geologic  
and Mineral Resource Maps of the  
Silver City 1°×2° Quadrangle,  
New Mexico and Arizona**



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Department of the Interior  
DONALD PAUL HODEL, *Secretary*



U.S. Geological Survey  
Dallas L. Peck, *Director*

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# **The Conterminous United States Mineral Assessment Program: Background Information to Accompany Folio of Geologic and Mineral Resource Maps of the Silver City 1°×2° Quadrangle, New Mexico and Arizona**

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## **ABSTRACT**

The Silver City 1°×2° quadrangle, consisting of about 20,650 km<sup>2</sup> in southwestern New Mexico and southeastern Arizona, has been investigated by a multidisciplinary research team for the purpose of assessing its mineral resource potential. The results of this investigation are in a folio of 21 maps that contain detailed information on the geology, geochemistry, geophysics, mineral deposits, and potential mineral resources of the quadrangle. This Circular provides background information on the various studies and integrates the component maps. It contains an extensive selected bibliography pertinent to the geology and mineral deposits of the quadrangle. The quadrangle has produced more than \$3.5 billion in mineral products since about 1850 and contains significant resources of gold, silver, copper, molybdenum, lead, zinc, iron, manganese-iron, zeolite minerals, and possibly tin and tungsten.

Much of the basic data for this folio was collected prior to 1977 in several U.S. Geological Survey and U.S. Bureau of Mines projects, university thesis studies, and investigations by the mineral industry. Since then an interdisciplinary team of Geological Survey scientists has carried on field, laboratory, and library studies necessary to provide the additional data for a mineral resource assessment. The folio consists of 21 maps on the geology, geochemistry, geophysics, and mineral deposits of the quadrangle (table 1). This circular provides a very brief description of the folio elements and an extensive bibliography of the geologic literature pertinent to the Silver City 1°×2° quadrangle.

## **INTRODUCTION**

### **PURPOSE AND SCOPE**

This Circular, together with a separately available group of related maps of the Silver City 1°×2° quadrangle, New Mexico and Arizona, is one of a series of U.S. Geological Survey folios that focuses on the mineral resource potential of the conterminous United States. This folio, prepared under the auspices of the Conterminous United States Mineral Assessment Program (CUSMAP), is intended to (1) provide information for national minerals policy, (2) aid in Federal, State, and local landuse planning, (3) provide data and guidance for minerals exploration, and (4) increase our geologic knowledge of the quadrangle.

## **GEOGRAPHY AND PHYSIOGRAPHY**

The Silver City 1°×2° quadrangle covers approximately 20,650 km<sup>2</sup> in southwestern New Mexico and southeastern Arizona between lat 32° and 33° N. and between long 108° and 110° W. (fig. 1). It includes parts of Grant, Hidalgo, and Luna Counties in New Mexico, and Cochise, Graham, and Greenlee Counties in Arizona. The principal population centers are Silver City and Lordsburg in New Mexico, and Safford and Willcox in Arizona. Interstate 10, U.S. Highways 70, 80, 180, and 666, and numerous state and county roads provide access to most of the quadrangle.

The quadrangle lies almost entirely within the southern Basin and Range province, an area of north- to northwest-trending mountain ranges and

TABLE 1.—Component maps of the Silver City 1°×2° quadrangle folio, New Mexico and Arizona

U.S. Geological Survey Miscellaneous Investigations Series (I) Maps	Subject
I-1310-A (Wynn 1981)	Gravity
B (Richter and Lawrence, 1983)	Mineral deposits
C (Drewes and others, 1985)	Geology
D (Klein, 1986)	Magnetics
E (Watts and Hassemer, 1986)	Interpretive geochemistry
F (Richter and others, 1986)	Mineral resource assessment
G (Klein, 1986)	Interpretive geophysics
H (Sharp, 1986)	Petrochemistry of igneous rocks
U.S. Geological Survey Miscellaneous Field Studies (MF) Map	Subject
MF-1183-A (Watts and others, 1986a)	Geochemistry of lead
B (Watts and others, 1986b)	Geochemistry of copper
C (Watts and Hassemer, 1980)	Geochemistry of fluorite
D (Watts and others, 1986c)	Geochemistry of zinc
E (Watts and others, 1986d)	Geochemistry of molybdenum
F (Watts and others, 1986e)	Geochemistry of silver
G (Watts and others, 1986f)	Geochemistry of tungsten
H (Watts and others, 1986g)	Geochemistry of bismuth and beryllium
I (Watts and others, 1986h)	Geochemistry of tin
J (Watts and others, 1986i)	Geochemistry of manganese
K (Watts and others, 1986j)	Geochemistry of barium
L (Hassemer and others, 1986)	Hydrogeochemistry of uranium
Q (Raines, 1984)	Limonitic alteration

basins. A small area in the northeast part of the quadrangle, characterized by broad volcanic uplands, is in the transition zone between the Basin and Range and the Colorado Plateau provinces. The westerly flowing Gila River and its tributaries form the principal drainage system in the quadrangle; two large playa basins and other smaller central basin areas are drained internally. Elevations range from a low of 820 m, where the Gila River leaves the northwest corner of the quadrangle, to a high of 3,257 m, 35 km south on Mt. Graham in the Pinaleno Mountains.

### HISTORY OF MINING ACTIVITY

The first known mineral development in the Silver City quadrangle was at Santa Rita and Tyrone in New Mexico where prehistoric Indians mined native copper and turquoise prior to Spanish conquest. From about 1801 to 1848, when the area became part of the United States, copper was mined in the Santa Rita area and shipped to Mexico for coinage.

During and immediately following the Civil War, prospecting activity was extremely vigorous, especially in the northeast corner of the quadrangle. By the late 1860's, the rich secondary silver deposits at Georgetown and Silver City, the gold lodes at Pinos Altos and in the Dos Cabezas Mountains, and the replacement and vein deposits at Fierro-Hanover and Bayard had been discovered, and many were being mined. Prospectors rapidly moved south and west across the quadrangle and, despite hostile Indian activity, the next two decades saw most of the principal mining areas established (fig. 2). By the early 1890's, many of the shallow, high-grade enriched precious metal ores were depleted, and the drop in the price of silver in 1893 closed most of the remaining mines. Attention shifted to the base-metal ores in the early 1900's, when copper, lead, and zinc were produced from many of the vein and replacement deposits such as those at Lordsburg, Fierro-Hanover, Santa Rita, Bayard, Steeple Rock, Safford, and Tyrone.

Low-grade, disseminated porphyry copper deposits were first recognized in the quadrangle

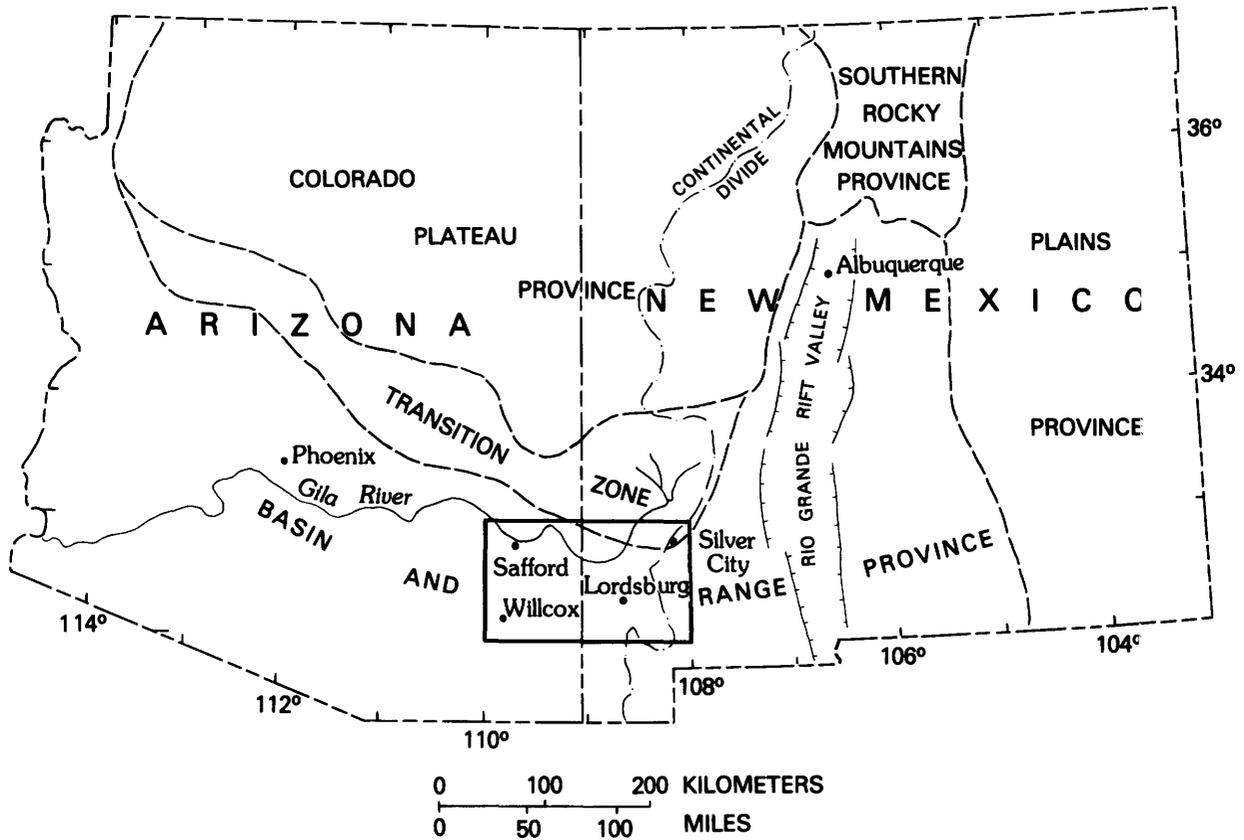


FIGURE 1. Index map of Arizona and New Mexico showing location of the Silver City 1°x2° quadrangle and some major geographic and physiographic features.

at Santa Rita in 1906, and in 1911 large-scale open-pit mining was started. The porphyry copper deposit at Tyrone was developed as a large open-pit mine in 1969, although high-grade copper ore had been produced from a number of underground mines in, and peripheral to, the deposit between 1880 and 1921. The large, buried porphyry copper deposits of the Safford area were not discovered until the 1950's and are now under consideration for development for underground mining.

Magnetite iron ore was mined from the limestone replacement deposits peripheral to the Fierro-Hanover stock between 1916 and 1931. Production of manganiferous iron ore also began in 1916 from the Silver City area and has continued intermittently up to the present time.

World Wars I and II spurred the search for strategic minerals throughout the quadrangle. During these periods of national emergency, especially during and following World War II, many generally small vein deposits of manganese

(Ash Peak, Cap Rock, and Lone Mountain areas) and fluorite (Duncan, Steeple Rock, Redrock, and Tyrone areas) were discovered and mined; except for the mining of fluorite at Redrock, neither commodity has been extensively produced since the late 1950's. Very small tungsten ore bodies from skarn-type deposits were mined following World War II.

The radium boom of the 1920's led to the redevelopment of gold- and silver-bearing veins in the White Signal area for their secondary uranium minerals. Following World War II, these deposits and others throughout the quadrangle were examined as potential sources of uranium, but total production for nuclear energy purposes has been negligible.

In 1950, zeolite minerals were recognized in late Cenozoic ash-fall beds within the lacustrine deposits of the San Simon basin near Bowie. The deposits have produced significant amounts of industrial zeolite minerals since 1960.

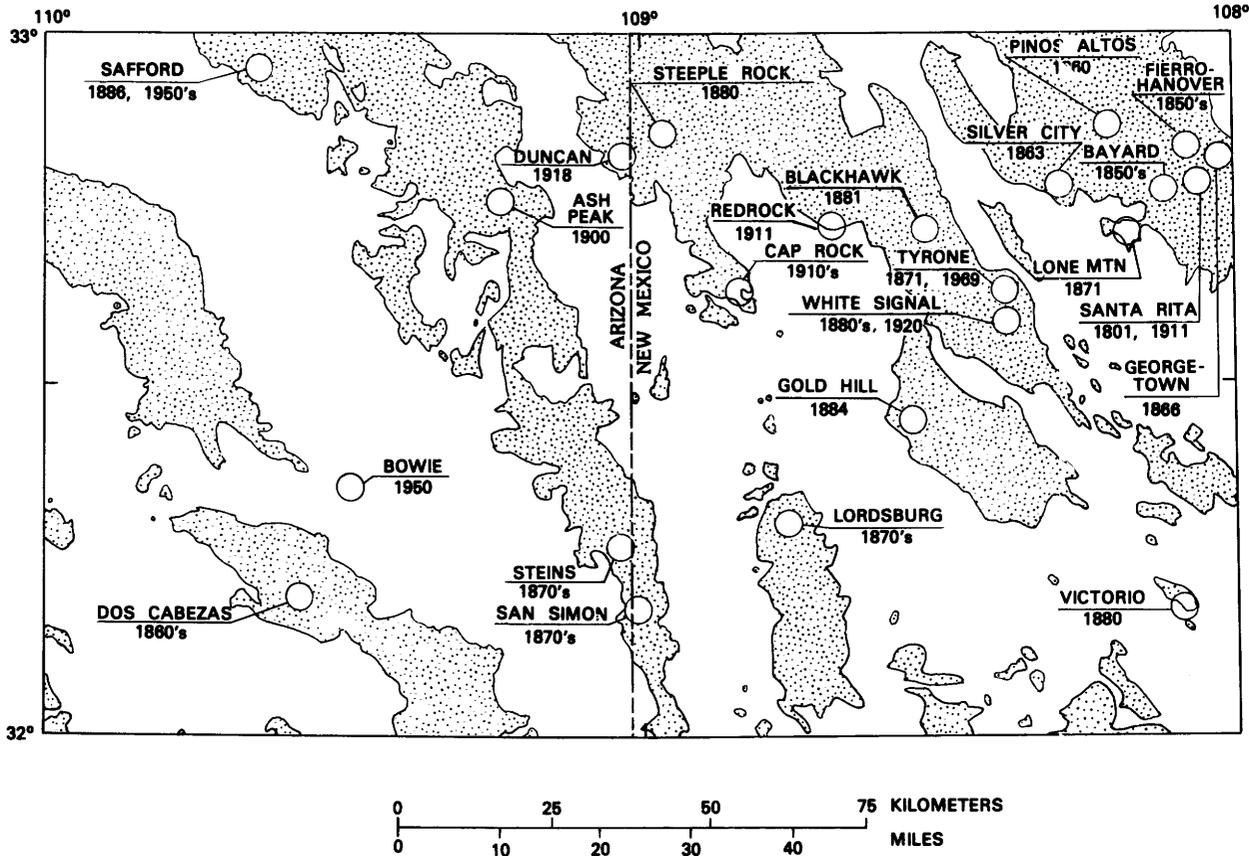


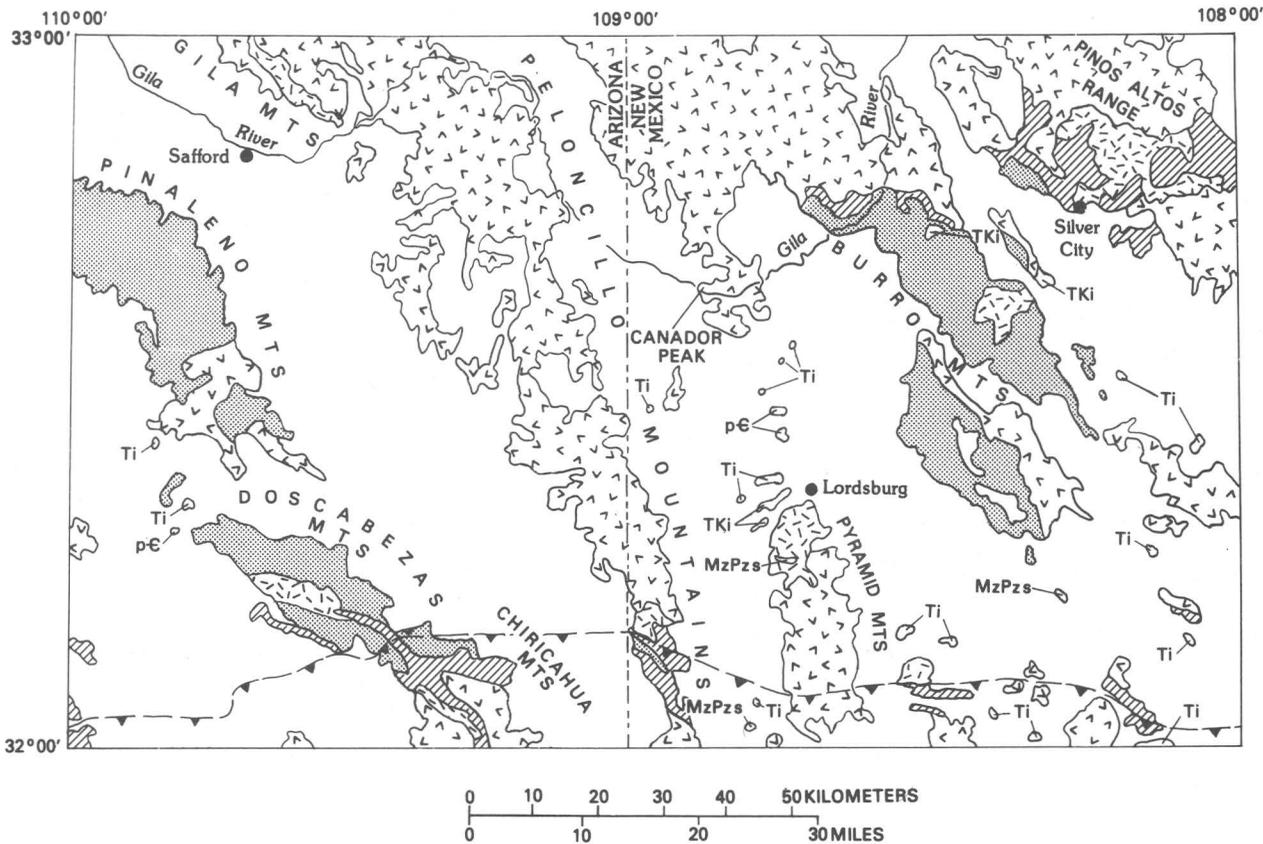
FIGURE 2. Map of the Silver City  $1^{\circ} \times 2^{\circ}$  quadrangle, New Mexico and Arizona, showing principal mining areas and year of discovery. Second date indicates rediscovery or other important milestone in the mining area. Bedrock areas are stippled.

## DESCRIPTION OF COMPONENT MAPS OF THE SILVER CITY $1^{\circ} \times 2^{\circ}$ QUADRANGLE FOLIO

### GEOLOGY (MAP I-1310-C)

The Silver City  $1^{\circ} \times 2^{\circ}$  quadrangle is composed of north- to west-northwest-trending block-faulted mountain ranges consisting of diverse rocks ranging in age from Precambrian through Cenozoic. The mountain ranges are separated by structural and topographic basins filled with late Cenozoic continental sedimentary rocks (fig. 3). Four main groups of rocks exposed in the ranges are, from oldest to youngest, (1) Precambrian metamorphic and plutonic rocks, (2) Paleozoic and Mesozoic sedimentary rocks, (3) Cretaceous and early Tertiary volcanic and plutonic rocks, and (4) mid-Tertiary volcanic and plutonic rocks.

The principal outcrop areas of Precambrian rocks are the Pinaleno and Dos Cabezas Mountains in the southwest and the Burro Mountains in the east. In both areas, thick sequences of chiefly pelitic sediments with lesser amounts of intermediate volcanic rocks (Pinal Schist in the southwest and Bullard Peak "Series" of Hewitt, 1959 in the east) were regionally metamorphosed to amphibolite facies during the Mazatzal revolution (Wilson, 1939; Anderson, 1951), which was between 1,550 and 1,680 m.y. ago. The metamorphosed rocks were intruded by large late-orogenic but chiefly postorogenic granite to granodiorite plutons about 1,450 m.y. ago. Near the close of the Mazatzal revolution, the region was cut by northwest-trending faults with significant offset—both strike-slip and dip-slip. Diabase dikes and other small igneous bodies, probably 1,200 m.y. old, cut both the metamorphic and plutonic rocks. The area was marked by a period of relative tectonic



EXPLANATION

QTs	Quaternary to upper Tertiary sedimentary rocks and surficial materials
Ti	Middle Tertiary volcanic and plutonic rocks
TKi	Lower Tertiary to Upper Cretaceous volcanic and plutonic rocks
MzPzs	Mesozoic to Paleozoic sedimentary rocks
pE	Precambrian metamorphic and plutonic rocks
▲ — ▲	Tectonic boundary—numerous thrust faults on sawtooth side

FIGURE 3. Generalized geologic map of the Silver City 1°x2° quadrangle, New Mexico and Arizona.

quiescence and erosion between about 1,200 m.y. and the beginning of Paleozoic sedimentation. The maximum thickness of Precambrian rocks in the quadrangle is unknown, but is certainly greater than several thousand meters.

Sedimentary rocks of Paleozoic and Mesozoic age are exposed mostly in the northeast part of

the quadrangle in the Pinos Altos Range along the Santa Rita horst and in the ranges in the southern one-third of the quadrangle. Part of the Paleozoic-Mesozoic section may also be present at depth beneath the volcanic rocks of the Gila Mountains in the northwest part of the quadrangle. This is suggested by the presence of large xenoliths of

Precambrian or Cambrian quartzite in Late Cretaceous-early Tertiary stocks on the southwest side of the Gila Mountains.

The lower Paleozoic section is a sequence of dominantly marine shelf sedimentary rocks about 2,200 m thick, with a Cambrian-Ordovician basal clastic unit unconformably overlying Precambrian basement rocks. The middle part of the section consists mostly of Ordovician through Devonian carbonate units. The upper part consists of Devonian through Permian mixed carbonate and clastic units. The sequence is interrupted by several regional disconformities, reflecting epeirogenic movements. Thus, not all units are present systematically across the area.

Mesozoic rocks reflect chiefly continental deposition during the Triassic and Jurassic, when sedimentary processes were strongly influenced by fault-bounded uplifts. Cretaceous marine, deltaic, and fluvial sedimentary rocks were deposited in and adjacent to shallow seas. Triassic-Jurassic rocks (for example, the Walnut Gap Formation) are present only in the Red Bird Hills and Dos Cabezas Mountains in the southwest part of the quadrangle and consist of clastic units with some volcanic rocks. During the Early Cretaceous, the Bisbee Group was deposited to the southwest of the Burro Mountains, and in the Late Cretaceous, the Virden (Elston, 1960) and Colorado Formations and the Beartooth Quartzite were deposited in the Silver City region. Post-Cretaceous uplift during the Cordilleran orogeny resulted in erosion of much of the Cretaceous section from the area to the northeast of the present Burro Mountains and caused a considerable variation in the thickness of the remaining sedimentary section. Northeast of the Burro Mountains the maximum thickness is 700 m; southwest of the Burros the section is 5,000–7,000 m thick.

The Cretaceous and older rocks in the southern part of the quadrangle were displaced by numerous northwest-striking thrust faults during the early compressional phase (beginning about 73–75 m.y. ago) of the Cordilleran orogeny. The amount of crustal shortening that resulted from telescoping along thrust faults is on the order of 15 km. Drewes (1978, 1981) has suggested that as much as 200 km of northeastward movement may have occurred along thrust faults of regional extent.

An extensive calc-alkalic volcano-plutonic arc developed in the later phase of the Cordilleran orogeny. Volcanic and plutonic rocks of Late

Cretaceous and early Tertiary age (70 to 50 m.y.) in the quadrangle are remnants of this arc. The volcanic rocks are chiefly andesitic to dacitic flows that are locally intruded by comagmatic, porphyritic to medium-grained granite, granodiorite, and quartz monzonite subvolcanic plutons. Late-orogenic dikes are commonly coincident with northeast-trending faults and shear zones in the Gila Mountains and with east-northeast-trending faults extending from the Pyramid Mountains northeast to Santa Rita. Most of the volcanic rocks are propylitized, and some of the subvolcanic intrusions are associated with significant copper porphyry deposits or other types of economic mineral deposits. Important areas of outcrop of the volcanic and plutonic rocks of the Cordilleran orogeny are north and east of Silver City and in the Burro, northern Pyramid, central Peloncillo, Dos Cabezas, and Gila Mountains.

A period of quiescence and subaerial erosion marked much of the Eocene. This was followed in Oligocene to mid-Miocene time by voluminous outpourings of volcanic rocks from numerous eruptive centers, consisting of stratovolcanoes, dome complexes, fissures, and plugs. The rocks have high-K calc-alkalic affinities and range in composition from basaltic andesite to rhyolite. They consist of flows, hypabyssal rocks, domes, air-fall and ash-flow tuff, and volcanoclastic conglomerate. Caldera complexes and their extensive ash-flow tuff sheets are particularly evident in the eastern half of the quadrangle and in the Chiricahua Mountains in the southwest. Various types of intermediate to silicic subvolcanic intrusive bodies and medium-grained granodiorite to quartz monzonite plutons were also emplaced during this time. The middle Tertiary rocks are exposed in all the ranges of the quadrangle except the Precambrian outcrop areas of the central part of the Pinaleno and Burro Mountains. Rocks of the middle Tertiary volcanic centers and associated flows form an extensive cover over all the older rocks in many ranges.

The youngest group of rocks in the quadrangle, comprising about 65 percent of the area, are Miocene through Holocene alluvial and lacustrine deposits in the basins and Quaternary surficial materials. The basin fill sediments, collectively grouped as Gila Conglomerate, occupy north- to northwest-trending basins formed by block faulting during the Basin and Range extensional tectonic event which began 12–16 m.y. ago in the area. Alkali basalt flows, ranging in age from 8 to

0.14 m.y., are locally interlayered with the sediments in some basins and are also locally present in some of the ranges. The maximum thickness of the Gila Conglomerate in the quadrangle is not known; however, it is as much as 2,590 m thick east of the Pinalenos, 27 km south of Safford, and it is probably more than 1,000 m in the deeper parts of most basins. The upper 300 m of the Gila Conglomerate is well exposed in basins in the northern part of the quadrangle where it has been dissected by the Gila River. Details of the development of the Gila River system are not known, but the presence of Lava Creek B ash (Izett and Wilcox, 1982) in gravel in the Gila River near Canador Peak suggests that the river became a through-flowing system prior to 600,000 yr ago. Much of the southern half of the quadrangle still has interior drainage and the basins are veneered with surficial materials.

### **MINERAL DEPOSITS (Map I-1310-B)**

The Silver City quadrangle contains a variety of mineral deposits that have produced about \$3.5 billion worth of mineral products, chiefly base and precious metals, since 1850. Map I-1310-B and its accompanying pamphlet are a descriptive compilation of more than 600 mineral deposits at 440 localities. The deposits described range from large operating mines to minor occurrences and are restricted generally to those that have been referred to in the literature. The compilation includes both metallic and nonmetallic deposits, but excludes such commodities as sand and gravel, rock, and most other construction materials that have a low cost per unit volume.

The mineral deposit data are grouped into 11 regional areas, each with a relatively distinct geologic terrane and to some degree a characteristic suite of deposit types. These areas include all the formal and informal mining districts in the quadrangle.

Forty-two specific mineral deposit types are recognized in the quadrangle. The deposits are classified in a broad genetic sense (hydrothermal, magmatic, and so forth) and then further subdivided into more specific types on the basis of physical form or process and metal or mineral content, such as porphyry Cu (Mo), Zn replacement, and fluorite vein. The pamphlet briefly describes the individual deposits in terms of ore minerals,

geologic features, and mining activity and includes a comprehensive economic geology bibliography.

The mineral deposits in the quadrangle range in age from Precambrian to late Tertiary. The major hydrothermal ore-forming systems in the quadrangle developed as a result of subduction-related events during two distinct orogenic periods in the formation of the western continental margin: (1) a medium-K calc-alkalic volcanic arc system in Late Cretaceous-early Tertiary time (the Cordilleran orogeny 80 to 50 m.y. ago) and (2) a high-K calc-alkalic volcano-plutonic arc system in middle Tertiary time (30 to 15 m.y. ago). The hydrothermal magmatic vein- and pegmatite-type deposits are probably Precambrian, and the syngenetic sedimentary and volcanic deposits range in age from Cambrian to late Tertiary or younger.

### **GEOCHEMISTRY (MAPS I-1310-E AND MF-1183-A THROUGH I)**

#### **INTRODUCTION AND METHODS**

Geochemical investigations in the Silver City 1°×2° quadrangle were initiated in the Central mining region of the northeast part of the quadrangle in 1974 (Watts and others, 1984). The scope of the investigation was enlarged to include the entire quadrangle when the Conterminous United States Mineral Assessment Program started in 1978.

The climate and physiography of the quadrangle have a bearing on the methods used to gather geochemical data. The arid to semiarid climate favors secondary dispersion of metals from mineral deposits by mechanical processes rather than by chemical solution. The Basin and Range physiography poses two separate geochemical sampling problems. The ranges can be effectively explored using stream-sediment concentrates, a technique that has been successful elsewhere in the southwest (Griffitts and Alminas, 1968). In contrast, the basin areas are not suitable for stream-sediment techniques because the basin-fill sediments in any given area are not necessarily derived from the underlying bedrock. Ground-water sampling was the approach selected for investigating the basins. Some deposits typical of the basin environment, such as sedimentary uranium deposits, are amenable to hydrogeochemical prospecting, and water interactions with subjacent bedrock may provide clues to metal deposits in the subsurface.

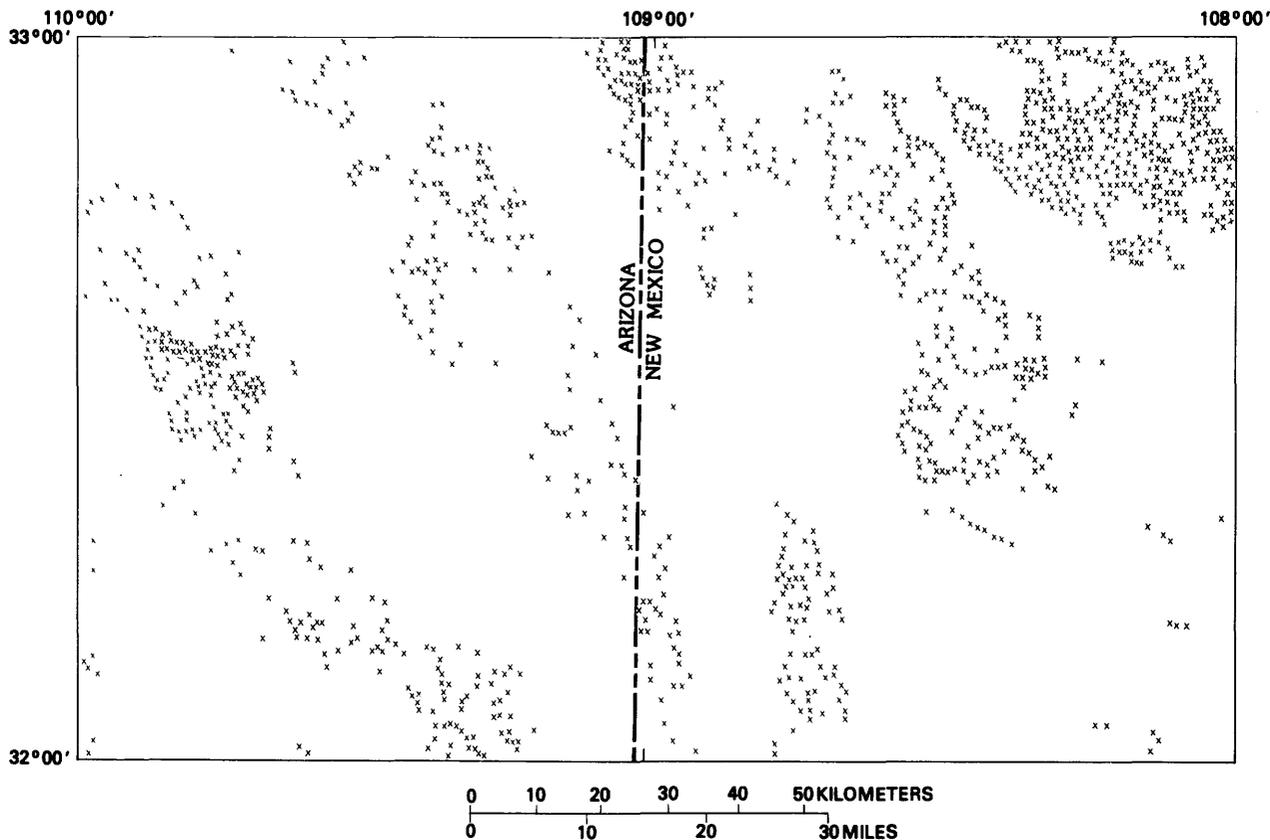


FIGURE 4. Map of the Silver City  $1^{\circ} \times 2^{\circ}$  quadrangle, New Mexico and Arizona, showing locations of stream-sediment samples.

During the geochemical program 2,345 stream-sediment samples (fig. 4), 328 ground-water samples (fig. 5), and 1,273 samples of both mineralized and nonmineralized rocks were collected. The 12 geochemical maps (MF-1183-A through L) of the folio are based chiefly on analyses of the heavy-mineral concentrates of the stream-sediment samples and analyses of the ground-water samples. The maps show element data by symbols representing ranges of analytical values for Pb, Cu, Zn, Mo, Ag, W, Bi, Sn, Mn, and Ba, and whether fluorite was identified in the concentrates. The concentrations of U,  $U/HCO_3$ , and Rn in ground-water samples are similarly shown. Map I-1310-E summarizes these data and presents interpretations relating to patterns of primary mineralization on a regional scale and the effects of erosion and weathering on these patterns.

The stream-sediment samples were collected from the active channels of first- and second-order streams along range fronts within 30 m of the contact between bedrock and basin fill, and on side

and headward tributaries of large canyons. Two types of stream-sediment samples were collected at each sample site: (1) a small (about 0.5 kg) screened sample of fine-grained material, and (2) a large (4-5 kg) bulk sample including sand and gravel. The small samples were sieved to  $< 0.18$  mm but not further separated. The large bulk samples, however, were treated in a series of steps to concentrate the heavy minerals.

Ground-water samples, chiefly from the basins of the quadrangle, were collected from 248 wells, 15 springs and seeps, and 51 storage tanks that were fed either by wells or springs at the site. Two samples of water were collected at each site: (1) an untreated sample used for the determination of the major chemical constituents and (2) a filtered sample ( $0.45\mu$ ) acidified to  $pH < 2$  with ultrapure nitric acid for the determination of trace metals. The majority of analyses were by atomic absorption spectrophotometry (14 elements) and inductively coupled plasma emission spectroscopy (17 elements).

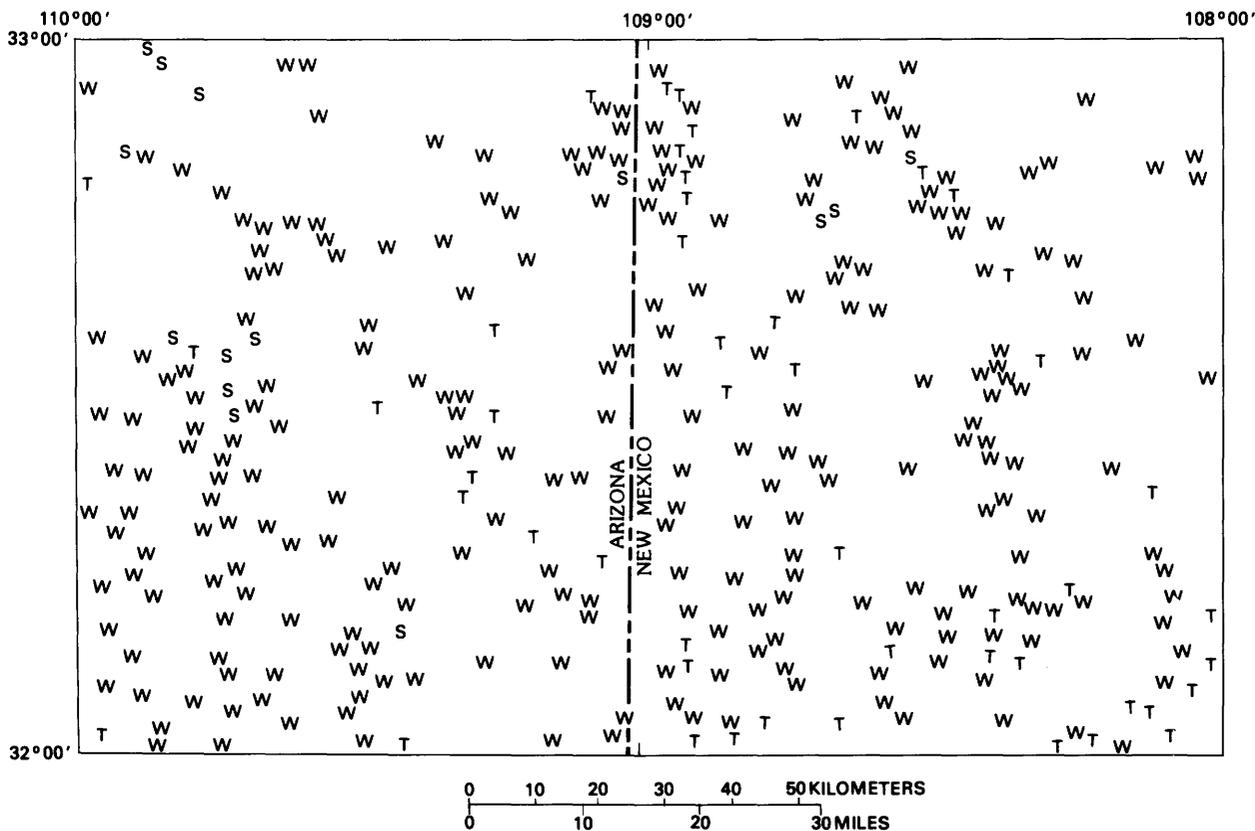


FIGURE 5. Map of the Silver City  $1^{\circ} \times 2^{\circ}$  quadrangle, New Mexico and Arizona, showing locations of ground-water samples: W, water well; T, storage tank; S, spring.

Analytical results for all stream-sediment, ground-water, and rock samples have been released on magnetic tape through the National Technical Information Service (McDanal and others, 1983). Available separately are analytical data on the samples from the northeast corner of the quadrangle (Watts and others, 1978) and the ground-water samples (Hassemer and others, 1983).

A variety of U.S. Geological Survey STATPAC computer programs (Van Trump and Miesch, 1976) were used to develop histograms, correlation diagrams, and map plots, and to do arithmetic manipulations of the geochemical data.

## RESULTS

All stream-sediment samples were analyzed for 30 or 31 elements by semiquantitative emission spectrographic methods (Grimes and Marranzino, 1968). The spectrographic data for the magnetic and nonmagnetic fractions of the heavy-mineral concentrates are shown on the MF-series

geochemical maps. Anomalies from the unconcentrated sieved sediments are subdued replicas of the anomalies shown by the heavy-mineral concentrates and mostly reflect exposed, sizeable mineral deposits. However, the heavy-mineral anomalies for some elements—even those that are weak—may define large areas of the quadrangle that have been affected by ore-forming processes.

The mineralogic composition of the heavy-mineral concentrates has a direct bearing on the geochemical interpretations. The nonmagnetic heavy concentrates contain light-colored accessory minerals (zircon, sphene, and apatite), skarn and gangue minerals (tremolite, diopside, hematite, epidote, carbonate minerals, and barite), rock-forming minerals (muscovite and sillimanite), and ore minerals (pyrite, galena, chalcopyrite, scheelite, cassiterite, fluorite, and wulfenite). The magnetic fraction contains mafic rock-forming minerals (pyroxene, hornblende, biotite), garnet, limonite, and the high-valence oxides of manganese. Element anomalies in the nonmagnetic fraction are related

to (1) primary and secondary ore minerals, (2) heavy gangue minerals, and (3) accessory minerals of unusual composition, such as sphene containing tin. Anomalies in the magnetic mineral fraction have diverse sources from (1) limonite derived from ore minerals and associated gossan in zones of intense chemical weathering, (2) metal-rich (Pb, Zn, Ba, W) oxyhydroxides of manganese and iron introduced by heated meteoric water, (3) oxides of iron and manganese in spring deposits, and (4) relatively magnetic ore minerals or ore minerals intergrown with ferromagnesian minerals from mineralized outcrops.

Anomaly patterns indicate that metals are enriched along regional linear trends and locally are zoned around centers of known or postulated mineralization. The suites of elements and mineral phases involved are, in part, a function of geologic setting and level of erosion. Three types of anomalies are recognized in the quadrangle:

1. Nonmagnetic fractions show anomalies of high contrast characterized by the elements Au, Cu, Bi, Mo, and W. In mining areas high contrast anomalies of Pb, Ag, Zn, Sb, As, and Cd show up as well.
2. Magnetic fractions show anomalies of low to moderate contrast characterized by the elements Pb, Zn, Ba, Mn, and Ag (sometimes with As and Au); these anomalies are associated with oxyhydroxides of manganese and iron, and form broad patterns that parallel the basins and ranges.
3. Anomalies of moderate to high contrast, characterized by the elements Pb, Sn, Be, Ag, Mn, Nb, Th, and U, and fluorite occur in certain nonmagnetic fractions, usually those associated with the middle-Tertiary eruptive centers and generally in combination with magnetic-fraction anomalies of type 2. Some samples taken from subvolcanic intrusions that are more deeply exposed also include anomalous amounts of Mo and Bi, and rarely Cu and Zn.

Two suites of elements from the nonmagnetic fraction at each sample site were used to interpret metal zonation around apparent hydrothermal systems: (1) the inner-zone suite of relatively immobile elements, including Au, Cu, Mo, Bi, and W, that are related to deposits in contact metasomatic and plutonic and subvolcanic environments; and (2) the peripheral-zone suite of relatively mobile elements, including Ag, Mn, Ba, Zn, and Pb, that

are commonly laterally and (or) vertically dispersed from centers of mineralization.

For each sample, the previously defined geochemical contrasts were determined; these values were then grouped according to suite and summed. Finally the sum for the inner-zone suite was divided into the sum for the peripheral-zone suite. The resulting ratio  $(Ag+Mn+Ba+Zn+Pb)/(Au+Cu+Mo+Bi+W)$  was posted by sample location; the map of ratio data was then contoured by cell averaging on the basis of the cumulative percent values on the statistical distribution curve (percentiles). The contour map (fig. 6) thus obtained shows patterns that we interpret to be indicative of zonation around discrete mineralized centers, including some centers that may lie well below the present ground surface. Linear portions of the contour patterns may indicate directional trends of mineralizing solutions.

Figure 6 shows that at least 10 of the middle Tertiary eruptive centers recognized in the quadrangle are dominated by dispersions of elements related to the peripheral-zone suite of elements. Some volcanic centers show anomaly patterns on their peripheries (for example, Ash Peak center); such patterns may be the result of distal hypogene leakage along ring fractures or other permeable zones. However, other eruptive centers (for example, Greasewood Mountain center) show centrally located, somewhat more subdued anomalies of the peripheral-zone suite. These centrally located anomalies, of moderate contrast, may be characteristic of dispersion zones above a shallow yet concealed mineralized mass, related to a partially exposed igneous cupola. In areas with these characteristics, portions of the inner-zone metal dispersions occur at the surface.

Most of the known mineral districts in the quadrangle (see fig. 2) occur in deeply eroded terrane that is depleted in the peripheral-zone suite of elements and therefore shows no patterns on figure 6. Where patterns do occur on figure 6 within an area of known mineral deposits (for example, in the northeast corner of the quadrangle), they may reflect either concealed, mineralized igneous cupolas or solution conduits peripheral to the center of mineralization.

The interpretive method used in figure 6 is experimental and is subject to confirmation through detailed studies. The emphasis of the approach is on detecting the outer fringe of vertically and laterally zoned mineralization in order to identify

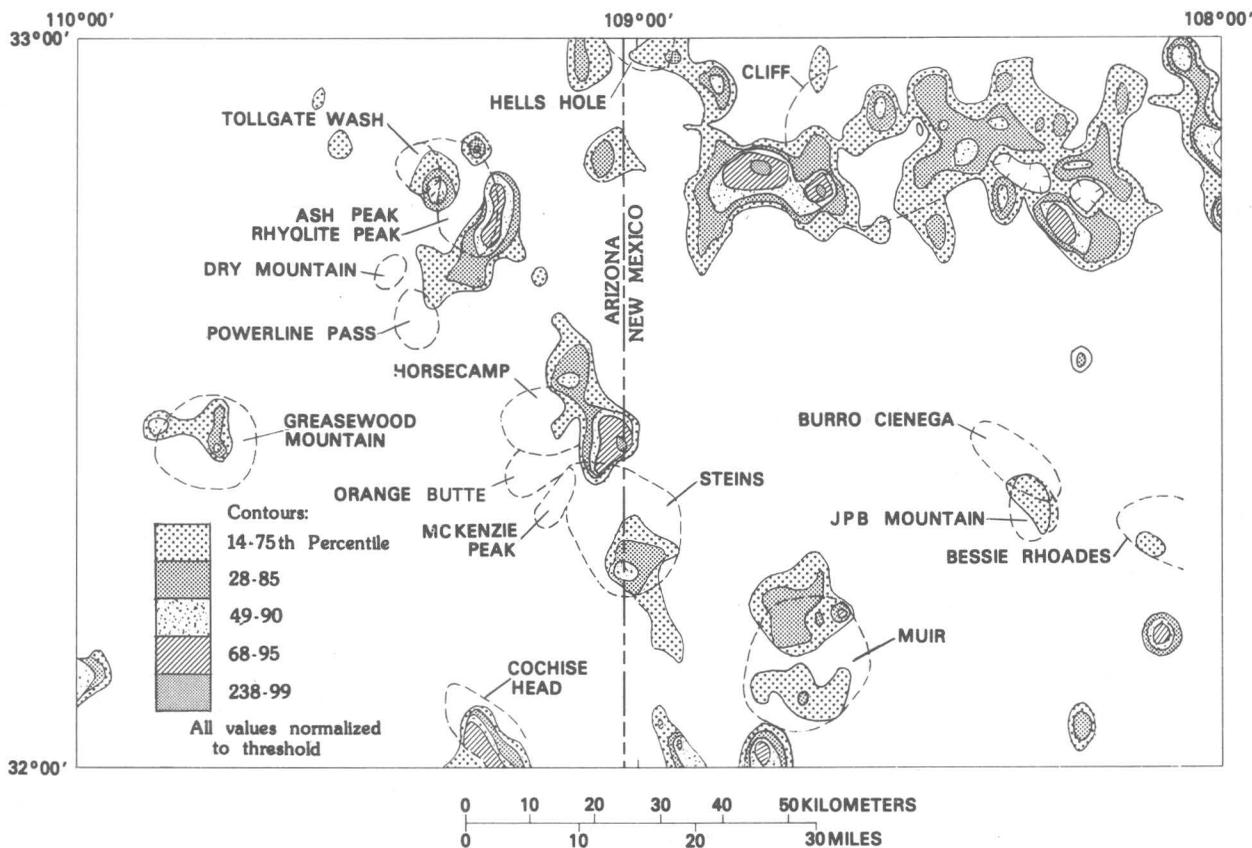


FIGURE 6. Map of the Silver City  $1^{\circ} \times 2^{\circ}$  quadrangle, New Mexico and Arizona, showing relationship of the ratio  $(Ag+Mn+Ba+Zn+Pb)/(Au+Cu+Mo+Bi+W)$  to middle Tertiary eruptive centers (dashed lines). The value of each element is the ratio of its concentration in the nonmagnetic fraction, at each sample site, to the regional background concentration. The values are summed, ratioed, and then contoured on the basis of the 75th, 85th, 90th, 95th, and 99th percentiles.

possible deep, concealed deposits, rather than on detecting areas where mineral deposits are essentially exposed or known. Certain assumptions about element mobilities in hydrothermal solution on which the interpretations are based are from both observations in the Silver City quadrangle and from descriptions in the literature.

### GEOPHYSICS (MAPS I-1310-A, D, AND G)

The complete Bouguer gravity map (I-1310-A, Wynn, 1981) and the aeromagnetic map (I-1310-D, Klein, 1985) of the quadrangle are the bases for a combined geophysical interpretive map (I-1310-G, Klein, 1986). The interpretive map, in two sheets, provides information on bedrock structures and their possible correlation with mineral deposits.

Variations of the gravity field over the quadrangle, which are due to variations of rock

density, may reflect geologic structures that are often buried beneath younger sedimentary and volcanic rock cover. In basin areas, gravity directly supplements geologic observations by allowing interpretation of the extent of relatively shallow bedrock beneath lower density alluvium. Within mountain ranges, the variations in density may reflect zones of subsurface faulting and intrusion that may, in turn, influence the localization of mineral deposits. Two examples of geophysical inferences in the quadrangle that rely in large part on gravity information are (1) the interpretation of a buried bedrock uplift connecting the Lordsburg mineralized area with the Summit Mountains mineralized area and (2) the interpretation of a large area of shallow bedrock northeast of the Victorio Mountains mineralized area. Both areas have the potential for undiscovered mineral deposits beneath a few hundred meters or less of alluvium.

Aeromagnetic data show lateral variations in the total intensity of the Earth's magnetic field, which is related to the vertical and horizontal distribution of magnetic minerals, mainly magnetite, in the crust. The data reflect the magnetic structure of the crust that is produced when different rock types are brought into contact by intrusion or faulting. The magnetization information, to a great extent, reflects geologic conditions hidden beneath alluvium or other cover, and like gravity, allows inferences on structures and rock variations that are not exposed at the surface. Although gravity and magnetic data may be complementary, density and magnetization properties are independent variables that do not necessarily parallel each other. An example, based mostly on magnetic but partly on gravity data, is a zone 10–20 km wide of geophysical features along the southern edge of the quadrangle in which the trend is noticeably more due west than similarly prominent northwest-trending geophysical features found to the north. This zone is interpreted as related partly to thrust-faulted contacts of nonmagnetic carbonate rocks against variable but more magnetic igneous, metamorphic, and volcanic rocks. Areas with similar trends mapped in the Dos Cabezas and Chiricahua Mountains are known to be locally favorable for vein- and replacement-type mineral deposits.

#### **PETROCHEMISTRY OF IGNEOUS ROCKS (MAP I-1310-H)**

The mineral content and major-, minor-, and trace-element chemistry of most of the Mesozoic and Cenozoic granitic intrusive rocks and rhyolitic eruptive centers are compiled and discussed in the two map sheets of Map I-1310-H. The investigation was aimed at determining the chemical and mineralogical characteristics of ore-producing magmas, especially those that may be the host for porphyry copper and molybdenum deposits, stockwork molybdenum deposits, and tin-tungsten deposits. In addition accessory minerals of the intrusive rocks and near-vent extrusive rocks were analyzed by microprobe in an attempt to establish specific residences of metals in the mineral assemblages. The multiple and complex black oxide accessories are particularly significant, as they are an indicator of the metal abundances in the magmas and may have rare metal (Nb, Ta, U, Sn) by-product potential.

Post-Precambrian magmatic activity began in the Late Cretaceous (about 80 m.y. ago) with the advent of the Cordilleran orogeny. This period of volcano-plutonic activity, related in current tectonic models to subduction of an oceanic plate along the western margin of North America (Coney and Reynolds, 1977; Damon and others, 1981), continued through the early Tertiary (about 50 m.y. ago) with the intrusion of an array of calc-alkalic granites and granodiorites. During this volcano-plutonic activity, the porphyry copper deposits and a variety of base- and precious-metal vein and replacement deposits in the quadrangle were formed. Following a period of magmatic quiescence between 50 and 40 m.y. ago, intrusive activity resumed in the Oligocene with the emplacement of both high-K and normal calc-alkalic granites and intrusive rocks. The appearance of high-K rocks may reflect the beginning of a change from compressional to extensional tectonism along the eastern side of the orogenic belt. By the beginning of the Miocene (about 26 m.y. ago), the shift from calc-alkalic magmatism to high-K calc-alkalic magmatism was complete as evidenced by the composition of extrusive rocks and assuming that the nature of the buried intrusive rocks is similar.

Many of the Miocene eruptive systems show characteristics that suggest chemically zoned magma chambers—a maturing process that has produced high-silica, high-K rhyolites and anomalous rare metal concentrations elsewhere. Some of these rocks are fayalite rhyolites; they are high in Rb, low in Sr and Zr, and contain fluorite, F-apatite, ilmenite  $\pm$  Nb, cassiterite, and uraninite as accessory minerals. Locally they are accompanied by small veins or segregations of gas-phase minerals containing Sn, W, Be, U, Mo, and F.

Minor-element plots of rhyolites from some of these middle Tertiary silicic eruptive centers, as well as plots for the granitic intrusive rocks, combined with criteria developed by Hildreth (1980) and Mutschler and others (1981) for assessing the degree of magma fractionation, enable selection of some eruptive centers as deserving further study and perhaps exploration for deposits.

#### **REMOTE SENSING (MAP MF-1183-Q)**

Laboratory remote-sensing studies, consisting of digital image processing and interpretation of Landsat imagery, were used to produce a map of

limonitically altered rocks or areas in the quadrangle. Numerous limonite anomalies in bedrock areas and two limonite anomalies in the late Cenozoic basins were mapped. Most of the bedrock anomalies and one of the basin anomalies are related to areas of known hydrothermally altered rock. The other basin anomaly, on Lordsburg Mesa, may be related to a mineralization process similar to that which produced the calcrete uranium deposits of western Australia.

#### **RESOURCE ASSESSMENT (MAP I-1310-F)**

Geologic, geochemical, and geophysical data from other investigations of the program have been used to assess the quadrangle's mineral resources. The resources evaluated include both metallic and nonmetallic commodities but exclude the organic fuels and most sand, gravel, and rock products. The 42 deposit types recognized in the mineral deposit component (Richter and Lawrence, 1983) of the folio have been adopted as the basic unit in this assessment. In addition to the known deposit types of the quadrangle, the resource potential of several other deposit types for which the geologic environment appears favorable is also discussed.

The assessment is based on identifying geologic terranes favorable for the occurrence of both known and possible deposit types and focuses chiefly on the mineral potential of the mountain ranges. Although favorable geologic terranes for mineralization undoubtedly underlie the late Cenozoic basin areas, their areal extent and the relatively great thickness of fill preclude an appraisal of the underlying bedrock. Locally, known geology of the mountain ranges can be extrapolated into areas of shallow basin fill, and in some places geophysical studies have resulted in a better understanding of regional subbasin geology, but delineation of favorable terranes on the basis of such results is not feasible. Likewise, the extensive areas of middle Tertiary volcanic rocks may cover favorable terranes and possibly significant ore deposits of Late Cretaceous-early Tertiary and older age. Some attempt has been made to peer under the volcanic cover by geophysical means, but again the data are not sufficient to warrant an appraisal.

The approach relies heavily on detailed information that facilitates inferences about the processes that have shaped the geology of the quadrangle and on developing physical-genetic models of the mineral deposit types likely to occur. In general,

the delineation of areas of favorability for the deposit types examined are based on three broad criteria: (1) known deposits, which imply a favorable geologic environment; (2) necessary geologic conditions, such as favorable host rocks, eruptive systems, structures, and source rocks, that indicate the presence of a favorable environment; and (3) suggestive conditions, such as associated deposit types and geochemical and geophysical anomalies, that suggest the presence of a favorable environment. Ranking areas in terms of favorability is largely avoided, although the type criteria used in delineating an area are an indirect guide to its favorableness. However, many areas of favorability based on suggestive criteria may, in fact, become increasingly significant in the future as ore-forming processes become better understood and as more sophisticated exploration techniques are developed. No estimation of the numbers of deposits that may occur in areas of favorability has been attempted, nor has there been any concerted effort to quantify the undiscovered resources (either hypothetical or speculative) of these areas by statistical methods.

In the pamphlet accompanying the map, each commodity, or group of related commodities, is discussed separately. Following a brief introductory statement, the deposit types in which the commodity is a significant constituent are modeled. For a few deposit types, especially some of the precious-metal vein-type deposits mined long ago, data are inadequate to allow more than suggestions about the geology of the deposits. From the models, the criteria used in delineating areas of favorability for each deposit type are tabulated, and the areas are shown on small-scale commodity maps. A summary statement at the end of each commodity section discusses the resource potential and, where possible, quantitative estimates of production, reserves, and identified resources are given. In a few cases the undiscovered resource is estimated, but usually this part of the total resource is discussed in less quantitative fashion.

The production and total resource of the principal commodities in the quadrangle are summarized in table 2. Production of copper, molybdenum, zinc, lead, gold, silver, iron, manganese-iron, fluorite, and zeolite with small amounts of manganese, tungsten, vanadium, bismuth, and uranium since 1850 is valued at about \$3.5 billion. Reserves and identified resources, chiefly of base and precious metals, are valued at more than \$30 billion at current

TABLE 2.—Summary of estimated production, reserves, and resources of the principal commodities in the Silver City 1°×2° quadrangle, New Mexico and Arizona

[Figures are in metric tons; n represents the uncertainty in the order-of-magnitude estimates, that is n is any number from 1 to 9]

Commodity	Production	Reserves	Identified resource	Undiscovered resource
Gold -----	26	200	$n \times 10^2$	$n \times 10$
Silver -----	1,300	1,000	$n \times 10^3$	$n \times 10^3$
Copper -----	4,450,000	8,200,000	8,000,000	$n \times 10^6$
Molybdenite (MoS <sub>2</sub> ) -----	23,000	50,000	38,000	$n \times 10^5$
Lead -----	140,000	-----	$n \times 10^4$	-----
Zinc -----	1,000,000	-----	$n \times 10^5$	-----
Iron -----	7,110,000	-----	$n \times 10^7$	$n \times 10^8$
(50-59% Fe)				
Manganese-Iron -----	2,000,000	10,000,000	$n \times 10^6$	$n \times 10^6$
(10-16 Mn, 30-40 Fe)				
Manganese -----	11,000	-----	$n \times 10^3$	$n \times 10^3$
(17-40 Mn)				
Tungsten -----	2,300	-----	$n \times 10^3$	$n \times 10^3$
(0.1-4 WO <sub>3</sub> )				
Fluorite -----	190,000	-----	$n \times 10^4$	-----
(50-70 CaF <sub>2</sub> )				
Zeolites -----	10,000	-----	$n \times 10^8$	-----

prices. The estimates of undiscovered resources are conservative and bound by existing technology and economics. These resources are restricted chiefly to known areas of favorability in the ranges, with little allowance for discoveries of either known or new deposit types beneath the extensive Cenozoic basins or middle Tertiary volcanic terranes.

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