UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology and gold deposits of the Oatman District Northwestern Arizona

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Open-File Report 86-0638

1986

This report is preliminary and has not been reviewed for conformity with U.S Geological Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

Location

The Oatman mining district, centered near the town of Oatman in the Black Mountains of Arizona, is about 32 km southwest of Kingman, Arizona, and 38 km northeast of Needles, California (fig. 1; all figures and tables are at end of report). In the past the district has been referred to as the Gold Road, Vivian, Boundary Cone, and Oatman districts. The Union Pass or Katherine district (Keith, Gest, and others, 1983; Keith, Schnabel, and others, 1983) is 20 km northwest of Oatman and contains deposits similar to those in the Oatman district, but it will not be described in this report.

History

Gold was discovered in the Oatman and Union Pass districts in 1863 by army personnel stationed along the Colorado River west of Oatman at Camp Mohave (Schrader, 1909; Ransome, 1923). The first production from the Oatman district was by John Moss from the Moss vein in 1863-1864. After a nonproductive period beginning about 1870, gold was found in the Gold Road vein during 1902-1903. In 1915 the rich orebody of the United Eastern mine on the Tom Reed vein was located and produced gold ore until 1924 (Clifton and others, 1980). Nearly all production from the Oatman district had ceased by 1943; only sporadic, small-scale leach operations and re-processing of mine tailings has continued to the present.

Production

Schrader (1909) and Ransome (1923) listed more than 85 mines in the Oatman district. The largest and most famous of these have been the Gold Road, Tom Reed, and United Eastern mines. Total production from the district, based on data of Wilson and others (1967) and unpublished yearly totals, has been estimated by Clifton and others (1980) at 3.8 million tons of ore that yielded 2.2 million oz (troy) of gold and 0.8 million oz (troy) of silver. Unpublished data from the Arizona Bureau of Geology and Mineral Technology credits the Oatman district with 3.9 million tons of ore that yielded 1.98 million oz of gold and 1.15 million oz of silver. If production data from the Union Pass district are included with those from the Oatman district, the Oatman area has produced 4.5 million tons of ore containing 2.07 million oz of gold and 1.51 million oz of silver. Only very minor amounts of base metals, chiefly copper, have been recovered from the gold-silver deposits of the Oatman district.

Reserves

Large-scale gold mining ceased in the Oatman area in 1943, due partly to exhaustion of ore and partly to government restrictions on gold mining during World War II. Despite past exploration in the area by numerous companies, no major production has come from the Oatman or Union Pass districts since 1943. However, reserves calculated from drill hole data are 200,000 tons averaging 0.2 oz per ton gold at the United Eastern mine in the Oatman district, and 300,000 tons averaging 0.1 oz per ton gold at the Tyro mine and 20,000 tons averaging 0.2 oz per ton gold at the Frisco mine in the Union Pass district (P. W. Durning (Fischer-Watt Mining Co.) and L. H. Knight (Hecla Mining Co., written commun., 1983).

Similar Deposits

The ore deposits of the Oatman area are gold-bearing quartz-calcite veins which occupy fault fissures in Tertiary volcanic rocks. The vein mineralogy (Lausen, 1931), temperatures of formation (Clifton and others, 1980; Smith, 1984), and restricted vertical range of the ore bodies suggest that they are epithermal in nature and are similar to Tertiary epithermal gold-bearing deposits at Tonopah, Nevada, Guanajuato, Pachuca Real del Monte, and Tayoltita, Mexico, and Cripple Creek and Creede, Colorado. Because of their virtual lack of base-metal minerals, extremely low pyrite content, and simple electrum mineralogy, the veins of the Oatman district most closely resemble those at Goldfield and at Jarbidge, Nevada (Buchanan, 1981; Ashley, 1979).

GEOLOGIC SETTING

The gold-bearing veins of the Oatman district (fig.2) are localized in mid-Tertiary volcanic rocks and associated hypabyssal stocks (Ransome, 1923; Lausen, 1931). Most of the volcanic and plutonic rocks are of late Oligocene to early Miocene age, about 30 to 15 Ma. Stratigraphic descriptions are from Thorson (1971), slightly modified by Clifton and others (1980) and by this study. Chemical data are from Ransome (1923), Wells (1937), Thorson (1971), and Conoco Minerals Company (unpub. data, 1985). A summary of the major element chemistry is presented in table 1.

Rock names used in this paper are based on the chemical classification of De la Roche and others (1980) and are listed in table 2. Even though a rock unit may have a formal name such as the Esperanza Trachyte (Ransome, 1923), the Esperanza will be referred to as a quartz latite in the text because of its major element chemistry and position on the De la Roche grid (fig. 3).

The volcanic and plutonic rocks at Oatman, with the exception of the youngest basalt flows, appear to be a cogenetic suite characterized by a distinct chemistry. All units are metaluminous (Shand, 1927) except for a few rocks from the Antelope Quartz Latite and the Alcyone Formation. Considered together, the units form an alkali-calcic suite with a Peacock (1931) index of SiO_2 = 55-58. In terms of combined Na_2O + K_2O (fig. 4A) the suite straddles the alkalic/subalkalic boundary used by Anderson (1983). All the units except the youngest basalt are high-K rocks (Peccerillo and Taylor, 1976) as shown in figure 4B and resemble shoshonites as defined by Morrison (1980). Most of the subalkalic units have Fe/Fe+Mg typical of magnesium-rich suites (Miyashiro, 1974), and most alkalic units have Fe/Fe+Mg typical of iron-rich suites (table 2).

Volcanic and volcaniclastic rocks

The oldest volcanic rocks of the Oatman area (fig. 2) are unnamed basalt flows and basaltic volcaniclastic rocks that unconformably overlie metasedimentary schist and metaplutonic gneiss of Precambrian X age and younger coarse-grained Katherine granite of Precambrian X or Y age.

The Alcyone Formation, a succession of tuffs, flows, sedimentary tuff breccias, welded tuffs, and landslide breccias, unconformably overlies the unnamed basaltic units and is present throughout the western part of the Oatman area. The lower and middle welded tuffs are iron-rich alkalic quartz trachyte (De la Roche and others, 1980) that have low calcium and high potassium contents, whereas the upper lava flows and plugs are subalkalic quartz latite. The tuffs and flows form distinctly bimodal groups on plots of major element chemistry (figs. 3, 4A and B) and trace element chemistry (figs.

5A and B). Welded tuffs and flows consist of 65 percent groundmass and 35 percent phenocrysts of sanidine, plagioclase, biotite, and minor pyroxene and quartz. The Alcyone is 450 to 730 m thick and shows local thickening in an inferred volcanic depression centered about 8 km northwest of Oatman.

A group of three units, the 'middle volcanics' of Thorson (1971), unconformably overlies the Alcyone Formation. From bottom to top, these units are the Esperanza Trachyte, Oatman Latite, and Gold Road Latite. The Esperanza is an alkalic quartz latite lava flow, or flows, that contains an average of 10 percent phenocrysts, predominantly plagioclase and biotite. The Esperanza is found only to the south of Oatman, from near the ghost town of Old Trails to south of Boundary Cone, (fig. 2) and ranges in thickness from 60 to 300 m.

The Oatman Latite is perhaps the most well-known rock unit in the area, as it hosts many of the gold-bearing veins of the district. The Oatman ranges in composition from a dacite to an andesitic basalt (fig. 3), but averages a subalkalic latitic andesite (table 2). It has been variously referred to as a latite (Thorson, 1971) or an andesite (Ransome, 1923; Lausen, 1931). The unit is composed of flows, tuffs, and flow breccias. A typical rock consists of 55 percent groundmass and 45 percent phenocrysts of plagioclase (An_{44-47}), orthopyroxene, and clinopyroxene. The Oatman overlies the Alcyone north of Old Trails, and thins markedly to the south away from the Tom Reed and Gold Road mines (fig. 2), where it is estimated to be 300 m thick (Clifton and others, 1980).

The Gold Road Latite conformably overlies the Oatman Latite and is composed of lithic ash beds, vent breccias, and flows. Most of the productive mines that are not in the Oatman Latite are in the Gold Road Latite. The Gold Road ranges from subalkalic to alkalic dacite. The lower part contains 30 percent phenocrysts of plagioclase (An_{40-47}), clinopyroxene, orthopyroxene, and minor amounts of quartz, biotite, and potassium feldspar; the upper part averages 40 percent of the same phenocrysts, but no quartz is present. The Gold Road attains a maximum thickness of 240 m, although Thorson (1971) suggested that it may have been as much as 900 m thick before erosion and deposition of the upper volcanics.

Considered as a co-magmatic group, the middle volcanics have a Peacock index of 57 and are magnesium-rich (table 2). They have anomalously high strontium and rubidium concentrations (fig. 5) as compared to high-K, calc-alkalic andesites and dacites (Gill, 1981).

The upper volcanics of Thorson (1971) unconformably overlie the middle volcanics and contain vein and fault-vein systems similar to the middle volcanics, but do not host any gold deposits in the Oatman area. From bottom to top, the upper volcanics consist of the dominantly volcanic Antelope Quartz Latite, Cottonwood Formation, Flag Spring Trachyte, and Meadow Creek Trachyte, and the dominantly volcaniclastic Sitgreaves Tuff, which is temporally equivalent to all the upper volcanic units.

The Antelope Quartz Latite and Cottonwood Formation are flows and domes of subalkalic rhyodacite to rhyolite, and rhyolite to alkali rhyolite, respectively (fig. 3). Both the Antelope and Cottonwood contain approximately 70 percent groundmass and 30 percent phenocrysts, the phenocrysts being dominantly plagioclase (An_{29-34} in Antelope), biotite, potassium feldspar, quartz, hornblende, and minor clinopyroxene and orthopyroxene. Both units have high rubidium contents; the Cottonwood has anomalously high strontium contents (fig. 5).

The Flag Spring Trachyte and Meadow Creek Trachyte are iron-rich, alkalic to subalkalic quartz latite flows, agglomerates, and flow breccias that compositionally resemble the Esperanza Trachyte (figs. 3, 4A and B). Both units contain 15 to 25 percent phenocrysts of plagioclase, biotite, and minor hornblende. Both units have very high strontium contents and appear to be transitional in chemistry between the middle volcanics and the Antelope and Cottonwood.

The Sitgreaves tuff is one of the few dominantly volcaniclastic units in the area. It contains much conglomerate and air-fall tuff, and many lithic fragments from the upper volcanics.

The upper volcanics are unconformably overlain by flat-lying to very gently east-dipping basalt flows and interbedded white conglomerate and rhyolitic ash. The entire sequence is as thick as 300 m. Phenocrysts in the basalt are plagioclase, olivine, and clinopyroxene. The basalt and rhyolite belong to a low-K suite that is probably younger and unrelated to the underlying high-K suite.

Regional Correlations

Thorson (1971) correlated the middle and pre-middle volcanic rocks in the Oatman area to the Patsy mine Volcanics (Longwell, 1963) in the Eldorado Mountains of Nevada, 85 km northwest of Oatman. The upper volcanics were correlated to the Golden Door Volcanics of Longwell (1963) in the Eldorado Mountains, and the capping olivine basalt was correlated to the Fortification basalt near Lake Mead (Thorson, 1971). Anderson (1978) slightly modified the correlations and suggested that the middle and pre-middle volcanic rocks in the Oatman area may be temporally equivalent to the lower part of the Patsy mine Volcanics, and that the upper volcanics were temporal equivalents of the middle part of the Patsy mine Volcanics. Anderson and others (1972) and Anderson (1978) suggested that the two areas contain no truly correlative rock units, inasmuch as the volcanic suites in the two areas, although chronologically and chemically similar, may have evolved separately. Tertiary volcanic rocks of similar chemistry were noted by Otton (1982) in the Date Creek basin, 130 km southeast of Oatman.

Intrusive Rocks

Two small stocks and a series of dikes intrude the volcanic rocks in the Oatman area. The Moss Porphyry is a north-northwest-elongate stock, 3 by 6 km, that intrudes the Alcyone Formation, Gold Road Latite, and Oatman Latite north of Silver Creek (fig. 2). The Times Porphyry is a roughly triangular-shaped laccolith that intrudes the Alcyone and is in fault contact with the Oatman south of Silver Creek and northwest of Oatman. Rhyolite and rhyolite porphyry dikes and small plugs intrude volcanic units as young as the upper flows in the Cottonwood; in the Oatman area they are localized along the same fractures as the northwest-trending gold-bearing veins and fault-veins. Boundary Cone and Elephant's Tooth (fig. 2), two prominent landmarks in the Oatman area, are volcanic necks composed of rhyolite porphyry.

The Moss Porphyry is a concentrically zoned stock with an outer monzodiorite border, an inner porphyritic tonalite to quartz monzonite margin, and a central tonalite-granodiorite core. The modal average (Streckeisen, 1973) of the core phase is monzogranite (table 2). Both porphyritic margin and core have the same mineralogy and are composed of plagioclase (An_{29-32} and An_{40-50} respectively), potassium feldspar, quartz, biotite, and minor amounts of clinopyroxene and orthopyroxene. The Moss Porphyry is subalkalic to slightly alkalic, and, in terms of Fe/Fe+Mg, is magnesium-rich. By virtue of its major element composition, the Moss most closely resembles the Gold Road Latite; its rubidium and strontium contents are intermediate between the middle volcanics and the upper volcanics.

The Times Porphyry is a reversely zoned granophyric laccolith with a highly siliceous border and a less siliceous core. Both border and core are subalkalic granite-alkali granite that have a similar mineralogy of potassium feldspar, quartz, plagioclase (An_{21}), biotite, and minor hornblende. Modal averages indicate the Times is a syenogranite (fig. 2). The Times most closely resembles alkali rhyolite of the Cottonwood in both major and minor element chemistry.

The rhyolite and rhyolite porphyry dikes, sills, and necks such as Boundary Cone and Elephant's Tooth have compositions similar to the Times Porphyry, but with extremely high K_2O contents (7-9 percent). This K_2O enrichment is probably the result of hydrothermal alteration associated with quartz-calcite-adularia veins which parallel the rhyolite bodies and locally cut them.

Initial strontium isotope ratios have been determined for the Oatman Latite and the Moss Porphyry (table 3). Both units have high initial ratios ($^{87}Sr/^{86}Sr_0$) that average 0.7106, indicating a crustal contaminant in the magmas or derivation of the magmas from Proterozoic crustal material. This contamination or derivation from a source region in the crust is consistent with the shoshonitic geochemistry of the Tertiary volcanic and plutonic rocks.

Age of the Stratified and Intrusive Units

Conventional K-Ar dates (Thorson, 1971) have been determined for two units in the volcanic sequence, the Gold Road Latite and the Antelope Quartz Latite (table 3). All dates have been recalculated with the decay constants recommended by Steiger and Jaeger (1977). Biotite from the Gold Road yields a date of 18.6 ± 0.9 Ma and biotite from the Antelope is 19.2 ± 0.9 Ma. Conventional K-Ar dates have also been determined by Thorson for the Moss Porphyry and Times Porphyry. Hornblende from the Times has a K-Ar date of 23.1 ± 1.8 Ma (DeWitt, unpub. data, 1986, reanalyzed this hornblende using the $^{40}Ar/^{39}Ar$ technique and obtained a plateau date of 18.8 ± 0.1 Ma) and biotite from the Moss has a date of 10.7 ± 0.5 Ma.

The dates from the Gold Road and Antelope overlap within analytical uncertainty and indicate that the volcanic units beneath the Antelope are older than about 19 Ma. The Alcyone Formation is intruded by the Times Porphyry and therefore must be older than about 18.8 Ma. Basalt flows beneath the Alcyone are undated, but are presumed to be of Miocene-Oligocene age. The 10.7 Ma biotite date from the Moss Porphyry should be interpreted only as a minimum age for the Moss, as the retention temperature of argon in biotite (~225° C) is much lower than the emplacement temperature of the pluton. If the Moss is temporally related to the Gold Road Latite, as its major and minor element chemistry suggests, the age of the pluton is probably about 20 Ma.

In order to more precisely determine the age of the volcanic and plutonic rocks, zircon from the Times and Moss Porphyries was dated by the U-Th-Pb method (table 4). Three nonmagnetic zircon fractions from the Moss have discordant dates and define a discordia with a lower intercept of 18.6 ± 4 Ma and an upper intercept of 1673 ± 36 Ma (York, Model 1 solution; uncertainties are 95% confidence limits). The analyzed zircon contain minute inclusions of dark, rounded zircon of presumed Proterozoic age. The discordia is thus interpreted as a mixing line between inherited Proterozoic zircon and new

Early Miocene zircon that crystallized during emplacement of the Moss Porphyry. The 18.6 ± 4 Ma crystallization age of the Moss is further substantiated by the $^{208}Th/^{232}Pb$ date of 20.9 Ma for the -400 mesh size fraction. Zircon from this size fraction is very thorium rich (U/Th ratio about 0.5) as compared to most zircon (U/Th about 2-4). Therefore the young thorogenic lead overwhelms the inherited Proterozoic thorogenic lead and the Th-Pb date is approximately the same as that derived from the lower intercept with concordia.

Dates of the finest-grained zircon available from the Times Porphyry are much more discordant than those from the Moss Porphyry, and hence a lower intercept defined by more than one point was not attempted. If the 1670 Ma upper intercept date of the Moss is used and a discordia is projected through the zircon from the Times, the lower intercept is about 18 Ma.

Ransome (1923) and Lausen (1931) considered the Moss to be older than the Times. Thorson (1971) cited intrusive relations and chemical trends as evidence that the Times was genetically related to the Alcyone Formation and was older than the Moss. The U-Th-Pb dating of the Moss and Times porphyries and the $^{40}Ar/^{39}Ar$ dating of the Times reported above indicates that both are about 18 to 19 Ma. The large component of Proterozoic zircon (and hence, radiogenic lead) in both porphyries and the saddle-shaped spectra of the reanalyzed hornblende of the Times Porphyry suggests that small amounts of excess argon (inherited from Proterozoic source material) are present in the amphibole dated as 23.1 ± 1.8 Ma by Thorson (1971). Whether or not the Times Porphyry is younger than the Moss Porphyry is not completely resolved.

Major and minor element chemistry, K-Ar dates, and field relations suggest four major volcanic-plutonic episodes: 1) eruption of the subalkalic to alkalic lavas of the Alcyone Formation in a volcanic depression; 2) eruption of the alkalic to subalkalic lavas of the Esperanza, Oatman, and Gold Road, and their intrusion by the comagmatic Moss Porphyry; 3) eruption of the subalkalic lavas of the Antelope and Cottonwood, intrusion of the Times Porphyry, and late emplacement of rhyolite dikes, plugs, and necks. The spatially associated Meadow Creek and Flag Spring Trachytes have chemical affinities to the Esperanza Trachyte of the older volcanic units and are interpreted as the last activity of the second episode. Ore deposition appears to have been a late feature associated with the third episode, especially the emplacement of rhyolite dikes and plugs; 4) late covering of all older units by olivine basalt and local rhyolite tuff units.

Regional Structure

In general, the oldest Tertiary volcanic rocks in the Black Mountains are exposed west of Oatman and successively younger rocks are exposed to the east. However, the Oatman and Gold Road Latites may be exposed on the far east side of the Black Mountains (fig. 2), indicating a synclinal structure paralleling the range crest. All volcanic units have a regional N20°W strike, with older units dipping 20-35° east and the youngest units being virtually flat-lying. Emplacement of the Times Porphyry has locally domed the Alcyone Formation. Northwest- to north-northwest-trending faults with moderate displacement cut the volcanic units. These faults are closely spaced and numerous in the Oatman area where they contain the gold-bearing vein deposits. A caldera related to the Alcyone volcanism has been proposed by Thorson (1971), but the vein deposits do not appear to be spatially or temporally related to it. Radially and concentrically oriented fracture sets in the Oatman area were noted by Clifton and others (1980), with the vein deposits being restricted to the radial set.

ORE DEPOSITS

Structure

The gold-bearing ore bodies in the Oatman district are localized along northwest-trending veins, faults, and combinations of the two (fig. 6). The ore bodies are located in dilatant zones of the vein-fault system that have formed by minor lateral slip along gently curving fault planes (Clifton and others, 1980). The deposits vary from fissure quartz veins with definite walls, through quartz-calcite stringer zones, and faulted and brecciated quartz veins, to gouge zones with only minor quartz-calcite vein filling. Veins in the Gold Road Latite commonly are more distinct, less sheared, and thinner than those in the Oatman Latite which are commonly stockworks of veins and country rock. The strikes of the veins and faults range from N75°W to N15°W, and the dips range from 50°NE to vertical, although dip reversals to the southwest are noted on the northwest ends of many veins. Most of the large mines are within a 10 by 6 km area approximately centered about Oatman, but gold-bearing veins are noted from the Moss mine in the north to south of Boundary Cone, a distance of 19 km (fig. 2). The vein and fault systems cut all the volcanic and plutonic units with the exception of the youngest basalt, but the majority of large mines are located in the Oatman and Gold Road units.

Deposits in two major structures, the Tom Reed vein and the Gold Road vein, have produced about 90 percent of the gold from the Oatman district. Only 2 ore bodies were exposed at the surface, one on the Gold Road vein, and one on the Tom Reed vein, but at least a dozen or more major ore bodies were discovered 15-150 m below the surface (Clifton and others, 1980). The Tom Reed vein occupies the Tom Reed fault, which has 120 m of normal displacement, all within the Oatman Latite (Ransome, 1923). The vein extends for at least 4.5 km, but major production was from a 3.5 km-long segment centered near Oatman. This segment contained 4 rather continuously-mineralized sections, each separated by barren sections along the vein. From north to south, the mineralized parts were 180 m, 730 m, 570 m, and 240 m long, indicating that half of the 3.5 km-long productive segment was of ore grade. Ore bodies within these mineralized parts averaged 130 m along strike, but ranged from 60 to 570 m. The ore bodies varied from 1 to 14 m in width and averaged about 4.5 m. The mined vertical interval ranged from 45 to 390 m and averaged 175 m.

The Gold Road fault is traceable for about 2.9 km, and has a maximum normal displacement of 90 to 120 m at its northwest end (Lausen, 1931). The fault is within Gold Road Latite at the surface, but juxtaposes Oatman Latite and Gold Road Latite in the subsurface; the fault trends northwest and dips 80-85° NE. The mineralized part of the Gold Road vein was at least 2 km long, and the ore-grade segment was nearly continuous for a distance of 1.6 km. Ore bodies within the Gold Road Latite averaged 1-2 m wide, but those in the Oatman Latite widened to nearly 7 m. Most of the ore bodies were exposed at the surface and extended to less than 370 m depth; their average vertical dimension was 190 m. The average strike length of ore bodies in the Gold Road vein was 320 m, notably longer than those in the Tom Reed vein.

Clifton and others (1980) and Buchanan (1981) noted that gold mineralization was restricted to a vertical dimension which is everywhere less than 310 m, and commonly averages 180 m. On a district scale, both bottom and top of this mineralized zone are concave downward. The center of this inverted saucer-shaped zone is midway between the United Eastern and Gold Road Mines (Clifton and others, 1980, figures 17, 18, and 19), and has a maximum relief of 240 m on the top of the zone and 180 m on the bottom. Therefore the maximum mineralized vertical dimension is greatest in the center of the zone (~350 m) and decreases outward to 120 m or less.

Wallrock Alteration

Ransome (1923) noted the alteration of feldspar to aggregates of calcite, quartz, and sericite, of biotite to chlorite, and of augite to calcite, plus the introduction of pyrite in wallrocks near many of the gold-bearing veins, but did not study the alteration in detail. Lausen (1931) noted kaolin as an alteration product of plagioclase, and calcite, quartz, and chlorite as products of the general breakdown of the groundmass of many flow units. He also remarked on the lack of secondary sericite next to many veins, suggesting that potassium enrichment did not occur in the adjacent wallrocks. Clifton and others (1980) studied alteration patterns in the Oatman district in detail and indicated that propylitic alteration near vein systems was nearly ubiquitous and consisted of the development of the assemblage chlorite-pyrite-carbonate minerals-montmorillonite-illite. Propylitic alteration, however, is not a useful guide to ore, as the alteration occurred over and adjacent to both barren and productive veins. Silicification and minor introduction of adularia and albite along vein walls are noted in ore-bearing veins. Presence of adularia is suggested by Smith (1984) to be one of the better guides to ore. Another alteration guide to ore is the low-pH assemblage of illite-montmorillonite with or without sericite-kaolinite, which Buchanan (1981) and Clifton and others (1980) reported to overlie all productive vein systems in the Oatman area.

Alteration intensity and type of alteration vary along and between veins in the district. The Tom Reed-United Eastern vein system has a wide phyllic zone that is most extensively developed near ore bodies. Within the Gold Road vein system, alteration products are only poorly developed in the Gold Road Latite, but are more abundant above and below the latite. Many post-mineral faults are characterized by argillic alteration minerals (Clifton and others, 1980).

Propylitically altered rocks from the Gold Road mine analyzed by Schrader (1909) and from Boundary Cone reported by Wells (1937) indicate that major and minor element exchange has taken place during alteration. SiO_2, Al_2O_3, Fe_{total}, MgO, MnO, and TiO_2 in altered rocks are unchanged from the averages reported by Thorson (1971) for fresh rocks, but CaO, Na_2O, K_2O, and Sr have changed notably. K_2O content has more than doubled, whereas CaO and Na_2O have been reduced to less than half, and Sr to one-third, of their average original values. Many of these changes probably have been accomplished by conversion of plagioclase to adularia by potassium metasomatism.

Mineralogy

The ore and gangue mineralogy of the vein deposits is remarkably simple. Virtually the only ore mineral is electrum which assays about 650 fineness. Shrader (1909) suggested telluride minerals occurred in minor quantities. Trace amounts of pyrite, chalcopyrite, sphalerite, galena, and marcasite(?) are noted. Hypogene gangue minerals are quartz, varicolored calcite, adularia, chlorite, and minor fluorite. Pyrite is fairly common in wallrocks adjacent to the veins, but is nearly absent in the veins. Fluorite is noted only in small veins which cut the hypabyssal plutons and appears to be absent in the larger vein deposits in the volcanic rocks. Calcite has coarse-grained textures indicative of open-space filling during vein formation. Adularia is normally microscopic and quartz is fine-grained. Supergene gangue minerals include minor gypsum, pyrolusite, psilomelane, hematite, limonite, wulfenite and possibly minium (Lausen, 1931). Silver is known only in electrum, and wire gold has been reported only from minor oxidized zones.

Electrum is seen only in high grade veins where it normally occurs within quartz and less commonly in adularia or fluorite. Lausen (1931) found no electrum within calcite, and very little gold in pyrite concentrates from wallrocks adjacent to the veins. As much as 0.15 percent tellurium in electrum is noted from samples in the Gold Road vein (Smith, 1984). Gold-bearing quartz is characteristically a honey-yellow color and has an oily luster (Ransome, 1923; Lausen, 1931); the color is due to minute inclusions of chlorite (Lausen, 1931; Clifton and others, 1980), corrensite, and an unidentified magnesium-rich mineral (Smith, 1984).

Lausen (1931) distinguished five stages of vein filling that are determined by the color and texture of quartz and the ratio of gold to silver in associated deposits. He suggested that early, colorless to yellow quartz has Au:Ag of 1:6 to 2:3, and that late, pale green to honey-yellow quartz has Au:Ag of 1:2 to 4:1 and contains more gold and silver than early quartz. Smith (1984) determined that most of the commercially valuable ore was deposited during the fourth of Lausen's five stages, and was positively correlated with the amount of adularia. Most of the samples from veins in the Oatman area analyzed by Smith had Au:Ag of 1:2 to 1:6, but much lower ratios (from 1:10 to 1:100) were noted. In a sample from the Gold Road vein representing Lausen's fourth or fifth stage and containing 35 discrete mineralized bands, Smith determined that gold and silver concentrations decreased and Au:Ag decreased from older to younger bands. These trends for one stage of mineralization are opposite to the overall trends noted above for the district.

Age of Mineralization

A mixture of adularia and quartz(?) from the Kokomo vein has a K-Ar date of 21.2 ± 2.1 Ma (table 3). Because the sample is impure (potassium content of 2.56 percent), the date is only an approximation of the time of mineralization, but it suggests that vein formation was partly coincident with the age of emplacement of the middle and upper volcanic sequences and the Times Porphyry. Also, because veins cut the Moss Porphyry, which has a U-Pb zircon date of 18.6 ± 4 Ma and a K-Ar cooling date of 10.7 ± 0.5 Ma, mineralization is restricted to the time interval of about 22 to 11 Ma.

Trace Elements

Few trace element studies have been made in the Oatman area, but Durning (1980; written commun., 1982) states that, although a few anomalies do exist, gold, silver, copper, lead, zinc, mercury, arsenic, antimony, and molybdenum show no consistent patterns over the tops of productive ore shoots.

Gold-Silver Zonation

Both gold grades of the district and Au/(Au+Ag) have a crude zonal pattern characterized by a central high located over the Tom Reed vein system and lows on either side of the vein (fig. 7A and B). Gold grades (Arizona Bureau of Geology and Mineral Technology, unpub. data, 1982) along the Tom Reed system range from 0.19 to 0.97 oz per ton and have a weighted average of 0.699 oz per ton. By comparison, the weighted average for the Gold Road vein, northeast of the Tom Reed, is 0.307 oz per ton. The region of highest Au/(Au+Ag) trends northwesterly through the center of the district and approximately coincides with the high-grade zone, but it is not coincident with the zone. Near the center, Au/(Au+Ag) averages more than 0.700 and decrease on either side to less than 0.400 (less than 0.300 on the southwest; fig. 7B). This regional pattern also was noted by Smith (1984) from samples collected along various vein systems.

The coincidence of high gold grades and high Au/(Au+Ag) of a regional scale is not true at the deposit level (fig. 8). The three largest mines in the district, the Gold Road, Tom Reed, and United Eastern, have Au/(Au+Ag) of 0.628 to 0.658 , but range in gold grade from 0.307 to 0.912 oz per ton. Individual mines in the Oatman district had very constant Au/(Au+Ag) throughout their productive history, suggesting very little gold-silver zonation in the ore bodies, either vertically or laterally. The Gold Road mine during 22 years of production of greater than 1000 tons of ore a year had Au/(Au+Ag) of 0.524 ± 0.062. The Tom Reed for 23 years of production of greater than 1000 tons of ore averaged 0.609 ± 0.189. The United Eastern during 8 years of production of greater than 1000 tons of ore had Au/(Au+Ag) of 0.584 ± 0.108.

Because electrum is the only gold-bearing mineral in the district, the simple gold-silver zoning (fig. 7B) suggests a gold-rich central area flanked by silver-rich margins. For individual ore bodies, gold grade is independent of both Au/Au+Ag and tonnage mined. Because most of the ore bodies in the district were not exposed at the surface, supergene enrichment is not believed to have greatly affected the pattern of gold grade and Au/Au+Ag in figure 7.

Fluid Inclusion Thermometry and Gas Analyses

Fluid inclusions in quartz, calcite, and fluorite from the Tom Reed, Gold Road, and Kokomo veins indicate temperatures of formation of ~200-240° C (Clifton and others, 1980; Buchanan, 1981). Smith (1984) notes that primary fluid inclusions in quartz and calcite have homogenization temperatures of 205-255° C, and secondary inclusions have a wider range, 175-335° C. Homogenization temperatures for both types of inclusions are slightly higher for samples from veins in the central part of the district than for samples from peripheral veins. Inclusions from the Gold Road, Midnight, Kokomo, and Ben Harrison vein systems have a wide range of homogenization temperatures, suggestive of local boiling of the hydrothermal fluid. Salinities of the inclusions average 1.47 ± 0.03 wt % NaCl equivalent. All inclusions noted by Smith (1984) contain liquid water and water vapor, with only minor amounts of CO_2 vapor. Expansion of the vapor bubble during crushing tests on a sample from the Midnight vein indicates a minimum fluid inclusion trapping pressure of 65 bars.

Gases (primarily species of carbon and sulfur) within the fluid inclusions are both more reduced and have lower ratios of total carbon to total sulfur than gases in inclusions from other epithermal gold-quartz veins for which there is data (Smith, 1984). In fact, most of the gas data from Oatman samples more closely resemble data from porphyry copper deposits and associated epithermal base-metal deposits in Arizona. In a sample containing 35 mineralized bands from the Gold Road vein, the ratio of the amount of oxidized gases to reduced gases decreased from older to younger bands, which was interpreted by Smith (1984) to indicate that boiling was strongest during deposition of the older mineralized bands. On a district scale the ratio of oxidized gases to reduced gases was highest in the center of the district, suggesting that boiling was more likely to have occurred in the center where hydrothermal fluids were hottest and gold mineralization was most concentrated.

CONCLUSIONS

Distinguishing Characteristics

The gold-bearing quartz veins of the Oatman district are, in many respects, typical epithermal deposits associated with mid-Tertiary volcanic rocks. However, they are unusual for such deposits in the western United States because of their virtual lack of base-metal minerals, extremely low pyrite content, and low silver content. The district has an unusually high Au/Ag ratio (~1.7), comparable only to Goldfield and Round Mountain, Nevada (Buchanan, 1981).

Ore Controls

Ore controls in the Oatman district appear to have been 1) curved fault planes and resultant dilatant zones; 2) distance below the paleosurface of the dilatant zones; and 3) fractured nature of wallrocks that controlled the associated hydrothermal alteration. Clifton and others (1980) stressed the importance of curved fault planes that formed during deformation and created dilatant zones that filled with vein material. Ransome (1923) and Lausen (1931) noted the restricted vertical dimension of ore bodies, and Clifton and others (1980) pointed out the inverted saucer-shape of the ore horizon in the veins as viewed on a district scale. All workers who have studied Oatman noted the difference between low fracture density in the Gold Road Latite and high fracture density in the Oatman Latite. This fracture density correlates positively with the low gold grade of ore in the Gold Road Latite (Gold Road vein, average 0.307 oz per ton), and high gold grade of ore in the Oatman Latite (Tom Reed vein, average 0.699 oz per ton Au). A characteristic low-pH alteration assemblage structurally overlies most ore bodies (Buchanan, 1981). Most gold-bearing veins contain trace to major amounts of adularia (Smith, 1984), implying that the hydrothermal fluids moderately enriched in potassium caused the alteration and deposition of precious metals.

The most important ore control may have been the chemistry of the associated volcanic rocks rather than the factors cited above. As noted in the section on stratigraphy, the volcanic rocks at Oatman are products of an alkalic to subalkalic, high-K magma series and are similar in many respects to shoshonitic rocks of continental margins (Morrison, 1980). Characteristically, such volcanic rocks contain abnormally high amounts of potassium, rubidium, strontium, and barium. Potassium metasomatism, in the form of disseminated sericite and fine-grained adularia, noted in the veins of the district, may have been facilitated by the high potassium content of the magma series. Similar Tertiary epithermal gold-silver vein deposits at Eldorado Canyon, Nevada (Hansen, 1962; Longwell and others, 1965) are associated with subalkalic to alkalic, high-K volcanic rocks (Anderson, 1978). Gold-silver deposits at Round Mountain, Nevada are spatially associated with subalkalic rhyolite that has anomalously high strontium and barium contents and moderately elevated K_2O contents (D. R. Shawe, written commun., 1982) The gold veins at Goldfield, Nevada are likewise localized in Tertiary volcanic rocks with elevated K_2O contents and anomalously high strontium and barium contents (Ashley, 1979; written commun., 1982).

Origin

The vein deposits of the Oatman district are a late-stage product of early Miocene shoshonitic volcanism, and were formed during extensional tectonism about 15-20 Ma. The veins are localized along northwest-trending faults, many of which are subparallel to, or are occupied by late-stage rhyolite dikes. The veins cut most of the dikes, but the heat and fluid source for the veins is believed to have been genetically related to emplacement of the rhyolite. The veins were filled by gold-bearing quartz, calcite, and adularia at temperatures of 200-240^{o} C as a response to local fluid boiling and change in pH (Buchanan, 1981; Smith, 1984). The ore bodies occupy restricted vertical intervals in the vein that were limited on the bottom by the boiling interface and on the top by their depth below the paleowater table (Clifton and others, 1980). Gold and silver are believed to have been derived from the shoshonitic magma and concentrated in hydrothermal fluids related to emplacement of late-stage rhyolite bodies. Many structural features have controlled the localization of ore bodies within the vein system, but the ultimate control and source of the gold and silver may been the shoshonitic magma and derivative volcanic rocks.

ACKNOWLEDGMENTS

This paper was reviewed by L. J. Buchanan and W. P. Durning of Fischer-Watt Mining Co, who contributed much unpublished data to the authors, and by L. H. Knight and Mike Winston of Hecla Mining Company. Conoco Minerals Company contributed unpublished whole rock analyses and strontium isotope data. Ralph Christian, George Van Trump, Greg Green, Rebecca Stoneman, and Anna Burack Wilson aided with the computer graphics and analyses. Discussions with R. P. Ashley, S. B. Keith, W. A. Rehrig, D. R. Shawe, R. E. Wilcox, and R. T. Wilson greatly improved the content of the paper.

REFERENCES CITED

Anderson, J. L., 1983. Proterozoic anorogenic granite plutonism of North America, in Medaris, L. G. Jr., and others, eds., Proterozoic geology: selected papers from an international Proterozoic symposium, Geological Society of America Memoir 161, p. 133-154.

Anderson, R. E., 1978, Chemistry of Tertiary volcanic rocks in the Eldorado Mountains, Clark County, Nevada, and comparisons with rocks from some nearby areas: U.S. Geological Survey Journal of Research, v. 6, p. 409-424.

Anderson, R. E., Longwell, C. R., Armstrong, R. L., and Marvin, R. F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, v. 83, p. 273-288.

Ashley, R. P., 1979, Relation between volcanism and ore deposition at Goldfield, Nevada, in Ridge, J. D., ed., Papers on mineral deposits of western North America: Nevada Bureau of Mines and Geology Report 33, p. 77-86.

Buchanan, L. J., 1981, Precious metal deposits associated with volcanic environments in the southwest, in Dickinson, W. R., and Payne, W. D. eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. XIV, p. 237-262.

Clifton, D. G., Buchanan, L. J., and Durning, W. P., 1980, Exploration procedure and controls of mineralization in the Oatman mining district, Oatman, Arizona: Society of Mining Engineers of AIME preprint 80-143, 38 p.

De la Roche, H., Leterrier, J., Grandclaude, P., and Marchal, M., 1980, A classification of volcanic and plutonic rocks using R_1-R_2 diagram and major-element analyses--its relationships with current nomenclature: Chemical Geology, v. 29, p. 183-210.

Durning, Perry, 1980, Geology, alteration and mineralizatiion in the Oatman mining district, Mohave County, Arizona: unpublished text of talk presented to Arizona Geological Society meeting, August 1980.

Gill, J. B., 1981, Orogenic andesites and plate tectonics: New York, Springer-Verlag, 334 p.

Hansen, S. M., 1962, The geology of the Eldorado mining district, Clark county, Nevada: Columbia, University of Missouri, unpublished Ph.D. dissertation, 328 p.

Keith, S. B., Gest, D. E., DeWitt, Ed, Woode Toll, Netta, and Everson, B. A., 1983, Metallic mineral districts and production in Arizona: Arizona Bureau of Geology and Mineral Technolgy Bulletin 194, 58 p.

Keith, S. B., Schnabel, Lorraine, DeWitt, Ed, Gest, D. E., and Wilt, Jan, 1983, Map description, and bibliography of the mineralized areas of the Basin and Range Province in Arizona: U.S. Geological Survey Open-File Report 84-0086, 129 p.

Lausen, Carl, 1931, Geology and ore deposits of the Oatman and Katherine districts, Arizona: Arizona Bureau of Mines Bulletin 131, 126 p.

Longwell, C. R., 1963, Reconnaissance geology between Lake Mead and Davis Dam, Arizona-Nevada: U.S. Geological Survey Professional Paper 374-E, p. E1-E51.

Longwell, C. R., Pampeyan, E. H., Bowyer, Ben, and Roberts, R. J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines Bulletin 62, 218 p.

Miyahsiro, A., 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321-355.

Morrison, G. W., 1980, Characteristics and tectonic setting of the shoshonite rock association: Lithos, v. 13, p. 97-108.

Otton, J. K., 1982, Tertiary extensional tectonics and associated volcanism in west-central Arizona, <u>in</u> Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 143-157.

Peacock, M. A., 1931, Classification of igneous rocks series: Journal of Geology, v. 39, p. 54-67.

Peccerillo, A., and Taylor, S. R., 1976, Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey: Contributions to Mineralogy and Petrology, v. 58, p. 63-81.

Ransome, F. L., 1923, Geology of the Oatman gold district, Arizona: U.S. Geological Survey Bulletin 743, 58 p.

Schrader, F. C., 1909, The mineral deposits of the Cerbat Range, Black Mountains, and Grand Wash Cliffs, Mohave County, Arizona: U.S. Geological Survey Bulletin 397, 226 p.

Shand, S. J., 1927, Eruptive rocks: New York, John Wiley and Sons, 488 p.

Smith, R. C., 1984, Mineralogy and fluid-inclusion studies of epithermal gold-quartz veins in the Oatman district, northwestern Arizona: Tucson, University of Arizona, M.S. thesis, 233 p.
Steiger, R. H., and Jaeger, E., 1977, Subcommission on geochronology: convention and use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359-362.
Streckeisen, A. L., 1973, Classification and nomenclature recommended by the I.U.G.S. subcommission on the systematics: Geotimes, v. 18, p. 26-30.
Thorson, J. P., 1971, Igneous petrology of the Oatman district, Mohave County, Arizona: Santa Barbara, University of California at Santa Barbara, Ph.D. dissertation, 189 p.
Wells, R. C., 1937, Analyses of rocks and minerals from the laboratory of the United States Geological Survey, 1914-1936: U.S. Geological Survey Bulletin 878, 134 p.
Wilson, E. D., Cunningham, J. B., and Butler, G. M., 1967, Arizona lode gold mines and gold mining: Arizona Bureau of Mines Bulletin 137, 254 p.

ILLUSTRATIONS

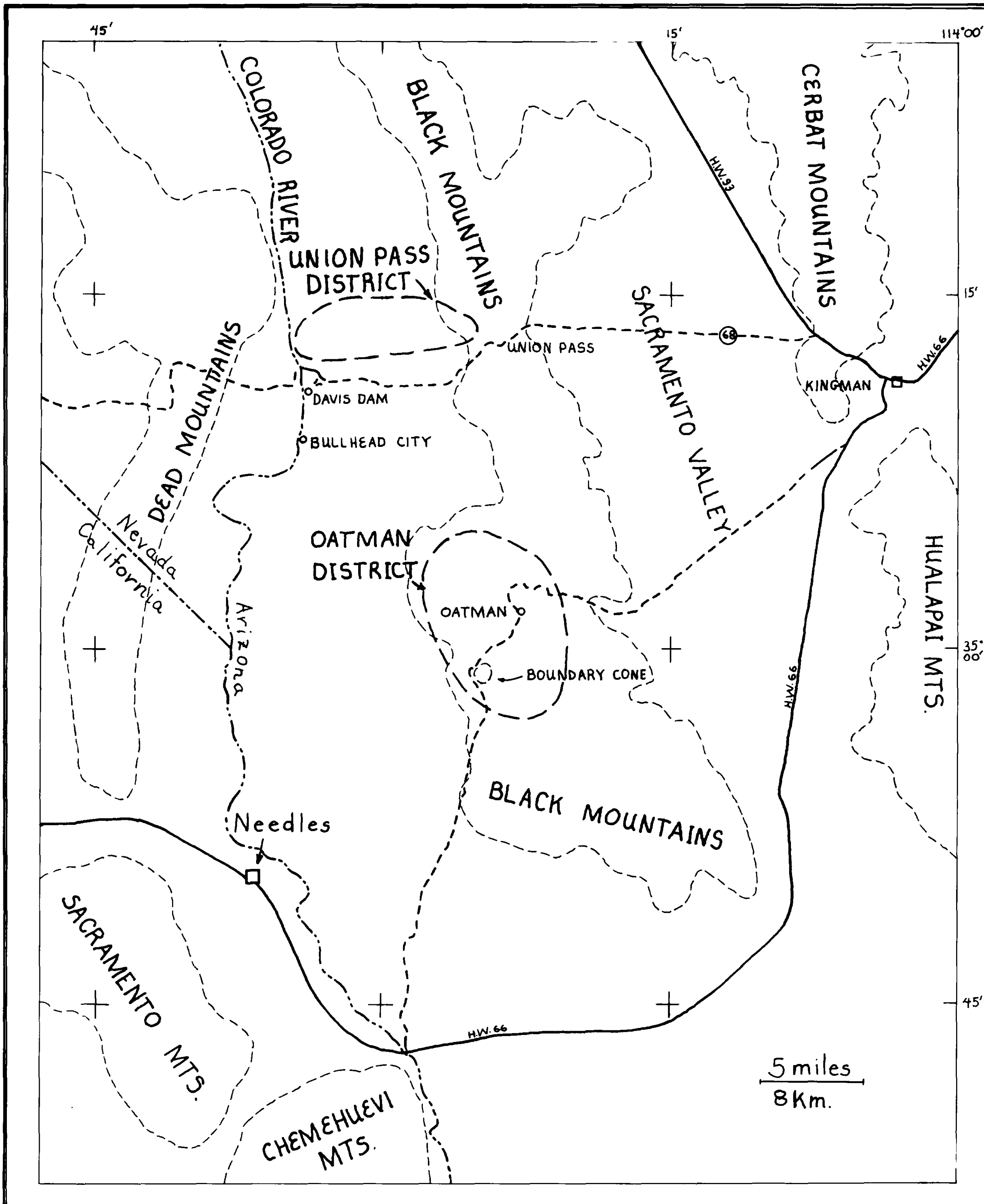


Figure 1. Location map of the Oatman area, northwestern Arizona.

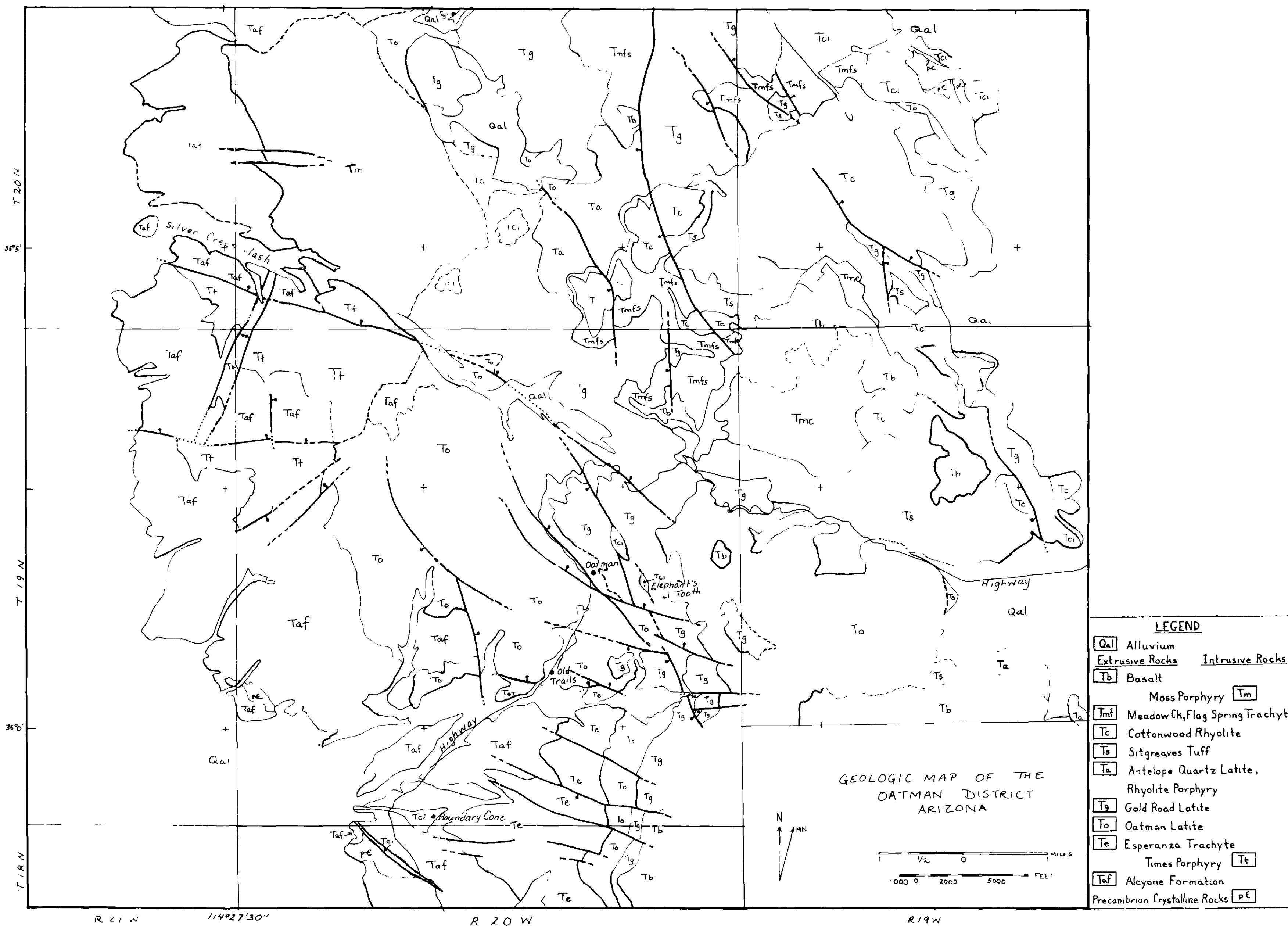


Figure 2. Geologic map of the Oatman district, Arizona. Compiled from Thorson (1971), Ransome (1923), and Clifton and others (1980).

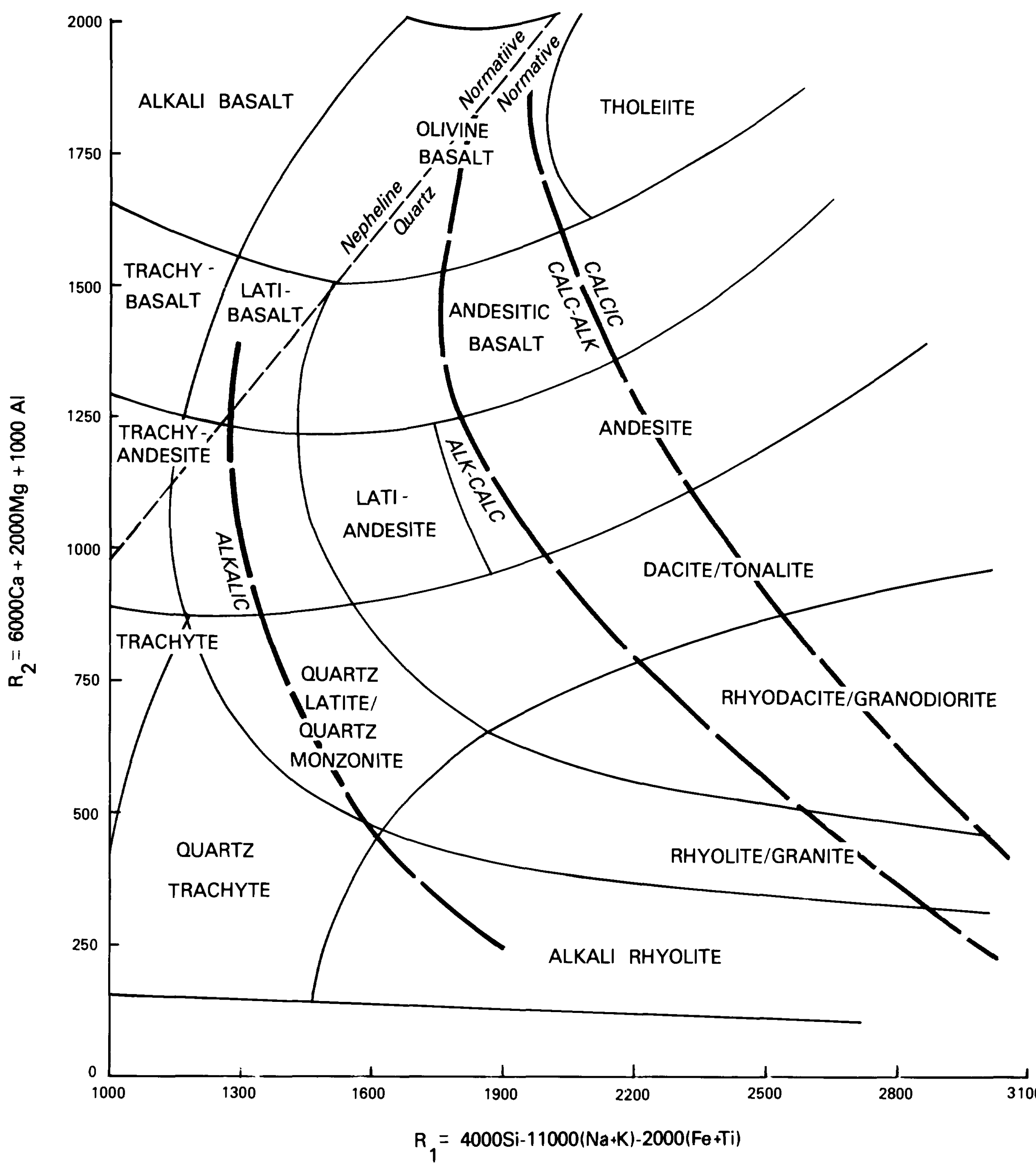
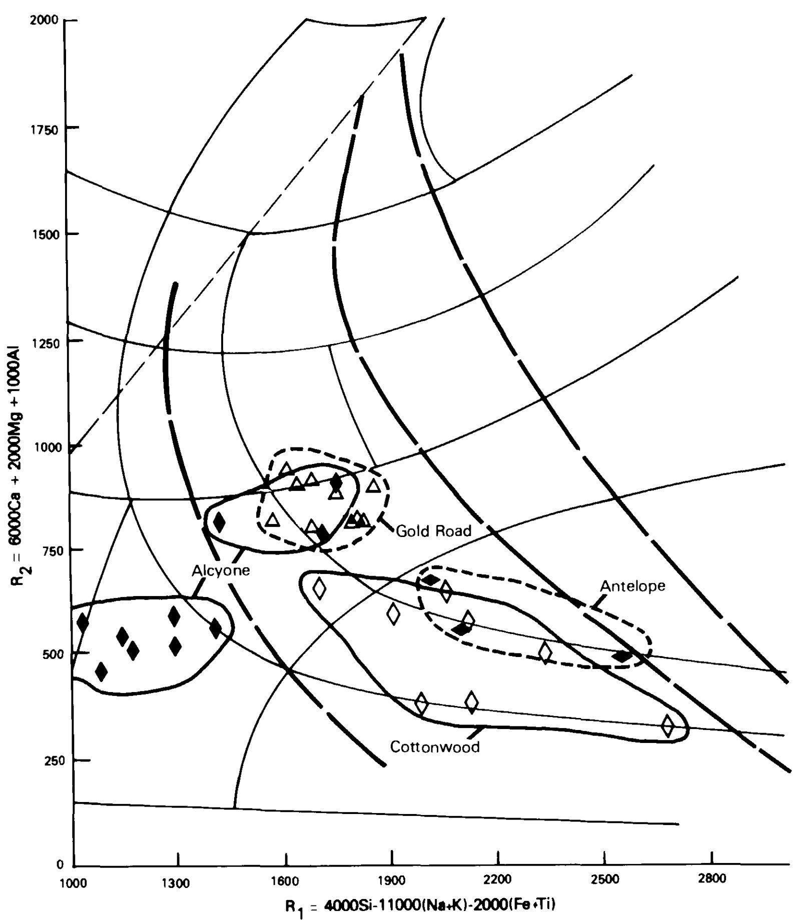
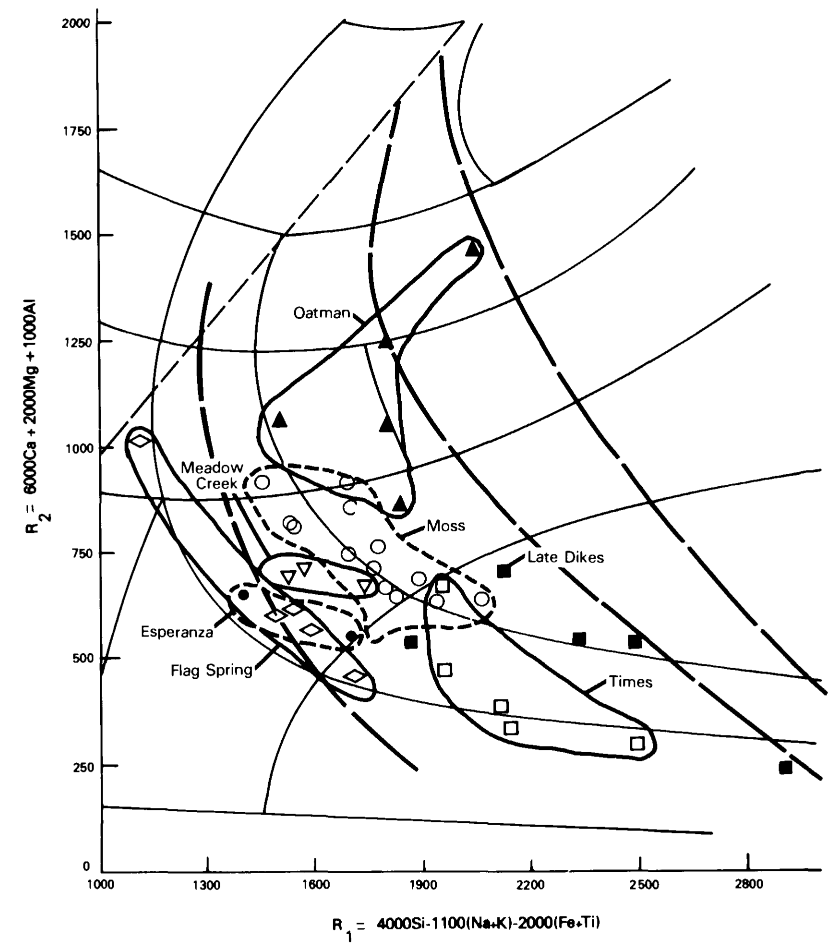


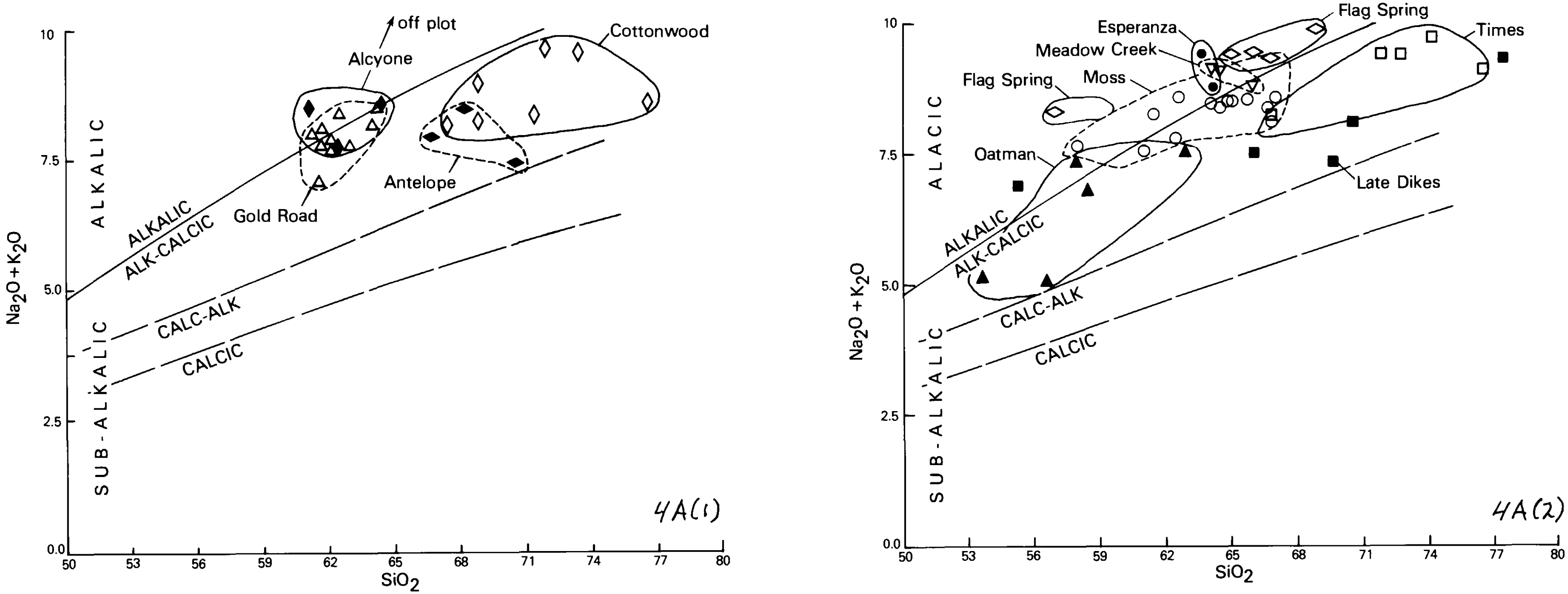
Figure 3A. R_1-R_2 rock classification diagram (De la Roche and others, 1980).



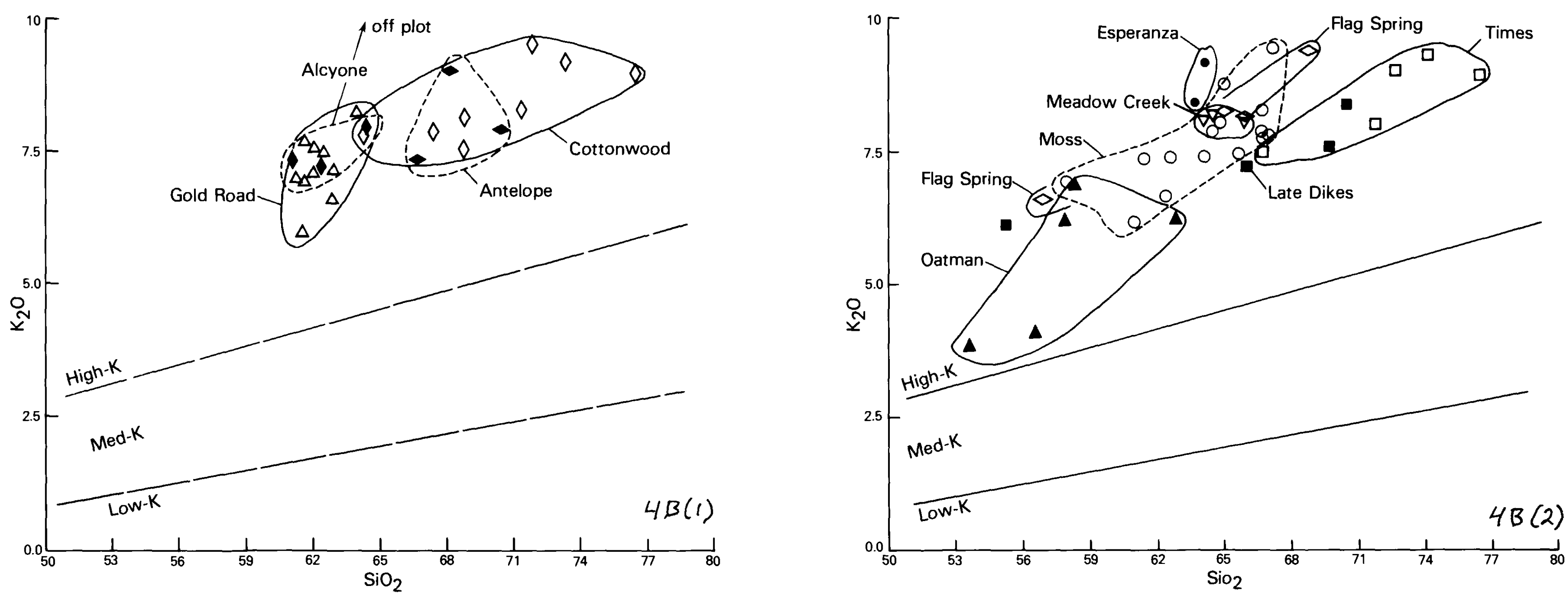


Figures 3B and 3C. R_1-R_2 classification diagram for representative rock samples of volcanic and plutonic rocks of the Oatman area.

- ◆ Alcyone Formation
- ◆ Antelope Quartz Latite
- ◇ Cottonwood Formation
- ● Esperanza Trachyte
- ◇ Flag Spring Trachyte
- △ Gold Road Latite
- ▽ Meadow Creek Trachyte
- ○ Moss Porphyry
- ▲ Oatman Latite
- □ Times Porphyry
- ■ Late dikes and rhyolite plugs



Figures 4A (1) and 4A (2). ($Na_2O + K_2O$) vs SiO_2 plots of volcanic and plutonic rocks of the Oatman area. Plotted points represent raw data, uncorrected for water content or loss on ignition. Alkalic-subalkalic field boundary in 4A (1) and 4A (2) from Anderson (1983). Symbols as in figure 3.



Figures 4B (1) and 4B (2). K_2O vs SiO_2 plots of the volcanic and plutonic rocks of the Oatman area. Plotted points represent raw data, uncorrected for water content or loss on ignition. High-K field boundary in 4B (1) and 4B (2) from Peccerillo and Taylor (1976). Symbols as in figure 3.

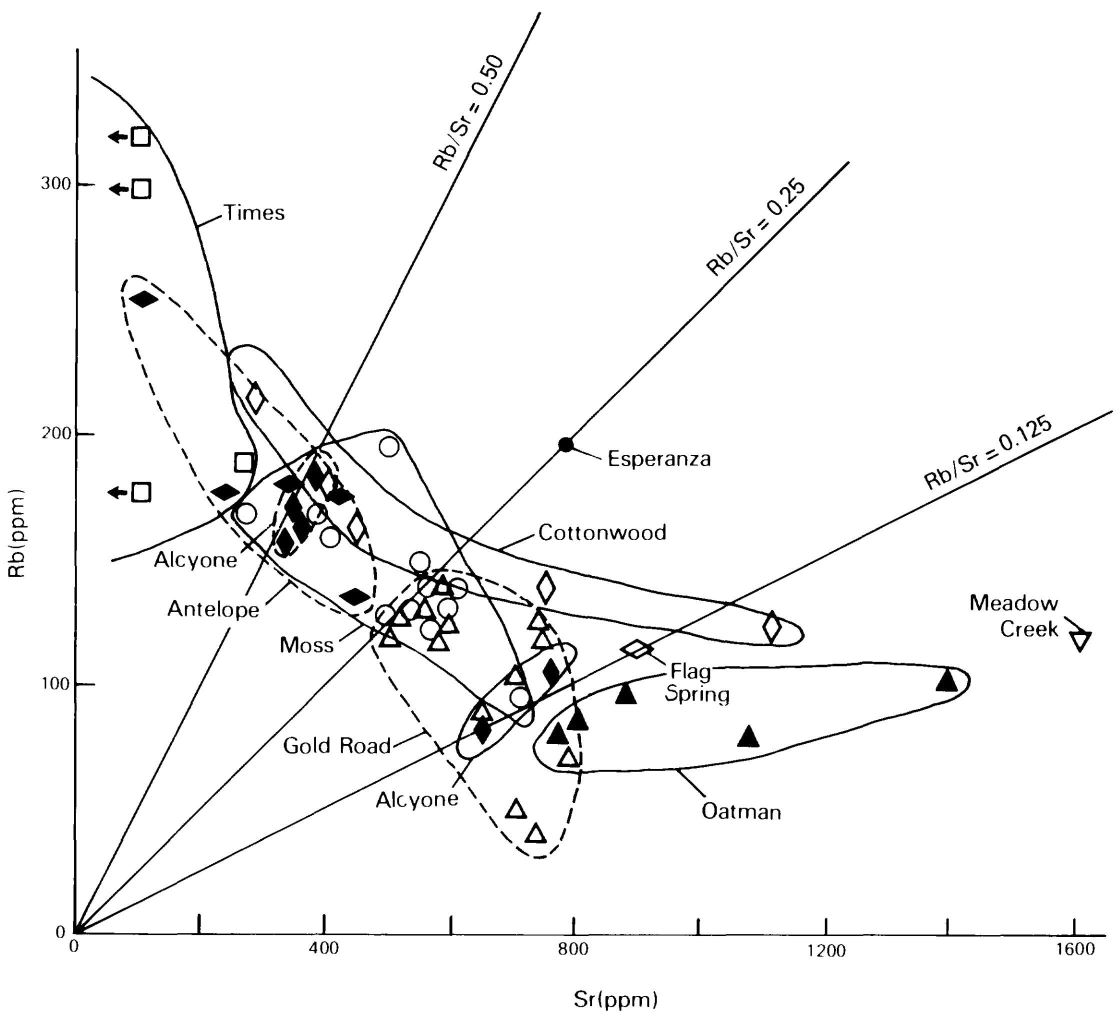


Figure 5A. Rb vs Sr plots of volcanic and plutonic rocks of the Oatman area. Symbols as in figure 3.

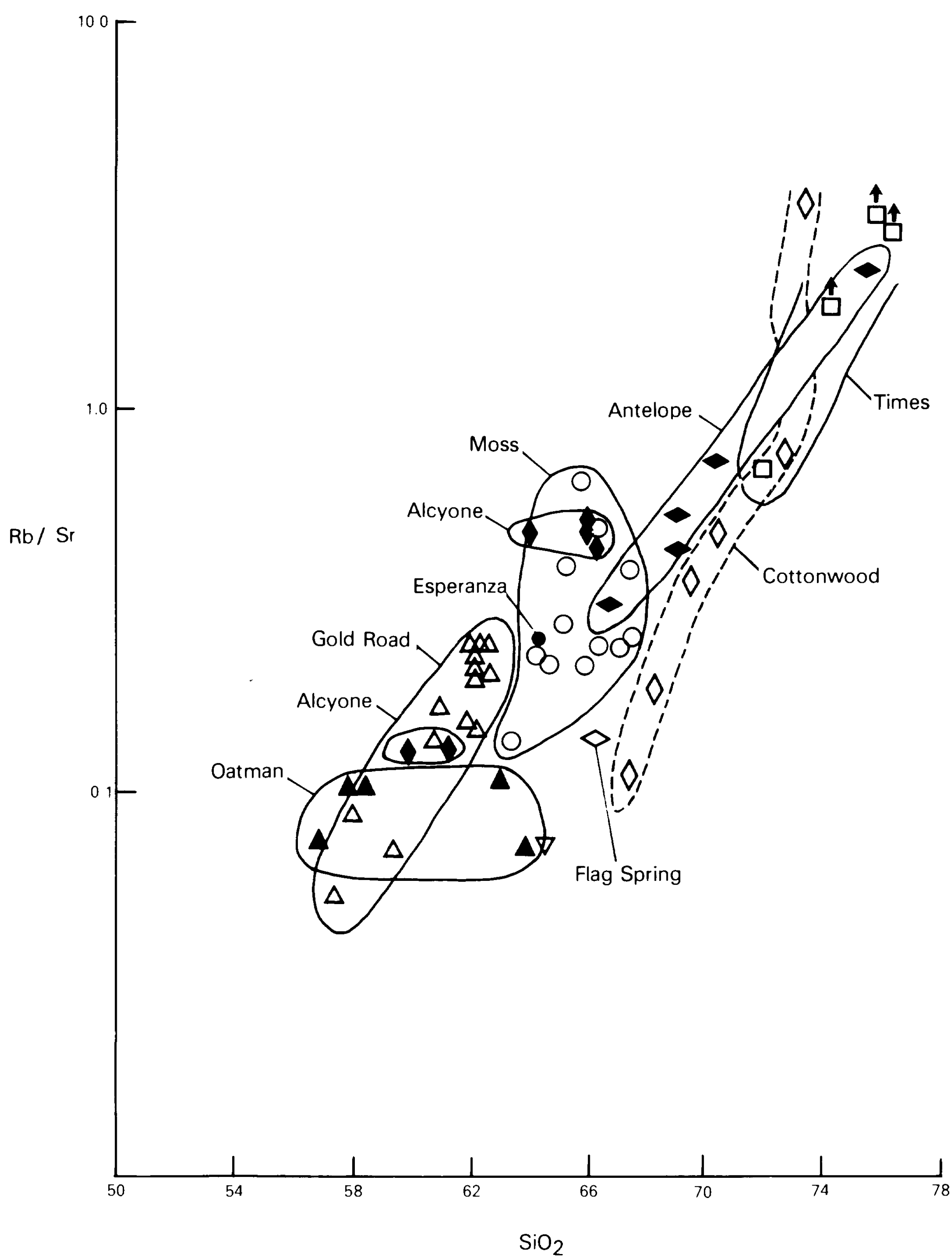


Figure 5B. Rb/Sr vs SiO_2 plots of volcanic and plutonic rocks of the Oatman area. Symbols as in figure 3.

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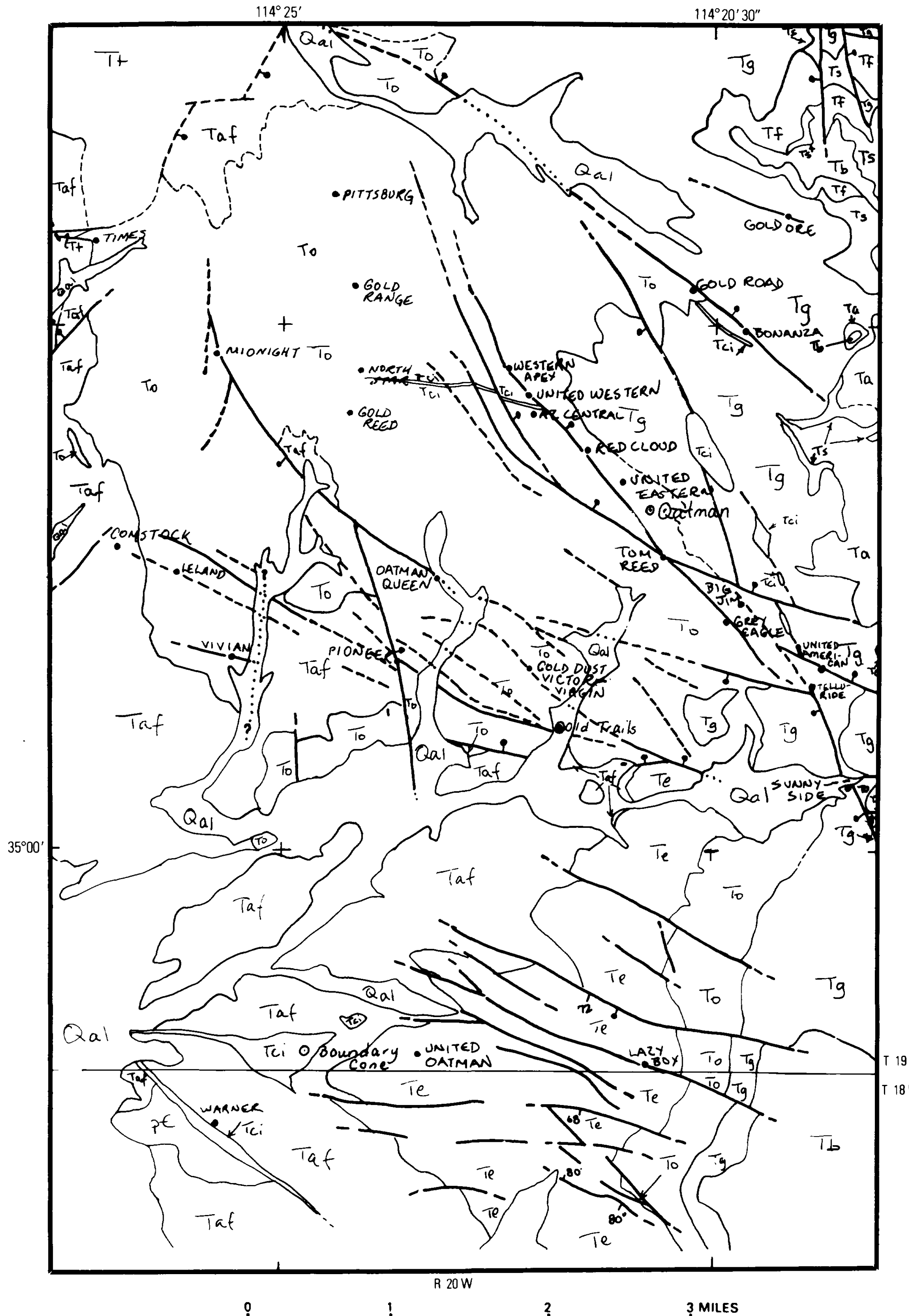

Figure 6. Detailed geology and location of mines in the Oatman district. Compiled from Thorson (1971), Ransome (1923), and Clifton and others (1980). pЄ, Precambrian; Taf, Alcyone Formation; Te, Esperanza Trachyte; To, Oatman Latite; Tg, Gold Road Latite; Ta, Antelope Quartz Latite; Ts, Sitgreaves Tuff; Tf, Flag Spring Trachyte; Tb, basalt; Tt, Times Porphyry; Tci, rhyolite porphyry intrusives; Qal, alluvium.

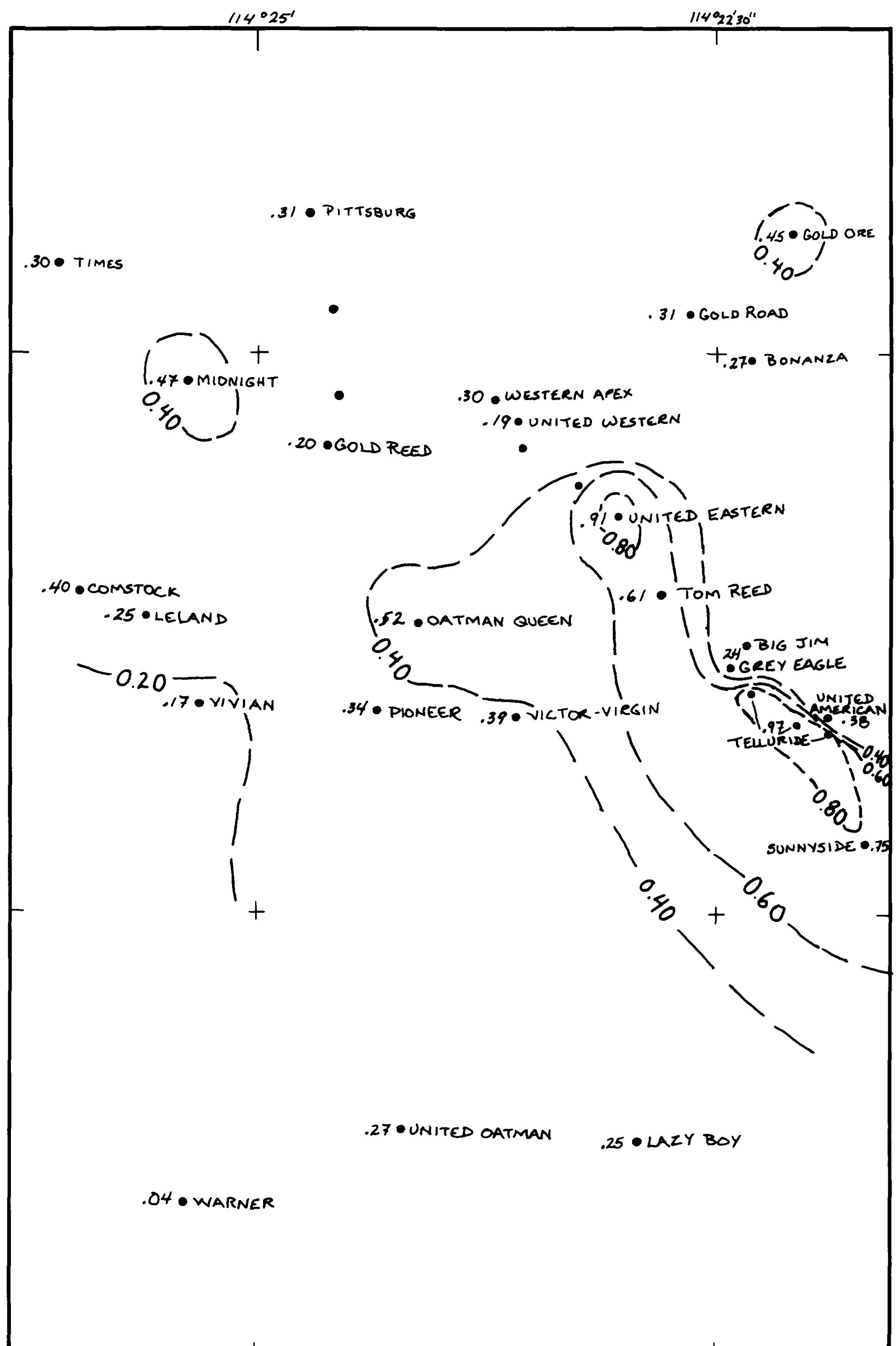

Figure 7A. Contour map of gold grade, in oz per ton, of individual deposits in the Oatman district.

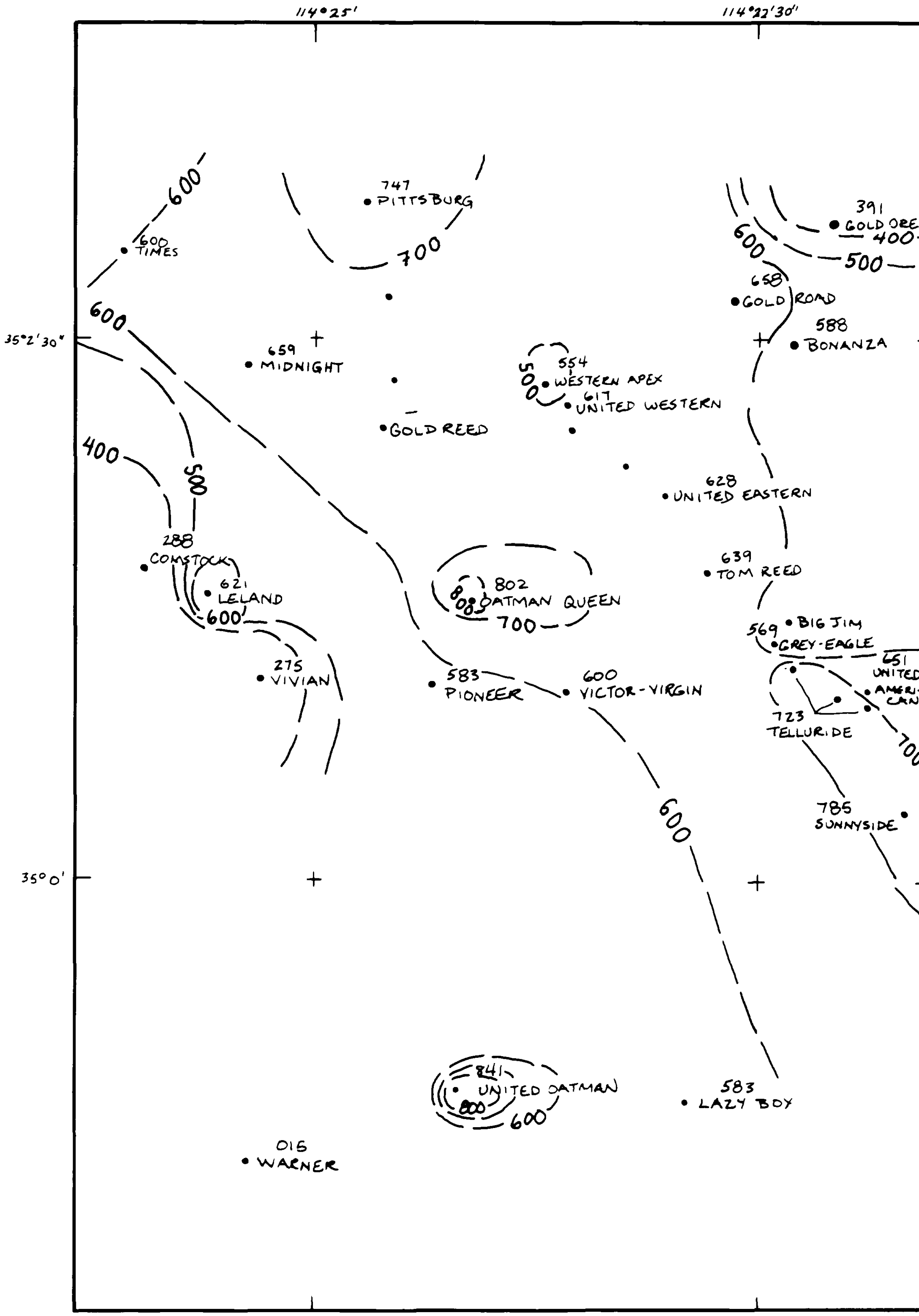

Figure 7B. Contour map of Au/(Au + Ag) ratios of individual deposits in the Oatman district. Values are multiplied by 1000 to eliminate decimal points.

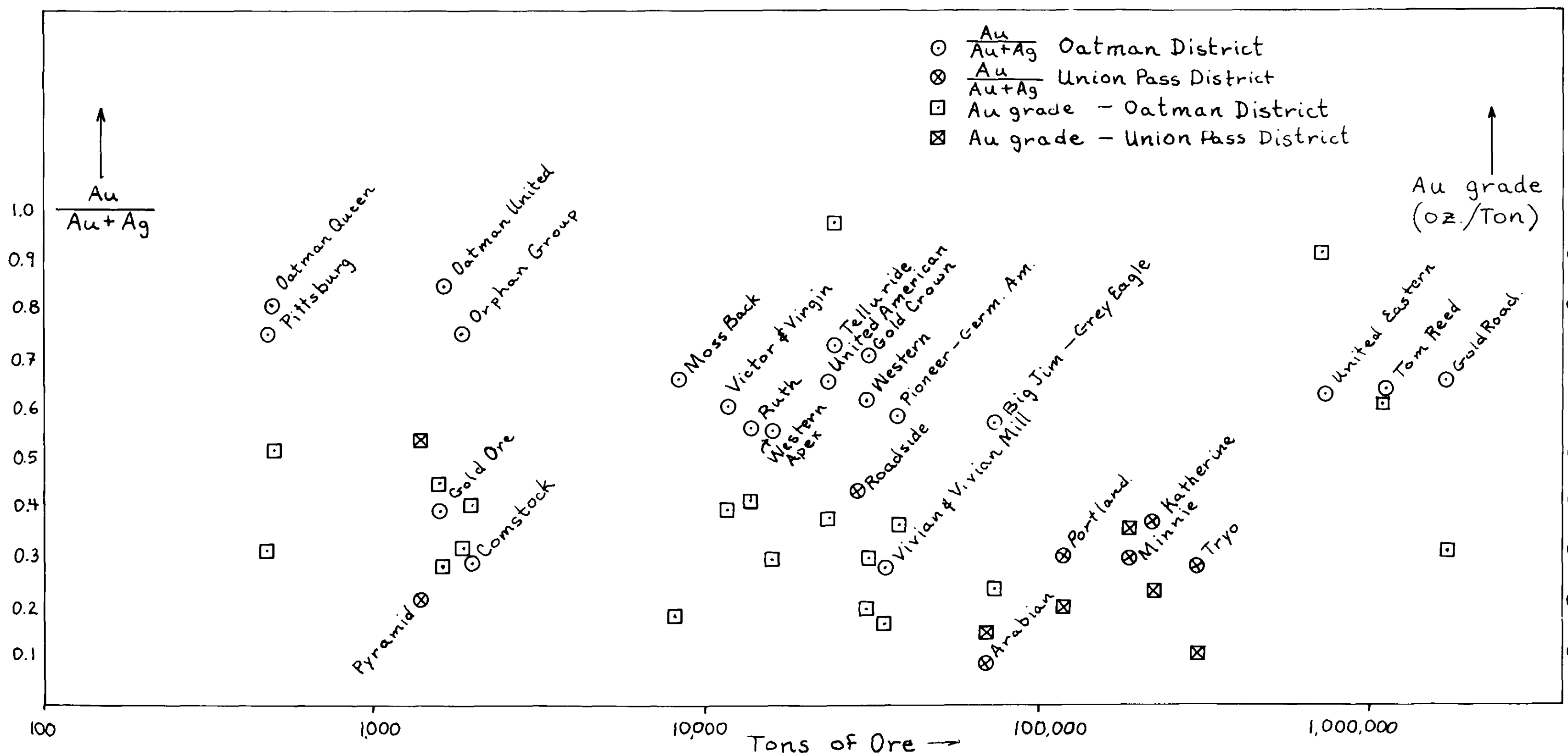

Figure 8. Plot of Au/(Au = Ag) vs tonnage and Au grade vs tonnage for individual deposits in the Oatman district. Deposits in Union Pass district plotted for comparison.

TABLES

Table 1.--Average chemical compositions of Tertiary volcanic and plutonic rocks in the Oatman area

[Data from Ransome (1923), Wells (1937), and Thorson (1971), and from Conoco Minerals Company (unpub. data, 1985). Analytical data in weight percent, except Rb, Sr, Zr in ppm. Standard deviations of the mean shown in parentheses beneath averages, if at least 3 analyses were available. n, number of analyses; leaders (---), no data; superscript number (2) indicates number of samples with available data]

	Alcyone			Esperanza	Oatman	Gold Road		Antelope		Cottonwood
	#1	#3	#5			lower	upper	flows	intrusives	#1,2,3
n	(7)	(4)	(7)	(3)	(14)	(12)	(15)	(16)	(8)	(13)
SiO_2	65.17 (0.76)	64.57 (0.90)	61.60 (1.46)	63.75 (0.53)	58.13 (2.77)	60.33 (1.92)	62.87 (1.08)	70.10 (2.69)	69.82 (1.38)	70.73 (2.25)
TiO_2	0.60 (0.06)	0.62 (0.01)	0.97 (0.10)	0.67 (0.10)	1.11 (0.16)	0.99 (0.10)	0.87 (0.10)	0.41 (0.12)	0.42 (0.07)	0.37 (0.11)
Al_2O_3	16.27 (0.49)	17.10 (0.30)	16.00 (0.53)	16.26 (1.41)	14.52 (3.87)	15.51 (0.56)	15.59 (0.71)	13.55 (0.74)	14.19 (0.45)	13.64 (0.77)
FeO_{total}	2.90 (0.49)	2.80 (0.13)	4.89 (0.43)	3.47 (0.24)	5.91 (0.78)	4.93 (0.70)	4.43 (0.40)	2.41 (0.82)	2.36 (0.26)	2.11 (0.54)
MgO	0.80 (0.08)	0.90 (0.07)	1.92 (0.41)	0.94 (0.14)	3.20 (0.70)	2.72 (1.21)	1.99 (0.46)	0.79 (0.28)	0.76 (0.22)	0.79 (0.30)
MnO	$0.04^{(5)}$ (0.01)	$0.06^{(2)}$	$0.07^{(2)}$	$0.05^{(2)}$	$0.08^{(10)}$ (0.03)	$0.08^{(9)}$ (0.03)	$0.06^{(10)}$ (0.01)	$0.05^{(7)}$ (0.01)	---	$0.05^{(4)}$ (0.01)
CaO	1.58 (0.50)	1.51 (0.22)	3.99 (0.54)	2.23 (0.56)	6.19 (1.33)	4.89 (1.03)	3.85 (0.40)	2.16 (0.57)	2.03 (0.54)	2.06 (0.54)
Na_2O	$3.99^{(5)}$ (0.26)	$4.13^{(2)}$	$3.69^{(5)}$ (0.37)	$3.83^{(2)}$	$3.14^{(11)}$ (0.43)	$3.33^{(5)}$ (0.32)	$3.61^{(10)}$ (0.24)	$3.08^{(7)}$ (0.45)	$3.07^{(13)}$ (0.35)	$3.40^{(6)}$ (0.44)
K_2O	6.90 (0.37)	6.98 (0.12)	4.36 (0.23)	5.25 (0.23)	3.56 (0.70)	4.05 (0.58)	4.47 (0.40)	5.00 (0.59)	5.06 (0.69)	4.90 (0.39)
LOI	1.13 (0.27)	1.20 (0.31)	2.70 (1.83)	2.94 (1.16)	$3.52^{(12)}$ (1.53)	2.97 (0.78)	$2.02^{(13)}$ (0.72)	2.03 (1.20)	1.77 (1.61)	1.93 (1.10)
CO_2	$0.45^{(2)}$ (0.28)	---	$0.02^{(1)}$	$1.59^{(3)}$ (0.52)	---	---	---	---	---	---
P_2O_5	0.23 (0.12)	---	---	$0.30^{(1)}$	$0.42^{(3)}$ (0.03)	---	$0.27^{(3)}$ (0.01)	$0.28^{(2)}$	---	$0.04^{(1)}$
Rb	$164^{(2)}$	$177^{(2)}$	$94^{(2)}$	$194^{(1)}$	$84^{(7)}$ (16)	$85^{(7)}$ (33)	$132^{(8)}$ (17)	$185^{(5)}$ (43)	---	$187^{(3)}$ (27)
Sr	$351^{(2)}$	$368^{(2)}$	$708^{(2)}$	$792^{(1)}$	$1024^{(7)}$ (222)	$728^{(7)}$ (45)	$569^{(8)}$ (41)	$310^{(5)}$ (136)	---	$383^{(3)}$ (86)
Zr	---	---	---	---	$303^{(2)}$	---	$400^{(2)}$	---	---	---

n	Cottonwood #4,5 (4)	Cottonwood #6 (4)	Flag Spring (6)	Meadow Creek (5)	Times Porphyry border (5)	Times Porphyry core (6)	Moss Porphyry border (4)	Moss Porphyry porphyry (7)	Moss Porphyry main (17)	Rhyolites (2)
SiO_2	66.49 (1.49)	75.34 (1.57)	66.71 (1.59)	64.91 (0.69)	75.81 (0.52)	73.09 (1.96)	59.43 (1.54)	64.62 (2.40)	65.47 (1.72)	77.80
TiO_2	0.48 (0.08)	0.10 (0.04)	0.46 (0.12)	0.60 (0.01)	0.15 (0.04)	0.32 (0.09)	1.06 (0.07)	0.69 (0.12)	0.70 (0.13)	0.11
Al_2O_3	15.43 (0.54)	12.53 (1.06)	16.25 (0.58)	16.51 (0.28)	11.98 (0.57)	13.39 (0.88)	15.11 (0.16)	15.02 (0.58)	15.05 (0.68)	12.05
FeO_{total}	2.85 (0.58)	0.64 (0.17)	2.56 (0.64)	3.71 (0.33)	0.83 (0.18)	1.55 (0.46)	5.88 (0.45)	3.85 (0.80)	3.64 (0.69)	0.88
MgO	0.96 (0.24)	0.18 (0.07)	0.55 (0.18)	0.79 (0.06)	0.17 (0.03)	0.37 (0.27)	3.20 (0.33)	1.97 (0.71)	1.63 (0.41)	$0.09^{(1)}$
MnO	$0.06^{(1)}$	$0.06^{(1)}$	$0.06^{(2)}$	$0.07^{(1)}$	$0.03^{(2)}$	$0.06^{(3)}$ (0.01)	---	$0.08^{(2)}$ (0.03)	$0.06^{(10)}$ (0.01)	$0.04^{(1)}$
CaO	2.83 (0.31)	1.01 (0.43)	2.04 (0.39)	3.13 (0.12)	0.56 (0.09)	0.87 (0.36)	4.12 (0.50)	3.21 (0.75)	2.95 (0.60)	0.39
Na_2O	$3.63^{(2)}$	$3.65^{(2)}$	$4.48^{(4)}$ (0.18)	$4.16^{(3)}$ (0.16)	$3.59^{(2)}$	$4.26^{(3)}$ (0.32)	$3.59^{(3)}$ (0.24)	$3.49^{(5)}$ (0.29)	$3.85^{(11)}$ (0.18)	$0.37^{(1)}$
K_2O	4.70 (0.09)	5.35 (0.29)	5.04 (0.32)	4.79 (0.11)	5.31 (0.05)	5.50 (0.46)	4.34 (0.47)	4.57 (0.77)	4.63 (0.40)	8.77
LOI	2.48 (1.07)	1.61 (1.52)	0.94 (0.11)	0.59 (0.23)	0.74 (0.36)	0.72 (0.65)	1.99 (0.97)	2.39 (0.78)	1.68 (0.55)	$0.70^{(1)}$
CO_2	---	---	---	---	---	---	---	---	$0.07^{(1)}$	$0.04^{(1)}$
P_2O_5	---	---	$0.17^{(1)}$	$0.24^{(1)}$	---	---	---	---	$0.30^{(2)}$	$0.02^{(1)}$
Rb	$127^{(1)}$	---	$124^{(1)}$	$118^{(1)}$	$308^{(2)}$	$229^{(2)}$	---	$165^{(2)}$	$141^{(11)}$ 26	---
Sr	$1113^{(1)}$	---	$901^{(1)}$	$1625^{(1)}$	---	$178^{(1)}$	---	$338^{(2)}$	$556^{(11)}$ 81	---
Zr	---	---	---	---	---	$238^{(1)}$	---	---	$246^{(1)}$	---

Table 2.--Chemical and modal classifications and range of SiO_2 content for Tertiary volcanic and plutonic rocks of the Oatman area

[FE, iron-rich; MG, magnesium-rich; SUB, subalkalic; ALK, alkalic]

Rock Unit[1]	Chemical Classification (De la Roche and others, 1980)	Modal Classification (Streckeisen, 1973)	Fe/Fe+Mg Classification (Miyashiro, 1974)	Alkali Classification (Anderson, 1983)	SiO_2 Range (data uncorrected for water content)
Times Porphyry					
core	granite	syenogranite	MG/FE	SUB	71-76
border	alkali granite	syenogranite	MG/FE	SUB	75-77
Moss Porphyry					
main phase	tonalite-granodiorite	monzogranite	MG	SUB/ALK	62-67
border	monzodiorite		MG	SUB/ALK	58-62
Flag Spring Trachyte	quartz latite		FE	ALK	65-68
Meadow Creek Trachyte	quartz latite		FE	ALK/SUB	64-65
Cottonwood Formation	rhyolite		MG	SUB	64-77
Antelope Quartz Latite	rhyodacite-rhyolite		MG	SUB	65-75
Gold Road Latite					
upper	dacite		MG	SUB/ALK	62-65
lower	latitic andesite-dacite		MG	SUB/ALK	58-63
Oatman Latite	latitic andesite		MG	SUB	56-63
Esperanza Latite	quartz latite		FE/MG	ALK	63-64
Alcyone Formation					
#5, quartz latite	quartz latite		MG/FE	SUB/ALK	60-64
#1, 3, trachyte	quartz trachyte		FE	ALK	64-66

[1]Rock names from Thorson (1971).

Table 3.--K-Ar data and age calculations and Rb-Sr data for Tertiary volcanic rocks and vein material of the Oatman area

Unit; mineral dated	% K	$^{40}Ar^*/^{40}Ar_t$ 1/	Date (Ma)	Reference
Moss Porphyry; biotite	6.230	0.588	10.7 ± 0.5	1
Antelope Quartz Latite; biotite	6.430	0.175	19.2 ± 0.9	1
Gold Road Latite; biotite	6.53	0.615	18.6 ± 0.9	1
Times Porphyry; hornblende	0.822	0.122	23.1 ± 1.8	1
Kokomo vein material; adularia + quartz(?)	2.56	not reported	21.2 ± 2.1	2

References
1, Thorson (1971), recalculated with decay constants in Steiger and Jaeger (1977)
2, Conoco Minerals Company (unpub. data, 1982, 1983)

1/ $^{40}Ar^*/^{40}Ar_t$, ratio of radiogenic argon to total argon.

Unit	Rb(ppm)	Sr(ppm)	$^{87}Sr/^{86}Sr_m$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr_i$
Moss Porphyry	146 ± 3	591 ± 5	0.7109 ± 0.0001	0.715	0.7107 ± 0.0001
Oatman Latite	91 ± 1	1052 ± 8	0.7105 ± 0.0001	0.250	0.7105 ± 0.0001

$^{87}Sr/^{86}Sr_m$, measured strontium isotopic ratio;
$^{87}Sr/^{86}Sr_i$, initial strontium isotopic ratio if rocks are assumed to be 22 Ma.

Table 4.--U-Th-Pb analytical data and age calculations for zircon from the Moss and Times Porphyries, Oatman area

Rock Unit (mesh size)	U (ppm)	Th (ppm)	Pb (ppm)	Atomic composition of lead[1]				$^{206}Pb/^{238}U$ Age (Ma)	$^{207}Pb/^{235}U$ Age (Ma)	$^{207}Pb/^{206}Pb$ Age (Ma)	$^{208}Pb/^{232}Th$ Age (Ma)
				204	206	207	208				
Moss Porphyry											
(-400)	381.98	785.78	4.24	1	93.75	21.06	69.79	34.0	52.3	99.6	20.9
(-325+400)	198.95	231.74	9.96	1	739.17	87.44	147.05	271.4	471.5	1617.9	108.4
(-250+325)	187.39	235.63	16.25	1	946.77	109.36	164.44	477.7	739.2	1642.4	161.6
Times Porphyry											
(-325+400)	236.96	426.90	6.44	1	415.14	53.62	120.60	136.7	253.2	1544.5	47.0

[1]Laboratory blank lead with isotopic composition $^{206}Pb/^{204}Pb$ = 18.7, $^{207}Pb/^{204}Pb$ = 15.6, $^{208}Pb/^{204}Pb$ = 38.2 removed. No common lead correction has been applied to these ratios.

Common lead correction used for zircon age calculations: $^{206}Pb/^{204}Pb$ = 18.67, $^{207}Pb/^{204}Pb$ = 15.63, $^{208}Pb/^{204}Pb$ = 38.59.