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EXPLORATION GEOLOGY AND GEOCHEMISTRY
OF THE TOMBSTONE-CHARLESTON AREA,
COCHISE COUNTY, ARIZONA

by

Roger Austin Newell

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A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF
APPLIED EARTH SCIENCES AND THE
COMMITTEE ON THE GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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FC Dinger
Principal Advisor

Charles F. Parkx.

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ABSTRACT

The Tombstone silver mining district in Cochise County, Arizona, was studied in detail prior to 1940, but following World War II, the district has seen little systematic scientific research. The present study applied modern concepts and methods to geologic and related mineral exploration problems at Tombstone.

In part, these problems centered around a complex structural and igneous history. As a means of attacking the structural history, the district was mapped at scales of 1:12,000 and 1:31,250. Field investigations with subsequent potassium-argon age determinations established two ages of mineralization. Silver mineralization at Tombstone, and base metal mineralization at Charleston, provided indistinguishable ages of 72 m.y. and 74.5 ± 3 m.y. respectively. Manganese, and possibly copper, mineralization at Tombstone dates at about 63 m.y. The Uncle Sam "porphyry" was shown to be a tuffaceous eruptive equivalent of the Schieffelin Granodiorite, instead of a previously conceived hypabyssal sill or laccolith. Northeast-trending fractures in the Uncle Sam are mineralized, and the possibility of extending the known mineralization was suggested.

Tombstone was studied from five different photographic scales. Regional structures were best observed on spacecraft photography. Large structures in the district were best studied on high altitude infrared photography. Low-level aerial photography was best suited for detailed mapping studies. Sun angle influences had profound

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Plate

1. Geologic map of the Charleston-Tombstone area,
Arizona; Scale, 1:31,250 in pocket
2. Geologic map of the Tombstone district, Arizona;
Scale, 1:12,000 "
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($\pm 5^{\circ}\text{C}$) at Tombstone proper, and between 243 and 318 $^{\circ}\text{C}$ ($\pm 5^{\circ}\text{C}$) at Charleston.

Seven potential mineral exploration target areas were identified. For further evaluation, three of these areas require the collection of additional geochemical samples, and four areas require drilling.

effects on the ability to observe various structures at different altitudes. Low sun angles of 10° to 30° above the horizon proved to be a valuable factor for increasing the ability to discern individual structures on all photographs studied. For purposes of effective minerals exploration, three different scales of low sun-angle photography are recommended.

Methods of mesquite biogeochemistry were investigated, and sampling problems were identified as a major source of erratic data. To minimize errors, samples should be restricted to uniform branch sizes, and twigs from at least three trees should form a composite sample for each site. Large linear features observed on spacecraft and high altitude photography often follow valleys filled with transported soil and rock debris. Mesquite biogeochemical methods were well suited for studying trace metal concentrations in areas of limited outcrop along large structural features.

Mine dumps were sampled as a means of establishing patterns of metal or chemical zoning in the district. A method of using logarithmic transformations of composite ratio values identified quantitative zones for copper, lead, molybdenum, silver, and zinc. Similar approaches can probably be pursued in other districts.

The nature of the silver mineralogy was studied, and primary silver-bearing minerals were found to include hessite, tetrahedrite, and galena. Electron microprobe studies resulted in the first reported occurrence of altaite at Tombstone. The first occurrence of gold-bearing hessite from the Empire mine was also reported. Fluid inclusion filling temperatures obtained from quartz associated with the major paragenetic minerals ranged between 205 and 279°C

CHAPTER I

INTRODUCTION

Purpose

The general purpose of this investigation was to evaluate the mining district at Tombstone, Arizona, for additional mineralization, through the application of modern geologic concepts and exploration methods. To assist in achieving this objective, the following specific questions were formulated:

1. How accurate were the previous geologic descriptions for the Tombstone district?
2. What is the nature and economic significance of the Uncle Sam "porphyry?"
3. What is the age of the mineralization?
4. What are the relative applications in mineral exploration of multiscale aerial and space photography?
5. Can mesquite biogeochemistry be used to sample trace element concentrations along linear structures identified on aerial photos? What are the limitations of the mesquite biogeochemical method?
6. Can patterns of element and mineral zoning be established for the Tombstone district? What is the mineralogy of the zones, and what were the temperatures at which the ore minerals formed?

Location and Accessibility

The area of this study includes about 137 square miles, and extends from about 2 miles east of the town of Tombstone to about

2 miles west of the San Pedro River (fig. 1). The northern boundary is about 2 miles north of Tombstone, and the southern boundary is about 11 miles south of the town.

Tombstone is about 60 miles southeast of Tucson, and can be reached by traveling east on Interstate Highway 10 to Benson, and then southeast along Arizona Highway 80. Bisbee lies 24 miles southeast of Tombstone. The Southern Pacific Railway, which serves Bisbee, traverses the area along the San Pedro River. Two short airstrips lie within the area; one is 3 miles southeast of Tombstone, and a second is about half a mile east of the Charleston lead mine. Access within the mapped area is by numerous dirt and gravel roads (pls. 1, 2).

Culture and Production

The town of Tombstone has about 1200 inhabitants. The residents thrive on Tombstone's rich historical background, and the town has been designated as a National Historical Monument. The first mining claim was located in the district in 1857 (Butler, Wilson and Rasor, 1938, p. 40; Keith, 1973, p. 12), but it was not until 1877 that Edward Schieffelin discovered rich silver deposits at Tombstone proper.

From its earliest days the district has been plagued by severe mine water problems and fluctuating silver prices. In March 1881 water was first encountered in the mines at a depth of 520 ft, and early in 1884 initial pumping procedures began. Pumping operations continued successfully until May 1886 when fire paralyzed the pumping works. Many of the rich deposits were already exhausted above the water table, and a low silver price (\$0.98/oz as compared to \$1.20/oz)

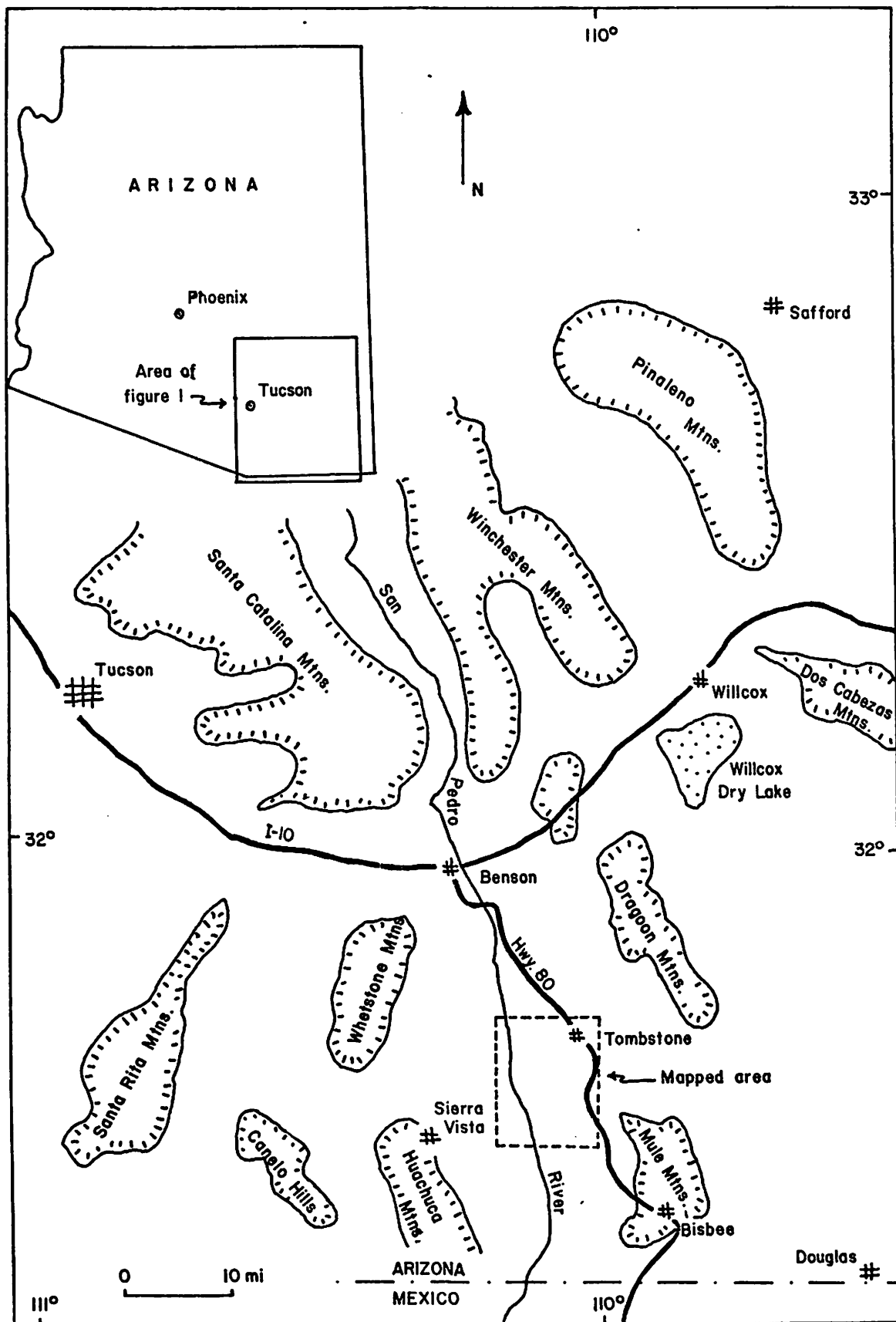


Fig. 1.--Index map of the Tombstone area, southern Arizona.

coupled with the loss of the pumping facilities forced many mines to close. By 1901 the larger mines were consolidated into a single company, and renewed efforts were made to drain the district. In 1906 a new pump shaft was completed to the 1000 ft level, and the mines were able to continue successful operations until 1909 when a defect in the pumping works caused the 1000 ft level pumps to cease operation. In 1910 the pumps on the 1000 ft level were recovered, and mining was resumed. Between 1908 and 1909, water was pumped from the mines at a rate of about 5 million gallons/day (gpd), and by January 1911, the financial strain of high pumping costs combined with a low silver price (\$0.50/oz) forced the closure of the major mines. The smaller companies continued with limited production above the water table, but by 1918 most of the mines were operated by lessees. With the exception of reprocessing of mine dumps, and minor lead and copper production, the district experienced little mining activity in the years following 1918.

Between 1879 and 1970, the total estimated production was about \$38.8 million (Keith, 1973). From 1879 to 1886 mineral production totaled about \$18 million (Butler, Wilson and Rasor, 1938, p. 38). Estimated production between 1936 and 1970 is about \$1.8 million (Keith, 1973). From 1879 to 1970, Keith estimated that the district produced about 1.5 million short tons of ore which yielded 3 million pounds of copper, 45 million pounds of lead, 240 thousand ounces of gold, 30 million ounces of silver, and 9 thousand tons of manganese ore.

Climate, Water Supply, and Vegetation

Tombstone's climate is semiarid, and typical of the intermediate altitudes in southern Arizona. The elevation at Tombstone is 4530 ft, and the maximum elevation in the surrounding hills is 5320 ft. The mean annual precipitation at Tombstone is 14.56 in., and the mean annual temperature is 62.7°F (Gilluly, 1956, p. 5). Seventy percent of the precipitation is from intense storms during July, August, and September (Hollyday, 1963, p. 5).

The northward flowing San Pedro River has perennial flow for several miles south of Charleston. North of Charleston, the San Pedro, as with all drainages in the mapped area, has intermittent flow. The initial permanent water supply for Tombstone was piped 27 miles from the Huachuca Mountains in the west. The pipeline, which was completed in 1882 (Engineering and Mining Journal (E/MJ), 1882, v. 34, p. 46-47), was capable of delivering 1.5 million gpd at a pressure of 170 lb/in.² Mine water, first encountered in the Sulphurette at a depth of 520 ft (E/MJ, 1881, v. 31, p. 252), was thought to flow at about 1000 gallons/minute (gpm). The water table was at an elevation of about 4120 ft, or only 120 ft above the elevation of the San Pedro River at Charleston. The present water supply for Tombstone is derived from nearby municipal wells.

Vegetation in the area is similar to that of other areas with intermediate elevations in southern Arizona. The flora includes cat's-claw, cholla, creosote, mesquite, ocotillo, paloverde, prickly pear, and walnut. The district does not contain timber suitable for mine use.

Previous Investigations

The geological and mining literature abounds with references to the Tombstone district, and attention will be limited to those which provide significant insight into the geology and the development of the area.

Between the years 1879 and 1886 E/MJ published numerous notes concerning the nature, extent, and progress of underground development work in the district. The interested reader is referred to these references, as many of them lie outside the scope of this dissertation. E/MJ (1881, v. 31, p. 316-317) stated the Tombstone silver ores were mostly of a carbonate or chloride nature, and that production was about 300 tons/day. Recoveries were about 80 percent, and the average yield was about \$75/ton. E/MJ (1883, v. 35, p. 267-269) reported that on the third level of the Westside mine the ore was assaying about 40 oz/ton silver and about 0.5 oz/ton gold. Manganese ore from the Lucky Cuss mine at a depth of 100 ft, carried about 25 oz/ton of silver. E/MJ (1883, v. 36, p. 229-230) announced the discovery, between the third and fourth levels, in the Westside mine, of several tons of telluride ore that averaged \$1200/ton.

Previous Geological Investigations

Blake (1882a, b, c, d) provided the earliest geologic descriptions of the district, and he recognized that the mineralization was closely associated with north-south trending dikes and cross-cutting northeast-southwest fissures. He also stated that, where either dikes or fissures crossed anticlinal structures, mineralization often developed

along crests of the folds as bedded replacement deposits. Comstock (1900, p. 1045, 1089) confirmed that folds were important to ore deposition at Tombstone, and he apparently recognized a possible influence of volcanism in the genesis of the mineralization.

Church (1902) described the location of Tombstone relative to other mining districts in southeastern Arizona and adjacent Mexico. He later attempted the earliest comprehensive description of general geologic features in the district (Church, 1903). Church believed that dikes in the district exercised a relatively minor control on the mineralization, and that the major controls were anticlinal folds and cross-cutting fissures. Lakes (1904) followed the interpretation of Church (1903), and compared anticlinal structures at Tombstone with those at Bendigo, Australia.

Between 1904 and 1920 little was published that dealt with the geology in Tombstone. Clark (1914) published a water analysis from the 1000 ft level of the Contention mine. Ransome (1916) correlated some stratigraphic units with those at Bisbee, and Staunton (1918) described the effects and nature of a relatively severe earthquake he experienced while underground at Tombstone in 1887.

Ransome (1920) described the manganese mineralization at Tombstone. High concentrations of manganese were associated with the Prompter fault (pl. 2), and the principal manganese production was derived from the Oregon, Prompter, Lucky Cuss, Luck Sure, Bunker Hill, and Comet mines. Psilomelane, the major manganese mineral, typically occurred in pipes and chimneys in limestone horizons, and part of the manganese was believed to have been derived from the limestones. Ransome also thought that some of the manganese

originally formed upper portions of the associated silver deposits. In either case, supergene processes were considered to have been responsible for forming the present manganese deposits. High grade mineralization contained between 70 and 80 percent MnO_2 after sorting, while low grade mineralization contained about 40 percent MnO_2 . Ransome mentioned that in 1917 the manganese ore contained between 7 and 8 oz/ton silver. Wilson and Butler (1930) described many known manganese deposits in Arizona, and these authors simply referred to Ransome's work for their discussion of the Tombstone deposits.

The geology at Tombstone was investigated in more detail during the later 1930's. Butler and Wilson (1937) noted that the mineralization was associated with north-south dike fissures, faults, anticlines, and northeast-southwest fissures. Rasor (1937) investigated the mineralogy and petrography of the district, and he found hypogene silver-bearing minerals to include hessite, tetrahedrite, and galena. Alabandite was found to be the only definitely hypogene manganese mineral. Bromeyrite, embolite, cerargyrite, argentite (acanthite), stromeyrite, native silver, and argentojarosite were identified as supergene ore minerals. The zone of oxidation was thought to be at least 600 ft deep (Rasor, 1937, p. 83), and bromeyrite was believed to be the most abundant supergene silver mineral. Butler, Wilson and Rasor (1938), and Butler and Wilson (1938) published detailed studies of the geology and ore deposits at Tombstone. These studies incorporated a considerable amount of previously unpublished data which were originally collected by Ransome. The investigations provided insight into a complex sequence of structural events in the district, and the authors also suggested a broad pattern of mineral zoning. Tenney (1938) reviewed

and summarized the findings of Butler, Wilson and Rasor (1938), and noted that their efforts provided a welcome addition to the study of ore deposits. Butler and Wilson (1942), in addition to the above publications, again summarized their work at Tombstone in Newhouse (1942).

Ingerson (1939) measured joint and platy inclusion orientations within the Uncle Sam "porphyry" (pls. 1, 2). The Uncle Sam unit lies west of Tombstone, and Ingerson attempted to confirm the presence of a suspected thrust fault below the "porphyry." He found that neither the joints nor the inclusions could be used as evidence to confirm a fault at depth. The emplacement of the Uncle Sam "porphyry" was discussed at length by Gilluly (1945), and he considered the body to be either laccolithic or sill-like in form. Furthermore, it was believed that the Uncle Sam unit had followed either a thrust fault plane or an unconformity during emplacement.

Gilluly, Cooper and Williams (1954) described the Late Paleozoic stratigraphy of central Cochise County. For the Tombstone portion of their study, these authors succeeded in subdividing a thick sequence of Pennsylvanian-Permian strata known as the Naco Limestone into six different formations. Later, Gilluly (1956) incorporated his earlier work on the Uncle Sam "porphyry," with the stratigraphy to provide an exhaustive description of the geology of central Cochise County.

In 1941 the United States Bureau of Mines began a study of the manganese deposits at Tombstone. The investigations involved underground sampling at a number of mines in the district, and about 2000 ft of underground drilling at the Oregon mine. Needham and Storms (1956)

summarized much of this work, and concluded that only small and scattered deposits of manganese ore were present. Farnham, Stewart and Delong (1961) studied the manganese deposits in eastern Arizona and visited the deposits at Tombstone. They found that manganese concentrations were often between 10 and 30 percent MnO_2 , and that silver in the manganese frequently ranged between 5 and 10 oz/ton.

Burnham (1959) studied trace element abundances in sphalerites and chalcopyrites from many localities in the western United States and northern Mexico. The elements studied included silver, bismuth, cadmium, gallium, germanium, indium, manganese, antimony, and tin. The silver content in three sphalerite samples from Tombstone ranged between 1 and 300 ppm. Burnham (1959) found that all major silver mining districts studied could be identified by relatively high silver concentrations in sphalerite and chalcopyrite.

Creasey and Kistler (1962) determined radiometric ages for an intrusive rhyolite and the Schieffelin Granodiorite (pls. 1, 2) by potassium-argon methods as 63 and 72 m.y. respectively.

Andreason, Mitchell and Tyson (1965) published an aeromagnetic map for the area around and including Tombstone. Background values at Tombstone were about 300 to 400 gammas, but the granodiorite was found to have values between 700 and 1000 gammas. Brant (1966) found the Schieffelin Granodiorite to have a magnetic susceptibility of 1800×10^{-6} (c.g.s. units). Brant assumed the Schieffelin to be of Tertiary age, and he stated that this relatively high susceptibility was typical for Tertiary intrusives in southern Arizona. In fact the Schieffelin is a Laramide intrusive (Drewes, 1971), and Brant (1966) stated that most Laramide intrusives in southern

Arizona have an average susceptibility of only 100×10^{-6} . Thus, for a Laramide intrusive, the Schieffelin is anomalously magnetic.

Jones (1961, 1963, 1966) studied tectonic deformation patterns in southeastern Arizona. He concluded that the contribution of overthrusting had been greatly exaggerated, and that processes of differential vertical uplift were responsible for much of the observed deformation.

Lee (1967) described the geology of the area surrounding the Charleston and State of Maine mines, both of which lie southwest of Tombstone. He suggested that the mineralization at Charleston and the State of Maine was epithermal, and that the mineralization closer to Tombstone was mesothermal.

Patch (1969, 1973) studied the petrology and stratigraphy of the Permian Epitaph Dolomite at Tombstone. She suggested that the Epitaph was most likely a dolomitized facies of the underlying Colina Limestone. Wilt (1969) studied the Colina Limestone, and she agreed with Gilluly *et al.* (1954) that the limestone ranged in age from Wolfcampian to Leonardian (lower Lower Permian to upper Lower Permian).

Ridge (1972) discussed the general geologic setting of Tombstone. He also speculated that the mineral deposits had formed in an environment which varied from xenothermal to epithermal conditions.

Previous Mineralogical Investigations

E/MJ (1881, v. 31, p. 316-317) reported that the Tombstone silver ores were mainly of chloride varieties, and that the ore contained a little lead. In 1883, E/MJ (v. 36, p. 229-230) reported

the discovery of several tons of telluride ore between the third and fourth levels of the Westside mine.

The earliest scientific discussion of the mineralogy at Tombstone was that of Hillebrand (1886). He reported the presence of emmonsite, a hydrated ferric tellurite. Genth (1887) described hessite from the Westside mine. Hillebrand (1889) published an analysis of descloizite from the Lucky Cuss mine. Panrose (1890) noted the presence of manganiiferous silver ore at Tombstone, and Moses and Laquer (1892) reported the existence of alabandite at the Lucky Cuss mine. Hewett and Rove (1930) discussed the occurrence of alabandite in the Lucky Cuss mine in association with calcite, quartz, and galena. Occurrences of silver-bearing manganese minerals in Arizona and New Mexico were studied by Hewett and Pardee (1933), and they found that silver was present as silver manganite. These authors observed that black calcite was commonly associated with the manganese deposits, and that the calcite had black manganese oxide intergrowths that could be manganite, but not hausmannite.

Rasor (1937) conducted the first detailed study of the mineralogy at Tombstone. He identified four main stages of hypogene mineralization, and his investigations were summarized by Butler, Wilson and Rasor (1938). Rasor (1938) apparently reported the first United States occurrence of bromeprite at Tombstone. He speculated that earlier reports of "horn silver" from Tombstone may actually have been mistaken, and that the mineral was possibly bromeprite. Rasor (1939) stated that psilomelane was the most abundant secondary manganese mineral, but that minor amounts of polianite, pyrolusite, manganite, hetaerolite, and wad were also present. He believed the secondary

manganese minerals were derived entirely from alabandite; however, Hewett and Radtke (1967) suggested the main source of secondary manganese at Tombstone was black mangiferous calcite. Hewett (1972) reviewed the origin of the manganese minerals manganite, hausmannite, and braunite. He concluded that hausmannite is a hypogene mineral, and that manganite and braunite are supergene minerals. Hewett also noted that neither hausmannite, manganite, nor braunite had been reported at Tombstone. For southern Arizona, Hewett observed that the minerals hollandite, psilomelane, and cryptomelane formed most of the manganese oxide deposits, and he assigned a hypogene origin to all of them. Ridge (1972) believed that sphalerite containing chalcopryrite blebs indicated possible xenothermal conditions, that tetrahedrite with silver-bearing galena suggested a kryptothermal environment, and that hessite with stromeyerite designated epithermal conditions.

Previous Milling and Smelting Investigations

The earliest mention of milling procedures at Tombstone (E/MJ, 1879, v. 27, p. 468) indicated the successful operation of a 10 stamp mill, which yielded a recovery of about 77 percent. In 1881 about 120 stamps were in operation at Tombstone, treating about 300 tons/day (E/MJ, 1881, v. 31, p. 316-317). Austin (1883) described early milling methods and machinery at Tombstone. Church (1887a, b) discussed metallurgical problems which arose during the treatment of sulfide ores and tailing slimes. Goodale (1889, 1890) discussed the treatment of silver-bearing manganese ore. Free milling methods recovered only 60 percent of the silver, and required more than 7 lb

of quicksilver per ton of ore treated. By using a chloride roasting method the recovery increased to about 90 percent, and the amount of quicksilver required was reduced by half.

Romslo and Ravitz (1947) reported the successful treatment of manganese-silver ore from Tombstone. Very poor results were obtained by direct cyanide and flotation methods, but a calcium dithionate process recovered 80 to 90 percent of the silver and 90 percent of the manganese.

Previous Hydrological Investigations

After water was first encountered in the Sulphurette mine in 1881, pumps with a capacity of 700 gpm were installed at the Contention and Grand Central mines in December 1883 (E/MJ, 1883, v. 36, p. 328, 400). The pumps worked successfully until 1886, when the Grand Central pumphouse burned (Dunning, 1959). E/MJ (1902, v. 73, p. 314-315) reported that new pumps, with a capacity of 1750 gpm, would be installed near the Contention mine. Blake (1904a, b) mentioned that the new pumps had successfully lowered the water level over 100 ft to near the 700 ft level of the Contention mine. E/MJ (1904, v. 77, p. 334-338) reported that pumping activities at the Contention mine had lowered the water table over 80 ft in the Lucky Cuss mine, which was more than a mile away. The water temperature was reported to be about 80°F.

Walker (1909) stated that water volumes of up to 4500 gpm were not uncommon. He also discussed the nature of the pumping facilities at Tombstone. On June 1, 1909, the pumps failed (Staunton, 1910; Butler, Wilson and Rasor, 1938, p. 47; Dunning, 1959, p. 187-189)

on the 1000-ft level. For a period of 10 days prior to the accident the pumps were yielding 4600 gpm. In 1910 larger pumps and new boilers were installed, and operations were resumed on the 1000 ft level. High pumping costs coupled with a low silver price (about \$0.50/oz) forced abandoning the operations on January 19, 1911. The water pumps still remain on the 1000-, 800-, 700-, and 600-ft levels (Butler, Wilson and Rasor, 1938, p. 47).

Hollyday (1963) considered that mine waters at Tombstone could provide a long term source for moderate amounts of municipal water. The water supply was determined to be sufficient for a town about the size of Tombstone.

Wallace and Cooper (1970) studied the dispersion of calcium, chlorine, magnesium, and sodium in groundwater near Tombstone. They found that most of the chlorine (10 to 40 ppm) was derived from the Schieffelin Granodiorite, and that sodium (20 to 70 ppm) was derived from granitic rocks at Tombstone as well as from similar rocks in the Dragoon Mountains to the east. Calcium and magnesium (30 to 80 ppm, and 10 to 25 ppm respectively) were derived from carbonate sedimentary rocks. The authors found calcium and magnesium to be excellent tracers of groundwater flow for the Tombstone area, and subsurface flow patterns were established by measuring the calcium and magnesium contents in the groundwater.

Present Investigations

The Tombstone district was thoroughly studied by the end of the 1930's, and little has been done to update the earlier investigations.

The present study is an attempt to re-evaluate the district through the use of relatively modern concepts and methods.

The portion of the district surrounding the town of Tombstone was mapped on a scale of 1:12,000. From this part of the investigation, it was hoped that the age of the mineralization could be determined, and that the presence of two small thrust faults (Gilluly, 1956, pl. 5) northwest of Tombstone (secs. 32, 33, T. 19 S., R. 22 E.) could be proved or disproved. In addition, it was intended to gain insight into the complex sequence of structural events.

In order to investigate the nature of the Uncle Sam "porphyry" (Gilluly, 1945, 1956), and to study the occurrence of mineralization near Charleston, the area west of the State of Maine mine (pls. 1, 2) was mapped on a scale of 1:31,250. During this portion of the investigation, efforts were made to determine dike patterns, joint patterns, and lava flowage patterns in the Uncle Sam "porphyry." An attempt was also made to extrapolate the northeast trending ore fissures (Butler, Wilson and Rasor, 1938, p. 67) through the Uncle Sam "porphyry."

Aerial and space photography are available for the Tombstone district, and the utility of multiscale and multiband photography in mineral exploration was investigated. Photography from the Apollo VI space flight, and the ERTS-1 (Earth Resources Technology Satellite-1) were examined. High altitude photography from an RB57F aircraft was integrated with the space photography and with two sets of lower level photography.

Two geochemical methods were utilized. Mine dumps were sampled, and the samples were analyzed for copper, lead, molybdenum, silver,

and zinc. The mine dump samples were used as an aid in the identification of trace and major element zoning patterns. Mesquite trees have been shown to be suitable for biogeochemical prospecting (Brown, 1970; Huff, 1970), and it was decided to utilize the method at Tombstone. The U. S. Department of Agriculture field office at Tombstone has investigated groundwater dispersion patterns in the area (Wallace and Cooper, 1970), and the biogeochemical data were integrated with the patterns of groundwater dispersion. Problems related to mesquite sampling and metal uptake rates were also studied.

A set of underground ore samples originally collected by Rasor (1937), from now generally inaccessible mine workings, was obtained from the Arizona Bureau of Mines. The silver mineralogy was re-examined, and fluid inclusion filling temperatures in quartz were measured. Similar studies were conducted on suitable samples obtained from mine dumps in the district.

In summary, the above-mentioned present investigations were selected to aid in evaluating the district for additional mineralization. The approach used at Tombstone is an example of how relatively modern exploration methods can be used to re-evaluate other mining districts. In addition to the strict utilization of new exploration methods, limitations of the various methods and problems inherent in their application were studied. Possible solutions to some of these problems are suggested. The integration of space photography, lower level aerial photography, field mapping, structural and petrologic interpretations, mesquite biogeochemistry, mine dump geochemistry, and detailed ore mineralogy provided considerable assistance in

the identification of previously unsuspected target areas for mineral exploration near Tombstone.

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CHAPTER II

GENERAL GEOLOGY

Regional Geology

Precambrian

Precambrian rocks, which are widespread in southern Arizona and southwestern New Mexico, have been divided into older and younger groups (Butler and Wilson, 1938). In the Grand Canyon, older Precambrian rocks lie below a distinct unconformity which separates the metamorphic rocks of the Vishnu Schist from overlying unmetamorphosed rocks of the Grand Canyon Series. At the Grand Canyon, in central Arizona, and in southeastern Arizona, the older Precambrian rocks are referred to as the Vishnu Schist, the Yavapai Series, and the Pinal Schist respectively. Anderson (1966) stated that the Vishnu Schist is about 25,000 ft thick, that the Yavapai Series may be about 40,000 ft thick, and that the Pinal Schist has a thickness of between 9000 and 20,000 ft. Younger Precambrian rocks at the Grand Canyon consist of the 12,000 ft thick Grand Canyon Series. The 1600 ft thick Apache Group, exposed in south-central Arizona, may be the younger Precambrian equivalent of the Grand Canyon Series (Anderson, 1966, p. 8). Minimum ages for the older Precambrian rocks range between 1200 and 1500 m.y., while 1075 ± 50 m.y. has been reported as a minimum age for the younger Precambrian (Anderson, 1966).

Paleozoic

Paleozoic sedimentation commenced following a long period of erosion in Arizona. The Cordilleran geosyncline, which formed west of a line from southern California to eastern Nevada during Cambrian time, was separated from the northern margin of the Sonoran geosyncline, in southeastern Arizona and southwestern New Mexico, by the Defiance Positive Area (Anderson, 1966, 1968). The Defiance Area thus existed in northeastern Arizona, and extended into central and northern New Mexico. Clastic and carbonate rocks were deposited in southeastern Arizona, during Cambrian and Ordovician time, near the northern edge of the Sonoran geosyncline. The shelf area of Cambrian sedimentation in southeastern Arizona was uplifted during Silurian time, and no Silurian rocks have been identified in southern Arizona. During Devonian and Mississippian time the shelf areas were again submerged, and served as depositional sites for mainly carbonate material. Pennsylvanian strata lie disconformably upon Mississippian strata, and are in turn conformably overlain by Permian deposits. In southern Arizona, the Pennsylvanian and Permian rocks are mainly marine carbonates, but northward these carbonates change to deltaic, floodplain, and sand dune red bed deposits.

Mesozoic

Following the deposition of carbonate rocks in southern Arizona, the land was uplifted, and during Triassic and Jurassic time, southern Arizona and southwestern New Mexico was a nondepositional area. Hayes, Simons and Raup (1965) have reported thick volcanic sequences

and large areas of plutonic rocks with Triassic and Jurassic ages in southern Arizona. Considerable deformation of the Paleozoic rocks occurred in southeastern Arizona, before the onset of Cretaceous sedimentation.

During Early Cretaceous time a new depositional basin formed in southeastern Arizona and southwestern New Mexico, and more than 20,000 ft of marine, continental, and volcanic rocks were deposited in this basin (Anderson, 1968; Hayes, 1970). During Late Cretaceous time in southern Arizona, Cretaceous and older rocks were severely deformed, intruded by plutonic rocks, and buried beneath thick sequences of volcanic rocks.

In contrast to the Paleozoic Era, igneous activity increased considerably during Mesozoic time. Intrusive activity during the interval from Late Jurassic to Middle Cretaceous time (140 to 80 m.y.) was far more extensive than that for the Late Cretaceous to Early Tertiary interval (80 to 40 m.y.). However, the younger intrusives have proven to be considerably more important in the genesis of ore deposits (Anderson, 1968, p. 1167). The majority of copper deposits in Arizona and western New Mexico apparently fall within an age range of 45 to 75 m.y. The importance of the time interval from the end of the Cretaceous to the Early Tertiary has been recognized by many workers (Damon and Bikerman, 1964; Mauger et al., 1965; Damon and Mauger, 1966; Anderson, 1968), who believe this Laramide period was a time of extensive volcanism, plutonism, and mineralization.

Cenozoic

The Basin and Range province and the Colorado Plateau were formed during the Cenozoic Era. The Basin and Range features are mainly the result of vertical movement on north-south trending normal faults. However, the north-south trend is known to vary from one part of the province to the next. In Arizona and New Mexico the basins and ranges often trend north to northwest, but in southwestern Arizona the trend is more west-northwest (Anderson, 1966, p. 12).

According to Butler and Wilson (1938), the southwestern United States experienced a lengthy period of erosion and sedimentation during early and middle Tertiary time. Thick conglomerate deposits were formed in places, and Laramide intrusives were exposed at other places. The area was later subjected to extensive volcanism which resulted in reburial of many of the previously exposed Laramide stocks and batholiths. This period of volcanic activity, which was also associated with the emplacement of granitic stocks and batholiths, was accompanied and followed by uplift of the present mountain ranges. Gilluly (1963), who believed that Basin and Range features began to form as early as the Eocene, stressed that the present relief was due to faulting during and after Pliocene time. This late period of uplift resulted in continued erosion and deposition of thick deposits known as the Gila Conglomerate. The Gila Conglomerate is faulted and folded, testifying to the fact that deformation and uplift continued into Quaternary time.

Local Geology

Precambrian Rocks

Two Precambrian units are exposed in the Tombstone Hills, and both lithologies crop out north, west, and south of Ajax Hill (pls. 1, 2). Precambrian rocks include the Pinal Schist and a granitic rock (table 1).

Pinal Schist

The oldest rocks found within the mapped area are those which have been grouped as the Pinal Schist. Ransome (1919) studied the type locality of the Pinal Schist in the Pinal Mountains near Ray and Globe, Arizona, approximately 120 miles to the north. The schist was first identified at Tombstone by Ransome (Butler, Wilson and Rasor, 1938, pl. III), and later confirmed by Gilluly (1956, p. 10). Exposures of the Pinal Schist are limited to an area near Ajax Hill.

The rock is a dark-greenish-gray to brownish-gray, moderately- to well-foliated, fine-grained, quartz sericite schist. Sericite in thin parallel bands often encloses interlocking aggregates of anhedral to subhedral quartz grains. Minor amounts of chlorite, zircon and rutile have been observed, and the texture is generally crystalloblastic. Foliation within the schist trends northeast and dips about 60° E.

Rocks of the Pinal Schist were originally fine-grained, siliceous, and sedimentary in nature. The thickness of the Pinal is unknown, but it is probably at least several thousand feet (Gilluly, 1956, p. 10). At Tombstone, only the upper 150 to 200 ft of the schist

Table 1

Age Sequence of Geologic Units

Permian	Naco Group	Concha Limestone: 1500 ft.	Quaternary	Phonolite porphyry dike
		Scherrer Quartzite: 150 ft		Basalt intrusive
		Epitaph Dolomite: 780 ft		Quaternary undivided
		Colina Limestone: 635 ft	Tertiary	Rhyolite porphyry: 63 m.y.
Earp Limestone: 595 ft		Cretaceous		Hornblende andesite
Horquilla Limestone: 1100 ft			Rhyodacite	
Mississippian	Escabrosa Limestone: 780 ft		Granophyre	
			Quartz latite porphyry	
Devonian	Martin Limestone: 230 ft		Uncle Sam Tuff: 71.9 ± 2.4 m.y.	
Cambrian	Abrigo Limestone: 844 ft		Schieffelin Granodiorite: 72 m.y.	
	Bolsa Quartzite: 440 ft		Andesite porphyry dikes	
Precambrian	Granite		Bronco volcanics Upper rhyolite member Lower andesite member	
	Pinal Schist		Bisbee Formation: 3000 ft+	

are exposed. Near Ajax Hill, the schist was intruded by a Precambrian granitic rock, and following an extensive period of erosion, both the Pinal and the granite were buried beneath the Cambrian Bolsa Quartzite.

Precambrian granite

A Precambrian granitic rock is exposed immediately west of Ajax Hill (Butler, Wilson and Rasor, 1938, p. 13; Gilluly, 1956). Butler et al. named the rock granodiorite, while Gilluly called it albite granite. Butler et al. suggested that the overlying Cambrian Bolsa Quartzite might be in fault contact with the intrusive, and that the granite could be equivalent to the much younger Schieffelin Granodiorite. Gilluly, however, believed that the granite was petrographically distinct from the Schieffelin Granodiorite. The present work clearly establishes that the granite is unconformably overlain by the Bolsa Quartzite; thus the intrusive is older than the quartzite. Examinations in several small prospect pits revealed a 4- to 6-in. thick bed of quartz-pebble conglomerate at the base of the Bolsa, and the granite was underlying the conglomerate. Immediately south of Ajax Hill, the conglomerate overlies the Pinal Schist.

Lithologically, the rock is a pinkish-gray to light-gray, medium-grained, biotite-granite, with a poorly- to moderately-well-defined gneissoid structure. The texture is hypidiomorphic-granular. Microscopically, the rock contains 10 to 15 percent quartz, 25 to 30 percent potassium feldspar, 10 to 15 percent plagioclase, 20 to 25 percent biotite, 1 to 5 percent muscovite and sericite, and 3 to 5 percent epidote. Trace amounts of apatite, zircon, monazite, and magnetite

were observed. Anorthite contents of the plagioclase averaged about 30, and Butler et al., reported that the plagioclase consisted of calcic oligoclase. Cores of the plagioclase grains have been partially replaced by sericite, and chlorite partly replaces biotite grains.

Paleozoic Rocks

Paleozoic rocks are well exposed in the Tombstone Hills, and a total of 10 Paleozoic formations have been identified (table 1). With the exception of the Ordovician and Silurian, every major Paleozoic time period is represented. Earlier workers (Church, 1903; Ransome, 1916; Butler, Wilson and Rasor, 1938; Gilluly et al., 1954; Patch, 1969, 1973; Wilt, 1969) have described the Paleozoic stratigraphy in detail. The present investigation relied heavily on these previous studies, and interested readers should consult the indicated references for more complete stratigraphic descriptions.

Cambrian System

Cambrian formations at Tombstone include the Middle Cambrian Bolsa Quartzite, and the Middle to Upper Cambrian Abrigo Limestone. Both formations were originally described by Ransome (1904) at Bisbee.

Bolsa Quartzite

The Bolsa Quartzite was originally named by Ransome (1904) from exposures in Bolsa Canyon southwest of Bisbee. Ransome (1916) later identified the Bolsa at Tombstone.

The formation, which is resistant to erosion, crops out south of Tombstone, on and near Ajax Hill. Ransome (1904, 1916) reported

thicknesses of 430 and 440 ft at Bisbee and at Tombstone respectively. The Bolsa is pale-orange on fresh surfaces, and light-brown on weathered exposures. The base of the formation, which nonconformably (Dunbar and Rodgers, 1958, p. 117) overlies the Pinal Schist and the Precambrian Granite, consists of a quartzite conglomerate about 6 in. thick. Pebbles in the conglomerate are usually between 0.5 and 1.5 in. in diameter, and are composed of milky-white quartz. The major part of the Bolsa consists of thick- to very thick-bedded, medium- to very coarse-grained, somewhat cross-bedded quartzite. The contact of the Bolsa with the overlying Abrigo Limestone is transitional, as fine-grained shaly deposits and micaceous sandstones are interbedded with thin- to very thin-bedded limestone. The bottom of the shaly zone, between the uppermost massive quartzite and the lowest thin limestone bed, is designated as the base of the Abrigo Limestone.

The Bolsa Quartzite was deposited by a shallow transgressing sea as it advanced across a smooth erosion surface on the Pinal Schist and the Precambrian Granite (Gilluly, 1956, p. 15). Deposition of the Abrigo followed immediately as the water depth increased, and wave action became unable to transport coarse sediments characteristic of the Bolsa. Fossils have not been found in the Bolsa, but Ransome (1904) believed the formation to be of Middle Cambrian age, because Middle Cambrian fossils are present in the overlying Abrigo Limestone.

Abrigo Limestone

Ransome (1904) first named the Abrigo Limestone from exposures in Abrigo Canyon, 3 miles southwest of Bisbee, and he later applied the name to similar rocks at Tombstone (Ransome, 1916).

Weathering of the Abrigo resulted in a subdued topography relative to that for the Bolsa Quartzite, and the limestone crops out in the valley east of Ajax Hill. Ransome (1904) measured a thickness of 770 ft for the Abrigo at Bisbee, and Gilluly (1956) determined a thickness of 844 ft at Tombstone. The Abrigo is the most distinctive formation in the mapped area, and diagnostic features are grayish-olive-green to dark-greenish-gray colors, conspicuous thin beds of edgewise conglomerates, and worm borings. The formation can be divided into three parts, with interbedded shale, limestone, and edgewise conglomerates prevailing in the lowest 400 ft. The central portion is about 150 ft thick, and consists of thin- to very thin-bedded crystalline limestone. The beds are commonly separated by wavy green laminae of epidote and chlorite. The upper 300 ft consists of medium- to thick-bedded sandy limestone, which is frequently cross-bedded, and interbedded with quartzite. A 2 ft thick quartzite bed marks the top of the formation.

The Abrigo Limestone was deposited in a relatively shallow sea, as suggested by intraformational conglomerates, cross-bedding, and worm borings. A fauna of trilobites and brachiopods suggests a Middle to Late Cambrian age for the formation. The uppermost quartzite bed was deposited as the shallow Cambrian sea withdrew. Ordovician, Silurian, and lower and middle Devonian rocks have not been identified at Tombstone, and were probably not deposited (Gilluly, 1956, p. 25-26). The area was probably near sea level during this time interval.

Devonian System--Martin Limestone

The Martin Limestone was first named at the type locality on Mount Martin at Bisbee (Ransome, 1904), and later extended to Tombstone (Ransome, 1916).

The Martin Limestone is weakly resistant to erosion, and the formation crops out in the intervening valley between Ajax Hill and Military Hill. Ransome reported a thickness of 340 ft at Bisbee; Gilluly (1956, p. 26-27) measured only 229.5 ft of Martin at Tombstone. Rocks of the formation are typically dark-gray to brownish-black, and are chert, limestone, sandstone, and shale. More than half the Martin is represented by sandstone and shale at Tombstone, whereas at Bisbee limestone predominates. Both the lower and the upper contacts of the Martin are disconformities, and the upper contact is arbitrarily placed where the lithology changes from dark-gray limestone to very pale-gray, thick-bedded, crinoidal limestone of the Escabrosa. Brachiopods and corals are typical fossils for the Martin, and these suggest a Late Devonian age. The Martin is a shallow sea deposit, and the increase in clastic material to the north suggests that a low-lying land mass existed north of the mapped area during the time of deposition.

Mississippian System--Escabrosa Limestone

Ransome (1904) first named the Escabrosa Limestone near Bisbee, and he later extended the name to Tombstone (1916).

The Escabrosa resists erosion, and forms a 2 mile long ridge through Military Hill. Another outcrop is located east of Military Hill and along Highway 80, about 2.5 miles southeast of Tombstone.

Gilluly (1956, p. 31) reported a thickness of 786 ft in the Tombstone Hills. The lower contact is poorly exposed, and often covered with talus. Above the talus, massive lower beds generally form prominent cliffs, while thinner higher beds typically form dip slopes. The lower 100 ft is composed of white to light-gray, massive limestone and dolomite. Two chert horizons exist in the formation. The lower chert zone is about 250 ft above the lower contact, and consists of dark-gray to black chert beds that are from 1 to 6 in. thick. The higher chert zone, about 550 ft above the base, consists of brown nodules that are approximately 6 in. thick. Fossils in the lower portion of the formation consist of abundant crinoid fragments and corals. Higher in the Escabrosa brachiopods become relatively more abundant. Fossil evidence suggests an Early Mississippian age for the Escabrosa (Gilluly, 1956, p. 33). The absence of sandstone and shale, and the presence of corals, crinoids, and brachiopods suggest that the Escabrosa was deposited in clear, relatively warm, and moderately shallow water. Late Mississippian rocks have not been identified at Tombstone, and Pennsylvanian rocks lie disconformably on the Escabrosa Limestone.

Pennsylvanian and Permian Systems--Naco Group

The Naco Formation was originally named by Ransome (1904) from exposures in the Naco Hills south of Bisbee. Gilluly et al. (1954) proposed the name Naco Group, and subdivided the rocks into six new formations. These formations include the Pennsylvanian Horquilla Limestone, the Pennsylvanian-Permian Earp Limestone, the Pennsylvanian-Permian Colina Limestone, the Permian Epitaph Dolomite, the Permian Scherrer Quartzite, and the Permian Concha Limestone.

Horquilla Limestone

Gilluly et al. (1954) first named the Horquilla Limestone from exposures at Horquilla Peak, about 1 mile southeast of Ajax Hill.

The Horquilla Limestone is somewhat less resistant to erosion than the underlying Escabrosa, and the Horquilla typically forms gentle slopes that are frequently interrupted by thick-bedded, ledge-forming limestone horizons. The formation consists of light- to dark-gray, medium-bedded to massive limestone. Like the Escabrosa, many of the beds contain abundant crinoid fragments, but the Horquilla contains red and green mudstones that are absent from the Mississippian formation. Gilluly et al. (1954) reported a thickness of about 1000 ft at the type section for the Horquilla. The presence of medium to large fusilinids, less than 0.3 in. long and 0.1 to 0.2 in. in diameter, is a distinctive feature of the Horquilla. Brachiopods and bryozoa are typical megafossils. The poorly-defined upper contact of the Horquilla was arbitrarily placed where reddish Earp shales became dominant over underlying massive limestone beds.

The Horquilla Limestone was deposited at moderate water depths, and the fauna suggests neritic conditions. The presence of shales increases towards the top of the formation, and this suggests that the Horquilla was deposited in shallower water than the Escabrosa. Fossil evidence indicates the formation age is Middle to Late Pennsylvanian (Gilluly, 1956, p. 46).

Earp Limestone

Gilluly et al. (1954) first named the Earp Limestone from exposures at Earp Hill in sec. 5, T. 21 S., R. 23 E., which is

immediately east of the mapped area. Within the area of this dissertation the Earp crops out along a prominent northwest-trending ridge about 2 miles southeast of Ajax Hill; the formation also is present immediately north of the Prompter fault, near the Prompter and Oregon mines.

The Earp Limestone characteristically forms low-lying topographic features. Shales near the base of the formation typically form gentle slopes, below persistent limestone ledges. Lithologically, the Earp is extremely varied. The lower part is dominantly shale with minor amounts of sandstone, and a few beds of limestone. The upper half of this 595 ft (Gilluly, 1956) thick formation is composed of pink to reddish-brown, medium- to very-thick limestone and dolomite beds. Characteristic features of the Earp are a red chert-pebble conglomerate near the center of the formation, and very cherty, somewhat cross-bedded limestone and dolomite beds near the top of the formation. Fossils in the Earp are not as common as in the Horquilla, but consist mainly of brachiopods and gastropods, with large fusilinids near the base. The upper contact of the Earp is at the top of a 5 ft dolomite bed, below dark-gray limestone beds of the overlying Colina.

The Earp was deposited under shallow marine conditions, and fusilinid evidence suggests the Pennsylvanian-Permian boundary is present a few hundred feet above the formation base (Bryant, 1968).

Colina Limestone

Gilluly et al. (1954) named the Colina Limestone from excellent exposures along the north-trending Colina ridge, about 2 miles south of Ajax Hill.

The formation crops out south of the Horquilla Peak fault, along Highway 80 south of Tombstone, north of the Prompter fault, and in sec. 7, T. 20 S., R. 22 E. Topographically, the Colina forms prominent ridges and hills that are only slightly less subdued than those of the Escabrosa. The basal contact was placed at the top of the uppermost dolomite bed in the Earp formation, and dark-gray, massive limestone beds of the Colina allow easy identification of the formation. Gilluly (1956), and Wilt (1969) reported thicknesses of 633 and 622 ft respectively. The Colina is a dark-gray to nearly black, medium- to thick-bedded, crystalline limestone. Characteristic features include the dark-gray color which weathers to pale-gray, and the presence of large gastropods. The upper boundary of the formation is gradational into the overlying Epitaph Dolomite. The dolomitic nature of the Epitaph grades into, and transects, beds of the Colina, and much of the dolomite is secondary (Patch, 1969, 1973).

The lack of clastic material suggests the Colina was deposited in deeper water than the Earp. The formation is wholly of Permian age, and probably Wolfcamp (lower Lower Permian) in the lower part and Leonard (upper Lower Permian) in its higher part.

Epitaph Dolomite

Gilluly et al. (1954) named the Epitaph Dolomite from exposures on the east side of Colina ridge, about 2 miles south of Ajax Hill.

The Epitaph Dolomite crops out at several localities east of Colina ridge and along Highway 80, northwest of Schieffelin Monument (about 2.5 miles north of Tombstone), south of the Lucky Cuss mine,

and on Comstock Hill at the northwest edge of Tombstone. Gilluly (1956) reported a thickness of 783 ft for the formation at its type section, and Patch (1969, 1973) measured 762.5 ft of Epitaph at the same locality. Patch noted that, in ascending order, the formation consisted of 318 ft of dolomite, 124 ft of calcitic siltstone, 189.5 ft of dolomite, and 131 ft of limestone. The upper part of the formation contains sedimentary breccias, cross-bedding, and ripple marks. At the type section, the gradational nature of the lower contact is contrasted with a very marked unconformity that separates the Epitaph from overlying Cretaceous rocks of the Bisbee Formation. However, on two low-lying hills about 1.5 miles northwest of Schieffelin Monument, the Epitaph is apparently disconformably overlain by the Scherrer Quartzite.

The clastic material of the lower Epitaph and the sedimentary structures in the upper portion suggest the formation was deposited in relatively shallow water. Fossils are not abundant in the Epitaph, but Bryant (1968) stated that those reported are similar to the fauna in the Colina. Bryant also indicated that the Epitaph Dolomite is probably of Early Leonard age (upper Lower Permian).

Scherrer Quartzite

The Scherrer Quartzite was first applied by Gilluly et al. (1954) to rocks along Scherrer Ridge in the Gunnison Hills of the Dragoon Quadrangle. This area is about 30 miles north of the Tombstone Hills. Rocks belonging to the Scherrer have not been previously identified at Tombstone.

The Scherrer Quartzite crops out on two small hills about 1.5 miles northwest of Schieffelin Monument. Gilluly et al. (1954)

reported a thickness of 687 ft for the formation at its type section, which in ascending order generally consisted of 67 ft of red siltstone, 300 ft of white to brownish sandstone and subordinate limestone, 160 ft of limestone and dolomite, and 160 ft of light-brown to pink sandstone (Bryant, 1968). Bryant also stated that the formation thins considerably to the east, and the unit consists of only 20 ft of sandstone above the Epitaph in the Big Hatchet Mountains of southwestern New Mexico. At Tombstone, the Scherrer consists of only the uppermost 150 ft thick pink sandstone equivalent. The sandstone, as typical for the Scherrer (Gilluly et al., 1954; Bryant, 1968), is recrystallized to an orthoquartzite with conspicuous cross-bedding. Gilluly (1956) originally mapped the outcrops identified here as Scherrer, as a thrust-faulted sliver of the Cretaceous Bisbee Formation. Gustafson (pers. comm.) indicated that the rocks in question might belong to the Scherrer Formation, and subsequent work by the author confirmed the suggestion.

Bryant (1968) stated that the Scherrer is probably of Early or Middle Leonard age (upper Lower Permian). Luepke (1971) believed the source area for the Scherrer clastics was a positive area to the northwest, and that the sandstones were either reworked beach and dune deposits, or possibly shallow water marine accumulations.

Concha Limestone

Gilluly et al. (1954), first named the Concha Limestone from exposures on Concha Ridge in the Gunnison Hills about 30 miles north of Tombstone. The Concha Limestone has not been previously identified at Tombstone, and Gilluly (1956) mapped the rocks herein termed

Concha, as representing faulted slivers of the Colina Limestone and the Epitaph Dolomite.

The Concha Limestone crops out at only four localities within about 1 mile from Schieffelin Monument. The outcrops are separated from each other by Quaternary deposits, which prevent a description of the entire formation. The lower boundary was placed at the top of the highest Scherrer Quartzite bed, which forms a distinct contact with medium-gray, thin- to medium-thick, silty limestone beds of the Concha. The thin beds of the lower Concha change upwards to more thick and massive beds at exposures along a railroad cut on the north side of Walnut Gulch. If the intervening covered areas are assumed to consist of unfolded and unfaulted Concha at depth, the indicated thickness is about 1500 ft. The upper contact is an erosion surface that is overlain by the Cretaceous Bisbee Formation and by Quaternary deposits.

The Concha Limestone was probably deposited in a subsiding marine basin, as indicated by the decrease in silty material towards the top. The fauna consist of large brachiopods, sponges, bryozoa, corals, crinoids, gastropods and pelecypods; Bryant (1968) stated that the lower part of the formation is of Leonard age (upper Lower Permian), and that the upper part may be of Guadalupian age (Middle Permian).

Mesozoic Rocks

Cretaceous System

Ten map units have been assigned a Cretaceous age (pl. 1). In ascending order these are: Bisbee Formation; Bronco Andesite; Bronco Rhyolite; andesite porphyry dikes; Schieffelin Granodiorite;

Uncle Sam Tuff; quartz latite porphyry; granophyre; rhyodacite; and a hornblende andesite plug and associated dikes.

Bisbee Formation

Dumble (1902) first used the name Bisbee beds for Cretaceous strata in the Mule Mountains, and Ransome (1904) later assigned these rocks to the Bisbee Group and subdivided the group into the basal Glance Conglomerate, the Morita Formation, the Mural Limestone, and the uppermost Cintura Formation. With the exception of the Glance Conglomerate, these formations have not been recognized at Tombstone, and the name Bisbee Formation thus includes all Cretaceous sedimentary rocks exposed in the Tombstone Hills (Gilluly, 1956, p. 76).

The Bisbee Formation crops out over extensive areas in the Tombstone Hills, and at numerous locations between Tombstone and the San Pedro River. Sandstone, mudstone, and relatively minor limestone beds of the Bisbee generally weather to smooth low-lying hills and gentle slopes. The base of the formation is exposed only east of the Ajax Hill fault, in sec. 35, T. 20 S., R. 22 E., and along the crest of the hill immediately south of the Lucky Cuss mine. The base of the Bisbee consists of conglomerate beds that contain pebbles and cobbles of the Bolsa, Abrigo, and Escabrosa Formations as well as material from the Naco Group. These conglomerates, which were deposited over an erosion surface developed on the Epitaph Dolomite, have a thickness of between 55 and 70 ft (Butler, Wilson and Rasor, 1938, p. 19). The Bisbee Formation is predominately maroon mudstone and siltstone, brown to buff sandstone, and a few thin limestone beds that contain both marine and fresh-water faunules (Gilluly, 1956, p. 78).

Glance
Cong

A complete Bisbee section does not exist in the district, and Butler, Wilson and Rasor (1938, p. 19) and Gilluly (1956, p. 78) respectively report minimum thicknesses of 3115 and 3097 ft. Ransome (1904) measured 4750 ft of Bisbee in the Mule Mountains; however the top of the formation was an erosion surface.

Conglomerates, cross-bedded and ripple-marked sandstones, and marine and non-marine limestones suggest shallow-water environments. The formation was probably deposited in a slowly subsiding estuary basin (Gilluly, 1956, p. 79).

Bronco volcanics

The Bronco volcanics, originally named by Gilluly (1945) from exposures near Bronco Hill and Charleston, include a lower andesite member and an upper rhyolite member.

*Like Silverbell
Sequence*

Bronco Andesite. The Bronco Andesite crops out at many scattered localities between the San Pedro River and the Ajax Hill fault. Gilluly (1956) also identified the andesite unit farther west, beyond the area of this investigation. Most andesite exposures are in topographically subdued areas related to pediment surfaces, and only occasionally do low andesite hills project above the erosion surface.

The Bronco Andesites erupted through the Bisbee Formation at numerous locations east of Bronco Hill, but andesite flows were also observed to cap low hills of Bisbee strata. The best exposed eruptive contacts of the andesite are near the central portion of sec. 8, T. 21 S., R. 22 E. Near the NE $\frac{1}{4}$ of the same section, andesite flows were observed overlying the Bisbee Formation. Gilluly (1956, p. 88)

reports an andesite thickness from near Bronco Hill of at least 3500 ft; however, diamond drill core from holes near the Charleston lead mine indicates thicknesses of between 1200 and 1400 ft. Farther to the east in sec. 22, T. 20 S., R. 22 E., flow rocks of the Uncle Sam Tuff were deposited directly on the underlying Bisbee Formation. Evidently, the Bronco Andesite is thickest near Bronco Hill, and thins both to the north and to the east.

Petrographically, the greenish-gray to moderate-red andesite consists of fine-grained plagioclase and hornblende phenocrysts in an aphanitic groundmass. The texture is porphyritic-aphanitic, with a poorly defined flow lineation. Plagioclase phenocrysts, of An₃₈₋₅₄, represent between 30 and 35 percent of the rock. The plagioclase phenocrysts are generally sodic plagioclase. Brown and green hornblende phenocrysts usually represent about 5 to 10 percent of the rock. The groundmass generally represents 40 to 45 percent of the rock, and typically consists of a very fine-grained, felted intergrowth of acicular plagioclase laths, with intergranular magnetite, ilmenite, and hematite grains. Hornblende grains usually alter to calcite and chlorite, while plagioclase phenocrysts alter to sericite, epidote, and calcite. The Bronco Andesites are separated from the overlying Bronco Rhyolite by an irregular and uneven surface that may nearly represent the original upper surface for the andesite flows.

Bronco Rhyolite. The Bronco Rhyolite crops out in the area between Charleston and the Charleston lead mine. A few scattered exposures also exist to the west of Charleston, across the San Pedro River. The rhyolite is slightly more resistant to erosion than the

underlying andesite, and topographically the rhyolite forms low hills and gentle slopes.

The rhyolite is composed of tuffaceous beds and flows that were deposited over an uneven surface at the top of the Bronco Andesite. Gilluly (1956, p. 88) estimated a minimum thickness of 900 ft for the unit, but at places near the andesite, the rhyolite is probably considerably thinner and on the order of several tens of feet.

Petrographically, the pale-orange to light-gray rhyolite is composed of fine- to very fine-grained quartz phenocrysts in a microcrystalline groundmass. The texture is porphyritic-aphanitic. Quartz forms the only phenocrysts and represents from 1 to 5 percent of the rock. The groundmass, which is thoroughly devitrified, consists of microcrystalline spherulites. A few altered biotite grains are frequently present. Near Charleston, the rock displays intense sericitic alteration, and commercial-grade sericite has been produced at the Charleston lead mine.

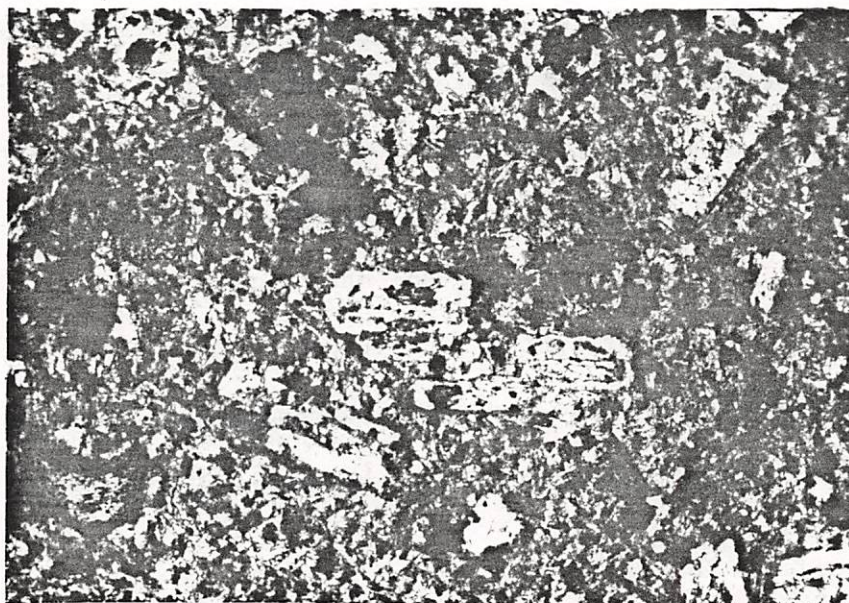
The Bronco Rhyolite has been intruded by the Uncle Sam Tuff which has an age of 71.9 ± 2.4 m.y. (Drewes, 1971), and thus the minimum age for the rhyolite is probably Late Cretaceous. Gilluly (1956, p. 89-90) thought the age of the Bronco volcanics was either Late Cretaceous or Early Tertiary.

Andesite porphyry dikes

Five andesite porphyry dikes traverse the district in a general N. 12° E. direction (pl. 2). From east to west the dikes are named the Michigan Central dike, the Grand Central-Contention-Empire dike,

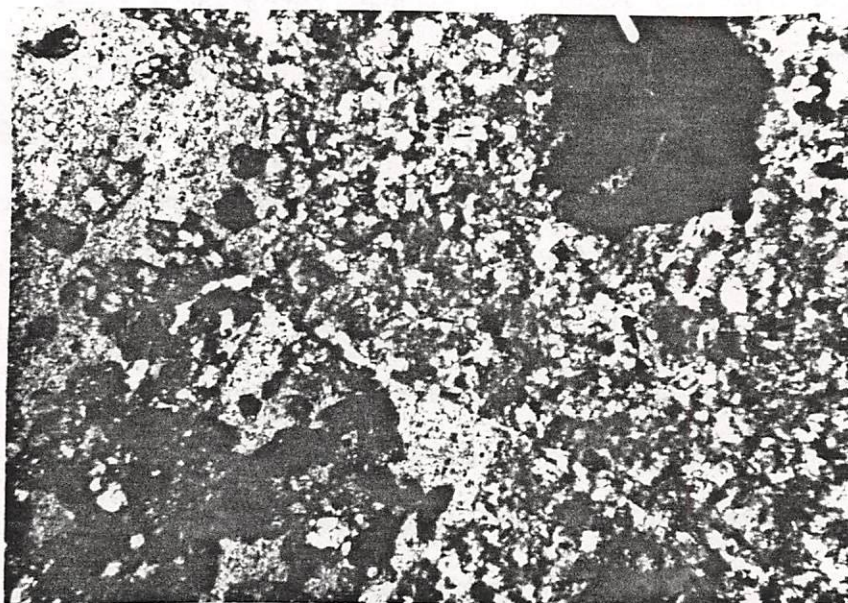
the Sulphuret dike, the Boss dike, and the Tribute dike. These dikes are generally intensely altered, and their outcrops are typically obscure.

Petrographically, the dark-greenish-gray to grayish-orange andesite consists of fine- to medium-grained phenocrysts in an aphanitic groundmass of felted plagioclase laths. About 30 percent of the rock consists of phenocrysts. Plagioclase phenocrysts, which represent between 15 and 30 percent, are of calcic andesine and sodic labradorite (An_{40-55}) varieties. Augite and hornblende generally represent between 1 and 2 percent of the rock. Alteration minerals of chlorite, calcite, epidote and sericite are typical, and indicate propylitic alteration (Williams, Turner and Gilbert, 1954, p. 97). The texture of the dike rocks is typically porphyritic-aphanitic. The Contention dike consists of a border phase as described above (fig. 2), and a more felsic central portion (fig. 3). The more felsic rock contains between 3 and 5 percent quartz, orthoclase, hornblende, and biotite. Medium- to coarse-grained plagioclase phenocrysts form between 30 and 35 percent of the rock, and are enclosed in an allotriomorphic-granular groundmass of quartz and orthoclase. The rock is intensely altered. Epidote replaces plagioclase, pennine replaces biotite and hornblende, and the rock is pervasively argillized. The rock was classified according to the scheme of Travis (1955) as a hornblende dacite porphyry. This more salic portion of the dike is unique to the central portion of the Contention, and the other andesite porphyry dikes examined were of relatively uniform lithologies. Perhaps it is significant that the best silver producing properties in the district were along the Contention dike.



0.5 mm

Fig. 2.--Photomicrograph of the andesite border phase of the Contention dike, showing fine-grained plagioclase phenocrysts in an aphanitic groundmass (48X, crossed nicols).



0.5 mm

Fig. 3.--Photomicrograph of the central dacite portion of the Contention dike with medium-grained plagioclase phenocrysts partially replaced by epidote, and accompanied by euhedral biotite in an alio-triomorphic-granular groundmass (48X, crossed nicols).

The typical, nearly north-south-trending dikes probably originated from an early differentiate of the Schieffelin Granodiorite. There is little doubt that the granodiorite underlies much of the main district, and yet dikes of this variety are not found in the Schieffelin itself. It is possible that the dacite portion of the Contention dike was intruded slightly later than the more mafic border rocks. Both varieties of dike rock were probably emplaced slightly prior to the final intrusive stages of the Schieffelin Granodiorite.

Schieffelin Granodiorite

The Schieffelin Granodiorite was originally named by Butler, Wilson and Rasor (1938) from exposures near Schieffelin Monument, about 2.5 miles northwest of Tombstone. Gilluly (1956) also applied the same name to similar rocks exposed near Lewis Springs and Bronco Hill. With the exception of Bronco Hill, weathering of the granodiorite typically results in subdued topographic forms.

The Schieffelin is clearly intrusive into all of the older rocks it is now in contact with. Near the Lucky Cuss mine, limestone beds of the Naco Group have been recrystallized to marble. Farther west the granodiorite has intruded and cut off the Ajax Hill fault. Contact alteration is probably best developed in beds of the Epitaph Dolomite at Comstock Hill. Rasor (1937) reported typical alteration minerals of diopside, pigeonite, and grossularite, with relatively minor amounts of olivine, clinozoisite, and wollastonite from alteration zones related to the granodiorite. These minerals indicate contact alteration conditions of the pyroxene-hornfels facies (Turner, 1968).

Petrographically, the light-gray to grayish-pink, medium-grained granodiorite consists of 35 to 45 percent plagioclase (An_{40-58}), 5 to 10 percent quartz, 15 to 20 percent orthoclase, 5 to 10 percent green hornblende, 3 to 5 percent biotite, 1 to 5 percent augite, and trace amounts of clinozoisite, zircon, magnetite, sphene and apatite. This holocrystalline rock has a hypidiomorphic-granular texture, and a poorly-defined lineation, as indicated by a subparallel alignment of the plagioclase grains. Hornblende was observed altering to biotite, epidote, and chlorite. Orthoclase and plagioclase are both somewhat argillized, and augite is partially altered to hornblende. Figure 4 is a photomicrograph of the Schieffelin Granodiorite.

The Schieffelin is closely related to the Uncle Sam Tuff.

Immediately east of Bronco Hill, the quartz latite tuff of the Uncle Sam is in contact with the granodiorite, and the following quote from Gilluly (1956, p. 104) indicates the confused relations between the Schieffelin and the Uncle Sam:

The Uncle Sam porphyry (tuff). . . is older than the granodiorite. This makes a close magmatic relation between them much less probable than would a reverse age relation, for the Uncle Sam porphyry (tuff) is more siliceous and contains plagioclase richer in albite than the Schieffelin. These characteristics are those normally found in more advanced stages of magmatic evolution and therefore make it improbable that the Uncle Sam and the Schieffelin were derived from the same local source. . . . If this is so the Uncle Sam porphyry (tuff) must have differentiated farther in its transit to the levels now exposed. . . than did the Schieffelin. . . .

The only evidence Gilluly had to support his statement that the Uncle Sam is older than the Schieffelin lies "in the western part of sec. 7, T. 21 S., R. 22 E., (where) a large dike of andesite porphyry cuts the Uncle Sam porphyry (tuff) and is cut off cleanly by the Schieffelin granodiorite" (Gilluly, 1956, p. 103). During the

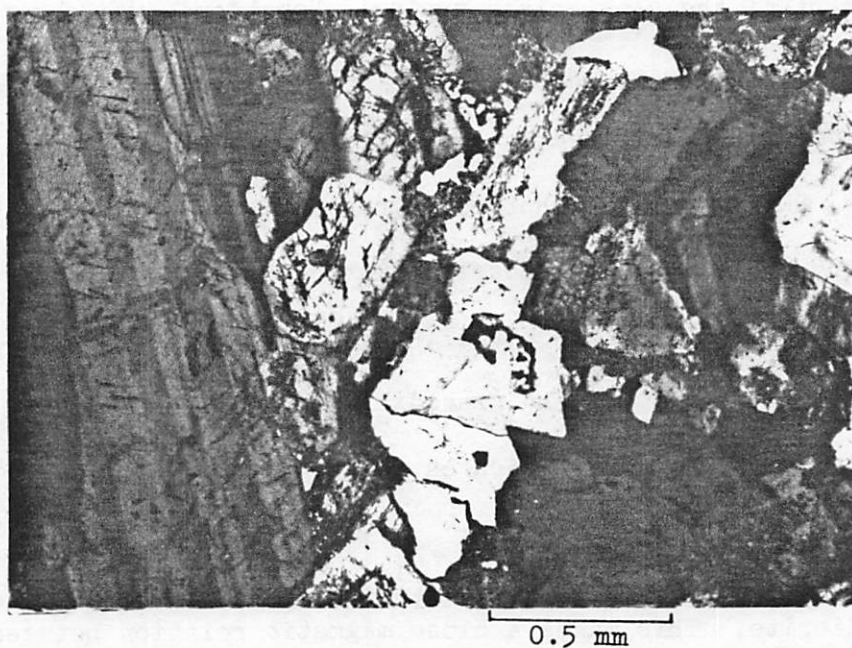


Fig. 4.--Photomicrograph of the Schieffelin Granodiorite, showing medium-grained plagioclase bordered with fine-grained quartz and orthoclase (48X, crossed nicols).

present field investigations, the dike which Gilluly stated was cut off by the Schieffelin was found and followed for at least 1000 ft into the granodiorite (pl. 1). Additional evidence of the confused relations is present in the statement:

. . . it is thus possible that the time that elapsed between the emplacement of these intrusions was so long that they should be referred to separate igneous cycles, . . . (and) the age (of the Schieffelin) is thus probably Middle Tertiary, though it (might) be Early Tertiary (Gilluly, 1956, p. 104).

The importance of these age relations becomes considerably more significant when the silver mineralization at Tombstone is viewed relative to its close proximity to the Schieffelin Granodiorite.

Following Gilluly's (1956) work, Creasey et al. (1962) and Drewes (1971) published potassium-argon ages of 72 and 71.9 ± 2.4 m.y. for the Schieffelin and the Uncle Sam respectively. Apparently, neither of the two authors attempted to relate the ages to each other or to the age of the Tombstone mineralization. The age of the mineralization will be discussed below, but both the Schieffelin and the Uncle Sam have virtually the same Late Cretaceous age, and they are probably related co-magmatically.

Uncle Sam Tuff

The Uncle Sam was first named by Butler, Wilson and Rasor (1938) from exposures on Uncle Sam Hill. These authors described the rock as an intrusive quartz latite porphyry. Ransome (1920) also described the rock as an intrusive, but he classified it as a rhyolite porphyry. Church (1903) considered the rock to be a rhyolite flow. Gilluly (1945, 1956) followed the terminology of Butler, Wilson and Rasor. The Uncle Sam is relatively resistant to erosion, and the rock forms

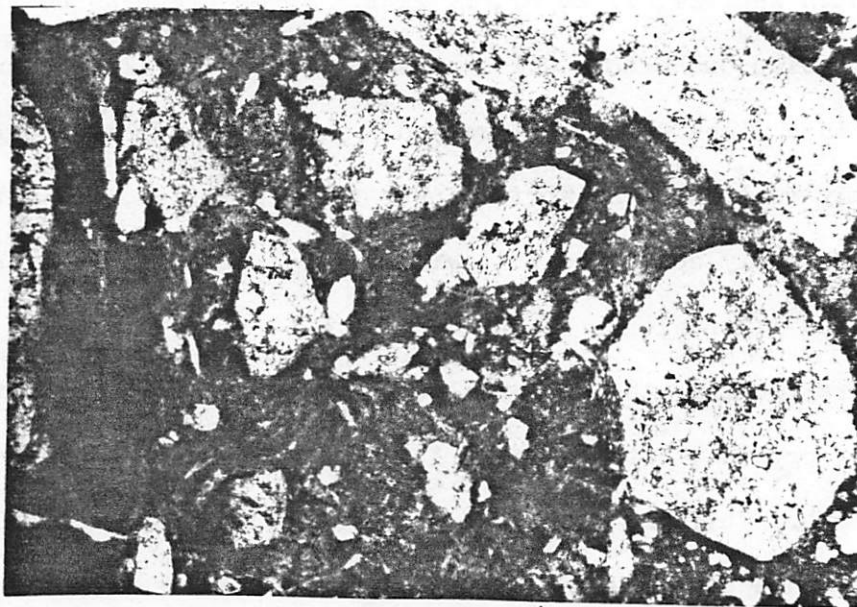
conspicuous hills. In areas of intense alteration and fracturing, the Uncle Sam is represented by a subdued topography.

Contact relations between the Uncle Sam and other lithologies are extremely varied. The unit has invaded the Colina Limestone, the Epitaph Dolomite, the Bisbee Formation, the Bronco volcanics, and the Schieffelin Granodiorite east of Bronco Hill. In turn, the Uncle Sam has been intruded by the rhyodacite west of Ajax Hill, and by numerous hornblende andesite dikes between Charleston and the State of Maine mine. Quaternary gravels and alluvium overlie the tuff at many locations along the San Pedro River and between Charleston and Ajax Hill.

In the area west of Ajax Hill, the Uncle Sam was observed to be in both cross-cutting and flow relations with the Bisbee Formation. The very irregular outcrop pattern in secs. 21 and 22, T. 20 S., R. 22 E., is due to a system of feeder dikes through which the tuff erupted. In the SE $\frac{1}{4}$ of sec. 22, T. 20 S., R. 22 E., the tuff is very clearly exposed as a flow rock. Figure 5 is a photograph of the tuff separated from the underlying Bisbee Formation by a thin horizon of pre-Uncle Sam gravels. The photograph was taken looking to the east in the SE $\frac{1}{4}$ sec. 22. Here the tuff is clearly a flow rock. In the south-central part of the same section, the Uncle Sam has an intrusive contact with the Epitaph Dolomite, and here the tuff erupted along the Ajax Hill fault. This normal fault, which has a minimum displacement of 5000 ft (Gilluly, 1956, p. 95), placed the Cretaceous Bisbee Formation in contact with the Precambrian granite and the Cambrian Bolsa Quartzite. The Uncle Sam was not involved in the faulting, and the tuff erupted after the fault was



Fig. 5.--Photograph of the Uncle Sam Tuff separated from the underlying Bisbee Formation by a thin horizon of pre-Uncle Sam gravels. Photograph taken looking to the east, SE $\frac{1}{4}$ sec. 22, T. 20 S., R. 22 E.



0.5 mm

Fig. 6.--Photomicrograph of the Uncle Sam Tuff, showing the pyroclastic texture of fine- to medium-grained phenocrasts in a groundmass of crystal ash and glass shards (48X, plane-polarized light).

formed. In places, Uncle Sam Tuff also erupted through the Bronco volcanics. In the drainage south and east of the small hill near the center of sec. 28, T. 20 S., R. 22 E., the tuff erupted through the Bronco Andesite. Similar relations with Bronco Rhyolite exist in the drainage north of the Charleston lead mine in sec. 25, T. 20 S., R. 21 E. The Uncle Sam forms the surface exposures at the State of Maine mine; however, the Bisbee Formation is exposed in the mine at an elevation of about 4300 ft (Butler, Wilson and Rasor, 1938, p. 101). The author examined this contact, and found the tuff to cut quartzite beds. The base of the Uncle Sam, which is very irregular, is controlled both by feeder dike locations and by the paleotopographic erosion surface at the top of the Bisbee Formation.

Several small intrusive breccia bodies exist in the Uncle Sam within the mapped area, and Gilluly (1956, p. 96) identified several more breccias west of the San Pedro River. Three intrusive breccias were mapped in sec. 29, T. 20 S., R. 22 E. These breccias consist of angular tuffaceous blocks which measure up to several feet in diameter, set in a fine- to medium-grained igneous matrix. The Uncle Sam evidently vented to the surface near these breccias, and eruptive activity apparently continued following partial solidification of the tuffaceous material.

Petrographically, the pale-yellowish-brown to light-brown tuff is a lithic, crystal, vitric quartz latite, with a moderately-defined flow structure. Tuff and ash-sized phenoclasts that are commonly embayed rest in a devitrified matrix. Glass shards are usually visible, and the rock is only slightly welded. The texture of this hypocrystalline rock, as seen in figure 6, is clearly pyroclastic.

What evidence?

Crystal fragments and lithic fragments together generally represent between 40 and 45 percent of the rock, with the remaining 55 or 60 percent consisting of groundmass material. Taken as a whole the rock contains 5 to 10 percent quartz, 5 to 10 percent plagioclase (with average anorthite contents of about 30), 5 to 7 percent biotite, 5 to 10 percent orthoclase, and 2 to 3 percent magnetite. Lithic fragments which comprise between 2 and 3 percent of the rock, consist mostly of accidental material derived from the Bisbee Formation and from the Bronco volcanics. The groundmass consists mainly of devitrified glass shards, microcrystalline plagioclase, and microspherulites of cristobalite and tridymite. Plagioclase grains are commonly partially altered to epidote and sericite, and biotite grains in many places are partially altered to chlorite.

The age of the Uncle Sam Tuff is Late Cretaceous, and Drewes (1971) obtained a potassium-argon age of 71.9 ± 2.4 m.y. from the rock. The Schieffelin Granodiorite is virtually the same age (72 m.y., Creasey et al., 1962), and the tuff is believed to be a slightly later differentiate of the same magma that formed the intrusive granodiorite. Table 2 lists the chemical and normative compositions for the Schieffelin and the Uncle Sam as reported by Gilluly (1956). The Uncle Sam has higher normative contents of quartz and albite, and lower contents of anorthite, clinopyroxene, orthopyroxene, magnetite, ilmenite, and hematite. The two rocks have nearly equal normative amounts of orthoclase and apatite. The close temporal and spatial relationship of the Schieffelin with the Uncle Sam, and a tendency of the Uncle Sam to be more siliceous and less mafic than

Table 2

Chemical and Normative Compositions for the Schieffelin
Granodiorite and the Uncle Sam Tuff

Chemical compositions (%)			Normative minerals		
Elements	Schieffelin	Uncle Sam	Minerals	Schieffelin	Uncle Sam
SiO ₂	62.33	67.60	Quartz	16.56	24.60
Al ₂ O ₃	16.92	16.22	Orthoclase	20.02	19.46
Fe ₂ O ₃	3.95	2.01	Albite	30.39	33.54
FeO	1.24	1.08	Anorthite	20.02	15.29
MgO	1.97	0.91	Clinopyroxene	1.30	-
CaO	4.48	2.91	Orthopyroxene	4.30	2.00
Na ₂ O	3.62	3.79	Magnetite	2.32	1.86
K ₂ O	3.36	3.58	Ilmenite	1.22	0.76
TiO ₂	0.63	0.41	Hematite	2.40	0.96
P ₂ O ₅	0.17	0.19	Apatite	0.34	0.34
MnO	0.07	0.10			
H ₂ O	1.35	1.20			
Totals	100.09	100.00			

Data from Gilluly (1956)

the granodiorite, suggest that the tuff is indeed a later differentiate from the same magma that produced the plutonic rock.

Quartz latite porphyry

The quartz latite porphyry is exposed only near the small hill north of Lewis Springs in sec. 19, T. 21 S., R. 22 E. The very limited outcrop area of the porphyry does not allow it to develop major topographic forms of its own, but the rock is relatively resistant to erosion since it caps the small hill mentioned above.

Petrographically, the light-gray, holocrystalline rock consists of medium-grained phenocrysts surrounded by a microcrystalline, allotriomorphic-granular groundmass. Phenocrysts generally represent between 35 and 40 percent of the rock, and they consist of 5 to 10 percent plagioclase (An_{28-43}), 5 to 10 percent quartz, 10 to 15 percent orthoclase, and 1 to 5 percent biotite. The groundmass represents 60 to 65 percent of the rock, and consists of microcrystalline quartz, potassium feldspar and plagioclase. Secondary minerals include chlorite after biotite, and sericite, clay and calcite after the plagioclase. Gilluly (1956, pl. 5) called this rock an andesite porphyry; however, petrographically the rock is best described as a quartz latite porphyry.

The porphyry has intrusive contacts with the Bisbee Formation and the Bronco Andesite. The Schieffelin Granodiorite is exposed less than half a mile to the north, and it probably underlies the quartz latite at depth. Compositionally, the rock is very similar to the Uncle Sam Tuff; however, the porphyry lacks a vitric groundmass and a pyroclastic texture. The quartz latite porphyry was

probably intruded as a hypabyssal intrusive, about the same time that the Uncle Sam Tuff erupted.

Granophyre

A thick granophyric dike crops out immediately west of Ajax Hill. The dike is relatively resistant to erosion, and forms bold outcrops that can be followed along strike for about 3500 ft.

In thin section, the grayish-orange-pink to pale-yellowish-orange rock is medium-grained, holocrystalline, with 35 to 40 percent quartz, 45 to 50 percent orthoclase, and 5 to 10 percent plagioclase. Minor accessory minerals include 1 to 5 percent epidote, and trace amounts of muscovite. The rock texture is micrographic, with cuneiform (Williams, Turner and Gilbert, 1954, p. 21) intergrowths of quartz and partially argillized orthoclase. Figure 7 is a photomicrograph of the granophyre.

The dike intruded along the Ajax Hill fault, and also invaded the Precambrian granite. The dike is somewhat sheared, and minor movement has occurred along the fault since the dike was emplaced. The age of the dike is difficult to define in narrow terms, but it is probably slightly older than the rhyodacite from which it is separated by the Ajax Hill fault. Possibly the intense silicification in the dike occurred during the intrusion of the rhyodacite.

Rhyodacite

The rhyodacite is exposed west of Ajax Hill, and along the west side of the Ajax Hill fault. The rock is weakly resistant to erosion, and crops out in saddles and on hill slopes.



0.5 mm

Fig. 7.--Photomicrograph of the granophyre, showing a micrographic texture with cuneiform intergrowths of quartz and argillized orthoclase (48X, crossed nicols).

Petrographically, the very pale-orange to dark-yellowish-orange rock consists of medium-grained phenocrysts in a devitrified ground-mass. The texture of the rock is porphyritic-glassy, and a moderately defined flow structure is generally present. Phenocrysts typically represent 40 to 50 percent of the rock, consist of 15 to 20 percent quartz, 5 to 10 percent orthoclase, 10 to 15 percent plagioclase (sodic andesine, An_{32-34}), and about 5 percent biotite. The ground-mass is generally composed of microcrystalline quartz, potassium feldspar, and devitrified glass. Trace amounts of epidote are also common. Secondary minerals include clays derived from the feldspars, and chlorite and iron oxides from biotite grains.

Like the closely associated granophyric dike, the rhyodacite has intruded along the Ajax Hill fault, and minor movement occurred on the fault following the emplacement of the rock. Intrusive contacts of the rhyodacite with the Uncle Sam were observed on the hill near the center of sec. 22, T. 20 S., R. 22 E., and thus the rhyodacite is at least slightly younger than the Uncle Sam. As mentioned above, the intense silicification in the granophyre may have formed during the emplacement of rhyodacite. Thus, the rhyodacite is believed to be slightly younger than both the granophyre and the Uncle Sam.

Hornblende andesite

A small hornblende andesite intrusive body crops out about 1 mile east of Bronco Hill. Numerous dikes of similar lithologies have also been mapped in the area between the San Pedro River and Tombstone. The dikes are probably genetically related to the andesite intrusive near Bronco Hill. The andesite is generally not very resis-

tant to erosion, and many of the outcrops are small and difficult to follow.

In thin section, the medium-bluish-gray to light-olive-gray andesite consists of medium- to coarse-grained hornblende phenocrysts and fine-grained plagioclase phenocrysts in a microcrystalline groundmass. Brown, pleochroic hornblende generally forms between 5 and 10 percent of the rock, and plagioclase phenocrysts (An_{42-51}) usually represent between 1 and 5 percent. The groundmass is typically dominated by microcrystalline plagioclase laths with occasional quartz, potassium feldspar, and epidote grains. Opaque grains in the groundmass can represent between 5 and 10 percent of the rock. In places the rock is intensely altered. Chlorite and epidote often replace the hornblende, and clay, sericite, calcite and epidote frequently replace plagioclase. At the Charleston lead mine, a thick andesite dike has been completely replaced by sericite.

Hornblende andesite dike rocks intrude the Bisbee Formation, the Bronco Andesite and Rhyolite, the Schieffelin Granodiorite (at Tombstone, and at Bronco Hill) and the Uncle Sam Tuff. The dike rocks are thus younger than the 71.9 ± 2.4 m.y. old (Drewes, 1971) Uncle Sam. The author collected a massive sericite sample from the dike at the Charleston lead mine, and the sample yielded a potassium-argon date of 74.5 ± 3 m.y. (Appendix I). These two dates, which represent maximum and minimum ages respectively, are virtually indistinguishable, and imply that the hornblende andesite is probably of Late Cretaceous age.

Cenozoic Rocks

Four map units have been assigned to the Cenozoic Era. These include a Tertiary rhyolite porphyry, Quaternary gravel and alluvial sequences, a basaltic dome, and a phonolite dike.

Tertiary System--rhyolite porphyry

The rhyolite porphyry is best exposed about 3 miles southeast of Tombstone along Highway 80, along the eastern portion of the Prompter fault, and as several sills between Ajax Hill and Military Hill. The main mass of the rhyolite along Highway 80 is fairly resistant to erosion, and the rock forms several small hills.

Petrographically, the grayish-pink rhyolite consists of medium- to fine-grained phenocrysts in a devitrified groundmass. The texture of the hypocrystalline rock is typically porphyritic-glassy or porphyritic-aphanitic. Phenocrysts consist of 5 to 7 percent rounded, embayed and resorbed quartz, and 1 to 3 percent sanidine. Opaque minerals can form between 1 and 2 percent of the rock. Devitrification products of quartz and potassium-feldspar form the groundmass. Microspherulites are common devitrification products also found in the groundmass.

The rhyolite intrudes many of the Paleozoic formations in the district, and many of the intrusive contacts are nearly conformable with the bedding. West of Highway 80 in the southeast corner of sec. 25, T. 20 S., R. 22 E., the rhyolite has domed the overlying Colina Limestone, and here the porphyry would be considered a passive intrusive. West of Military Hill, the rhyolite has clearly cut across an andesite porphyry dike. In sec. 13, about 1.5 miles south

of Tombstone, the rhyolite intruded the Prompter fault. However, the Rattlesnake branch of the Prompter fault system has offset a rhyolite sill (SE $\frac{1}{4}$ sec. 14) by about 200 ft in a left-lateral direction. Thus the major portion of the movement on the Prompter system pre-dates the emplacement of the rhyolite. Creasey et al. (1962) obtained a potassium-argon age of 63 m.y. for the rhyolite. While the porphyry is younger than the Schieffelin (72 m.y., Creasey et al., 1962) and the Uncle Sam (71.9 ± 2.4 m.y., Drewes, 1971), dikes and sills of the rhyolite are spatially associated with manganese mineralization in the southern part of the main district. In the Side Wheel mine, west of Military Hill, manganese vein deposits occur in and adjacent to a dike of the rhyolite, and this mineralization can confidently be assigned an Early Tertiary age of about 63 m.y.

Quaternary System

Quaternary undivided

Rocks and alluvial deposits of Quaternary age were generally not separated during this investigation. Lithologies included are the Plio-Pleistocene (?) Gila Conglomerate, or its equivalent (Gilluly, 1956, p. 120), and modern gravel and alluvial deposits.

Rocks possibly related to the Gila Conglomerate are exposed along Walnut Gulch, south and east of Tombstone. These rocks are tilted and faulted, and in sec. 7, T. 20 S., R. 23 E., rocks of probable Gila equivalent were observed in fault contact with the Bisbee Formation. Gilluly (1956, p. 119) notes that the conglomerates

are at least 700 ft thick north of Tombstone. This figure is probably a minimum, and the conglomerate deposits appear to be considerably thicker east of Walnut Gulch. The Gila equivalent is covered by a thin layer of modern gravel and alluvium, and about 1 mile north-east of Tombstone the conglomerates are intruded by a small basaltic dome.

Basalt and phonolite dike

The small basaltic dome crops out along the east side of Walnut Gulch. The basalt is only moderately resistant to erosion, and the exposed surface is about level with the surrounding conglomerates and Quaternary gravels.

Petrographically, the dark-gray to grayish-black basalt was found to have a microcrystalline pilotaxitic texture. Very fine-grained olivine, diopside, and enstatite are interstitially placed between felted plagioclase laths. The rock consists of 55 to 60 percent plagioclase (An_{52-65}), 10 to 15 percent olivine, 15 to 20 percent opaques, and trace amounts of enstatite and diopside.

A very pale-orange to pale-yellowish-brown phonolite dike is enclosed within the basalt near its southwest corner. The dike, which is only about 200 ft long and 5 to 10 ft wide, is a holocrystalline rock with a porphyritic-aphanitic texture. Medium-grained phenocrysts are composed of 10 to 15 percent titaniferous augite, 5 to 10 percent orthoclase, and 1 to 2 percent hypersthene. The groundmass, which represents 75 to 80 percent of the rock, consists of 60 to 65 percent plagioclase (An_{28-34}), about 10 percent nepheline, and 2 to 3 percent

opaques. Secondary minerals include iron oxides developed around hypersthene grains, and scolecite and calcite as vesicle fillings.

The contact between the basalt and the surrounding conglomerates is well exposed in prospect pits, and the basalt has clearly intruded the young sediments. Foliations are well developed in the rock and tend to parallel the contact and to dip back into the basalt.

Gilluly (1956, p. 120) believed the basalt represented a ring dike; however, the present study indicates that the body is more likely a small collapsed dome. The interior of the circular structure does not contain conglomerates, as would probably be required for a ring dike, but well-bedded, fine-grained, poorly-consolidated silty sediments. These sediments were probably deposited in the central part of the structure following collapse. The basalt is believed to have intruded along a zone of weakness at the intersection of the northeast-trending fissures with a large fault buried beneath the gravels in Walnut Gulch.

CHAPTER III

STRUCTURAL GEOLOGY

Regional Structural Features

Tombstone is about 200 miles south of the Colorado Plateau, and the district lies in the southern part of the Basin and Range physiographic province. The mapped area is also in the intersection of the Wasatch-Jerome zone with the Texas zone as proposed by Schmitt (1966). Much of the following is summarized from Schmitt.

Three major tectonic zones have been proposed for the southwestern U. S. (fig. 9). The Wasatch-Jerome zone in Arizona is represented by high-angle faults with associated horst and graben features. The Front Range zone in New Mexico is composed of thrust faults, high-angle faults, folds, and horst and graben structures. The major influence within this zone has been one of uplift. The Texas zone is approximately 100 miles wide, and strikes about N. 75° W. Schmitt believed the zone could represent a root system for a now largely eroded mountain belt. While summarizing the work of previous investigators, Schmitt (1966, p. 24) mentioned that the Texas zone perhaps formed during the Precambrian, and that the zone was a depositional trough in Mississippian and in Early and Late Cretaceous time. In southern Arizona high-angle normal faults and thrust faults apparently characterize the Texas zone. Taken as a group, the three belts are old, linear, and persistent zones of

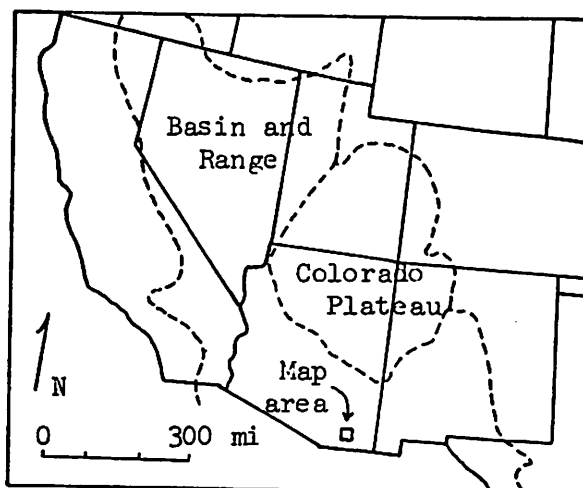


Fig. 8.--Generalized map showing the location of the thesis area within the Basin and Range province, and relative to the Colorado Plateau.

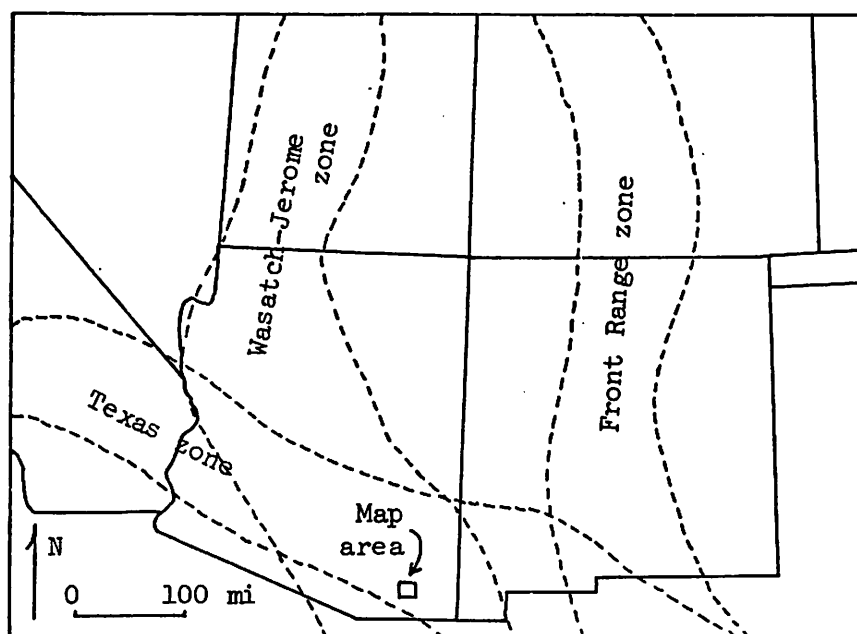


Fig. 9.--Generalized map showing the location of the thesis area relative to the Texas zone, the Wasatch-Jerome zone, and the Front Range zone (modified from Schmitt, 1966).

deformation. Their characteristic features include horsts, grabens, and thrust faults.

Structural Features of the Tombstone- Charleston Area

The Tombstone district is quite complex structurally, and many of the ore bodies have been shown to be structurally controlled (Butler and Wilson, 1942). A major emphasis of the present investigation was directed towards unraveling the complexities, and establishing a chronological sequence for the various structural events. This emphasis had as its ultimate purpose the determination of the age of the mineralization in the district.

Folding in the Tombstone District

A series of three broad anticlines and associated synclines have developed in the central portion of the district. The folds, which plunge slightly to the southeast, are truncated by the Schieffelin Granodiorite to the northwest. The folds are believed to pre-date the 72 m.y. age (Creasey et al., 1962) of the intrusive.

Prompter-Horquilla Faults

The east-west trending Prompter fault zone is a reverse fault that dips 60 to 80° S. Gilluly (1956, p. 129) stated that the Prompter fault has at least 4000 ft of displacement near its western margin, and about 1500 ft of offset farther to the east. The Horquilla Peak normal fault, south of Ajax Hill, was considered to have about 2000 ft of displacement. Gilluly believed both faults

had predominately east-west movement, with the Prompter displaying left-lateral and the Horquilla displaying right-lateral offset. It is to be emphasized that much of the apparent offset could also be explained by differential uplift of the Ajax Hill horst. The area of maximum uplift would lie in the vicinity of Ajax Hill.

Some of the movement on these two faults is probably pre-Cretaceous, as the Bisbee Formation is offset about 2800 ft (apparently left-lateral) by the Prompter fault. If the maximum offset is 4000 ft, about 1200 ft of movement on the Prompter is probably pre-Cretaceous. Due to relatively poor exposures, and to less distinctive lithologies along the Horquilla Peak fault, it is difficult to assess the pre-Cretaceous movement along this fault. It is possibly safe to assume that perhaps a third of the movement is pre-Cretaceous, which is in agreement with that along the Prompter.

There have been at least three periods of movement on the Prompter system. As shown above, one period is probably pre-Cretaceous. A second period post-dates the Ajax Hill fault (about 2800 ft), and a third period post-dates the emplacement of the rhyolite porphyry dike immediately south of the Prompter shaft (SE $\frac{1}{4}$ sec. 14, T. 20 S., R. 22 E.).

The projected trend of the Prompter fault beneath the Bisbee Formation and the Uncle Sam Tuff is of considerable interest since the Prompter fault zone is known to contain sizeable ore bodies (Oregon-Prompter, Bunker Hill, Dry Hill, and Contact mines). Butler, Wilson and Rasor (1938, pl. III) placed a northwest bend in the Horquilla Peak fault to the southwest of Ajax Hill. Here the fault separates the Bisbee Formation from the Colina Limestone and the

Epitaph Dolomite. If this general trend is projected farther to the northwest, and the westerly trend of the Prompter fault is extended, a projected intersection of the two faults may exist to the south and west of Uncle Sam Hill.

Ajax Hill Fault

The Ajax Hill normal fault lies immediately west of Ajax Hill, and trends north-south. To the south of Ajax Hill, in sec. 27, T. 20 S., R. 22 E., the fault is occupied by a small dike of the rhyodacite. Immediately west of Ajax Hill, the fault is occupied by the rhyodacite and by the granophyre. These rocks, which are undoubtedly closely related to the Uncle Sam Tuff, indicate that the Ajax Hill fault was in existence prior to their emplacement. To the north of the Prompter fault, the Ajax Hill fault was intruded and cut off by the Schieffelin Granodiorite.

The Ajax Hill fault has placed the Bolsa Quartzite in contact with the Bisbee Formation, and the indicated displacement is at least 5400 ft. While the fault has served as a conduit through which the Uncle Sam Tuff erupted, the structure probably does not represent a ring fracture for a caldera. The fault is a linear structure which yielded fissure-type eruptions.

Northeast-Trending Ore Fissures

Numerous northeast-trending fractures of small displacement are widespread in the district. These fractures commonly strike N. 30-55° E., and east of the Ajax fault the fractures dip steeply southeast. West of the fault the fractures generally dip northwest. Butler, Wilson

and Rasor (1938, p. 67) have shown that these fractures served as channels for the silver-bearing hydrothermal solutions. As mentioned by these authors, the ore fissures cut all rocks older than the Quaternary gravels.

East Boundary Fault

The eastern equivalent of the Ajax fault is the East Boundary fault. The fault, which is generally poorly exposed, can be seen along Highway 80, in the western half of sec. 18, T. 20 S., R. 23 E. Here, the Colina Limestone is in contact with the Bisbee Formation. The fault strikes about N. 35° W., and dips almost vertically. It probably extends beneath the Quaternary deposits, through the town-site. Approximately 1 mile farther east, the East Boundary fault is paralleled by a major northwest-trending structure which follows Walnut Gulch. These two faults have resulted in a two-step down dropping of the eastern side of the district beneath the Quaternary deposits. The small basaltic dome in Walnut Gulch has intruded along the easternmost fault.

Note X sects Plate 3 shows both normal & reverse movement - an error? Ask RAN

Chronological Summary--Igneous and Structural Activity

The following chronological summary is based on field relations and age dates from selected igneous rocks. The summary is presented in a tabulated form to allow better separation and understanding of the complex structural history.

1. Pre-Cretaceous movement along the Prompter-Horquilla faults.

Evidence: Total maximum offset on the Prompter fault is SW

Horst development prior to Kb. may indicate the Kb was never deposited between the PF & the HF to west of AF. From expl. point of view, repective lower Plio ls. may lie closely or directly below the UST in this projected horst area. This not supported by X sect D-D' - but Kb could be very much thinner

If so, Note page 66 - suggestion that Prompter & Horquilla faults intersect at U. Sam Hill.

about 4000 ft, and the Cretaceous Bisbee Formation is offset only about 2800 ft.

2. Folding of the Bisbee Formation in the central portion of the Tombstone district. Evidence:

a. The Tombstone basin is bounded on the west by the Ajax Hill fault.

b. Fold trends are cut by the Schieffelin Granodiorite, which also cuts the Ajax Hill fault.

3. Movement along the Ajax Hill fault. Evidence:

a. The Ajax Hill fault cuts the Prompter fault.

b. The Ajax Hill fault is cut by the Schieffelin Granodiorite.

c. The Ajax Hill fault bounds the western margin of the Tombstone basin.

4. Extrusion of the Bronco Andesite, followed by extrusion of the Bronco Rhyolite. Evidence:

a. The Bronco Rhyolite cuts the andesite, immediately north of the Charleston lead mine.

b. The Uncle Sam Tuff cuts the Bronco Andesite (center sec. 28, T. 20 S., R. 22 E.).

c. The Uncle Sam Tuff intrudes the Ajax Hill fault. Note: The Ajax Hill fault is not in contact with the Bronco volcanics, and the possibility exists that these volcanics pre-date the Ajax Hill fault.

5. Intrusion of the north-trending andesite porphyry dikes.

Evidence:

a. The dikes cut folds within the Bisbee Formation.

Folds in Kb must exist at base of Kb between Ksg & S. of Main mine (as indicated by mapping)

- b. The dikes occur in sedimentary rocks which contain the Schieffelin Granodiorite at depth.
- c. The dikes do not cut the Schieffelin Granodiorite.
- 6. Intrusion of the Schieffelin Granodiorite. Evidence:
 - a. The granodiorite cuts the Ajax Hill fault.
 - b. The Schieffelin is less siliceous than the Uncle Sam Tuff.
 - c. Creasey et al. (1962) dated the granodiorite at 72 m.y.
- 7. Renewed movement along the Prompter fault. Evidence:
 - a. The Prompter fault cuts andesite porphyry dikes.
 - b. The Prompter fault offsets the Ajax Hill fault.
- 8. Emplacement and extrusion of the Uncle Sam Tuff. Evidence:
 - a. The Uncle Sam Tuff cuts the Bronco volcanics (sec. 28, T. 20 S., R. 22 E., and sec. 25, T. 20 S., R. 21 E.).
 - b. The Uncle Sam Tuff follows the Ajax Hill fault.
 - c. A hornblende andesite dike cuts the Schieffelin Granodiorite and the Uncle Sam Tuff north of Bronco Hill.
 - d. The Uncle Sam Tuff is more siliceous than the Schieffelin Granodiorite.
 - e. A potassium-argon date (71.9 ± 2.4 m.y., Drewes, 1971) from the Uncle Sam Tuff indicates the same age as the Schieffelin Granodiorite.
- 9. Emplacement of the quartz latite porphyry. Evidence:
 - a. The quartz latite porphyry cuts the Bronco Andesite.
 - b. The quartz latite porphyry is compositionally very similar to the Uncle Sam Tuff. Note: The quartz latite porphyry is probably an equivalent of the Uncle Sam Tuff, but

textural evidence suggests the porphyry did not vent to the surface.

10. Emplacement of the granophyre. Evidence:

- a. The granophyre intrudes the Ajax Hill fault.
- b. The granophyre is intensely altered, and this may be due to the emplacement of the rhyodacite.

11. Emplacement of the rhyodacite. Evidence:

- a. The rhyodacite intrudes the Ajax Hill fault.
- b. The rhyodacite intrudes the Uncle Sam Tuff.
- c. The rhyodacite probably altered the granophyre.

12. Earliest fracturing along the northeast-trending fissures.

Evidence:

- a. The fissures cut the Uncle Sam Tuff.
- b. The fissures are intruded by hornblende andesite dikes.

13. Emplacement of the hornblende andesite dikes. Evidence:

The dikes follow the northeast-trending fissures, in the Uncle Sam Tuff, and in the Schieffelin Granodiorite.

14. Introduction of hydrothermal solutions and formation of the base-metal and silver deposits at Charleston and at Tombstone. Evidence:

- a. Hornblende andesite dikes are hydrothermally altered (Charleston lead mine; sericite date 74.5 ± 3 m.y., Appendix I).
- b. The mineralization followed northeast-trending fractures at Tombstone (Butler and Wilson, 1942, p. 201).
- c. Alteration along the Contention dike yielded a potassium-argon date of about 72 m.y. (Gustafson, pers. comm.).

15. Emplacement of the rhyolite porphyry, and associated dikes and sills. Evidence:
 - a. A rhyolite dike cuts an andesite porphyry dike immediately west of Military Hill.
 - b. The rhyolite intruded the Prompter fault zone.
 - c. Creasey et al. (1962) obtained a potassium-argon date of 63 m.y. for the rhyolite.
16. Renewed minor fracturing along the northeast-trending fissures. Evidence: A northeast-trending fissure cuts the rhyolite dike west of Military Hill.
17. Renewed movement along the Prompter fault. Evidence:
 - a. A rhyolite porphyry dike is cut and offset left laterally about 200 ft by the Prompter fault system.
 - b. The northeast-trending fissures do not cross faults belonging to the Prompter system.
18. Introduction of the manganese mineralization, in the southern part of the district. Evidence:
 - a. Manganese mineralization is intimately associated with the rhyolite porphyry in the Side Wheel mine west of Military Hill.
 - b. Alteration related to silver mineralization along the Contention dike yielded an age of about 72 m.y. (Gustafson, pers. comm.).
 - c. The age of the rhyolite porphyry is about 63 m.y. (Creasey et al., 1962)
 - d. Manganese deposits are closely associated with the Prompter fault (Butler, Wilson and Rasor, 1938, p. 80),

and the rhyolite porphyry has intruded along the Prompter fault.

- e. Quartz veinlets were observed paralleling the ore fissure which cuts the rhyolite dike west of Military Hill.

19. Partial district tilting to the northeast possibly associated with the northwest faulting. Evidence:

- a. Quaternary (?) conglomerate beds along Walnut Gulch dip 40° NE.
- b. Northwest-trending faults (Grand Central, East Boundary, and Walnut Gulch) have progressively lowered the district to the northeast.
- c. Northwest-trending faults post-date the mineralization (Butler, Wilson and Rasor, 1938, p. 37).

20. Emplacement of the basalt and phonolite in Walnut Gulch.

Evidence: The basalt cuts Tertiary and Quaternary (?) gravels.

Age of the Mineralization

Prior to this study, the age of the mineralization was largely unknown. Gilluly (1956, p. 104) considered the Schieffelin Granodiorite to have a Middle or Early Tertiary age. He also believed the Uncle Sam was older than the Schieffelin, and he (Gilluly, 1956, p. 106) gave the rhyolite porphyry a questionable Tertiary age. It should be emphasized that Gilluly's work was conducted mainly in the late 1930's before age-dating methods became generally available. Subsequent work by Creasey et al. (1962) established the age of the Schieffelin at 72 m.y., and the age of the rhyolite porphyry at

63 m.y. Drewes (1971) determined the age of the Uncle Sam at 71.9 ± 2.4 m.y. Neither of these authors attempted to relate their dates to the age of the mineralization. Previous investigations (Butler, Wilson and Rasor, 1938, p. 30) established that the northeast-trending fissures were the channelways through which the mineralizing solutions advanced. These authors stated that the fissures "cut all the rocks earlier than the Cenozoic gravels except some dikes (hornblende andesite porphyry dikes) that have the same trend as the fissures and (are) probably later." Based on this information and on the 63 m.y. date by Creasey et al. (1962) for the rhyolite porphyry, one would conclude that the maximum age of the mineralization was 63 m.y. The corresponding minimum age would necessarily be Late Pliocene or Early Pleistocene.

The question of the age of the mineralization at Tombstone takes on added significance when it is realized that "fifteen of the sixteen known porphyry copper deposits in Arizona are intimately related to the Late Cretaceous or Early Tertiary plutons of the Laramide (75 to 55 m.y.) igneous epoch" (Livingston et al., 1968, p. 30). Of these 15 deposits, 10 had dates between 55 and 65 m.y., and only two had dates greater than 70 m.y. The importance of determining the age of the Tombstone mineralization is thus clearly defined.

As a result of the field investigations, it was apparent that a second mineralized center existed near Charleston, and it became important to determine the age of this mineralization, as well as that at Tombstone proper. Intense alteration has developed considerable amounts of sericite at the Charleston lead mine, and a sample of this sericite was submitted to S. C. Creasey of the U. S. Geological Survey in

Menlo Park. The potassium-argon age of the sericite was 74.5 ± 3 m.y. (Appendix I). This age is virtually indistinguishable from those of the Schieffelin Granodiorite and the Uncle Sam Tuff. The sericite date is believed to represent the age of the mineralization at Charleston.

The next critical question is, how does this age relate to that at Tombstone? The evidence presented indicates that there are two ages of mineralization in the main district. Hydrothermal alteration related to silver mineralization along the Contention dike yielded an age of about 72 m.y. (Gustafson, pers. comm.). Similar ages have been reported for the Schieffelin Granodiorite and the Uncle Sam Tuff (Creasey et al., 1962; Drewes, 1971). The rhyolite porphyry associated with manganese mineralization in the southern part of the district is considerably younger with an age of about 63 m.y. (Creasey et al., 1962).

The relatively old ages of the silver and base-metal mineralization at Charleston and at Tombstone, in southern Arizona, do not eliminate the possibility of discovering a major porphyry copper deposit in the district, but the chances of such a discovery are reduced. If base-metal mineralization could be found associated with the 63 m.y. old manganese mineralization, the chances of discovering a porphyry copper deposit at Tombstone would be increased. The Emerald mine, which reportedly contained the largest copper deposit in the district (Butler, Wilson and Rasor, 1938, p. 104), lies about 1300 ft south of the Prompter fault, and important manganese mineralization exists along the fault (Butler, Wilson and Rasor, 1938, p. 80). The Emerald mine workings bottomed in ore at a depth of about 880 ft when the water table was reached. According

to Butler, Wilson and Rasor (1938, p. 72), a carload of chalcocite was shipped from the bottom level of the mine. Spatially, the copper in the Emerald mine may be related to the rhyolite porphyry, and the nature and extent of the mineralization below the water table remains undetermined. The possible significance of the copper mineralization at the Emerald will be discussed more thoroughly near the end of Chapter V.

CHAPTER IV

AERIAL SENSING INVESTIGATIONS

Introduction

Considerable amounts of aircraft and spacecraft photography are available for the Tombstone district, and this chapter is concerned with the utility of various photo scales for mineral exploration purposes near Tombstone. Characteristics of the photography examined during this investigation are summarized in table 3.

Five sets of photography were studied from altitudes between 913 km and 1.8 km. Corresponding photo scales ranged from 1:1,000,000 to 1:12,000. The photography was flown in the interval between February 25, 1956, and December 26, 1972, and local standard times during exposure periods ranged from 07:46 to 13:50 hrs. Several authors (Hackman, 1967; Wise, 1968, 1969; Lyon et al., 1970) have emphasized that topographic expression can be enhanced by photographing the terrain under low sun-angle conditions. The photography studied for Tombstone had sun-angle elevations of between 21 and 50° above the horizon, and the influence of sun-angle variation on photograph interpretation was noted. Sun azimuth angles for the Tombstone photography varied from 92° (E-W) to 215° (SW-NE).

Photograph resolution is "a complex subject (but) resolution, for purposes of practical photointerpretation, may be defined as the size of the smallest object of interest that is visible on a

Table 3
Photographs Used for Geologic Comparisons

Photography	Film and filter	Altitude	Scale	Date	Local standard time	Sun angle	Sun azimuth	Ground resolution
ERTS-1 (E-1156-17283-5,7)	Multispectral scanner Bands 5 & 7	913 km	1:1,000,000	12/26/72	10:28 hrs	28°	149°	224-316 m
Apollo VI (AS6-2-1442)	SO-121	230 km	1:855,000	4/4/68	07:46 hrs	21°	98°	50-125 m
R357F	Green: 24C2 filter 58 Red: 24C2 filter 25A Solar IR: 2424 filter 89B Color IR: SO-117 Nat. color: 2448	17.4 km	1:114,000	6/16/70	09:01 hrs	50°	92°	± 12 m
Army Map Service	Plus X: 34017	7.6 km	1:50,000	2/25/56	13:50 hrs	42°	215°	± 5 m
Low level photography	Double X: ?	1.8 km	1:12,000	1/12/68	10:30 hrs	34°	156°	± 2 m

Note: 1 km = 0.621 miles

photograph" (Amsbury, 1969, p. 494). In the present study, where published resolution data were lacking, effective ground resolution values were estimated according to the method adopted by Amsbury. For the Tombstone photography, resolution values were between 316 and 2 m. Amsbury compared the relative applications of spacecraft and aircraft photography to general geological mapping studies. He examined photography with original film scales of between 1:3,000,000 and 1:20,000, and the effective ground resolution of his photography ranged from about 100 m to approximately 1.5 m. Resolution was the major limiting factor that governed interpretation, and Amsbury recommended the use of two different photo scales. Scales of 1:2,500,000 and 1:60,000 were ideal for regional mapping and reconnaissance studies, but 1:250,000 and 1:24,000 scales were better suited to detailed studies. Amsbury's study pre-dated the availability of ERTS-1 (Earth Resources Technology Satellite-1) data.

Spacecraft Photography

ERTS-1

During the present investigation, ERTS-1 imagery was studied for red and far-infrared bands (band 5, 0.6 to 0.7 μ m; and band 7, 0.8 to 1.1 μ m respectively). Color composite imagery was not examined. The altitude of the spacecraft orbit is about 913 km (Colvocoresses, 1972), and the scale of the imagery is 1:1,000,000. Colvocoresses determined the effective ground resolution to be between 224 and 316 m. The imagery date was December 26, 1972, and the local time at exposure

was 10:28 hrs. The indicated sun elevation and azimuth are 28 and 149° respectively.

Band 7 was found to be superior for structural studies, since topographic features were better expressed. Tonal contrasts were better expressed by Band 5. The most prominent linear feature within the mapped area, as seen on the imagery, was the north-trending San Pedro River valley. The Ajax Hill fault was easily recognized, and a northeast topographic grain was represented by the trend of the Three Brothers Hills north of the State of Maine mine. A northwest trend was indicated by the southeast spur of Horquilla Peak, and an indistinct east-west linear feature could be traced through Government Draw.

Identification and separation of individual rock types (sedimentary, volcanic, and igneous) was not possible on the imagery, and areas of hydrothermal bleaching and iron staining could not be identified. In summary, the ERTS-1 imagery was most useful for identifying regional structural trends.

Apollo VI

Natural color Apollo VI photography was examined at a scale of 1:855,000. The elevation of the spacecraft was about 230 km (Colvocoresses, 1972), and he determined that the effective ground resolution was between 50 and 125 m. The date of the photography was April 4, 1968, and local time at exposure was about 07:46 hrs. The indicated sun elevation was about 21° , from an azimuth of 98° .

The San Pedro River valley was very prominent and the Ajax Hill fault was better defined than it was on the ERTS imagery. The

indistinct Government Draw linear on the ERTS imagery was easily identified on the Apollo photo. Another only slightly less prominent feature than the Government Draw linear could be identified immediately north of Tombstone. This feature is nearly parallel to that in Government Draw. A distinct north-northwest linear trend could also be identified along Walnut Gulch, and this feature intersected the east-west linear in Government Draw, beyond the southeastern edge of plate 1. The northeast alignment of the Three Brothers Hills was more evident than it was on the ERTS imagery.

The limestone ridges south of Ajax Hill could be separated from the Uncle Sam volcanics. The limestones were distinctly grayer than the reddish-buff colored volcanics. Evidence of hydrothermal alteration could not be recognized. In summary, the lower sun angle and the better resolution of the Apollo photography make it slightly superior to the ERTS imagery.

High Altitude RB57F Photography

High altitude (17.4 km) RB57F photography is available for the Tombstone area. This photography was studied at a scale of 1:114,000 for green, red, solar infrared, and color infrared bands (0.5 to 0.6 μm , 0.6 to 0.7 μm , 0.7 to 0.9 μm , and 0.5 to 0.8 μm respectively). Natural color (0.4 to 0.7 μm) photography at the same scale was also examined. The RB57F photography was obtained by the National Aeronautics and Space Administration (NASA) mission 131 on June 16, 1970, at a local time of 09:01 hrs. The sun elevation was about 50° from an azimuth of about 92° . Due to the lack of more detailed information, Amsbury (1969, p. 495) used house sizes to estimate

effective ground resolution values, and during the present study, houses could be recognized, but individual automobiles could not. An effective ground resolution value was estimated to be about 9 m.

Green Band

High altitude green band (0.5 to 0.6 μm) photography showed only moderate topographic clarity. Ridge crests were sharp and distinct, but finer details of drainage fabrics were poorly defined. All major structural features were easily identified; however, the subtle northeast-trending fractures in the Uncle Sam Tuff were indistinct.

Tonal contrasts for the various rock types were only moderately distinct. Lighter tones were observed for limestone ridges relative to the Bisbee Formation and to the volcanics. The major drainages were easily identified as their relatively light tones were contrasted against darker tones for the surrounding lithologies. However, hydrothermally bleached areas could not be identified on the basis of their light tones.

Red Band

Topographic features as observed on red band (0.6 to 0.7 μm) photography were unusually distinct. Ridge crests were more sharply defined than in the green band, and drainage fabric details were more easily observed. Major structural features were easily identified, and the northeast fissures in the Uncle Sam more clearly expressed than they were in the green spectrum.

Tonal contrasts were also better developed in the red band than they were in the green band. The limestone ridges near Horquilla Peak were slightly lighter-toned than they were in the previous band, but they were still easily separable from the slightly lighter gray tones of the Uncle Sam. Drainages were quite distinct as their lighter tones were sharply contrasted against those from nearby lithologies. Vegetation along many of the drainages showed darker tones than were present in the green band. Areas of hydrothermal bleaching could be identified by their slightly lighter gray tones.

Solar Infrared Band

Topographic features observed on the solar infrared band (0.7 to 0.9 μm) were generally easily identified, but they were more diffuse than in the green and red bands. Drainage fabric details were somewhat obscure in this band. The northeast fissures in the Uncle Sam volcanics could be identified, but as with other structural features in this band they were not distinct.

Tonal contrasts were generally poorly expressed in this band. Carbonate rocks near Horquilla Peak showed slightly darker tones than did the volcanic rocks. Clastic sediments of the Bisbee Formation were only slightly darker toned than the carbonates. In some instances, vegetation contrasts were better developed by the solar infrared band than they were in the green band. Along the road to Gleeson, just east of the basalt dome in Walnut Gulch, is an area of apparent over-grazing. This over-grazed area was less distinct on the green band than on the solar infrared band. However, the same area shows a better contrast on the red band than it does on this infrared band.

Areas of hydrothermal bleaching between the State of Maine mine and the Charleston lead mine could be identified, with difficulty.

Color Infrared Band

The color infrared band (0.5 to 0.8 μm) was the most useful of any of the RB57F photography examined. Topographic features were unusually prominent, and even the most subtle northeast fractures in the Uncle Sam were easily identified. Carbonate lithologies were characterized by pale reddish grays, while clastic strata were represented by pale reddish-brown colors. Volcanic rocks had light-red to moderate-pink colors. Drainage patterns were extremely well expressed by light grayish-pink colors along the dry stream beds. Vegetation following dry wash margins characteristically had deep-red hues, which formed an excellent contrast against the lighter colored dry wash beds. The sharp vegetation-drainage contrast undoubtedly helped to enhance the topographic expression for many features in the study area.

Tonal contrasts were only moderately well developed over areas of hydrothermal bleaching. However, areas of intense iron staining were easily identified. A portion of the Courtland-Gleeson area in the Dragoon Mountains to the east of Tombstone was covered by the RB57F flight, and here iron-stained intrusive rocks could be easily identified by their characteristic moderate reddish-brown hues on the color infrared photos. The combination of sharp tonal contrasts and distinct topographic expressions make the color infrared photography an excellent tool for geologic studies in the Tombstone area.

Natural Color Band

Natural color (0.4 to 0.7 μ m) photography was found to be somewhat inferior to the infrared photos for structural studies. Topographic clarity and sharpness were less distinct than in the infrared format. The major structural features were still easily identified, but the northeast fractures in the Uncle Sam were less conspicuous. Ridge crests were generally sharply defined, but slightly less so than on the infrared photos.

Tonal contrasts, while frequently well developed, were inferior to the infrared contrasts. Carbonate rocks displayed greenish-gray hues while volcanic rocks yielded greenish-brown colors. Near areas of iron staining, clastic sedimentary rocks had darker brownish colors than did the volcanics. Away from the altered zones, these sedimentary rocks generally had lighter hues than those of the volcanics. The very distinct drainage patterns observed on the infrared photography were less clear in the natural color photos. The dry washes maintained their light-gray to white colors, but the green vegetative hues failed to form the very sharp contrast mentioned above. Areas of hydrothermal bleaching usually showed pale-tan to light-gray hues, and areas of iron staining generally had light-to moderate-brown colors. Both zones were less conspicuous than they were in the infrared photos. The less distinctive tonal contrasts and the decreased topographic clarity combined to make the natural color photography slightly inferior to the infrared format.

Army Map Service Photography

Army Map Service photography, at a scale of 1:50,000, was obtained from U. S. Government sources for the Tombstone area. The photography was flown on February 25, 1956, at an altitude of about 7600 m. The local time at exposure was about 13:50 hrs, and the photography was flown without regard for low sun-angle considerations. The sun elevation was about 42° from an azimuth of 215° . Automobiles are the smallest recognizable objects, and following the method of Amsbury (1969), the effective ground resolution was estimated at about 5 m.

Prominent structural features such as the Horquilla and Prompter faults were readily observed. The Ajax fault, the East Boundary fault, and the linear trend along Walnut Gulch could also be identified. However, to fully appreciate these structures more than one stereo pair had to be examined. Appreciation for linear trends along the San Pedro River and Government Draw was greatly reduced at this relatively large scale. The northeast-trending fractures in the Uncle Sam could be identified, but these structures would no doubt be even more enhanced if the photography had been flown under lower sun-angle conditions.

In general, tonal characteristics of this photography were poor. The limestone ridges near Horquilla peak were only slightly lighter toned than was the Uncle Sam on the Three Brothers Hills. The Bisbee Formation and the Bronco Andesite displayed similar tonal features. Contrast along drainages was moderate to poor. Areas of hydrothermal alteration were difficult to recognize on these black

and white photos. Photography at this scale is often quite useful for district reconnaissance studies, but decidedly more information could have been obtained from the photos if they had been flown under lower sun-angle conditions and in either a natural color or an infrared format.

Low-Level Photography

A partial set of large scale (1:12,000) black and white photographs was obtained for the area between the Charleston lead mine and the Ajax Hill fault. The photography was flown at an altitude of about 1.8 km on January 12, 1968. The local time at exposure was about 10:30 hrs, with a sun elevation of about 34° from an azimuth of 156° . The smallest recognizable features were mesquite trees, and the estimated effective ground resolution was about 2 m.

These photos proved to be quite useful, as relatively detailed structures were first identified on the photos and then located and followed on the ground. The Ajax and Prompter faults were very prominent, but more than one stereo pair was required to follow them. Of greatest significance at this scale were the northeast-trending fractures in the Uncle Sam. The fractures appeared as numerous, close-spaced, persistent structures.

For black and white photos, the tonal contrast quality was moderate to good. Dry wash contrasts, observed as very light-gray to white hues, against the darker colors of the surrounding lithologies, were well expressed. Many drainages followed along the northeast fractures, and assisted in the identification of the prevailing structural grain. Areas of hydrothermal bleaching were moderately

well defined on the photos, and these lighter tones paralleled the northeast fractures. Tonal contrasts for areas of iron staining were only moderately developed in dark-gray and black hues. Limestone beds were generally lighter colored than light grays associated with the unaltered Uncle Sam. At this scale, individual trees could be identified, and their dark gray tones helped to develop sharp dry wash contrasts. Color photographs at this scale would have provided more information. However, for large scale photography, color is not as important as it is for somewhat smaller scale photographs. Low-level, large-scale photos are most useful during semi-detailed and detailed investigations of individual mining districts.

Discussion

Sun-Angle Effects

Figure 10 illustrates the inter-relationships of sun angle, scale, and sensor altitude on photograph quality. For purposes of high quality photo interpretation, it is apparent that small scale space-craft photography requires low illumination angles, and that large scale photography can tolerate somewhat higher illumination angles. At scales smaller than 1:50,000 photo interpretation is best accomplished with sun angles less than 30° . Photography with scales larger than 1:50,000 has a high degree of interpretability for sun angles up to about 40° . The ability to interpret linear features on photography at any scale is progressively improved as the illumination angle is decreased to a minimum of between 10° and 15° .

In the case of the high-altitude photography, with sun angles of about 50° , the quality of the various spectral bands, and

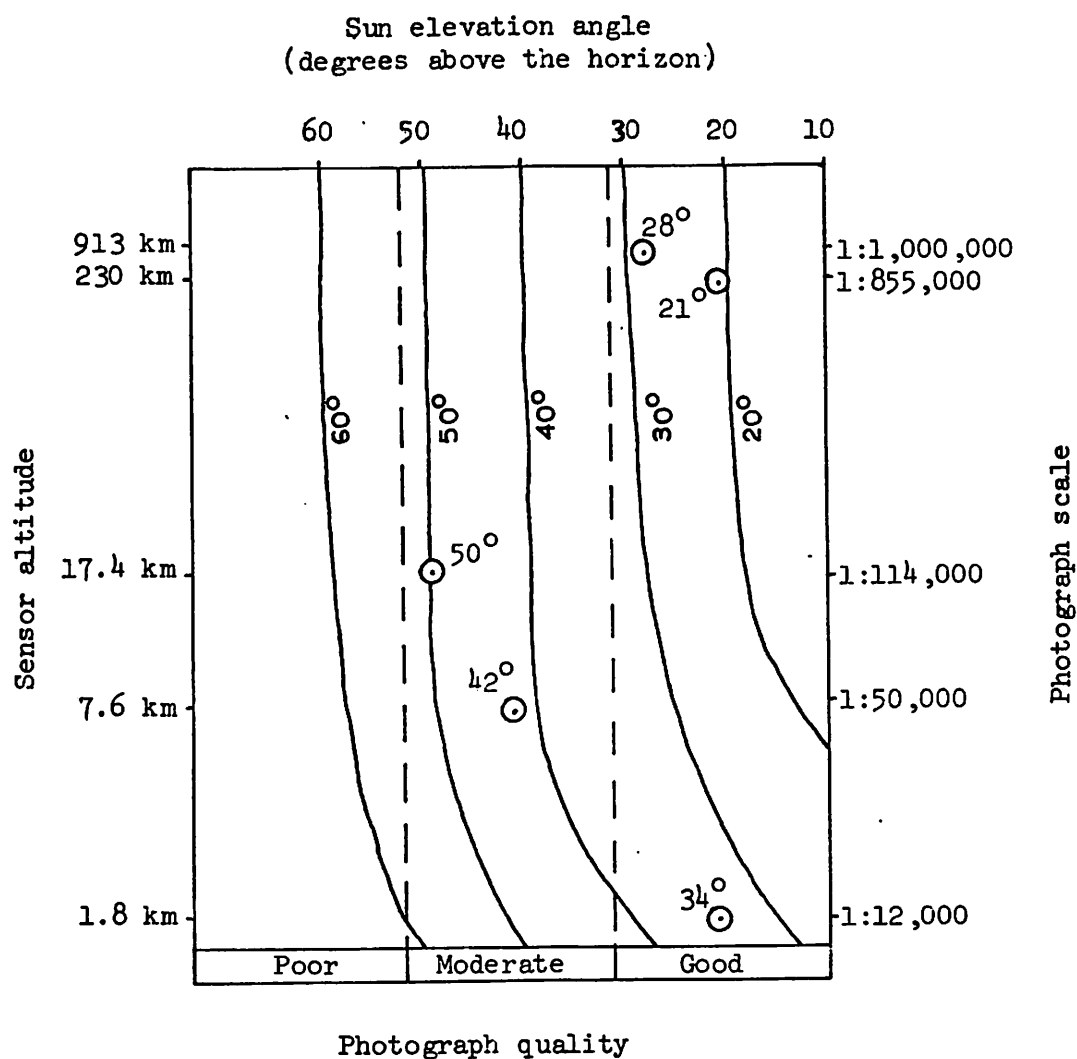


Fig. 10.--Illustration showing the interrelationships of sun angle, scale, and sensor altitude on photograph quality. A logarithmic scale was used to insure proper interval spacing of photo scales. Sensor altitudes were placed to correspond with the appropriate photo scale. Sun-angle elevations for the photography studied are also indicated. Solid lines indicate iso-sun-angle elevations.

particularly the natural color band, would be considerably improved if exposed at sun-angles of about 30° . Under controlled experimental conditions, Hackman (1967) found that topographic features were best displayed with low sun-angle conditions, and that color tones were best expressed by high sun angles. He found that sun angles of between 20 and 30° provided the most information if only one photograph was to be taken. The loss of topographic expression, due to relatively high sun-angle (50°) effects on the natural color RB57F photography, were compensated by the use of color infrared techniques. With color infrared photography, in arid regions such as Tombstone, contrasts of red vegetation against white dry-wash drainages served to enhance structural and topographic features. Thus, the damaging effects created by a relatively high sun angle, were reduced through the use of color infrared photography.

Photograph Scale Effects

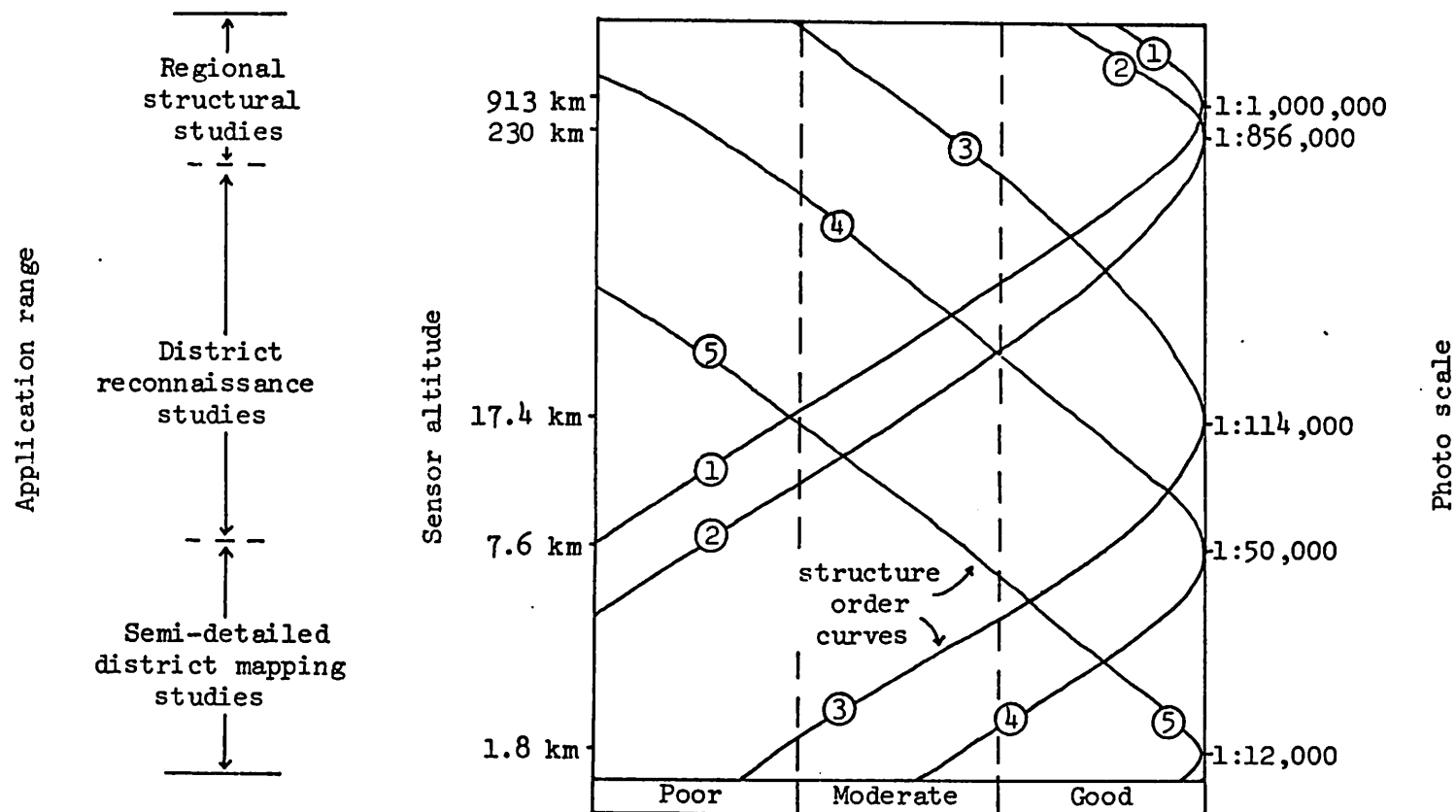
The major structural features near Tombstone were classified into five categories on the basis of length (table 4). The north-northwest-trending San Pedro River valley, with a length of about 170 km, is the largest and only first-order structure near Tombstone. Second-order structures include the east-west linear feature in Government Draw (32 km), and the northwest-trending structure along Walnut Gulch (15 km). The north-south-trending Ajax Hill fault with a length of about 7 km is a third-order structural feature. Fourth-order structures include the east-west-trending Prompter-Horquilla faults (7 km), and the northeast-trending fractures (0.8 km) in the Uncle Sam Tuff are fifth-order structures.

Table 4
Structure Classifications

<u>Order</u>	<u>Structure name</u>	<u>Length (km)</u>
1st	San Pedro linear	±170
2nd	Government Draw; Walnut Gulch	32; 15
3rd	Ajax fault	7
4th	Prompter-Horquilla faults	4
5th	Northeast-trending fractures	0.8

The ability to study individual structures on the photographs was related to structure length, photograph scale, and sun-angle elevation (figs. 10, 11). The linear feature along the San Pedro River valley was very prominent on both the ERTS-1 imagery and the Apollo VI photography. However, due to larger scale effects, as shown in fig. 11, the strength and linear extent of the feature were poorly realized on the high-altitude aerial photography (scale 1:114,000). The Government Draw and Walnut Gulch structures were visible on the ERTS-1 imagery, but these structures were considerably more distinct on the Apollo VI photography. The imagery and the photography have comparable scales, and the increased clarity of these second-order structures on the Apollo VI photography is due to lower sun angle conditions (21° vs. 28°) which existed for the Apollo VI photograph (fig. 10). The increased scale of the high-altitude photography did not allow full appreciation of the Government Draw and Walnut Gulch linears, and the complete structures were best studied on the Apollo VI photographs.

Aircraft photography was well suited for the study of third-, fourth-, and fifth-order structures. The third-order Ajax fault was best displayed as a complete feature on high-altitude photography at a scale of 1:114,000. Fourth- and fifth-order structures were best studied on photographs with scales of 1:50,000 and 1:12,000 respectively. It should be noted that the northeast-trending, fifth-order fractures, which exercised an important control on the Tombstone ore deposits, are only moderately visible on 1:50,000 scale photos and poorly visible on 1:114,000 scale photos. The



Structure classification:

- 1st order: San Pedro linear
- 2nd order: Government Draw-Walnut Gulch
- 3rd order: Ajax fault
- 4th order: Prompter-Horquilla faults
- 5th order: NE-trending fractures

Ability to recognize and follow structures of a given order

Fig. 11.--Diagrammatic illustration showing the relative application ranges, and inter-relationships of structure order, photo scale, and sensor altitude on photo interpretation.

fifth-order structures could not be identified on either the ERTS-1 imagery or on the Apollo VI photography.

Figure 11 illustrates that as the length of a structure decreases, the structure is more efficiently studied on progressively larger scale photography. However, optimum scales and altitudes exist for studying structures of any given order, and the ability to recognize and follow a particular structure diminishes as the sensor is moved either too close to or too far away from the feature. If the length of a particular structure is not between one-fourth and one-half the size of a given photograph, the individual structure is more efficiently studied on either smaller or larger scale photographs.

For purposes of effective minerals exploration, photographs of three different scales should be utilized. Regional structural studies are best conducted on spacecraft imagery or photography at scales between 1:1,000,000 and 1:800,000. Reconnaissance studies within individual mining districts should employ photography at scales between 1:500,000 and 1:50,000. Photograph scales between 1:50,000 and 1:10,000 should be utilized for semi-detailed district mapping studies.

Aircraft and Spacecraft Exploration Summary

Six structural features identified on the aircraft and spacecraft photography have potential interest for mineral exploration purposes near Tombstone. After studying the Apollo VI photography, it became apparent that the Schieffelin Granodiorite at Lewis Springs (pl. 1) had intruded the north-trending San Pedro structure at its intersection with the east-west-trending Government Draw linear. Lowell (1973) suggested that the San Pedro trough was an important

structure for the localization of porphyry copper deposits. Thus, the presence of the Schieffelin Granodiorite at the San Pedro-Government Draw intersection indicates that the area near Lewis Springs is of potential exploration interest.

Another structural intersection of exploration interest is formed where the east-west Government Draw linear meets the northwest-trending Walnut Gulch structure. This intersection was identified on the Apollo VI photography. The area of this intersection is covered by transported gravels, which originated from surrounding hills, and the bedrock is not exposed.

One mile north of Tombstone, in the SE $\frac{1}{4}$ sec. 35, T. 19 S., R. 22 E. (pls. 1, 2), the north-northwest-trending drainage for Walnut Gulch swings abruptly to the west. This west-trending portion of Walnut Gulch is nearly parallel with the Government Draw structure, and a prominent structural intersection was identified on the Apollo VI photography at the point where Walnut Gulch changes direction. On the ground, the intersection is covered by alluvial sand and gravel deposits. However, the Schieffelin Granodiorite and associated host rocks, which are exposed about 1 mile to the southwest, may lie beneath the surface gravels. If this is the case, previously unsuspected mineralization could be concealed below the alluvial deposits.

The east-west-trending Prompter and Horquilla faults form right-angle intersections with the north-striking Ajax fault and these intersections are of exploration interest. These intersections occur in areas of relatively good outcrop, and while the structures can be mapped in detail on the ground, they can also be easily identified on both the high-altitude (1:114,000) and the Army Map Service

photography (1:50,000). The Prompter fault is known to have exercised an important control on the mineralization in the southern part of the main Tombstone district (Butler, Wilson and Rasor, 1938, p. 80-84). The Dry Hill mine is at the Ajax-Prompter intersection. Much of the early production from this mine is unrecorded, but Butler, Wilson and Rasor state that between 1933 and 1937, production totaled 3116 tons of ore which yielded 131 oz of gold, 52,957 oz of silver, and 10,401 lb of copper. The Horquilla-Ajax intersection is also of potential exploration interest. The dump, from a small mine located at the intersection, was sampled and found to contain 0.20 percent copper, 3.92 percent lead, 2.56 percent zinc, 85 ppm silver, and 11 ppm molybdenum. While higher concentrations of mineralization were associated with the Prompter-Ajax intersection, both the Horquilla and the Prompter intersections with the Ajax fault are sites of known mineralization, and both intersections were easily identified on the aerial photographs.

Potentially important northeast-trending fractures in the Uncle Sam Tuff were easily identified on the low-level photographs. Similar structures are known to have exercised important controls on the mineralization in the main part of the district (Butler, Wilson and Rasor, 1938, p. 97-102). The northeast fractures in the Uncle Sam are of considerable interest, since they are largely unexplored, and significant mineralization is associated with the structures at the Charleston lead mine and at the State of Maine mine.

The use of multiscale aircraft and spacecraft photography assisted in the identification of six new areas of potential exploration interest. These areas include:

1. The intersection of the San Pedro linear with the Government Draw linear north of Lewis Springs
2. The intersection of the Government Draw linear with the north-northwest-trending Walnut Gulch linear
3. One mile north of Tombstone, where the north-northwest-trending Walnut Gulch structure intersects an east-west structure
- 4-5. The intersection of the east-west-trending Horquilla and Prompter faults with the north-south-trending Ajax Hill fault
6. The northeast-trending fracture zone, in the Uncle Sam Tuff, southwest of the State of Maine mine and northeast of the Charleston lead mine.

These six areas of potential mineral exploration interest will be discussed in more detail in the following chapter.

CHAPTER V

GEOCHEMICAL INVESTIGATIONS

Two exploration geochemical methods were used to evaluate the Tombstone area for additional mineralization. Twigs from mesquite trees (Prosopis juliflora) were analyzed for their trace metal (copper, molybdenum, silver, zinc) contents. The second method involved the analysis of mineralized rock chips from mine dumps in the district. The mine dump samples were analyzed for copper, lead, molybdenum, silver and zinc.

Mesquite Biogeochemistry

Introduction

Metal contents in trees and shrubs were first examined by Goldschmidt (1937). He observed that humus in forest soils was often enriched in many trace metals, and since the humus was derived from plant material, Goldschmidt reasoned that the plants must also contain enriched trace metal concentrations. He proposed that the systematic analysis of plant material could be useful as a prospecting method.

The theory of biogeochemical prospecting is based on the fact that tree root systems sample large volumes of subsurface ground, and that metals present in the subsurface will be collected and transported to the upper parts of the trees (Hawkes and Webb, 1962,

p. 290). In practice, biogeochemical prospecting is considerably more complex than either soil or rock geochemistry, because the use of vegetation as a sampling medium depends on the response of plants to their environment (Brooks, 1972, p. 1). Hawkes and Webb (1962, p. 291) state that even in generally alkaline soils, the surface of a root tip is highly acid. Hydrogen ions from the roots participate in cation-exchange reactions by leaving the root tips and adsorbing and displacing metal ions present on clay mineral surfaces. The displaced metal ions are then free to migrate to the roots where they are later absorbed into the plant. Under uncontrolled conditions which exist in natural environments, this relatively simple cation-exchange mechanism is subject to considerable variation. These variable factors which affect metal accumulation in plants were summarized by Brooks (1972, p. 99-111) as: the type of plant; the age and health of the plant and plant organ; the pH of the soil; the depth of the root system; the soil drainage characteristics; the intensity and duration of sunlight received by the plant; and the presence of antagonistic chemical elements in the soil. In spite of these complications, biogeochemistry is considered to be a valuable mineral exploration method.

Mesquite biogeochemistry has been shown to be suitable for mineral exploration purposes in southern Arizona (Brown, 1970; Huff, 1970), and the chemical analysis of mesquite twigs from areas with thin soil horizons on pediment surfaces is a particularly valuable application of the method. Pediments are mantled with transported gravels and soils, and it is generally difficult or impossible to obtain rock or soil samples from pediment surfaces that are

representative of bedrock conditions. In addition, caliche layers typically form several feet below the ground surface in southern Arizona, and these carbonate horizons act as effective barriers for many upward migrating trace elements. Mesquite is a phreatophyte with long penetrating roots, and Huff (1970, p. C17) reported probable mesquite roots exposed in an open pit mine at a depth of 175 ft. Mesquite trees, by penetrating the caliche, essentially allow the collection of a geochemical sample from below the troublesome carbonate layer. Large linear features identified during the aerial sensing portion of this study occur adjacent to pediments and in valleys with poor outcrop conditions. Since the gravels and soils in these valleys are of a transported nature, and the caliche layer is nearly everywhere present, mesquite trees represent the best sampling medium. Mesquite is relatively abundant in the area, and during this study particular care was taken to collect mesquite samples along the linear features identified on the aerial and space photography.

Orientation Survey

An orientation survey was conducted within the area to establish parameters necessary for the interpretation of the data. The distribution of copper, molybdenum, silver, and zinc in rocks, soils, dry wash sediments, and mesquite ash was studied at eight locations within the mapped area. In addition, a railroad bed composed of mineralized rock fragments was sampled, and mesquite trees growing in the rail bed were also sampled. Variation of metal contents as related to twig diameter was also studied. Huff (1970, p. C13) mentioned

that most of the error in the method was probably related to inadequate sampling methods, and these were likewise investigated.

Element distributions

Distributions of the elements in rocks, soils, dry wash sediments, groundwater, and mesquite ash were studied at nine different sites and the data are summarized in table 5. Rocks and soils were found to contain element concentrations of approximately the same order of magnitude. Dry wash sediment samples from the same locations generally had two to three times the concentrations of the rocks and the soils. In many places, dry wash sediments were probably derived from upstream sources, and thus they would not indicate conditions in immediately surrounding rocks and soils. Water samples from wells have considerably lower concentrations than do rocks, soils, or dry wash sediment samples. The pH values for the well waters averaged about 7.9; these values were obtained from the U. S. Department of Agriculture in Tucson (Wallace, pers. comm.). Mesquite ash generally contains higher metal concentrations than do the surrounding media. This is illustrated by mesquite enrichment ratios in table 6. These ratios were calculated by dividing the appropriate concentrations into the corresponding concentration found in mesquite twig ash. Thus, for the nine localities sampled, copper in mesquite ash was 1.7 times more enriched than it was in the surrounding rocks. Mesquite trees commonly grow along dry wash margins, and enrichment ratios for dry wash sediment data indicate a relatively close correspondence between metal concentrations in the sediment with that in the mesquite ash.

Table 5

Mean Element Distributions
for Nine Localities

	Rocks(ppm)	Soils(ppm)	Dry wash sediment(ppm)	Water(ppb)	Mesquite(ppm)
Cu	72	22	104	19	121
Mo	0.5	0.4	1.7	3.2	4.9
Zn	145	143	334	401	422
Ag	0.1	0.3	1.8	0.3	1.3

Note: pH values of water samples averaged 7.9.

Metal values in water samples are quoted in parts/billion (ppb).

Table 6

Mean Mesquite Enrichment Ratios
(e.g. mesquite/rock)

	Rock	Soil	Dry wash sediment	Water
Cu	1.7	5.5	1.2	6300
Mo	9.8	12.2	2.9	1500
Zn	2.9	2.9	1.3	1100
Ag	13	4.3	0.7	4300

Twig size

The influence of twig diameter was found to be a potential source of relatively large error. The mean copper, molybdenum, silver, and zinc contents of a tree were determined by sampling the tree in the NE, NW, SW, and SE quadrants. Twig diameters for the samples were between 0.25 and 0.5 in. A long branch collected from the central portion of the same tree was cut into segments with lengths between 0.5 and 1 in. These segments were then separated into four groups of varying diameters (1 in., 0.75 to 0.5 in., 0.5 to 0.25 in., and <0.25 in.).

Mean metal contents found for the tree as a whole, using 0.25 to 0.50 in. diameter twigs were: copper = 114 ppm; molybdenum = 10 ppm; silver = 1 ppm; and zinc = 386 ppm. Metal values in the one limb sampled ranged between: copper, 100 to 195 ppm; molybdenum, 1 to 8 ppm; silver, 1 to 2 ppm; and zinc, 210 to 590 ppm. These data, as indicated in table 7, imply that metal contents can be expected to show wide fluctuations if twig diameters are allowed to vary.

During the field study, twig diameters were closely controlled. Warren and Delavault (1949), from investigations in British Columbia, found 1/8- to 1/4-in. diameter twigs to be most satisfactory. Warren, Delavault and Fortescue (1955) reported that metal contents in first-year twigs varied during the growing season, and it was recommended that second-year twigs be used for biogeochemical prospecting purposes. According to the terminology, first-year growth applies to the youngest shoots on a limb, and second-year growth to the next youngest shoots. First- and second-year growths do not mean actual twig age. First-year mesquite twigs were found to have diameters of both less than and greater than 1/8 in., and it was decided to sample twigs with

Table 7

Metal Contents from Various Size Fractions
of a Single Mesquite Limb

Limb diameter	Ag	Cu	Mo	Zn
1 in.	2	100	4	210
3/4-1/2 in.	1	115	6	270
1/2-1/4 in.	1	110	8	425
1/4 in.	1	195	1	590

Note: All metal values are reported as parts/
million (ppm) in twig ash.

diameters between 0.25 and 0.5 in. Twigs of this size were found generally to correspond to second-year growth.

Number of trees sampled per site

The optimal number of trees to sample at each site was investigated. Samples obtained from the north sides of trees were compared with samples collected from the south side, and also with samples from both the north and south sides. Ten trees at each of two sites were studied in this fashion. The first eight trees (four from each site) were sampled a year earlier than the later 12 trees, and the data for the two years were within the margin of error (15 to 30 percent) inherent in the method. Seasonal fluctuations of metal contents in mesquite trees are probably relatively minor, if the last year's growth is not included in the sample.

The data from the two study sites were combined, and 90 percent confidence intervals were calculated for departures from mean values, as a function of the number of trees sampled. This information is shown graphically in figure 12. It is apparent that as more trees are sampled, one becomes increasingly confident that the data obtained will more closely represent a "true" value for a given site. If a true mean could be determined for a particular site, and 10 trees were sampled at that site, one could be 90 percent confident that the value obtained for copper would fall between ± 15 percent of the "true" copper value. For example, if after collecting a composite sample from 10 trees, a copper value of 100 ppm is obtained, the "true" value for that site would fall between 85 and 115 ppm, 90 percent of the time. If the north sides of four trees were sampled to obtain a molybdenum value, the "true" value would lie between ± 84 percent of

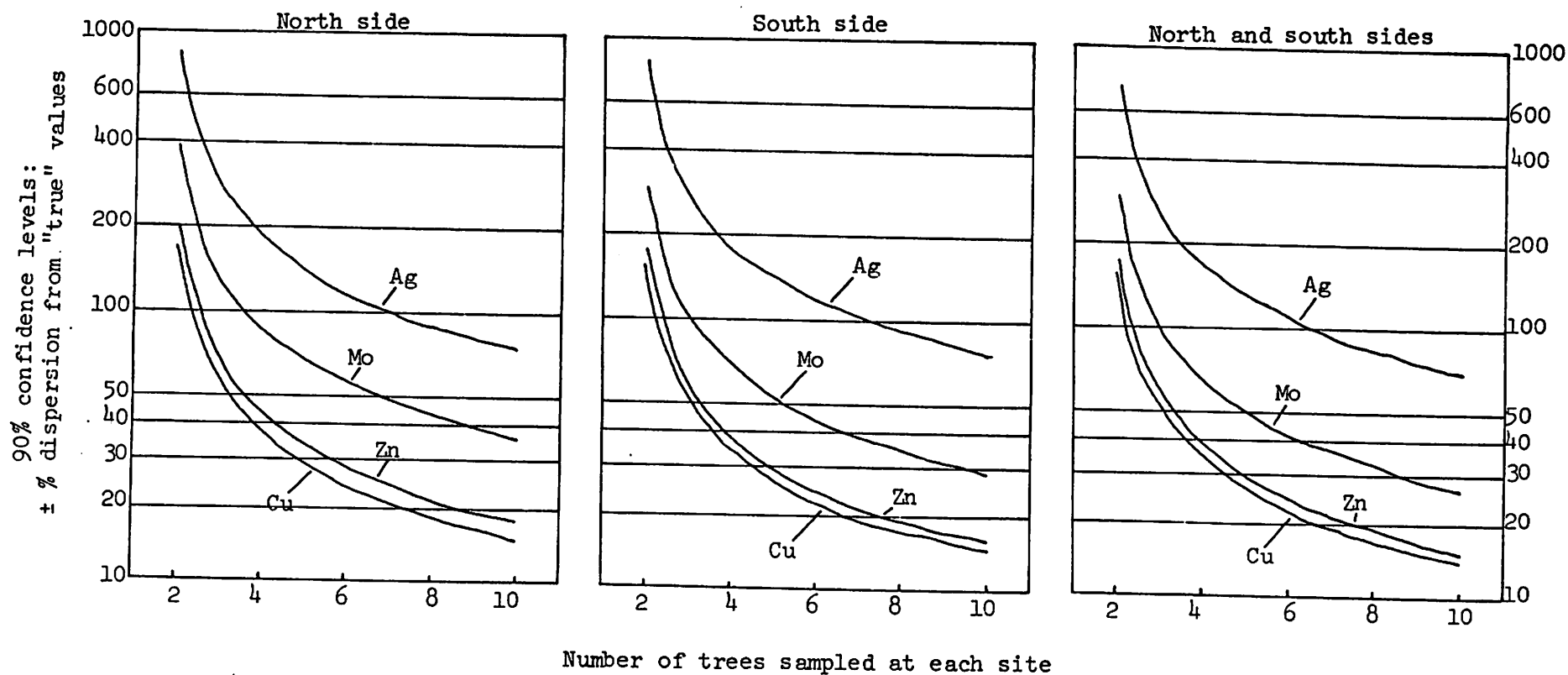


Fig. 12.--Graphs indicating $\pm$ percent departures of mean metal values in mesquite trees from "true" values, at the 90% confidence level, as a function of the number of trees sampled at a particular site.

the molybdenum value obtained, 90 percent of the time. The curves also indicate that little difference exists in data obtained from either the north side, the south side, or the north and south sides combined.

In general, it is too time consuming to sample 10 trees at each site during the course of a survey. It is usually necessary to optimize the amount of time spent collecting the samples with the quality of the data. During the present study three trees were sampled where possible at each site. Three trees are an absolute minimum, and preferably four or five trees should be sampled at each site.

The curves in figure 12 indicate that, at the 90 percent confidence level, little difference exists between data obtained from the north and south sides of the trees. However, the data obtained from the 20 trees studied to construct the curves of figure 12 indicated that 60 percent of the south side samples had higher metal contents than did the north side samples. About 15 percent of the trees had equal sample values on both the north and south sides, and about 25 percent of the trees had higher concentrations on their north sides than they did on their south sides. Silver did not show a north side or south side preference. The maximum copper difference was 35 ppm with the south side having the larger amount. Copper, for the 20 trees, averaged only 6.7 ppm higher on the south side than on the north side. For molybdenum, the maximum difference was 13 ppm, with the north side having the larger amount. However, the average difference for the molybdenum data from the 20 trees was only 0.05 ppm, in favor of the north side. This is clearly of little significance. The largest zinc difference was 200 ppm, and the south side had the

higher value. The mean zinc difference for all 20 trees was only 36.5 ppm, again in favor of the south side. The data presented above indicate that it makes little difference whether or not the north sides, south sides, or both sides of the trees are sampled. Brown (1970), without presenting data to support his statement, believed that significant differences existed between data from the north and south sides of mesquite trees. He chose to sample only on the north side. While admitting that south side values were often higher, he believed north side values to be less erratic. As illustrated by the data presented above it would seem to make little difference which side was sampled; however, during the course of a survey, it is probably best to sample consistently. For this study, both the north and south sides were sampled to take advantage of the slightly higher metal values on the south sides.

Field Survey

Three hundred and fifty-two mesquite samples were collected during the field survey near Tombstone. The samples were analyzed for copper, molybdenum, silver, and zinc, and the data are summarized in table 8 and in figures 13-16. An effort was made to collect at least one sample from each quarter section in the area selected for this survey, and many quarter sections contained two or more sample sites. In general, the north and south sides of three trees were sampled per site.

Copper in mesquite ash

Copper values in mesquite ash ranged from 40 to 295 ppm, and the mean value was about 119 ppm. The standard deviation was about

Table 8
Mesquite Biogeochemical Data Summary

	Cu	Mo	Ag	Zn
Range	40-295	1-36	1-8	120-1600
Mean	119	4	1.2	390
Standard deviation	29	5	1	145

Note: All values reported as parts/million (ppm).

29 ppm. For copper, the curves of figure 12 indicate a ± 50 percent spread about the mean value, and since the mean is close to 100 ppm, the data was grouped at intervals of at least 50 ppm.

Anomalous values were obtained at Tombstone proper, but copper values tended to show low threshold values surrounding the town site (fig. 13). Copper tended to increase from low threshold concentrations (101 to 150 ppm) to high threshold values (150 to 200 ppm) near the San Pedro-Government Draw structural intersection, but no anomalous values were found in this area. At the Government Draw-Walnut Gulch structural intersection, beyond the east boundary of plates 1 and 2, anomalous copper values (200 to 275 ppm) occurred in secs. 2 ⁴, T. 21 S., R. 23 E. The Colina Limestone occupies the hills ^N of the anomaly, and the Bisbee Formation is exposed immediately south of Government Draw. The Bisbee is composed of maroon sandstones, mudstones, and shales, and some of the high copper values may have originated from the Bisbee rocks. Nevertheless, the reason for high copper values is largely unknown. Background and low threshold copper values were found near the structural intersection north of Tombstone, where Walnut Gulch changes direction (SE ¹/₄ sec. 35, T. 19 S., R. 22 E.). Similar copper concentrations occurred at the intersection of the Ajax fault with the Prompter fault in secs. 15 and 16, T. 20 S., R. 22 E. However, in sec. 27, T. 20 S., R. 22 E., where the Horquilla fault intersects the Ajax fault, low threshold to anomalous copper values were found. Background and low threshold concentrations occurred near the northeast-trending fractures in the Uncle Sam (secs. 19, 20, 29, and 30, T. 20 S., R. 22 E.). In summary, the Government Draw-Walnut Gulch anomaly is the most promising, and additional samples

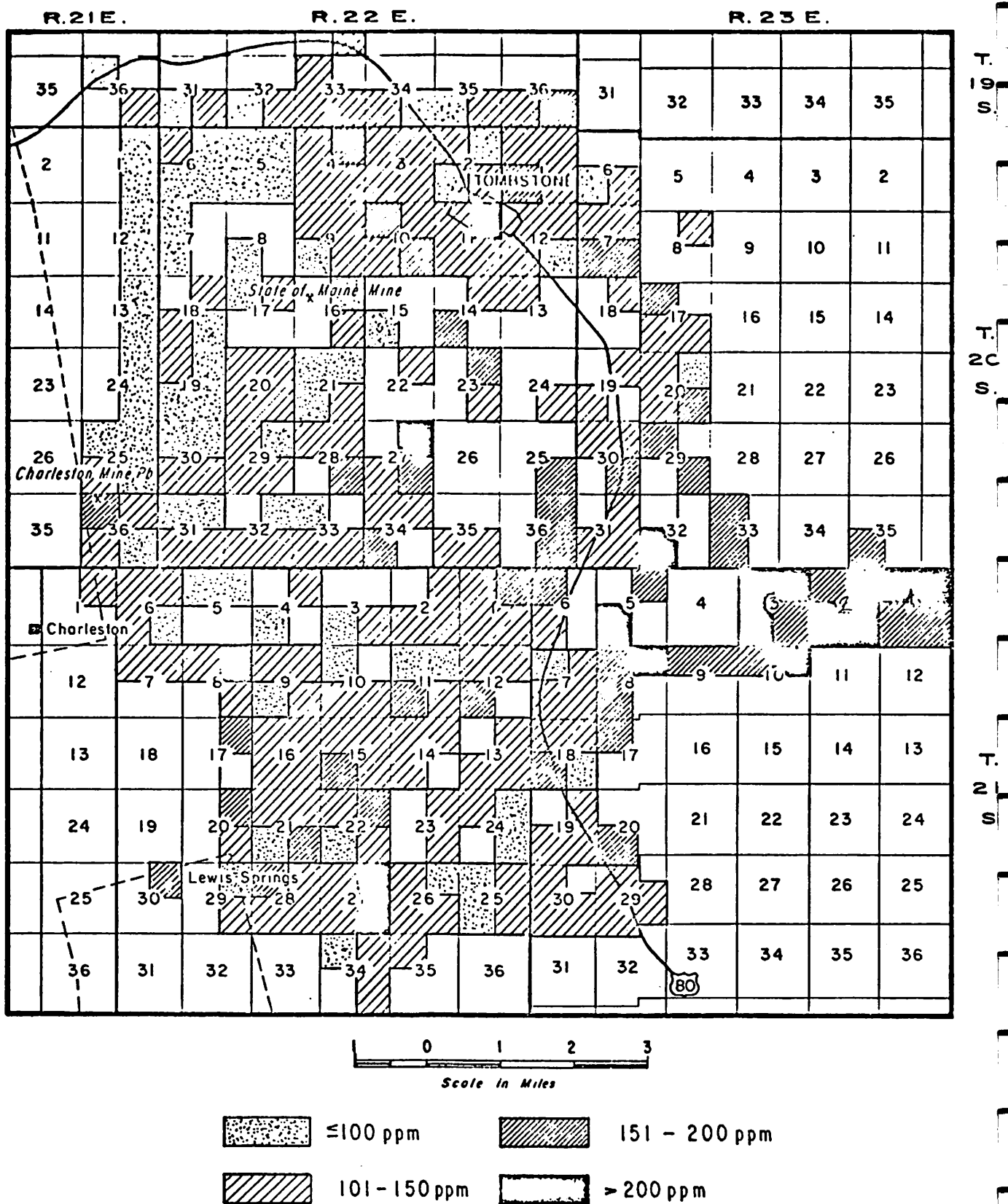


Fig. 13--Copper in mesquite trees.

should be collected to more closely define the anomalous area.

Brown (1970) found values of between 200 and 300 ppm copper in mesquite ash near the Kalamazoo ore body northeast of Tucson; in the Tombstone area, any sample of 200 ppm or more may indicate a need for more samples.

Molybdenum in mesquite ash

Molybdenum values in mesquite ash ranged from 1 to 36 ppm. The mean value was about 4 ppm, and the standard deviation was about 5 ppm. Curves from figure 12 indicate departures of about ± 100 percent from the mean value. It was decided to divide the data into groups with at least 4 ppm ranges. The molybdenum data are shown on figure 14.

Near Tombstone, molybdenum had anomalous values of about 15 ppm, and high threshold values of between 10 and 12 ppm. Similarly, high values of 10 to 16 ppm were found near Lewis Springs at the San Pedro-Government Draw intersection. In this area, molybdenum increased to the west, from background to anomalous values; this increase may have been due to possibly high molybdenum concentrations associated with the Schieffelin Granodiorite north of Lewis Springs. Background concentrations occurred at the Government Draw-Walnut Gulch structural intersection in secs. 2 and 3, T. 21 S., R. 23 E. A strong copper anomaly was associated with this area, and the lack of correspondingly high molybdenum values suggested that some of the copper may have been derived from the Bisbee Formation to the south. However, Brown (1970) did not find high molybdenum concentrations associated with the copper anomaly near the Kalamazoo ore body, and the lack of anomalous molybdenum values in Government Draw should not eliminate this site as a potential target area. Background values were also found over the

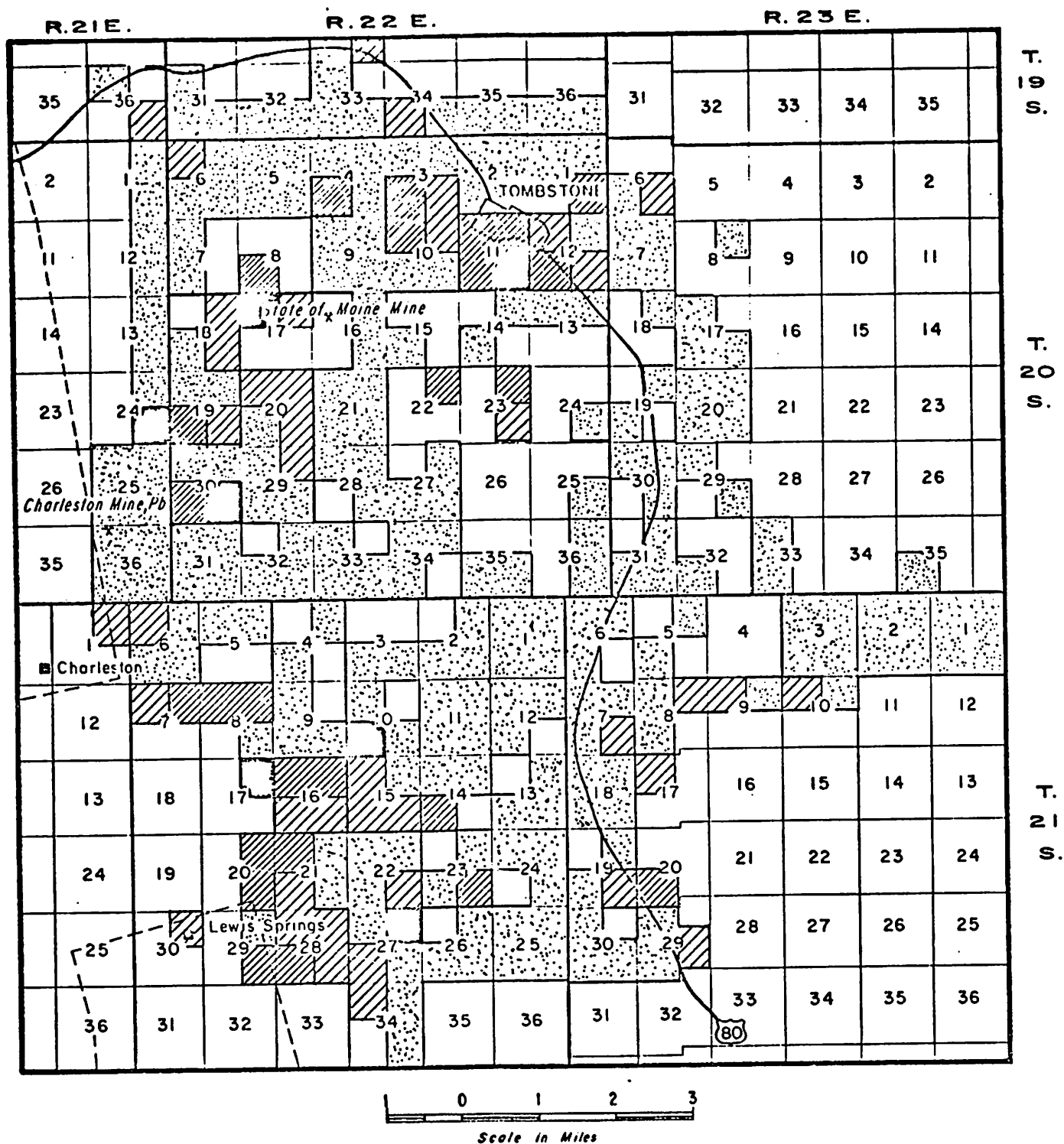


Fig. 14--Molybdenum in mesquite trees.

structural intersection north of Tombstone, where Walnut Gulch swings abruptly to the west (SE $\frac{1}{4}$ sec. 35, T. 19 S., R. 22 E.). Likewise, background molybdenum values occurred at both the Prompter and the Horquilla intersections (secs. 15 and 27, T. 20 S., R. 22 E.) with the Ajax fault. In contrast to these large structural features, the smaller northeast-trending fractures in the Uncle Sam (secs. 19, 29, and 30) were associated with both background and anomalous molybdenum concentrations. The Uncle Sam displayed considerable amounts of argillic alteration in this area, and several intrusive breccias were found in sec. 29. The positive molybdenum response over these northeast-trending fissures suggests that the site should be considered as a potential target area. In summary, two areas of exploration interest have been suggested by the molybdenum data. The area in the Uncle Sam is perhaps the most promising, because high molybdenum values are near the intrusive breccias and associated fractures and alteration. The second area of interest lies north of Lewis Springs near the Schieffelin Granodiorite. However, to better define this second anomaly, more samples should be collected farther to the west in secs. 17, 18, 19, and 20, T. 21 S., R. 22 E.

Silver in mesquite ash

Silver values in mesquite proved to be quite low, and their range was from <1 to 8 ppm. The mean value was about 1.2 ppm, and the standard deviation was about 1 ppm. The curves on figure 12 indicate ± 200 percent departures about the mean value, and thus the data ideally should be grouped at intervals of not less than 2 ppm.

Because of the very low values obtained, it was decided to group the

data at 1 ppm intervals, but it should be realized that 1 ppm intervals may be beyond the sensitivity of the method. The silver data are shown in figure 15.

Note
Relatively high silver values were found in and around the Tombstone town site, but the highest value was only 3.5 ppm. Silver values were low near the intersection of the San Pedro and Government Draw structures north of Lewis Springs. Scattered, high threshold silver concentrations were found farther to the east in secs. 13, 14, and 15, T. 21 S., R. 22 E. The reason for these relatively high values is unknown, and more samples could possibly confirm or negate the current data. In the NE $\frac{1}{4}$ sec. 25, T. 21 S., R. 22 E., an average of 4.5 ppm was obtained from five samples. This concentration level is highly anomalous, but the anomaly is strictly confined to a single quarter section. Livestock feeding facilities exist near where the samples were collected, and some of the silver may have been introduced, but the cause of the anomalous values remains undetermined.

Background and low threshold concentration levels prevailed for the Government Draw-Walnut Gulch intersection (secs. 2 and 3, T. 21 S., R. 23 E.), for the Horquilla-Prompter intersections with the Ajax fault (secs. 15 and 27, T. 20 S., R. 22 E.), and for the Walnut Gulch intersection north of Tombstone (SE $\frac{1}{4}$ sec. 35, T. 19 S., R. 22 E.). Background and low threshold silver values persisted along the northeast-trending fractures in the Uncle Sam (secs. 20, 29, and 30, T. 20 S., R. 22 E.). However, the low threshold samples for this area are relatively closely spaced, and tend to form a slightly higher concentration group surrounded by background values. This group of low threshold values may indicate high silver concentrations

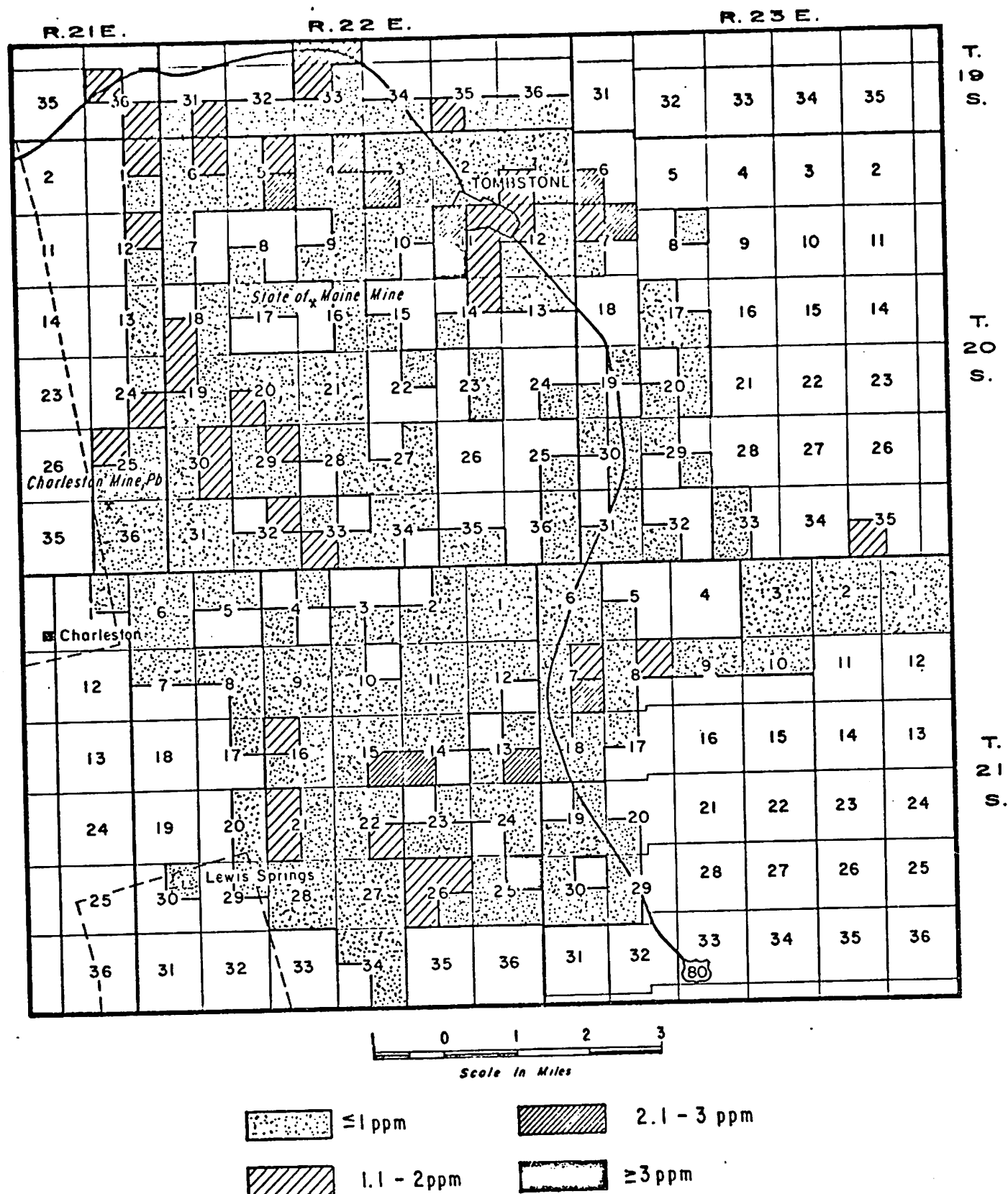


Fig. 15--Silver in mesquite trees.

at depth. The dump from the Mustang mine, in sec. 30, was found to contain about 40 oz/ton silver (Appendix III), and additional mesquite samples from this area could possibly result in a better definition of the weak anomaly. Ore from the Mustang mine dump also contained about 20 percent lead (Appendix III), and additional mesquite samples should probably be analyzed for lead.

In general, the very low silver values in mesquite suggest that silver is not well suited to mesquite biogeochemical methods. Hawkes and Webb (1962, p. 372) indicate the average silver value in plant ash is <1 ppm. Since silver is often associated with lead, it is advisable to consider analyzing for lead in place of silver in future mesquite surveys. Hawkes and Webb (1962, p. 367) report an average lead value in plant ash of 70 ppm, and concentrations of this order are easier to analyze for than are the typically low silver values.

Zinc in mesquite ash

Zinc values in mesquite ash ranged from 120 to 1600 ppm. The mean value was about 390 ppm, and the standard deviation was about 145 ppm. The curves in figure 12 indicate the mesquite method for zinc has a sensitivity of about 50 ppm. Because of the relatively wide range of zinc values, it was decided to group the samples at intervals of 200 ppm, and all values exceeding 800 ppm were considered to be anomalous. The data are illustrated in figure 16.

Anomalous zinc values are centered around Tombstone, and the values gradually decrease away from the town in a northwest direction. This decrease follows Tombstone Gulch to where it merges with Walnut Gulch, a distance of 3.5 to 4 miles. The zinc values along Tombstone

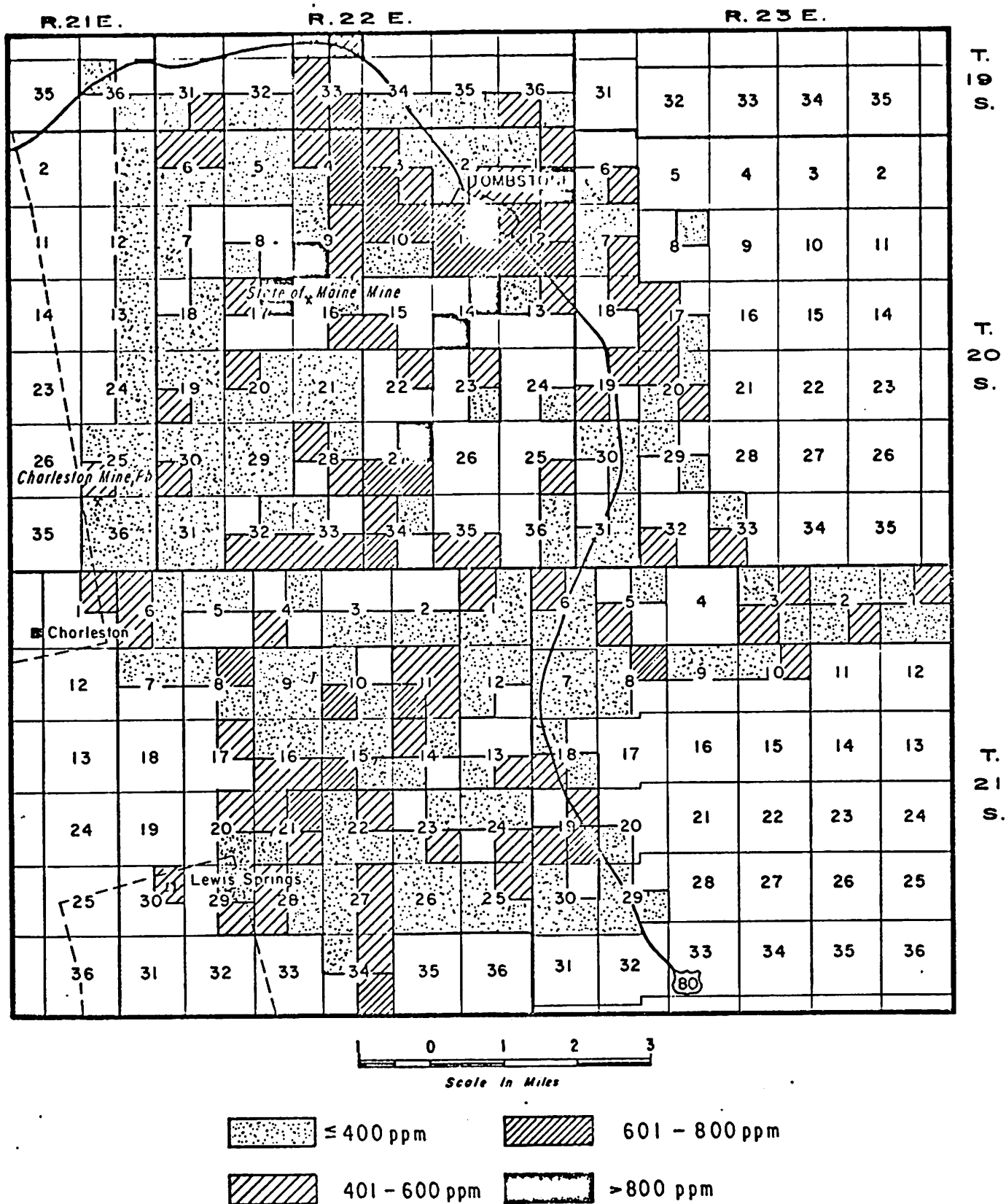


Fig. 16.--Zinc in mesquite trees.

Gulch are undoubtedly traveling down the drainage from the central part of the mining district. The anomalous value of 1000 ppm in the NE $\frac{1}{4}$ sec. 14 immediately south of the town site was collected near the Contention dike, one of the better mineralized parts of the district.

Low and high threshold values occurred near the Government Draw-San Pedro intersection, north of Lewis Springs. Similar concentrations were also found at the Government Draw intersection with Walnut Gulch (secs. 2 and 3, T. 21 S., R. 23 E.). Only background zinc values (<400 ppm) existed over the area north of Tombstone where the Walnut Gulch drainage changes to a westerly direction (SE $\frac{1}{4}$ sec. 35, T. 19 S., R. 22 E.). Low threshold concentrations were present near the Prompter-Ajax intersection in the SE $\frac{1}{4}$ sec. 15, T. 20 S., R. 22 E., but high threshold and anomalous zinc values were identified near the Horquilla-Ajax intersection in the ^{NE $\frac{1}{4}$? error?} SW $\frac{1}{4}$ sec. 27, T. 20 S., R. 22 E. Background concentrations occurred along the northeast-trending fractures in the Uncle Sam (secs. 19, 20, 29, and 30, T. 20 S., R. 22 E.), but low threshold values tend to form a crude circular pattern around the background values. Threshold and anomalous concentrations of copper and molybdenum respectively were identified in this circular pattern formed by the zinc values, and there appears to be a suggestion of a pattern progressing from a central molybdenum zone, through an intermediate copper zone, to a peripheral zinc zone. Anomalous values were obtained from the SW $\frac{1}{4}$ sec. 9 and the NE $\frac{1}{4}$ sec. 17, about 3 miles west southwest of Tombstone. These samples reflect values near the State of Maine and San Pedro mines.

In summary, zinc was found to respond quite well to the mesquite biogeochemical method. Zinc concentrations progressively decreased away from Tombstone, and known mineralization along the Prompter fault (Emerald mine, SW $\frac{1}{4}$ sec. 14) and at the San Pedro and State of Maine mines all resulted in anomalous values. The zinc values also indicated a possible zonation pattern with copper and molybdenum. Zinc analyses should probably be included in future mesquite biogeochemical surveys.

Biogeochemical discussion

Mesquite samples were collected along linear features identified during the aerial sensing part of this investigation, and the trace element concentrations are summarized in table 9.

The San Pedro-Government Draw structural intersection north of Lewis Springs had low to high threshold values for both copper and zinc. Molybdenum had high threshold to anomalous values, and only background values existed for silver. Copper and molybdenum showed a tendency to increase towards the west, and more samples should be collected beyond the western edge of the currently sampled area.

The structural intersection at Government Draw and Walnut Gulch contained anomalous copper values, and low to high threshold concentrations of zinc. Only background values of molybdenum and silver were present in this area. The high copper values may possibly be related to red beds present in the Cretaceous Bisbee Formation south of Government Draw. In any case mesquite and soil samples should be collected from around the anomaly to determine the source of the high copper concentrations. If the anomalous values persist to the south for an additional 2 or 3 miles, the Bisbee Formation probably

Table 9
Mesquite Trace Element Response

<u>Structural intersections</u>	<u>Metal response</u>			
	<u>Cu</u>	<u>Mo</u>	<u>Ag</u>	<u>Zn</u>
San Pedro-Government Draw	Lth-Hth	Hth-A	B	Lth-Hth
Government Draw-Walnut Gulch	A	B	B	Lth-Hth
Walnut Gulch north of Tombstone	B-Lth	B	B	B
Prompter fault-Ajax fault	B-Lth	B	B	Lth
Horquilla fault-Ajax fault	Lth-A	B	B	Hth-A
Northeast-trending fractures in the Uncle Sam Tuff	B-Lth	B-A	B-Lth	B-Lth

Note: A = anomalous
Hth = high threshold
Lth = low threshold
B = background

represents the copper source. Should the copper values decline to the south, a more restricted copper source would be indicated near the present anomaly.

The structural intersection north of Tombstone, where Walnut Gulch swings abruptly to the west (SE $\frac{1}{4}$ sec. 35, T. 19 S., R. 22 E.), contained only background concentrations of molybdenum, silver, and zinc. Copper showed background to low threshold values. The lack of high threshold or anomalous data for this intersection indicates that the present sample coverage is adequate, and that the intersection is probably not mineralized. At least if it is mineralized the mineralization is not reflected in the mesquite data.

may simply indicate lack of mineralization related to the two faults

The Prompter-Ajax fault intersection did not respond well to the mesquite biogeochemical method. Molybdenum, silver, and zinc all had background values, and copper showed both background and low threshold concentrations. Mineralization from the Dry Hill mine, at this intersection, contained significant amounts of copper and silver (Butler, Wilson and Rasor, 1938, p. 84), and this mineralization should have been reflected in the mesquite data. Only one sample was collected from this quarter section, and the sample site was about 500 ft east of the point where metal values from the Dry Hill mine would enter the main drainage. If additional samples were collected at the confluence of the Dry Hill drainage with the main Prompter drainage, the mesquite data would probably reflect the known mineralization at the Dry Hill mine.

The mesquite response near the Horquilla-Ajax intersection was good for copper and zinc. Copper showed low threshold and anomalous concentrations while zinc had high threshold and anomalous values.

Molybdenum and silver had only background values. Minor mineralization is associated with this intersection, and the positive copper and zinc responses could indicate the presence of undetected mineralization in this area. The Abrigo Limestone, which is well mineralized at Bisbee (Ransome, 1920), is exposed near this intersection, and some undetected mineralization may exist in the Abrigo. A more detailed collection of mesquite samples could possibly help identify additional mineralization in this area.

Background to low threshold values were found for copper, silver, and zinc in mesquite along the northeast-trending fractures in the Uncle Sam Tuff. Molybdenum values ranged from background to anomalous concentrations. The fractures are associated with intrusive breccias, hornblende andesite dikes, and intense argillic alteration. The mesquite data suggested a possible outward zonation of copper and zinc around a molybdenum center, and while copper and zinc values were relatively low, anomalous molybdenum values are present in the SE¹/₄ sec. 30, T. 20 S., R. 22 E. Additional mesquite samples from this quarter section would perhaps confirm the current data.

In summary, the mesquite biogeochemical survey produced encouraging results for four of the six structural intersections identified on the spacecraft and aircraft photography. Anomalous copper values were found at the Government Draw-Walnut Gulch intersection, and both copper and zinc were anomalous near the Horquilla-Ajax fault intersection. Molybdenum responded in an anomalous fashion near the San Pedro-Government Draw intersection as well as along the northeast-trending fractures in the Uncle Sam Tuff. The mesquite method failed to respond at the structural intersection in Walnut Gulch north of

Tombstone, and at the Prompter-Ajax fault intersection. Mineralization necessary to create a positive response may be lacking in the former instance, and more careful sampling would probably have produced a positive response in the latter case. The positive results, for four of the six areas tested, suggest that where properly applied, mesquite biogeochemical methods are well suited for examining trace element concentrations along linear features identified on aerial photographs. The most useful application of the method occurs in areas of poor outcrop and transported soil horizons.

Mesquite Biogeochemical Summary

The present study was an effort to use trace metal concentrations in mesquite twig ash for mineral exploration purposes. During the orientation survey, metal distributions in rocks, soils, dry wash sediments, groundwater and mesquite twigs were examined, and mesquite ash was found to be an effective metal accumulator. Metal contents in a given mesquite limb were found to increase towards the youngest shoots, and twig size or age should be rigidly controlled during the course of a survey. In this study, twig diameters were confined between 0.25 and 0.5 in. Ninety percent confidence intervals were calculated for the sampling of up to 10 trees at a given site, and the calculations illustrated that at least three trees should be sampled per sample site. Somewhat higher metal contents were found to exist in twigs from the south sides of mesquite trees, and during the field survey, trees were sampled on both their north and south sides. Elements analyzed included copper, molybdenum, silver, and zinc, and with the exception of silver, the elements were well suited

to mesquite biogeochemical methods. In future surveys lead analyses should possibly replace those for silver.

The current study was directed towards sampling along linear features identified on aerial photographs. The larger linear features typically occurred in gravel-covered valleys where it was either difficult or impossible to obtain meaningful rock or soil samples. Four of the six structural features tested produced positive results, and the lack of a response in a fifth area was possibly due to an absence of mineralization. With careful application and interpretation, mesquite samples can be confidently substituted for soil and rock samples, and the method allows a rapid and relatively inexpensive way of testing subsurface metal concentrations.

Mine Dump Geochemical Survey

Introduction

The purpose of the mine dump geochemical survey was to investigate metal zoning patterns in the Tombstone-Charleston area. Eighty-five samples were collected from mine dumps in the area, and the samples were analyzed for copper, lead, molybdenum, silver, and zinc. The assay data were examined through a series of ratios, and the resulting metal distribution patterns suggest several areas of potential exploration interest.

Previous investigations

The fact that metal ratios provide quantitative zoning patterns is of considerable importance in mineral exploration. Goodell and Petersen (1974) recently indicated that, since both physico-chemical

conditions and structural influences control metal values at any given site, raw assay data do not provide clear patterns of metal zoning. These authors also contend that mineralogic changes are largely qualitative when used to describe zoning patterns in base metal deposits. The use of metal ratios was suggested as a means of alleviating the above complications. Ratios are largely independent of structural controls, and thus reflect chemical changes in a given ore deposit or across a given mineralized district.

In addition to the work of Goodell and Petersen, several earlier studies successfully used metal ratios to establish zoning patterns. Broderick (1929), at the northern Michigan copper deposits, found an important relation between the depth of mineralization and the ratio $As/(As+Ag+Cu)$. Brown (1935) used the ratios of Zn/Pb , Fe/Pb , and Fe/Zn to develop zoning patterns for the Austinville mine, Virginia. The Zn/Pb ratio showed a striking increase with depth, and indicated a direction of flow for the hydrothermal solutions. Gross (1956) determined flow directions for the mineralizing solutions at the Blyklippen mine, Greenland. He used a Pb/Zn ratio. Contours of equal ratio values indicated hydrothermal solution flow directions, and ratio values gradually increased away from the source. The direction of flow was further substantiated by decrepitation temperatures in fluid inclusions, asymmetric crystal growth banding, and ore control structures. Sims and Barton (1962) examined Ag/Au and Cu/Zn ratios for the Central City district, Colorado. In addition to ratios, the authors used mineralogy changes, sphalerite compositions, and fluid inclusion filling temperatures to establish a central zone, an intermediate zone, a peripheral zone, and an outer barren

zone. Gold mineralization was best developed at the margin of the central zone, where Ag/Au values were low. Silver increased away from the central zone, and formed important ore bodies only in the peripheral zone, where high Ag/Au ratios existed. Important copper mineralization was restricted to the outer part of the central zone and to the inner part of the intermediate zone. Lead and zinc attained maximum relative abundances at the margin of the intermediate zone with the peripheral zone.

Metal distribution patterns in porphyry copper deposits were summarized by Jerome (1966) and by Lowell and Guilbert (1970). In porphyry deposits, molybdenum is generally concentrated near the core of the intrusive, and lead, silver, and zinc are typically found in peripheral zones. Highest copper values occur at intermediate positions between the core and the peripheral zones.

Patterns of metal zoning, if identified during mineral exploration programs, are of considerable aid in the selection of target areas, particularly if they suggest locations of mineralized centers. The above studies were conducted with well-controlled data, but during exploration investigations one must use what materials are available. Mine dumps can usually be sampled, even though underground workings are inaccessible, but the objective of most mine dump sampling studies is to determine the mean grade or the mean metal content of a particular dump. Thus, ore and host rock materials are commonly mixed together to form a given sample. This procedure was followed in an earlier study at Tombstone, and the resulting data failed to identify patterns of metal zoning (Gustafson, 1972, pers. comm.).

Present investigations

Since the purpose of this study was to investigate metal zoning patterns, considerable care was taken to insure the collection of only ore grade or potential ore grade material found on mine dumps. Host rock fragments were excluded from the samples. No attempt was made to determine accurate mean metal values for individual dumps, and in fact the highest metal values were carefully sought out. Metal patterns based on either host rocks, or on host rocks and mineralized fragments, are likely to lead to spurious results. In the first case, the host rocks may or may not reflect zonal patterns of mineralization, and in the second instance two probably distinct and separate populations are sampled as one. For purposes of establishing district zoning patterns, sample fragments should be restricted to ore grade material. The material left on mine dumps is undoubtedly a function of many different and oftentimes unrelated factors, the least of which may be the grade of an individual mine. Assay results from mine dumps necessarily reflect such things as: the care of individual miners to pick up ore grade material once it reaches the surface; the number of mineral collectors who have visited a given dump; natural leaching of the dump material; and the grade of an individual deposit. A valid interpretation of the straight assay data was virtually impossible, and to maximize chemical or metal zoning patterns, the assay data were examined through a series of ratios.

Raw assay values from the dumps sampled are listed in Appendix III, and are summarized in table 10. The assays were log-normally distributed, and to normalize the distribution, the assay data were transformed to $\log_{10}$ values. The transformed data are summarized

Table 10

Dump Sample Assay Data Summary

	Cu (ppm)	Zn (ppm)	Mo (ppm)	Pb (ppm)	Ag (ppm)
Range	10-13,800	30-150,000	n.d.-490	20-24,200	n.d.-1389
Mean	2300	14,500	22.3	20,000	251
Standard deviation	2900	25,000	85.5	39,000	293

Note: 1 ppm = 0.0001%; 32 ppm = 1 oz/ton; n.d. = none detected

Table 11

Transformed ($\log_{10}$) Dump Sample Data Summary

	Cu	Zn	Mo	Pb	Ag
Range	1.000-4.140	1.477-5.176	n.d.-2.690	1.301-4.384	n.d.-3.143
Mean	2.938	3.632	0.02	3.826	2.016
Standard deviation	0.723	0.852	1.120	0.776	0.794

Note: n.d. = none detected

in table 11. Correlation coefficients were calculated using the transformed data, and the coefficients are listed in table 12. Except for molybdenum, all element pairs analyzed had positive correlation coefficients between 0.546 and 0.674. Molybdenum did not correlate with any of the other elements, and in fact molybdenum had a -0.324 correlation coefficient with zinc, and thus the geographic distribution of high molybdenum and zinc ratios became important. The mean assay values for molybdenum and silver were considerably below those for the other elements. To allow assay changes for molybdenum and silver to be reflected in the ratio values, assays for these two elements were multiplied by factors of 1000 and 100 respectively. As with the assay data, ratio values were log-normally distributed, and the ratios were normalized with a $\log_{10}$ transformation. Also, to avoid working with negative numbers, the metal ratios were multiplied by a factor of 10^{10} , before the log values were calculated.

The following ratios were used to establish metal zonation patterns:

$$\text{Ag ratio value} = \log \left(\frac{\text{Ag} \times 100}{\text{Cu} + (\text{Mo} \times 1000) + \text{Pb} + \text{Zn}} \times 10^{10} \right)$$

$$\text{Cu ratio value} = \log \left(\frac{\text{Cu}}{(\text{Ag} \times 100) + (\text{Mo} \times 1000) + \text{Pb} + \text{Zn}} \times 10^{10} \right)$$

$$\text{Mo ratio value} = \log \left(\frac{\text{Mo} \times 1000}{(\text{Ag} \times 100) + \text{Cu} + \text{Pb} + \text{Zn}} \times 10^{10} \right)$$

$$\text{Pb ratio value} = \log \left(\frac{\text{Pb}}{(\text{Ag} \times 100) + \text{Cu} + (\text{Mo} \times 1000) + \text{Zn}} \times 10^{10} \right)$$

$$\text{Zn ratio value} = \log \left(\frac{\text{Zn}}{(\text{Ag} \times 100) + \text{Cu} + (\text{Mo} \times 1000) + \text{Pb}} \times 10^{10} \right)$$

The calculated ratio values are listed in Appendix IV. To illustrate the calculation procedure, the copper ratio is calculated for sample

Table 12
Transformed ($\log_{10}$) Correlation Coefficients
for the Dump Sample Data

	Cu	Zn	Mo	Pb	Ag
Cu	1.000				
Zn	0.564	1.000			
Mo	-0.017	-0.324	1.000		
Pb	0.625	0.590	0.191	1.000	
Ag	0.674	0.546	-0.114	0.639	1.000

number 1008W. The assay data (all values are reported in ppm) listed for this sample in Appendix III are:

<u>Cu</u>	<u>Zn</u>	<u>Mo</u>	<u>Pb</u>	<u>Ag</u>
2700	105	1	20	0.1

$$\begin{aligned}
 \text{Cu ratio value} &= \log \left(\frac{2700}{10 + 1000 + 20 + 105} \times 10^{10} \right) \\
 &= \log (2.378 \times 10^{10}) \\
 &= \log 2.378 + \log 10^{10} \\
 &= 0.374 + 10 \\
 &= 10.374 \\
 &\approx 10.4
 \end{aligned}$$

The copper ratio for sample 1008W as indicated in Appendix IV is 10.4.

Calculated ratio values were plotted on their respective maps.

The values obtained for a given metal were then subdivided into four groups, and contoured as either high, high-intermediate, low-intermediate, or low ratio values. After the ratios were calculated and plotted, areas of high ratio values were identified and plotted on separate maps (figs. 18-23).

The locations of 85 sampled mine dumps are shown in figure 17. The sample sites were limited by mine dump locations, and to separate sampled areas from those without samples, a square area (2000 ft/side) of influence was assigned to each sample point. The outer boundaries of the combined areas of influence are shown on figure 17 as well as on the accompanying metal distribution maps. The Ajax, Horquilla, and Prompter faults are also shown on the maps.

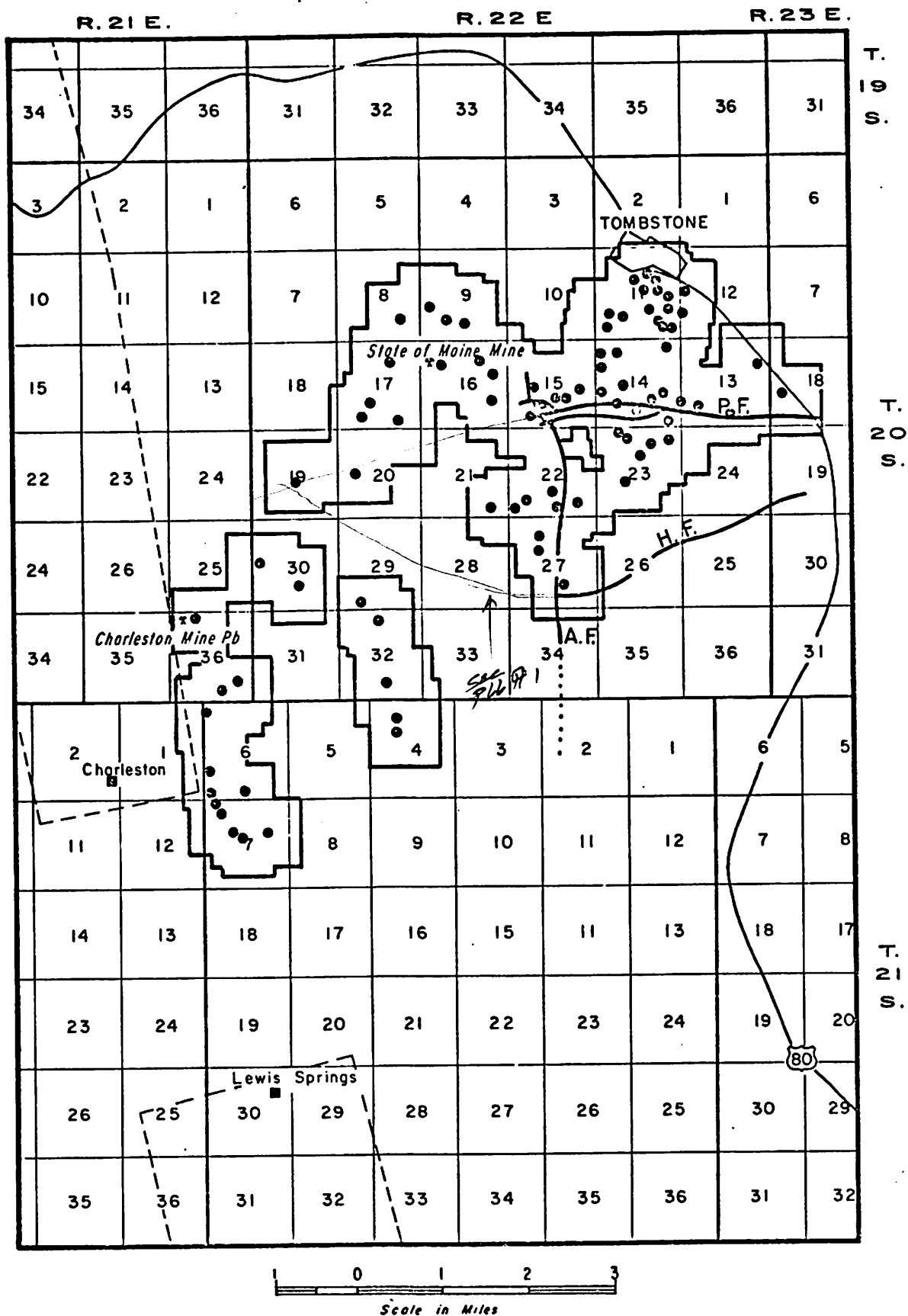


Fig. 17.--Dump sample location map, showing area of influence boundaries, and the Ajax fault (A.F.), Prompter fault (P.F.), and Horquilla fault (H.F.).

Ratio Distribution Patterns

The distribution of 29 high silver ratio values is shown in figure 18. High silver ratios were restricted to those values which exceeded 10.0. Near Tombstone the high values generally tend to follow along the Schieffelin Granodiorite contact with the country rock. From the central part of sec. 14, high ratio values trend through the Lucky Cuss, Old Guard, and Herschel mines (pl. 1). In sec. 11, the highest ratio values include the Toughnut and Northwest mines. Near Tombstone, there is a marked absence of high values near the eastern edge of the district. High ratios were found south of the Prompter fault, and the pattern extended in a westerly direction towards the Ajax fault. High values followed the Ajax fault, and the pattern appears to strengthen somewhat near the Ajax-Prompter intersection. In the western part of the district, the high values formed a peripheral pattern; this pattern is similar to those described by Sims and Barton (1962) at Central City, Colorado. Jerome (1966) and Lowell and Guilbert (1970) also described high silver concentrations in the peripheral zones of porphyry copper deposits.

Figure 19 illustrates the distribution pattern for 26 high zinc ratios. The high values were restricted to those which exceeded 9.5. High ratio values for zinc followed along the Prompter fault to near the Emerald mine, and then the pattern trends towards the southwest before crossing the Ajax fault between secs. 22 and 23, south of Ajax Hill. North of the Prompter fault the high zinc zone extends through the Luck Sure, Lucky Cuss, Old Guard, and Ingersol mines. The Empire, Tranquility, and Sulphurette mines were also located in a high zinc

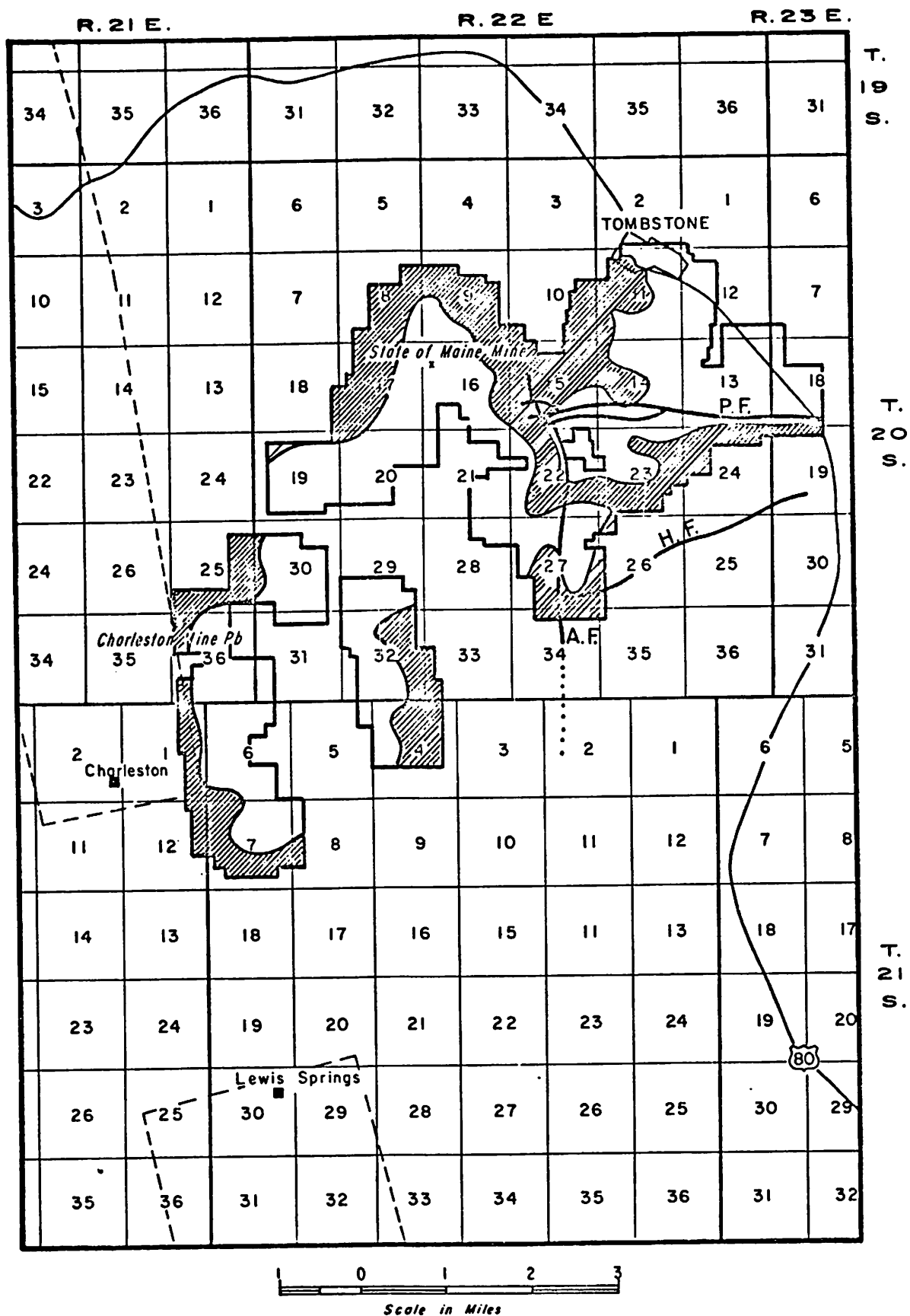


Fig. 18.--Distribution pattern for high silver ratios in dump samples. (A.F. = Ajax fault, P.F. = Prompter fault, H.F. = Horquilla fault. Shading indicates high ratio values within area sampled).

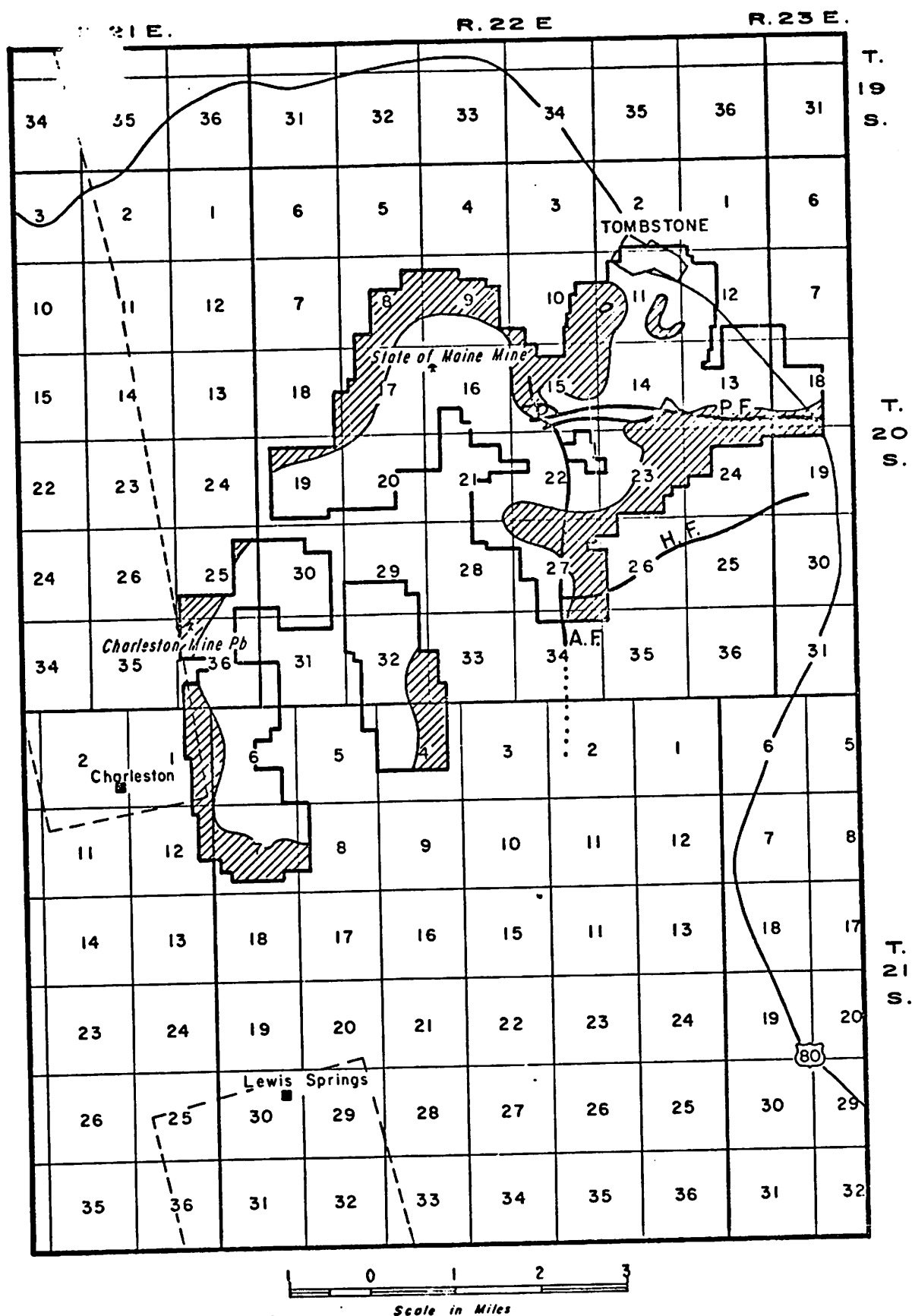


Fig. 19.--Distribution pattern for high zinc ratios in dump samples. (A.F. = Ajax fault, P.F. = Prompter fault, H.F. = Horquilla fault. Shading indicates high ratio values within area sampled).

zone near the central portion of the main district. West of the Ajax fault high zinc ratios showed a peripheral pattern similar to those for silver, and this general pattern of peripheral high zinc concentrations resembles those described by Sims and Barton (1962), Jerome (1966), and Lowell and Guilbert (1970).

The distribution pattern of 25 high lead ratio values which exceeded 9.5 is shown in figure 20. High lead values like those for zinc followed the Prompter fault, and then extended to the southwest, towards the Ajax fault. The pattern crossed the Ajax fault near the Horquilla-Ajax intersection. East of the Ajax fault, the following known mines had high lead ratio values: Emerald, Little Joe, Tombstone Extension, Sulphurette, Northwest and Herschel. West of the Ajax fault, high lead values showed a peripheral pattern similar to those for silver and zinc. In this area the Mustang mine, Charleston lead mine, Mamie mine, and the State of Maine mine had high lead ratio values. This pattern of high peripheral lead concentrations also resembles those described by Sims and Barton (1962), Jerome (1966), and Lowell and Guilbert (1970).

The high ratio pattern for 25 copper values which exceeded 8.5 is shown in figure 21. The relatively continuous patterns for lead, silver, and zinc are sharply contrasted by the irregularly broken pattern for copper. A locus of high copper values is near the Emerald and Bunker Hill mines along the Prompter fault. Another group of high copper ratios follows the northeast-trending fractures (pl. 2) through the Contact, Boss, Westside, Toughnut, Ingersol, Luck Sure, Goodenough, and Empire mines. Known mines from the western part of the district with high copper ratios include the San Pedro mine, Charleston lead

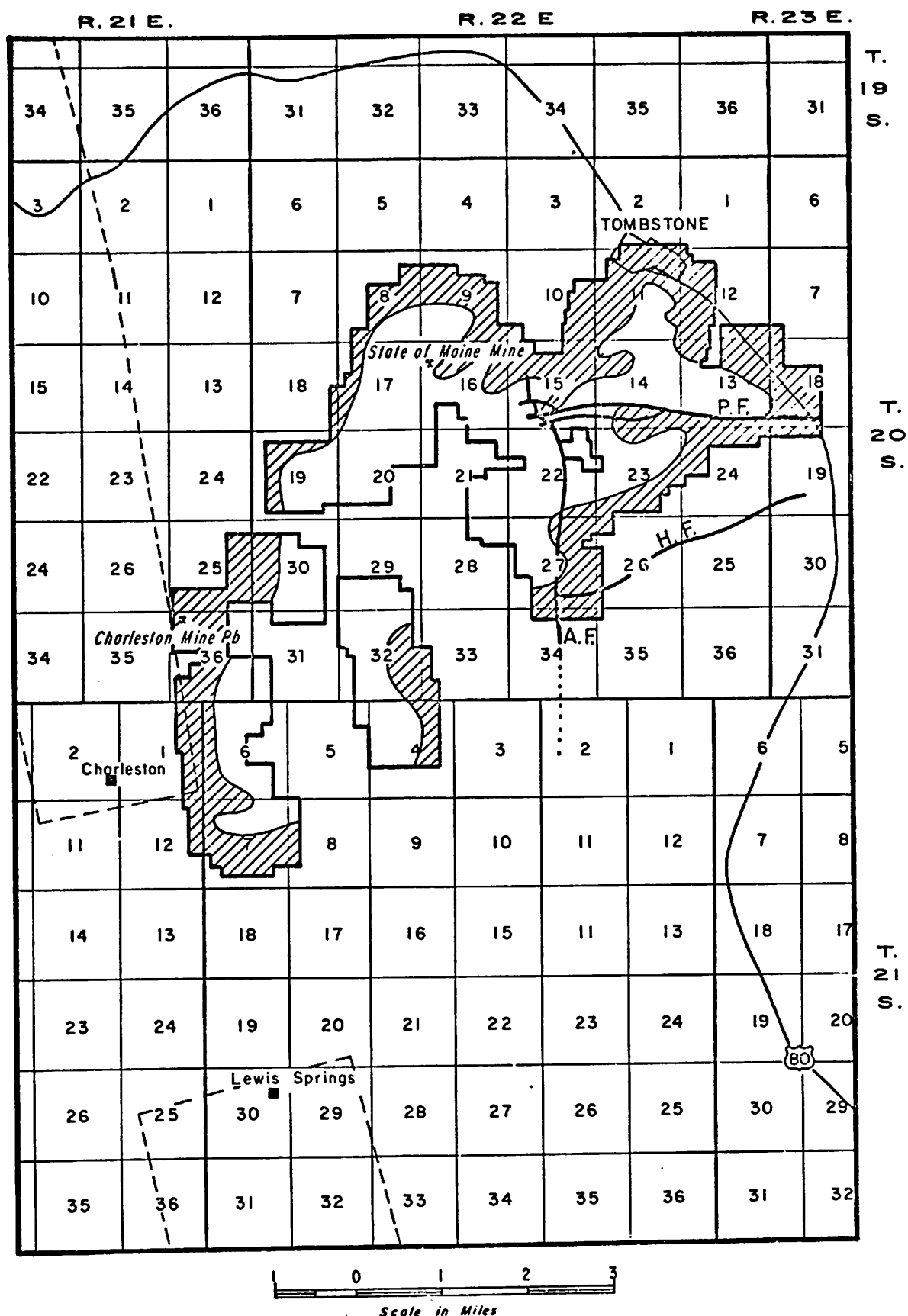


Fig. 20.--Distribution pattern for high lead ratios in dump samples. (A.F. = Ajax fault, P.F. = Prompter fault, H.F. = Horquilla fault. Shading indicates high ratio values within area sampled).

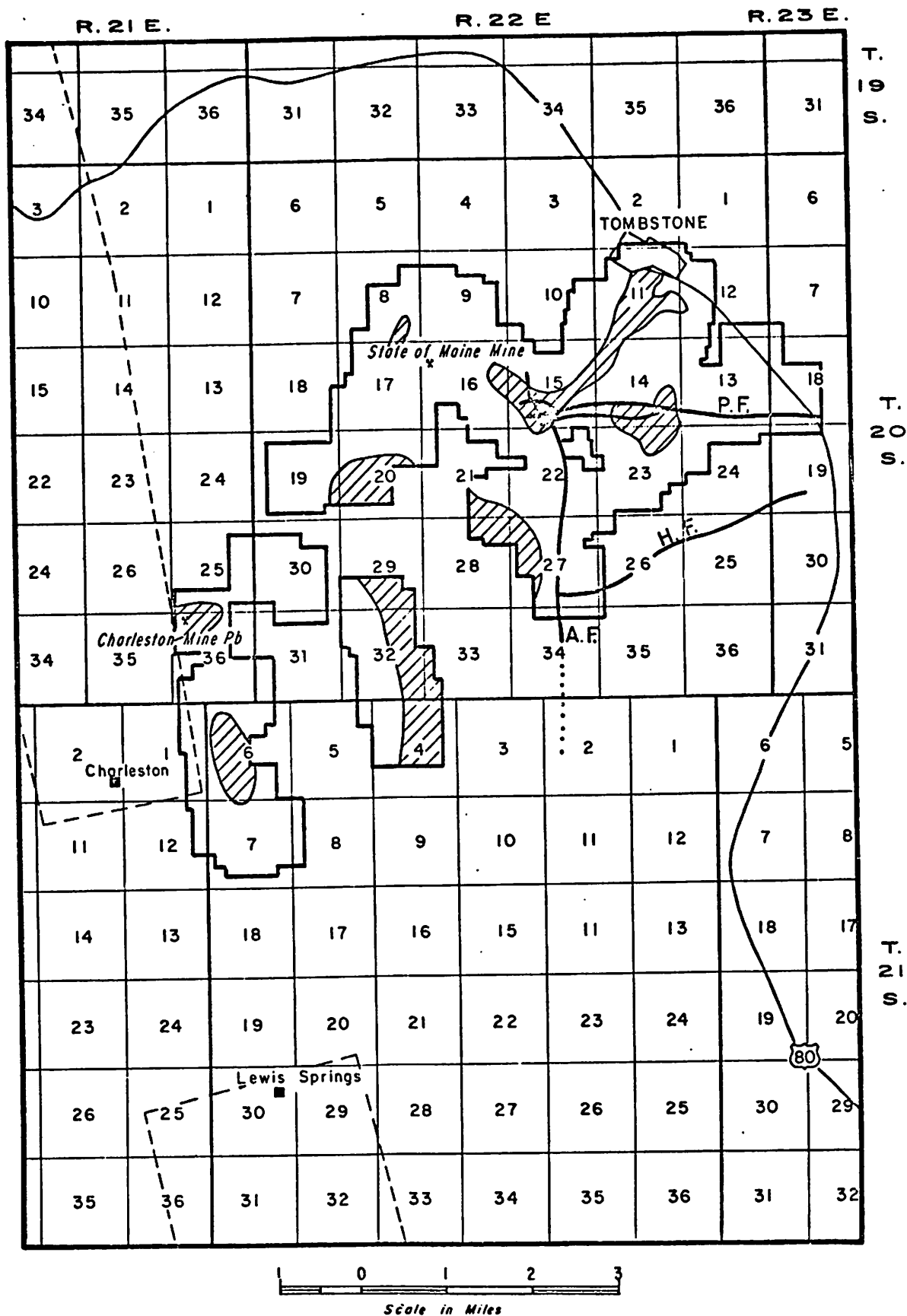


Fig. 21.--Distribution pattern for high copper ratios in dump samples. (A.F. = Ajax fault, P.F. = Prompter fault, H.F. = Horquilla fault. Shading indicates high ratio values within area sampled).

mine, and the Mamie mine. West of the Ajax fault, the sampling interval was not close enough to allow connecting the high value patterns in secs. 20, 21, 28, and 29. These fragmented high ratio areas appear to be centered around the NE $\frac{1}{4}$ sec. 29 and the NW $\frac{1}{4}$ sec. 28, and if the high ratio areas were connected, the pattern would indicate a large area of high copper ratios. The ratio pattern for copper occupies positions slightly within the peripheral lead, silver and zinc zones. Sims and Barton (1962), Jerome (1966), and Lowell and Guilbert (1970) place copper at intermediate positions, and the pattern established for the area west of the Ajax fault also suggests that copper is intermediate between molybdenum, and lead, silver, and zinc.

The distribution pattern of 17 high molybdenum ratio values which exceeded 9.5 is shown in figure 22. The molybdenum pattern is significantly different than those for the other elements, and this difference was suggested earlier by the low correlation coefficients for molybdenum with copper, lead, silver, and zinc. Known mines with high molybdenum ratios include the Santa Ana, the Contention, the Silver Thread, and the Toughnut. The large area of high molybdenum values lies entirely west of the Ajax fault. If the pattern is projected across sampling boundaries, the molybdenum zone appears to be centered near the NW $\frac{1}{4}$ sec. 29. This area, which is near the intrusive breccias in the Uncle Sam Tuff, fills the gaping voids present in the copper, lead, silver, and zinc zones. The negative correlation coefficient of -0.324 for molybdenum and zinc (table 12) suggested that samples with high molybdenum values were associated with low zinc values and vice versa. The distribution of high molybdenum and high zinc ratios is shown in figure 23, and the general lack of overlap

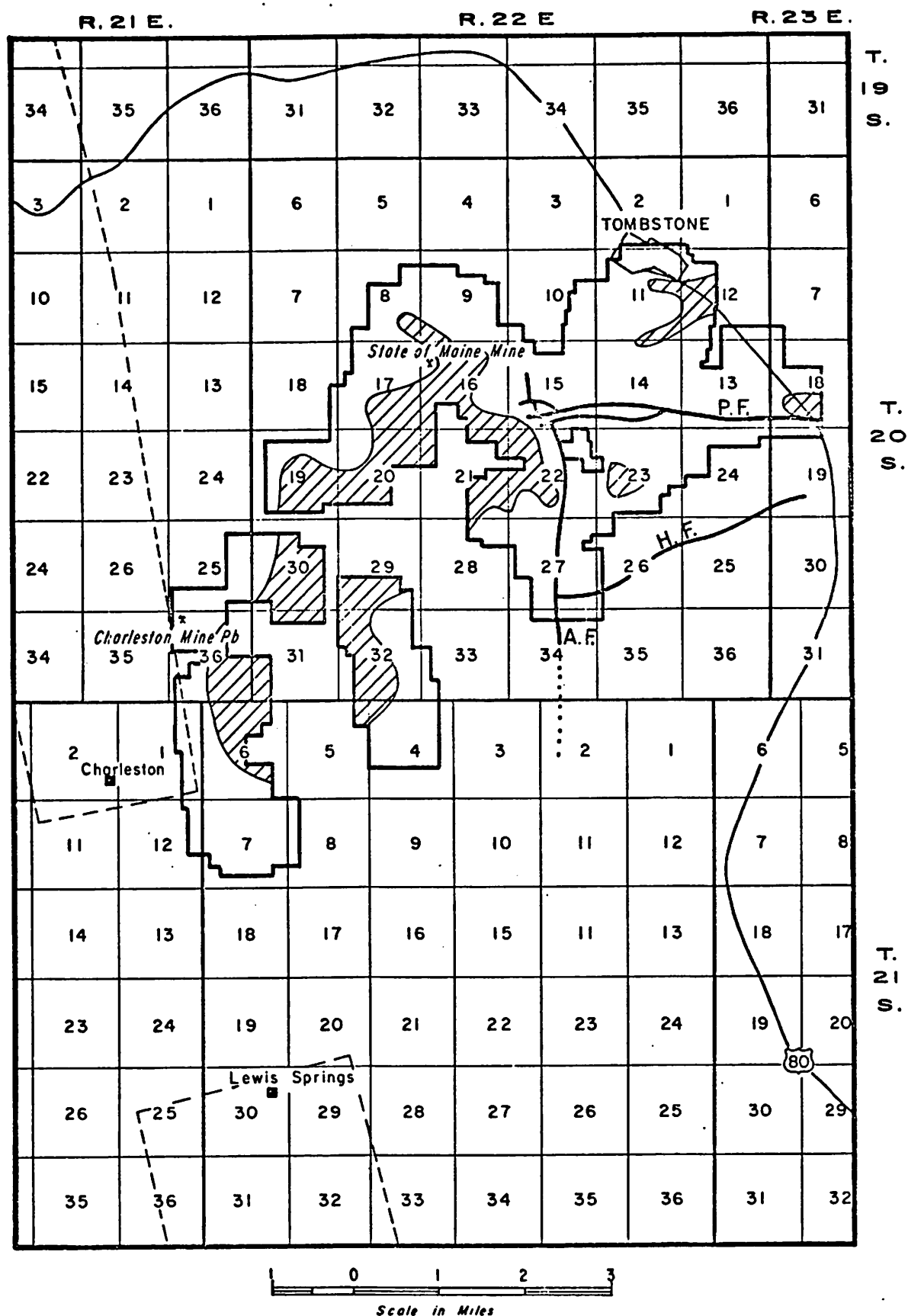


Fig. 22.--Distribution pattern for high molybdenum ratios in dump samples. (A.F. = Ajax fault, P.F. = Prompter fault, H.F. = Horquilla fault. Shading indicates high ratio values within area sampled).

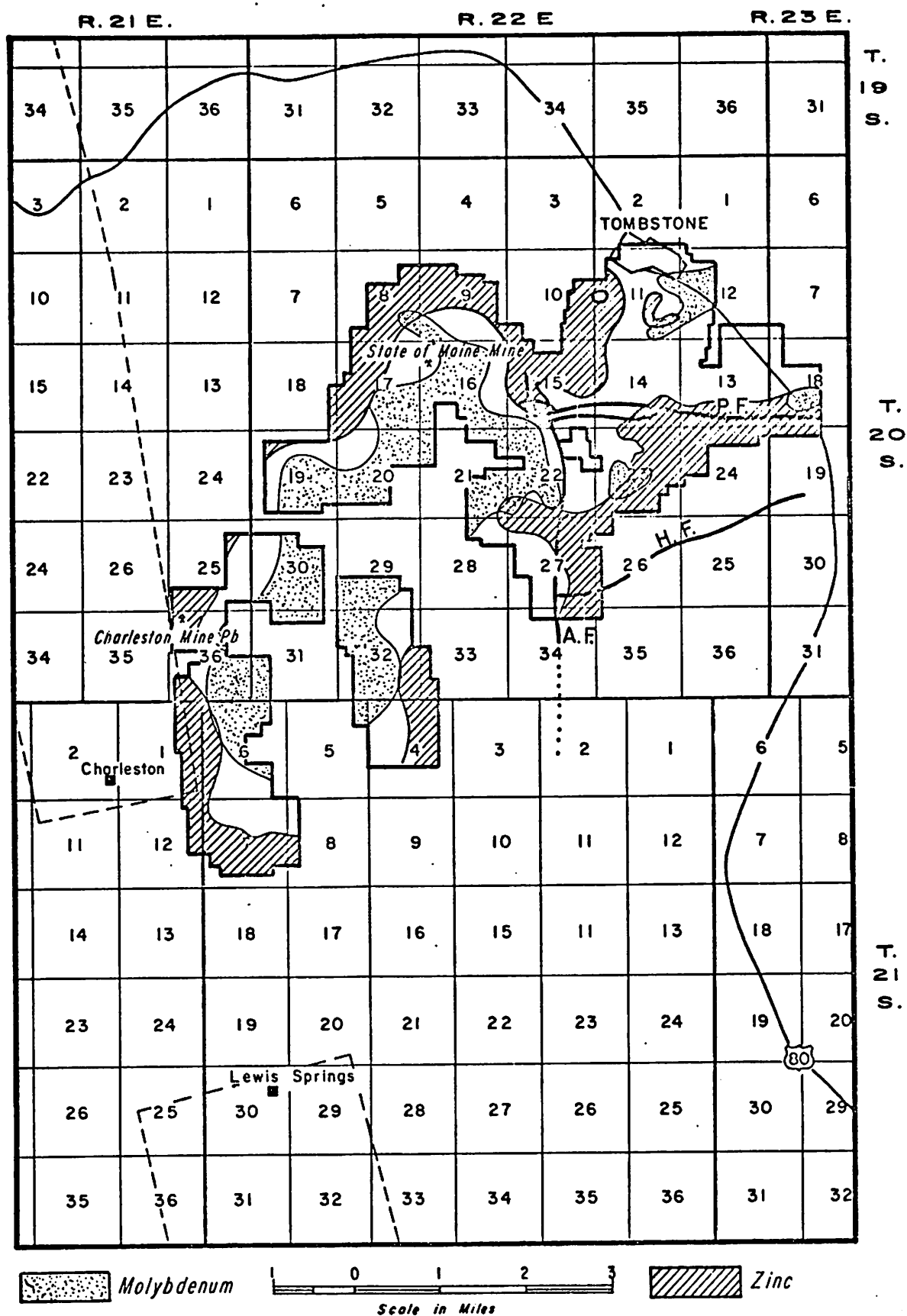


Fig. 23.--Distribution patterns for high molybdenum and high zinc ratios in mine dump samples, (A.F. = Ajax fault, P.F. = Prompter fault, H.F. = Horquilla fault).

between the two zones is readily apparent. Thus, for the area west of the Ajax fault, the indicated metal zoning patterns consist of a central molybdenum zone, an intermediate copper zone, and peripheral lead, silver and zinc zones. Jerome (1966) and Lowell and Guilbert (1970) have described similar patterns associated with porphyry copper deposits, and the present patterns suggest that a mineralized center may exist at depth below the Uncle Sam Tuff near the NW $\frac{1}{4}$ sec. 29.

Discussion and Summary of the Mine Dump Geochemical Investigations

The Tombstone district is divided into a western half and an eastern half by the Ajax fault, and the major mines lie on the eastern or upthrown side of the fault. With the exception of the Charleston lead mine, the State of Maine, the Santa Ana, and the San Pedro mines, those mines on the western or down-dropped side of the Ajax fault, in the Uncle Sam Tuff, have seen relatively minor production. The entire area between the State of Maine mine and Charleston lead mine is largely unexplored, and yet the high ratio values for molybdenum are mainly confined to this portion of the district. The molybdenum distribution pattern suggests that a mineralized center may exist between the Charleston lead mine and the State of Maine mine.

Statistical significance levels were calculated (Spiegel, 1961, p. 167-176) for ratio values east and west of the Ajax fault (table 13). Ratio values for molybdenum were significantly higher, at the 0.1 level, west of the Ajax fault. The values for copper and zinc were significantly (0.1 level) higher east of the fault. Ratio values for lead and silver were not significantly (0.1 level) different east or west of the Ajax fault. Thus, lead and silver appear to have equal

Table 13

Dump Sample Ratio Summary

		West & east	West	East	Mean difference (west-east)	Side of Ajax fault with highest mean ratio value (0.1 level of significance)		
						West	East	Equal
Ag	Range	7.1-11.0	7.1-11.0	9.0-10.8				
	Mean	9.6	9.4	9.7	-0.3			X
	Std. dev.	0.8	1.1	0.5				
Cu	Range	5.8-10.4	5.8-10.4	7.5-9.3				
	Mean	8.3	8.1	8.4	-0.3		X	
	Std. dev.	0.6	0.8	0.4				
Mo	Range	6.6-12.6	6.9-12.6	6.6-10.5				
	Mean	8.5	8.9	8.2	0.7	X		
	Std. dev.	1.3	1.5	1.1				
Pb	Range	6.7-10.6	6.7-10.6	8.4-10.6				
	Mean	9.3	9.2	9.4	-0.2			X
	Std. dev.	0.6	0.8	0.5				
Zn	Range	6.4-10.4	6.4-10.7	7.8-10.4				
	Mean	9.1	8.7	9.4	-0.7		X	
	Std. dev.	0.9	1.1	0.6				

Note: East = east side of Ajax fault
 West = west side of Ajax fault
 West & east = both west and east sides of the Ajax fault

concentrations in both the eastern and western parts of the district. Copper and zinc are more concentrated east of the Ajax fault, and molybdenum is significantly more concentrated west of the fault. The significantly (0.1 level) higher ratio values for molybdenum west of the fault confirm the molybdenum distribution pattern in figure 22, and lend support to the concept of a mineralized center between the Charleston lead mine and the State of Maine mine. This molybdenum zone is apparently centered near the NW $\frac{1}{4}$ sec. 29. East of the Ajax fault, in secs. 11 and 12, another high molybdenum zone is centered around the Silver Thread mine; Butler, Wilson and Rasor (1938, p. 104) indicate that molybdenum is most abundant near the Silver Thread mine (NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 12). The high molybdenum pattern near the Silver Thread mine appears to be strengthening towards the east, but the absence of mine dumps in this area prevented further sampling. The ratio pattern for lead was even stronger at the eastern boundary of the sampled area. It is possible that additional mineralization could be found slightly east of the old district in sec. 12. Butler, Wilson and Rasor (1938, p. 104) stated that copper appeared to be best developed along strong northeast-trending fissures, and that the Emerald mine probably contained the largest copper ore body. Both of these statements are supported by the copper ratio distribution pattern. The ratio pattern for copper shows a northeast-trending zone extending from near the Prompter-Ajax fault intersection through the Luck Sure, Westside, and Toughnut mines. Another high copper zone is centered near the Emerald mine, just south of the Prompter fault zone in the SE $\frac{1}{4}$ sec. 14. Also, west of the Ajax fault, high copper ratios exist in

secs. 20, 21, 27, 28, and 29, and the ratio pattern appears to be centered around the NW $\frac{1}{4}$ sec. 28 and the NE $\frac{1}{4}$ sec. 29.

In summary, the method developed to investigate metal distribution patterns has suggested four possible target areas. The high lead and molybdenum zones at the extreme eastern edge of the main mining district in sec. 12 suggest that additional mineralization may exist to the east of the presently mined area. High copper, silver, and zinc ratios exist near the Prompter-Ajax fault intersection, in the SW $\frac{1}{4}$ sec. 15. The Dry Hill mine located near this intersection produced important amounts of copper, gold, and silver ore, and the mine workings did not extend below the 200 ft level (Butler, Wilson and Rasor, 1938, p. 84). Important mineralization could possibly exist at depth below the present Dry Hill workings. The Emerald mine, just south of the Prompter fault system in the SE $\frac{1}{4}$ sec. 14, bottomed in chalcocite ore at the water table (Butler, Wilson and Rasor, 1938, p. 71), and the depth of the workings was about 900 ft. High copper ratios exist for this area, and the mineralization may continue for a considerable distance below that exposed by the Emerald workings. In the western part of the district, lead, silver, and zinc form peripheral zones around an intermediate zone of copper, and a central molybdenum zone. The fact that similar zonal sequences have been identified from other districts (Jerome, 1966; Lowell and Guilbert, 1970) testifies that these patterns are not unique, but resemble zoning patterns that are commonly associated with porphyry copper deposits. The molybdenum zone appears to be centered near the NW $\frac{1}{4}$ sec. 29, and this area also contains several intrusive breccias with associated argillic alteration. It is possible that the molybdenum

zone, intrusive breccias, and alteration are surface expressions of a mineralized center at depth.

Finally, many of the mine dumps sampled during this survey are themselves a potential source of ore. For purposes of establishing metal zoning patterns, the many problems inherent in mine dump sampling (e.g. differences of operator skill from one mine to the next, the number of times a given dump has previously been sampled relative to other dumps in the district, the length of time ore materials have been exposed to natural leaching processes on mine dumps) can be partially compensated by the use of ratios. Thus, during the present study, the highest metal values exposed on a given dump were carefully sought out, and no attempt was made to determine mean metal values for individual dumps. Dump locations and assay results are listed in Appendix III, and consideration should be given to re-sampling those dumps with high metal contents, so that mean metal concentrations could be determined. For example, of the 85 dumps sampled, 43 samples assayed at least 5 oz/ton (160 ppm) silver. If the mean grade of enough dumps is sufficiently high, they could possibly be processed for their metal contents.

Comparison of the Mesquite Biogeochemical Method
and the Mine Dump Geochemical Method

High metal zones identified during the mine dump geochemical survey showed only fair correspondence to those biogeochemical areas with high threshold or anomalous values. Mesquite results indicated high threshold and anomalous silver values (fig. 15) in the W $\frac{1}{2}$ sec. 11. High silver ratios from the dump samples (fig. 18) were determined

for this area, but elsewhere high silver ratios corresponded to either low or low threshold values for silver in mesquite. High threshold and anomalous zinc areas in mesquite (fig. 16) corresponded with several areas of high zinc ratios (fig. 19). Both methods indicated relatively high zinc values in the $S\frac{1}{2}$ sec. 11, the $E\frac{1}{2}$ sec. 27, and the $SW\frac{1}{4}$ sec. 9. The peripheral pattern of high zinc ratios for the region between Charleston and the State of Maine mine was only weakly reflected by an increase from background zinc values in mesquite for the central area to low threshold values at the periphery. Only three areas of high copper ratios contained high threshold or anomalous mesquite values (figs. 13, 21). Near Tombstone, the $NE\frac{1}{4}$ sec. 11 and the $SW\frac{1}{4}$ sec. 14 contained high copper ratio values along with relatively high copper values in mesquite ash. Similar results were found for the $NW\frac{1}{4}$ sec. 36, T. 20 S., R. 21 E. All other areas of high copper ratios in mine dump samples contained only background or low threshold copper values in mesquite. Only two areas contained high molybdenum ratios in mine dumps and either high threshold or anomalous molybdenum concentrations in mesquite ash (figs. 14, 22). South of Tombstone, the $SE\frac{1}{4}$ sec. 11 and the $SW\frac{1}{4}$ sec. 12 contained high molybdenum ratios along with relatively high molybdenum concentrations in mesquite ash. Similar relations were found for the $S\frac{1}{2}$ sec. 30, northeast of Charleston, and this area is near the center of the high molybdenum ratio zone in the $NW\frac{1}{4}$ sec. 29.

In spite of this generally poor correspondence between the two geochemical methods, the mesquite data support three of the four target areas indicated by the mine dump ratios. East of Tombstone, the $W\frac{1}{2}$ sec. 12 contains both high molybdenum ratios, and anomalous

molybdenum concentrations in mesquite ash. The area near the Emerald mine (SW $\frac{1}{4}$ sec. 14) yielded high copper and zinc ratios, while providing anomalous and high threshold concentrations for copper and zinc respectively in mesquite ash. The high ratio zone for molybdenum, in the western part of the district, is centered near the NW $\frac{1}{4}$ sec. 29, and while anomalous molybdenum concentrations in mesquite ash were not found in that section, anomalous and high threshold molybdenum values exist in the adjacent section (S $\frac{1}{2}$ sec. 30). The only area of high mine dump ratio values (copper, silver, and zinc) that failed to have corresponding high threshold or anomalous mesquite values was the Prompter-Ajax fault intersection in the SW $\frac{1}{4}$ sec. 15. As mentioned earlier in this chapter (Biogeochemical discussion), the failure of the mesquite method to respond at this structural intersection may be the result of inadequate sampling.

Geochemical Target Area Summary

The mesquite biogeochemical survey identified four potential target areas. The Government Draw-San Pedro intersection contained anomalous molybdenum values. Anomalous copper values were found at the Government Draw-Walnut Gulch intersection, and anomalous copper and zinc values were present near the Ajax-Horquilla fault intersection. Anomalous molybdenum values in mesquite were found along the northeast-trending fractures in the Uncle Sam Tuff, between the Charleston lead mine and the State of Maine mine.

The mine dump geochemical survey indicated four potential exploration target areas. High lead and molybdenum ratios at the eastern edge of the main Tombstone district suggest that additional

mineralization may exist farther to the east, beyond the presently mined area. This area also contains high threshold concentrations of molybdenum and zinc in mesquite ash. The Prompter-Ajax fault intersection contains high ratio values for copper, silver, and zinc. Another potential target area is near the Emerald mine, where high copper and zinc ratios exist. The fourth target area is at the center of the high molybdenum zone, between the Charleston lead mine and the State of Maine mine in the NW $\frac{1}{4}$ sec. 29.

Thus, a total of seven potential exploration target areas has been identified by the two geochemical methods. These target areas are listed in table 14, and illustrated in figure 24. Continued exploration efforts are required to further evaluate these areas.

For the San Pedro-Government Draw intersection, additional mesquite samples should be collected beyond the western edge of the presently sampled area. The results from these samples will allow a better definition of the present molybdenum anomaly. Likewise, for the Government Draw-Walnut Gulch copper anomaly, additional mesquite and soil samples should be collected around the anomalous area. In order to determine whether or not the high copper values could have been derived from red beds present in the Bisbee Formation south of Government Draw, mesquite and soil samples should be collected in secs. 11, 12, 13 and 14, T. 21 S., R. 23 E. The area of the Horquilla-Ajax fault intersection in sec. 27, T. 20 S., R. 23 E., contains anomalous copper and zinc values in mesquite ash. The Abrigo Limestone, which is well mineralized at Bisbee (Ransome, 1920), is exposed near this fault intersection, and additional mesquite samples from the anomalous area could possibly aid in the identification of a mineralized zone.

Table 14

Potential Mineral Exploration Target Areas

Target areas	Mesquite response	High mine dump ratios
Government Draw-San Pedro intersection secs. 17 and 18, T. 21 S., R. 22 E.	Mo; A	n.d.a.
Government Draw-Walnut Gulch intersection sec. 2, T. 21 S., R. 23 E.	Cu; A	n.d.a.
Horquilla-Ajax fault intersection sec. 27, T. 20 S., R. 22 E.	Cu; Lth-A Zn; Lth-A	Ag,Pb
Northeast-trending fractures in the Uncle Sam Tuff secs. 29 and 30, T. 20 S., R. 22 E.	Mo; B-A	Mo
Eastern edge of the main Tombstone district NW $\frac{1}{4}$ sec. 12, T. 20 S., R. 22 E.	Mo; Lth-Hth Zn; Hth	Pb,Mo
Prompter-Ajax fault intersection SW $\frac{3}{4}$ sec. 15, T. 20 S., R. 22 E.	Zn; Lth	Ag,Cu,Zn
Emerald mine area S $\frac{1}{2}$ sec. 14, T. 20 S., R. 22 E.	Cu; Hth Zn; A	Cu,Zn

Note: A = anomalous
 Hth = high threshold
 Lth = low threshold
 B = background
 n.d.a. = no dumps available

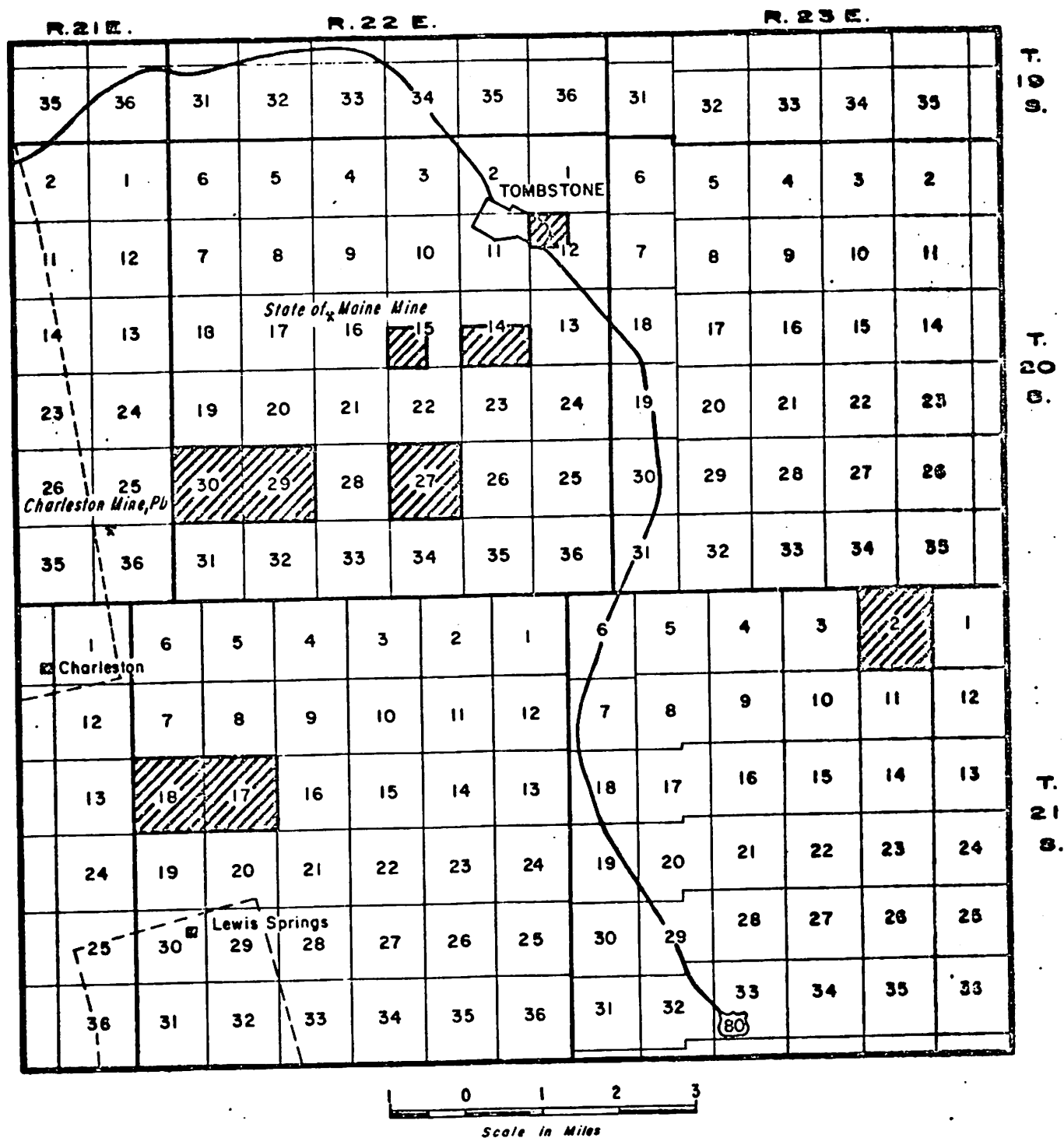


Fig. 24. Potential target area locations as listed in table 14.

Four potential drilling targets exist in the area of this study. The area of the northeast-trending fractures in the Uncle Sam Tuff (secs. 29 and 30, T. 20 S., R. 22 E.), contains anomalous molybdenum concentrations in mesquite, and the high molybdenum ratio zone is also centered near the NW $\frac{1}{4}$ sec. 29. Intense argillic alteration along with several intrusive breccia bodies are present in this area, and a possible mineralized center may exist at depth below the Uncle Sam Tuff. The best location for a drill site is midway between the two intrusive breccias mapped on plate 1, in the SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 29. In order to allow adequate penetration of the Uncle Sam and possibly of the Bisbee Formation, the projected drilling depth should be about 4000 ft. A drill hole near the Charleston lead mine penetrated about 1200 ft of volcanics and an additional 2200 ft of Bisbee rocks, before bottoming at a depth of about 3400 ft (Gillette, pers. comm.). Only scattered veinlets of copper, lead, and zinc mineralization were reported from this hole, and it was apparent that the hole failed to intersect a mineralized center. On the basis of the high molybdenum ratio pattern, the anomalous molybdenum values in mesquite, the intense hydrothermal alteration, and the intrusive breccia bodies, the mineralized center, if one exists, appears to lie at depth in the NW $\frac{1}{4}$ sec. 29.

A second potential drilling target lies immediately east of the main Tombstone mining district, in the NW $\frac{1}{4}$ sec. 12. This area lies northeast of existing mine workings and is on strike with the northeast-trending fractures that exercised an important ore control in the main district (Butler, Wilson and Rasor, 1938, p. 97-102). The basaltic dome in Walnut Gulch (pl. 2) has intruded the large Walnut Gulch structure at a projected intersection with the northeast-trending

fracture zone, and the fractures probably lie concealed beneath the surface gravels in the NW $\frac{1}{4}$ sec. 12. High lead and molybdenum dump ratios were present at the extreme northeastern edge of the main district, and high threshold and anomalous zinc values in mesquite were found in the NW $\frac{1}{4}$ sec. 12, and in the adjacent SE $\frac{1}{4}$ sec. 1. The possibility of extended mineralization in this area could be tested by a relatively shallow drill hole situated on the small ridge about 500 ft west of the Gleeson Road, in the SE $\frac{1}{4}$ NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 12. This site lies on strike with the Westside fissure, which is centrally located in the fracture zone, and which contained important mineralization in the main district (Butler, Wilson and Rasor, 1938, p. 98-99). Cross-section D-D' (pl. 3), which extends through the proposed drill site, suggests that the Bisbee Formation lies beneath about 100 ft of gravels, and a 500- to 600-ft drill hole would be adequate to test for possible mineralization in this area.

The third drilling target is at the Prompter-Ajax fault intersection in the SW $\frac{1}{4}$ sec. 15. The Dry Hill mine at this intersection contained significant copper, gold, and silver mineralization, and the maximum reported depth of mine workings was only about 200 ft (Butler, Wilson and Rasor, 1938, p. 84). Extreme amounts of movement have occurred at this fault intersection. The normal Ajax fault has brought rocks of the Cretaceous Bisbee Formation into contact with the Cambrian Bolsa Quartzite, for a total offset of at least 5500 ft (Gilluly, 1956, p. 129). The reverse Prompter fault has brought the Bolsa into contact with the Pennsylvanian Horquilla Limestone, and the indicated movement is at least 4000 ft (Gilluly, 1956, p. 129). Both of these faults were in existence prior to the emplacement of

the Schieffelin Granodiorite and the Uncle Sam Tuff (see Ch. III and Gilluly, 1956, p. 129), and this structure may contain more mineralization than is currently realized. The large pre-mineral displacements along the Ajax and Prompter faults, and the presence of high ratios for copper, silver, and zinc suggest that more mineralization may be present than that exposed by the Dry Hill mine. A relatively shallow drill hole sited about 450 ft S. 70° W. of the Dry Hill shaft, in the SW $\frac{1}{4}$ NE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 15, could test the continuation of the mineralization at depth. Cross-section line D-D' (pl. 3) suggests that the depth of the Schieffelin Granodiorite beneath the intersection is only about 500 ft, and a drill hole to this depth would examine the Schieffelin contact zone, at the intersection of the Prompter and Ajax faults.

The fourth drilling target is near the Emerald mine in the SW $\frac{1}{4}$ sec. 14. High-threshold and anomalous copper and zinc values in mesquite, along with high dump ratios for copper and zinc exist in this area. The Emerald mine contained the largest copper ore body in the district (Butler, Wilson and Rasor, 1938, p. 104), and when the water table was encountered, mine workings bottomed in chalcocite at a depth of about 880 ft. As suggested in Chapter III, the copper mineralization could possibly be related to the 63 m.y. old (Creasey et al., 1962) rhyolite porphyry. This places the mineralization in a similar age range with other porphyry copper deposits in southern Arizona. Butler, Wilson and Rasor (1938, p. 71) stated that the mineralization formed a N. 20° E.-trending ore shoot that was about 1100 ft long, and up to 10 ft wide. The ore apparently continued in a more-or-less continuous fashion from the surface to the deepest mine workings. The extent and nature of the chalcocite could be determined by a 1500 ft drill

hole located about 400 ft S. 20° W. of the Emerald shaft. The 1500 ft depth should determine whether the chalcocite at the water table is related to a disseminated source at depth or not.

CHAPTER VI

ORE MINERALOGY

The mineralogy at Tombstone has been described in detail by Rasor (1937, 1938, 1939). Bromeyerite was found to be the main supergene silver mineral. Other supergene silver minerals identified were embolite, cerargyrite, argentite, stromeyerite, native silver, and argentojarosite. Rasor (1937) determined that hessite, tetrahedrite, and galena were the hypogene silver-bearing minerals. During the present investigations, a large portion of Rasor's collection was obtained from the Arizona Bureau of Mines. Samples from this collection, along with additional samples collected from mine dumps, were examined by reflected light and electron microprobe methods.

Paragenetic Relations

The paragenetic scheme presented by Rasor (1937, p. 74-77) was checked and generally confirmed. However, bournonite, famatinite (stibioluzonite), alabandite, ruby silvers, and opal were not found in the available samples, and only those minerals presently identified are included in the paragenesis (table 15). In addition to the paragenesis for the main Tombstone district, an additional paragenetic scheme was determined for samples collected at the Charleston lead mine. Fluid inclusion filling temperatures were likewise determined

Table 15
Paragenesis, and Fluid Inclusion Filling
Temperatures, Tombstone-Charleston Ores

Tombstone		Charleston	
Mineralogy	Maximum filling temperatures ($^{\circ}\text{C}$)	Mineralogy	Maximum filling temperatures ($^{\circ}\text{C}$)
Quartz	325	Quartz	263
Pyrite	279	Pyrite	311
Sphalerite	-	Sphalerite	318
Tetrahedrite	225	Galena	318
Chalcopyrite	261	Chalcopyrite	243
Galena	272		
Altaite	205		
Hessite	-		

Note: Fluid inclusion filling temperatures are accurate to $\pm 5^{\circ}\text{C}$.

for quartz associated with the various mineral species. The temperature and mineralogical data are listed together in table 15.

Mineral Descriptions

In the following discussion, minerals are described in the order indicated in the paragenetic sequence. Only primary ore and gangue minerals are described; Rasor (1937) provided a detailed description of secondary minerals which he observed.

Quartz (SiO_2)

Quartz was a ubiquitous mineral in the ore specimens examined, and the silicate formed from less than one volume percent to more than 80 percent of the ore. Two varieties of quartz were observed.

The most common type of quartz was a fine-grained translucent variety, which typically formed veins associated with pyrite and galena. Many apparently barren veins were also composed of this milky white variety of quartz. The second type consisted of glossy, almost transparent, fine- to coarse-grained, euhedral crystals. Where observed, this less common variety either formed barren veins or was predominately associated with pyrite and occasionally with galena.

Fluid inclusion filling temperatures were obtained from quartz of both varieties that was associated with the various ore minerals listed in table 15. At Tombstone, these temperatures ranged between 225 and 325°C, and at Charleston filling temperatures were between 243 and 318°C. Filling temperatures represent minimum temperatures

of formation, and the range measured at Tombstone and at Charleston suggests that mesothermal conditions existed at the time of ore deposition.

Pyrite (FeS_2)

Pyrite was the most common sulfide mineral, and it was generally present in granular aggregates of fine- to coarse-grained euhedral crystals. In the ore specimens examined, pyrite ranged from less than one volume percent to nearly 100 percent, while averaging about 15 percent.

Pyrite and quartz intergrowths were relatively common. Pyrite crystals from the Westside mine were surrounded by translucent quartz, but pyrite from the McCann ore shoots, west of the Lucky Cuss mine, have been fractured, and the fractures were later filled with quartz.

Pyrite was most commonly associated with galena and sphalerite. Pyrite from the Empire 410 stope was surrounded and replaced by galena, and both sphalerite and galena replaced pyrite from the Westside mine. Euhedral, granular aggregates of pyrite from the Ingersol and Tombstone Extension mines were surrounded and partially replaced by anhedral galena crystals.

Fluid inclusion filling temperatures were determined for quartz associated with pyrite from the Ingersol and Northwest mines, and these temperatures were 279 and 272°C respectively. Quartz associated with pyrite from the Charleston lead mine yielded filling temperatures of about 311°C.

Sphalerite (ZnS)

Sphalerite was fairly common in the Tombstone ores, and Butler, Wilson and Rasor (1938, p. 104) believed that the largest sphalerite deposit was near the Silver Thread mine. Rasor (1937, p. 15), mentioned that sphalerite was also abundant in the Sulphuret mine. In the present study, sphalerite was found in samples from the Contact, Empire, Girard, Ingersol, Silver Thread, Toughnut, Westside, and Charleston lead mines. The average sphalerite content in samples from these mines was about 15 volume percent, and the color of the sphalerite ranged from reddish- to dark-brown. Individual crystals were generally subhedral to anhedral in outline, and they ranged in size from less than 0.01 mm to greater than 1 cm.

Sphalerite was most commonly associated with chalcopyrite, galena, and pyrite. An interesting feature in most of the samples examined was the presence of microscopic blebs of chalcopyrite along sphalerite grain boundaries (fig. 25). The presence of these small chalcopyrite blebs may suggest that sphalerite re-equilibrated under slightly higher sulfur pressures as paragenetically later minerals were deposited. A similar mechanism has been proposed by Williams (1974, p. 669) to explain pyrrhotite "exsolution" blebs in sphalerite from the Zeehan district, Tasmania.

At Tombstone proper, the absence of suitable quartz, associated with sphalerite, prevented the determination of fluid inclusion filling temperatures. However, fluid inclusions in quartz associated with both sphalerite and galena at the Charleston lead mine provided filling temperatures of 318°C.

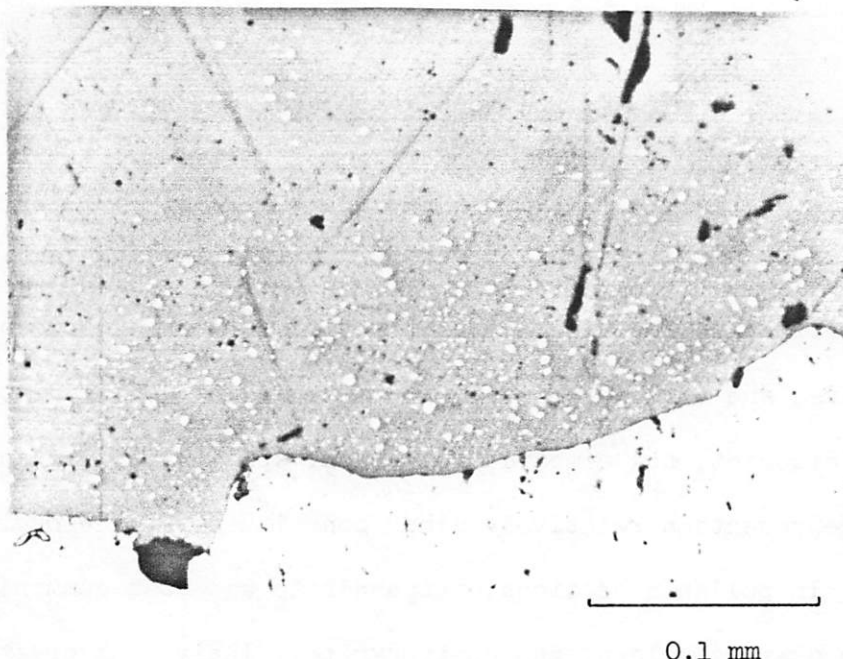


Fig. 25a.--Photomicrograph of exsolution chalcopyrite (gray spots) in sphalerite (dark gray) adjacent to galena (light gray), from the Charleston lead mine. (300x, uncrossed nicols)

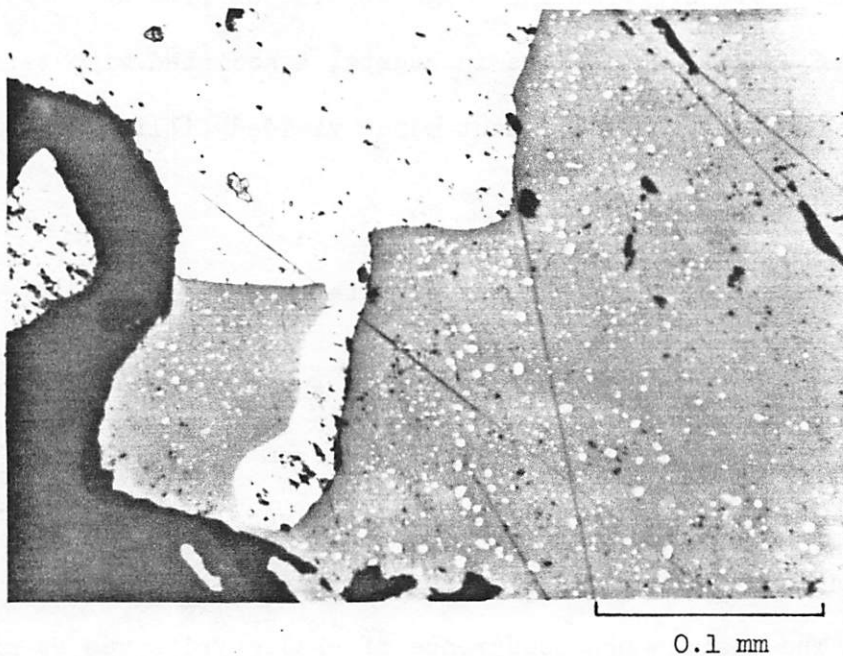


Fig. 25b.--Photomicrograph of exsolution chalcopyrite (gray spots) in sphalerite (gray) adjacent to galena (light gray), from the Charleston lead mine. (300x, uncrossed nicols)

Tetrahedrite (Cu_3SbS_3)

Tetrahedrite has been reported from the Toughnut, Lucky Cuss, and Ingersol mines (Rasor, 1937, p. 21-22), and during the present investigation the mineral was identified in ore specimens from Emerald, Empire, and Toughnut mines. The mineral was widely distributed in the district, but compared to galena, sphalerite, and chalcopyrite, it represents a relatively minor constituent of the ore.

In polished sections, tetrahedrite was most commonly associated with quartz, galena, and chalcopyrite. Individual crystals generally had subhedral outlines, and ranged in size from less than 0.09 mm to about 3 mm. Tetrahedrite formed about 5 volume percent in several polished sections, but its average content in Tombstone ores is probably less than 1 percent. Rasor (1937, p. 22) reported that tetrahedrite ore from the Toughnut mine carried up to 85 oz/ton silver. Fluid inclusions in quartz, associated with tetrahedrite, from the Empire and Toughnut mines yielded filling temperatures of 190 and 225°C respectively.

Chalcopyrite (CuFeS_2)

Chalcopyrite was widespread in the Tombstone ores, and during the present study it was identified from the following mines: Contact, Empire, Girard, Ingersol, Silver Thread, Skip, Tombstone Extension, Toughnut, Westside, and Charleston lead mine.

The most common occurrence of chalcopyrite was as exsolution blebs in sphalerite (figs. 25a, b). The maximum size of these chalcopyrite grains was about 0.01 mm, and they averaged about 0.002 mm.

As suggested earlier, these blebs possibly formed as sphalerite was subjected to influences of paragenetically later forming minerals.

A second, and relatively less common occurrence of chalcopyrite was as anhedral grains, which occasionally enclosed and replaced pyrite, sphalerite, and tetrahedrite. This variety of chalcopyrite was noted in samples from the Charleston lead mine, Contact, Empire, Silver Thread, Tombstone Extension, and Toughnut mines. Polished ore specimens from these mines contained up to 30 volume percent chalcopyrite, and individual grains ranged in size between 0.01 mm and 5.0 mm. The mean grain size was about 0.9 mm, and the average abundance was about 10 percent. Fluid inclusions in quartz, associated with chalcopyrite, from the Charleston lead mine and from the Toughnut mine, yielded filling temperatures of 243 and 261°C respectively.

Galena (PbS)

Galena was a common mineral in the ore specimens examined, and it was identified from the following mines: Contact, Emerald, Empire, Girard, Ingersol, Lucky Cuss, Northwest, Silver Thread, Tombstone Extension, Toughnut, Westside, Mustang, and the Charleston lead mine. Galena was commonly associated with pyrite, sphalerite, chalcopyrite, and less frequently with tetrahedrite. Both hessite and altaite grains were present in galena specimens from the Empire mine.

In polished sections, pyrite, sphalerite, and tetrahedrite were partially replaced by galena. Anglesite commonly formed as an oxidation product along cleavage cracks and around individual galena grains. When present, the galena content of individual polished

specimens ranged between about 2 and 95 volume percent. The average content was about 30 volume percent. Individual grains generally had euhedral outlines, but anhedral grains were observed in samples from the Contact, Ingersol, and Northwest mines. Rasor (1937, p. 11-12) found that galena from the Skip shaft fissure, on the 4th level of the Empire mine, assayed 2.46 oz/ton gold and 237.84 oz/ton silver. During the present investigation, electron microprobe analyses of galenas from the 4th level of the Empire mine suggested that silver values were mainly due to the presence of hessite. These same hessite samples contained about 0.2 weight percent gold. The high gold and silver assays reported by Rasor for "clean galena ore" from the Empire mine are at least partially explained by the presence of gold-bearing hessite grains in galena.

Fluid inclusion filling temperatures in quartz associated with galena were measured for samples from the Charleston lead mine, the Empire mine, and the Northwest mine. Samples from the Empire mine yielded temperatures between 202 and 206°C, while those from the Northwest mine provided temperatures of about 272°C. Filling temperatures from the Charleston lead mine were about 318°C.

Altaite (PbTe)

Altaite had not been previously identified at Tombstone, and during present investigations, the mineral was found in specimens collected by Rasor (1937) from the Contact, Empire, and Ingersol mines. This telluride mineral occurred as highly reflective, minute blebs in galena (fig. 26). Rasor (1937, p. 10), after obtaining a positive microchemical test for tellurium on similar grains,

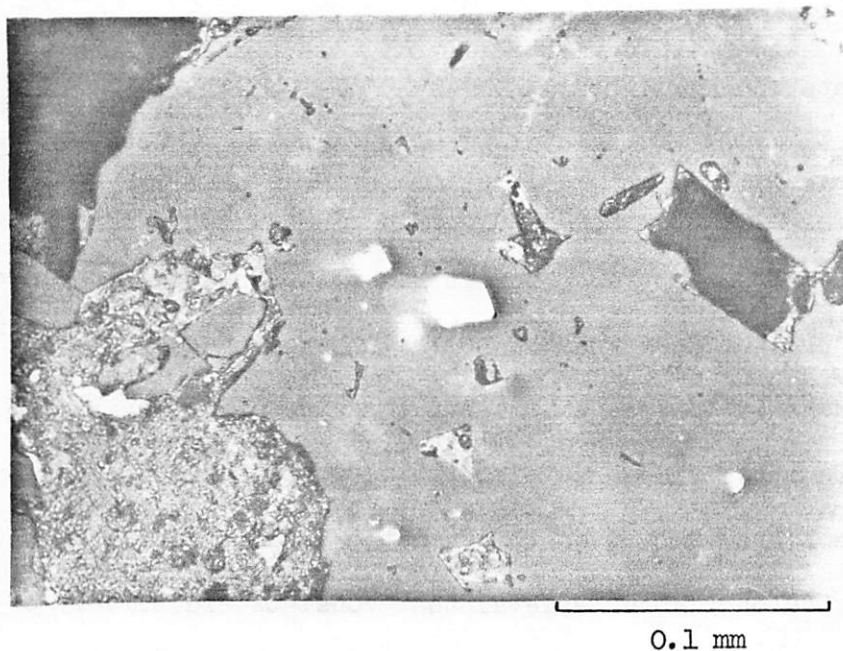


Fig. 26.—Photomicrograph of altaite grains (white) in galena (light gray). Sample collected by Rasor (1937) from the 400 level of the Empire mine, near the Skip shaft fissure.

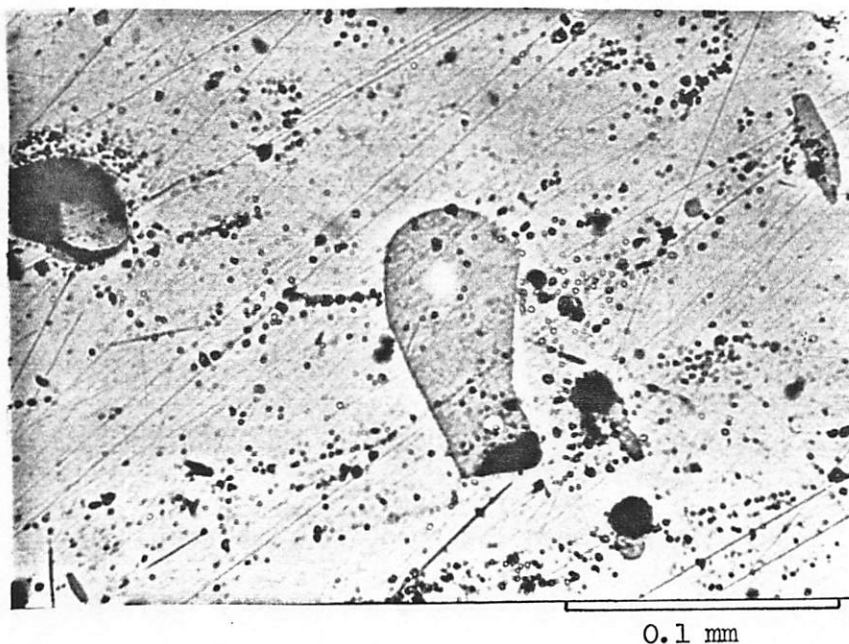


Fig. 27.—Photomicrograph of hessite (light gray) in galena (gray). Sample collected by Rasor (1937) from the 410 stope of the Empire mine.

tentatively identified the material as native tellurium. The small grain size, together with the galena host apparently prevented positive identification, as Rasor (1937, p. 60) further stated, "altaite. . . has been sought for, but it has not been found on close examination of polished sections of tellurium-bearing ores." Highly reflective grains in galena, similar to those described by Rasor (1937, p. 10), were subjected to an electron microprobe spectral scan analysis, and the blebs were found to consist of lead and tellurium. Altaite is the only known mineral that consists exclusively of lead and tellurium.

Altaite was thus identified in samples collected by Rasor in stopes 409, 410, and 488 of the Empire mine. The mineral was also found in samples from unspecified locations in the Contact and Ingersol mines. This telluride mineral represented less than one volume percent of the polished sections examined, and the blebs ranged in size from about 0.02 mm to 0.06 mm. These microscopic grains had euhedral to subhedral outlines, and they were entirely enclosed by galena. Fluid inclusions in quartz associated with altaite-bearing galena from the Empire 488 stope, yielded filling temperatures of about 205°C.

Hessite (Ag_2Te)

Hessite has been reported from the Westside mine (Genth, 1887) and from the Flora Morrison mine (Rasor, 1937, p. 20). The mineral was presently identified in samples collected by Rasor from the 410 stope of the Empire mine.

Hessite (fig. 27) formed microscopic blebs in galena, and when present, the mineral constituted up to about 5 volume percent of the ore. Typically, the silver telluride formed rounded to elliptical, subhedral to anhedral grains, that ranged in size from less than 0.1 mm to about 0.3 mm. Quantitative electron microprobe analyses (table 16) for 10 hessite grains yielded mean values (weight percent) of 60.9 percent silver, 38.6 percent tellurium, and 0.2 percent gold. These mean values agree well with the ideal or theoretical composition also listed in table 16. Semiquantitative analyses of galena hosts indicated that only about 0.1 weight percent silver was present in galena adjacent to the hessite. No gold was detected in the galena. These results suggest that the large gold and silver values, reported by Rasor (1937, p. 11-12) for "clean galena ore" from near the Skip shaft on the fourth level of the Empire mine, may be due to the presence of gold-bearing hessite grains in galena.

Quartz, suitable for fluid inclusion studies, was not found in association with hessite, but fluid inclusions associated with altaite-bearing galenas from the fourth level of the Empire mine yielded filling temperatures of about 205°C, and the hessite probably formed at similar temperatures.

Discussion and Summary

Many of the observations described above were made on mine dump samples used to establish the various high ratio zones mentioned in Chapter V. In general, high copper ratios resulted from the presence of chalcopyrite and secondary covellite. Many hand specimens from the high copper ratio zone also contained visible malachite.

Table 16

Electron Microprobe Analyses of Hessite

	1	2	3	4	5	6	7	8	9	10	11	12
Ag	62.86	61.3	61.9	61.5	61.5	61.7	61.5	60.2	57.4	60.2	61.6	60.9
Te	37.14	37.8	38.0	37.7	37.7	37.9	37.7	39.1	42.1	40.3	37.5	38.6
Au	0.00	0.1	0.1	0.1	0.1	0.0	0.9	0.2	0.3	0.1	0.1	0.2
Total	100.00	99.2	100.0	99.3	99.3	99.5	100.0	99.5	99.8	100.6	99.2	99.7

Note: 1. Calculated theoretical value
 2-11. Hessites from 410 stope of the Empire mine
 12. Mean values for samples 2-11.

High lead ratios were generally accounted for by galena, and its oxidation products of anglesite and cerussite. Sphalerite and its oxidation products of smithsonite, and hemimorphite, were responsible for most of the high zinc ratios. No primary silver minerals were observed in the dump samples, and high silver ratios were partially explained by the presence of silver-bearing galena and tetrahedrite. In addition, many samples contained silver-bearing manganese oxides. No primary molybdenum minerals were found in the dump samples; however, wulfenite was present in several underground samples collected by Rasor (1937) from the Empire and Toughnut mines. Molybdenite has been reported from the Charleston lead mine, and most of the high molybdenum ratios probably resulted from secondary minerals that were derived from molybdenite.

In summary, hypogene ore minerals identified during the present investigation include pyrite, sphalerite, tetrahedrite, chalcopyrite, galena, altaite, and hessite. Electron microprobe analyses resulted in the first identification of altaite from the Tombstone ores. In addition, microprobe analyses resulted in the identification of microscopic hessite grains in galena samples from the Empire mine, and the hessite samples also contained about 0.2 weight percent gold. Much of the silver production at Tombstone was from supergene ore, and hessite was possibly the dominant hypogene silver mineral. For the Tombstone ores, fluid inclusion filling temperatures indicated that minimum temperatures of ore deposition ranged between 205 and 279°C ($\pm 5^\circ\text{C}$). Similar determinations for Charleston ore minerals ranged from 243 to 318°C ($\pm 5^\circ\text{C}$).

CHAPTER VII

CONCLUSIONS

As initially stated, the purpose of this dissertation was to evaluate the Tombstone mining district for additional mineralization, through the application of modern geologic concepts and exploration methods. Following this general statement, a number of more specific questions was posed. The purpose of this concluding chapter is to concisely answer the specific questions, and to specify potential exploration target areas near Tombstone.

The Tombstone silver mining district was studied in detail prior to 1940, and in general the early investigators (Blake, 1882a, b, c, d; Church, 1903; Ransome, 1916, 1920; Rasor, 1937; Butler, Wilson and Rasor, 1938; Gilluly, 1945, 1954, 1956) are to be congratulated for their efforts. Blake believed major ore controlling structures to be north-trending dikes, and associated, cross-cutting, northeast-trending fissures. These findings were later confirmed in part by Church, but he also considered anticlinal folds to represent important ore controls. While agreeing that dikes were important ore localizers, Butler, Wilson and Rasor favored the findings of Church. Ransome contributed substantially to our knowledge of the mineral deposits, and he also provided valuable insight into the stratigraphic setting at Tombstone. Rasor furnished significant insight into the mineralogy of the Tombstone ores. Gilluly first recognized problems relating

to the Uncle Sam "porphyry," and he also succeeded in subdividing the Pennsylvanian-Permian Naco Limestone. Gilluly was the only early investigator to consider large scale thrust faults as important structural features in the district. Jones (1961, 1963, 1966) later questioned Gilluly's thrust concepts, and illustrated how processes of differential vertical uplift could explain much of Gilluly's evidence.

During the present investigation, what Gilluly considered to be a narrow thrust faulted sliver of Bisbee Formation, between outcrops of Epitaph Dolomite, was found to be Scheerer Quartzite. This was the first reported occurrence of Scheerer at Tombstone, and identification of characteristic Scheerer prompted recognition of the overlying Concha Limestone.

The nature and emplacement of the Uncle Sam "porphyry" was reconsidered, and the previously conceived (Gilluly, 1945, 1956), thrust fault controlled, hypabyssal sill or laccolith, was re-defined as a tuffaceous volcanic eruptive. The Uncle Sam was shown, for the first time, to be genetically related to, and contemporaneous with, the Schieffelin Granodiorite. Economically important mineralization at the Charleston lead mine, Mustang mine, San Pedro mine, and the State of Maine mine is located along northeast-trending fractures in the tuff, and additional mineralization may exist at depth beneath the volcanic unit.

Ages of mineralization in southern Arizona can provide important guides to porphyry copper exploration. Livingston et al. (1968) determined that fifteen of sixteen known porphyry copper deposits had dates between 75 and 55 m.y., and of the fifteen only two dated in excess of 70 m.y. Sericite from the mineralized zone at Charleston

provided a potassium-argon date of 74.5 ± 3 m.y., and alteration related to major silver mineralization along the Contention dike in Tombstone dated at about 72 m.y. Thus, the ages of the Charleston and Tombstone mineralization are indistinguishable, and the ages (72 to 74 m.y.) are at the extreme upper limit of the porphyry copper interval. These relatively old ages do not eliminate the possibility of discovering a major copper deposit at Tombstone, but they do tend to reduce the chances of such a discovery. South of the Prompter fault, manganese mineralization is associated with dikes of a 63 m.y. rhyolite porphyry, and copper mineralization in the Emerald mine may also be related to the same rhyolite. A 63 m.y. date is suggestive of porphyry copper mineralization in southern Arizona.

Tombstone was studied from five different photographic scales. Spacecraft imagery and photography were best suited for studying influences of regional structures on the district. High-altitude photography in the infrared band was ideally suited for studying large district sized structures. Low-level, large-scale photography was best suited for detailed mapping purposes. Sun-angle changes had a profound effect on photograph quality. Sun angles of less than 30° are a prerequisite for high quality interpretation of structural features on small scale photographs. Sun angles of up to about 40° allow high quality interpretation on large scale photography. In general, photo interpretation of structural features is improved as illumination angles decreased to a minimum of 10 to 15° . The study of multiscale photography resulted in the identification of six structural features of potential mineral exploration interest.

Mesquite biogeochemical methods were applied at Tombstone, and particular care was taken to sample the six structural features observed on spacecraft and high-altitude photographs. Problems of mesquite sampling were found to represent a major source of erratic data. To obtain meaningful data, twig size should be rigidly controlled, and at least three trees must be sampled per sample site. Elements analyzed included copper, molybdenum, silver, and zinc, and with the exception of silver, the elements were well-suited to the mesquite method. In future surveys, lead analyses should possibly replace those for silver. The six structural features of potential exploration interest were sampled, and four structures produced positive results. The lack of a response in a fifth area was possibly due to inadequate sampling, and a sixth area probably lacked sufficient mineralization to produce a response. On pediments, and in other areas of transported overburden, with careful application and interpretation, mesquite samples can be confidently substituted for soil and rock samples. The procedures allow a rapid and relatively inexpensive method of testing subsurface metal concentrations.

Mine dumps were sampled to establish patterns of district zoning. The highest metal values exposed on given dumps were carefully sought out, and no attempt was made to determine mean metal values for individual dumps. Samples were analyzed for copper, lead, molybdenum, silver, and zinc, and the assays were examined through a series of composite ratios. In the western part of the district, between the Charleston lead mine and the State of Maine mine, high ratio zones of lead, silver, and zinc were peripheral to a central molybdenum zone, and an intermediate copper zone. Similar metal patterns have been reported

for porphyry copper deposits (Jerome, 1966; Lowell and Guilbert, 1970). East of the Ajax fault, high lead and molybdenum ratios were found at the extreme eastern edge of the district. High copper, silver, and zinc ratios exist near the Prompter-Ajax fault intersection, and the copper ratio pattern extended along northeast fractures through the Luck Sure, Westside, and Toughnut mines. High copper ratios were also present near the Emerald mine. A crude pattern of district zoning was suggested by Butler, Wilson and Rasor (1938, p. 102-105), and the present zoning patterns, based on carefully collected mine dump samples, not only confirmed, but greatly expanded previous zoning concepts. The use of ratios proved advantageous since it allowed a quantitative understanding of zoning patterns.

Mineralogic data for the high metal zones was developed by studying a duplicate set of dump samples. High copper ratios were due to chalcopyrite and secondary covellite. Many hand specimens from high copper zones also contained visible malachite. High lead ratios were accounted for by galena, and its oxidation products of anglesite and cerussite. Sphalerite, smithsonite and hemimorphite were responsible for the high zinc ratios. No primary silver minerals were observed in the dump samples, and high silver ratios were partially explained by silver-bearing galena and tetrahedrite. Many samples also contained silver-bearing manganese oxides. No primary molybdenum minerals were found, but wulfenite was relatively common in underground samples collected by Rasor (1937). Molybdenite has been reported from the Charleston lead mine, and most of the high molybdenum ratios probably resulted from secondary minerals that were derived from molybdenite. Electron microprobe studies, of samples collected by

Rasor (1937), resulted in the first identification at Tombstone of altaite and the initial recognition of hessite from the Empire mine. Primary silver minerals were found to include hessite, tetrahedrite, and silver-bearing galena. Fluid inclusion filling temperatures from Tombstone proper indicated minimum temperature ranges for ore deposition of between 205 and 279°C ($\pm 5^\circ\text{C}$). At Charleston filling temperatures ranged from 243 to 318°C ($\pm 5^\circ\text{C}$).

Seven potential target areas have been suggested by the exploration methods discussed above. These areas include the: Government Draw-San Pedro structural intersection; Government Draw-Walnut Gulch intersection; Horquilla-Ajax fault intersection; northeast-trending fractures in the Uncle Sam Tuff; eastern edge of the main Tombstone district; Prompter-Ajax fault intersection; and the Emerald mine area. To further evaluate the present geochemical anomalies, the first three areas require the collection of additional mesquite/soil samples. Drilling is required to test the last four target areas.

In summary, this current re-evaluation of the Tombstone district has necessarily involved a number of different and generally unrelated investigative approaches. The intent was to reconsider the district's mineral potential by using modern geologic concepts and methods. Similar approaches can be profitably integrated and applied to other mining districts with comparable geologic settings.

APPENDICES

Appendix I contains the analytical data for the K-Ar age determination on hydrothermal sericite from the Charleston lead mine.

The sericite sample was submitted to S. C. Creasey, U. S. Geological Survey, Menlo Park, California, and the analysis was conducted by E. H. McKee in the Survey laboratories.

Appendix II contains a complete listing of the analytical data for all mesquite samples collected during this study.

Appendix III contains a complete listing of the analytical data for all mine dump samples collected in the Tombstone-Charleston area.

Appendix IV is a listing of the calculated mine dump ratio values.

Appendix I

Analytical data for K-Ar age determination on hydrothermal sericite, from the Charleston lead mine:

K_2O (%)	Ar^{40} (moles/g)	$\frac{Ar^{40} \text{ rad.}}{Ar^{40} \text{ total}}$
9.31	1.046×10^{-9}	0.747
9.32		

Age: 74.5 ± 3 million years

Constants: $\lambda_e = 0.585 \times 10^{-10} \text{ yr}^{-1}$

$\lambda_\beta = 4.72 \times 10^{-10} \text{ yr}^{-1}$

$K^{40}/K_{\text{total}} = 1.19 \times 10^{-4} \text{ moles/mole}$

K_2O determined by flame photometer, using lithium as an internal standard

Ar determined by Neir-type 6-in. radius mass spectrometer

Analyst: E. H. McKee, September 18, 1973

Appendix II

Appendix II is a complete listing of the mesquite analytical data. Analyses were performed by Rocky Mountain Geochemical Corporation, Tucson, Arizona. Copper, zinc and silver were determined by atomic absorption, and molybdenum was determined colorimetrically. All values are reported in ppm, and n.d. = none detected.

Location coordinates are listed as (X,Y) or as (east,north) of an arbitrary origin selected at the southwest corner of the Tombstone 15' quadrangle published by the U. S. Geological Survey. The longitude and latitude of the origin are $110^{\circ}15'$ W., $31^{\circ}30'$ N. For example, the (east,north) coordinates for sample no. 103 are (5600,16800), and this sample was collected at a point 5.600 miles east, and 16.800 miles north of the origin. This particular sample site is in the NW $\frac{1}{4}$ sec. 36, T. 19 S., R. 21 E.

Appendix II
Mesquite Data

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
101	125	470	n.d.	2	3800,15400	1-e8-1
102	100	310	1	2	8410,17400	6-a7-1
103	140	490	7	2	9200,17500	6-a9-1
104	85	250	n.d.	2	5600,16800	6-b2-1
105	120	420	n.d.	2	8500,16600	6-b8-1
106	155	780	n.d.	3	9200,16000	6-c9-1
107	70	385	n.d.	2	5950,15900	6-d2-1
108	130	640	11	3	9600,15200	6-10e-1
109	135	420	6	n.d.	9800,15050	6-10e-2
110	155	690	13	n.d.	9800,14950	6-10e-3
111	130	750	8	n.d.	9900,14800	6-10f-1
112	80	265	1	2	5900,14875	6-2f-1
113	100	930	2	1	8400,14175	6-7g-1
114	80	250	4	1	9150,13850	6-9g-1
115	105	240	7	2	6450,12950	7-4a-1
116	90	270	3	2	6750,13100	7-4a-2
117	70	300	6	n.d.	6950,13300	7-5a-1
118	85	280	10	n.d.	7050,13450	7-5a-2
119	70	270	13	n.d.	6000,12500	7-3b-1
120	80	180	3	n.d.	6200,12650	7-3b-2
121	90	340	5	n.d.	7850,12600	7-6b-1
122	130	320	4	n.d.	8300,12850	7-7b-1
123	125	420	6	n.d.	8050,12620	7-7b-2
124	115	510	11	2	5800,12350	7-2c-1
125	75	160	9	n.d.	6400,12225	7-3c-1
126	40	120	1	n.d.	6100,12300	7-3c-2
127	95	420	8	n.d.	6900,12000	7-4c-1
128	100	290	14	n.d.	6620,12300	7-4c-2
129	70	280	n.d.	2	7400,12150	7-5c-1
130	90	230	14	2	7100,12000	7-5c-2
131	85	260	n.d.	1	7500,12375	7-6c-1
132	160	630	1	2	7650,12410	7-6c-2a
133	95	350	6	2	8200,11800	7-7d-1
134	90	220	n.d.	1	7610,11075	7-6e-1
135	125	630	n.d.	1	7750,11150	7-6e-2
136	90	250	n.d.	2	7800,10700	7-6f-1
137	95	190	n.d.	n.d.	8610,10500	7-8f-1
138	140	780	n.d.	n.d.	9500,10850	7-10f-1
139	100	290	1	n.d.	9890,10800	7-10f-2
140	120	185	n.d.	n.d.	9500,10510	7-10f-3
141	120	260	5	n.d.	6320,10200	7-3g-1
142	110	410	n.d.	n.d.	8230,10175	7-7g-1
143	105	300	1	2	8290,10250	7-7g-2
144	150	660	n.d.	2	8380,10100	7-7g-3
145	160	650	n.d.	1	9370,10000	7-9g-1

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
146	110	450	9	n.d.	5350, 9600	7-1h-1
147	130	280	11	n.d.	5750, 9650	7-2h-1
148	130	490	9	n.d.	5950, 9900	7-3h-1
149	110	470	n.d.	n.d.	6100, 9820	7-3h-2
150	110	230	3	n.d.	6600, 9650	7-4h-1
151	140	545	n.d.	1	8300, 9900	7-7h-1
152	110	240	n.d.	n.d.	8200, 9450	8-7a-1
153	120	210	11	n.d.	6500, 8600	8-4b-1
154	150	280	12	1	6620, 8720	8-4b-3
155	150	200	8	n.d.	7060, 8880	8-5b-1
156	120	180	4	n.d.	8210, 8600	8-7b-1
157	150	380	8	n.d.	8310, 8350	8-7c-1
158	75	240	1	1	8100, 8100	8-7c-2
159	100	200	1	1	7790, 7880	8-6d-1
160	80	290	8	2	7820, 6050	8-6g-1
161	80	360	n.d.	1	8710, 6110	8-8g-1
162	120	315	n.d.	n.d.	8740, 6260	8-8g-2
163	155	510	9	n.d.	6610, 5720	8-4h-1
164	155	480	7	1	7780, 5690	8-6h-1
165	130	280	9	1	8650, 5700	8-8h-1
166	100	175	2	n.d.	7650, 5350	9-6a-1
167	110	545	14	n.d.	7690, 5160	9-6a-2
168	105	315	6	n.d.	8740, 4730	9-8a-1
169	120	370	9	n.d.	8210, 4820	9-7b-1
170	95	240	7	n.d.	8720, 4750	9-8b-1
171	110	230	6	n.d.	9110, 5000	9-9b-1
172	120	460	1	n.d.	9220, 4550	9-9b-2
173	140	650	4	n.d.	9190, 4010	9-9c-1
174	80	330	n.d.	2	10410, 16100	11-1c-1
175	110	375	1	1	11380, 15900	11-3d-1
176	120	480	n.d.	1	11850, 16600	11-4d-1
177	125	430	6	1	13000, 15400	11-7e-1
178	125	670	8	1	10380, 14700	11-1f-1
179	120	650	5	n.d.	10070, 14700	11-1f-2
180	130	760	3	n.d.	10190, 14700	11-1f-3
181	140	940	9	3	10620, 14550	11-2f-1
182	110	860	13	4	10500, 14650	11-2f-2
183	130	320	n.d.	1	14020, 14750	11-9f-1
184	130	520	6	3	10890, 13380	11-2g-1
185	140	450	11	4	10790, 14400	11-2g-2
186	100	760	6	1	11900, 14100	11-4g-1
187	95	530	4	1	10250, 8700	13-1b-1
188	95	260	n.d.	n.d.	14200, 12750	12-9b-1
189	110	230	n.d.	n.d.	10100, 10600	12-1f-1
190	110	280	4	n.d.	12100, 7620	13-5d-1
191	110	240	n.d.	n.d.	10820, 7000	13-2e-1
192	140	600	5	4	11200, 7280	13-3e-1

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
193	110	360	n.d.	n.d.	10750, 6610	13-2f-1
194	120	380	3	n.d.	10500, 6710	13-2f-2
195	135	280	n.d.	2	11310, 6950	13-3f-1
196	90	230	n.d.	n.d.	11250, 6600	13-3f-2
197	90	260	n.d.	1	11020, 5680	13-3h-1
198	113	413	n.d.	4	11550, 5700	13-4h-1
199	90	220	3	n.d.	11000, 4910	14-3b-1
200	120	300	n.d.	n.d.	11520, 4880	14-4b-1
201	140	330	1	n.d.	12150, 4750	14-5b-1
202	130	315	1	n.d.	12720, 4750	14-6b-1
203	130	300	4	1	13120, 4840	14-7b-1
204	95	407	17	1	7400, 13550	6-5h-1
205	105	225	6	2	6500, 13250	7-4a-4
206	110	320	6	n.d.	7340, 13000	7-5a-3
207	105	340	3	1	6300, 12600	7-3b-3
208	110	280	6	n.d.	7150, 12980	7-5b-1
209	85	210	6	1	7000, 12800	7-5b-2
210	110	250	3	1	7200, 12650	7-5b-3
211	164	525	6	1	7560, 12940	7-6b-2
212	60	170	n.d.	2	8700, 12760	7-8b-1
213	130	445	24	3	6000, 12080	7-3c-3
214	95	270	4	2	7180, 12160	7-5c-3
215	100	240	7	2	7520, 12390	7-6c-3
216	90	235	n.d.	1	8350, 12140	7-7c-1
217	70	200	n.d.	1	5350, 11710	7-1d-1
218	80	210	2	2	5260, 11540	7-1d-2
219	120	300	3	4	5510, 11760	7-2d-1
220	75	160	8	1	5550, 11520	7-2d-2
221	110	310	4	1	7130, 11580	7-5d-2
222	93	340	1	1	7520, 11480	7-6d-1
223	110	360	19	2	6800, 11400	7-4e-2
224	135	365	16	1	6920, 11390	7-4e-3
225	130	530	12	n.d.	6700, 11380	7-3f-1
226	105	330	n.d.	1	6220, 10660	7-3f-1
227	100	350	n.d.	n.d.	7260, 9550	7-5h-1
228	120	300	1	1	7510, 9520	7-6h-1
229	185	690	36	2	8760, 8140	8-8c-1
230	140	475	19	3	8110, 7520	8-7d-1
231	135	525	13	2	7810, 6810	8-6f-1
232	170	440	9	3	9200, 6980	8-9f-1
233	115	360	7	2	9630, 6890	8-10f-1
234	140	385	7	2	9380, 6150	8-9g-1
235	125	410	4	2	9800, 6490	8-10g-1
236	110	285	6	2	9790, 5660	8-10h-1
237	120	305	3	2	9730, 5340	9-10a-1
238	175	680	9	3	13250, 8620	13-7b-1

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
239	165	400	6	1	14010, 8680	13-9b-1
240	160	370	2	1	14480, 8640	13-10b-1
241	155	380	n.d.	1	12890, 8420	13-6c-1
242	140	330	12	3	10050, 6850	13-1f-1
243	80	210	5	2	10520, 5500	13-2h-1
244	120	370	1	2	12280, 8380	13-5c-1
245	130	320	7	3	12480, 8150	13-C6-2
246	110	320	8	1	13480, 4900	14-8B-1
247	230	500	7	n.d.	15000, 8650	18-1B-1
248	160	400	8	n.d.	15300, 9000	18-1B-2
249	105	350	n.d.	1	10990,16190	11-C2-1
250	94	260	1	1	10900,15820	11-D2-1
251	115	340	2	1	10500,15920	11-D2-2
252	100	360	1	1	9850,16250	6-C10-1
253	125	640	3	1	9150,16350	6-C9-2
254	125	370	8	1	9500,16280	6-C10-2
255	115	300	1	1	9940,15710	6-D10-1
256	75	230	n.d.	1	10550,15400	11-E2-1
257	140	450	3	1	9500,16670	6-D9-1
258	145	420	1	1	8650,16290	6-C8-1
259	120	380	1	1	8260,16320	6-C7-1
260	80	200	n.d.	1	7700,16290	6-C6-1
261	85	220	n.d.	1	7390,16000	6-C5-1
262	75	220	3	1	7210,15520	6-D5-1
263	85	290	3	1	7400,15120	6-E5-1
264	90	260	1	1	6490,15320	6-E3-1
265	90	280	n.d.	1	6050,15090	6-E3-2
266	130	300	8	2	5980,16130	6-C3-1
267	110	500	8	1	6450,16000	6-C3-2
268	110	370	2	1	6570,16200	6-C4-1
269	145	800	23	1	11200,14260	K-1A-2
270	135	670	12	1	11370,14310	K-2A-1
271	125	1000	2	2	11090,13710	J-D9-1
272	215	870	20	1	11060,14620	F-9G-1
273	170	1500	10	1	10900,14660	F-9G-2
274	115	530	6	1	10950,14720	F-9G-3
275	115	420	n.d.	1	11440,16150	11-C3-1
276	160	360	n.d.	1	11970,16290	11-C5-1
277	125	410	1	1	10980,15390	11-E2-2
278	120	770	6	1	11580,14600	11-F4-1
279	160	500	5	n.d.	11450,15080	11-E4-1
280	145	1600	10	1	11900,15300	11-E4-2
281	120	550	1	1	12200,14920	11-F5-1
282	140	280	1	1	12540,14880	11-F6-1
283	95	200	2	1	12700,15110	11-E6-1
284	105	280	n.d.	1	12890,14600	11-F6-2
285	165	410	1	1	13120,14300	11-G7-1

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
286	145	450	2	1	6950,16500	6-B4-1
287	95	500	1	n.d.	7100,16000	6-C5-2
288	120	470	2	1	8500,15950	6-D8-1
289	85	210	1	n.d.	8150,15810	6-D7-1
290	95	290	n.d.	1	8010,15450	6-E7-1
291	135	360	10	1	8450,15420	6-E7-2
292	150	660	1	1	8910,15410	6-E8-1
293	165	370	3	n.d.	9900,14450	6-G10-1
294	115	270	5	n.d.	9710,14090	6-G10-2
295	105	440	2	n.d.	8740,13480	6-H8-1
296	150	900	6	n.d.	8010,13620	6-H7-1
297	120	400	6	1	7050,13750	6-H5-4
298	90	290	12	n.d.	7600,14350	6-G6-1
299	110	400	2	n.d.	8450,14920	6-F7-1
300	125	420	1	n.d.	8850,14460	6-G8-2
301	110	450	2	n.d.	9000,14770	6-F9-1
302	100	480	2	n.d.	9700,13280	7-A10-1
303	150	550	14	1	9900,12600	7-B10-1
304	185	1100	3	1	10710,13150	12-A2-1
305	125	350	8	n.d.	11100,12460	12-C3-1
306	160	560	14	n.d.	11210,12850	12-B3-1
307	170	520	3	n.d.	11800,13620	11-H4-1
308	185	370	n.d.	n.d.	12750,14200	11-G6-1
309	135	490	1	n.d.	13100,13790	11-H7-1
310	155	480	2	n.d.	13510,13720	11-H8-1
311	140	490	2	n.d.	13740,13420	12-A8-1
312	105	360	n.d.	n.d.	13900,13150	12-A9-1
313	130	510	1	n.d.	12850,12620	12-B6-1
314	110	430	1	1	12650,12200	12-C6-1
315	130	350	3	1	12500,11890	12-D6-1
316	105	330	1	1	12250,12250	12-C5-1
317	170	530	2	n.d.	11900,11400	12-E5-1
318	155	330	5	n.d.	12200,10350	12-G5-1
319	120	370	3	n.d.	12400,10020	12-G6-1
320	110	370	1	n.d.	13000,10110	12-G7-1
321	240	480	3	n.d.	13500,10050	12-G8-1
322	190	390	3	n.d.	13260, 9700	12-H7-1
323	170	400	2	n.d.	12000,10590	12-F5-1
324	130	270	2	n.d.	11600,13890	11-H4-2
325	135	270	8	n.d.	8000,12340	7-C7-3
326	70	230	1	n.d.	6420,11610	7-D4-2
327	100	360	3	n.d.	6140,11300	7-E3-1
328	100	340	1	n.d.	5860,10400	7-G2-1
329	115	350	1	n.d.	5610,10210	7-G2-2
330	165	330	2	n.d.	5300,10520	7-F1-1
331	135	580	3	n.d.	5500,11200	7-E2-2
332	85	210	1	n.d.	6000,11700	7-D3-3

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
333	85	190	1	n.d.	5980,11110	7-A3-2
334	85	300	n.d.	n.d.	6100,13980	6-G3-2
335	95	310	n.d.	n.d.	6710,14040	6-G4-1
336	80	310	n.d.	n.d.	6000,14380	6-G3-3
337	105	250	n.d.	n.d.	6020,14540	6-F3-1
338	80	320	n.d.	n.d.	6450,14720	6-F3-2
339	100	380	n.d.	n.d.	8840,12900	7-B8-2
340	120	250	3	n.d.	8850,12300	7-C8-2
341	140	500	2	n.d.	8700,11800	7-D8-1
342	130	270	n.d.	n.d.	9120,11950	7-D9-1
343	245	830	2	n.d.	10210,11600	12-D1-1
344	155	690	1	2	10190,11210	12-E1-1
345	140	680	n.d.	n.d.	9490,11120	7-E10-1
346	135	470	n.d.	n.d.	8850,10210	7-G9-2
347	200	460	2	n.d.	9190,11250	7-E9-1
348	105	310	2	n.d.	7790,11230	7-E6-4
349	110	380	2	n.d.	7490,11700	7-D6-2
350	150	260	2	n.d.	13100,10620	12-F7-1
351	175	360	1	n.d.	13190,11100	12-E7-1
352	125	370	n.d.	n.d.	13090,11890	12-D7-1
353	135	400	n.d.	n.d.	13420,12300	12-C8-1
354	150	470	1	n.d.	13900,12910	12-B9-2
355	195	530	1	n.d.	14250,12410	12-C9-1
356	175	280	2	n.d.	13650,11650	12-D8-1
357	165	370	1	n.d.	13990,11360	12-E9-1
358	170	260	5	n.d.	14400,10870	12-F10-1
359	140	270	3	n.d.	14580,10100	12-G10-1
360	205	720	2	n.d.	14710,10000	12-G10-2
361	225	310	2	n.d.	16600, 9600	17-H4-1
362	195	230	n.d.	n.d.	16780, 9250	18-A4-1
363	200	380	3	n.d.	17350, 9170	18-A5-1
364	225	250	3	n.d.	16780, 9610	17-H4-2
365	250	290	2	n.d.	17090, 9650	17-H5-1
366	230	490	3	n.d.	17690, 9810	17-H6-1
367	180	440	5	2	16750,10150	17-G4-1
368	215	360	2	n.d.	15820, 9280	18-A2-1
369	140	230	1	n.d.	15710, 9460	17-H2-1
370	205	520	3	n.d.	16310, 9000	18-B3-1
371	150	330	2	n.d.	15400, 9280	18-A1-1
372	275	440	2	1	15400, 9700	17-H1-1
373	200	300	2	n.d.	14900, 9500	18-A1-2
374	220	490	2	n.d.	15050, 9060	18-A1-3
375	205	520	3	n.d.	15300, 8700	18-B2-1
376	295	760	3	1	13600, 8640	13-B8-1
377	135	300	1	n.d.	12200, 8950	13-B5-1
378	130	170	n.d.	n.d.	12450, 9200	13-A6-1

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
379	130	300	n.d.	n.d.	11980, 9100	13-A5-1
380	155	500	1	n.d.	11700, 9650	12-H4-1
381	195	250	1	n.d.	11270, 9700	12-H3-1
382	135	450	1	n.d.	11020, 10100	12-G3-1
383	145	600	n.d.	n.d.	10700, 10050	12-G2-1
384	135	510	1	n.d.	10750, 9880	12-H2-1
385	130	560	1	n.d.	10520, 9600	12-H2-2
386	145	390	3	n.d.	10780, 9580	13-B2-1
387	145	380	2	n.d.	11280, 8470	13-C3-1
388	160	390	1	n.d.	10900, 8180	13-C3-2
389	115	300	1	n.d.	10810, 9010	13-A2-1
390	120	190	3	n.d.	11250, 9350	13-A3-1
391	130	260	2	n.d.	10310, 9000	13-A1-1
392	115	480	1	n.d.	10520, 7900	13-D2-1
393	90	520	n.d.	n.d.	9850, 8520	13-B1-3
394	110	380	1	n.d.	9410, 8250	8-C10-1
395	175	750	3	n.d.	9710, 8090	8-C10-2
396	135	320	1	n.d.	9810, 8900	8-B10-1
397	120	320	1	n.d.	9420, 9180	8-A10-1
398	85	340	3	n.d.	8950, 8600	8-B9-1
399	75	260	1	n.d.	8710, 8950	8-B8-1
400	145	910	14	n.d.	8700, 8000	8-C8-2
401	115	370	23	n.d.	8650, 7950	8-C8-3
402	140	470	11	n.d.	8610, 8210	8-C8-4
403	125	370	1	n.d.	7960, 8750	8-B7-2
404	140	430	n.d.	1	7900, 9020	8-B7-3
405	205	630	11	n.d.	7300, 8620	8-B5-3
406	220	410	3	n.d.	11700, 9210	13-A6-2
407	95	220	n.d.	n.d.	11820, 8600	13-B4-1
408	115	310	2	n.d.	11720, 7950	13-D4-1
409	180	370	2	n.d.	12800, 8120	13-C6-3
410	170	580	6	n.d.	12780, 7580	13-D6-1
411	135	340	1	n.d.	12400, 7020	13-E6-1
412	140	530	3	n.d.	12300, 7720	13-D5-2
413	130	400	2	n.d.	11490, 7490	13-E4-1
414	165	510	5	n.d.	12050, 6810	13-F5-1
415	125	510	2	n.d.	12300, 6380	13-G5-1
416	115	640	6	n.d.	12410, 6120	13-G6-1
417	160	360	10	n.d.	12800, 5810	13-H6-1
418	130	360	1	n.d.	13040, 5590	13-H7-1
419	130	380	1	n.d.	12480, 4800	14-B6-2
420	140	280	1	n.d.	10520, 4950	14-B2-1
421	220	420	1	n.d.	9410, 5100	9-A10-2
422	150	330	2	n.d.	9070, 5700	8-H9-1
423	265	500	16	n.d.	9360, 5700	8-H9-2
424	155	320	6	n.d.	8000, 5760	8-H7-1
425	170	480	5	n.d.	8310, 6020	8-G7-1

Appendix II--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
426	105	310	2	n.d.	9030, 6420	8-G9-2
427	155	410	2	n.d.	9390, 6440	8-G10-2
428	105	600	14	n.d.	5410, 5080	9-A5-1
429	115	270	10	n.d.	7510, 6060	8-G6-2
430	180	460	11	n.d.	7500, 6590	8-G6-3
431	150	720	1	n.d.	8260, 6680	8-F7-1
432	80	210	3	n.d.	7190, 10900	7-F5-1
433	80	340	1	n.d.	6700, 10900	7-F4-3
434	177	920	10	n.d.	6090, 9810	7-H3-2
435	145	600	3	n.d.	6410, 9410	8-A3-3
436	80	200	1	n.d.	6250, 9000	3-A3-4
437	140	350	6	n.d.	5820, 8600	8-B3-5
438	105	250	3	n.d.	11910, 5600	13-H5-1
439	135	430	1	n.d.	11780, 6120	13-G4-1
440	100	410	1	n.d.	11310, 6280	13-G3-1
441	185	560	16	n.d.	7490, 7650	8-D6-3
442	145	500	8	n.d.	7990, 7050	8-E7-1
443	130	390	11	n.d.	8500, 7610	8-D7-2
444	125	390	8	n.d.	8810, 7620	8-D8-1
445	125	330	3	n.d.	9210, 7700	8-D9-1
446	125	310	1	n.d.	10210, 7780	13-D1-1
447	150	580	2	n.d.	9810, 7660	8-D10-1
448	105	550	8	n.d.	8300, 6960	8-F7-2
449	185	700	6	n.d.	8810, 6920	8-F8-2
450	105	320	3	n.d.	9790, 6250	8-G10-3
451	110	430	11	n.d.	10280, 6150	13-G1-1
452	125	230	n.d.	n.d.	7500, 8260	8-C6-1

Appendix III

Appendix III contains a complete listing of the mine dump analytical data. Analyses were performed by Rocky Mountain Geochemical Corporation, Tucson, Arizona. Copper, zinc, silver, and lead were determined by atomic absorption, and molybdenum was determined colorimetrically. All values are reported here in ppm, and n.d. = none detected.

Location coordinates were determined in a similar manner to the mesquite coordinates. The coordinates are listed as (X,Y) or as (east,north) of an arbitrary origin selected at the southwest corner of the Tombstone 15' quadrangle published by the U. S. Geological Survey. The longitude and latitude of the origin is $110^{\circ}15'$ W., $31^{\circ}30'$ N. For example, the (east,north) coordinates for sample no. 1001W are (7710,11050), and this sample was collected at a point 7.710 miles east, and 11.050 miles north of the origin. The particular sample site is in the SW $\frac{1}{4}$ sec. 29, T. 20 S., R. 22 E. Sample numbers are followed by a W or an E, which indicates whether the particular mine dump is located west or east of the Ajax Hill fault or its projection.

Preceding the analytical data is a list of sample numbers, mine names (where known) and mine locations. Unless otherwise stated all sections numbers are in T. 20 S., R. 22 E.

Appendix III

Mine Locations

<u>Sample no.</u>	<u>Mine name</u>	<u>Location</u>
1001W		SE ¹ ₄ SW ¹ ₄ sec. 29
1002W		E ¹ ₂ NE ¹ ₄ sec. 7, T. 21 S., R. 22 E.
1003W		SE ¹ ₄ SW ¹ ₄ sec. 17
1004W		NE ¹ ₄ SW ¹ ₄ sec. 17
1005W		SW ¹ ₄ NE ¹ ₄ sec. 17
1006W	San Pedro mine	SE ¹ ₄ sec. 8
1007W		SE ¹ ₄ SE ¹ ₄ sec. 17
1008W		W ¹ ₂ sec. 20
1009E		NW ¹ ₄ SE ¹ ₄ sec. 22
1010W		NE ¹ ₄ NW ¹ ₄ sec. 4, T. 21 S., R. 22 E.
1012W		SE ¹ ₄ NW ¹ ₄ sec. 4, T. 21 S., R. 22 E.
1013W		NW ¹ ₄ SE ¹ ₄ sec. 19
1014W	Mustang mine	SW ¹ ₄ NW ¹ ₄ sec. 30
1015W		NW ¹ ₄ SE ¹ ₄ sec. 30
1016W	Charleston lead mine	NE ¹ ₄ NW ¹ ₄ sec. 36, T. 20 S., R. 21 E.
1017W		SW ¹ ₄ SE ¹ ₄ sec. 36, T. 20 S., R. 21 E.
1018W		SE ¹ ₄ SE ¹ ₄ sec. 36, T. 20 S., R. 21 E.
1019W		NW ¹ ₄ NW ¹ ₄ sec. 6, T. 21 S., R. 22 E.
1020W		W ¹ ₂ SW ¹ ₄ sec. 6, T. 21 S., R. 22 E.
1021W		SW ¹ ₄ SE ¹ ₄ sec. 6, T. 21 S., R. 22 E.
1022W		SW ¹ ₄ SW ¹ ₄ sec. 6, T. 21 S., R. 22 E.
1023W		NW ¹ ₄ NW ¹ ₄ sec. 7, T. 21 S., R. 22 E.
1025W		NW ¹ ₄ NE ¹ ₄ sec. 7, T. 21 S., R. 22 E.
1026W		SW ¹ ₄ NE ¹ ₄ sec. 7, T. 21 S., R. 22 E.
1029E	Empire mine	NE ¹ ₄ NE ¹ ₄ SE ¹ ₄ sec. 11
1030W	Santa Anna mine	NE ¹ ₄ NE ¹ ₄ sec. 16
1031W	Mamie mine	SE ¹ ₄ NE ¹ ₄ sec. 16
1032W	Randolph mine	NE ¹ ₄ SE ¹ ₄ sec. 16

Appendix III--continued

<u>Sample no.</u>	<u>Mine name</u>	<u>Location</u>
1034E		NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 14
1035E	Lucky Cuss mine	NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 14
1036E	Luck Sure mine	SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 14
1037E	Dry Hill mine	NE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 15
1038E	Oregon mine	NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 15
1039E	Prompter mine	NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 14
1040E	Telephone mine	NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 14
1041E	Contact mine	NW $\frac{1}{4}$ NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 15
1042E		E $\frac{1}{2}$ SW $\frac{1}{4}$ sec. 15
1043E		SE $\frac{1}{4}$ NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 15
1044E		SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 14
1045E		center SE $\frac{1}{4}$ sec. 14
1046E	Bunker Hill mine	NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 14
1047W		SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 15
1048E	Emerald mine	SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 14
1049E	Silver Plume mine	NW $\frac{1}{4}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 23
1050E	Side Wheel mine	NE $\frac{1}{4}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 23
1051E	Contention mine	SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
1052E		SE $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
1053E	Little Joe mine	NE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 14
1054E	Tombstone Extension mine	SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 13
1055E		NW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 13
1056E		NE $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 13
1057E		SE $\frac{1}{4}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 18, T. 20 S., R. 23 E.
1058E		SE $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 14
1059E		SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 13
1060E	Comet mine	NE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 23
1063W		SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 21
1064E		SE $\frac{1}{4}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 23
1065E		NW $\frac{1}{4}$ SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 23

Appendix III---continued

<u>Sample no.</u>	<u>Mine name</u>	<u>Location</u>
1066W		SW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 22
1067W		NE $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 22
1068E		NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 23
1069E		SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 22
1070E		SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 22
1071W		NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 27
1072W		SE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 27
1073E		NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 27
1076W		SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 32
2000W		N $\frac{1}{2}$ sec. 32
2001E	Silver Thread mine	NW $\frac{1}{4}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 12
2002E	Bass mine	NW $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
2003E	Tranquility mine	NE $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
2004E	Sulphurette mine	center SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
2005E		SW $\frac{1}{4}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 12
2006E	Northwest mine	SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 11
2007E	Goodenough mine	N $\frac{1}{2}$ SW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 11
2008E	Westside mine	NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
2009E	Toughnut mine	SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 11
2010E	Girard mine	NW $\frac{1}{4}$ NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
2011E	Old Guard mine	SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 11
2012E	Herschel mine	NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 11
2013E	Ingersol mine	SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 11
2014E		NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 9
2015W		SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 9
2016W	Merrimac mine	SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 9
2017W	State of Maine mine	NW $\frac{1}{4}$ sec. 16

Appendix III

Mine Dump Analytical Data

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Pb (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
1001W	30	200	480	250	6	7710,11050	7-6e-3
1002W	40	560	n.d.	840	3	6570, 8630	8-4b-2
1003W	35	350	n.d.	660	14	7620,13110	I-1g-1
1004W	2600	4600	31	12,000	578	7790,13310	I-2f-1
1005W	490	370	2	1600	125	7890,13710	I-3d-1b
1006W	2300	170	14	2400	390	8110,14180	I-4a-1
1007W	10	30	111	300	3	8100,13090	I-4g-2
1008W	2700	105	1	20	n.d.	7590,12510	M-1b-1e
1009E	12	34	n.d.	27	2	9890,12320	N-3c-5f
1010W	40	280	n.d.	220	9	8110, 9810	Q-4h-1
1012W	6900	2400	13	10,200	290	8100, 9660	U-4a-2a
1013W	10	40	6	70	n.d.	6830,12480	7-4b-3a
1014W	4400	140	104	242,000	1389	6500,11540	7-4d-1b
1015W	65	45	5	400	5	6860,11320	7-4e-1b
1016W	2900	7000	1	55,500	30	5750,10940	7-2f-1b
1017W	360	540	178	35,200	15	6050,10060	7-3g-2b
1018W	500	495	490	30,600	10	6200,10180	7-3g-3
1019W	2000	17,300	1	34,900	115	5800, 9890	7-2h-2b
1020W	1700	8400	n.d.	13,900	65	5870, 9280	8-2a-1b
1021W	8000	8300	n.d.	32,000	665	6200, 9000	8-3a-1b
1022W	730	2800	n.d.	11,800	250	5870, 8970	8-2b-1b
1023W	420	380	n.d.	3200	435	5890, 8820	8-2b-2b
1025W	1300	11,500	1	38,100	85	6310, 8570	8-3b-1b
1026W	510	6400	n.d.	10,100	80	6190, 8700	8-3b-2
1029E	11,800	63,000	28	39,300	684	11310,14460	G-1h-1b
1030W	610	300	100	6100	1350	9080,13810	I-9c-1b

Appendix III--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Pb (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
1031W	2500	5600	n.d.	21,100	205	9190,13610	I-10d-1b
1032W	410	15,600	n.d.	4600	596	9200,13300	I-9f-1b
1034E	1700	11,600	7	32,400	50	10640,13890	J-7c-2b
1035E	2700	36,800	n.d.	7000	470	10460,13910	J-6c-2b
1036E	2400	19,600	n.d.	2100	435	10410,13710	J-6d-1b
1037E	590	4800	n.d.	1100	390	9710,13480	J-2e-1b
1038E	430	10,700	n.d.	900	65	10240,13480	J-5e-1b
1039E	1200	10,300	n.d.	5200	370	10430,13430	J-6e-2b1
1040E	2400	29,000	n.d.	9400	825	10770,13490	J-8e-2b
1041E	13,800	9500	n.d.	5100	586	9890,13380	J-3f-1b
1042E	5500	28,200	n.d.	17,000	390	9780,13310	J-3f-2b
1043E	670	5000	n.d.	5500	100	10020,13380	J-4f-1b
1044E	4200	17,100	n.d.	7500	425	10680,13270	J-7f-1b
1045E	1800	27,500	n.d.	8900	320	11080,13300	J-9f-1b
1046E	2700	38,500	n.d.	8800	200	11180,13360	J-10f-1b
1047W	1200	300	6	700	105	9600,13090	J-2g-1b
1048E	13,600	41,900	n.d.	94,500	330	10800,13200	J-8g-1b
1049E	240	5400	n.d.	2500	25	10710,12980	J-8h-1b
1050E	220	3300	n.d.	900	165	10790,12920	J-8h-2b
1051E	325	4700	10	2200	45	11210,14090	K-1b-1b
1052E	280	14,400	2	5600	60	11310,14100	K-2b-1b
1053E	530	1400	3	33,200	90	11210,13910	K-1c-2b
1054E	2300	16,700	6	139,000	285	12190,13780	K-6d-1b
1055E	630	4100	24	149,000	105	11360,13250	K-2f-1b
1056E	4900	158,000	n.d.	38,400	360	11580,13250	K-3f-1b
1057E	285	4600	8	6400	15	12600,13320	K-8f-1b
1058E	3600	18,000	n.d.	13,400	195	11290,13050	K-1g-2b
1059E	3400	95,000	4	29,800	515	11910,13170	K-5g-1b

Appendix III--continued

<u>Sample number</u>	<u>Cu (ppm)</u>	<u>Zn (ppm)</u>	<u>Mo (ppm)</u>	<u>Pb (ppm)</u>	<u>Ag (ppm)</u>	<u>Coordinates (east,north)</u>	<u>Field number</u>
1060E	2500	38,500	n.d.	14,100	415	11310,12880	K-2h-1b
1063W	610	4200	n.d.	1900	35	9200,12090	M-10d-1b
1064E	1600	7400	n.d.	3600	225	11000,12820	N-9a-2b
1065E	930	19,000	n.d.	6400	100	109,0,12690	N-9a-3b
1066W	5700	90,500	42	46,000	515	9420,12090	N-1d-1b
1067W	1100	8300	n.d.	18,100	620	9530,12160	N-1d-2b
1068E	175	1400	16	1600	25	10800,12460	N-8b-1
1069E	350	27,800	23	67,500	470	9900,12110	N-3d-3
1070E	370	18,700	n.d.	23,700	75	10210,12150	N-5d-1b
1071W	130	29,100	n.d.	6500	20	9780,11890	N-3f-1
1072W	390	4700	1	6700	200	9770,11800	N-3f-2b
1073E	2000	25,600	11	39,200	85	10020,11280	N-4h-1b
1076W	930	10,100	16	14,900	50	8020,10180	Q-3f-1b
2000W	3245	3000	n.d.	3150	362	7880,10890	Q-3c-1a
2001E	310	9700	18	12,000	132	11400,14500	G-2h-1
2002E	9400	15,500	1	8500	375	10990,14300	J-9a-1a
2003E	1900	46,000	1	10,500	50	11250,14340	K-1a-1a
2004E	920	21,700	1	14,500	75	11150,14190	K-1a-3
2005E	11,300	2800	63	52,000	115	11360,14310	K-2a-1
2006E	1500	1300	3	11,000	195	10870,14600	F-8g-1
2007E	7500	17,000	14	18,000	400	11010,14690	F-9g-4a
2008E	3900	5400	6	8000	305	10920,14480	F-9h-1
2009E	5500	500	40	7500	205	11080,14590	F-10g-1a
2010E	585	1700	1	12,500	405	11090,14500	F-10h-2a
2011E	445	22,000	2	4500	300	10490,14130	J-6b-2a
2012E	220	800	n.d.	4500	50	10530,14290	J-7a-3
2013E	3300	25,000	1	15,000	150	10680,14280	J-7a-4
2014W	85	21,500	n.d.	3000	10	8390,14410	6-g7-2
2015W	780	4600	n.d.	7000	200	8700,14300	6-g8-1
2016W	695	4500	n.d.	5200	500	8830,14230	6-g8-3a
2017W	366	1015	16	35,308	133	8570,13710	I-6d-1

Appendix IV

Appendix IV contains a complete listing of the calculated mine dump ratio values. These values were calculated by using the ratio equations in Chapter V, and the analytical data in Appendix III.

Appendix IV
Mine Dump Ratio Values

<u>Sample number</u>	<u>Cu ratio</u>	<u>Zn ratio</u>	<u>Mo ratio</u>	<u>Pb ratio</u>	<u>Ag ratio</u>
1001W	5.8	6.6	12.6	6.7	7.1
1002W	8.3	9.6	8.8	9.9	9.3
1003W	8.1	9.2	8.6	9.5	10.1
1004W	8.4	8.6	9.6	9.1	10.1
1005W	8.5	8.3	9.1	9.0	10.4
1006W	8.6	7.5	9.5	8.6	10.3
1007W	6.0	6.4	12.2	7.4	7.4
1008W	10.4	8.4	9.5	7.8	7.4
1009E	8.5	9.0	9.6	8.9	10.1
1010W	8.4	9.3	8.8	9.2	10.1
1012W	9.1	8.6	9.4	9.3	10.0
1013W	7.2	7.8	11.7	8.1	7.2
1014W	8.0	6.5	9.4	10.0	9.6
1015W	8.0	7.9	10.7	8.9	9.0
1016W	8.6	9.0	8.2	10.6	8.7
1017W	7.2	7.4	10.7	9.3	7.8
1018W	7.0	7.0	11.2	8.8	7.3
1019W	8.5	9.5	8.2	10.0	9.3
1020W	8.8	9.6	7.5	9.9	9.4
1021W	8.9	8.9	6.9	9.6	10.1
1022W	8.3	8.9	7.4	9.6	10.2
1023W	7.9	7.9	7.3	8.9	11.0
1025W	8.3	9.4	8.2	10.2	9.2
1026W	8.3	9.5	7.6	9.8	9.7
1029E	8.8	9.6	9.2	9.4	9.7
1030W	7.4	7.1	9.8	8.4	10.1
1031W	8.7	9.1	7.3	9.9	9.8
1032W	7.7	9.3	7.1	9.1	10.4
1034E	8.5	9.4	9.1	10.1	9.0
1035E	8.5	9.8	7.0	8.9	10.0
1036E	8.6	9.6	7.2	8.5	10.3
1037E	8.1	9.1	7.3	8.4	10.8
1038E	8.4	10.1	7.7	8.7	9.7
1039E	8.4	9.4	7.3	9.0	10.3
1040E	8.3	9.5	6.9	8.9	10.3
1041E	9.3	9.1	7.1	8.8	10.3
1042E	8.8	9.7	7.0	9.4	9.9
1043E	8.5	9.5	7.7	9.5	9.9
1044E	8.8	9.5	7.1	9.1	10.2
1045E	8.4	9.8	7.2	9.2	9.9
1046E	8.6	10.1	7.2	9.2	9.6
1047W	8.8	8.2	9.7	8.6	10.1
1048E	8.9	9.5	6.7	10.0	9.3
1049E	8.4	10.0	8.0	9.5	9.5
1050E	8.0	0.3	7.7	8.7	10.6

Appendix IV--continued

<u>Sample number</u>	<u>Cu ratio</u>	<u>Zn ratio</u>	<u>Mo ratio</u>	<u>Pb ratio</u>	<u>Ag ratio</u>
1051E	8.2	9.4	9.9	9.1	9.4
1052E	8.0	10.0	8.9	9.4	9.4
1053E	8.1	8.5	8.8	10.4	9.4
1054E	8.1	9.0	8.5	10.4	9.2
1055E	7.5	8.3	9.2	10.6	8.8
1056E	8.3	10.3	6.6	9.3	9.3
1057E	8.1	9.5	9.8	9.6	8.9
1058E	8.8	9.7	7.3	9.5	9.7
1059E	8.3	10.0	8.3	9.3	9.6
1060E	8.5	9.7	7.1	9.3	10.0
1063W	8.8	9.8	8.0	9.4	9.7
1064E	8.7	9.4	7.5	9.1	10.2
1065E	8.4	10.0	7.4	9.3	9.6
1066W	8.4	9.8	9.3	9.4	9.4
1067W	8.1	9.0	7.0	9.4	10.4
1068E	7.9	8.8	10.5	8.9	9.1
1069E	7.3	9.3	9.2	9.8	9.6
1070E	7.9	9.8	7.3	9.9	9.2
1071W	7.5	10.5	7.4	9.3	8.7
1072W	8.1	9.2	8.5	9.4	10.2
1073E	8.4	9.6	9.2	9.9	9.0
1076W	8.3	9.4	9.7	9.7	9.1
2000W	8.9	8.8	7.3	8.9	10.6
2001E	7.8	9.3	9.7	9.5	9.5
2002E	9.2	9.4	8.1	9.1	10.0
2003E	8.5	10.4	8.2	9.3	8.9
2004E	8.3	10.0	8.4	9.7	9.3
2005E	8.9	8.3	9.9	9.8	8.9
2006E	8.6	8.6	9.0	9.6	10.1
2007E	8.9	9.3	9.2	9.4	9.9
2008E	8.9	9.0	9.1	9.2	10.1
2009E	8.9	7.8	10.1	9.1	9.6
2010E	8.0	8.4	8.2	9.4	10.5
2011E	7.9	9.8	8.5	8.9	10.0
2012E	8.3	8.9	8.0	9.9	9.9
2013E	8.8	9.9	8.2	9.5	9.5
2014W	7.5	10.7	7.6	9.1	8.6
2015W	8.4	9.2	7.5	9.4	10.2
2016W	8.1	8.9	7.2	9.0	10.7
2017W	7.7	8.2	9.5	10.1	9.4

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