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EXPLORATION PROCEDURE AND CONTROLS OF MINERALIZATION IN THE OATMAN MINING DISTRICT, OATMAN, ARIZONA

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Abstract. The Oatman District produced approximately 2.2×10^6 ounces of gold and 0.8×10^6 ounces of silver between 1897 and 1942. A total of 3.8×10^6 tons of ore averaging 0.58 O/T gold and 0.17 O/T silver was extracted from eight major orebodies and a number of lesser deposits.

Oatman lies at the center of a trachyte-latite-rhyolite volcanic complex which contains at least one resurgent caldera. The orebodies are typical epithermal quartz-calcite ± adularia lode deposits which are very deficient in sulfur. Ore deposition has occurred within dilatant zones on faults which radiate from a common point within the complex.

Fischer-Watt Mining approached the Oatman District with an integrated exploration program utilizing four basic procedures to define the characteristics of past productive areas, the results of which were applied to unexplored portions of the vein system. These procedures listed in their order of usefulness in defining known and prospective mineralized zones are: vein contouring, detailed alteration mapping, fluid inclusion temperature determinations, and geochemical sampling.

All known deposits were found to be located at particular points of curvature on the veins and all, irrespective of the level exposed in the hydrothermal system, exhibited a distinctive and predictable alteration signature. Fluid inclusion studies indicated boiling or nonboiling conditions during deposition, temperature of deposition at the sample point, level of exposure relative to the boiling interface and, by establishing a paleogeothermal gradient to the ore horizon, a depth control for drilling. Geochemical sampling has produced inconsistent and, at times, misleading indications of mineralization at depth. The method has to date been of limited use in the determination of location of known oreshoots or new targets. Approximately one man year was expended in establishing these relationships before drilling was recommended.

Introduction

Precious metal vein deposits occurring in Tertiary volcanic terrains - the so-called epithermal vein deposits - have received little attention by American exploration groups in the last 40-50 years. Numerous factors have contributed to this, including the low price of silver and fixed price of gold, escalating labor and materials costs, and an interest in longer term, larger tonnage operations such as porphyry copper and molybdenum deposits. In addition, with few exceptions, no significant precious metal vein deposit has been discovered in the United States since the 1920's and many deposits which have been mined for years, such as the Idarado and Camp Bird mines in Colorado, have recently become uneconomic. The relative difficulty in evaluating vein systems for ore reserves, their limited size, erratic grades, and the requirement of underground mining methods have also discouraged exploration.

With the recent rise in precious metal prices, increased capital costs of bulk tonnage operations, and the high cost of borrowed money, low capital cost, rapid return high grade vein mining operations are once again becoming attractive. Cash flow analyses indicate intermediate size deposits (0.5 to 1.0 million tons) of intermediate grade (0.25 O/T Au equivalent, at today's price of $500 per ounce) can support 300 to 500 TPD operations which show a rapid payback and a high rate of return on investment.

An example is the Bulldog Mountain mine in Creede, Colorado. Brought into production at 300 TPD in 1969 by Homestake Mining Company, the Bulldog Mountain vein deposit averages about 17 O/T Ag and 2% Pb. Past production plus estimated reserves total 1.5 million tons (1). Another example, is the Northair mine, a 300 TPD Au, Ag, Pb, Zn vein mining operation located 50 miles north of Vancouver, British Columbia. Brought into production in May 1976, at a cost of $5.5 million, the operation was "in the black" in January 1979 (2). Net profits for 1979-80 should be about $6 million (3). A production decision was made based on 330,000 tons of ore averaging 0.37 O/T Au, 4.5 O/T Ag, 2.7% Pb, and 4% Zn. Although a "mesothermal" base metal deposit, the Northair mine serves to illustrate the economics of a small to intermediate size vein deposit. These two examples indicate that a multi-million ton deposit of high grade gold-silver ore — the "bonanza" type made famous by Comstock, Tonopah, and Goldfield — is not a necessary prerequisite to a successful vein-type operation at today's economics.

Despite the rise in precious metal prices and the opening of several new mines, little serious exploration effort is being directed to veins in the western United States. Vein deposits must still compete with large, low grade gold deposits such as Carlin and Jerritt Canyon, Nevada, or more modest investments such as reprocessing mill tails, low grade heap leach, or reopening old mines. The several new vein deposit discoveries have not caught the imagination of the exploration groups, probably because of the shadows cast by the bulk tonnage low grade deposits; but perhaps, also, because the discoveries were not the climax of a well conceived exploration program. The Bulldog Mountain deposit was discovered by Manning W. Cox utilizing the data and recommendations of Stephen and Ratté (4) generated during mapping of the Creede caldera. Despite the fact the Bulldog Mountain structure lies between the highly productive Amethyst and Alpha-Corsair veins, Cox had great difficulty in interesting a mining company in exploring for hidden reserves, mainly because the vein contained no significant values on the surface. Cox was finally compelled to approach the Office of Mineral Exploration (OME) of the U.S. Government for initial exploration funding. The discovery of the only other epithermal vein deposit to be put into production in recent years, the Gooseberry mine near Virginia City, Nevada, was equally uninspiring. This deposit, now estimated to contain in excess of 1 million tons of 0.2 O/T Au and 8 O/T Ag, was found by blind luck by a California rancher sinking a shaft on an altered vein structure carrying minor silver values at the surface. The mine is operated by West Coast Gas and Oil and will be put into production at 450 TPD.

The characteristic unmineralized surface expression of epithermal vein deposits in these two cases was, respectively, the downfall of the "sophisticated" mining company and the triumph of the "unsophisticated" rancher who had faith in a poorly mineralized, altered outcrop. To quote

Cox's (5) comments on the vein exploration efforts of most major mining companies:

> "Beyond the fact that Bulldog is a mine, there is the fact in my judgement much more important, namely that solidly conceived geological hypotheses such as went into the Bulldog project do not get tested by mining companies because absolutely no mineralization can be found in which to start... If it were not for the OME Bulldog would not have been undertaken."

We feel the return of vein deposits as attractive exploration targets awaits the publication of exploration-useful vein deposit descriptions and an example where a major new discovery was the result of an exploration effort concentrating on the characteristics which strictly typify epithermal vein deposits.

Several vein exploration programs now in progress, which attempt to make use of vein characteristics, have not been overly successful. We feel these efforts, although relatively enlightened, fail to concentrate on the most important characteristics of vein deposits, do not utilize the most efficient tools, and employ a conceptional model which may have shortcomings. Several of these programs have also been burdened by tonnage requirements which cannot be expected in the typical epithermal vein deposit.

The Oatman District was approached with the following philosophy:

A) Intermediate size and grade precious metal vein deposits are economically attractive.

B) The western United States is essentially virgin hunting ground for poorly exposed vein deposits, some of which will be the size and grade of Comstock, Tonopah, or Goldfield.

C) Vein deposits are amenable to low cost, labor intensive, scientific exploration.

D) The necessary exploration tools are available or can be defined and can be incorporated into an exploration procedure.

Our work at Oatman was directed toward two goals. The first, of course, to find ore. The second, and rated just as important, was the development of techniques and procedure which could be applied to other epithermal vein systems. The following discussion will, therefore, concentrate more on exploration methods as applied to veins, rather than on regional geology or vein mineralogy of the Oatman deposits. We feel existing reports for most mining districts fail to be useful as exploration guides because they concentrate more on regional geologic environment and on vein mineralogy rather than on ore controls. The methods to be discussed are particularly useful in past productive districts but can be useful during grass roots exploration as well.

Location

Oatman is approximately 100 miles southeast of Las Vegas, Nevada, and midway between Needles California and Kingman, Mohave County, Arizona on old Highway 66 (Figure 1). The Colorado River lies 15 miles to the west of town. The district is about 10 miles long and 7 miles wide and is situated within Tertiary volcanics of the Black Mountains.

History and Production

The history and production of the Oatman District are summarized from reports by Schrader (6), Ransome (7), Lausen (8), and Wilson et al. (9).

Gold was first discovered in 1863 by soldiers from Camp Mohave on the Colorado River in the Moss vein, approximately 5 miles northwest of the present site of Oatman (Figure 2). Additional prominent veins outcropping to the southwest of present-day Oatman were located shortly thereafter. Prospecting was curtailed for many years following Indian uprisings in 1866, but was resumed in the 1880's. In 1900 gold was discovered in the Gold Road vein, one mile north of Oatman, and in 1901 on the Tom Reed vein where the town of Oatman was later built (Figure 3). Rich ore was discovered in 1906 in what later became the Tip Top and Ben Harrison orebodies of the Tom Reed vein. In 1916 the Big Jim and Aztec orebodies were discovered on the southeast end of the Tom Reed vein. In the same year the famous United Eastern orebody was discovered under the west end of town on a hanging wall split of the Tom Reed structure. The resultant boom, the last of its kind in the American West, brought 10,000 people to Oatman in the next few years.

In 1924 the United Eastern orebody became exhausted after yielding 550,000 tons of 1.1 O/T Au. Production from the Tom Reed orebodies was by lessees between 1922 and 1924, as was all production in the district in the late 1920's and 1930's. The Gold Road mine produced from 1900 to 1916, again in 1922, and again from 1934 to 1942.

In this report the <u>central district</u> refers to the productive portion of the Oatman District centered around the Tom Reed-United Eastern and Gold Road veins.

Production estimates compiled to 1937 by Wilson et al. (9) and supplemented by annual report production figures from 1931 to 1942 show the Oatman District produced approximately 2.2 million ounces of gold and 0.8 million ounces of silver between 1897 and 1942 (Table 1). This equates to over $1 billion gross value at a present day price of gold of $500 per ounce. A total of 3.8 million tons of ore was extracted averaging 0.58 O/T Au and 0.17 O/T Ag.

Regional Geology and Structure

Geologic maps covering the Oatman District have been compiled by Ransome (7), Lausen (8) and Thorson (10). Several modifications pertaining to the geology of the district have been made by the staff of Fischer-Watt Mining and have been incorporated in the composite map presented in Figure 2.

The Oatman District lies on the western flank of the Black Mountains, a fault-bounded Tertiary volcanic pile composed of trachyte, latite, rhyolite and basalt situated at the southern end of the Basin and Range province (Figure 4). The Black Mountains are deeply incised on its western flank but are little eroded on its eastern. Exposures of Precambrian basement are found on the western margin and north end of the district. Except for the capping basalts the volcanic center appears to have been in the Oatman area. This is supported by a concentration of rhyolite and latite dikes and plugs and two high level (epizonal) plutons within a two mile radius of

Oatman and a thick volcanic sequence which thins rapidly away from the Oatman area. The volcanic pile has a 10° easterly dip, attributed by others to regional tilting. However, measurements taken near Oatman suggest the easterly dip may be related to a central volcanic edifice at Oatman or related to late stage magmatic doming. The local volcanic stratigraphy, summarized from Thorson (10), is presented in Figure 5.

The Tertiary volcanics rest on a Precambrian basement composed of biotite schist, granitic gneiss and garnet gneiss, and intrusive biotite granite (the Katherine Granite). The Precambrian is overlain by the Eocene Alcyone Formation, a sequence of trachyte welded tuffs, quartz latite flows, sedimentary tuff breccias, landslide breccias, and minor carbonaceous shales and limestones. The entire sequence was intruded by the Times Porphyry, a granophyre laccolith dated at 22.6 ± 1.6 m.y. Thorson (10) interprets the Times Porphyry as the final phase of a resurgent caldera sequence based on type and distribution of the volcanics and petrologic considerations which indicate the Times Porphyry is comagmatic with the Alcyone Formation. The Alcyone Formation is termed the lower volcanics after Thorson (10).

The Alcyone Formation is unconformably overlain by the Esperanza Formation, a trachyte flow which may have as its origin a separate volcanic source to the south of Oatman.

The Esperanza Formation is conformably overlain by the Miocene Oatman and Cold Road Formations. The Oatman Formation, termed the "chloritic andesite" by Schrader (6) and the Oatman Andesite by Ransome (7) is a sequence of massive to vesicular non-biotitic pyroxene latite flows, latite tuffs, and flow breccias. The Oatman Formation is approximately 1000 feet thick at Oatman but thins rapidly from the central district.

The Oatman Formation is conformably capped by the Cold Road Formation, a sequence of biotitic pyroxene latite flows and latite lithic ash flows. Maximum thickness is about 800 feet. A K/Ar determination on the highest unit in the sequence gave a date of 18.2 ± 0.9 m.y. A transition zone separating the Oatman and Cold Road Formations is composed of coarse-grained lithic, crystal, biotite latite ash near the central district, but grades into a biotite-poor fluvial arenite to the west. Earlier workers have included the unit with the Oatman Latite lithology but because of the presence of biotite we interpret it as part of the Cold Road Formation. The Esperanza, Oatman, and Cold Road Formations are collectively termed the middle volcanics (10).

Based on the similarity of distribution of the Oatman and Cold Road Formations and on their transitional petrologic character, Thorson (10) felt these rocks were comagmatic and originated at a shield volcano centered near the town of Oatman. In support of this idea, Thorson (10) cites as evidence several large latite dikes and plugs in the area. However, no breccia pipes or vertically laminated rocks suggestive of a vent have been found.

The middle volcanics are unconformably overlain by the upper volcanics, a series of trachyte, quartz latite, and rhyolitic tuffs and lavas. The lowest unit, the Antelope Quartz Latite, has been K/Ar dated at 18.7 ± 0.9 m.y., indicating the volcanic hiatus between the middle and upper volcanics was short lived. The upper volcanics are in turn unconformably overlain by olivine basalts which in Pliocene time covered much of the region.

The middle volcanics were intruded by a 2 x 4 mile quartz monzonite pluton, the Moss Porphyry. Considerable debate has revolved around the age of the Moss Porphyry relative to that of the Times Porphyry, middle, and upper volcanics. Ransome (7) felt the Moss Porphyry predated the Times Porphyry but detailed field work by Thorson (10) refutes this. Thorson (10) found the Moss to intrude the lower and middle volcanics but because of erosion could not directly establish crosscutting relationships between the Moss and upper volcanics. However, based on two other lines of evidence he concluded the Moss postdated the upper volcanics. This evidence included a K/Ar date of 10.4 ± 0.5 m.y. for the Moss Porphyry, and an intense argillic alteration, interpreted by Thorson to be a late phase of the Moss Porphyry intrusive event, which affects the lower through the middle volcanics, plus a lower unit of the upper volcanics.

Thorson's (10) conclusion that the Moss intruded the upper volcanics is probably correct, but the date and alteration event are, in our opinion, misinterpreted. Thorson (10), based on chemical and petrological data, did establish that the Moss Porphyry, middle, and upper volcanics were comagmatic, and reasonably interpreted the Moss Porphyry as a late stage epizonal pluton which intruded its own volcanic cover. Unlike the Alcyone Formation, however, the middle and upper volcanics contain no collapse breccias or ash flow sheets indicative of a collapse or resurgent caldera.

Structural relationships shed some light on the temporal and genetic relationships between the Moss Porphyry and the post-lower volcanic events. Figure 2 shows the main structural features in the Oatman District. Included are the positions of the Times and Moss Porphyrys, the larger rhyolite dikes, and the limits of the argillic alteration.

The structural pattern is dominated by a set of concentric fractures which define a near perfect 5 mile diameter circular feature. This feature was identified during study of Landsat imagery and high altitude aerial photography. Cutting the concentric fracture set is a separate set of fractures which radiate from a common point near the center. The ore deposits of the central district are located within a wedge of radial fractures which cut the concentric set 3 miles southeast of the center point. The following cross cutting relationships should be noted:

1) The concentric fractures cut the Moss Porphyry and the upper volcanics.
2) The concentric set predates the rhyolite dikes.
3) The radial set postdates the rhyolite dikes and the concentric set.
4) The radial set hosts the mineralization in the central district.
5) The radials are found to predate the argillic alteration.

Because the concentric and radial fracture sets appear to be related by symmetry and age, postdate the Moss Porphyry, but predate the mineralization in the central district, the development of the fractures is interpreted by the authors as representing a separate stage in the evolution of the district. This stage is rated just as important and as distinct as the preceding Alcyone resurgent caldera stage and the middle and upper volcanic-Moss Porphyry stage.

What is the nature of this third stage? The volcanic units cut by the concentric fracture set are not offset, nor have any major breccia zones been discovered along them. The concentric set therefore does not appear to represent a major fault system. Rather, the concentric fractures resemble a joint set, perhaps developed during ascent or descent of an underlying magma. The dimensions of the magma may correspond to the dimension of the circular feature and the radial fractures may have been caused by distension during magma ascent. The fracture or joint pattern found in Oatman is strikingly similar to theoretical fracture geometries which would be developed above diapiric intrusions penetrating an elastic crust (11, 12, 13).

This hypothetical magma may, or may not, be the source for the lower through upper volcanics and the Moss Porphyry. The development of the circular and radial fracture set over this possible source is interpreted as heralding a third stage of magmatic activity which is responsible for the rhyolite dikes and the quartz-calcite-gold mineralization.

Recent mapping has shown the argillic alteration is centered around a previously unrecognized rhyolitic center located on the east margin of the Moss Porphyry. Rhyolite dikes from this center cut the Moss Porphyry. The alteration is therefore interpreted as postdating the Moss Porphyry and is a product of the third stage. The argillic overprint which affected the Moss Porphyry - interpreted by Thorson (10) to be a late phase of the intrusive event - probably affected the biotite which Thorson (10) selected for dating. The 10.4 ± 0.5 m.y. date obtained for the Moss Porphyry appears to be too young, particularly for a pluton which intruded its own co-magmatic volcanic cover dated at 18.7 ± 0.9 m.y. A suggestion which is more attractive, although little work has been done to substantiate it, is that the Moss Porphyry represents the magma chamber which produced the middle and upper volcanics. As mentioned previously, isopachs of the Oatman and Gold Road Formations indicate a source in the Oatman area. In spite of this and the efforts of several able mappers, no volcanic vents have been found near Oatman. Recent mapping near the Moss Porphyry shows an apparent transitional character across the Moss Porphyry-middle volcanic interface which, although highly altered by hydrothermal activity, is not inconsistent with a gradation from plutonic to volcanic source.

Local Geology and Structure

Production in the central district came from two major veins, the Tom Reed and the Gold Road. Each vein occupies a north-dipping radial fracture (Figure 3). At least one similar vein exists, the Kokomo; however, this structure has been only partly explored and has had no significant production. These radial fractures form a wedge approximately 1.5 miles wide at the intersection with the concentric fracture set. The locus of mineralization appears to be associated with this intersection as is the majority of earlier emplaced rhyolite dikes and plugs.

The most productive vein of the district is the Tom Reed. The vein splits beneath the town of Oatman into the United Eastern and Olla Oatman segments. Each segment dips north for approximately 3000 feet, then undergoes a dip reversal to the south. The Olla Oatman segment splits and horsetails northwest of the point of dip reversal, but the United Eastern segment continues to the center of the circular feature. The point of dip reversal coincides with a change of strike orientation on each segment. The Tom Reed-United Eastern structure is a normal fault which dropped the Gold Road Latite against the Oatman Latite. The Olla Oatman may have dip slip movement but because it is entirely hosted by the Oatman Latite no displacement has been determined. Although there was appreciable dip slip movement on the Tom Reed-United Eastern structure, 3000 feet northwest of the United Eastern mine a pre-mineralization rhyolite dike is not appreciably offset by the structure. Structural relationships indicate the dike predates the radial fracture; therefore, it would appear the majority of movement on the structure was taken up southeast of the point of dip reversal. This is a possible explanation why no large (>50,000 ton) orebodies have been found on south dipping sections of this vein (see below).

The Kokomo vein dips north on its southeast end, then reverses dip on a line which is coincident with the reversal points on the United Eastern and Olla Oatman veins. Similar to these two veins, the bearing of the Kokomo changes at the point of dip reversal to a more northerly direction. The axis of dip reversal is subparallel to the concentric fractures. This axis appears to correspond to the interface of two structural domains. No dip reversal is found on the Gold Road vein. There is no evidence to indicate the dip reversal on the Olla Oatman, United Eastern, and Kokomo structures was caused by post-structure tectonic movement.

The Tom Reed, Kokomo, and Gold Road structures are the most persistent in strike length. None appear to continue more than a mile beyond the perimeter of the circular feature. The Tom Reed vein is cut by the Mallery fault, a south dipping structure which branches and parallels a large rhyolite dike between the Tom Reed and Kokomo structures. The fault splits and parallels the Tom Reed vein along its southeast extension. The Oatman fault, a northerly dipping structure, cuts the Mallery near the Big Jim mine.

Several additional north dipping structures are found one mile southwest of the Tom Reed vein (Figure 2), but none of these have had significant production. They are shorter on strike length and appear to be part of a discontinuous fracture zone which parallels the Tom Reed. Most of the structures in this zone dip to the southwest and are hosted by the Oatman Latite.

One vein in this area is positioned at the fault contact of the Oatman Latite and Alcyone Trachyte. The vein persists for several thousand feet on strike and probably owes its planer character to the sharp contrast in rock properties across the fault.

As will be discussed below, orebodies in the Oatman Latite tend to be stockwork type with brecciation and vein filling restricted to finite strike lengths, generally 1/2 to 1 times the dip length. The Cold Road vein, unlike the Tom Reed, is a fissure type and is developed almost entirely in the Cold Road Latite. This volcanic unit exhibits fissile fracturing, producing very long, narrow, and continuous openings for mineralization. Below the Cold Road Latite the transition zone is encountered. This unit is of Cold Road Latite petrology but behaves like the Oatman Latite during deformation. Orebodies in this horizon along the Cold Road vein are podular and of the stockwork type found in the Tom Reed vein.

The Kokomo vein is in Cold Road Latite at the surface but is expected to pass into the transition zone or Oatman Latite at about 500 feet depth. The mode of mineralization is expected to change from fissure type to stockwork type across the interface. The effect of different rock types on the mode of fracturing and development of deposits in the Oatman District is seen in Figure 6.

From Figure 3, crosscutting relationships indicate the rhyolite dikes were emplaced prior to the formation of the radial fractures. Most of the dikes dip 80° to the south and southwest while the past-productive sections of the veins dip 80° north. The dikes have a general east-west trend west of the central district, but tend to parallel the vein structures within the district. An example is the above-mentioned dike which is crosscut by the United Eastern segment of the Tom Reed vein. Within the workings of the United American mine on the southeast end of the Tom Reed vein, Hershey (14) notes a rhyolite dike which is altered and closely associated with the orebody. Separate rhyolite dikes parallel the Kokomo and Cold Road veins. These relations indicate the vein structures had at least their beginnings in the same structural framework which determined the emplacement of the rhyolite dikes. Because these trends parallel one another for at least a mile, the structures which host the rhyolite dikes and the veins are probably genetically related.

As noted previously, the intersection of the radial and concentric fractures at Oatman is also the locus of the majority of rhyolite dikes and plugs, as well as mineralization. This area was obviously a preferred avenue for the release of siliceous magma and volatiles such as CO_2. Near the Kokomo vein the rhyolite dike blossoms into a rhyolite plug. A similar plug, the Boundary Cone, is situated 2 miles south of Oatman (Figure 2).

Ore Deposits

The orebodies of the central district, hosted by the Tom Reed and Cold Road structures, account for approximately 90% of the production of the Oatman District. A breakdown of grade and tonnage for the major orebodies is presented in Table 2.

The orebodies occupy dilatant zones within the Tom Reed and Cold Road fault structures. They have, in typical epithermal vein fashion, bottoms and tops which are sharp and follow subparallel horizontal datums. In the case of the Tom Reed structure and the northwest end of the Cold Road structure, the orebodies have restricted strike length and are periodically located along strike. In the Cold Road Latite portion of the Cold Road vein, the orebody occupies a continuously open fissure. Longitudinal sections of the Tom Reed and Cold Road systems are presented in Figures 7 and 8.

Individual orebodies within the Tom Reed-United Eastern vein vary from a maximum width of 45 feet in the United Eastern orebody to 2 or 3 feet in the Telluride. Widths of 35 feet are reported from the Big Jim orebody and 10 to 20 feet from the Tip Top and Ben Harrison. The United American and Black Eagle averaged 10 feet and the United Western 6 feet. Vertical intervals of ore deposition ranged from 1300 feet in the Tip Top and Cold Road to 300 feet in the United Western. In general, the size (in all dimensions) and grade of the orebodies on the Tom Reed-United Eastern vein decrease away from the center of production at the town of Oatman.

Only two orebodies outcropped: The Ben Harrison and Cold Road. The remainder were discovered 50 to 500 feet below the surface.

The Cold Road orebodies averaged 3 to 6 feet wide within the Cold Road Latite, but widened to 22 feet in the No. 1 orebody which is within the underlying transition zone. Three large, generally richer orebodies, including the No. 1, were discovered beneath the Cold Road Latite along this vein. The northwest extension was apparently faulted off but never recovered.

Along the Tom Reed vein system the orebodies are separated by fault gouge or narrow stringers of calcite or quartz. The structure is found to pinch tight lateral to the main orebodies. The width of the barren structures varies but probably averages 5 to 10 feet. The structures have experienced movement before, during, and after ore deposition. Movement during or after has been slight, resulting in crushing or rotation of rock or vein material. Pre-mineralization dip slip movement was in the order of hundreds of feet. Pre-mineralization strike-slip movement was probably not greater than a few hundred feet, based on structural analysis which will be discussed below.

The form of the orebodies varies from tabular fissure fillings to complex stockworks of broken, vertically orientated latite slabs separated by quartz-calcite veins ranging from fractions of an inch to 15 feet wide.

Vein Mineralogy

The following is abbreviated from the detailed accounts of Ransome (7) and Lausen (8).

Five stages of quartz-calcite ± adularia deposition are recognized in the district, although no single deposit contains all five. Each stage was accompanied by calcite, the last two by adularia. All five stages are gold bearing, but only the last three are associated with commercial ore. The ratio of gold to silver in the quartz increased from 1:6 in the first stage to 4:1 in the last stage. The quantity of gold and silver for each stage of calcite has not been determined. Gold was rarely found in the native state, except in fault zones which were supergene enriched. The vast majority of gold was found associated with silver in electrum. The electrum is microfine and assays about 800 fine. No base metals or sulfide minerals other than pyrite have been found in the central district. A trace of malachite has been seen in some highly oxidized fault zones. Green to yellow fluorite occurs locally in the areas of the Times Porphyry and Moss Mine (Figure 2).

Pseudomorphic textures show quartz replaced calcite in all stages but the last. The final three stages of quartz have green to yellow coloration and a greasy feel and luster. The greenish color is caused by microscopic disseminated chlorite.

The green to yellow generations of quartz have been recognized in veins from several miles south of Oatman to the Katherine District 20 miles to the north. The source of the quartz (and presumably calcite) is obviously larger than a local thermal source such as a pluton, or country rock caught up in a single cell of a geothermal system. A larger thermal source which gave rise to at least several local thermal centers is indicated.

Summary

The data summarized above are typical of the descriptions available for most large mining districts in the western United States and Mexico. Other than augmenting field work with geochemical sampling it is also typical of the type of data collected by most exploration geologists today. Recent studies by some university workers have stressed, in addition, fluid inclusions, isotopic, and geochemical relationships but few of these, even in conjunction with detailed field work, have produced a synthesis which is useful to exploration. A notable exception is Kamilli and Ohmoto (15).

Exploration Methods

The characteristics of the Oatman deposits are similar to many epithermal vein deposits around the world. Some of the characteristics have only recently become recognized and taken advantage of. It is these characteristics which will enable explorationists to assess epithermal systems in a more efficient and intelligent manner.

Within a past productive district the useful exploration tools are those which define the structural control, the alteration and geochemical signatures, and thermal source associated with the ore deposits. Broad scale geology and tectonic synthesis, vein mineralogy, paragenetic relationships, and petrologic investigations are secondary in importance.

At Oatman our efforts began with identifying the structural control, alteration type, and horizon of ore deposition of the known orebodies. No drilling was attempted on new targets until these relationships were established to a point of certainty that the location of all known ore shoots could be identified without qualification. In the process of determining these controls, new targets were identified and a total geologic-geochemical synthesis partially completed.

The readily identifiable and useful characteristics of vein deposits can be grouped under structural controls and chemical effects associated with the ore deposition process. These can be identified and applied during exploration utilizing the following tools:

A) Structural Controls
  - Vein Contouring: definition of structural traps

B) Chemical Effects
  - Detailed Mapping: wallrock alteration
  - Fluid Inclusions: temperature and depth of deposition
  - Geochemical Sampling: leakage and geochemical imprint

Each of these will be discussed and the data collected pertaining to each will be presented. Application to exploration will be discussed by comparing the "before and after" evaluation of known deposits and new targets based on work completed to date.

Structural Controls

Planar structures such as faults, fissures, or lithologic contacts which host vein type deposits usually appear fairly uniform in small scale but can be highly irregular in large scale. The small scale image of the structure is too often used as the exploration target. This is because the entire host structure has often been assumed, within limits, to be fair game for additional deposits. The longitudinal section of the Tom Reed vein (Figure 7), which is similar to many veins in epithermal districts, shows the shortsightedness of this approach. Considerable money has been wasted by companies who drilled between, above, or below old (or virgin) orebodies because the structural control of the known deposits was not established at an early stage of exploration.

The large scale image of the host structure is determined through the vein contouring technique. The three dimensional control of an orebody can very often be determined if the plane defined by the footwall or hanging wall is contoured against an inclined reference plane passed parallel to it (Figure 9). The technique has been described by Connolly (16) and has been used effectively by the authors in Magollon, New Mexico; Mother Lode, California; Idaho Springs, Colorado; and Guanajuato, Mexico. A recent application in England is cited by Gough (17). The method has also been successfully used on the stratiform massive orebodies at Broken Hill, Australia (18).

Figure 10 shows a typical situation where a sub-planar structure has undergone a small amount of strike slip of dip slip movement. The openings produced, the loci for later hydrothermal ore deposition, are created at pre-existing irregularities in the plane of the structure. The width of the opening(s) produced is generally many times smaller than the strike length of the structure. For instance, most epithermal deposits, including the "bonanza" deposits of several famous districts, rarely exceeded 50 feet in width, while the host structure often exceeded a mile in length. The magnitude of the dilation, relative to the strike length, was often less than 1 or 2 percent. Because the size of the dilation may be influenced by intersecting structures or plastic (versus brittle) deformation of the host rock, the size of the original irregularity on the structure may be even less. In any case, on the ground, on maps, or from aerial photos, the decisive bend, or flexure on the structure may be invisible due to its small relative size and to the effects of topography.

Vein contouring accentuates internal inhomogeneties in the vein structure relative to its own average attitude. This application differs from the more commonly used technique which determines the thickness of the mineralization within the vein. In practice, the structure or vein is located on a large scale topographic map or is surveyed in at 50 to 100 foot intervals. Strike and dip is recorded at each survey point. Close horizontal and vertical control is necessary at intervals which are several times smaller than the anticipated strike length of an orebody. An average dip and strike of the structure is selected and a reference plane of like attitude passed parallel to the vein, usually several hundred feet into the footwall (Figure 9). A plan of the vein is produced by selecting a random elevation, say 100 feet below the lowest outcrop of the vein, and plotting the distance of all control points on the vein from the control plane. The points on the vein are corrected to the selected elevation according to the measured dip at the surface. If subsurface data are available, such as drill intercepts or mine maps, the down dip morphology of the vein can be determined. The map produced is a longitudinal section of the vein showing the deviation of the structure from a perfect plane. Superimposing the outline of the known orebodies on the contour map will identify the structural regime which hosted ore. Periodicity, rake, width and depth control will usually be identifiable. Vertical and lateral pinchouts are usually identifiable by steepening of contours. Figures 11, 12, and 13 are the plan and contour results obtained for the Cold Road, Tom Reed, and Kokomo structures, respectively.

Discussion

The contours of the upper levels of the Cold Road vein (Figure 11) do not indicate clearly the points of dilation which hosted the wider ore shoots in this essentially continuously mineralized structure. The plan view is more informative. The wider zones can be seen to occupy dilatant zones which are periodically positioned along strike. These dilatant zones originated during largely dip slip movement which had some right lateral strike slip component. Because the Cold Road Latite behaved brittley during deformation, the opening produced is sharp and continuous on strike. The mineralizing event deposited vein material throughout the structure producing a fissure-like deposit.

On the northwest end of the vein the plan view changes character reflecting the change in style of deformation as the fault propogated through the underlying transition zone and Oatman Latite. The contour map illustrates this difference as a steepening of the contours. Deformation in this area was more plastic than in the overlying Cold Road Latite. The orebodies in the transition zone and Oatman Latite are nodular, wider and, in general, closely resemble the stockwork orebodies on the Tom Reed structure.

If the contour and plan maps of the Cold Road vein are used for exploration purposes the following points become evident. Drilling between the dilatant zones may produce narrow ore intercepts but will not appreciably add to reserves. The areas correspond to pinch zones. On a smaller scale, the vein shows long wavelength periodicity of barren and productive sections on strike. Between the No. 1 orebody and the beginning of the continuous mineralization in the Cold Road Latite there is a nonproductive "step" or barren zone. A similar barren zone exists on the southeast end of the vein, past the last working within the mine. Beyond this barren stretch should be another productive stretch of similar, periodically located dilatant zones. A similar feature is found in the Tom Reed structure. Exploration should be directed along this southeast limb. In addition, an effort should be made to locate the remainder of the productive limb on the northwest end of the vein.

With appropriately detailed mine maps, highly accurate contour maps can be constructed which allow identification of other features in the old workings. Change of rock type, as illustrated by the Cold Road Latite-transition zone contact, may be indicated by a change of character of the contours. Faulting of the vein or orebody may be indicated by mismatched or dislocated contours. Further, a contour and plan map of a vein offers the structural geologist an unparalled view of the morphology of large planar structures which can be used in regional structural analysis. Three dimensional stress orientations can be obtained from this type of study.

The Tom Reed Vein (Figures 12a and 12b) displays distinctly concave north bends which, like the Cold Road vein, are coincident with major ore deposits. Subtle points of curvature along the vein are hosts to narrower orebodies such as the United American and Black Eagle. There is excellent correlation between the size of the curvature and the width and total tonnage of the deposits. All orebodies within north dipping sections of the vein are located in concave north bends. Concave bends which are opposite the direction of vein dip appear to be zones of pinching and are nonproductive. The lateral cutoff point for ore deposition within the dilatant zones corresponds to the northwest flank of each concave north bend.

The division of the Big Jim orebody by the post mineral Mallery fault (Figure 12b) is seen in the contour map as a translation of matching contours. This displacement can be used as a crude estimation of the displacement on the Mallery fault.

The Tom Reed shows the periodic productive and nonproductive stretches like the Cold Road vein. The blank interval between the Ben Harrison and Big Jim orebodies (Figure 12b) was explored by drifts from both mines and by subsurface drilling from an exploratory drift to the east. Except for a very small body of ore in the Ben Harrison exploration drift no mineralization was found in this section of the structure. The small body of ore does correspond to the only small concave bend found on the plan view within this section of the vein. The lack of ore in this section of the vein had been attributed to the Oatman fault which cuts the Mallery fault just north of the Big Jim orebody. The fault is thought by some workers to merge with the Tom Reed vein, downdropping it to the northeast. A review of past drilling efforts by Vaara (19) indicates the holes may not have been deep enough to intercept the hypothetical downdropped block based on the measured dip slip of the Oatman fault. In any case, our contouring results indicate this stretch of the vein lacks the concave north bend(s) necessary for significant ore deposition. This is believed to be correct in spite of the periodically located individual orebodies on the productive stretches adjoining to the northwest and southeast. Simply assuming the periodicity continues between the productive sections would indicate the possibility of 2 or 3 orebodies totaling about 1 million tons. A rather aggressive drilling program could have been initiated on this assumption. However, our structural analysis indicates low probability for additional orebodies and the target has been relegated to a much lower priority. This decision was supported by additional evidence which will be discussed below.

The Tom Reed vein, like the Gold Road vein, has indications of another productive stretch to the southeast, based on favorable structure. A nonproductive stretch exists between the United American and Argo shafts (Figure 3). Beyond the Argo the outcrop of the Tom Reed vein goes up an escarpment and has not been explored by shafts or drifts. However, preliminary field mapping shows characteristic ore-associated alteration (see below) along the vein and indications of a zone of curvature.

The unproductive Olla Oatman segment of the Tom Reed vein displays no concave north curvature; therefore, vein contouring data is not presented.

The United Eastern segment (Figure 12a) contains the western arm of the concave north bend which began on the Tom Reed vein near the Ben Harrison workings. Its east arm hosts the Tip Top and Ben Harrison orebodies. It is interesting to note that on the surface and within the mine workings the "y" junction of the Olla Oatman and United Eastern segments with the Tom Reed structure is symmetric, with nothing to indicate which segment was the preferred direction of mechanical release. The junction of these structures, rather than being an area of high permeability for hydrothermal fluids, was only part of a larger zone of curvature which was the avenue of fluid flow. The observation that the structural intersection itself was not the focus for fluid flow and ore deposition was made by Lausen (20), thereby distinguishing Oatman from many districts where structural intersections were in fact the preferred area for ore deposition. On the Tom Reed, however, the junction itself is unmineralized and ore exists lateral to it on the flanks.

Northwest of the United Eastern orebody a dip reversal occurs near the Red Cloud shaft. This is also a zone of concave north curvature and intense alteration. The combination of a zone of dip reversal with a zone of strong curvature has no analog in the productive parts of the veins. If these two characteristics accentuate each other and produce a zone of increased dilation and brecciation is uncertain and remains to be tested. Indications are that the zone was indeed favorable for ore deposition, based on the associated alteration at the surface (see below).

The United Western is the most northwesterly orebody on the Tom Reed system. It is located in a shallow concave north zone of curvature on the south dipping portion of the United Eastern segment. The orebody has limited vertical extent and is of lower average grade than the other orebodies on the Tom Reed-United Eastern structure. As noted previously, this portion of the vein shows little strike slip component. The long, horizontal configuration of the United Western orebody may reflect the dilation effects of dip slip movement without an appreciable strike slip component.

Figure 13 shows the plan and contour maps for the Kokomo structure as deduced from survey data. The contour map was constructed by measuring the distance of points on the surface of the vein to points on the reference plane. Although the down-dip contours are conjectional they do give a picture of the shape of the structure. The plan section can be compared with the bends on the Tom Reed-United Eastern structure and an idea gained as to the location of potential orebodies within the bend.

The Kokomo exhibits a profound concave north curvature along a strike length of 1000 feet. This is comparable in size to those bends hosting the two major mineralized sections on the Tom Reed structure. This, coupled with intense alteration at the surface (see below) makes this an attractive exploration target.

Summary

Plan and contour maps of the productive veins in the central district have allowed quick and precise identification of the preferred structural zones of ore deposition. Both productive and nonproductive sections of the veins are accounted for, as well as the non-mineralized areas between individual orebodies. Application of the data for the location of new targets on unexplored structures is straight forward.

Chemical Controls

Ore deposition in epithermal vein deposits is, like all hydrothermal deposits, governed by the interplay of temperature, pressure, and solution chemistry. Obtaining a measure of the inter-dependence of these parameters in an ore deposit is a formidable task. Studies incorporating field data with comprehensive chemical-thermodynamic modeling schemes have only recently been attempted (21, 22). This is an avenue of geochemical research which is very new and promises many insights into the ore-forming process. The usefulness to the explorationist remains to be tested. Utilizing available tools a measure of the individual parameters can be made, however. These measurements are clues about the ore deposition process which can be used to advantage by the explorationist. If what is measured is cause or effect is a distinction which is probably irrelevant. What is important is that these measured characteristics are associated with the ore-forming process and can, therefore, be searched for in new areas.

The most exploration-useful results of the ore deposition process are:

a) wallrock alteration

b) fluid inclusions in the minerals of the alteration or ore assemblage

c) dispersion of trace elements beyond the confines of the orebody itself

These three products were studied at Oatman. The characteristics of each in the district will be discussed and the results of the application of each to exploration will be presented.

Wallrock Alteration

Detailed alteration mapping has been found to be as important and definitive as vein contouring in pinpointing the location of known ore deposits in the Oatman District. These two methods alone or used in conjunction would enable the explorationist to evaluate the ore controls and to locate the vast majority of new targets in the central district. However, the use of additional tools such as fluid inclusion temperature determinations and geochemical sampling have been found to make the search much more time and cost efficient and more intelligently directed.

Recent work by Buchanan (23,24) in Guanajuato, Mexico, has shown that relatively deeply buried (1000 feet) orebodies can have unique alteration assemblages which extend above the orebody to the paleosurface. This is not surprising if one recognizes the similarities between epithermal vein systems and present-day geothermal systems. This assemblage, especially when developed far above the orebody, may be quite limited in areal extent. Length and width dimensions of the assemblage at the surface may be measureable in hundreds or even tens of feet. Because of this the usual mapping scales of 1"=500', or smaller, are inadequate.

At Oatman a mapping scale of 1"=100' was used. Field base maps consisted of black and white photo prints enlarged to approximately 1"=100' from 1"=500' airphoto negatives. The field data were collected and transfered to 1"=500' master geology and alteration topographic maps. Mapping at this scale enables the staff to delineate relatively small outcrops of variably altered rock. Concentrating initially on the ore-bearing structures, the rock type, mineralization, alteration, and structure were recorded. Coverage was later expanded to extensions of the veins and ground between parallel veins. Coverage was accomplished at the rate of about 2 sections per man month. The time required to discover and fully document the characteristic alteration assemblage along the Tom Reed vein was approximately one man month. The distribution of this assemblage was found to correlate perfectly with the structural "traps" identified by vein contouring.

In the central district a simple volcanic stratigraphy and minor post mineral faulting allowed fast compilation of basic geology during mapping. Mapping of alteration actually consumed more time than rock types, structure, or mineralization, although each was recorded simultaneously.

In the field a subjective criteria was used for delineation of alteration types and intensities. The precise identification of the alteration suite was not considered important in the early stages. Later, after the alteration haloes above the known orebodies were recognized and mapping advanced outward from the productive areas, X-ray diffraction work was undertaken to obtain a precise idea of the alteration minerals. One instance where this was particularly important was the distinction between the phyllic (illitic) alteration halo found above the orebodies and the argillic (alunitic) assemblage found in some post-mineral faults and in the strongly altered area near the Moss Porphyry (Figure 2).

Three types of alteration were mapped in the field: argillic, propylitic, and silicic. The "argillic" was later divided into phyllic and argillic based upon X-ray work. Along the productive veins this distinction did not affect our earlier conclusions regarding the type of alteration signature associated with ore deposition.

The following field criteria were used. Note how imprecise the criteria can be and still be adequate for defining alteration intensities and grades. Note as well that the criteria is based upon the appearance of rocks and not the identification of minerals. The following descriptions apply to typical dark gray-green to black latite, the dominant rock of the district. Weaker alteration, which is often indistinguishable from deuteric alteration, was not mapped, except where weak phyllic alteration appeard to affect a large area.

A) Propylitic
- Moderate - Outcrop has irregular green patches but original gray color or rock is still largely visible.
- Strong - Pale green throughout outcrop. Feldspars usually tinted light green.

B) Phyllic and Argillic
- Moderate - Rock is visibly whitened or "bleached", although pronounced shades of green or gray may still persist. Original rock textures are discernible, but outcrop is softened although not crumbly.
- Strong - Rock is white to yellow (due to oxidation of pyrite) although shades of green or "clots" of nearly fresh rock may persist. Textures are largely destroyed. Rock is crumbly in hand samples.

Except for the presence of alunite, the phyllic and argillic grades have similar appearances. The shape of the respective alteration haloes differs, however (see below).

C) Silification
- Moderate - Rock is hardened due to introduction of quartz along microfractures. Volumetrically, introduced quartz is generally less than 20%.
- Strong - Rock is heavily invaded by quartz veins and fracture fillings. Outcrop may constitute a low grade stockwork orebody. Segments between veinlets is silicified to dense, gray, "cherty" rock.

The results of alteration mapping to date in the central district are presented in Figure 14. A diagram illustrating the type and shape of the alteration halo developed at Oatman and the present-day level of exposure of the known orebodies relative to it is presented in Figure 15. The following points should be noted:

a) A wide zone of moderate to intense phyllic alteration is found above every known orebody on the Tom Reed-United Eastern vein system. These zones are restricted on strike but "blossom" laterally, particularly into the hanging wall. The size of the alteration zone is proportional to the size of the orebody (or more precisely to the size of the dilatant zone at the point on the structure).

b) Narrow, linear alteration zones are found on the post-mineral Mallery fault. These zones do not "blossom" and are thought to represent very late stage, low temperature ground water movement, or to represent the effects of a separate thermal event to the northwest. Preliminary X-ray diffraction work indicates this alteration is argillic and not phyllic.

c) Alteration along the Cold Road vein within the Cold Road Latite is poorly developed, except for silification which is coincident with the orebody itself. Where the vein enters the upper volcanics a phyllic halo is developed. Beneath the Cold Road Latite and within the transition zone phyllic alteration is once again strongly developed, as on the Tom Reed vein.

d) Alteration in the very northwest end of the United Eastern structure is argillic. This correlates with a broad, intense argillic event which has been mapped on the east margin of the Moss Porphyry (Figure 2).

On the Tom Reed vein each zone of phyllic alteration is directly correlatable with a zone of structural curvature seen in Figures 12a and 12b. Inflection points on relatively straight stretches of the vein, such as the one located above the United American orebody, also exhibit phyllic haloes. The barren stretch between the Ben Harrison and Big Jim orebodies contains no phyllic alteration, consistent with the lack of curvature in this portion of the vein. These two facts indicate this stretch has limited potential for significant mineralization.

No phyllic alteration is found on the Olla Oatman segment of the Tom Reed vein. This detracts from the possibilities of there being significant mineralization in this portion of the vein.

Between the United Eastern and United Western orebodies a large phyllic halo is found in an area where a large concave north bend is coincident with a zone of dip reversal. This is the only untested phyllic zone on the Tom Reed vein system in the central district, other than one recently discovered southeast of the Argo shaft.

All known orebodies in Oatman, no matter how deeply buried, exhibit phyllic alteration on the surface.

An example of the need for correlating both structural and alteration signatures was demonstrated on the Pasadena vein one mile west of the United Western orebody (Figure 14). This structure dips south and parallels the northwest extension of the United Eastern structure. The vein is continuously mineralized with early calcite and quartz for 3000 feet along strike. Geochemical samples were anomalously high coincident with a zone of concave south curvature centered at the Pasadena shaft. No phyllic alteration was seen. Three drill holes, the deepest of which intercepted the structure at 600 feet below the surface, failed to intercept any vein material assaying over 0.1 O/T Au. The quartz-calcite mineralization actually died out several hundred feet below outcrop. These blank holes lend strong support to the idea that both structure and alteration must be present before significant mineralization can be anticipated. Our reservations concerning geochemical sampling as a guide to ore in epithermal districts was also substantiated. The geochemical anomaly found on the Pasadena vein is apparently due to supergene enrichment.

The Kokomo Vein contains a large phyllic halo over the concave north zone of curvature (Figure 13). This is regarded as very positive evidence for significant mineralization at depth. The fact that the phyllic alteration is so strongly developed in the Cold Road Latite is particularly impressive when the lack of alteration along the Cold Road vein is considered. Several small areas of advanced propylitic and phyllic alteration are found to the northwest of this zone. These zones of alteration have anomalous geochemical signatures and are situated in a zone of dip reversal.

Summary

A unique, spatially restricted phyllic alteration assemblage was identified above every known orebody in the central district in the course of large scale (1"=100') mapping. The phyllic zones correlated perfectly with zones of curvature on the vein structures which are known to host ore grade mineralization at depth. The use of alteration mapping in conjunction with vein contouring eliminates areas which are structurally attractive but have received no significant mineralization. The occurrence of phyllic alteration outside of zones of curvature must be individually evaluated.

Fluid Inclusions

Several detailed fluid inclusion studies have been made on epithermal vein deposits similar to Oatman. These include the Tayoltita (25), Guanajuato (23,24), and Pachuca (26) deposits in Mexico; Finlandia, Peru (15); Sunnyside, Colorado (27); Creede, Colorado (28); and the Baquio District, Philippines (29).

The application of fluid inclusions to the study of temperatures in ore deposits has been reviewed by Roedder (30), and Roedder and Bodnar (31) have discussed the application of fluid inclusions for pressure determinations. A new approach to chemical analysis of fluid inclusions was applied by Buchanan (23,24) based on a highly sensitive wet chemical method developed by Clark (32).

In Oatman, fluid inclusion temperature determinations were initially used for reconnaissance purposes only. Samples of quartz, calcite, or fluorite were collected from veins from around the district. About two dozen samples were collected from the Tom Reed, Cold Road, and Kokomo vein systems. The temperature and textures obtained from these largely random ore-stage samples, unqualified as to position in the hydrothermal system or thermal source, gave us immediate information on the temperature range of ore deposition in the central district and corresponding data for productive and nonproductive veins removed from the central district. Textural information, in conjunction with temperature information, helped to define if the system was boiling or not at the time of ore deposition. The presence of daughter minerals indicated high salinity solutions and, tentatively, that the sample point was below the boiling interface. Collection of ore stage material at outcrop above known orebodies gave temperature information which, when plotted against the known depth to the top of the orebody, resulted in a crude, empirical representation of the paleogeothermal gradient in the system at the time of ore deposition. Such a plot, shown in Figure 16, can be used to guide the depth of drilling of new targets if a temperature can be obtained on ore-stage material collected at the surface.

Fluid inclusions obtained along the Tom Reed vein average 220-240°C and were boiling, as evidenced from highly variable homogenization temperatures and "explosion" textures described by Roedder (30) and Buchanan (23, Figure 17). Samples from the Cold Road vein were too fine-grained to be useful for temperature determinations. Textural evidence indicates the solutions boiled periodically, however. Samples from the zone of curvature on the Kokomo structure gave temperatures in the range of 200-220°C, indicative of a horizon of ore deposition which is elevated relative to the Tom Reed and Cold Road systems. Several samples collected in the argillically altered area near the Moss Porphyry ran about 200°C, consistent with the assumption that the alteration represents a high level, near surface event which gave rise to acid, oxidizing solutions.

The fluid inclusion apparatus cost about $10,000, including microscope and heating stage, and is located on the job site in Oatman. We feel it has paid for itself several times over during this exploration phase of the project by establishing a depth control for drilling and, most importantly, eliminating certain vein systems which otherwise are very attractive. An example is the Boundary Cove system to the south of Oatman (Figure 2) which on the surface shows large quantities of late stage quartz and widespread silicic alteration. Geochemical samples were unimpressive but experience showed such sampling was not definitive. No phyllic alteration was seen, but because the host was not Oatman Latite phyllic alteration was not necessarily anticipated. Orebodies at depth were certainly a possibility and a significant portion of the drilling budget was preliminarily earmarked for this area. Later, several rocks taken from the vein outcrop were examined for fluid inclusions. To our disappointment (and relief, for we were running out of ways to assess the vein system short of drilling it) many fluid inclusions were found which contained daughter salts and would not homogenize below 400°C. We concluded that the system represents the root zones of a once larger system, now largely removed by erosion. This conclusion will be checked by mapping and further fluid inclusion work. In this case an expensive drilling program was delayed for reevaluation.

Summary

The ability to generate temperature, textural information, and estimates of salinity (based on the presence or absence of daughter minerals) from fluid inclusions is the fastest and most accurate method of establishing a level within a system, distinguishing between otherwise similar looking hydrothermal systems, and identifying the thermal center(s) of the district.

Geochemical Sampling

Due to the success of vein contouring and detailed alteration mapping in identifying the position of known mineralization, the identification of a potentially unique trace element signature in vein material or wall rocks above orebodies has not been attempted. Assay results for gold and silver in vein outcrops have been highly inconsistent when related to the size and grade of known mineralization at depth. Samples taken within feet of the tops of the Big Jim and Tip Top orebodies gave only trace amounts of gold and silver while the barren Pasadena vein produced assays up to 0.25 O/T Au. These results are typical for the district as a whole.

The vertical control of ore deposition exerted by the boiling mechanism in epithermal deposits (to be discussed) may partially account for the sudden cut off of values above the orebodies. Structural pinches which are filled by early calcite and quartz may block higher advance of later solutions. All or none of the multiple stages of vein filling may persist above the main vertical interval of ore depositions. Those which do persist may be partially or completely stripped of their precious metal content. All these factors, when combined with the effects of supergene enrichment, can relegate the practice of geochemical sampling to a position of near uselessness if the technique is not combined with several more reliable methods. The study of the distribution of other trace elements, particularly mercury, arsenic, thallium and the like, may be of greater reliability regardless of the associated precious metal content. The limited applicability and dangers inherent in attempting to assess epithermal veins by precious metal geochemical sampling has been vindicated at Oatman. No area which exhibits a geochemical anomaly in gold and/or silver is seriously considered unless associated with other positive evidence such as definitive alteration or structural characteristics.

Applications to Exploration in Oatman

The foregoing observations provide the framework for efficient and intelligent exploration in the Oatman District. Additional methods are presently being evaluated for defining the higher-level expression of potential ore shoots in slightly eroded structures in Oatman. These methods primarily involve trace element geochemistry of the altered wallrock, gas analyses of the alteration minerals, and chemical analyses of fluid inclusions, if present. Knowledge gained in this area will be applied to the many relatively deeply buried vein systems which remain to be explored in the western United States.

An assessment of the usefulness of the methods applied at Oatman can be made by examining the geologic indications of ore shoots and targets before and after our study.

Known Orebodies:

A) United Eastern (Figure 7)

Before: The classic "blind" orebody denoted by Ransome (7) and Lausen (8) as having no surface expression. Vein structure not mappable on surface, depth to orebody 400 feet.

A) United Eastern - con't

After: Largest single zone of advanced phyllic alteration along the Tom Reed-United Eastern structure (Figure 14). Located on north-west flank of large, concave-north bend of the structure (Figure 12a).

B) Tip Top, Ben Harrison (Figure 7)

Before: High silicified ridge with green, gold-bearing quartz exposed on surface. Expression of vein analogous to earlier-discovered Cold Road and Moss veins. Orebody virtually at surface.

After: Large phyllic alteration zone which conforms closely to length and breadth of mineralization below surface (Figure 14). Orebodies located on southeast flank of large concave north bend of the structure (Figure 12a). Geochemical samples for Au and Ag largely negative, although taken within feet of top of oreshoots. Fluid inclusions indicate repeated boiling episodes in late stage, green quartz.

C) Big Jim, Aztec (Figure 7)

Before: Tom Reed structure is largely covered by up to 50 feet of detritus and cut by Mallery fault which is parallel to Tom Reed vein at this location. Tom Reed structure indicated by fault contact of Oatman and Gold Road Latites. Orebodies found by sinking exploratory shafts.

After: Intense phyllic alteration found in available outcrops along large concave north bend of structure (Figures 12b and 14). Alteration on Mallery fault distinguishable from similar appearing alteration associated with ore deposition by X-ray diffraction.

D) Black Eagle, United American (Figure 7)

Before: Orebodies found at 400 foot depth by exploratory shafts. No vein material in Tom Reed structure at surface.

After: Small but intense phyllic alteration zone above orebodies and strong propylitic alteration developed in Oatman Latite footwall (Figure 14). Orebodies located in shallow concave north bend on Tom Reed structure (Figure 12b).

E) United Western (Figure 7)

Before: Located northwest of United Eastern orebody near intersection of United Eastern structure and rhyolite dike. Narrow calcite-quartz vein on surface, but contains no gold or silver. Orebody found at 500 foot depth by exploratory shaft.

After: Small, weakly developed phyllic alteration zone found above west end of orebody (Figure 14). Orebody located on shallow, concave north bend on south dipping section of structure (Figure 12a). Fluid inclusions from vein material give temperatures which are consistent with paleogeothermal gradient of Figure 16.

F) Gold Road (Figure 8)

Before: Vein outcrops strongly for several thousand feet. Orebodies in Oatman and Gold Road Latite exposed at surface.

After: Concentrations of ore along vein corresponds to mappable dilatant zones (Figure 11). Alteration poorly developed along vein within Gold Road Latite, but is developed in overlying tuffaceous units of upper volcanics and in underlying Oatman Latite (Figure 14). Fluid inclusions show boiling textures.

New Targets:

A) Tom Reed "faulted extension" (Figure 7)

Before: Located between Ben Harrison and Big Jim orebodies, each of which yielded about 250,000 tons. Evidence of down-faulting along section if Oatman fault is assumed to join Tom Reed structure and continue northwest along it. No vein on surface, but Tom Reed structure is strong along this section. A small body of ore found in 500' level exploratory drift from Ben Harrison. Room for 1 million tons, based on periodicity of oreshoots on both ends of barren section.

After: This section of Tom Reed structure possesses no concave north bend(s) or phyllic alteration. A naturally occurring barren stretch in this portion of the structure may have analogs in the Gold Road vein and southeast end of Tom Reed vein. Oatman fault tentatively does not join Tom Reed structure based on detailed mapping in area of poor outcrop.

B) Kokomo (Figure 7)

Before: 10 foot wide crush zone with gold-bearing green quartz at the surface. Exploratory shaft sunk in 1920's at southeast end of structure encountered 24 inches of 0.55 O/T Au at depth of 550 feet. Structure parallels and is located midway between the Gold Road and Tom Reed structures. Area difficult to get to, drilling will be expensive and probably deep because of high topographic exposure of the structure.

After: Structure possesses very large concave north bend and long zone of intense phyllic alteration (Figures 13 and 14). Fluid inclusion studies suggest top of potential ore shoot approximately 200 feet below outcrop, based on Figure 16. Vein contouring also indicates shape of concave north bend is similar to United Eastern-Tip Top-Ben Harrison bend, thus allowing preliminary control on drill hole locations.

C) Pasadena Vein (Figure 7)

Before: Strong, 3000 foot long, 5-10 foot wide calcite-quartz fissure vein. One section 800 feet long consistently runs 0.05 to 0.25 O/T Au on surface. Explored by 350 foot shaft in 1920's at point of highest assays. No production.

After: Position of shaft is at center of concave south bend, where a dilatant zone should be for a south dipping structure (Figure 10). However, no phyllic alteration seen, despite proximity to nearby rhyolite dike. Drilled by Fischer-Watt Mining and found to be barren below immediate outcrop. Structure horsetails and disappears below 300 vertical feet. No silicification found at depth (Figure 15). Lessons learned: phyllic alteration must be present even when vein contouring indicates favorable bend, geochemical results must be qualified by other data.

D) Boundary Cone (Figure 2)

Before: Very large silicified breccia zones with large quantities of green quartz. Inconsistent but encouraging assays. Several deep shafts failed to find major orebodies.

After: Vein contouring not carried out. Random fluid inclusion samples indicate high temperatures (400°C) and salinities (>23%), as evidenced by daughter salts. Area interpreted as representing the root zone of a now eroded vein system, perhaps related to nearby rhyolite plug.

New Targets - con't

E) Red Cloud-United Eastern #3 Area (Figure 7)

Before: Location is immediately northwest of United Eastern orebody. Vein on surface is slightly silicified, iron stained ledge 3-10 foot wide and several feet high. Very little calcite or quartz in outcrop. Drilling from bottom of both shafts intersected wide width (10-30 feet) of low grade (<0.3 O/T Au) vein material. No production due to low grade.

After: Large area of intense phyllic alteration exists along impressive concave north bend (Figures 12a and 14). Center of bend coincides with dip reversal. Would have been drilled on these merits alone.

Ore Deposition at Oatman: a Preliminary Analysis

A detailed analysis of the geochemistry of ore deposition at Oatman has not been attempted by the authors because of time limitations during the exploration phase. Some observations can be made, however, which indicate the Oatman vein deposits are very similar to other epithermal vein systems which have been studied (cf.33). The outstanding difference between the Oatman deposits and other vein systems with which we are familiar is the remarkable lack of sulfur in the hydrothermal system as a whole. Whereas veins in many districts are sulfide-deficient near the surface but become increasingly sulfide-rich at depth, the Oatman veins are barren of any sulfide, except pyrite, which rarely exceeds 0.5% by volume, from top to bottom. The occurrence of chalcopyrite or chalcocite in some mines was essentially limited to single grains exposed in the vein during mining operations. Highly propylitized latite adjacent to the veins will contain up to 5% pyrite, but generally averages 1-2%. Another peculiarity of the Oatman District is the occurrence of very fine, disseminated chlorite in the late stage quartz.

On a district-wide basis Lausen (8) documented five stages of quartz-calcite ± adularia deposition, each separated by a period of fracturing. Each period of fracturing allowed later stages of vein material to enter and, at times, replace earlier stage material. The greatest concentration of quartz-calcite ± adularia along the Gold Road and Tom Reed structures was within the dilatant zones identified in Figures 11 and 12a-b, the location of the commercial orebodies. Historically, bodies of quartz-calcite which exceed several tens of thousands of tons on the Gold Road and Tom Reed structures have been economic. Several large bodies of vein material not on these structures have not been economic. These include the Pasadena vein and the eastern extension of the Moss vein (Figures 2 and 3). The Pasadena vein may contain in excess of 500,000 tons of quartz and calcite (no adularia) but averages less than 0.05 O/T Au. The Moss vein may contain similar tonnage and grade over its length. The Pasadena, based on drilling and surface exposure, appears to have received only early-stage quartz and calcite. The Moss vein may also owe its general deficiency in gold to a lack of later stage solutions, or deep erosion.

Observations by the authors in veins throughout the district indicate two things: a) when a structure was mineralized by any stage of quartz and/or calcite it was completely filled from wall to wall; partially filled veins or veinlets are extremely rare; and b) veins which have experienced movement after initial filling are always refilled by later mineralization; unhealed veins or veinlets are also extremely rare. The exception is post mineral faulting which clearly took place after the main hydrothermal event(s) in the district. These two observations suggest that the geothermal system(s) which gave rise to the mineralization (not necessarily commercial) in the Oatman District was restricted in its access to the paleosurface by structures which, when periodically opened during tectonism, were completely filled with quartz and/or calcite by ascending solutions. The self-sealing geothermal system — an example of which may have existed at Oatman — has been described by Facca and Tonani (34), Keith et al.(35), and Batzle and Simmons (36). A detailed account of ore deposition in another self-sealing geothermal system has been made by Buchanan (23,24) at Guanajuato, Mexico.

Episodic fracturing caused by tectonic adjustments, hydrofracturing, or other causes allows access of hydrothermal fluids to the surface and a sudden pressure drop within the contained geothermal reservoir. The pressure drop may initiate boiling within the system, if the fluid is above the liquid-vapor curve at the depth of containment. There is increasing evidence, primarily from fluid inclusion studies, that boiling is an important factor in ore deposition in subaerial hydrothermal systems (15,37,38,39,40). The banded character of many epithermal veins, including Oatman, may be caused by short term, recurrent boiling which deposits successive layers of vein material within a structure repeatedly or continuously opened by tectonic adjustment.

Evidence for recurrent boiling in the Oatman veins comes from fluid inclusion studies which show that finely banded late-stage quartz often owes its banded character to alternating layers of fluid inclusion-rich and fluid inclusion-poor quartz. The layers which are inclusion-rich are composed of a mosaic of quartz crystals, each containing a rosette of thousands of fluid inclusions radiating outward from the center of the crystal. Identical textures have been described by Roedder (30) from other boiling systems and Buchanan (23) at Guanajuato, Mexico. The inclusion-rich layers also host the disseminated chlorite.

From Lausen (8) we know that later-stage chlorite-rich (green) quartz is also the richest in gold. Apparently, boiling was responsible for deposition of the gold-rich, chlorite-bearing green quartz which produced ore grade material in the Oatman veins. A similar relationship has been found by Buchanan (23,24) for the silver-rich quartz-acanthite-adularia-sericite bands in the Guanajuato, Mexico veins.

A trend, noted by Lausen (8) from barren, white quartz in the early stages of mineralization to gold-bearing, green quartz in the later stages, may represent a gradual change from non-boiling-induced deposition to boiling-induced deposition. Alternatively, the trend may be explained by a gradual change in composition or temperature of the hydrothermal fluids over time. The five stages of mineralization identified by Lausen (8) might be explained by a characteristic of self-sealing geothermal systems discussed by Ellis (41, p. 636). These systems commonly alternate between short periods (10^3 years) of major water outflow and long periods (10^4-10^5 years) of minor water outflow due to sealing. Periods of outflow would be associated with periods of deposition in the veins. Perhaps the five "stages" of Lausen (8) might be related to five periods of water outflow during the life of the geothermal system.

Interestingly, the later stages are characterized by many substages comprised of alternating layers of white, green, and greenish yellow quartz, white to black calcite, and adularia. It is possible that the thermochemical history experienced by each of the later stages of quartz-calcite deposition represents a microcosm of the kind of thermochemical history experienced by the geothermal system as a whole. In the same sense that the evolution of a volcanic system may be reflected in individual flow units containing basic through acid products, the history of the geothermal system which produced the Oatman deposits may be crudely represented within the individual stages of quartz-calcite deposition.

Fluid inclusions from late-stage, green quartz show boiling textures, low salinities (no exact measurements available), and deposition temperatures in the range 220-240°C. Solutions of this temperature and salinity (assumed <5%) would boil under hydrostatic conditions at about 1000 feet below the paleowatertable according to Haas (42). The amount of rock removed by erosion from above the tops of the Oatman deposits is estimated to be 1000 feet based on depth of volcanic cover directly east of Oatman. If the average vertical extent of the Oatman deposits is 1000 feet, then the level of boiling - coincident with bottom of the deposits (Figure 15) - must have been at least 2000 feet below the paleosurface. In order to be consistent with the data of Haas (42) this requires that the paleowatertable had to be 1000 feet deep.

This apparent requirement can be explained in two ways. In self-sealing geothermal systems precipitation of vein material above the boiling interface may eventually seal the hydrothermal conduit from the upper level of deposition down to the boiling interface itself. If this occurs all upward fluid flow is stopped and a new "top" to the geothermal system is established. The effective hydrostatic head above the reservoir will now be measured from the sealed cap. If the cap is broken by fracturing and pressure is suddenly released boiling will commence 1000 feet below the cap due to normal hydrostatic constraints on vaporization. This boiling, actually termed flashing or throttling under these conditions (43), will be unusually violent due to the difference in pressure of the solutions (which is equivalent to lithostatic before the cap is broken) and the pressure exerted by the effective hydrostatic head measured at the cap. Deposition by the solutions will begin at the new level of boiling 2000 feet below the paleowatertable (assumed here to be coincident with the paleosurface) and continue upward. When the fluid column reaches 1000 feet below the paleosurface normal boiling will take over because true hydrostatic constraints are reestablished. Deposition may continue above this level if the solutions are not already depleted. Conversely, deposition above the lower boiling interface may reseal the conduit, again blocking significant fluid flow and deposition within the upper 1000 feet of the system. Ore deposits formed under the conditions of self-sealing described here would be located between 1000 and 2000 feet below the paleosurface. This is consistent with what is seen at Oatman.

The second explanation requires that some component of the fluid phase caused it to boil at a depth which is greater than normally possible for low-salinity water at hydrostatic conditions. One such component is CO_2. Evidence that the Oatman hydrothermal solutions were rich in CO_2 is found in the enormous amount of calcite deposited in veins throughout the district and liquid CO_2 discovered in fluid inclusions from late stage quartz. The affect of a high partial pressure of CO_2 in the fluid phase will cause the fluid to vaporize (boil) at a higher pressure at the same temperature. A partial pressure of CO_2 of about 26 bars is required to lower the elevation of vaporization 1000 feet under hydrostatic conditions (38).

At this time there is little supportive evidence for the first mechanism in the Oatman District. In contrast to what was found at Guanajuato, Mexico (23,24), there is no evidence of a second level of mineralization in the Oatman veins (above or below the known level of mineralization) or overlapping alteration assemblages. We therefore tentatively conclude that a high CO_2 content in the hydrothermal solutions is responsible for the abnormally deep level of the base of the deposits below the paleosurface.

In the Boundary Cone system 2 miles south of Oatman (Figure 2) high temperatures, high salinity (>23% equivalent NaCl) fluid inclusions from random samples indicate greater depth in the geothermal system relative to Oatman. Alternatively, this area may represent a separate geothermal system from that which produced the Oatman deposits or a different cell within the same geothermal system. Assuming the systems were active at the same time and were, as they are today, about the same elevation, a very steep lateral geothermal gradient must have existed between the two areas. This aspect of geothermal systems would be considered when ancient geothermal systems are assessed for their ore potential.

Efforts are presently being made to determine if the high temperature, high salinity solutions found in fluid inclusions from the Boundary Cone area were, prior to boiling, the precursors of the solutions which produced the Oatman deposits. Alternatively, these solutions may represent the concentrated residual phase left behind after boiling. Studies by Drummond and Ohmoto (40), White (44), and Wahl (45) show that significant concentration of dissolved species can occur at the level of boiling in geothermal systems.

A major objective in the evaluation of an epithermal vein district should be the identification of the thermal center or centers. These thermal centers can be point sources such as buried plutons of small extent or local hot spots or exit points in a larger geothermal system. The exploration potential in reconstructing paleohydrologic systems has been pointed out by Skinner (46).

A simple but effective method of identifying possible thermal centers has been applied at Oatman. Using information which is generally available, the elevations of the tops and bottoms of the individual oreshoots are contoured. A third contour map is constructed by contouring the value in feet of the vertical interval of ore deposition within the oreshoots. The relative position of the oreshoots in vertical and horizontal space must be corrected for post-mineral faulting prior to contouring. The resultant maps, and a cross section thereof, for the Oatman District are presented in Figures 17-20.

The most interesting observation concerning these maps is the doming of the horizon of ore deposition above the area of rhyolite dike emplacement. From Figure 20 it can be seen that the top of the horizon of ore deposition is about 300 feet higher than the flanks. The bottom of the horizon also appears to be elevated based on information from the Cold Road and Tom Reed veins. Relatively high fluid inclusion temperatures obtained from the surface of the Kokomo vein are consistent with an elevated horizon of deposition in this area. The apparent doming of the ore horizon suggested by Figure 17-20 is interpreted as indicating a thermal high. If the high represents a buried point source or single cell within a district-wide geothermal system is not known at this time. However, underground mapping by Nolan (47) and isotopic work by Taylor (48) at Tonopah, Nevada, have identified a thermal dome, of similar dimensions as the one in Oatman, which is interpreted as reflecting a buried pluton.

The exploration advantages of establishing a symmetrical relationship between the vertical interval of ore deposition (or other factor, such as metal ratios, mineral assemblages) and a common center are obvious. Unfortunately, the shape of the horizon of ore deposition above the thermal center can have virtually any shape and may not resemble a dome in every case. The parameters which influence deposition can vary significantly in the geologic environment. These parameters include: shape and value of the isotherms above the thermal source, configuration of the paleosurface, and salinity, temperature, and composition of the hydrothermal solutions. The theoretical interdependence of these parameters has been studied in some detail by Norton (49,50), Norton and Knapp (51), Norton and Knight (52), and Norton and Cathles (53).

Summary and Conclusions

This report has centered around one basic idea: epithermal vein deposits are amenable to quantitative, scientific analysis and, therefore, should be considered as tractable exploration targets if economic considerations are favorable. These types of deposits should not be viewed as largely random geochemical events associated with youthful volcanic systems. The recent attention given to active geothermal systems offers the explorationist a growing source of geochemical and physical data which can be applied to advantage in the study of fossil geothermal systems which may host epithermal vein deposits.

The search for ore deposits, which are typically a small part of a much larger and complex geothermal event, should not only focus on those characteristics which are strictly associated with the ore-forming process, but particularly those characteristics which are of greatest areal extent. These characteristics include: the avenues of fluid flow and areas of deposition - the structures and the structural traps; the alteration signature associated with ore deposition; the temperature regime of ore deposition; the local thermal "high" or geothermal cell through which the fluids circulated. Trace element geochemistry should be applied to broad effects manifested in the altered wallrocks. Geochemical sampling for precious metals restricts ones target to the smallest magnitude expression of the ore-forming process, the orebody itself.

The procedure and tools utilized at Oatman can be applied in other past-productive districts and, with some modifications, in grass roots exploration. Our procedure was as follows:

A) Establish at least 2 characteristics which are similar between each and every known oreshoot. At Oatman these characteristics included particular points of curvature on host structures, a unique alteration signature at the surface which was relatable to depth of exposure, and a specific temperature range associated with ore deposition. The tools which were used were, respectively: vein contouring, detailed alteration mapping, and fluid inclusion studies.

B) Apply this set of conditions to other parts of the district. The area which was searched was restricted in size by establishing an apparent thermal center under the central district by reconnaissance fluid inclusion studies and contouring the tops and bottoms of the known oreshoots (corrected for post-mineral faulting).

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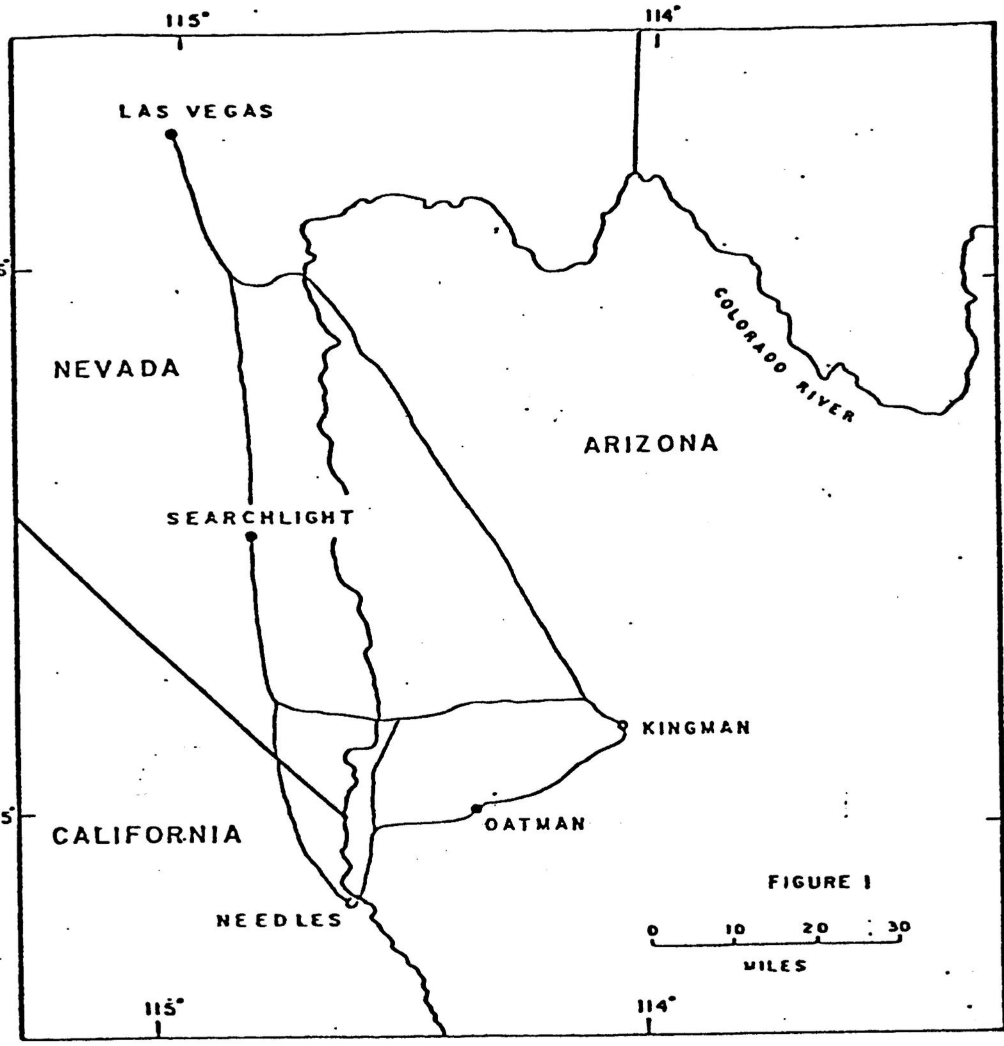
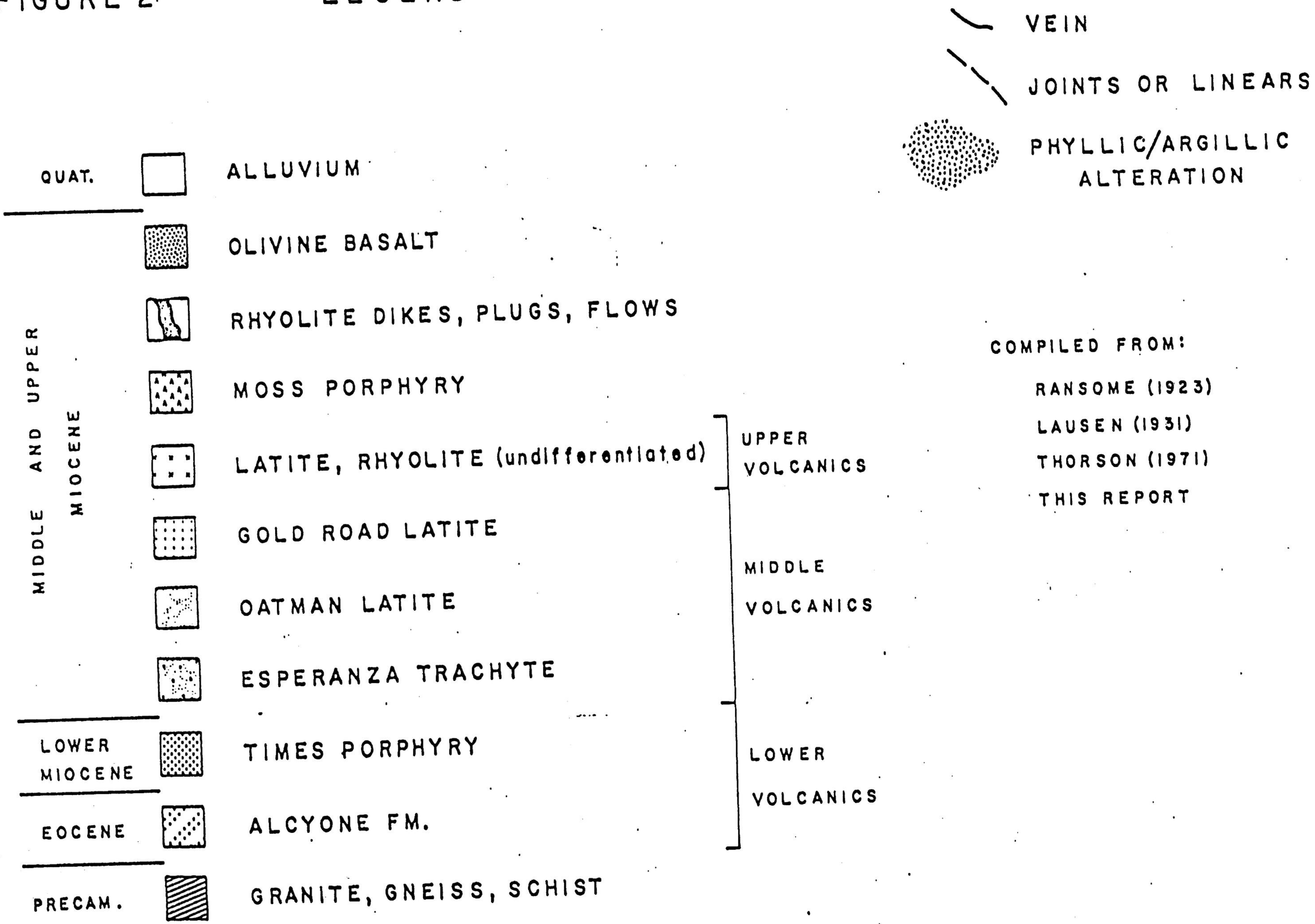


FIGURE 1

LOCATION MAP

FIGURE 2 LEGEND



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LAUSEN (1931)
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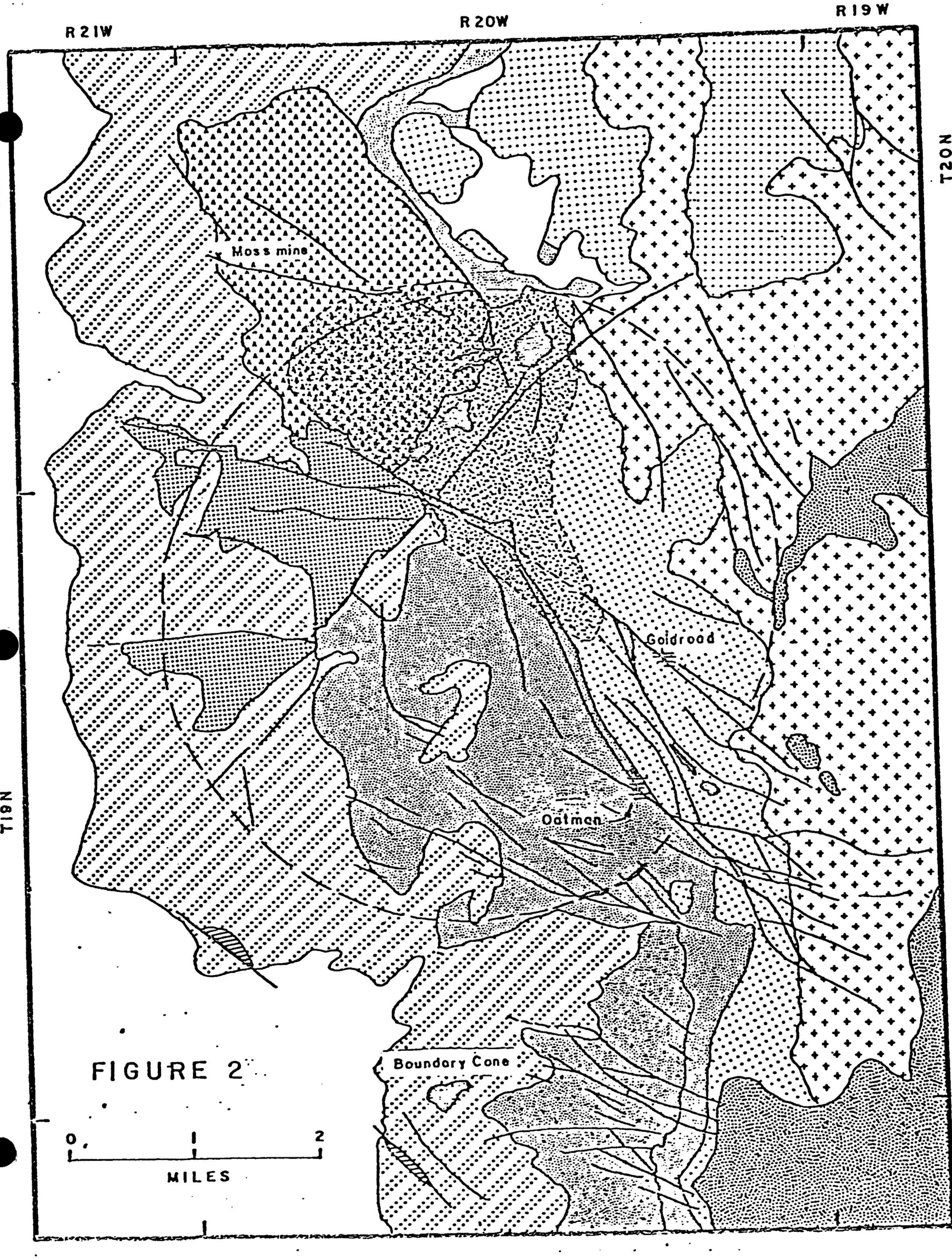


GEOLOGY AND STRUCTURE OF THE OATMAN DISTRICT

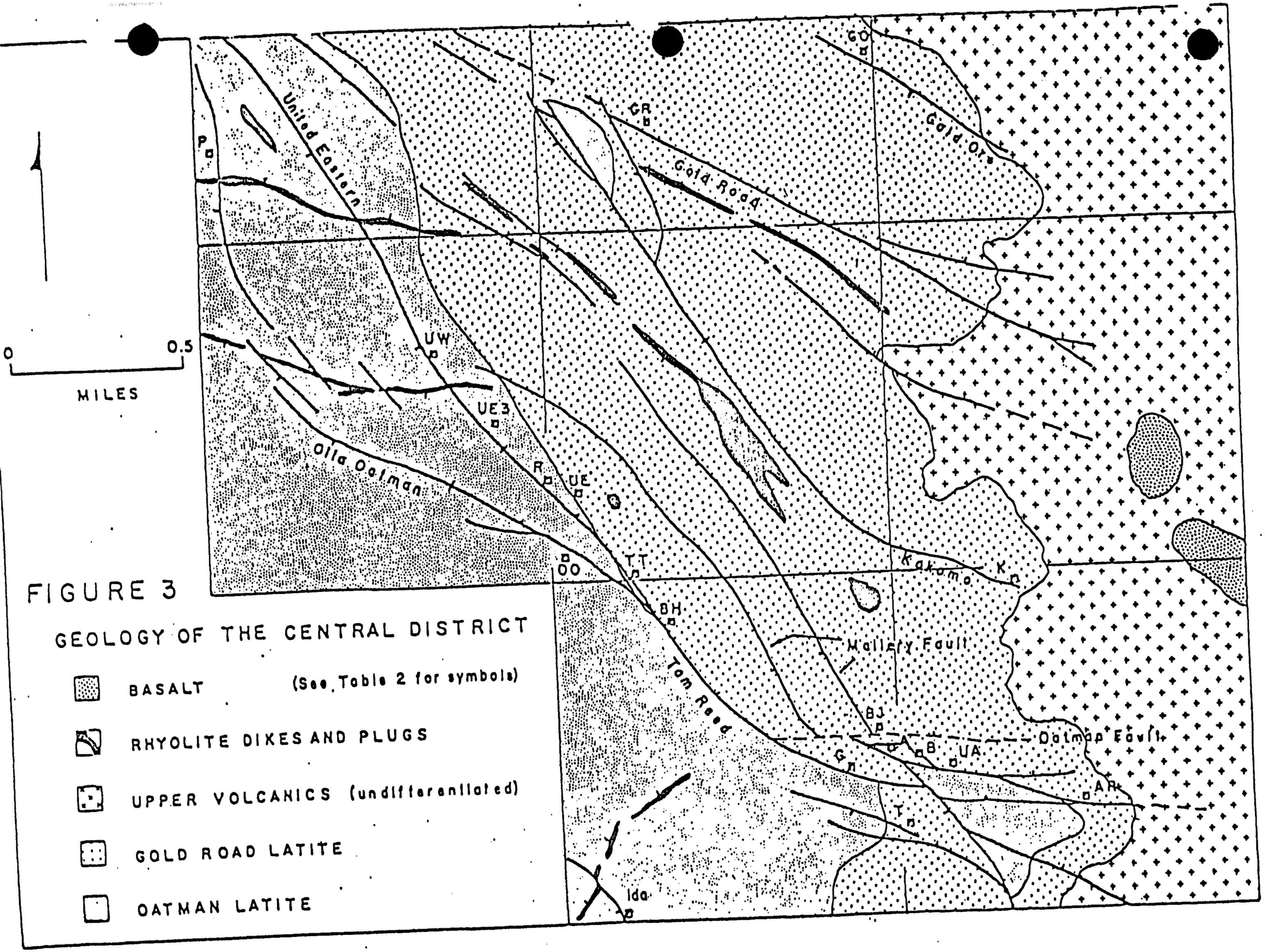
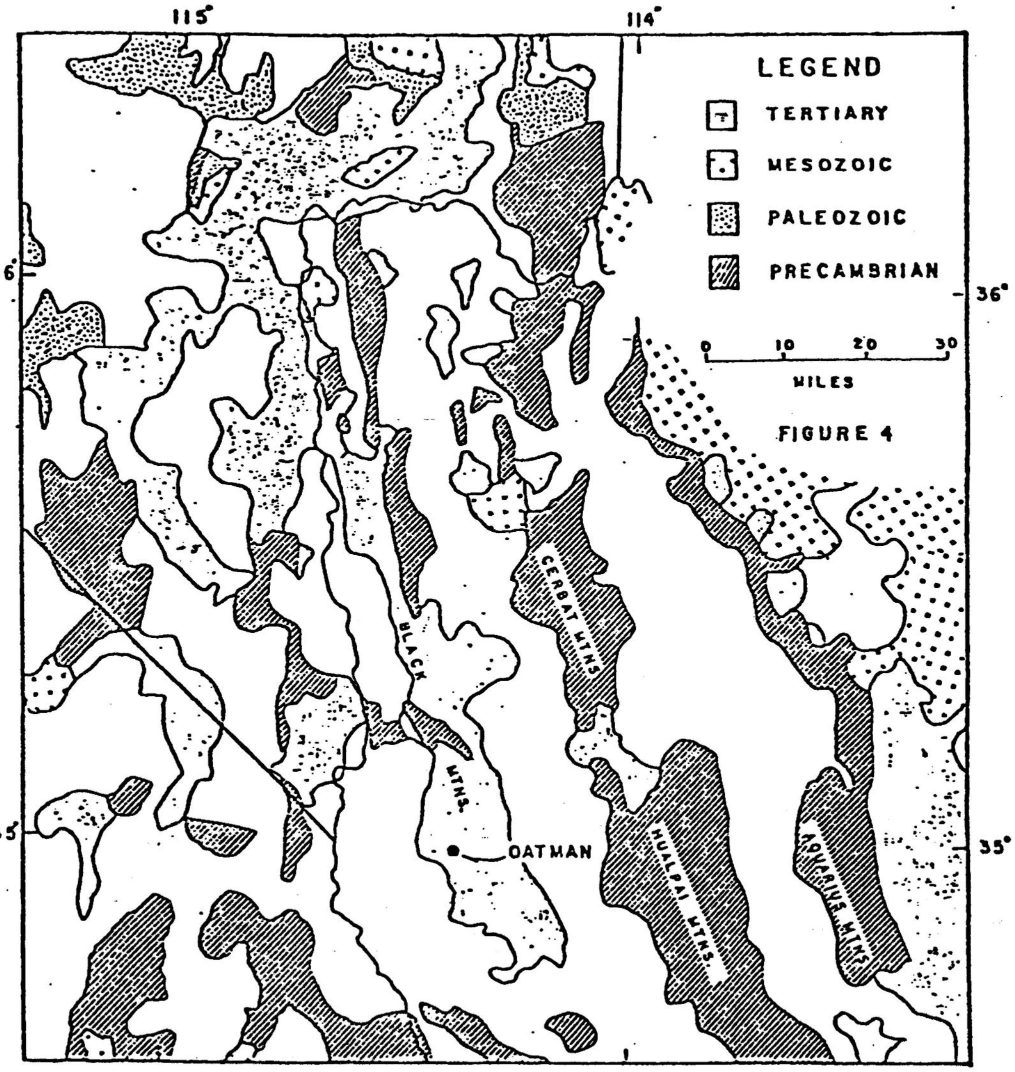
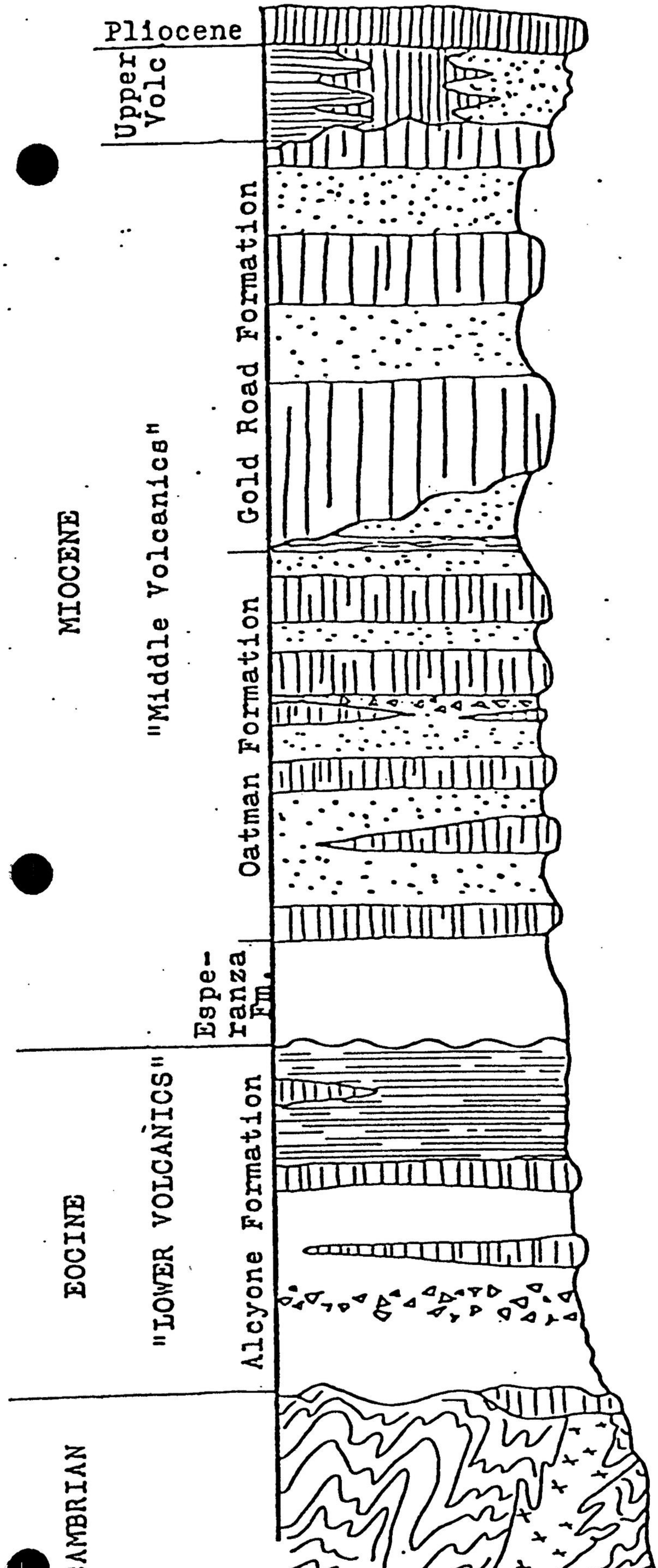


FIGURE 3

GEOLOGY OF THE CENTRAL DISTRICT



REGIONAL GEOLOGY



Olivene basalt flows

Sitsgreaves rhyolitic tuffs; Cottonwood Fm., Antelope quartz latite flows; Flag Springs trachy

Black, brown, and red biotite latite flows separated by white a grey biotite latite lithic ash flows.

Transition Zone: White coarse-grained lithic, crystal, biotite latite ash locally underlain by g medium-grained fluvial biotite-po arenite. Base is biotite-poor li crystal latite ash.

Vesicular pyroxene latite flow un (40-50' thick) separated by latit tuffs and flow breccias.

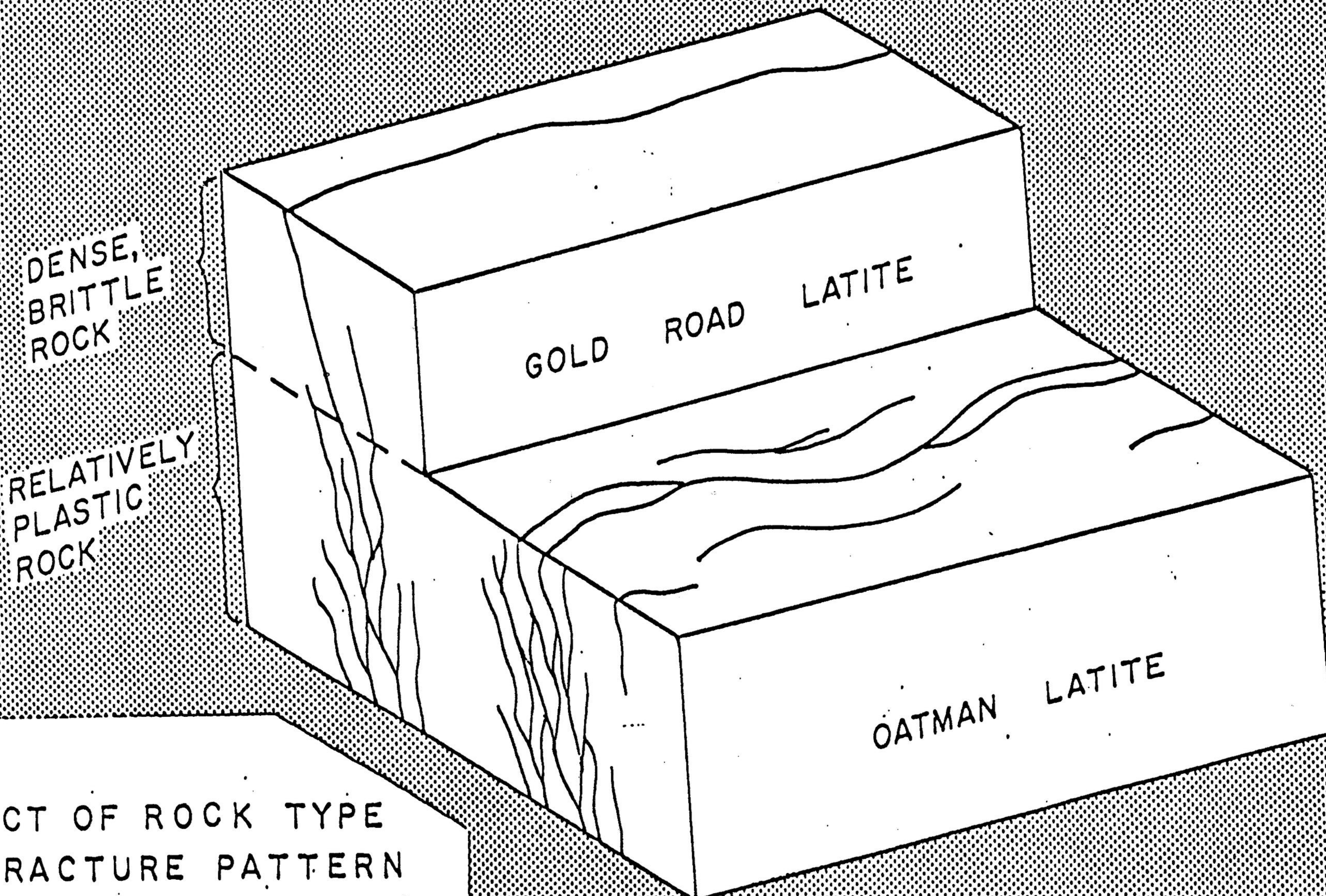
Fine-grained, flaggy, trachyte.

Thinly laminated to thick bedded green and grey trachytic welded t landslide deposits, lahars, unwel tuffs, and quartz latite flows.

Pre-Alcyone basalt.

Schist, gneiss, granite, quartzit

FIGURE 5 GENERALIZED STRATIGRAPHY



EFFECT OF ROCK TYPE
ON FRACTURE PATTERN

FIGURE 6

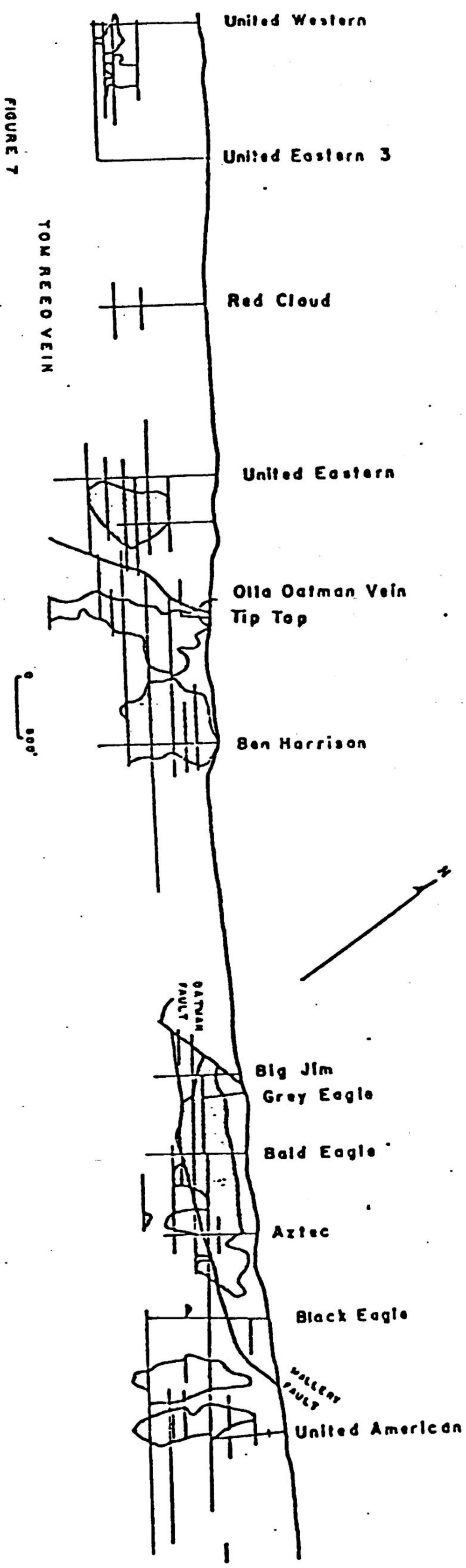
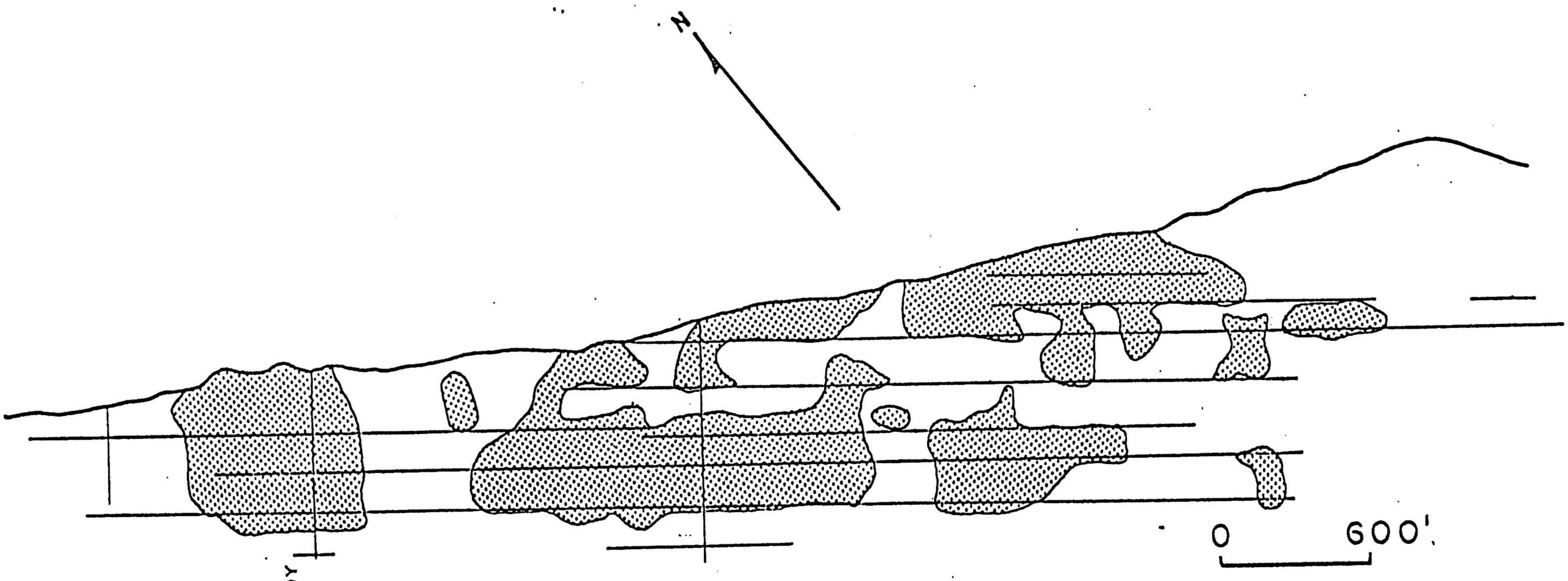


FIGURE 7

TOM REED VEIN



GOLD ROAD VEIN

FIGURE 8

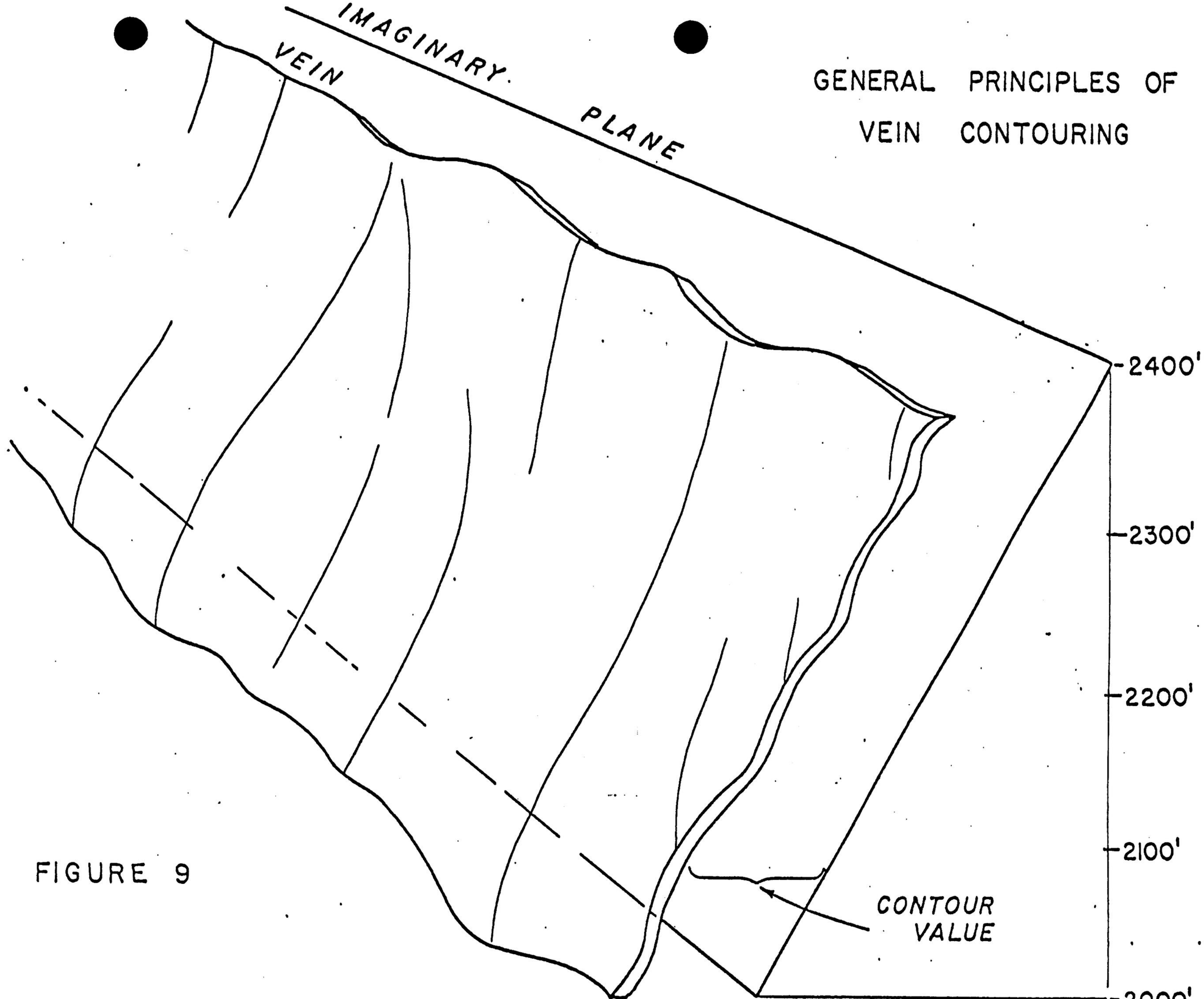
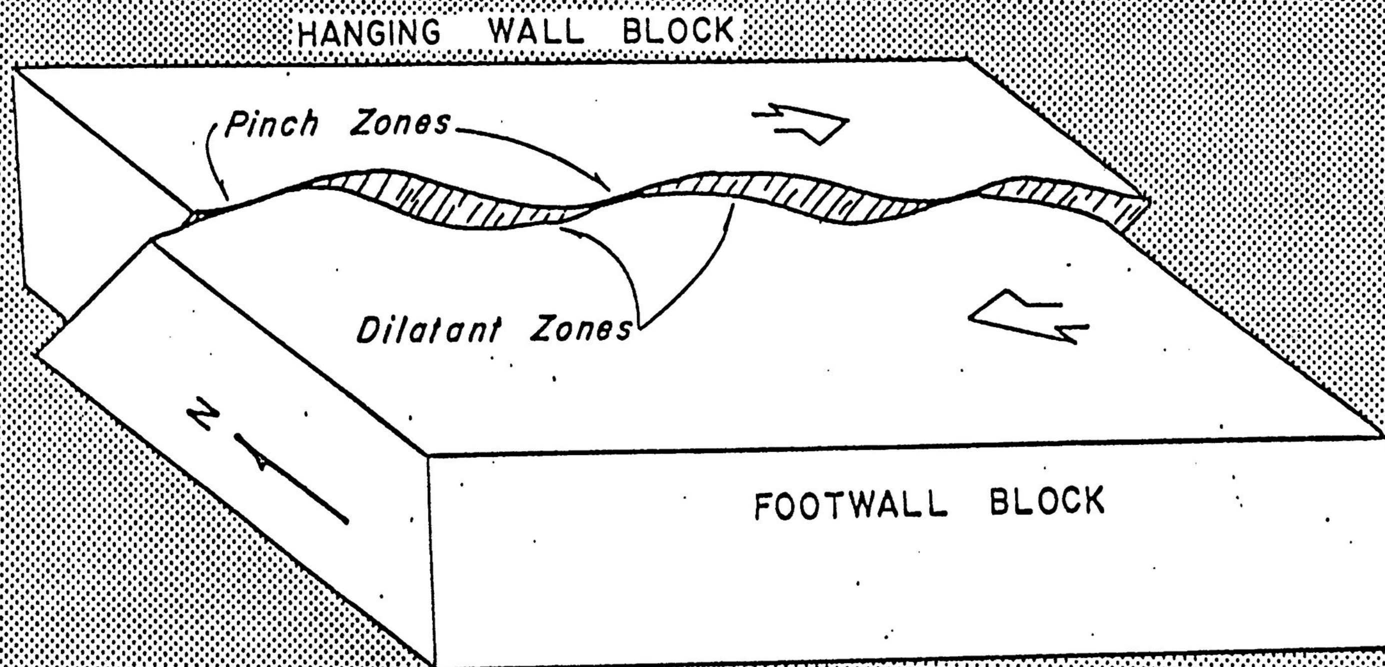
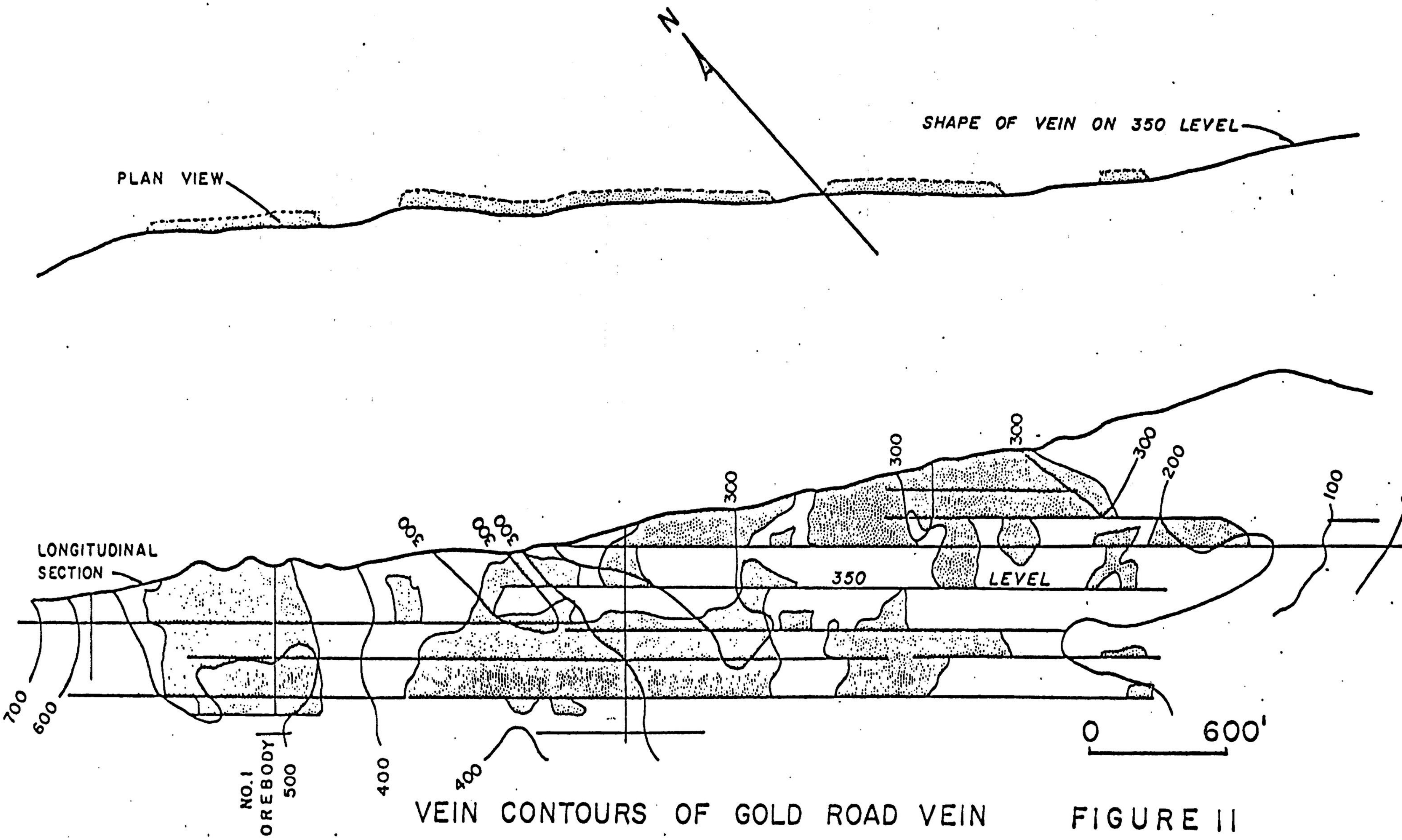

GENERAL PRINCIPLES OF
VEIN CONTOURING
IMAGINARY PLANE
VEIN
CONTOUR VALUE
-2400'
-2300'
-2200'
-2100'
-2000'

FIGURE 9

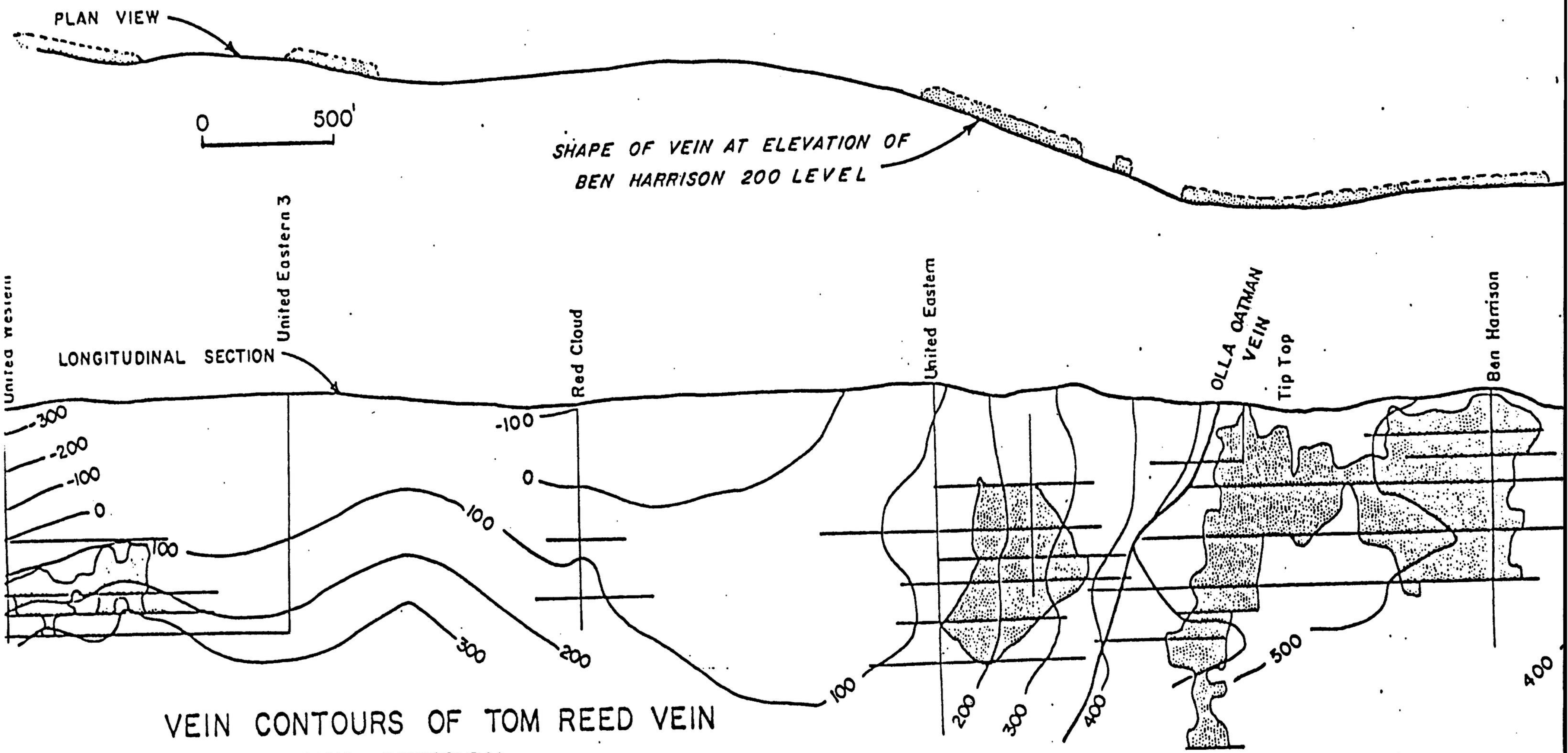


NORTHEAST ORIENTATED DILATANT ZONES PRODUCED BY RIGHT LATERAL STRIKE-SLIP MOTION

FIGURE 10

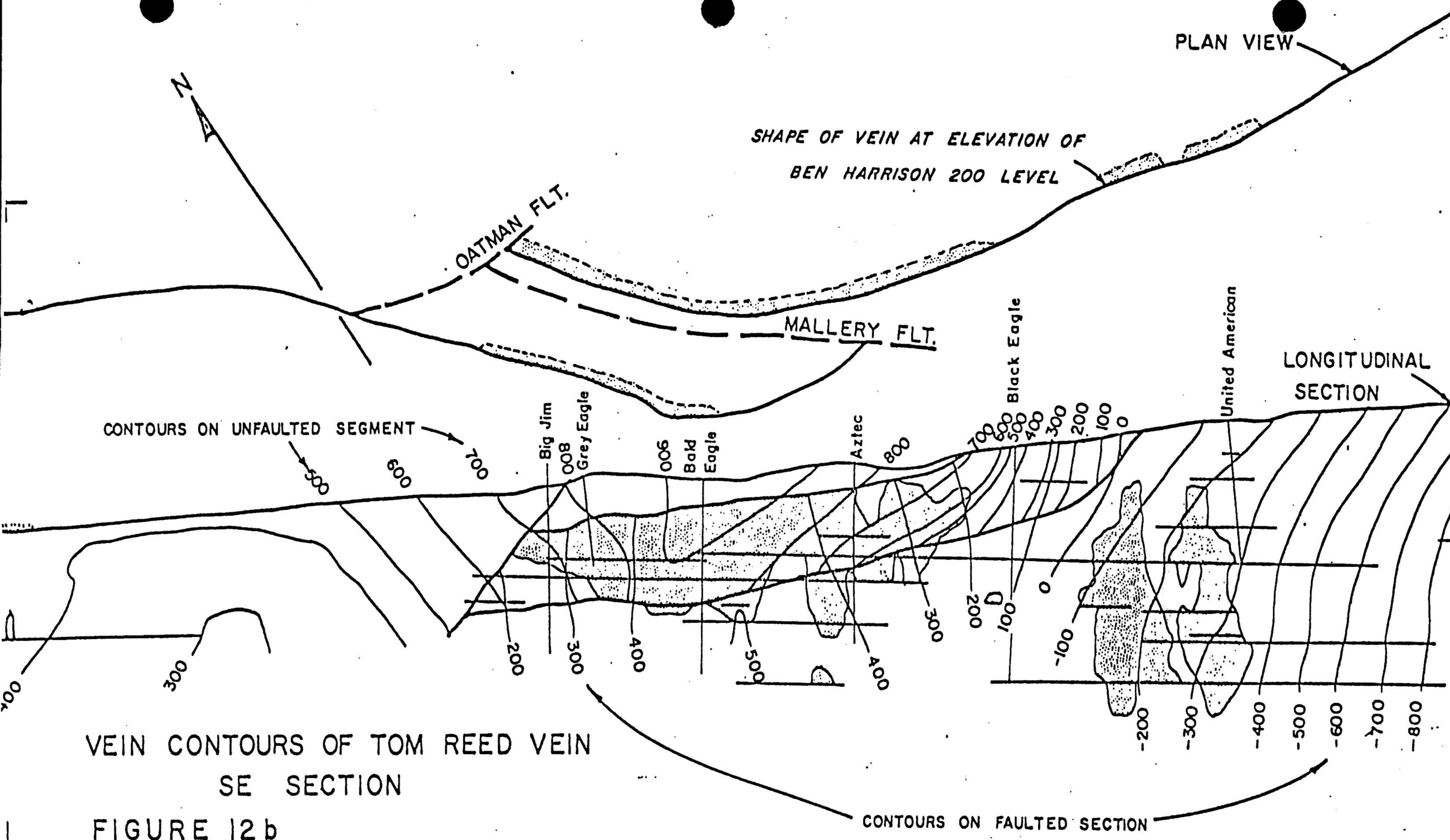


VEIN CONTOURS OF GOLD ROAD VEIN FIGURE II



VEIN CONTOURS OF TOM REED VEIN
NW SECTION

FIGURE 12a



VEIN CONTOURS OF TOM REED VEIN
SE SECTION

FIGURE 12b

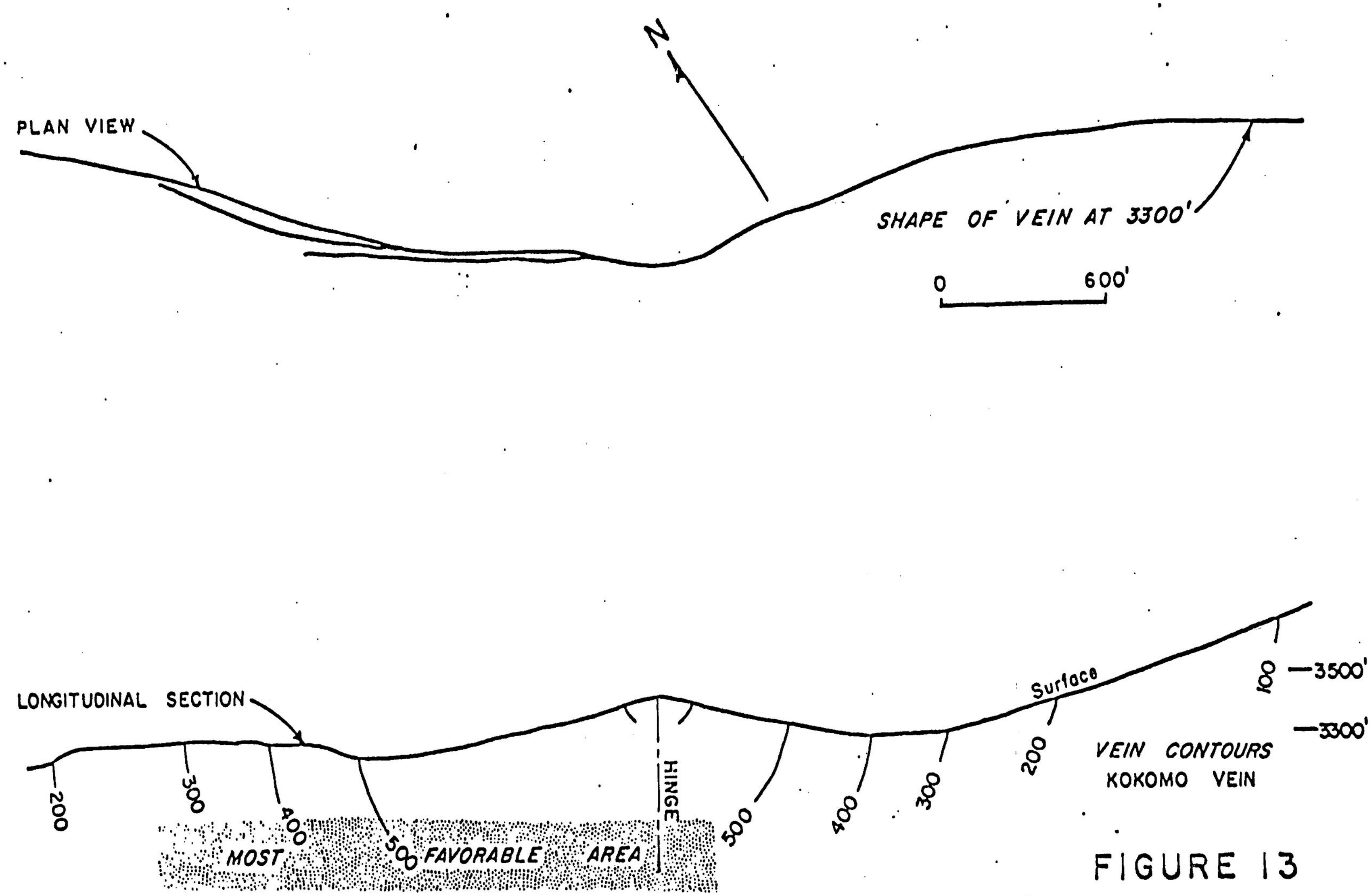

PLAN VIEW
N
SHAPE OF VEIN AT 3300'
0
600'
LONGITUDINAL SECTION
Surface
100
—3500'
—3300'
200
300
400
500
HINGE
MOST FAVORABLE AREA
VEIN CONTOURS
KOKOMO VEIN

FIGURE 13

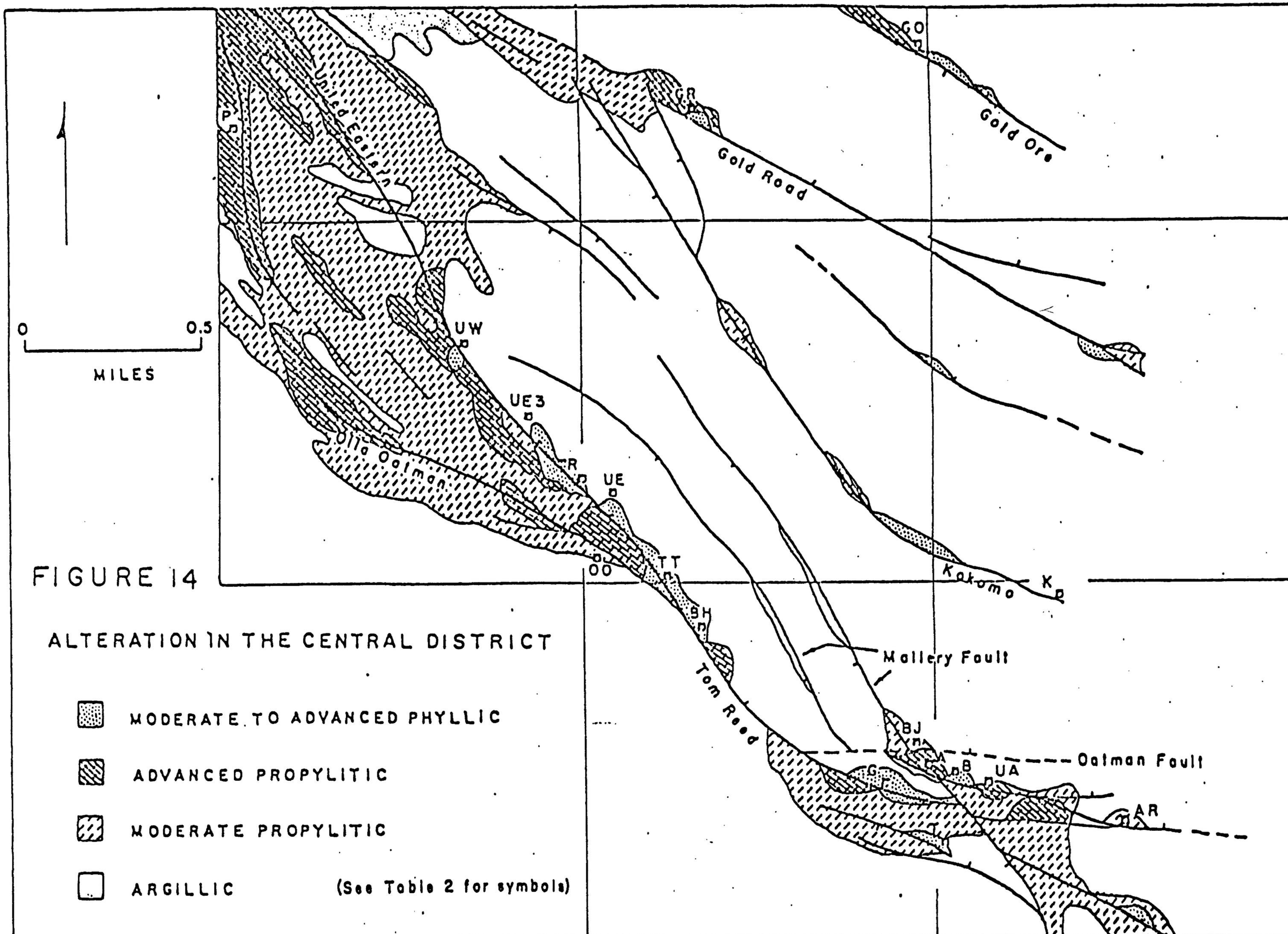
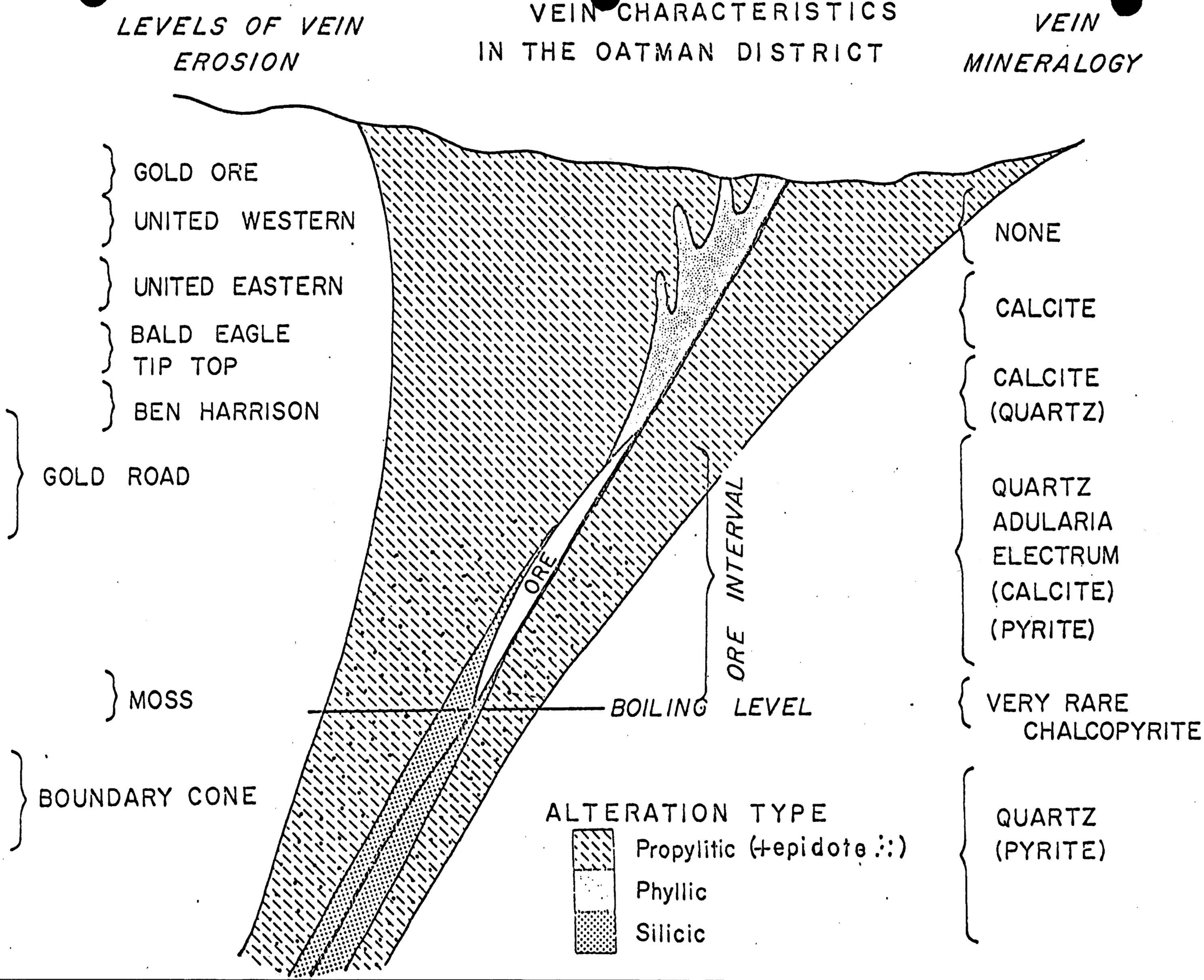


FIGURE 14

ALTERATION IN THE CENTRAL DISTRICT

FIGURE 15

VEIN CHARACTERISTICS IN THE OATMAN DISTRICT



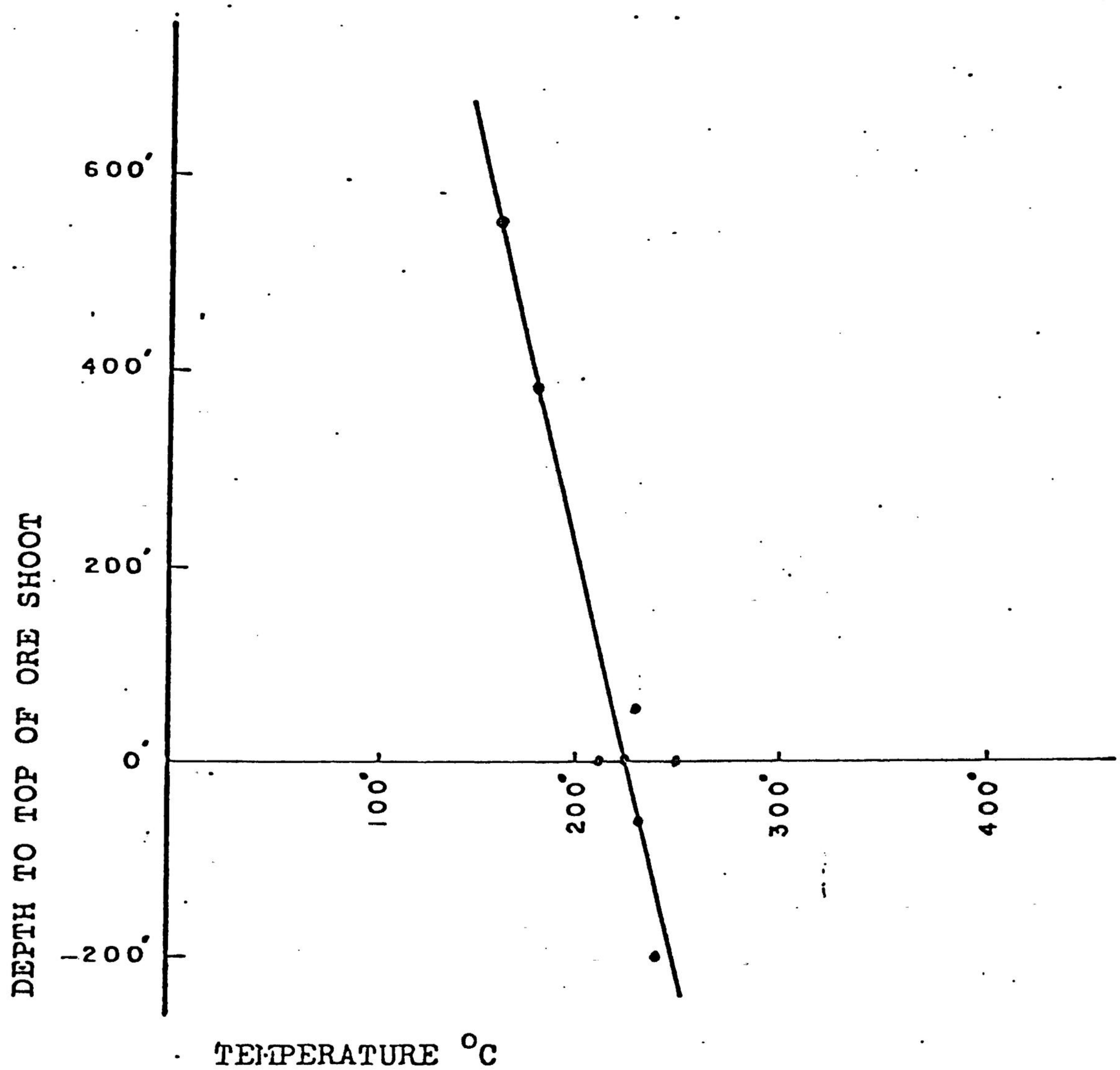


FIGURE 16 Fluid inclusion homogenization temperatures obtained on ore-stage quartz from selected points along the Tom Reed, Kokomo, and Ida veins, plotted against known depth to top of ore shoots. Several samples obtained from within mine workings. Slope is measure of paleogeothermal gradient existing at time of ore deposition.

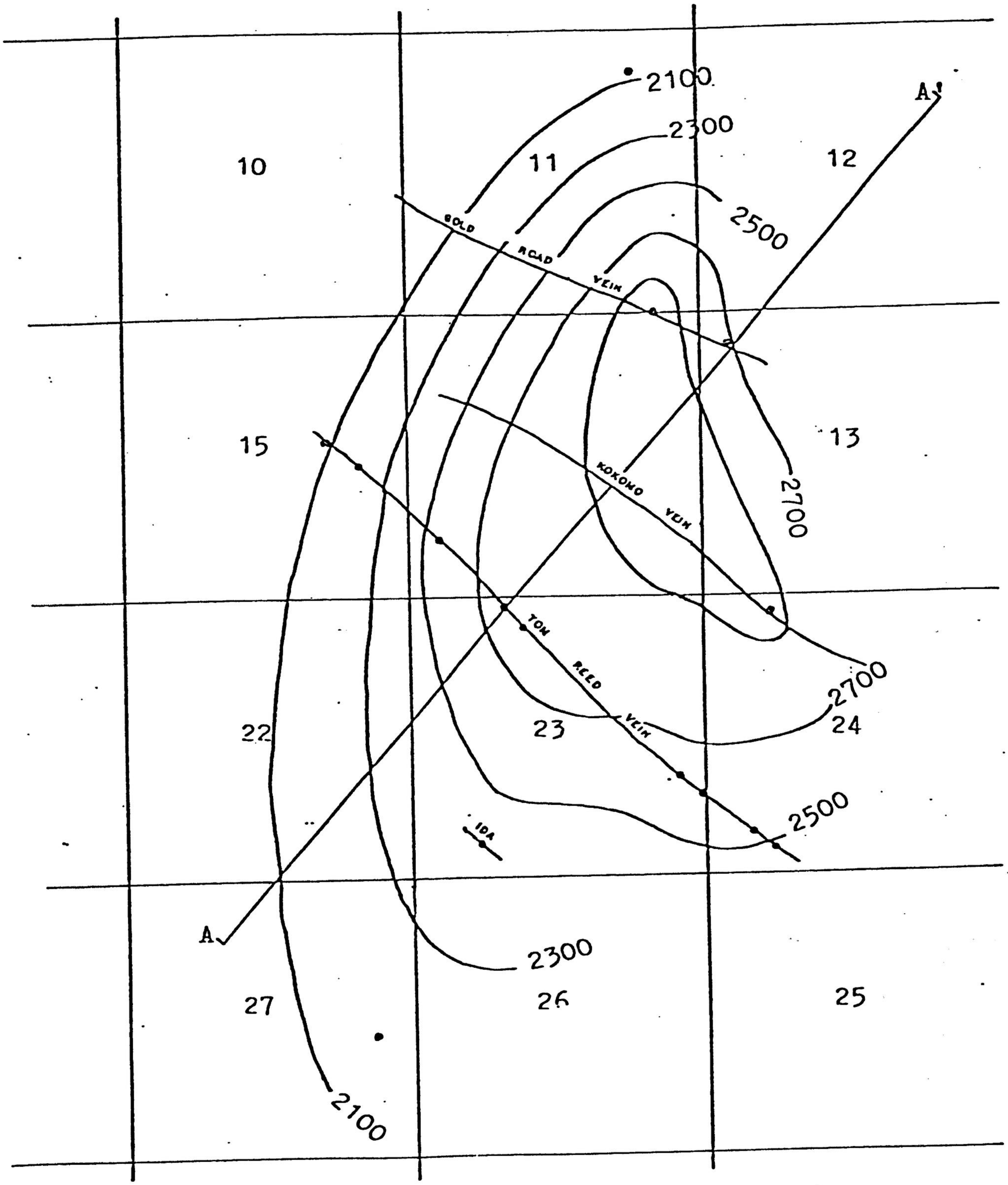


FIGURE 17 Elevations, in feet above sea level, of the tops of ore shoots.
• DATA POINT

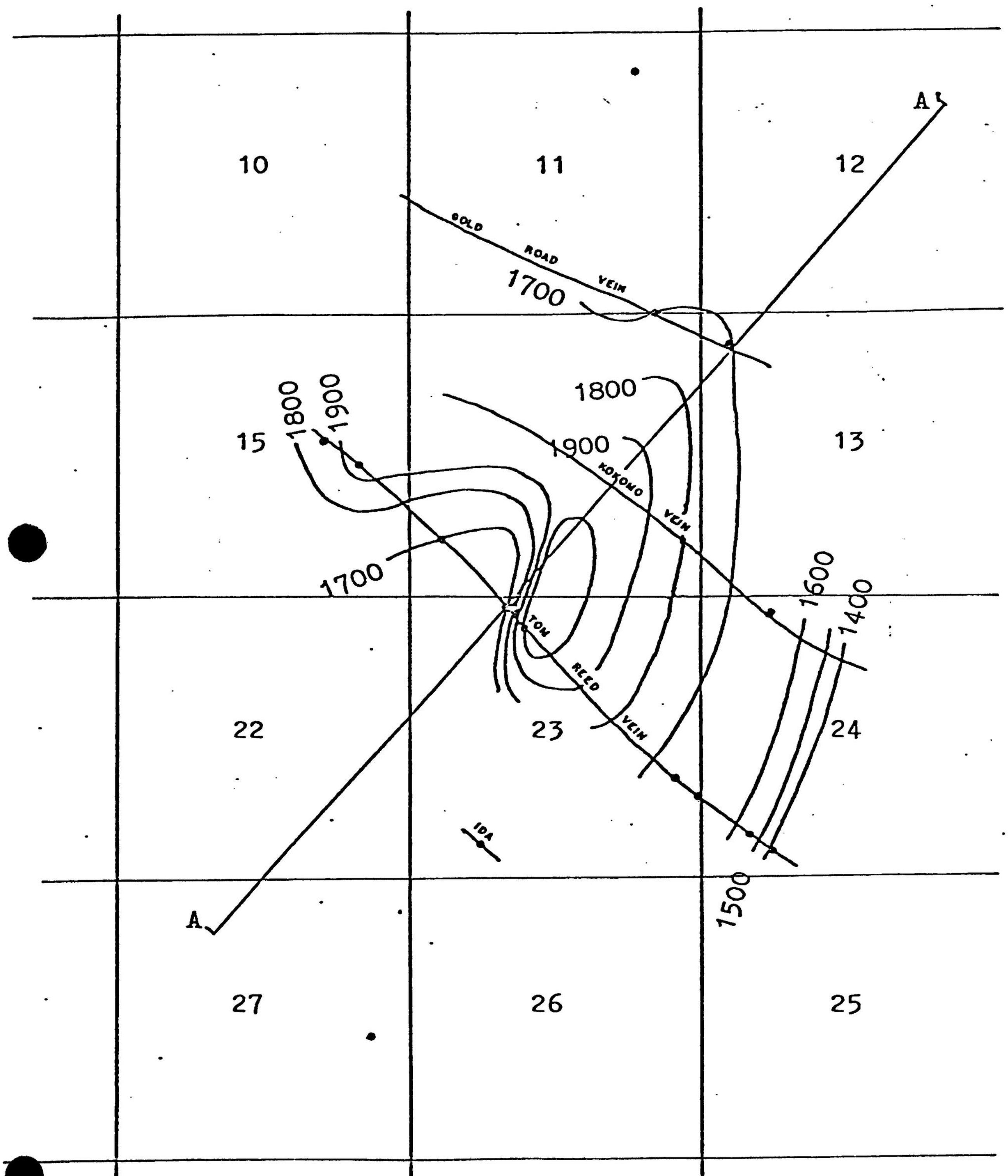


FIGURE 18 Elevations, in feet above sea level, of the bottoms of ore shoots.
• DATA POINT

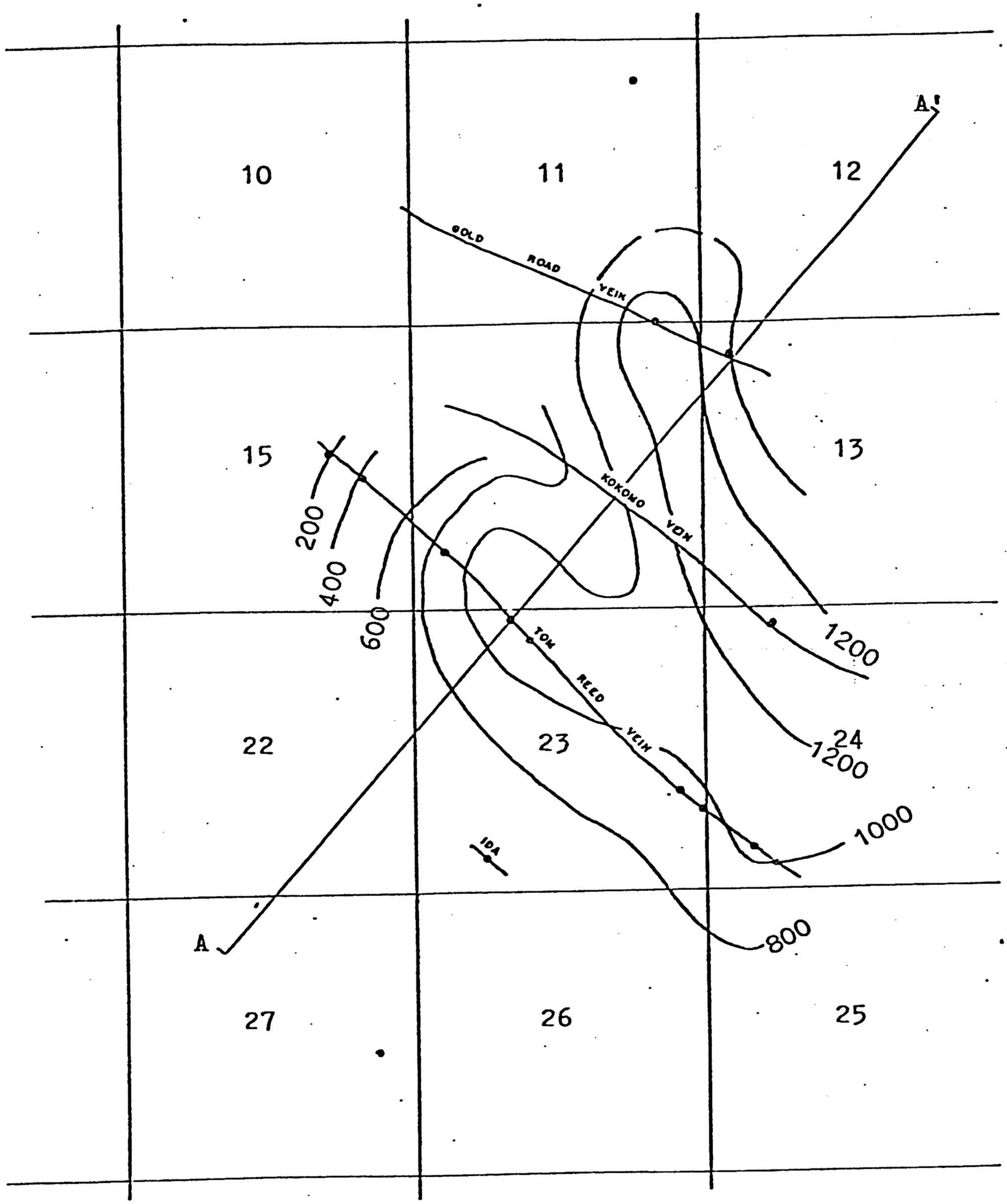


FIGURE 19 Vertical interval of ore, in feet, in the horizon of ore deposition.
• DATA POINT

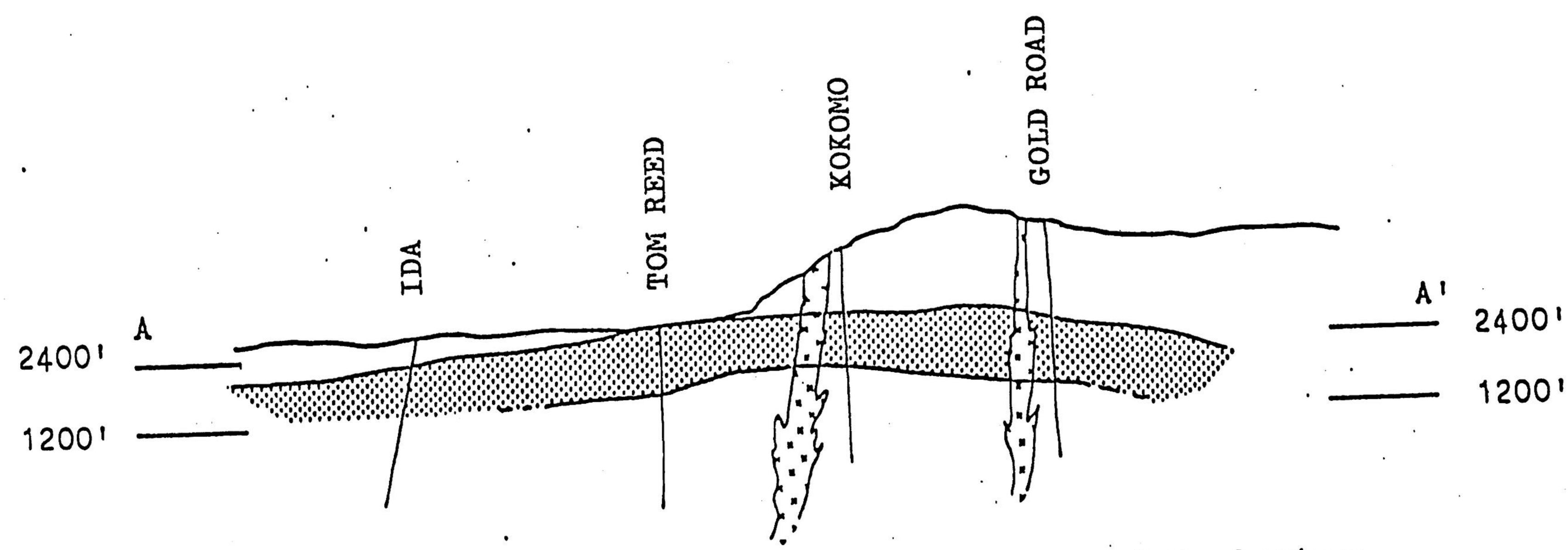


FIGURE 20 Section A-A', view N50W. Top and bottom of the horizon of ore deposition at the time of ore formation. Section is corrected for post-ore faulting and is relative to present-day topography and position of rhyolite dikes. Elevations in feet above sea level.

REFERENCES: #12, #165

DISTRICT: OATMAN

PRODUCTION: Au, Ag, Cu

GEOLOGIC SETTING: Quartz-calcite-adularia veins bearing electrum cut the Gold Road and Oatman latites. The veins strike NW and in many cases are associated with late-stage rhyolite porphyry dikes. Sulfides are rare except for pyrite in wallrocks adjacent to the veins. Propylitic alteration is district wide, while an alunite-illite-montmorillonite alteration assemblage lies above all productive veins in the district.

AGE: K-Ar dates from the Oatman district volcanics give late Oligocene to early Miocene ages. The mineralization is almost certainly related to volcanism, and hence is of mid-Tertiary age.

REFERENCES: #37, #118, #143, #165, #183

DISTRICT: OWENS

PRODUCTION: Ag, Au, Pb, Cu, Zn

GEOLOGIC SETTING: Veins and replacements above a mid-Tertiary detachment fault. This district is in close geographic proximity to the Buckskin-Rawhide detachment fault system, and Keith and others (1983a,b) infer that mineralization is related to faulting. A thorough literature review did not reveal any substantive geologic descriptions of this mineral district, and the relationship of mineralization to detachment faulting should be considered speculative at present.

AGE: If mineralization is related to the Buckskin-Rawhide detachment fault, then this is a mid-Tertiary mineral district; should this relationship not be demonstrable then the age should be considered unknown.

REFERENCES: #106, #107, #167, #168

DISTRICT: PILGRIM

PRODUCTION: Au, Ag

GEOLOGIC SETTING: Free gold in veins cutting across the fault contact between hangingwall rhyolites and footwall andesites. The volcanic rocks are probably equivalent to the Patsy Mine volcanics. Rhyolite porphyry dikes are commonly found in the fault zones. Veins are filled by quartz, calcite, pyrolusite and minor sulfides. Wallrocks are extensively silicified and brecciated. Red fault gouge and waxy green-yellow quartz mark high-grade ore zones.

AGE: If these volcanic rocks are time equivalent with the Miocene Patsy Mine volcanics, then a mid-Tertiary age is appropriate. There is little doubt about the

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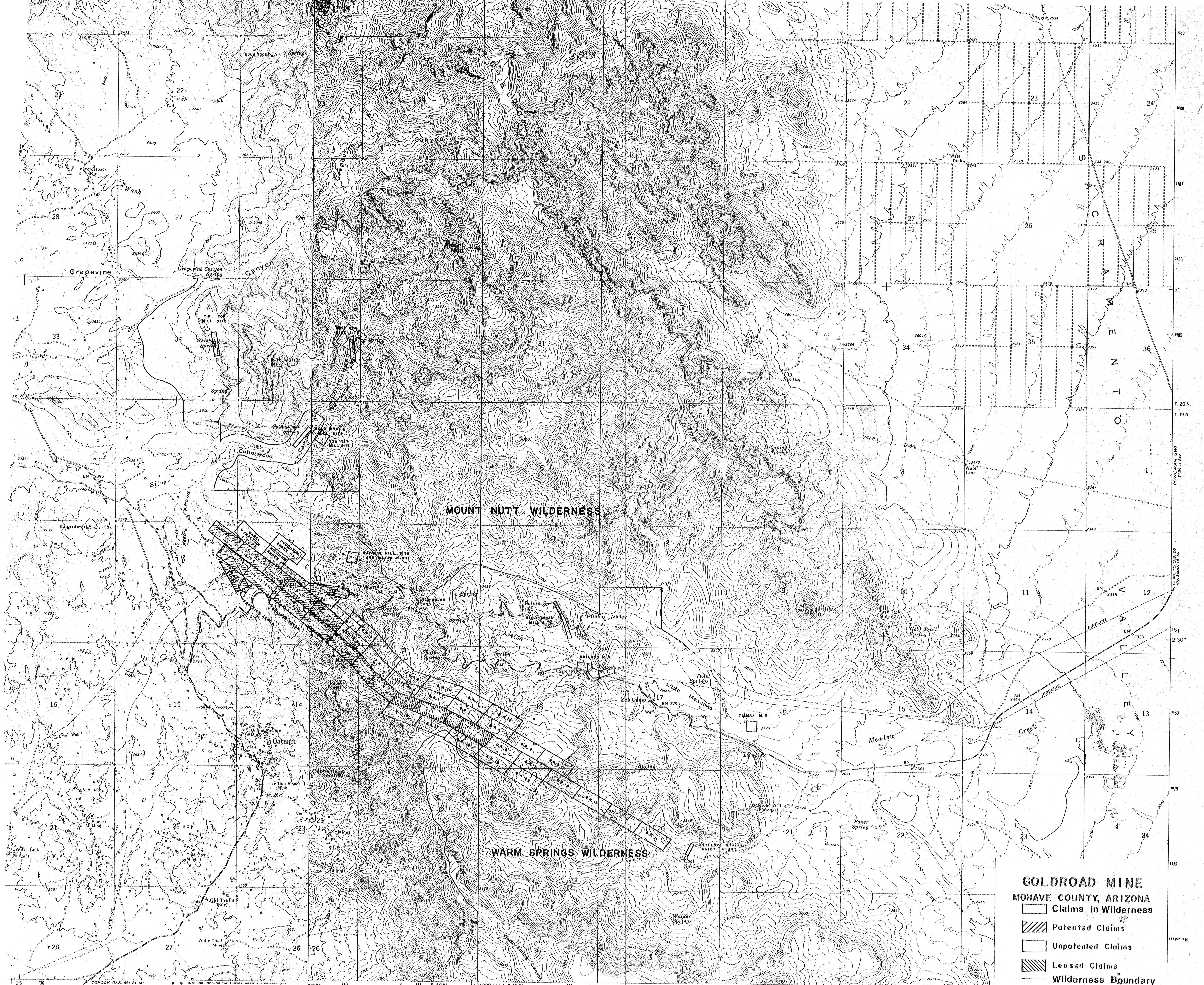

Mapped, edited, and published by the Geological Survey

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Topography by photogrammetric methods from aerial photographs taken 1965. Field checked 1967

Polyconic projection. 1927 North American datum
10,000-foot grid based on Arizona coordinate system, west zone
1000-meter Universal Transverse Mercator grid ticks, zone 11, shown in blue

ROAD CLASSIFICATION
Medium-duty ——— Light-duty ———
Unimproved dirt - - - - -

ARIZONA
QUADRANGLE LOCATION

OATMAN, ARIZ.
N3500—W11422.5/7.5
1967
AMS 3154 III SW—SERIES V898

UTM GRID AND 1967 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
GN MN
1°32' 27 MILS
15° 267 MILS

SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

ARIZONA
QUADRANGLE LOCATION

ROAD CLASSIFICATION
Medium-duty ——— Light-duty ———
Unimproved dirt - - - - -

MOUNT NUTT, ARIZ.
N3500—W11415/7.5
1967
AMS 3154 III SE—SERIES V898

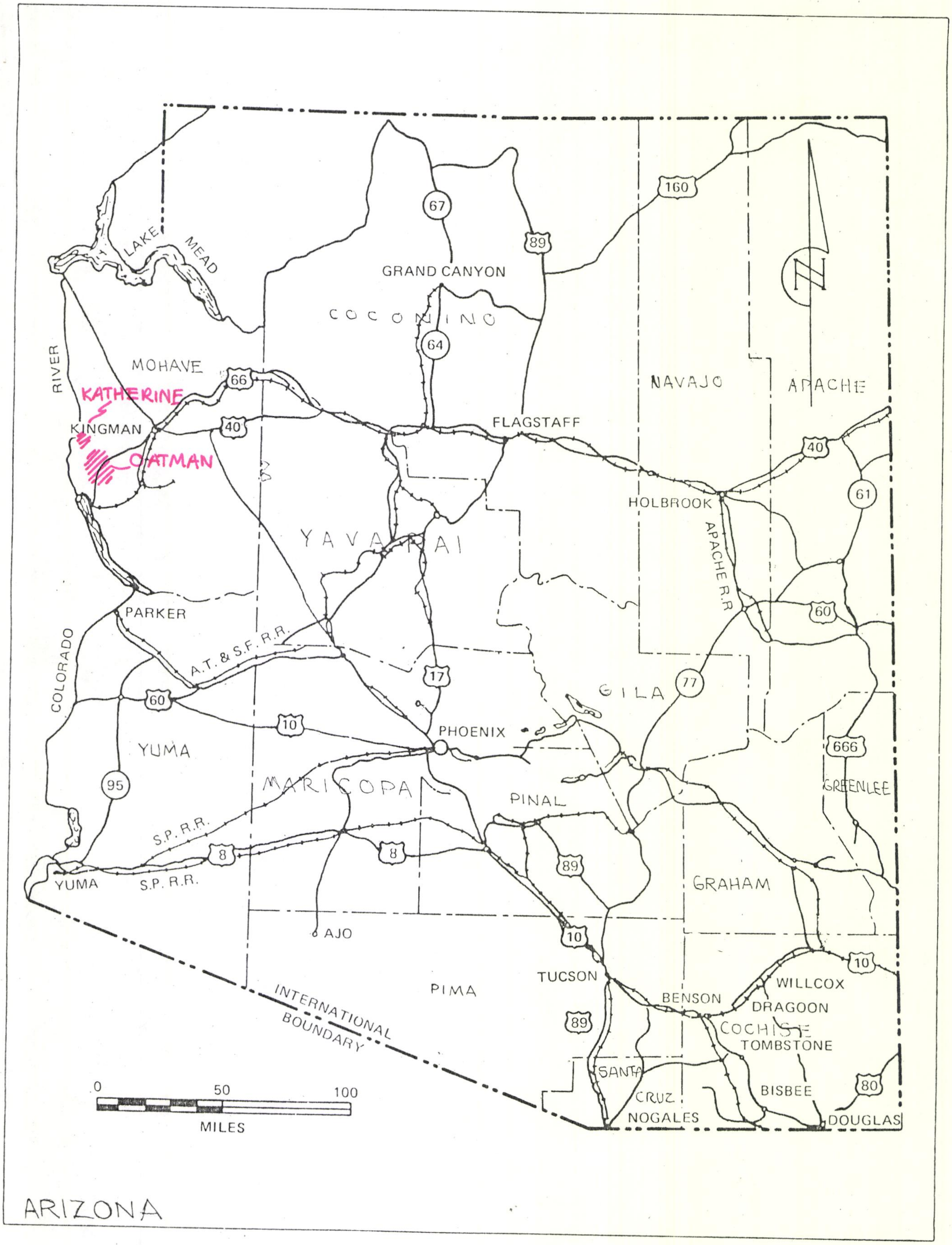


Figure 1 - Project Area

PLATE II

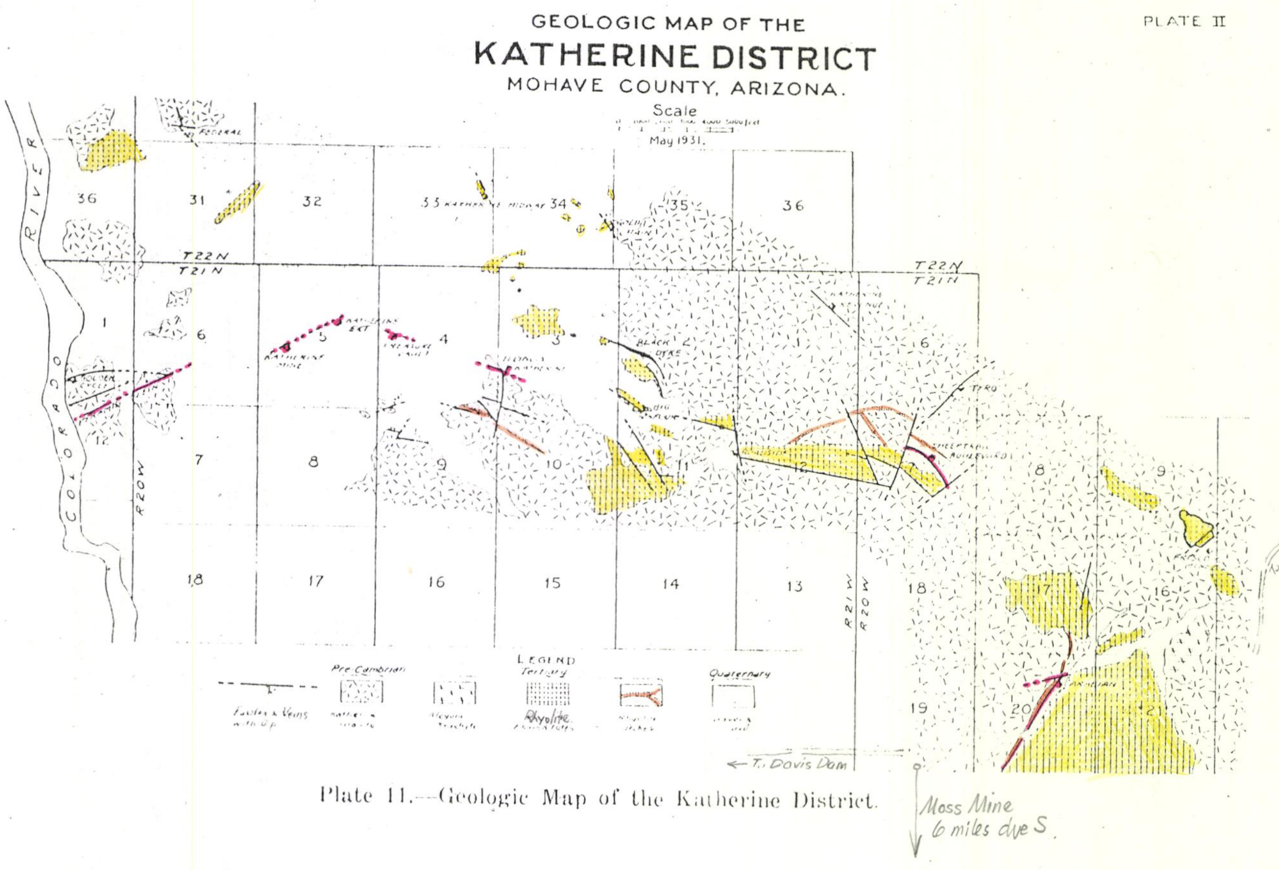
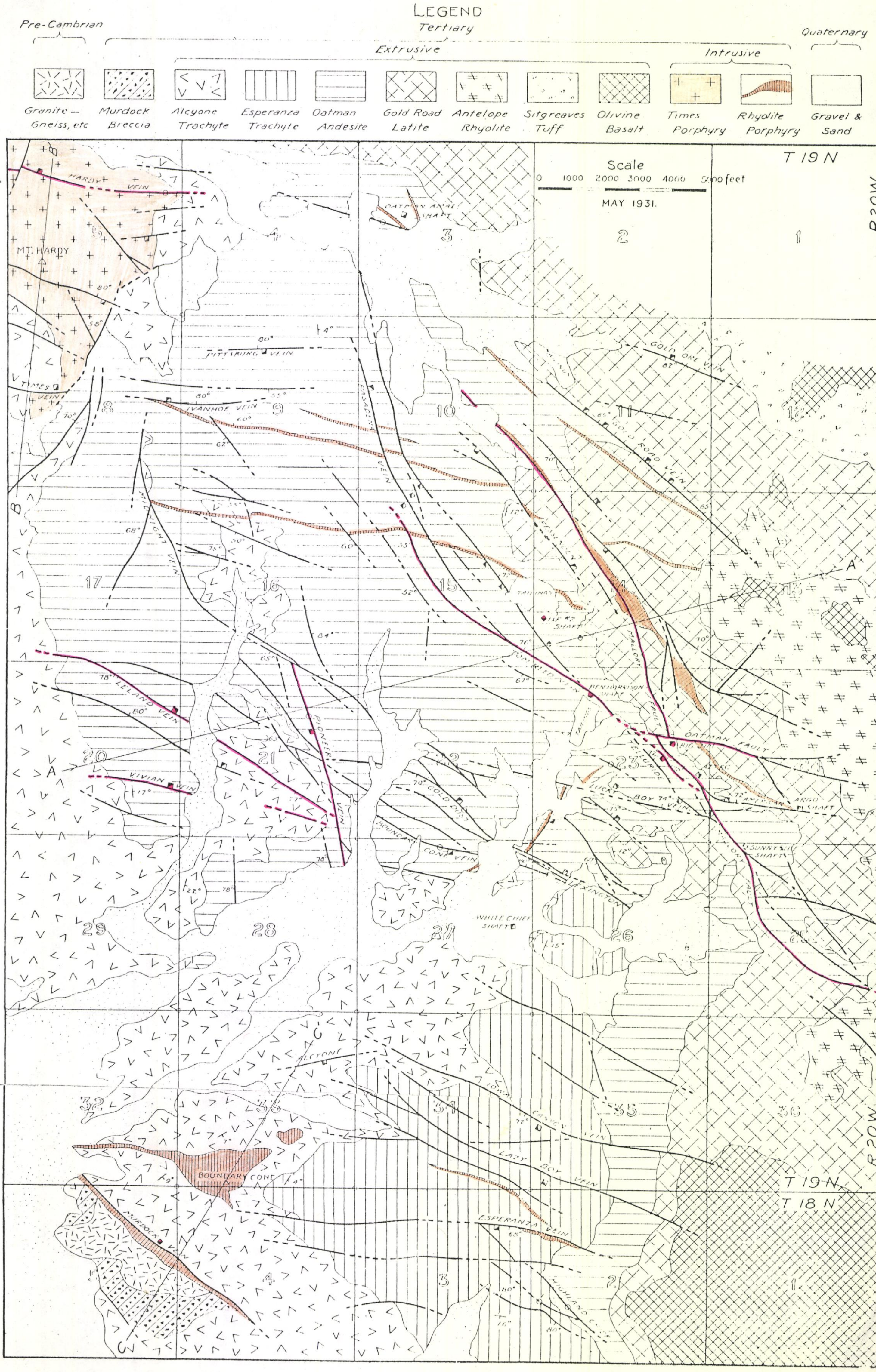


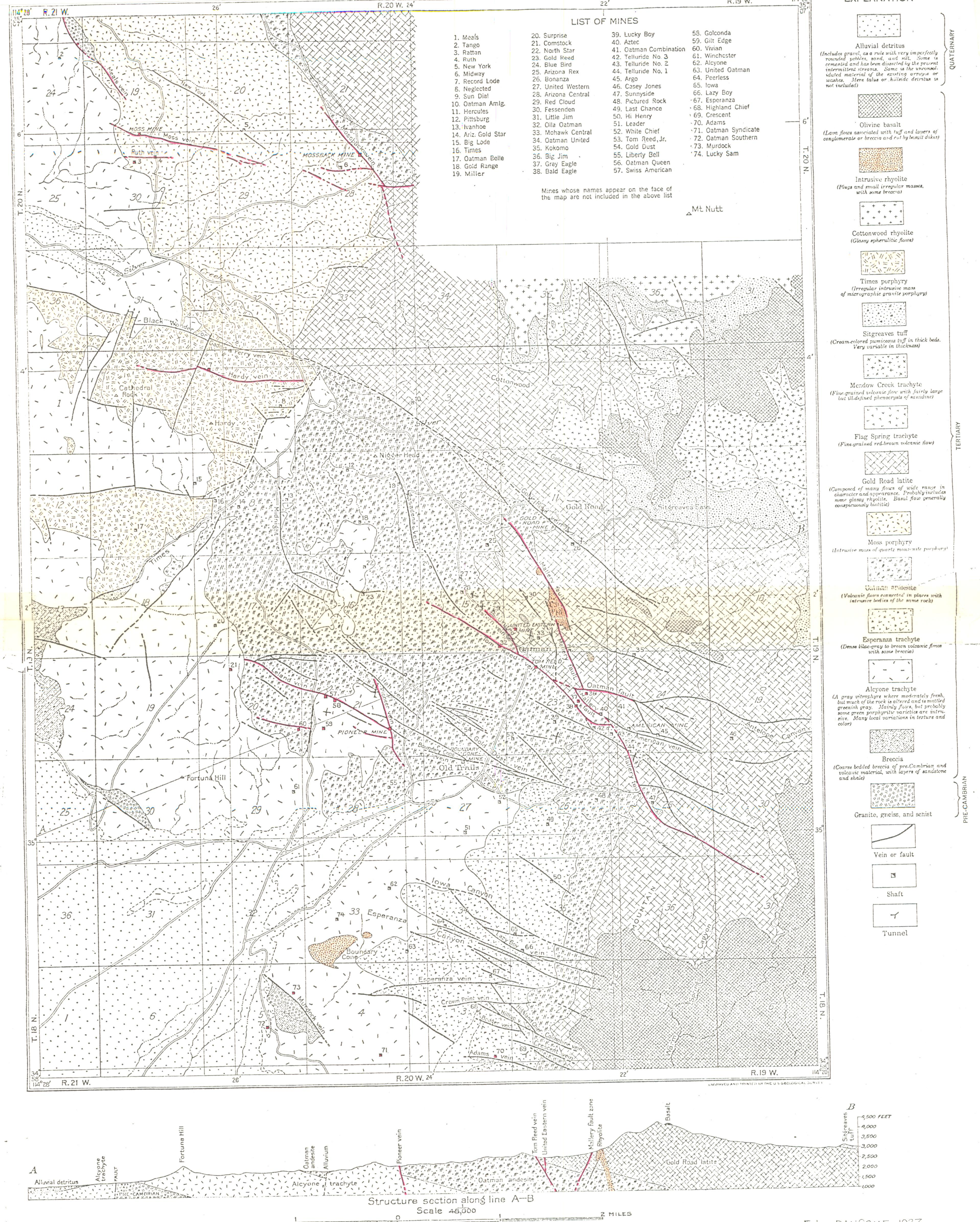
Plate II.—Geologic Map of the Katherine District.

Moss Mine
6 miles due S.

GEOLOGIC MAP OF THE OATMAN DISTRICT

MOHAVE COUNTY, ARIZONA.





GEOLOGIC MAP OF THE OATMAN DISTRICT, ARIZONA

F. L. RANSOME, 1923
USGS BULL. 743 PLATE 1

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology and gold deposits of the Oatman District Northwestern Arizona

By

Ed DeWitt[1], Jon P. Thorson[2],

and Robert C. Smith[3]

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 Porphry. 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.

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ILLUSTRATIONS

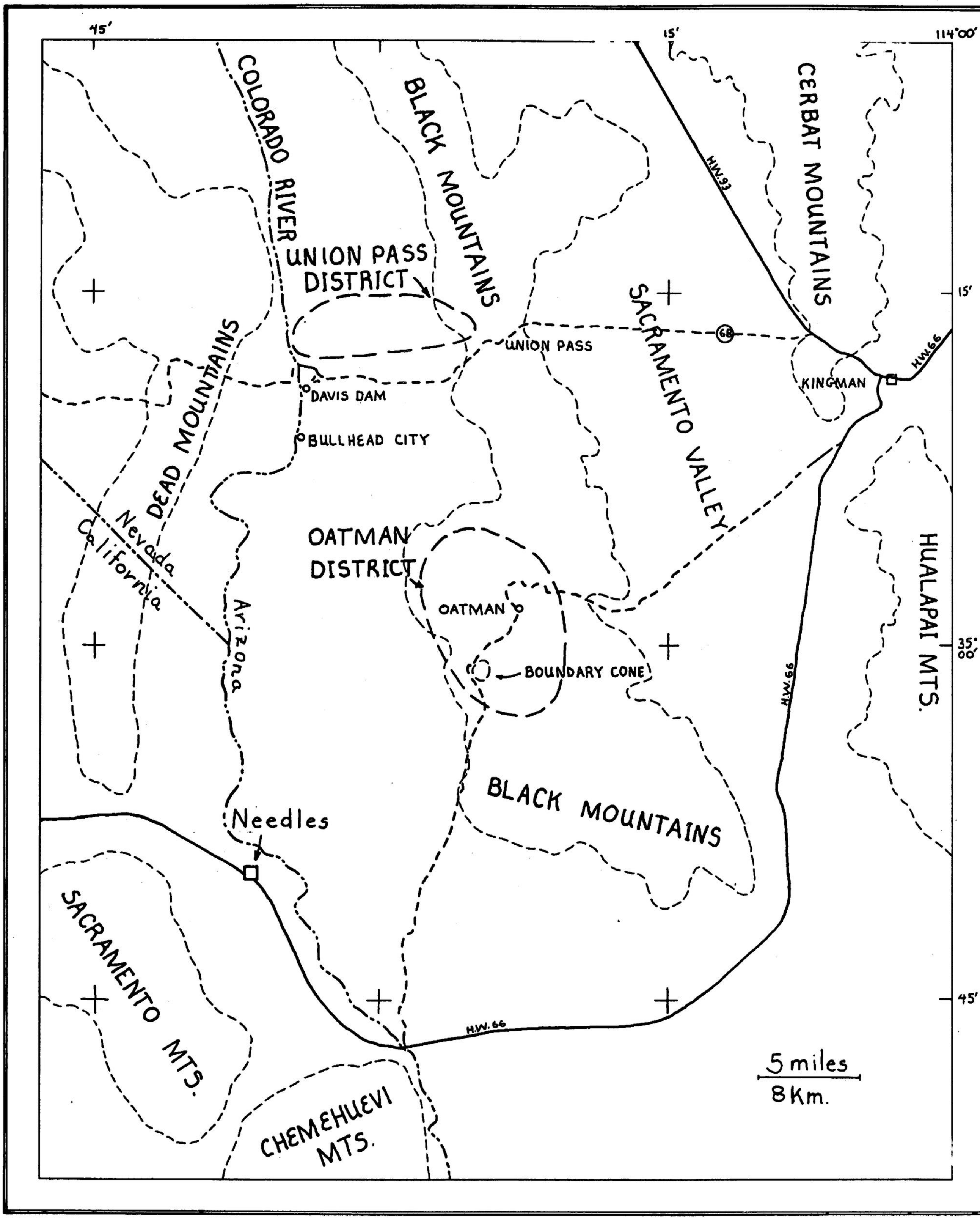


Figure 1. Location map of the Oatman area, northwestern Arizona.

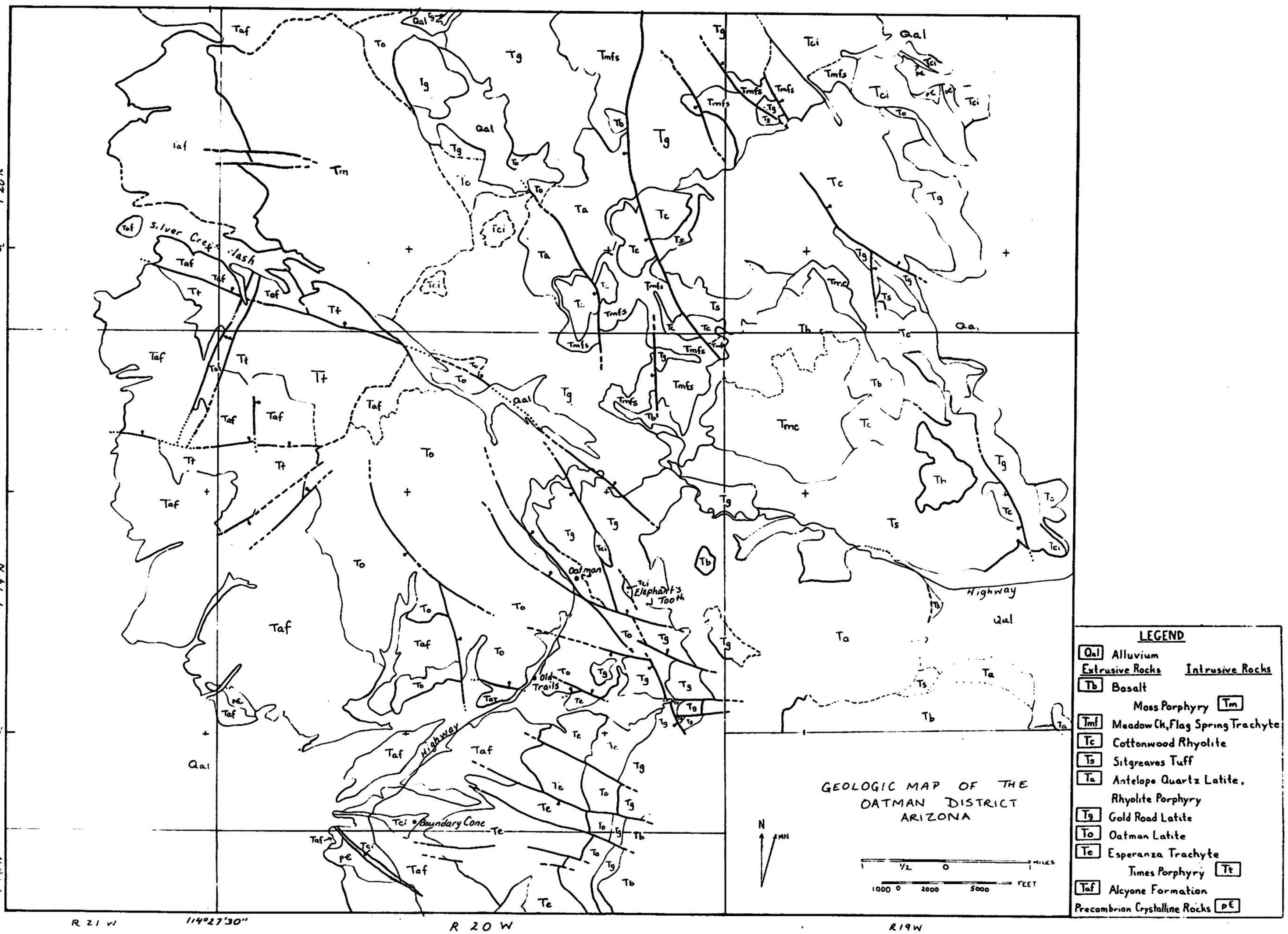


Figure 2. Geologic map of the Oatman district, Arizona. Compiled from Thorson (1971), Ransome (1923), and Clifton and others (1980).

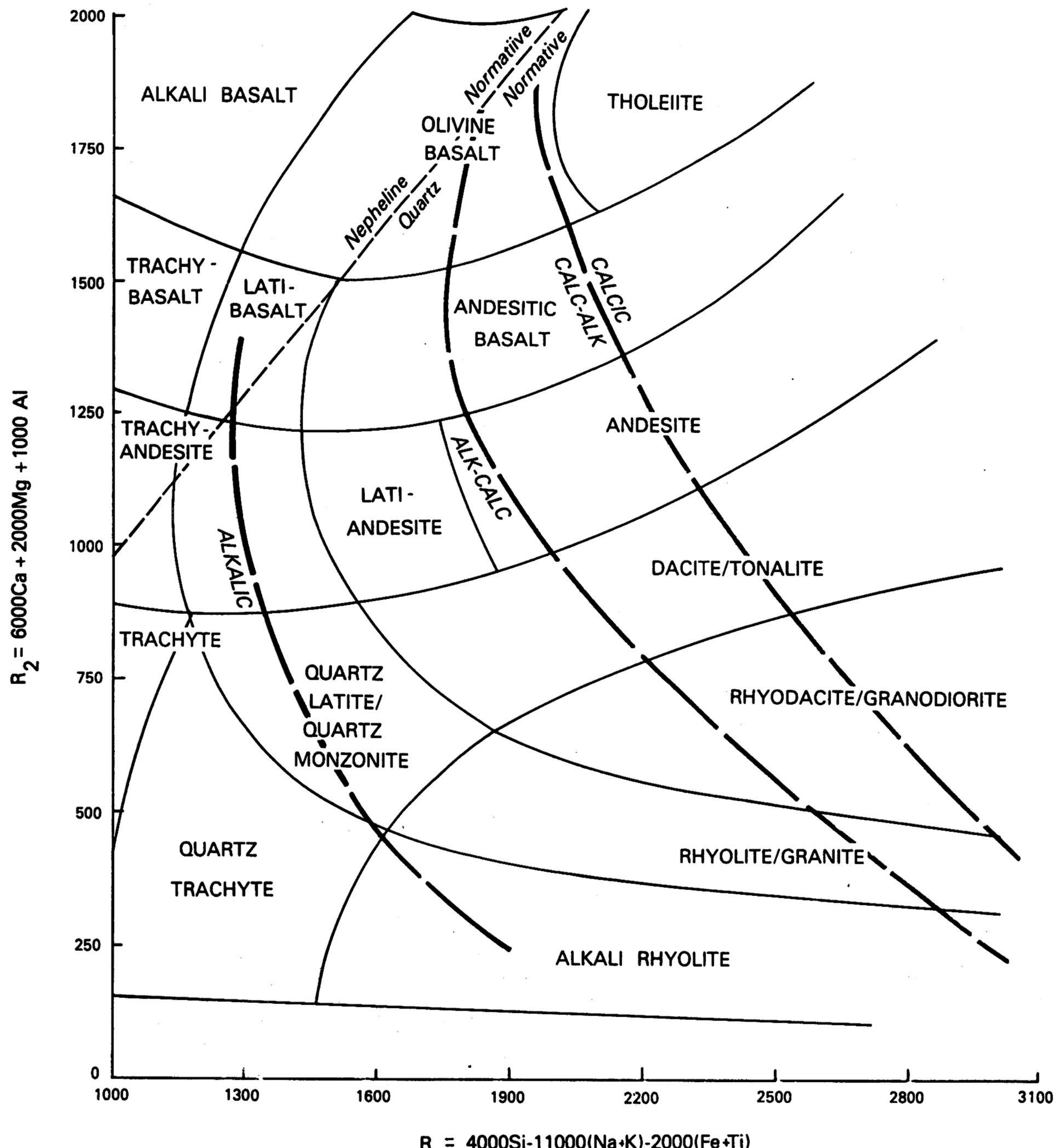
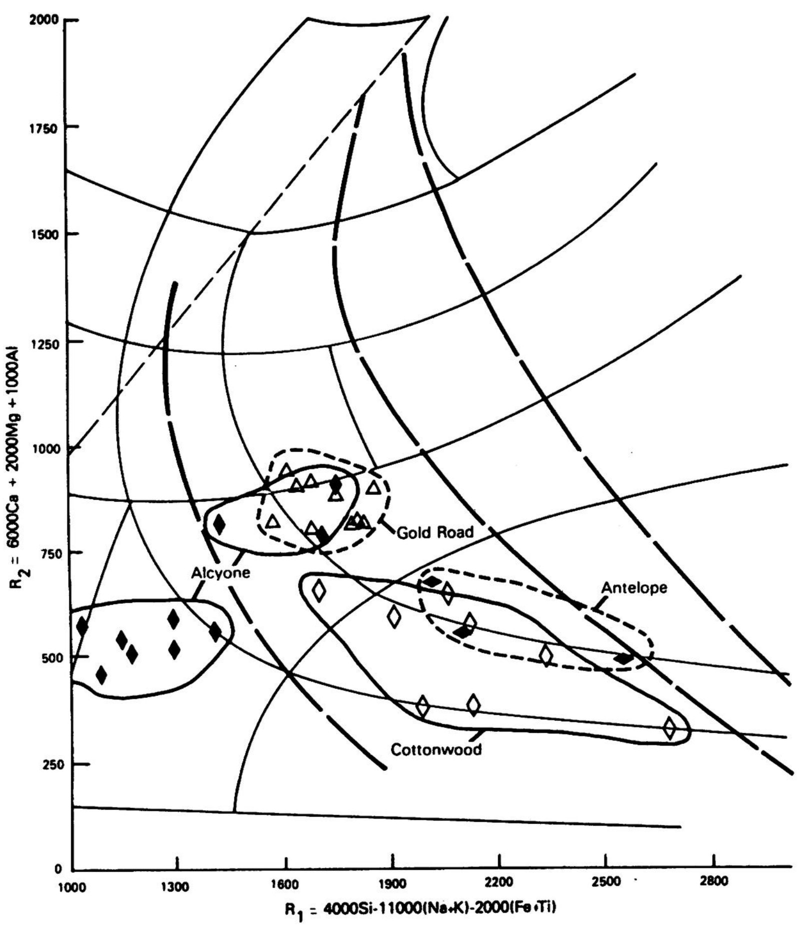
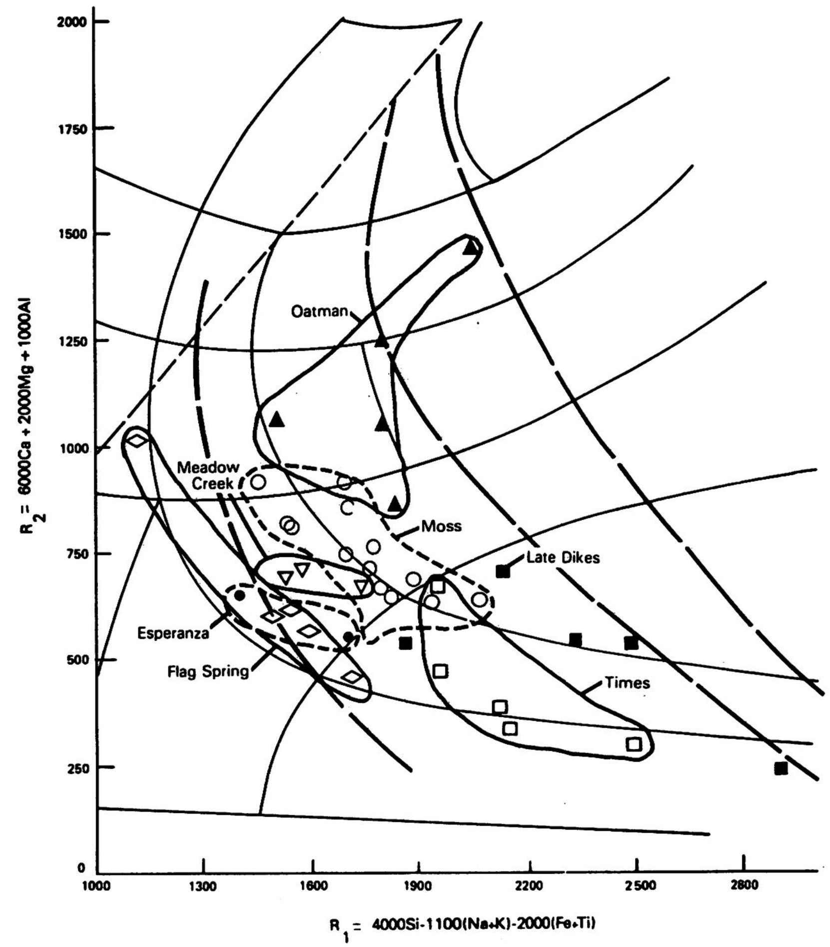


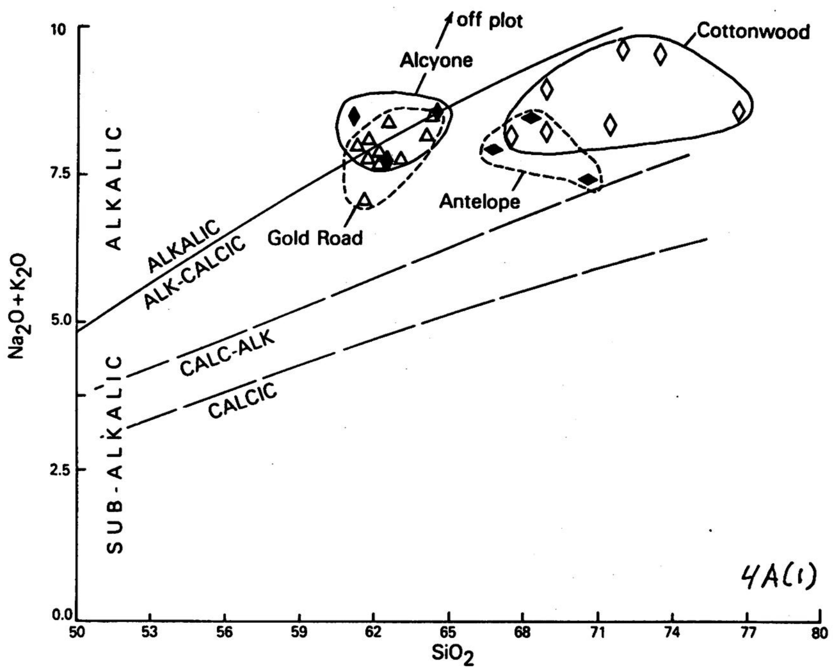
Figure 3A. R_1-R_2 rock classification diagram (De la Roche and others, 1980).

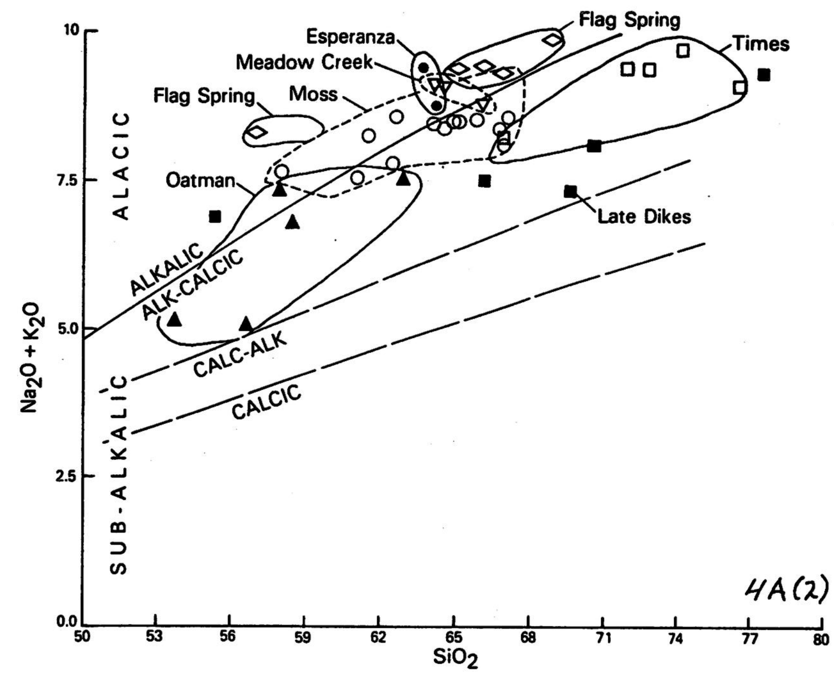




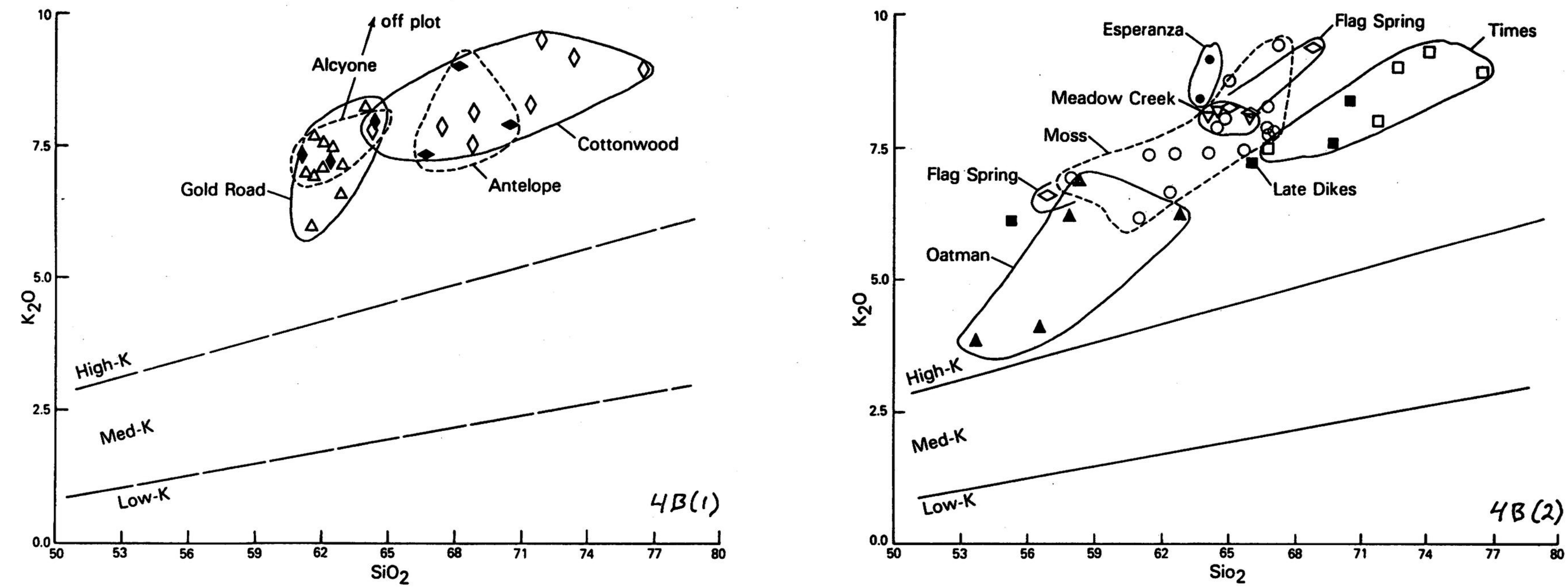
Figures 3B and 3C. R_1-R_2 classification diagram for representative rock samples of volcanic and plutonic rocks of the Oatman area.

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





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.

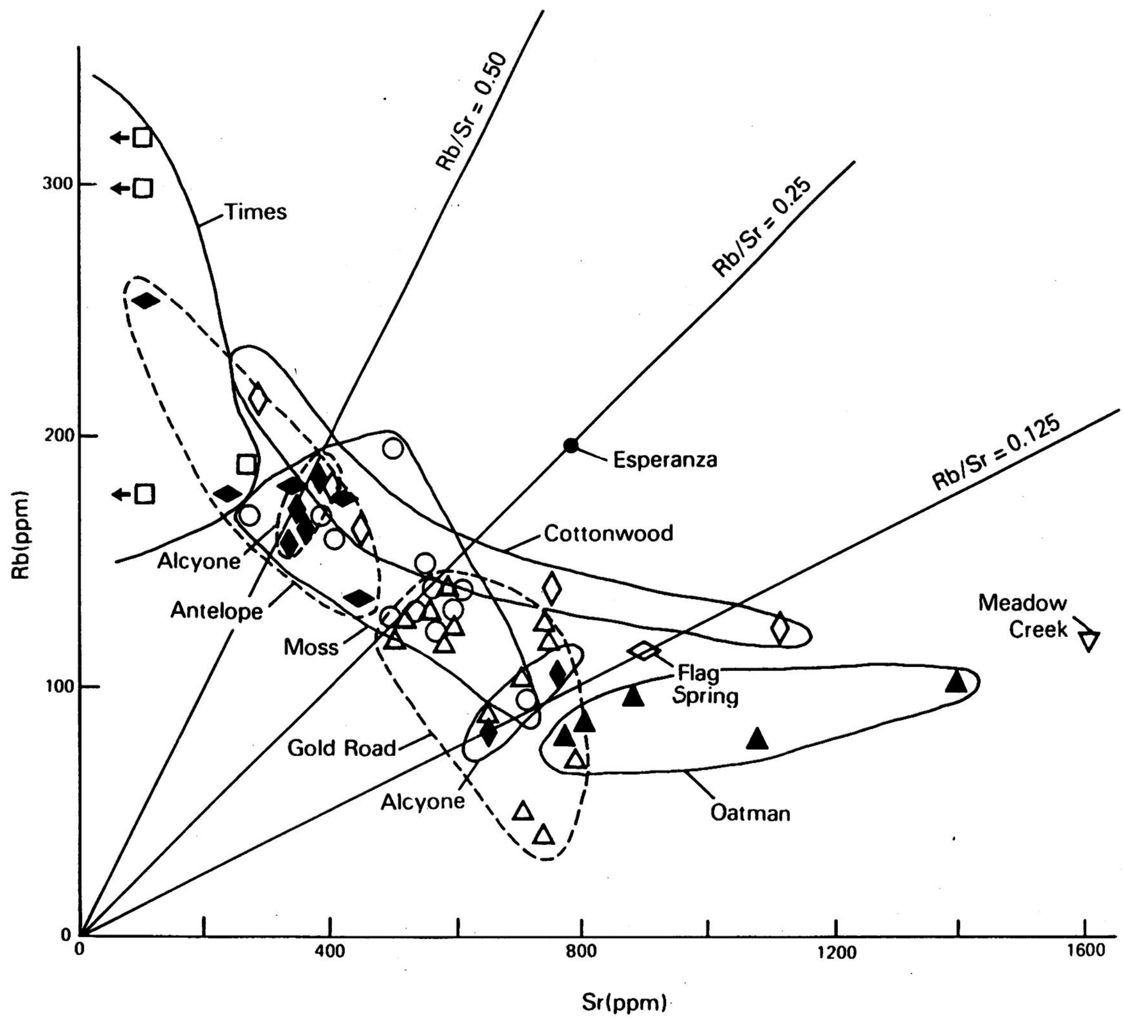


Figure 5A. Rb vs Sr plots of volcanic and plutonic rocks of the Oatman area. Symbols as in figure 3.

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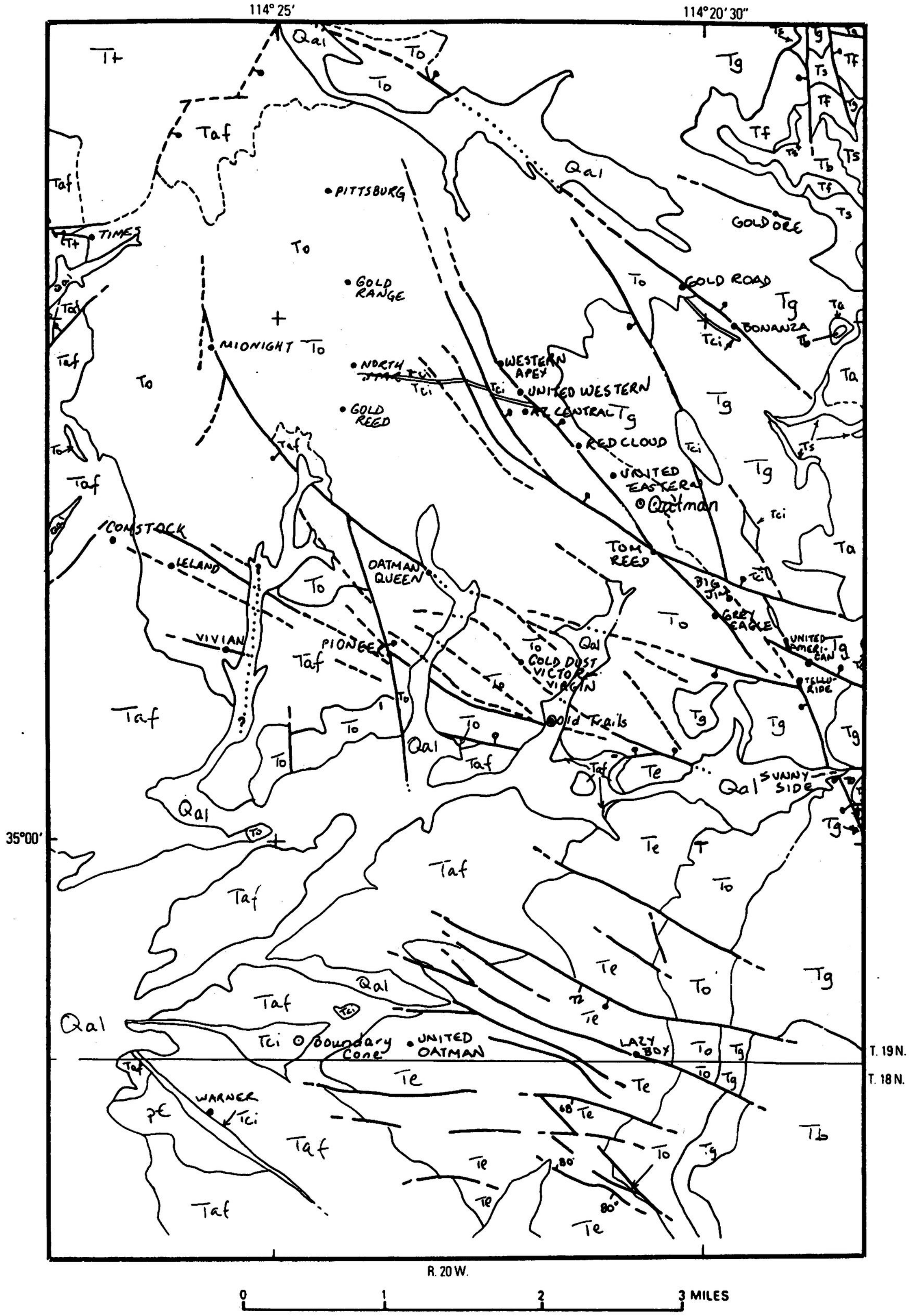

Figure 6. Detailed geology and location of mines in the Oatman district. Compiled from Thorson (1971), Ransome (1923), and Clifton and others (1980). p€, Precambrian; Taf, Alcyone Formation; Te, Esperanza Trachyte; To, Oatman Latite; Tg, Gold Road Latite; Ta, Antelope Quartz Latite; Ts, Sitgreaves Tuff;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

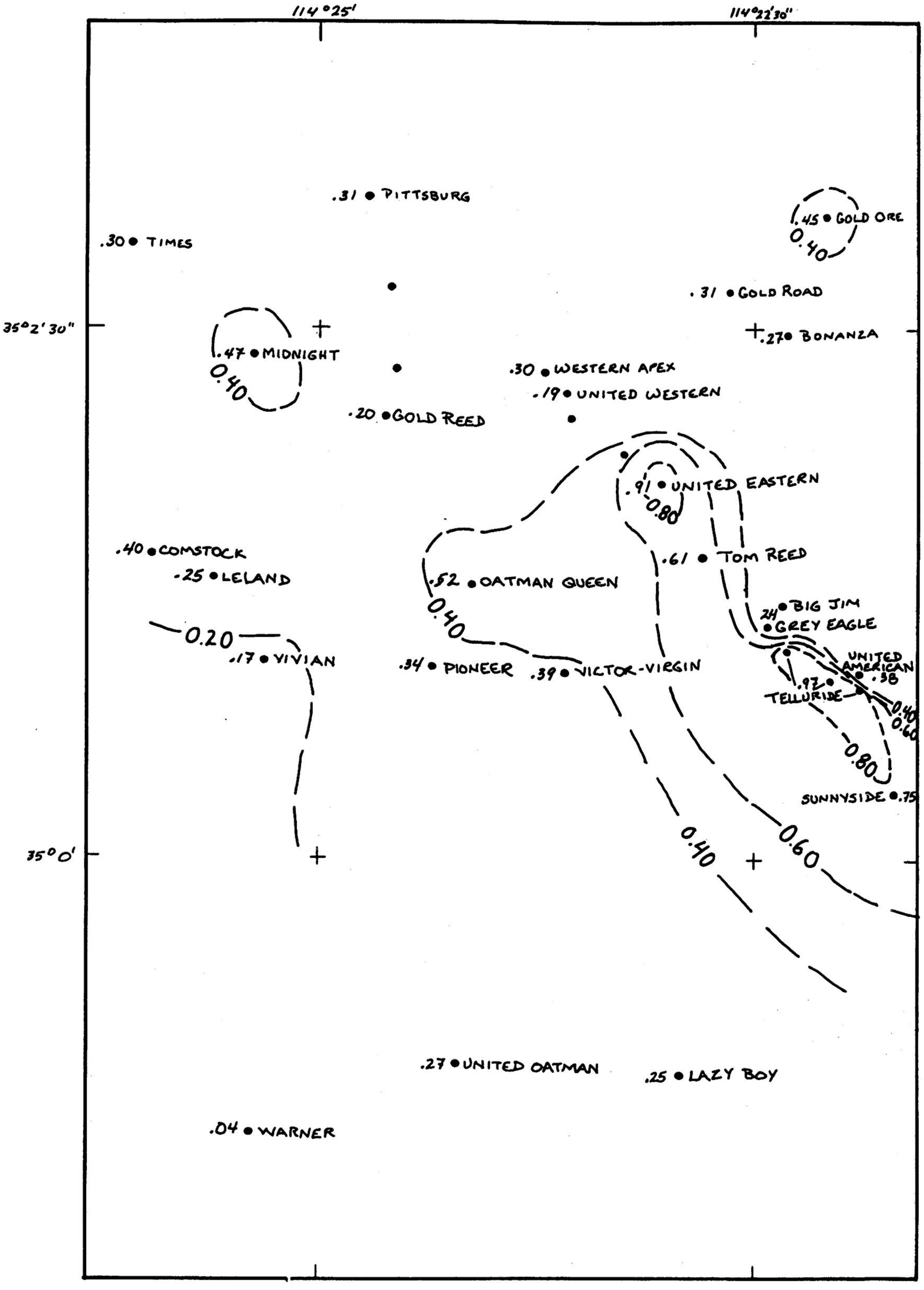

Figure 7A. Contour map of gold grade, in oz per ton, of individual deposits in the Oatman district.

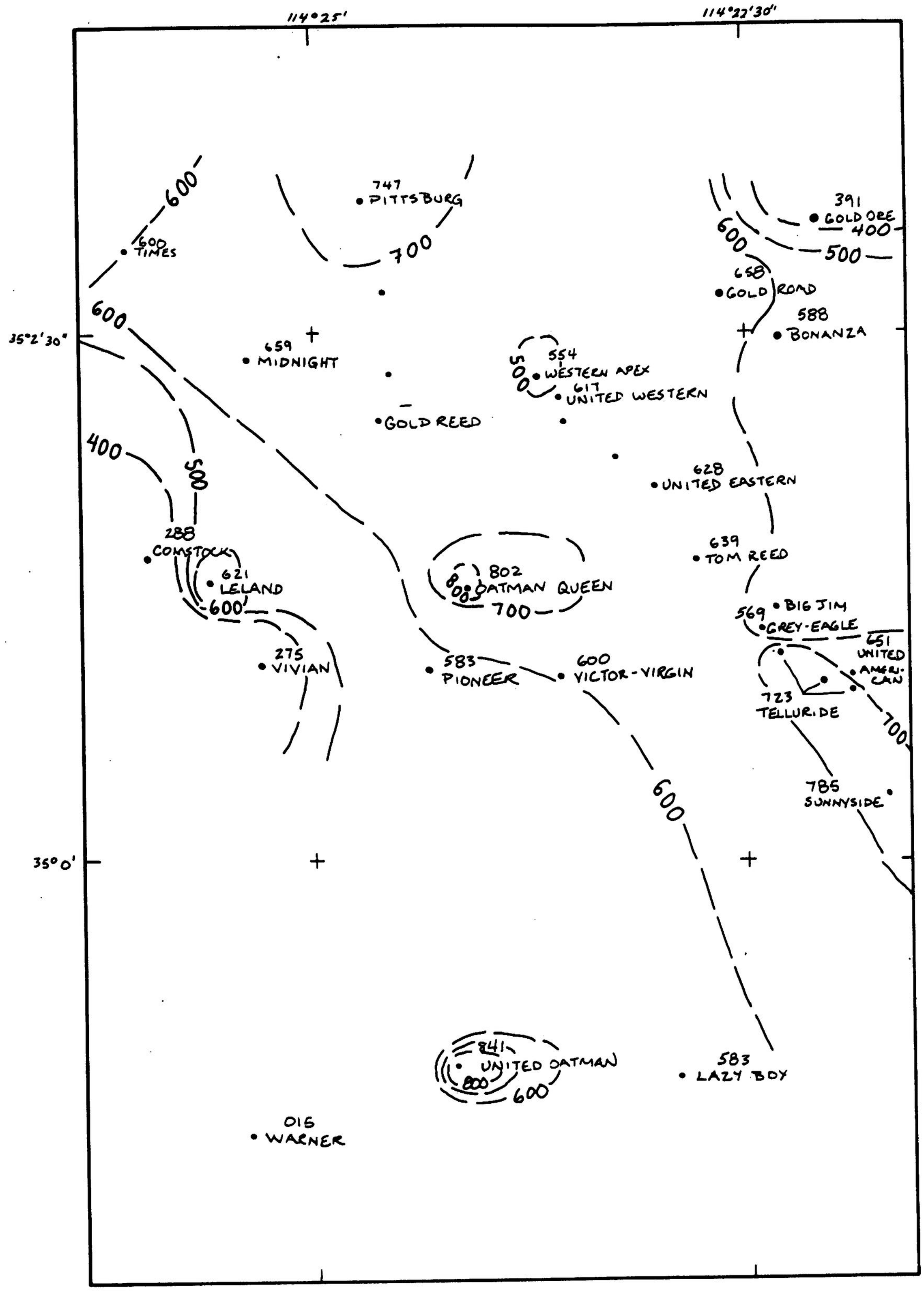

Figure 7B. Contour map of Au/(Au + Ag) ratios of individual deposits in the Oatman district. Values are multiplied by 1000 to eliminate decimal points.

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: $^{206}Pb/^{204}Pb = 18.67$, $^{207}Pb/^{204}Pb = 15.63$, $^{208}Pb/^{204}Pb = 38.59$.

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The Geology and Ore Deposits of Oatman, Arizona

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Abstract

The Oatman District, Mohave Co., Arizona, has produced 2,200,000 oz. Au and 800,000 oz. Ag from 3,800,000 tons of ore produced from sulfide-deficient quartz-calcite-adularia-electrum veins in Miocene volcanics. Hosts to the veins are the Oatman Formation, a 1000' thick series of latitic andesite flows and tuffs, and the 18.2 my old Gold Road Formation, a series of latitic andesite and dacite flows. Mineralized fissures strike northwesterly and dip steeply north with few exceptions. Ore shoots within otherwise subore grade fissures are located on the northwest flanks of concave-east bends in the fissure, believed occupying dilatant zones formed during a right lateral component of net slip. Ore shoot location is further limited by elevation above sea level, with the areal distribution of ore shoots forming a domed ore horizon. Finally, wider and larger tonnage ore shoots are largely confined to the Oatman Formation host rock, however, veins hosted by the Gold Road Formation may be much more continuously mineralized on strike, although narrow. Mineralized fissures are in a widespread propylitic alteration envelope. A more narrowly restricted illitic alteration zone, mostly in the hanging wall of veins, crops out above ore shoots. Silicification along the vein exposures varied from absent to intense, and does not necessarily indicate ore at depth. Detailed mapping in the Oatman District, paying particular attention to zones of illitic alteration and to structural configuration of the fissures, should lead to additional ore discoveries.

Introduction

Epithermal vein districts, those romantic deposits that helped populate the west, start and end wars, build generations of wealth, create boom or bust - epithermal vein districts with histories replete with bonanzas and empires and overnight fortunes - epithermal vein districts, the Tonopahs, Comstocks, Auroras, and Goldfields whose very names command such awe and even today stir the imagination of young geologists - epithermal vein districts like Oatman, what can they offer today? For decades ignored, thought worked out, thought depleted of their bonanzas, while the industry moved toward lower grade, lower cost, and much larger tonnage deposits. Oatman, the third largest gold producer from epithermal veins in the Basin and Range Province, is an anomaly in that it is the only major volcanic-hosted epithermal vein district in Arizona; but otherwise Oatman is like the rest: Her secrets are difficult to discover, more difficult to utilize, and always of interest.

This report will summarize from published and unpublished data our present understanding of the geology and ore controls of the gold mineralization at Oatman. The principal data sources are Schrader (1909), Ransome (1923), Lausen (1931), Wilson (1967), Thorson (1971), Buchanan (1979b), Clifton and others (1980), Durning (1980), DeWitt and Thorson (1982), and Knight and Winston (1983). Data have been freely drawn from these sources and, if required, modified to reflect changes in our understanding of the ore deposits. Much data have been drawn from private files of Fischer-Watt Mining Co., whose permission and encouragement to write this paper are greatly appreciated.

Numerous geologists have helped collect and interpret the data presented in this paper, and special credit must be given to: F. Haynes, D. Muchow, L. Knight, M. Winston, M. Nelson, A. Morris, C. Clifton, and R. Smith.

Location

The Oatman District is located in the southern portion of the Black Mountains about 30 miles southwest of Kingman, Mohave County, Arizona, approximately 100 miles south-southeast of Las Vegas, Nevada (Figure 1). Access is via U.S. Highway 66, which passes through the central part of the district.

History and Production

The original discovery of gold ore at Oatman was made in 1863 by John Moss, an army officer from Camp Mohave. The Moss Vein, located in the western part of the district, produced about 12,000 ounces of gold prior to forced closure by unfriendly Indians in 1866. Mining activities resumed in the 1880's but is was not until the discovery of the Gold Road Vein in 1900 that prospecting activities

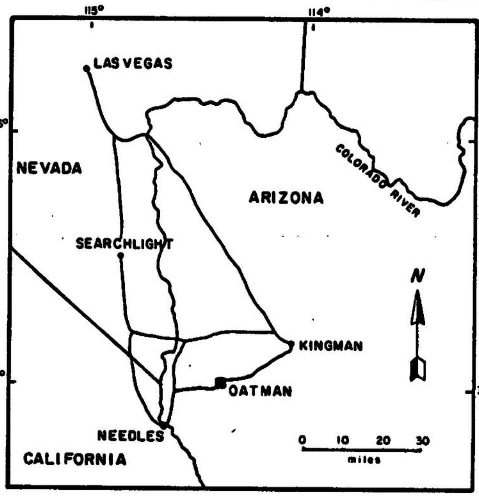


FIGURE 1: LOCATION MAP

moved to the central part of the district. In 1901, gold was found on the Tom Reed Vein, near the present Oatman townsite, but it was not until 1906 that rich ore in the Tip Top and Ben Harrison ore shoots was discovered. In 1915 and 1916, the Big Jim, Aztec and United Eastern orebodies were discovered on the Tom Reed Vein and the resultant boom swelled the population of Oatman and Gold Road to over 10,000 people. By the mid 1920's Oatman's population had dwindled to a few hundred and most of the mines had turned to leassor operations. An increase in the gold price from $20 to $35 per ounce in 1933 resulted in the reopening of the Tom Reed and Gold Road Mining Company properties until they were closed by War Board Order L-208 in 1942.

Fischer-Watt Mining entered the district in 1979, hoping that with detailed geologic mapping, the past productive non-outcropping ore shoots could be characterized and new exploration targets defined. To accomplish this end, the central part of the district was mapped at 1" = 100'. This mapping resulted in the recognition of distinctive geologic features in the past productive area and the identification of several unexplored targets. Evaluation of several of these targets by 42,000 feet of hammer and core drilling identified a moderate tonnage of low grade ore (+0.20 o/T Au).

Total production for the Oatman District between 1897 and 1942 was about 2.2×10^6 ounces Au and 0.8×10^6 ounces Ag. The metal was derived from 3.8×10^6 T of ore with an average recovered grade of 0.58 o/T Au, and 0.21 o/T Ag (Table 1). The majority of this production came from ten major ore shoots on the Tom Reed and Gold Road Veins (Table 2). All other mines contributed about 10% of the total district production.

Regional Geology

Geologic maps covering the Oatman District compiled by Ransome (1923), Lausen (1931), and Thorson (1971), provide regional geologic coverage.

The Black Mountains lie approximately 40 miles from the eastern edge of the Basin and Range Province. The Oatman District lies on the southwest flank of the Black Mountains within a thick sequence of +23 to 18 my old andesite, trachyte, latitic dacite, dacite, and rhyolite volcanic rocks which are intruded by monzonite to granite hypabyssal plutons (Figure 2). These volcanic rocks lie unconformably upon, or prehaps in low angle fault contact with, a basement of Precambrian granite, gneiss, and schist.

The Black Mountains are deeply incised on their western flank but are little eroded on their eastern flank. Exposures of the Precambrian basement are found in sparse outcrops on the western margin of the district. The volcanic center appears to have been in the Oatman area, as evidenced by a concentration of rhyolite to latite dikes and plugs and two high level (epizonal) plutons within a two mile radius of Oatman. Furthermore, the thick volcanic sequence thins rapidly away from Oatman (Clifton and others, 1980).

The volcanics show a 10° - 35° easterly regional dip, attributed by Thorson (1971) and others to regional tilting. Clifton and others (1980) suggest this dip may be due to a "central volcanic edifice at Oatman or related to late magmatic doming". Recent work by Fischer-Watt 8 miles to the north at the Roadside Mine and by Frost and Mathis (1982) 20 miles west in the Newberry Mts. suggests the east dipping volcanics are due to rotation along a west-dipping low angle detachment fault near the Precambrian-Tertiary contact. This hypothesized fault was perhaps cut by a deep drill hole below the United Eastern Mine, described by Lausen (1931) as "old highly sheared granite". The proposed detachment fault surface has not been identified in the field: However, the description from the United Eastern drill hole, the existence of a detachment fault to the north extending from the Roadside Mine to Lake Mead, and the east dipping Tertiary volcanics suggest this detachment environment perhaps extends beneath the volcanics exposed at Oatman.

The volcanic stratigraphy of the Oatman District is taken from Thorson (1971) and summarized and locally modified by Buchanan (1979b).

The Tertiary volcanic rocks rest on or are in fault contact with a Precambrian basement composed of biotite schist, granite gneiss, and intrusive biotite granite, the Katherine Granite (Figure 2). The Precambrian is overlain by the Late Miocene Alcyone Formation - a sequence of welded trachyte tuffs, quartz latite flows, sedimentary tuff breccias, landslide breccias, and minor carbonaceous shales and limestones. The Alcyone Formation is termed the lower volcanics by Thorson (1971).

TABLE 1

INDIVIDUAL MINING COMPANY PRODUCTION

OATMAN MINING DISTRICT, MOHAVE COUNTY, ARIZONA

Mine	Gold $20.67/oz 1897-1933 Tons of Ore	Mined Grade oz/T	Gold $35/oz 1934-1942 Tons of Ore	Mined Grade oz/T	Total Tons of Ore	Average Mined Grade oz/T
Tom Reed Mining Co.	981,090	0.70	205,125	0.32	1,186,215	0.64
United Eastern Mining Co.	687,038	1.12	Ø	Ø	687,038	1.12
Gold Road Mining Co.	737,926	0.47	775,895	0.22	1,513,823	0.32
Total Production	2,406,054	0.74	981,020	0.24	3,387,076	0.59
Other mines	(estimated)					

Source: Clifton and others (1980)

TABLE 2

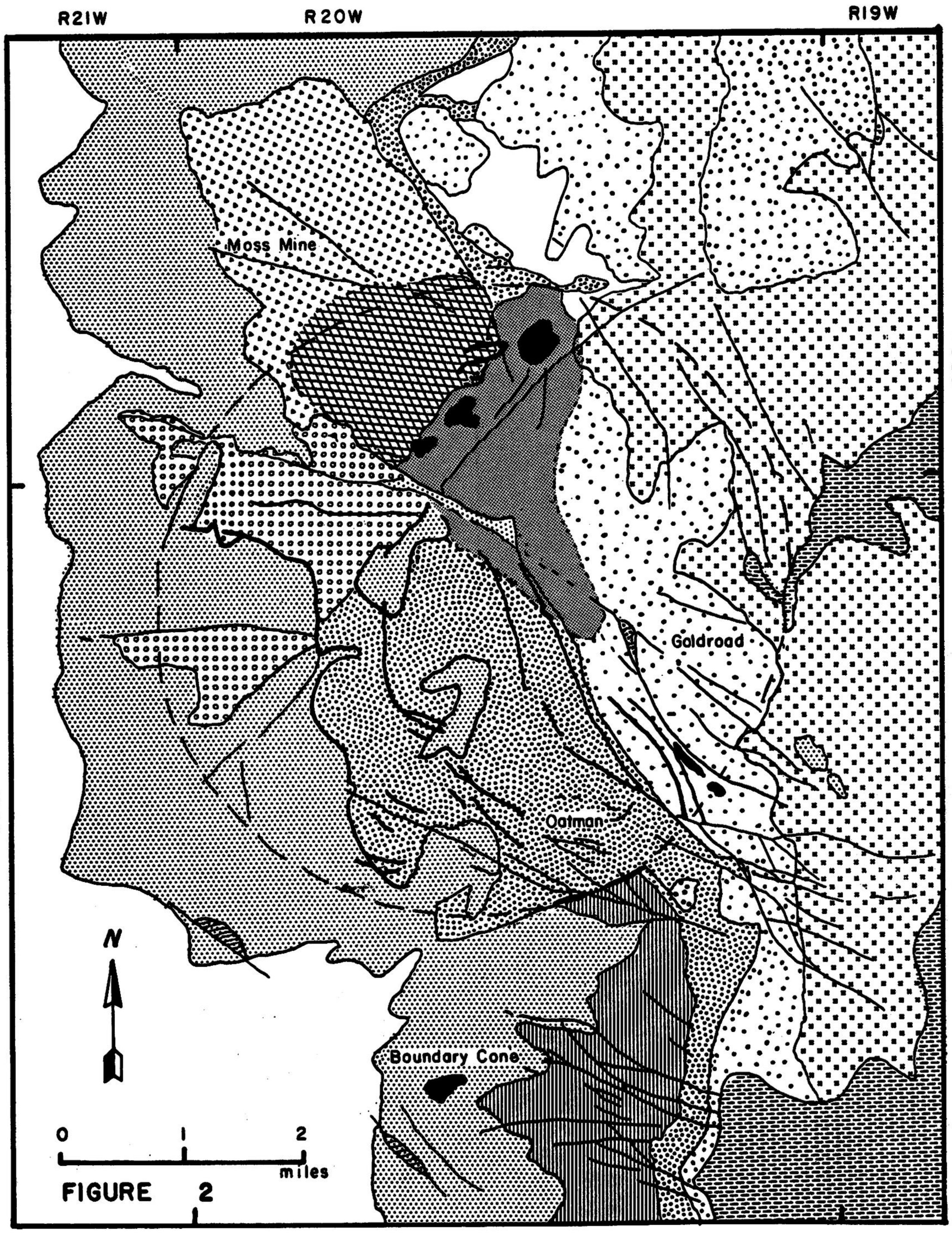
SUMMARY OF OREBODY CHARACTERISTICS IN THE

TOM REED-UNITED EASTERN AND GOLD ROAD VEINS, OATMAN, ARIZONA

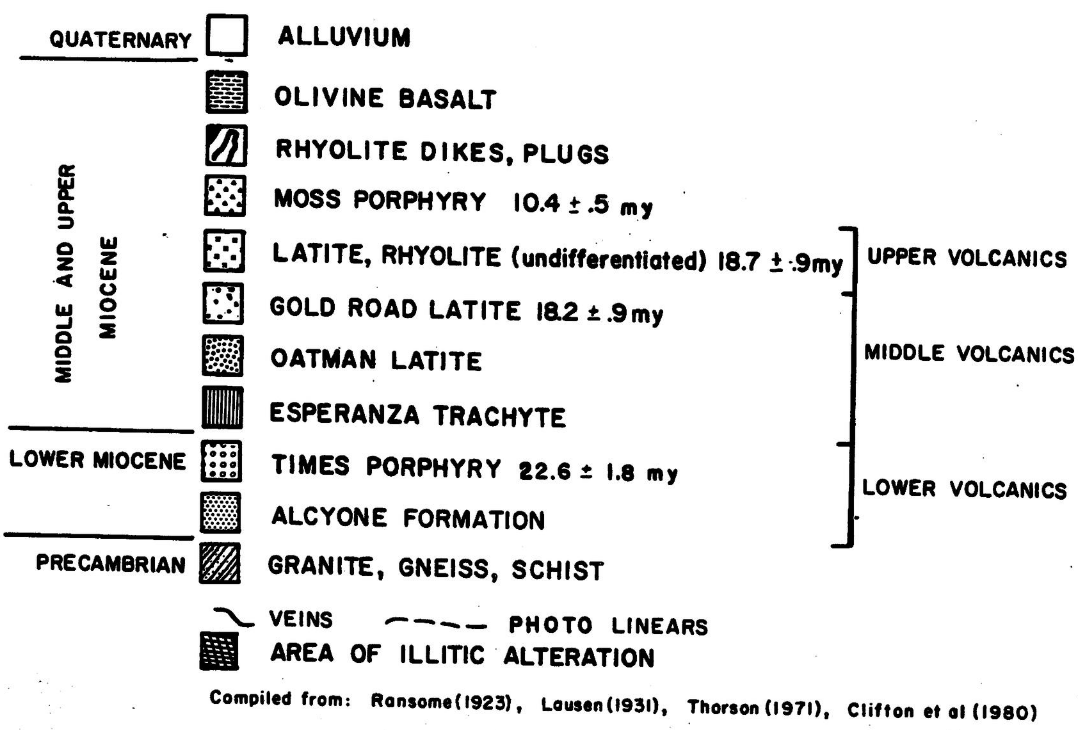
Orebody	Symbol	Tonnage	Grade O/T Au	Maximum Dimensions Length	Width	Height
United Eastern	(UE)	550,000	1.10	450'	45'	700'
Tip Top	(TT)	250,000	±0.70	500'	20'	1300'
Ben Harrison	(BH)	250,000	±0.70	650'	20'	750'
Big Jim and Aztec	(BJ)	±500,000	±0.75	1950'	35'	800'
Black Eagle	(B)	±200,000	±0.50	350'	10'	1000'
United American	(UA)	±140,000	±0.50	300'	10'	1000'
United Western	(UW)	40,000	0.30	990'	6'	300'
Gold Road	(GR)	1,500,000	0.32	6200'	22'	1300'
Telluride	(T)	20,000	1.0	200'	2-3'	200'

Figures are estimates

Source: Clifton and others (1980)



GEOLOGY AND STRUCTURE OF THE OATMAN DISTRICT



LEGEND TO FIGURE 2

The Alcyone Formation is unconformably overlain by the Esperanza Formation, a quartz latite lava flow from 180 to 1,000 feet thick. The Esperanza crops out south of Oatman from near Old Trails to well south of Boundary Cone. This formation thickens to the south of Oatman and may have had its source from that direction.

The Esperanza Formation is conformably overlain by the Late Miocene Oatman and Gold Road Formations. The Oatman Formation, termed the "chloritic andesite" by Schrader (1909), the Oatman Andesite by Ransome (1923), and the Oatman Latite by Thorson (1971), is a sequence of massive to vesicular non-biotitic pyroxene latitic andesite flows, tuffs, and flow breccias. The Oatman Formation, host for most of the ore at Oatman, is approximately 1,000 feet thick at the Oatman townsite but thins rapidly away from the central part of the district.

The Oatman Formation is conformably capped by the Gold Road Formation, a sequence of biotitic pyroxene latitic andesite to dacite lava flows and lithic ash flows (DeWitt and Thorson, 1982). Maximum thickness is about 800 feet. A K/Ar determination on the highest unit in the sequence gave a date of 18.2 ± 0.9 my (Thorson, 1971). A transition zone separating the Oatman and Gold Road Formations is composed of coarse-grained lithic, crystal, biotite, latitic andesite ash near the central district; but it grades into a biotite-poor fluvial arenite to the west. Earlier workers have included this lowest unit with the Oatman Formation lithology, but because of the presence of biotite, Clifton and others (1980) interpret it as part of the Gold Road Formation. The Esperanza, Oatman, and Gold Road Formations are collectively termed the middle volcanics (Thorson, 1971).

Based on the similarity of distribution of the Oatman and Gold Road Formations and on their transitional petrologic character, Thorson (1971) felt these rocks were comagmatic and originated at a shield volcano centered near the town of Oatman. In support of this idea, Thorson (1971) notes there are several large latite dikes and plugs near Oatman.

The middle volcanics are unconformably overlain by the upper volcanics, a series of trachyte, quartz latite, and rhyolitic tuffs and flows. The lowest unit, the Antelope Quartz Latite, has been K/Ar dated at 18.7 ± 0.9 my.

Two small stocks and a series of dikes and plugs intrude the volcanic rocks in the Oatman area.

The Times Porphyry is a 22.6 ± 1.8 my, 2 mile x 2 mile granophyric laccolith which intrudes the Alcyone Formation, and has a highly siliceous border and less siliceous core. The border and core are sub-alkali to alkali granites and chemically they closely resemble, in major and minor element chemistry, the alkali rhyolites in the Cottonwood Formation of the upper volcanics (DeWitt and Thorson, 1982). Thorson (1971) interprets the Times Porphyry as the final phase of a caldera sequence. Field evidence and petrography indicate it is genetically related to the Alcyone Formation and is older than the Moss Porphyry (DeWitt and Thorson, 1982).

The Moss Porphyry is a 2 mile x 4 mile concentrically zoned stock with an outer monzonite border, an inner porphyritic tonalite margin and central tonalite-granodiorite core. The Moss Porphyry major element chemistry is intermediate between the middle and upper volcanics (DeWitt and Thorson, 1982). An age date by Thorson (1971) on the Moss Porphyry is 10.4 my and is far younger than any other age dates in the district and is perhaps misleading. Clifton and others (1980) feel the age date represents an argillic alteration event associated with late stage rhyolites found to intrude the Moss Porphyry, while DeWitt and Thorson (1982) feel the young age represents the upper age limit of the Moss Porphyry.

The rhyolite and rhyolite porphyry dikes and sills are compositionally similar to the Times Porphyry and are frequently localized along northwest trending faults. The Elephant's Tooth rhyolite and Boundary Cone rhyolite are two prominent rhyolite plugs intruded into the Gold Road and Alcyone Formations respectively. One age date of the Elephant's Tooth rhyolite is 19.6 ± 0.9 my but it clearly intrudes the Gold Road Formation at 18.2 ± 0.9 my and dikes of similar composition intrude the Antelope Formation dated at 18.7 ±0.9 my.

The age dates clearly create some confusion, but perhaps what can be said is that there was a fairly continuous period of volcanism characterized by three major volcanic-plutonic episodes.

Local Geology

Within the central part of the past productive district the principal geologic feature is a thick sequence of Oatman Formation conformably overlain by the Gold Road Formation. These rocks are cut by a series of northwest trending, north dipping faults. These faults radiate from a central point near the center of a circular feature identified from high altitude aerial photographs (Figure 2). This five mile diameter feature is identified on the ground as a series of concentric fractures and joints with little or no displacement, and inwardly dipping faults and dikes. These may be reflective of concentric fractures developed during the ascent or descent of a magma within a near-surface magma chamber (Clifton and others, 1980). Local vein geology is shown in Figures 5 and 6.

The NW-SE radial faults locally show significant dip slip displacement, crudely estimated at 300 to 600 feet along portions of the principal faults. These radial faults acted as zones of weakness into which rhyolite dikes and plugs were intruded and also

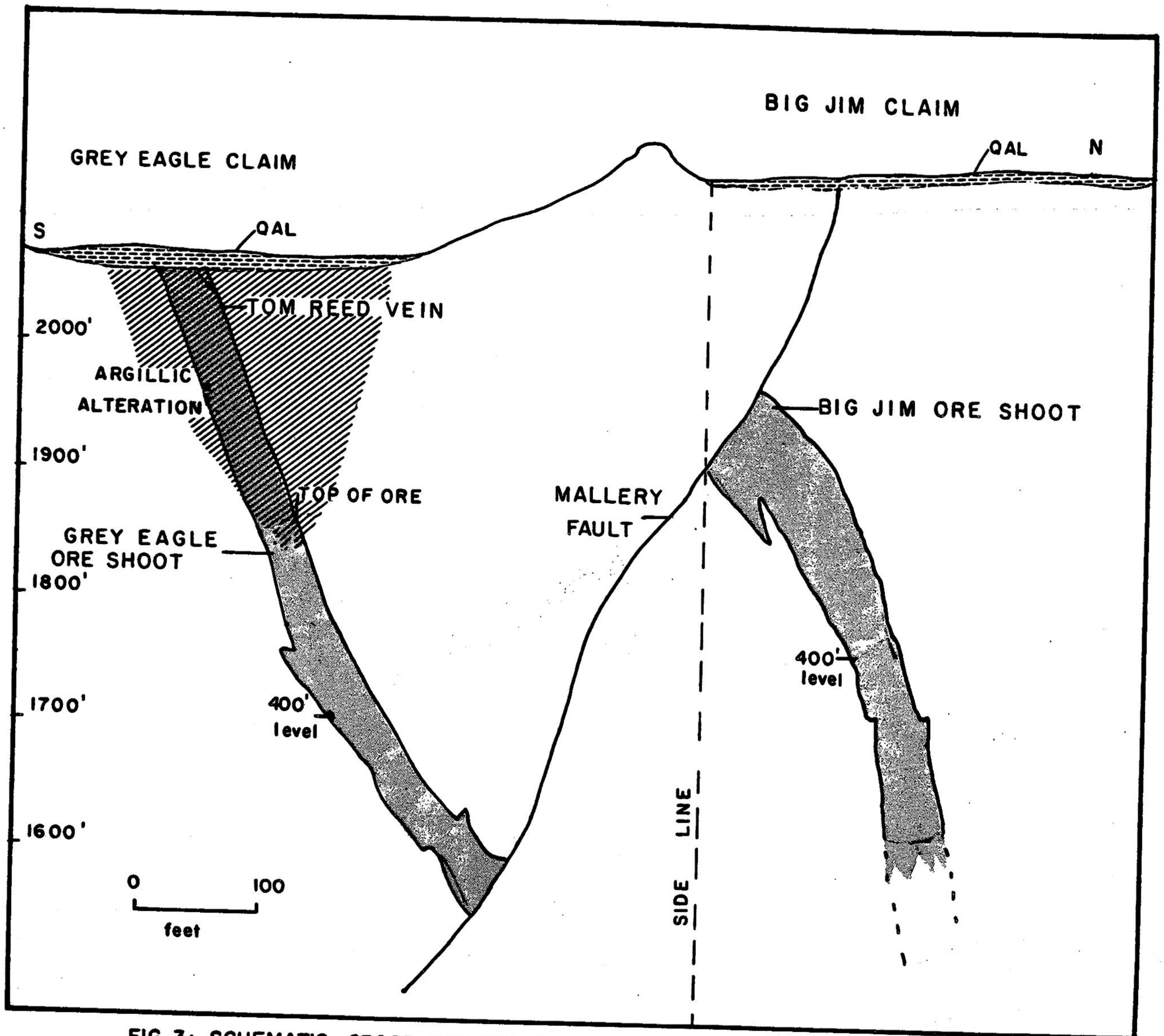


FIG. 3: SCHEMATIC CROSS SECTION OF BIG JIM / GREY EAGLE ORE SHOOTS

form the structural host for most of the large past productive ore shoots.

As the major radial faults are traced from the central radiating point to the SE, maximum displacement is found near the town of Oatman. To the southeast beyond the photo-mapped concentric fracture the faults split into many faults of small displacement. Two miles beyond the concentric fractures the major radial fractures appear to die out.

The largest and highest grade ore shoots at Oatman occur along the radial fractures - principally the Tom Reed and Gold Road faults, and most ore has been produced from a one-mile radius from the town of Oatman and within the general area where the radial faults intersect the faults and joints of a concentric feature (Figure 2).

Post mineral fault movement has also occured along all the radial fractures with displacements of up to 400 feet along the south dipping Mallery fault and the north dipping Oatman fault. This post mineral movement has locally brecciated otherwise coherent veins, providing avenues for secondary enrichment in instances of minor movement; but, in the case of both the Oatman and Mallery faults, it displaced productive ore shoots over 400 feet. In one instance the Mallery fault has displaced the top of the Grey Eagle/Big Jim ore shoot over 400 feet vertically and 200 feet laterally. This faulted ore shoot was the basis for the precedent setting Apex Suit, between the Tom Reed Gold Mining Company, owners of the Apex and Grey Eagle orebody, and the United Eastern Mining Company, owners of the non-outcropping fault-bounded vertically-projected apex of the Big Jim ore shoot (Figure 3). Interestingly, the ruling was in favor of the United Eastern Company, stating that although in the geologic past the Grey Eagle and Big Jim orebodies were one continuous ore shoot, they were now

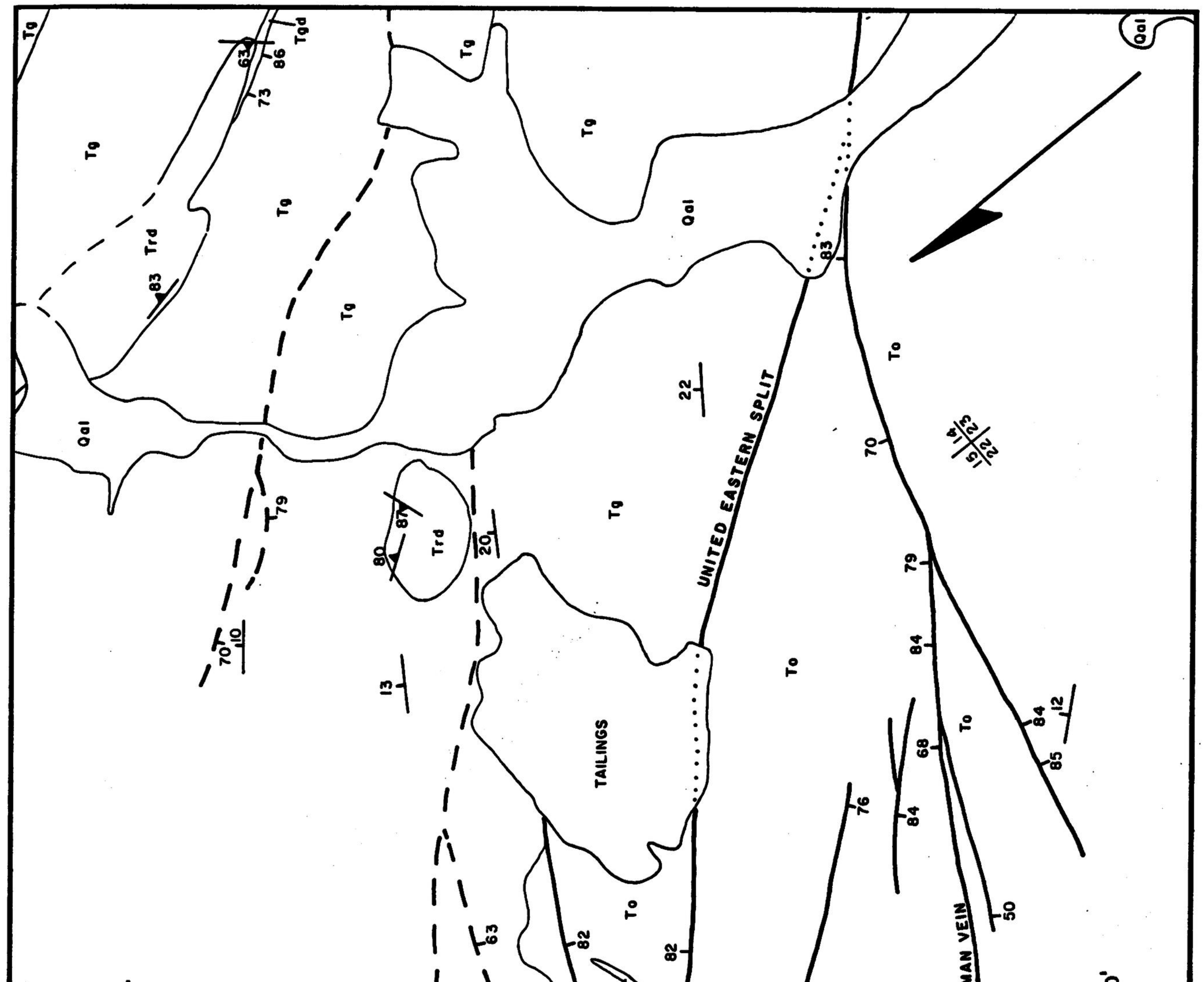


FIG. 5: GEOLOGY OF N.W. PORTION OF OATMAN DISTRICT

FOR LEGEND, SEE FIG. 6

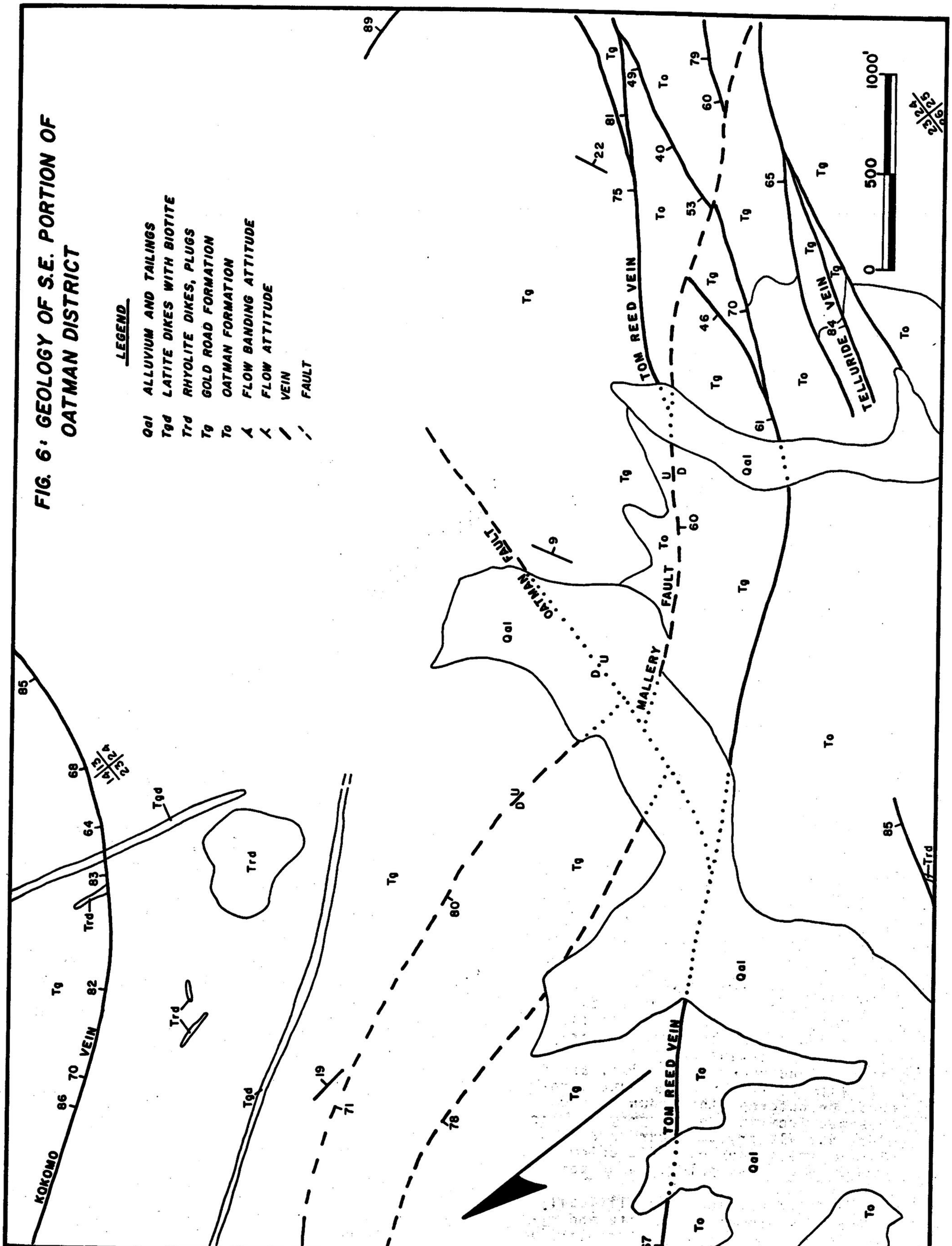


FIG. 6: GEOLOGY OF S.E. PORTION OF OATMAN DISTRICT

separated by over 400 feet along a post mineral fault. Thus, since the vertical projection of the fault-bounded apex of the Big Jim orebody stayed within the Big Jim claim boundary, ownership was granted to United Eastern Mining Company. United Eastern subsequently mined 225,000 T grading 0.75 o/T Au from the Big Jim ore shoot.

Alteration

Vein associated alteration is a broadly distributed propylitic alteration which envelopes a more restricted ore shoot related illitic alteration. Immediately above ore (50 - 100'), massive silicification may occur. Alteration patterns in the main part of the Oatman District are clearly presented in Figures 7 and 8.

At Oatman the majority of the past productive shoots show no outcropping ore or vein material. Their only surface expression is subtly altered volcanics which give no distinctive geochemical anomaly. Based on a model developed by Buchanan (1979b, 1980) at Guanajuato and further refined by Buchanan (1981), it was felt that careful mapping of changes in alteration types and intensities, associated with changes in strike and/ore dip along the vein structures would allow:

1. Characterization of the high level alteration and structural expression of past productive ore shoots, and

2. The identification of unexplored or inadequately explored portions of the past productive veins.

To this end the central part of the Oatman District was outcrop mapped on enlarged airphotos at 1" = 100'. As a result of this mapping every ore shoot was found to be characterized by distinctive alteration and structural features. In addition, several inadequately explored alteration blossoms with coincident dilatant zones along the faults were identified.

Classification of alteration grades and intensities was based on the field-oriented criteria summarized below. These criteria permitted a rapid field determination based on outcrop or hand sample colors and obvious mineralogy:

1. Deuteric Alteration: This type was not mapped. Deuteric alteration in the Oatman Formation ash flows, ash falls, and breccia flows took the form of sericite and clay replacement within crystal fragments and on crystal walls, associated with pyrite in and around pyroxenes. On outcrop, the groundmass was unchanged from its normal grey or black color, but all crystals were a dull chalky white. Minor deuteric chlorite and pyrite were visible in hand samples.

2. Propylitic Alteration: Propylitically altered rocks contain chlorite and pyrite as irregular blebs and veinlets in the groundmass of the rocks and as chlorite and pyrite replacements on crystal edges and crystal twin planes and cleavages. Pyroxenes are altered to chlorite. Pale green chlorite floods potassium feldspars and brownish-green chlorite replaces pyroxenes, plagioclase, and the groundmass. Epidote is uncommon, but when encountered is as coatings on joints and as crystalline druses in vesicles. The Alcyone trachyte contains more epidote than chlorite, but this is a rare exception. Propylitiza tion was divided into three intensities based on outcrop colors:

   a. Weak: Rock color is unchanged. Phenocrysts are pale to dark green.

   b. Moderate: The rock is partially green and partially unchanged in color on outcrop, resulting in a mottled or patchy green and grey outcrop. This is due to chlorite flooding along fractures, microfractures, or permeable horizons, with areas between fractures unaffected.

   c. Strong: The entire outcrop is pale to dark green. Upon weathering, the pyrite oxidizes and the outcrop is converted to brownish-yellow color.

3. Illite Alteration: Illitically altered rocks contain large amounts of illite with small amounts of interlayered montmorillonite. Illite replaces feldspar phenocrysts as a mosaic of minute crystals and replaces the rock groundmass as a flooding of the rock along crystal boundaries. Microveinlets of illite are common. Clays and illite are usually present replacing feldspars. In weakly illitized rock, illite crystals form on the rims of phenocrysts and fill microveinlets only. Illitic alteration was divided into three intensities based on outcrop appearance.

   a. Weak: Feldspar phenocrysts were clouded and turned to a chalky white, but the normal groundmass color was unchanged. This alteration was so similar in appearance to deuteric alteration that the two were often mistakenly interchanged.

   b. Moderate: The rock was visibly whitened although pronounced shades of green or grey may still exist. Rock textures are still discernable but the outcrop is softened although not crumbly.

   c. Strong: The rock is white or yellow (due to oxidized pyrite) although pale shades of grey or green may persist. The outcrop is soft and crumbly, breakable by hand. Rock textures are largely, although not entirely, obliterated.

4. Silicification: Silicification is characterized by introduction of quartz. Silicified vein outcrops stand in bold

relief above the surrounding rocks. Quartz is along micro and macro fractures and often replaces pheocrysts and groundmass as a mosaic of interlocking subhedral crystals. The rock color is reddened or browned. Pyroxenes appear less silicified than the feldspars. Minute pyrite cubes are common in the groundmass.

The field identification of alteration intensities (weak, moderate, and strong) of the propylitic and illitic grades are subjective. When uncertainty arose on specifying the intensity for a particular outcrop, the lower intensity was selected. Also, if two or more alteration grades overlapped in a single outcrop, all were noted in the field maps but the illitic alteration grade (if present) took pre-eminence in drafting Figures 7 and 8. This was done because the significance of illitic alteration as a guide to ore was recognized early in the mapping program.

Three areal patterns of alteration have been recognized:

1. Alteration related to post ore faults,
2. Alteration related to barren segments of mineralized veins,
3. Alteration related to ore deposits.

Alteration related to post ore faults - Post ore faults typically contain from a few feet to up to 20 feet wide zones of illitized wall rock. These zones are long, linear features following the fault itself and never are observed to form broad, widespread alteration blossoms. It is believed that much of the illitic alteration is within fault gouge and in intensely sheared rock adjacent to the fault, resulting in the linear alteration pattern. A halo of weak to strong propylitic alteration often, but not always, surrounds illitized rock. More often than not, the propylitic alteration coincides with and overlaps the illitic alteration, and both alteration grades pass abruptly into essentially unaltered latite.

Faults showing only post ore movement are unmineralized except for minor barren calcite. Post ore fault zones are usually easily eroded and typically occupy valleys. The post ore faults are easily mappable as a linear zone of illitic alteration.

Alteration related to barren segments of mineralized veins - This alteration contains the same alteration pattern as the ore grade segments (see below) but lack the illitic alteration blossoms characteristic of proximity to ore. Barren vein segments are normally bounded by narrow to wide propylitic halos, with the width and intensity of alteration apparently related to the intensity of pre-alteration fracturing. The width of moderate and strong propylitic alteration increases in the area of horsetailing of the Tom Reed Vein, probably a reflection of the numerous closely spaced, thin veins present in that area. On the other hand, where the Tom Reed Vein is a single fracture, the width of the propylitic zone greatly diminishes.

Alteration related to ore deposits - Ore related alteration is more complex than those previously described. Above the ore shoots and in part adjacent to the ore shoots is an illitic (1M mica) zone (containing and interlayered with minor montmorillonite). This alteration assemblage, when strong, superficially resembles the illitic zone adjacent to post ore faults. The shape differs considerably, in that ore related illitic alteration zones are wide into the vein hanging wall. The strike length of the illitic zone is apparently controlled by the strike length of the underlying ore shoots. The illitic zone is normally in the hanging wall of the vein although narrow selvages exist in the footwall. At the Grey Eagle Mine the illitic zones diminish in width downward toward the ore zone, and should cease to exist as a mappable unit somewhere near the middle or base of the ore shoot.

As the illite zone decreases with depth below the present surface, silicification increases with depth toward the top of the ore shoot. The silicification extends only a few score of feet above the ore shoot top (observed on the Grey Eagle, Ben Harrison, and the Tip Top orebodies) and extends downward at least to the base of the ore shoot. Below the United Eastern ore shoot, deep drilling found massive quartz and calcite veins with very spotty gold and silver values between propylitically altered walls. As with all types of ore deposits, it is important at any early stage in exploration to identify the vertical position of the outcrops in the overall hydrothermal system. Silicification may occur both above and below ore shoots and usually carries spotty gold-silver values. Silicification with hanging wall illitic alteration generally indicates the outcrop is above the ore level. Silicification hosted by propylitically altered wall rocks indicates a position below the ore horizon and that little potential for ore exists at depth. Silicification also exists along barren segments of the vein, and thus has little to no ore-related illitic alteration in its hanging wall.

An additional control of the shape and intensity of alteration is the amount of permeability in a volcanic unit. During field mapping, it has been repeatedly noted that permeable ash, tuff, and breccia layers were much more susceptible to propylitic and illitic alteration than were dense, hard latite flows. Although the patterns are modified somewhat by the differences in permeability, when the field maps (at 1" = 100') are studied in detail the permeability-controlled patterns become obvious and can be placed in their proper context. Volcanic sandstone within the Oatman and Gold Road latites are propylitically altered where observed in the district, no matter their distance from a major fracture.

Beautiful examples of silicification, illitic and propylitic alteration can be found at the Oatman townsite. Immediately south of the firehouse is a bold silicified outcrop over the Tip Top orebody on the Tom Reed Vein. This outcrop carries low grade gold values in a stockwork of quartz and calcite veining and silica flooding. Although not ore grade, it lies only 50 feet above the top of the Tip Top ore shoot.

An instructive walk showing propylitic through strong illitic alteration can be taken from the old Oatman schoolhouse (propylitically altered Oatman Formation) to the north along the school access road across the paved road to a small arroyo (strong illitic alteration). The outcrop in the arroyo directly overlies the United Eastern ore shoot. At this level of exposure (300 feet above the top of the United Eastern ore shoot) there is no quartz or calcite veining, no detectable gold or silver, and no trace element geochemical anomaly. A cross section near this outcrop is shown in Figure 4. The United Eastern ore shoot produced 550,000 T of 1.12 o/T Au.

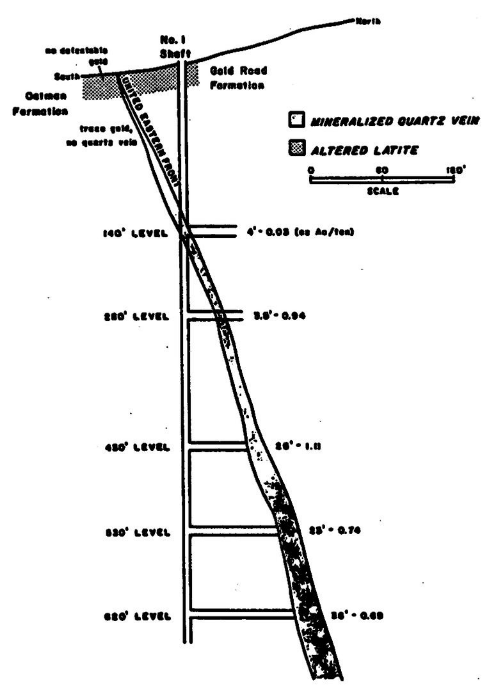


FIG. 4 · Schematic Cross Section of United Eastern Ore Shoot

Perhaps the most informative traverse can be made along the strike of the Gold Road Vein. The starting point is where Route 66 crosses the Gold Road Vein in the S1/2 SE1/4 SE1/4 Section 11, Township 19 North, Range 20 West. From this point for more than 3,000 feet to the SE the vein is more or less continuously mineralized and stoped at depth. At the roadcut, the vein is exposed as a six foot wide massive banded quartz, calcite, adularia vein, grading 0.5 o/T Au, between walls of Gold Road Formation. The vein is bordered by a couple of feet of hanging wall and foot wall silicification. Weak stockwork veining and illitic alteration form the hanging wall. Walking SE, the vein pinches and swells along strike with local blossoms of illitic alteration and silicification. About 2,000 feet along strike a small collapsed stope exposes a 20 foot wide massive outcrop of illitic alteration with a 6 inch to 12 inch wide quartz vein enveloped in 2 to 3 feet of silicified Gold Road latite. Further along strike, where the vein crosses the microwave tower access road, a road cut across the vein shows very strong illitic alteration with no identifiable veining and no detectable gold. Further along the vein until it crosses the saddle, illitic alteration with small discontinuous chalcedonic quartz veins (less than one inch wide) are the only surface expression of the ore grade mineralization below.

Ore and Ore Controls

General - The orebodies at Oatman are quartz, calcite, adularia, chlorite and electrum fissure fillings, with ore occuring in discreet ore shoots within otherwise barren to very sub-ore grade quartz veins. Most veins show evidence of penecontemporaneous (Ransome, 1923) and post-ore fault movement, as well as the pre-ore faulting that created the original fissure. No vein is mineralized equally throughout its strike or dip length. In some segments of any vein, zones of gouge and breccia separate other zones of quartz and calcite vein fillings. Some veins, such as the upper levels of the Gold Road, are simple tabular bodies with sharp wall rock contacts; however, most veins and most orebodies are stringer zones of quartz and calcite veins and veinlets ramifying through blocks and horses of silicified latite.

As in most epithermal districts, the location, size and grade of an individual ore shoot are functions of several parameters:

a. The location is directly related to the configuration of the host fissure and of elevation above sea level.

b. The size (width and tonnage) of an ore shoot is a function both of structural configuration and of host rock lithology.

c. And finally, the grade of any deposit appears related to its areal position within the district; however, this is an empirical conclusion based on limited data.

All of these parameters will be discussed below.

The Ore Shoots - Ore at Oatman comprises, in generally decreasing order of abundance, quartz, calcite, adularia and chlorite. Gold occurs as microscopic grains of electrum; visible gold is very rare. The electrum contains variable amounts of silver, but secondarily enriched gold (remobilized and precipitated during weathering) contains under 10% silver (Lausen, 1931). Gold tenor increases with an increase in adularia in the vein (Lausen, 1931) and also with an increase in vein chlorite. Sulfides are notable for their absence. A few specks of chalcopyrite have been reported by Ransome (1923) from the Gold Ore Vein and by Lausen (1931) from the Big Jim orebody. Pyrite is present in altered wall rocks but is exceedingly scarce in the veins. Minium and wulfenite have been reported by Lausen (1931) from the Big Jim Mine. Pale green fluorite is an abundant gangue mineral, often containing included gold, from the mines and prospects near the Moss and Times Porphyry, but is rare to absent from the more centrally located Oatman ores.

Calcite is a common gangue mineral, but probably contains no gold values. Quartz pseudomorphs after calcite are common, and it is evident from vein textures that multiple episodes of calcite introduction and replacement by quartz occurred during formation of the ore shoots.

The quartz is reported by Lausen (1931) to have been introduced in 5 stages, each apparently separated by a period of fracturing to allow the subsequent quartz stage to enter and precipitate in the veins.

Lausen's (1931) quartz paragenesis is summarized below:

It must be noted that differentiating quartz stages on the basis of color is often misleading under the best of circumstances, and nowhere have the authors found all five stages present in close proximity. Quartz varies from banded chalcedonic (Gold Road Vein) to coarsely crystalline vug fillings, but by far most quartz is present as a very fine-grained, white, green and yellow banded vein filling. Bands of individual colors vary from microscopic to 10's of centimeters thick. The milky white color is due in part to included adularia, the green to chlorite crystals, but the yellow color is as yet unexplained. Quartz pseudomorphs after calcite, and possibly after fluorite (Durning, 1980), can be of any quartz color.

Adularia is present as subhedral to euhedral microscopic crystals embedded in a fine-grained mosaic of quartz crystals. Rarely, bands of adularia up to 2" wide are encountered (Lausen, 1931). Adularia appears to be more commonly associated with the 4th and 5th stages of Lausen's (1931) paragenesis; hence its close association with higher gold values.

Structural Control of Ore Shoots - Table 2 illustrates the widely variable nature of the shapes and sizes of known ore shoots. In

TABLE 3

SUMMARY OF THE CHARACTERISTIC FEATURES OF THE VARIOUS STAGES OF QUARTZ DEPOSITION

Stage	Texture	Color	Range of oz. gold per ton.	Ratio of gold to silver	Relative Distribution in the veins
1st	Coarse to fine grained.	Colorless, white, Amethystine.	Up to 0.006	1 to 6	Abundant
2nd	Fine grained. Often shows casts of calcite	White, rarely yellow.	Up to 0.008	1 to 6	Abundant
3rd	Fine grained, banded.	Various colors.	0.06 to 0.40	2 to 3	Relatively scarce
4th	Fine grained, often shows casts of platy calcite.	Pale green to yellow.	0.20 to 1.00	1 to 2	Abundant only in ore shoots.
5th	Fine to medium grained usually banded.	Pale to deep honey-yellow.	1.00 up	4 to 1	Abundant only in ore shoots.

Source: Lausen (1931)

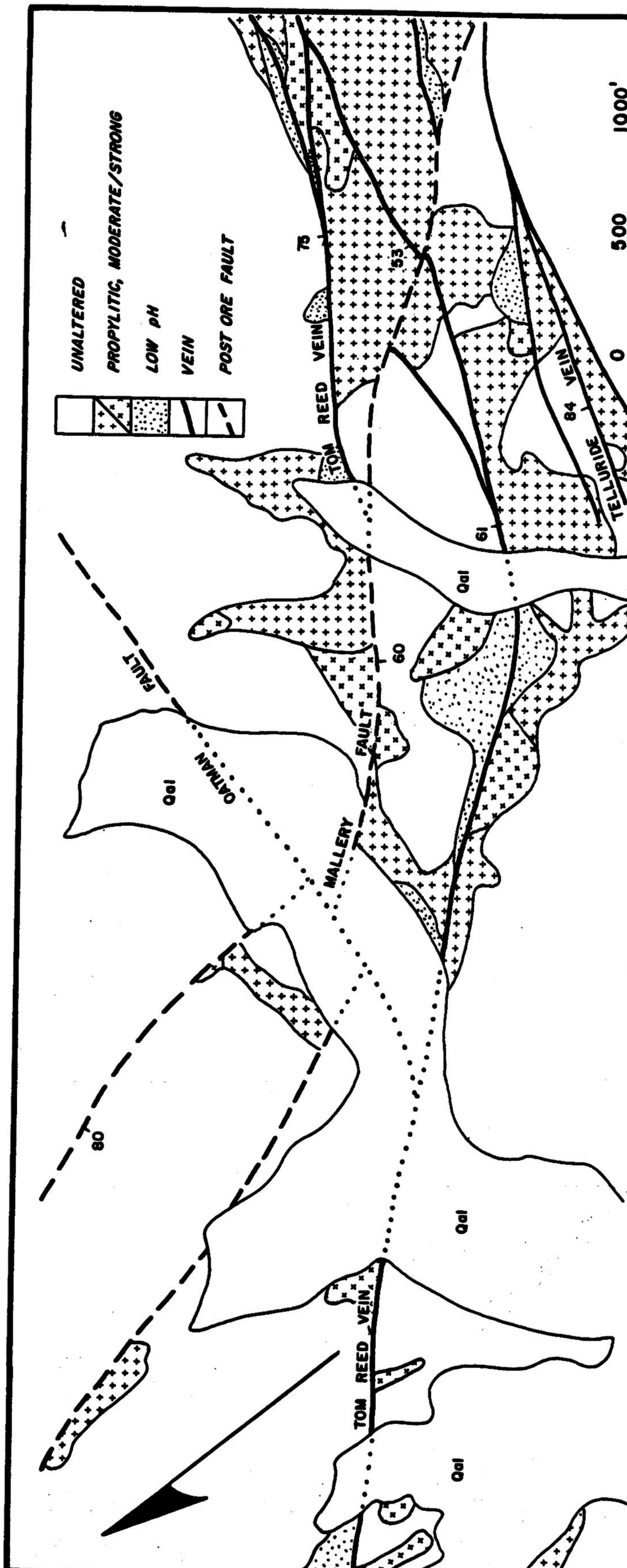


FIGURE 8A: PLAN VIEW OF S.E. PORTION OF THE TOM REED VEIN SHOWING WALL ROCK ALTERATION

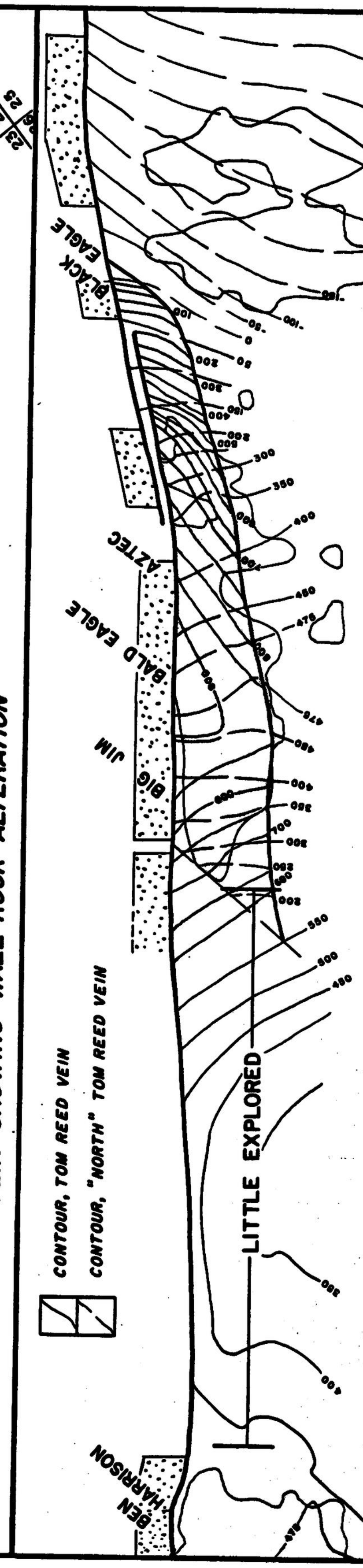


FIG. 8B: LONGITUDINAL SECTION OF THE TOM REED VEIN SHOWING ORE SHOOTS AND LOW pH "CAPS", AND SHOWING VEIN CONTOURS (in feet).