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Mineral Resource Assessment of the Ajo and Lukeville 1° by 2° Quadrangles, Arizona

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INTRODUCTION

Southern Arizona is rich in mineral commodities and has potential for the discovery of new ore deposits. This report, prepared as part of the Conterminous United States Mineral Assessment Program (CUSMAP) of the U.S. Geological Survey, assesses the mineral resource potential for the Ajo and Lukeville 1° by 2° quadrangles in southwestern Arizona, where porphyry copper, skarn, and numerous small polymetallic vein deposits have been mined. The boundaries of these quadrangles lie approximately 100 km west of Tucson, Ariz., 50 km south of Phoenix, Ariz., and 60 km east of Yuma, Ariz. The Ajo 1° by 2° quadrangle is located between latitudes 32° and 33° north and between longitudes 112° and 114° west. Its southwest corner lies in Mexico. The Mexico-United States boundary also crosses the Lukeville 1° by 2° quadrangle leaving within Arizona a triangular part of the northeast corner from latitudes $31^{\circ}37'$ to 32° north and longitudes 112° to $113^{\circ}15'$ west. This study does not evaluate Mexican lands. Most of the Ajo and Lukeville 1° by 2° quadrangles (usually called the quadrangle or the Ajo quadrangle throughout this report) contain Federal and Indian lands to which access has been limited for several decades (fig. 1). The Luke Air Force Range covers the western, central, and southwestern part of the Ajo quadrangle; the southwestern part of the quadrangle also includes the Cabeza Prieta National Wildlife Refuge. The U.S. Army Yuma Proving Ground and Kofa National Wildlife Refuge extend into the northwest corner of the quadrangle. Organ Pipe Cactus National Monument includes the south-central part of the quadrangle. The eastern part of the quadrangle is covered by the Papago Indian Reservation. Corners of the Ak Chin and Gila Bend Indian Reservations extend from the north into the quadrangle. Private and state owned land comprises a strip along the northern edge of the Ajo quadrangle and an area surrounding Ajo. Because of the many years of restricted access to much of the Ajo quadrangle, new exploration techniques and new deposit-type models have largely gone untested in the quadrangle.

In 1978-81 the U.S. Geological Survey comprehensively assessed the mineral resource potential of the Papago Indian lands. The assessment was presented to the Papago tribe in an administrative report through the U.S. Bureau of Indian Affairs. The Papago tribe asked the U.S. Geological Survey not to use geochemical data from the administrative report for evaluating their portion of the Ajo quadrangle. We indicate the proprietary nature of this data in the appropriate tables throughout the paper and evaluate the Papago Indian lands using published information only.

This mineral resource assessment, designed to aid government agencies in classifying land for various uses and to aid in mineral exploration, incorporates geologic, geochemical, geophysical, and remote sensing data collected during 1979-1983. Some of the data are available in other papers resulting from this CUSMAP study and in published material about known mineral deposits in the quadrangle. The report's organization by deposit types allows each type of deposit that could be present in the quadrangle to be evaluated independently. Cox (1983d, e) provides brief descriptions and reference citations for many of the deposit types and this text cites other appropriate references.

This assessment uses the methods of Singer (1975) developed for the Alaska Mineral Resource Assessment Program of the U.S. Geological Survey, in which probabilistic, quantitative estimates of the mineral resources are constructed for each deposit type that may occur within the region. The method considers discovered, undiscovered, and currently economic and

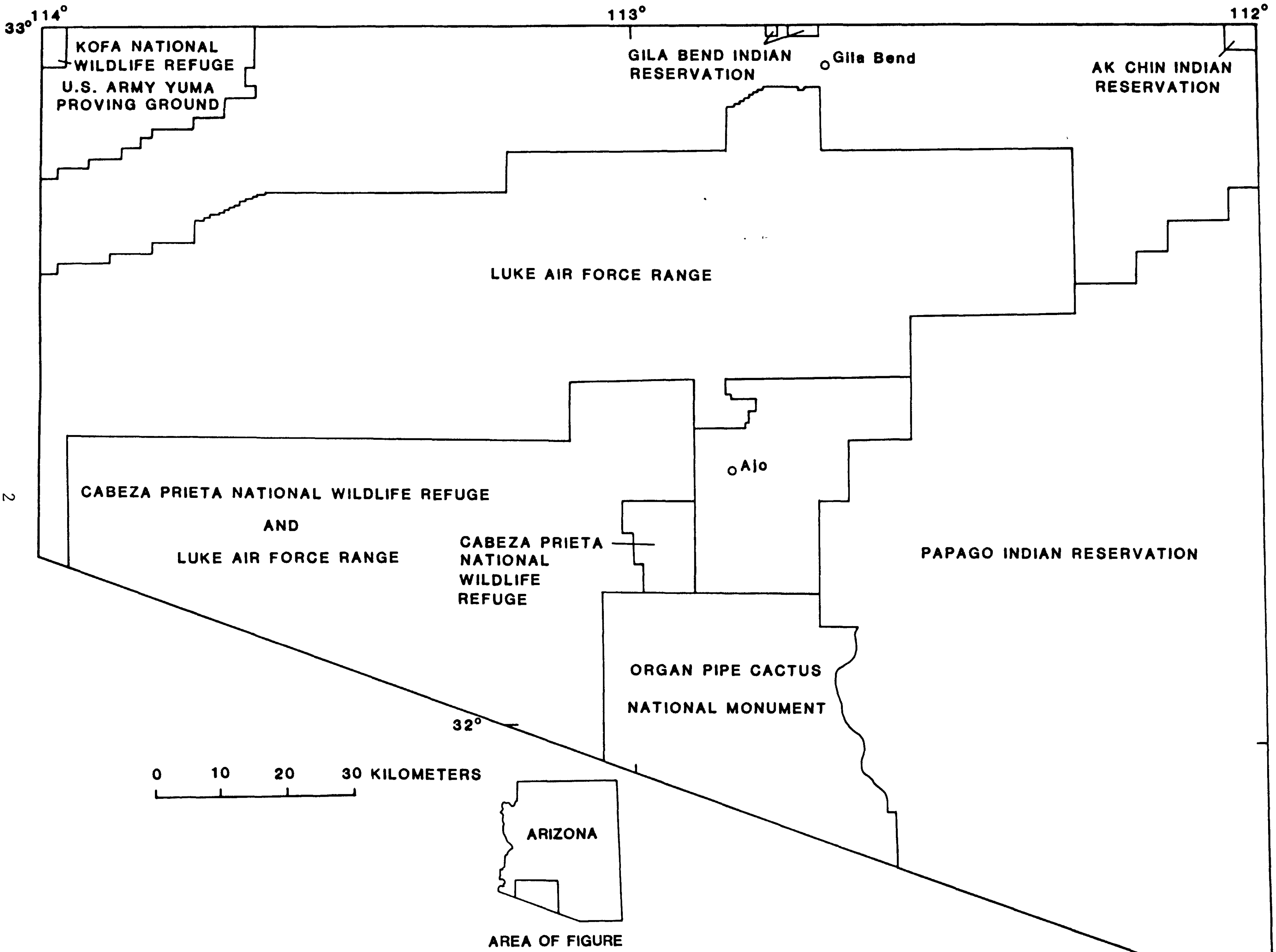

Figure 1. Land status of land within the Ajo and Lukeville 1° by 2° quadrangles. Undesignated areas are under state and private ownership.

uneconomic resources. Estimates are probabilistic, because mineral resource estimates are typically highly uncertain, but quantitative to allow for explicit evaluation. Producing such estimates requires three steps. The first step is to develop deposit-type models that include geologic and grade-tonnage characteristics (see Singer and Mosier, 1983a, b). Significant correlations between grades and tonnages for each deposit type are not present unless otherwise stated. The second step is to delineate tracts permissive for the presence of deposits of each type. The third step is to estimate the number of deposits, by type, that might occur within the designated tracts. Estimated deposits are expected to have the geologic and grade-tonnage characteristics of the deposit type being considered. Throughout this report grade and tonnage curves are presented. For several of the deposit types being considered, the data for the known mines and prospects are not well represented by the curves. Commonly, the deposits used in generating grade and tonnage curves are large, which averages out local variabilities in grade and excludes small prospects. Therefore, tracts permissible for and known prospects of any given deposit type may fail to fit the grade and tonnage curves available. Nevertheless, the prosepcts testify that ore-forming processes of a given type occurred at that locality. Undiscovered deposits may be small and of highly variable grade like the known deposits, but they could also be larger and conform to the grade and tonnage curves.

We present our evaluations in the following format. We introduce each deposit type, commonly including a brief statement about the quadrangle which indicates why we included the deposit type, and then present a list of criteria favorable for the presence of that deposit type. Explanations or discussions of some criteria accompany the list. We used the criteria both to aid in delineating the tracts and to determine how favorable each tract is. Descriptions of known deposits (or mineralized areas suggestive of the deposit type) in, or in some cases near, the quadrangle provide details about known mineral resources within the quadrangle. Lastly, we assess the mineral resource potential for each deposit type. Maps (pls. 1, 2, 3) on which permissive tracts for each deposit types are delineated accompany the evaluation. Tracts for several deposit types lie totally or partially beneath the pediment surface. Such tracts portray areas where bedrock presumably occurs within 1,000 m of the surface as suggested by residual gravity data, but precise boundaries of such tracts are not known.

We delineated permissive tracts for each deposit type by comparing the geology, geochemistry, and geophysics of the quadrangle to the favorable criteria for the occurrence of each deposit type. Usually more than one criterion had to be satisfied before a tract was drawn, because outcrops of potential host rocks are widespread, whereas known deposits or the places within the quadrangle where strongly favorable criteria are satisfied are more restricted. We evaluated each tract for its potential to containing one or more undiscovered deposits. For porphyry copper, skarn, stockwork molybdenum, and continental evaporite deposits we provide probabilistic estimates of the number of undiscovered deposits by type as outlined in Singer (1975). Our assessment uses subjective probability estimates based on estimates made by five members of the CUSMAP team who worked in and are knowledgeable about the Ajo quadrangle and its regional geology, ore-deposits geology, geochemistry, or geophysics. Each person ranked the tracts according to his or her evaluation of their favorability for the discovery of one or more deposits of each type and then provided probabilistic estimates of the number of undiscovered deposits for an aggregation of all tracts of each type for 90 percent, 50 percent, and 10 percent confidence levels. Where the estimate of undiscovered deposits was zero for any of these three confidence levels, this percent was not reported in the text. Although highly favorable tracts are identified for some deposit types, this paper does not show individual rankings and probabilistic estimates. However, a Kendall rank correlation analysis (Moroney, 1968) of the individual rankings for each deposit type indicates with at least a 95 percent certainty that the rankings show a consensus about which tracts are most favorable for undiscovered deposits. The individual probabilistic estimates for each deposit type agree closely. We believe, therefore, that this paper presents good quantitative estimates of the number of undiscovered deposits within the quadrangle for those deposit types for which we used this method.

This quantitative approach has certain limitations for the Ajo quadrangle. Several deposit types do not have adequate descriptive models; other deposit types lack grade-tonnage models. Where grade and tonnage curves fail to adequately represent the known mines and prospects within the quadrangle (see discussion above), a quantitative approach was not used, because undiscovered deposits may or may not fit the curves. Available geophysical data consist primarily of aeromagnetic data acquired along flight lines spaced at 1.6 km at 1,219 m elevation, and gravity data collected at spacings of about one station per 4.6 km^2 (Klein, 1982; Boler and Baer, 1981). Stream-sediment samples constitute the primary geochemical data (Barton and others, 1982), and only limited rock geochemical data are available. Many of the deposit models are not sufficiently developed to deal with subtle geophysical and geochemical expressions formed around mineralized areas. Because we have very limited data for the sediment-filled basins, assessment of the mineral resource potential in the basins is largely speculative. It is based on similarities between the geologic environment of the basins in the quadrangle with that of basins elsewhere that contain known deposits such as evaporites. Owing to these limitations the tracts delineated for many of the deposit types are evaluated non-quantitatively.

Due to insufficient data, some deposit types may not have been recognized or currently unrecognized new deposit types may be found in the future. The approach of this report allows for incorporation of such new information as it becomes available. This is a geologic evaluation and not an economic evaluation.

Acknowledgements

We thank all the members of the Ajo team who provided us with information contained in this report. We particularly thank D.P. Klein for greatly improving the geophysical interpretations presented here, P.K. Theobald who provided geochemical information and interpretations, and R.M. Tosdal who greatly improved the section on vein deposits based on his field work at many of the vein localities and who provided us with the descriptive model for the gneiss-hosted gold deposits. These people also critically reviewed and made substantial improvements to early versions of this manuscript. We also thank W.D. Menzie and D.A. Singer for sharing with us many of their techniques for assessing 1° by 2° quadrangles.

GEOLOGIC SUMMARY OF THE AJO-LUKEVILLE QUADRANGLES

The Ajo and Lukeville quadrangles lie within the Sonora Desert section of the Basin and Range physiographic province, an area characterized by long narrow mountain ranges, that trend predominantly northwest, separated by deep sediment-filled basins. The western continental margin of the North American craton includes this area. Previous studies (Haxel and others, 1980; 1984) have indicated that the eastern part of the quadrangle can be divided into two distinct lithologic and tectonic terranes, termed the northern and southern Papago terranes (fig. 2). The gradational boundary between these terranes defines a broad arc through the Papago Indian Reservation into Organ Pipe Cactus National Monument. Briefly, the southern Papago terrane differs from the northern Papago terrane in that it lacks Proterozoic rocks and has few outcrops of Paleozoic rocks; garnet-two-mica granites rather than hornblende-biotite granitoids are present; the region underwent a Late Cretaceous to early Tertiary orogenic episode. It is important to distinguish these two terranes when evaluating the mineral deposits potential of the area, because hornblende-biotite granitoids in the northern terrane are more likely to contain porphyry copper and related deposits such as skarns, whereas two-mica granites in the southern terrane are more likely to contain tungsten deposits. Stockwork molybdenum deposits can form in either terrane but are more probable in the hornblende-biotite granitoids of the northern terrane.

Lower and Middle Proterozoic rocks crop out primarily in the northeast corner of the quadrangle, around Ajo, and in the Mohawk and Agua Dulce Mountains. In addition, most of the metamorphic rocks in the western half of the quadrangle are probably Proterozoic (Gordon Haxel, written commun., 1985). Schistose to gneissic metasedimentary and minor metavolcanic (Pinal Schist) and granitic (Oracle Granite and Chico Shuni Quartz Monzonite) rocks characterize these Proterozoic rocks. The Middle Proterozoic Apache Group is restricted to small exposures in the northeastern part of the quadrangle, mostly in the Vekol Mountains. These unmetamorphosed or locally thermally metamorphosed sedimentary strata rest unconformably on the Proterozoic crystalline rocks and are intruded by Middle Proterozoic diabase. About 200 km northeast of the quadrangle in Gila County, Ariz., the Dripping Spring Quartzite, one formation in the Apache Group, contains uranium deposits (Granger and Raup, 1959). In the Vekol Hills, the diabase is an important host for porphyry style mineralization at the Vekol Hills porphyry copper deposit (Steele, 1978).

Outcrops of Paleozoic rocks including Cambrian, Devonian, Mississippian, and Pennsylvanian age formations are sparse in the quadrangle but Paleozoic strata are important host rocks for skarn and replacement deposits. Most of the Paleozoic units are calcareous; limestone is more abundant than dolomite. These rocks crop out mostly as thin sequences having limited exposure in the northeastern part of the quadrangle, but several isolated outcrops are found as far west as Lime Hill near Growler Pass.

Jurassic metavolcanic and granitic to metagranitic rocks crop out extensively in the southern Papago terrane and are particularly widespread around the La Abra Plain. In addition, some of the metamorphic rocks in the western part of the quadrangle may be Mesozoic rather than Proterozoic (Gordon Haxel, written commun., 1985). Jurassic rocks host several small vein deposits, particularly near Quijotoa and in the Agua Dulce Mountains. Some of these rocks resemble gneisses farther west in Arizona and California that contain disseminated gold mineralization. Granitoid rocks dated at 163 m.y. (Creasey and Kistler, 1962) at Bisbee, Ariz., host porphyry copper and polymetallic replacement deposits (Bryant and Metz, 1966). Jurassic and (or) Cretaceous conglomerate and Cretaceous sandstone that contain subordinate volcanic and hypabyssal rocks crop out in the eastern and central parts of the quadrangle (Briskey and others, 1978).

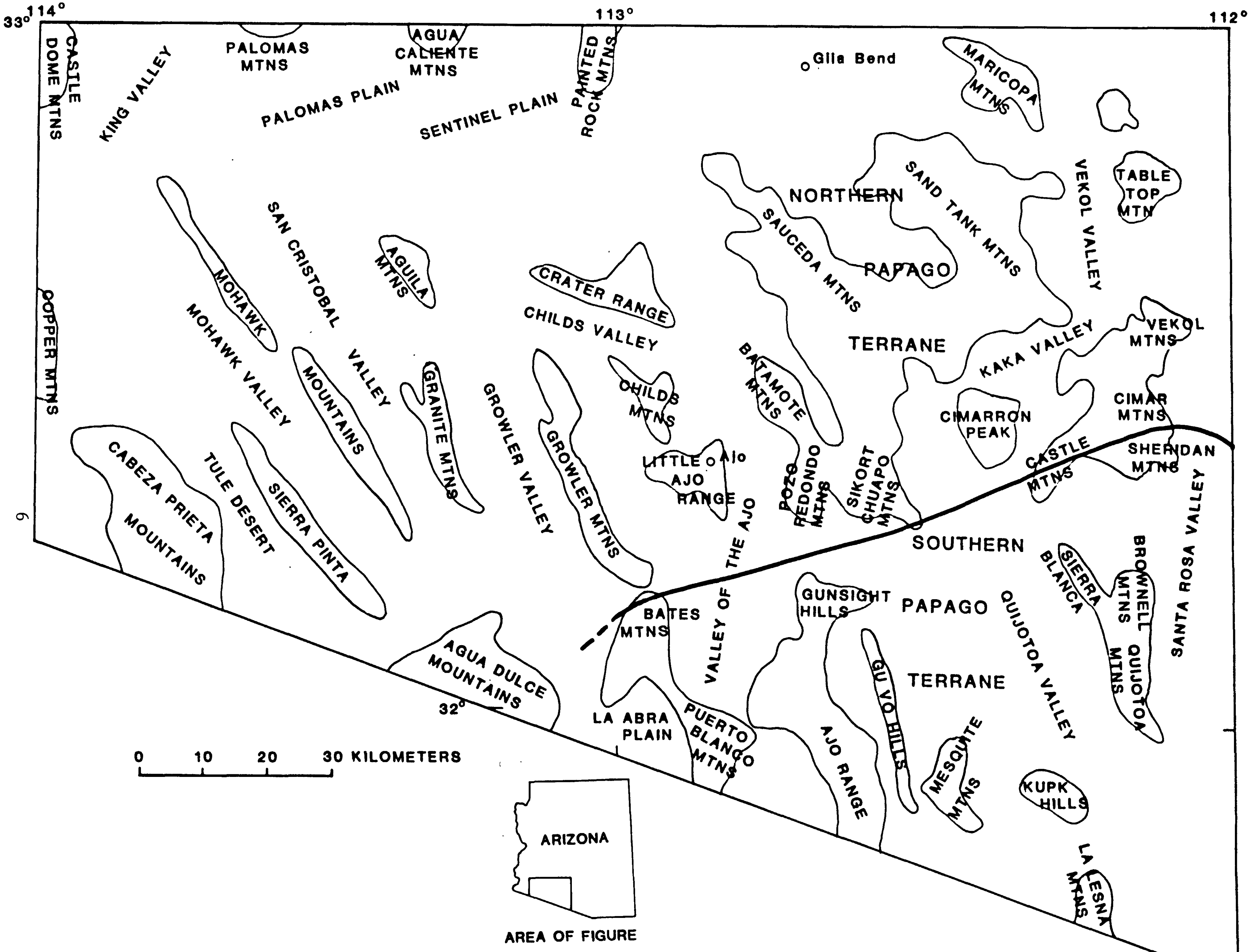

Figure 2. Location of and approximate boundary (heavy line) between the Northern and Southern Papago terranes defined by Haxel and others (1980) and physiography of the Ajo and Lukeville 1° by 2° quadrangles.

Crustal shortening, metamorphism, plutonism, and minor volcanism occurred between Late Cretaceous and Eocene time (Haxel and others, 1984). Laramide age hornblende-biotite granitoid stocks of Laramide age intruded the region of southern Arizona that includes the northern Papago terrane. These plutons are 60 to 70 m.y. old (Tosdal, 1979; Livingston and others, 1968). Throughout southern Arizona, northern Sonora, and elsewhere in the western United States this type of pluton is commonly spatially and genetically related to porphyry copper deposits. However, not all such plutons are mineralized and some porphyry copper deposits formed from plutons of other ages (for example, Bisbee, Titley, 1982a). Nevertheless, these plutons, and similar plutons that possibly are buried in the shallow pediment, are extremely important in assessing the mineral resources of the area. In the southern Papago terrane, plutons of similar age consist largely of garnet-two-mica granites. Such rocks crop out extensively in the Granite, Mohawk, Sierra Pinta, and Cabeza Prieta Mountains and locally in the Sierra Blanca and Puerto Blanco Mountains. These rocks can contain tungsten-bearing veins and possibly stockwork molybdenum deposits (see below). They are not expected to contain base-metal deposits.

The Tertiary volcanic field around Ajo includes rocks spanning the compositional range from basalt to rhyolite and is divided into three sequences (Gray and Miller, 1984a, b). The field extends from Mexico to the northern edge of the quadrangle and from the Growler Mountains eastward to the Sand Tank Mountains. Subaerially deposited flows dominate. Flows show scant evidence of reworking and few sediments are intercalated with the flows, which indicates desert conditions at the time of deposition. Each of the three volcanic sequences is separated by an angular unconformity. The oldest sequence of Late Oligocene to Early Miocene age, exposed primarily in the western part of the field, consists of steeply dipping fanglomerate (including the Locomotive Fanglomerate) and coarse arkosic sandstone intercalated with andesite, rhyolite, rhyodacite, and, locally pyroclastic rocks (Gray and Miller, 1984a). These volcanic rocks yielded a K-Ar biotite age of 23.8 m.y. Recent work (L.T. Silver, oral commun., 1984) indicates a middle Tertiary age for granitoid rocks of the Cornelia pluton. R.J. Miller (oral commun., 1985) reported a K-Ar age of 24 m.y. on biotite from the pluton. The relation between this plutonic activity and volcanism that produced the lower volcanic sequence is not understood. The middle sequence, which is the most widespread of the three, contains Early and Middle Miocene basalt, latite, and silicic flows, and associated pyroclastic rocks. The youngest sequence consists of Middle Miocene andesite and basaltic andesite which formed the Batamote Mountains northeast of Ajo and minor vents and cinder cones in the Growler and Bates Mountains and the Cipriano Hills. Scattered Tertiary volcanic rocks farther east (Dockter and Keith, 1978; Rytuba and others, 1978; Briskey and others, 1978) are probably older and unrelated to the Ajo volcanic field. The lowest sequence in the Ajo volcanic field may be an important indicator for some ore deposits in the quadrangle. Fanglomerates may be indirectly associated with porphyry copper deposits (Lukanuski and others, 1976) and rocks of the lowest sequence host epithermal vein deposits in the Painted Rock Mountains. Middle Tertiary granitoids of the Cornelia pluton show textures, fluid inclusions, and alteration characteristics of porphyry copper deposits but contain no copper mneralization (Cox and Ohta, 1984). Volcanic-hosted gold deposits and rhyolite-hosted tin deposits may have formed in vent complexes associated with silicic rocks of the middle sequence.

The Sentinel and Pinacate basalt flows adjacent to the northern and southern borders of the quadrangle postdate Basin and Range block faulting.

Warm-water wells in the quadrangle are possibly related genetically to these basalts.

The alluvial-filled basins contain material eroded from the mountains. The alluvium is coarse at the edges of the basin edges and finer grained toward the center. Such environments can contain several types of mineral deposit types, including palcer gold, evaporites, and uranium.

DEPOSITS RELATED TO CRETACEOUS AND (OR) TERTIARY HORNBLENDE-BIOTITE INTRUSIVES

Porphyry copper, skarn, and polymetallic replacement deposits are related genetically to each other and are associated with calcalkaline intermediate intrusives. Porphyry copper deposits form in a wide variety of host rocks, whereas the other deposit types are most favored by carbonate sequences. Base- and precious-metal veins peripheral to these deposits will be discussed below in a separate section.

Porphyry Copper Deposits

The porphyry copper deposits within the Basin and Range province of southern Arizona comprise one of the richest porphyry copper provinces in the Pacific Basin (Titley, 1982b). The Ajo quadrangle lies on the western edge of this province and contains two known porphyry copper deposits, the Ajo (New Cornelia) deposit near the town of Ajo and the Vekol Hills deposit in the Papago Indian Reservation. The Lakeshore deposit lies 9 km east of the quadrangle and several other deposits occur nearby (Sacaton, Silver Bell, West Casa Grande). The Ajo and Lakeshore deposits have been mined and the Vekol Hills deposit has been drilled and evaluated (Metals Week, 1974). Because areas elsewhere in the quadrangle are geologically similar to the known deposits, other porphyry copper deposits might exist.

Typical porphyry copper deposits contain large tonnages and low, fairly uniform ore grades. Copper sulfide minerals form disseminations, veins, or stockwork veinlets in or near calcalkaline intrusions that have a porphyritic phase and an aphanitic quartz-feldspar groundmass (Cox and Ohta, 1984; Evans, 1980). Host rocks include the intrusion and pre-ore rocks such as other plutonic rocks, volcanic rocks, limestone, and other calcareous rocks. A typical alteration pattern around porphyry copper deposits consists of an inner or lower potassic zone, a phyllic (sericitic) zone, an argillic zone, and an outer propylitic zone (Titley, 1982c; Lowell and Guilbert, 1970). Exposed root zones at some deposits contain sodic-calcic alteration (Cox and Ohta, 1984; Carten, 1981, 1979).

Criteria favorable for the occurrence of porphyry copper deposits within 1,000 m of the surface are listed below. These criteria were used to delineate permissive tracts and to estimate the number of undiscovered porphyry copper deposits in the quadrangle.

Strongly Favorable Criteria

1. Disseminated copper minerals (Titley and Hicks, 1966)
2. Stockworks of quartz veinlets (Sillitoe, 1979)
3. Polyphase quartz-bearing calcalkaline intrusive (hornblende-biotite type) (Sillitoe, 1979; Stringham, 1966)
4. At least one phase of intrusive in criterion 3 above is a porphyry having a microaplitic groundmass (Cox and Ohta, 1984; Stringham, 1966)
5. Potassic and (or) widespread, pervasive phyllic and argillic alteration

(Beane, 1982; Lowell and Guilbert, 1970)
6. Laramide age of intrusion (Titley, 1982a)
7. Anomalous Cu, Mo
8. Zoned anomalies from center outward of Cu, Mo, W; Cu, Zn, Pb, Au; Cu, Au, Sb, Ag in molybdenite-bearing deposits and Cu, Au, Ag; Mo, Pb, Zn, Mn in gold-rich deposits (Cox, 1983c)

Weakly Favorable Criteria

9. Mesozoic to early Tertiary age of intrusion (Titley, 1982a)
10. Anomalous Au, Ag, Zn, Pb, B, Hg, As, Sb, Sn, W, and Te (Boyle, 1974)
11. Propylitic alteration, narrow zones of phyllic or argillic alteration, sodic-calcic alteration (Carten, 1981, 1979; Lowell and Guilbert, 1970)
12. Proterozoic to lower Tertiary favorable host rock
13. Indication of hydrothermal alteration using remote sensing techniques
14. Nearby skarn and (or) base and precious metal vein deposits
15. Nearby porphyry copper deposits or a position along trends of porphyry copper deposits (Titley, 1982a; Mayo, 1958). The relation between ore deposits and lineaments has been a controversial subject. Linear features would cover much of Arizona if all those described in the literature are used. Despite the controversy and skepticism surrounding the definition and importance of lineaments, two linear trends of porphyry copper deposits may be plausible in and near the quadrangle. There is a rough northeast alignment of deposits from Ajo to deposits in the Miami-Inspiration district including the Casa Grande, Sacaton, and Poston Butte deposits. This trend approximately coincides with the Jemez trend of Mayo (1958). The Vekol, Lakeshore, and Silver Bell deposits form a northwest alignment that projects into the northeast corner of the quadrangle.
16. Area on the flanks of a steep magnetic high or subtle magnetic high surrounded by magnetic low caused by magnetic contrasts related to intrusion and alteration of magnetite to pyrite (D.P. Klein, written commun., 1984). Aeromagnetic and gravity data are inconclusive in exploration for porphyry copper deposits, although known deposits commonly are located on the flanks of aeromagnetic highs that probably indicate the main intrusive center of a porphyry copper system. Magnetite in the mineralized phase of the intrusion is generally extensively replaced by pyrite in the phyllic alteration assemblage. This mangetite depletion can produce subtle magnetic lows. Electrical geophysics, primarily induced polarization methods, effectively delineates the location of disseminated sulfides (Brant, 1966), but this technique is employed more commonly by industry when other evidence suggests a possible target at relatively shallow depth beneath post-mineralization cover.
17. Cretaceous andesitic volcanic rocks (Sillitoe, 1979; Stanton, 1972)
18. Abundant faulting and rotation of crustal blocks
19. Gravity or magnetic highs over pediment areas indicating a possible buried pluton (D.P. Klein, oral commun., 1984)
20. Locomotive-type fanglomerate (Lukanuski and others, 1976). Porphyry copper deposits ordinarily formed in areas where crustal blocks rotated during and shortly after mineralization. Deep sedimentary basins created by such fault rotation accumulated thick Locomotive-type fanglomerate sequences over several porphyry copper deposits, including the deposit at Ajo (Lukanuski and others, 1976). These fanglomerates contain unusual differentiated volcanic products that are possibly directly related to porphyry copper mineralization (Lukanuski and others, 1976). Some

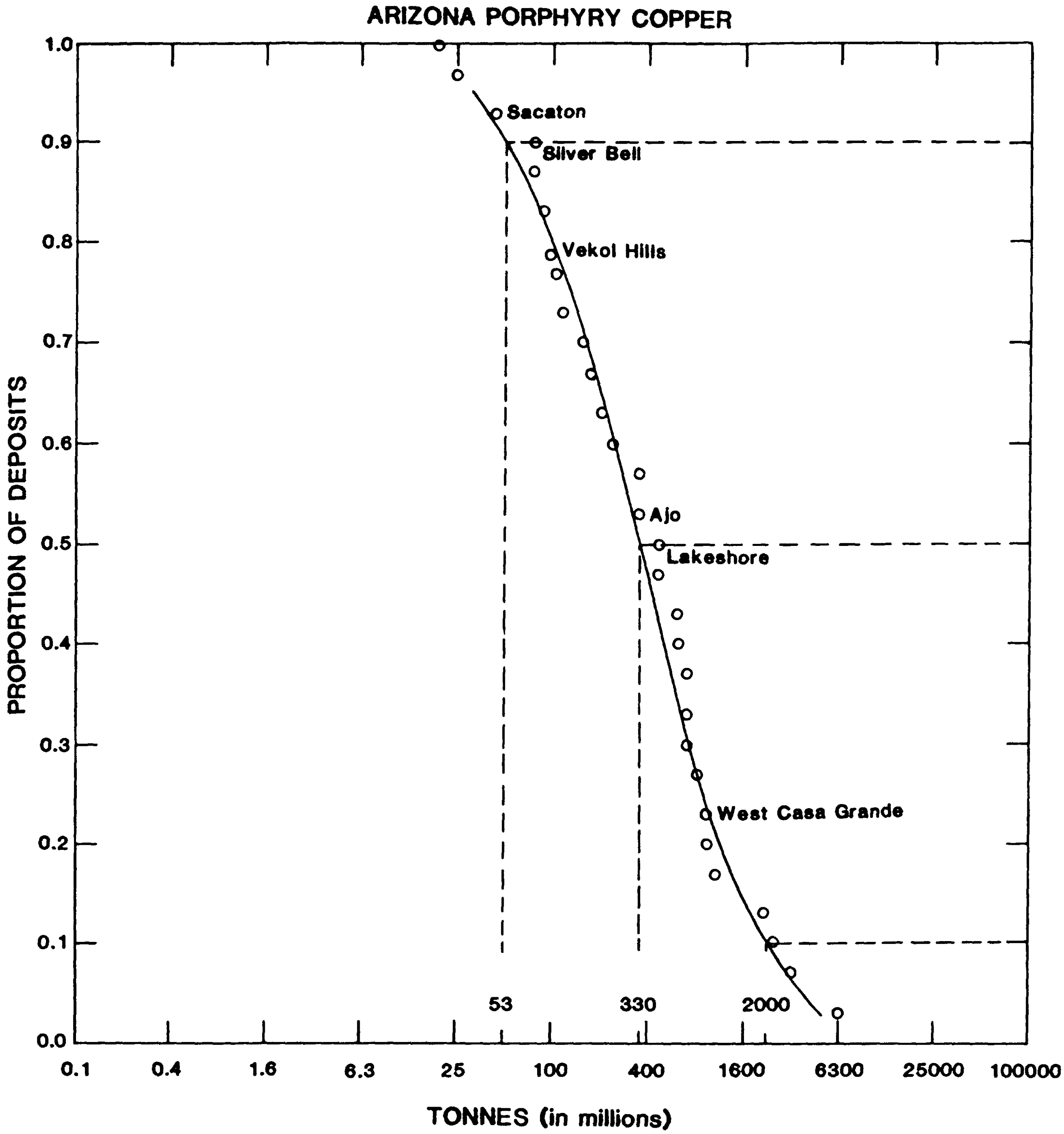

Figure 3. Inverse cumulative distribution of copper tonnage in porphyry copper deposits in Arizona (D.A. Singer, written commun., 1984) showing tonnages for deposits in and near the Ajo quadrangle. Tonnages and grades for this type of deposit are not significantly correlated.

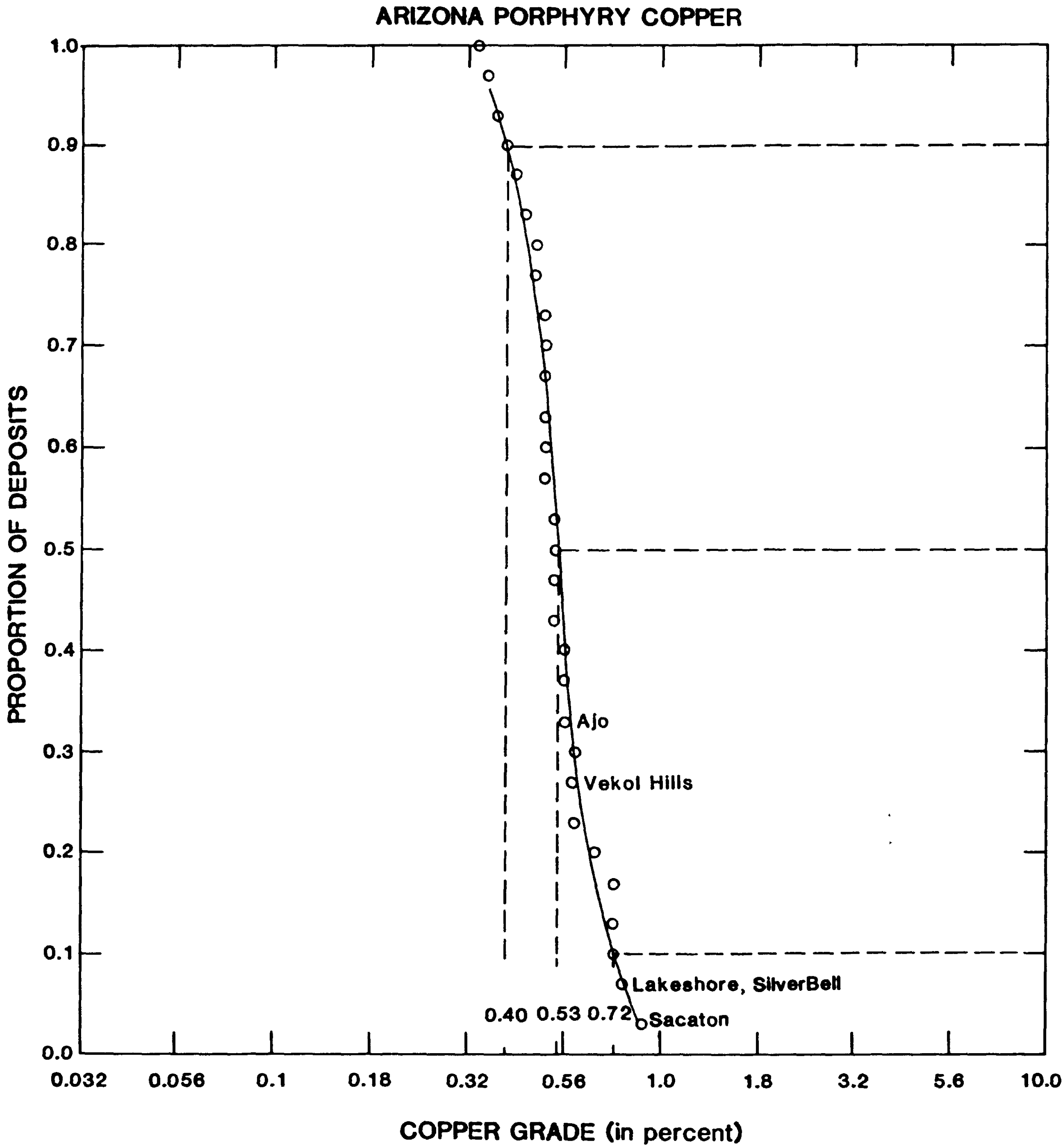

Figure 4. Inverse cumulative distribution of copper grade in porphyry copper deposits in Arizona (D.A. Singer, written commun., 1984) showing copper grade for deposits in and near the Ajo quadrangle.

geologists from this study contend, however, that such fanglomerates are widespread and simply indicate areas where porphyry copper deposits might be preserved. The fanglomerates perhaps, instead, resulted from the early evolution of the Tertiary volcanic field, when magma introcuction caused regional uplift.

Description of Deposit

Of the three known porphyry copper deposits within and immediately adjacent to the quadrangle, the Ajo deposit was discovered first (area C1, pl. 1). The other known porphyry copper deposits have significant skarn mineralization and are discussed below in the section on porphyry copper-related skarn deposits. The Ajo deposit lies at the eastern end of a series of structural blocks in the apex of an offshoot of the Cornelia pluton (Gilluly, 1946). Ore minerals, primarily chalcopyrite and bornite, formed in a porphyritic phase of the pluton and in probable Cretaceous andesitic to rhyolitic volcanic flows, flow breccia, and tuff (Dixon, 1966). Molybdenite is disseminated throughout the ore body in the rhyolitic volcanic rocks and small amounts of gold and silver are reported (Gilluly, 1946). This deposit is somewhat similar to the Dos Pobres system near Safford, Ariz., (Langton and Williams, 1982) in that magnetite as well as pyrite is an important alteration mineral. Two periods of enrichment formed a small amount of chalcocite and a great variety of copper oxide minerals, some of which are known only from this deposit. Abundant secondary K-feldspar and anhydrite indicate that potassic alteration predominates. Chlorite has replaced early biotite, and the eastern end of the ore body contains phyllic alteration.

The New Cornelia mine produced about 45,360 tonnes of copper per year during the 1950's to 1970's. In 1979 it produced 39,000 tonnes of copper (Pay Dirt, 1981), but due to lower copper prices in the early 1980's, production over the past few years has been declining and the mine is currently (1985) closed. Phelps Dodge Corporation planned to expand the mine so that it could remain productive until the year 2010 and a molybdenum circuit has been installed but the amount of molybdenum produced is not available. The Ajo deposit ranks above about 50 percent of the porphyry copper deposits in Arizona in tonnage and above about 65 percent in grade (figs. 3 and 4), although exact reserve data are proprietary. Figures 3 and 4 and other grade and tonnage curves shown throughout this paper represent inverse comulative frequency curves. The x axis on such curves represents the tonnage or grade for the particular type of deposit, usually presented on a logarhythmic scale, and the y axis represents the proportion of deposits of that type which have higher tonnages or grades than the given deposit. For example, figure 3 shows the tonnages for several porphyry copper deposits. Ninety percent of the porphyry copper deposits in Arizona have higher tonnages than the Sacaton deposit, whereas only 25 percent have higher tonnages than the West Casa Grande deposit.

Porphyry Copper-related Skarn Deposits

The other two deposits, Lakeshore and Vekol Hills, are porphyry copper-related skarn deposits. Many deposits of this type occur in southern Arizona. They formed where mineralizing porphyry stocks intruded rocks favorable for replacement by copper minerals, particularly limestones of Cambrian through Pennsylvanian age in which economic concentrations of copper occur with calc-silicate replacement. Proterozoic diabase sills occur in

Middle Proterozoic Apache Group rocks and host disseminated chalcopyrite in potassically altered zones. This mineralization commonly augments the tonnage of skarn deosits in the overlying Paleozoic rocks.

The following criteria are favorable for the discovery of porphyry copper-related skarn deposits within the quadrangle. They are used to delineate permissive tracts and to estimate the number of undiscovered porphyry copper-related skarn deposits. Deposits within the tracts are assumed to occur within 1,000 m of the surface for this resource assessment.

Strongly Favorable Criteria

1. Limestone or calcareous sedimentary rocks (Einaudi, 1982a; Einaudi and Burt, 1982) or Proterozoic diabase (Steele, 1978)
2. Calc-silicate minerals and magnetite (Einaudi, 1982a; Einaudi and Burt, 1982)
3. Polyphase quartz-bearing calcalkaline intrusive (hornblende-biotite type) (Einaudi, 1982a, b; Einaudi and Burt, 1982)
4. Disseminated copper minerals in limestone (Einaudi, 1982a; Einaudi and Burt, 1982)
5. Masses of silica-pyrite replacing skarn (Einaudi, 1982b)
6. At least one phase of intrusive is a porphyry with microaplitic groundmass (Stringham, 1966)
7. Potassic and (or) widespread, pervasive phyllic and argillic alteration (Einaudi, 1982a; Lowell and Guilbert, 1970)
8. Laramide age of intrusion (Titley, 1982b)
9. Anomalous Cu, Mo
10. Zoned geochemical anomalies from center outward of Cu, Mo, W; Cu, Zn, Pb, Au; Cu, Au, Sb, Ag in molybdenum-bearing deposits and Cu, Ag, Au; Mo, Pb, Zn, Mn in gold-rich deposits (Cox, 1983c)
11. High amplitude magnetic anomaly possibly due to magnetite development in a skarn (D.P. Klein, oral commun., 1984). The magnetite content of skarn deposits may cause large amplitude magnetic anomalies, such as schematically proposed by Jerome (1966). The extremum of the aeromagnetic signature of such a case is well exemplified by the Santa Rita deposit of southwest New Mexico (Jones and others, 1964), whereas the signatures of the Lakeshore or Vekol Hills deposits are more subtle (U.S. Geological Survey, 1980).

Weakly Favorable Criteria

12. Anomalous but not zoned Au, Ag, Zn, Pb, B, Hg, As, Sb, Sn, W, Te (Boyle, 1974). This criterion lists the same anomalous elements given for porphyry copper deposits because of the similar nature of these two types of deposits.
13. Propylitic alteration, narrow zones of phyllic or argillic alteration (Einaudi, 1982a; Lowell and Guilbert, 1970)
14. Middle Proterozoic quartzite present (Steele, 1978)
15. Mesozoic to early Tertiary age of pluton (Titley, 1982b)
16. Indication of hydrothermal alteration using remote sensing techniques
17. Nearby porphyry copper deposits or occurrence along trends of porphyry copper deposits (Titley, 1982a; Mayo, 1958)
18. Nearby veins or other skarns
19. Abundant faulting (Einaudi, 1982b; Titley, 1982a)
20. Gravity highs or magnetic highs in pediment indicating a possible buried

pluton adjacent to exposed calcareous rock (D.P. Klein, oral commun., 1984)
21. Locomotive-type fanglomerate (Lukanuski and others, 1976)
22. Limestone clasts in Tertiary fanglomerates (Gilluly, 1946). Gilluly (1946) found limestone cobbles in the Locomotive Fanglomerate near Ajo, although he does not specify an exact location. In the spring of 1983 during a reconnaissance field trip two of the authors (D.P. Cox and J.A. Peterson) found a limestone cobble in an outcrop just south of the Little Ajo Mountains. This could indicate a limestone unit near Ajo that is not now exposed. Because there is a known porphyry copper deposit at Ajo, a limestone unit in the area, if present, also may have been mineralized.

Description of Deposits

The Lakeshore deposit is both a porphyry copper and a porphyry-related skarn deposit. North of the mine a composite Late Cretaceous quartz-monzonite-granodiorite stock intruded Proterozoic Pinal Schist (Blacet and others, 1978; Johnson, 1972). North and east of the deposit are Proterozoic and Paleozoic sedimentary rocks and diabase. Cretaceous volcanic and sedimentary rocks and Tertiary andesite crop out south of the deposit.

Much of the mineralization consists of secondary copper and iron minerals (chalcocite, chrysocolla, brochantite ($Cu_4(SO_4)(OH)_6$)). Primary minerals in the skarn in limestone include chalcopyrite, some pyrite, magnetite, and traces of molybdenite, galena, and sphalerite in a calc-silicate gangue (Noranda Lakeshore Mines, Inc., unpublished report, 1980; Hallof and Winniski, 1971; Harper and Reynolds, 1969). The skarn generally has 1 to 6 percent pyrite, 1 to 4 percent chalcopyrite, and pyrite to chalcopyrite ratios of 1:2 to 4:1. The skarn has the highest gold content, which is generally low throughout the deposit. Both the sulfide and calc-silicate minerals are zoned away from the pluton (Einaudi, 1982a).

Biotite porphyry sills that intrude both the sedimentary rocks and overlying andesite contain high concentrations of chalcopyrite, minor bornite, and traces of covellite, molybdenite, gold, and silver. The andesite also contains disseminated copper minerals. Shattered parts of these host rocks are more intensely mineralized. High molybdenum concentrations are related spatially to the sills rather than to the volcanic rocks. Potassic alteration pervades the system; phyllic alteration took place on the fringes of the deposit and along major faults.

The skarn ore zone averages about 25 m thick at 1.5 percent copper (fig. 5) (Noranda Lakeshore Mines, Inc., unpublished report, 1980) which places this deposit at a grade above 75 percent of all porphyry copper-related skarns. The porphyry ore zone averages 0.82 percent copper at 0.5 percent cutoff grade with a column height of 120 m. Large areas of slightly less than ore-grade rock are adjacent to the reserves. The porphyry ore grade is higher than about 90 percent of porphyry copper deposits in Arizona (fig. 4). Total tonnage for Lakeshore is about 425 million tonnes (Skillings' Mining Review, 1976), larger than about 55 percent of the deposits in Arizona (fig. 3).

At the Vekol Hills deposit, located in sec. 4, T. 10 S., R. 3 E. (area S2, pl. 1) a short distance west of the Lakeshore deposit, data from drilling have outlined the extent of the ore body but no mining has begun (Metals Week, 1974). Proterozoic Pinal Schist and monzogranite form a basement complex upon which the Apache Group was deposited and subsequently intruded by Proterozoic diabase. A Paleozoic sedimentary sequence, which hosts porphyry copper-related skarn deposits in the Vekol Mountains north of the Vekol Hills

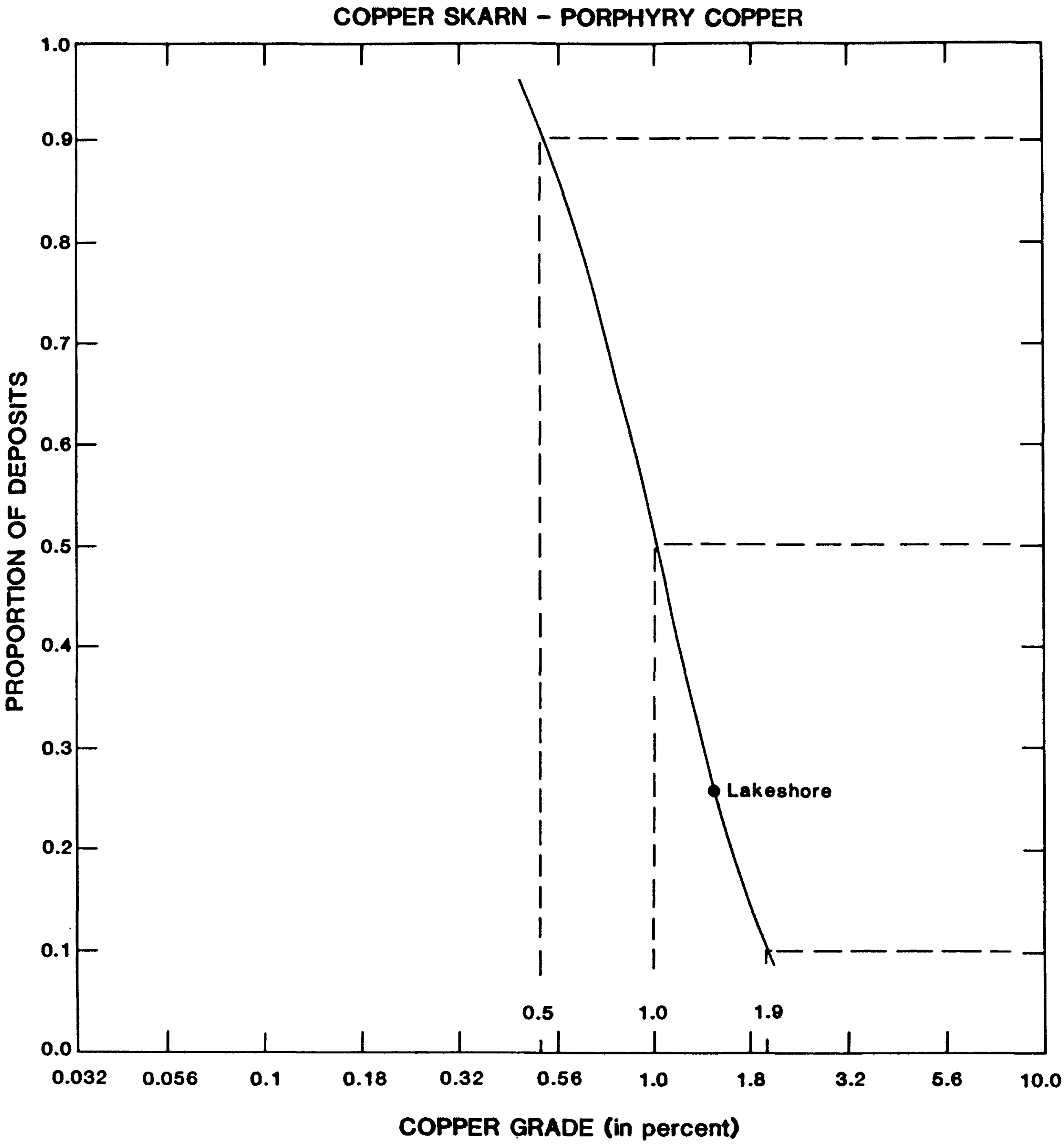

Figure 5. Inverse cumulative distribution of copper grade in porphyry copper-related skarn deposits (modified from Singer, 1983b, p. 45) showing copper grade in the Lakeshore skarn body (Noranda Lakeshore Mines, Inc., 1980).

deposit, and Mesozoic quartzite and conglomerate overly the Proterozoic rocks. Late Cretaceous or early Tertiary porphyritic stocks, dikes, and sills intrude all pre-Mesozoic units (Steele, 1978). The country rocks host most of the copper ore, although minor mineralization of the porphyritic rock took place. The youngest mineralized country rock may be Pennsylvanian (Dockter and Keith, 1978). The primary sulfide minerals pyrite, chalcopyrite, and molybdenite are disseminated throughout the host rocks and fill fractures. At this deposit supergene enrichment is relatively unimportant.

Evaluation of Porphyry Copper and Porphyry Copper-related Skarn Deposits

Because porphyry copper and porphyry copper-related skarn deposits are so closely related spatially, genetically, and in terms of grade-tonnage curves (table 1; figs. 3,4,6,7,8; Singer, 1983, p. 43-48), they are considered together in this mineral resource evaluation. Plate 1 shows that large areas of the quadrangle contain potential host rocks for porphyry copper and porphyry copper-related skarn deposits. Within these areas of permissive rocks several tracts, labeled C1 through C12 and S1 through S10, are delineated as having potential for porphyry copper-type mineralization based on the criteria presented above. Tracts labeled "C" are permissive for porphyry copper only; those labeled "S" are permissive for both types of deposits. Tracts C1 and S2 that contain the known Ajo and Vekol Hills deposits, respectively, are unlikely to contain other deposits and therefore are excluded from the estimate of undiscovered deposits. Tables 2 and 3 show how well the known information about each tract correlates with the lists of criteria. Using the data from these tables we believe there is a 50 percent chance that there are 1 or more undiscovered deposits, and a 10 percent chance that there are 4 or more undiscovered deposits within the quadrangle.

Skarn Deposits

In addition to the porphyry copper-related skarn deposits described above, there are important skarns containing zinc-lead, copper, and iron that are related to unmineralized igneous intrusions. All are hosted by carbonate and (or) calcareous clastic sedimentary rocks intruded by mafic to felsic plutons and are associated with calc-silicate contact metamorphic minerals (Einaudi, 1982a, b). Such skarns occur in the Vekol Mountains area of the quadrangle.

The list of criteria for skarn deposits is similar to that for porphyry copper related skarn deposits. They were used both to delineate permissive tracts and to estimate the number of undiscovered deposits. Deposits being evaluated for this assessment would be within a few hundred meters of the surface.

Strongly Favorable Criteria

1. Limestone or calcareous sedimentary rocks (Einaudi and Burt, 1982; Einaudi and others, 1981)
2. Mafic to felsic pluton near carbonate rocks (Einaudi and Burt, 1982; Einaudi and others, 1981). The plutonic rocks that can form skarn deposits are not as restricted compositionally as those that form porphyry copper deposits. They are mafic to felsic and can be dikes as well as small plutons (Einaudi and Burt, 1982; Einaudi and others, 1981).
3. Calc-silicate minerals and (or) magnetite in country rock (Einaudi and

Table 1.--Deposits used to construct grade-tonnage curves shown in figures 3, 4, 6, 7, and 8 for Arizona porphyry copper deposits.

Deposit	Deposit	Deposit
Ajo	Helvetia	Red Mountain
Bagdad	Inspiration	Sacaton (east and west)
Blue Bird	Ithica Peak	Safford (KCC)
Carpenter	Kalamazoo	Safford (PD)
Castle Dome	Lakeshore	Sanchez
Copper Basin	Metcalf	San Juan
Copper Cities	Mineral Butte	San Xavier
Copper Creek	Morenci	Silver Bell
Esperanza	Pima-Mission	Twin Buttes
Florence	Ray	Vekol Hills

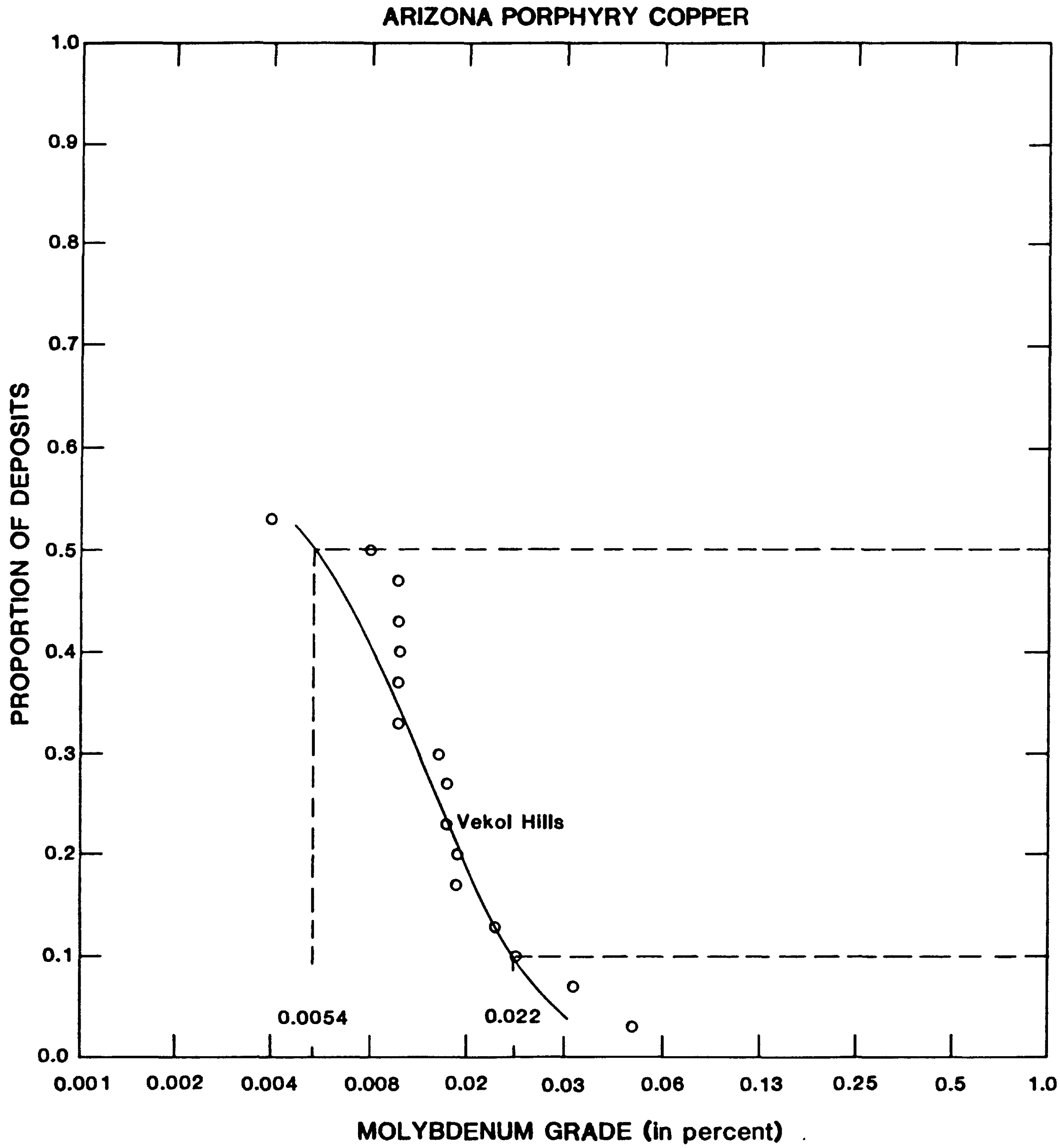

Figure 6. Inverse cumulative distribution of molybdenum grade in porphyry copper diposits in Arizona (D.A. Singer, written commun., 1984).

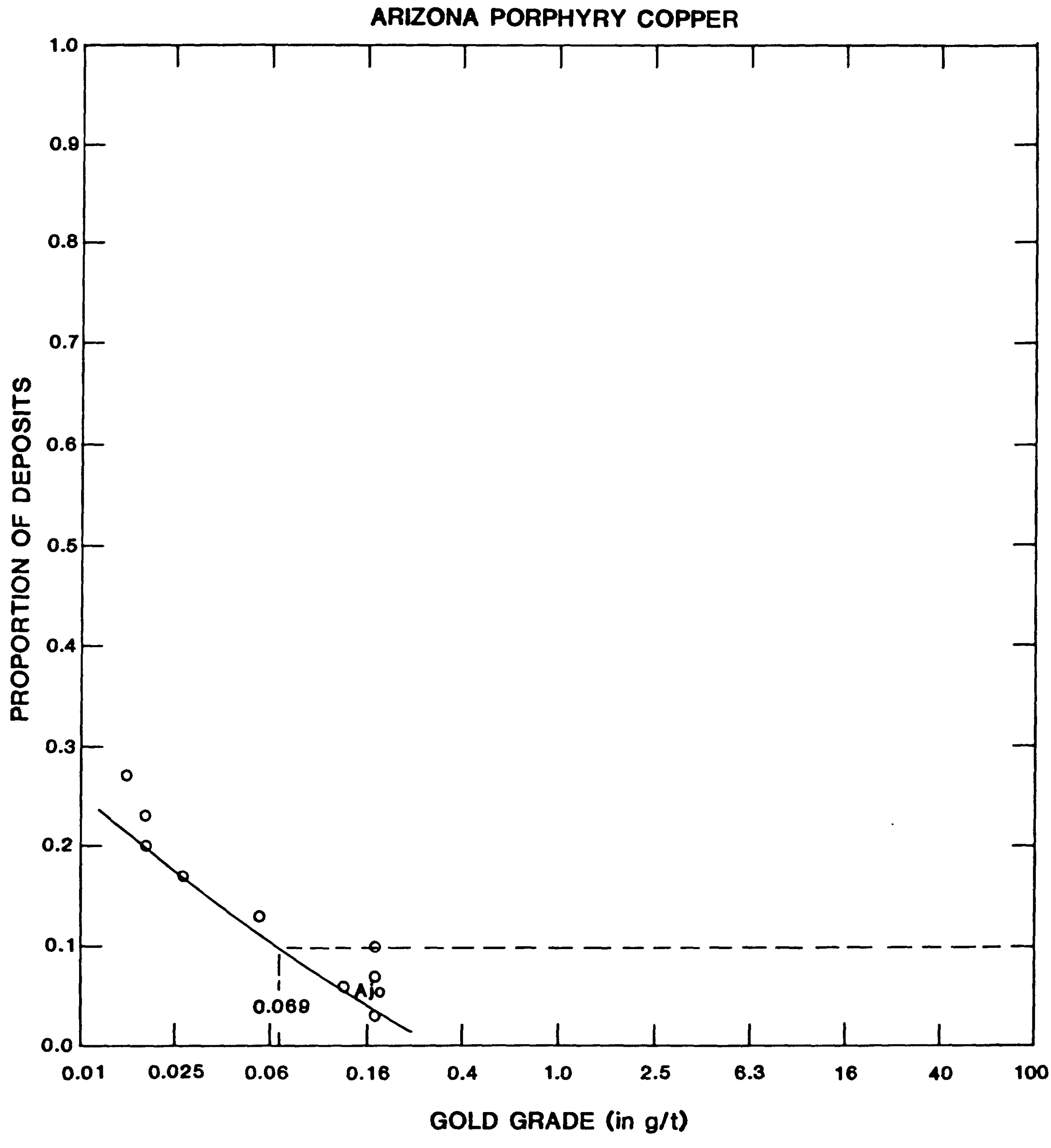

Figure 7. Inverse cumulative distribution of gold grade in porphyry copper deposits in Arizona (D.A. Singer, written commun., 1984) showing gold grade for the Ajo deposit (Wilkins, 1984a).

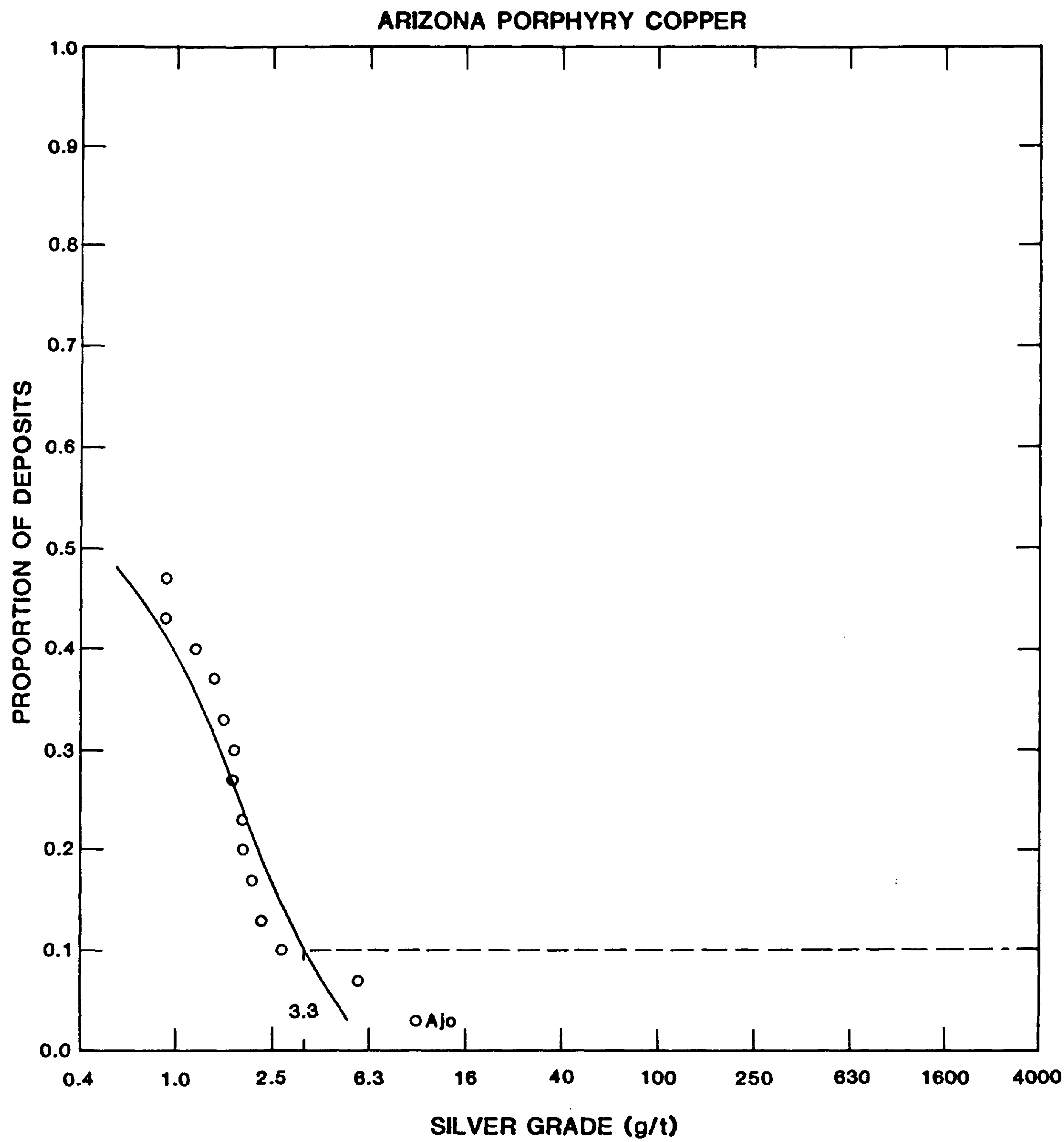

Figure 8. Inverse cumulative distribution of silver grade in porphyry copper deposits in Arizona (D.A. Singer, written commun., 1984) showing silver grade for the Ajo deposit (Wilkins, 1984a).

Table 2.--Relation of porphyry copper tracts (pl. 1) to criteria for evaluation of undiscovered deposits in the Ajo and Lukeville 1° by 2° quadrangles
[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element; blackened boxes, data that are proprietary to the Papago Indian Tribe]

	Tract										
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
					Strongly favorable criteria						
Disseminated copper minerals	X					X					
Stockwork of quartz veinlets	X										
Calcalkaline intrusive	X	X						X			X
Porphyritic phase with microaplitic groundmass	X										
Potassic; widespread phyllic, argillic alteration	Potassic										
Laramide age of intrusion	X	X						X			X
Anomalous Cu, Mo; zoned anomalies	Cu, Mo	[redacted]				Cu	Cu	Mo	[redacted]	[redacted]	
					Weakly favorable criteria						
Mesozoic to early Tertiary pluton age	X	X						X			X
Anomalous Au, Ag, Zn, Pb, and so on	Pb	[redacted]				As, Sb, Sn, Ag	Sn, Mn	Bi, Pb, W	[redacted]	[redacted]	
Propylitic; narrow phyllic, argillic alteration	Phyllic										
Precambrian to lower Tertiary host rocks	X			X							
Remote sensing indication of hydrothermal alteration						SW of small anomaly		Small anomaly nearby			
Nearby skarn or vein deposits		X							X		
Nearby porphyry copper or copper trends	X		X	X		X	X	X	X		
Aeromagnetic favorability for porphyry copper											
Cretaceous andesitic volcanic rocks	X										
Abundant faulting	X					X					
Geophysical evidence of buried pluton			X	X	X	X					
Locomotive-type fanglomerate	X		X	X	X						
Remarks		1				2	3	4	5	5	

REMARKS:
1 Granite has Ajo-type fluid inclusions
2 Oxide coatings in fractures contain Cu, Bi, As, Be, Sb, Sn
3 Geochemical evidence of mineralization at depth is more suggestive of a stockwork molybdenum system than a porphyry copper system (P.K. Theobald, oral commun., 1984).
4 Pluton appears to be barren; magnetic low suggests silicic rocks under area (D.P. Klein, written commun., 1984)
5 This area has vegetative reflectance similar to Silver Bell east of the quadrangle (R. Schmidt, written commun., 1984)

Table 3.--Relation of skarn tracts (pl. 1) to criteria for evaluation of undiscovered porphyry copper-related skarn deposits in the Ajo and Lukeville 1° by 2° quadrangles

[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element; blackened boxes, data that are proprietary to the Papago Indian Tribe]

	Tract										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
					Strongly favorable criteria						
Limestone or other calcareous rock, diabase	X	X	X	X	X	X	X		X	X	X
Calc-silicate minerals and magnetite	X		Wollastonite								X
Calc alkaline intrusive	X	X	X	X				X		X	X
Disseminated copper minerals in carbonate rock		X									
Silica-pyrite replacing skarn											
Porphyritic phase with microaplitic groundmass		X									
Potassic; widespread phyllic, argillic alteration											
Laramide age of intrusion	X	X	X	X				X			
Anomalous Cu, Mo; zoned anomalies	[redacted]	[redacted]	Cu	[redacted]	[redacted]		[redacted]			[redacted]	[redacted]
High amplitude magnetic anomaly											
					Weakly favorable criteria						
Anomalous Au, Ag, Zn, Pb, and so on	[redacted]	[redacted]		[redacted]	[redacted]		[redacted]			[redacted]	[redacted]
Propylitic; narrow phyllic, argillic alteration											
Upper Precambrian quartzite		X									
Mesozoic to early Tertiary pluton age	X	X	X	X				X			
Remote sensing indication of hydrothermal alteration	X	X		X		N of small anomaly			X		
Nearby porphyry copper or copper trends	X	X	X	X		X	X	X			
Nearby vein or skarn deposits	X	X									
Abundant faulting		X									
Geophysical evidence of buried pluton											
Locomotive-type fanglomerate								X			
Limestone clasts in Tertiary fanglomerate								X			
Remarks			1						2		

REMARKS:

[1]Pluton appears to be barren; see table 4

[2]Small limestone outcrops is adjacent pegmatite area and near geochemical anomalies suggestive of stockwork molybdenum mineralization (P.K. Theobald, oral commun., 1984)

Burt, 1982; Einaudi and others, 1981)

4. Potassic or phyllic alteration assemblages or alteration to epidote, pyroxene, and garnet in pluton (Einaudi and others, 1981)
5. Fe, Cu, Co, Au, (Sn) anomalies in Fe skarn; Cu, Pb, Zn, Au, Ag, Mo, W, (Bi) anomalies in Cu skarn; Zn, Pb, Cu, Co, Au, Ag, W, Sn, F, Mn anomalies in Pb-Zn skarn (Cox, 1983a, b, f; Einaudi and Burt, 1982)
6. Primary or secondary sulfide minerals (Einaudi and Burt, 1982; Einaudi and others, 1981)

Weakly Favorable Criteria

7. Mesozoic to Tertiary age of pluton (Einaudi and others, 1981)
8. Spatial association with porphyry copper deposits, other skarns, and (or) replacement deposits
9. Gossan (Cox, 1983a, f)
10. Indication of hydrothermal alteration using remote sensing techniques
11. Gravity highs or magnetic highs in pediment indicating a possible buried pluton adjacent to exposed calcareous rock (D.P. Klein, oral commun., 1984)
12. Middle Proterozoic quartzite and (or) diabase present (Steele, 1978). Quartzite and diabase indicate possible nearby limestone rather than skarn mineralization.

Description of Deposits

Skarn deposits in the Ajo quadrangle are located mainly in the Vekol Mountains. Currently, no skarn deposits are being mined in the quadrangle. Abundant sphalerite, pyrite, and associated calc-silicate minerals in a mine dump near an abandoned shaft in the northeast corner of sec. 4, T. 10 S., R. 3 E. suggests a zinc-lead skarn deposit. The Reward Mine 1.6 km to the north is a copper skarn deposit. Ore minerals there include chalcopyrite, minor sphalerite and galena, plus chrysocolla, malachite, and azurite (Carpenter, 1947). The skarn also contains hematite and several calc-silicate minerals. The Reward Mine yielded an estimated 205 tonnes of copper (Carpenter, 1947), a tonnage much less than those of the deposits used in constructing the tonnage curves for copper skarn deposits worldwide (Jones and Menzie, 1983). The source rocks for these skarns are not exposed and presumably lie under alluvial cover to the east. No iron skarns are known in the Ajo quadrangle.

Polymetallic Replacement Deposits

Replacement deposits are concordant, massive ore bodies of copper, lead, zinc, silver, and gold in carbonate rocks, but they lack the calc-silicate minerals associated with skarn deposits (see Morris, 1983). They are found in similar environments as skarn deposits and, except for a couple of significant differences, possess common characteristics. As with skarn deposits, these are evaluated only if expected within a few hundred meters of the surface. Tracts for replacement deposits are the same as those for porphyry copper-related skarns (pl. 1).

Strongly Favorable Criteria

1. Limestone or calcareous sedimentary rocks (Jensen and Bateman, 1979)
2. Sulfide minerals in limestone (Jensen and Bateman, 1979)
3. Lack of calc-silicate minerals (Morris, 1983)
4. Dolomitized or silicified limestone in vicinity (Morris and Lovering, 1979). Unlike skarn deposits, replacement deposits lack calc-silicate minerals and commonly occur in dolomitized and silicified limestone.
5. Mafic to felsic pluton near carbonate rock (Morris and Lovering, 1979)
6. Geochemical zoning from Cu in the center to Pb, Zn, Ag to Zn, Mn on the periphery (Morris and Lovering, 1979)
7. Early dolomitic, chloritic; argillic; silicic, calcic; late potassic, silicic, baritic alteration (Morris and Lovering, 1979)

Weakly Favorable Criteria

8. Abundant fracturing (Jensen and Bateman, 1979; Morris and Lovering, 1979)
9. Widespread As, Sb, Bi anomalies (Morris, 1983)
10. Association with other skarns and (or) replacement deposits
11. Middle Proterozoic quartzite and (or) diabase
12. Gravity highs or magnetic highs in pediment indicating possible buried pluton adjacent to exposed calcareous rock (D.P. Klein, oral commun., 1984)

Description of Deposit

The Vekol Mine on the west flank of the Vekol Mountains is a replacement deposit from which the highly oxidized ore was mined for its silver content. The deposit occurs in Mississippian Escabrosa Limestone as small pods and mineralized areas up to 10 m across (Carpenter, 1947). The locations of individual ore bodies were controlled by fractures, joints, and bedding. The deposit yielded about $1,000,000 worth of silver between 1882 and 1916.

Evaluation of Skarn and Replacement Deposits

Because skarn and replacement deposits are intimately connected to carbonate host rocks, they are evaluated together. Grade and tonnage data for skarn and replacement deposits (Mosier and Menzie, 1983b, p. 34-37; Jones and Menzie, 1983, p. 38-42; Mosier, 1983c, p. 26-31) indicate that these deposits are typically small but of higher grade than disseminated deposits that contain the same commodities. Plate 1 shows all areas in the quadrangle where limestone crops out. All limestone outcrops are designated as tracts having potential for skarn or replacement deposits and are designated by "S", the same tracts used for porphyry copper-related skarn deposits. In addition, unexposed limestone possibly lies beneath the Locomotive Fanglomerate or pediment south of Ajo (tract S8). Limestone northeast of Growler Pass (tract S3) cotains wollastonite. Sulfide minerals were not seen during a short visit to that area; however, chemical analyses of two rock samples yielded high copper concentrations and detectable silver and gold (table 4). Other limestone outcrops outside the Papago Indian Reservation do not contain calc-silicate minerals. Tables 5 and 6 show which criteria are satisfied for each tract. Using the data from table 5 we believe there is a 50 percent chance that there are 1 or more undiscovered deposits, and a 10 percent chance that there are 4 or more undiscovered deposits within the quadrangle. Because

Table 4.--Chemical analyses of two limestones from the Lime Hill area. Elements sought but not detected include As, Cd, Mo, Sb, W and Th. N indicates element not detected. All elements except gold were analyzed by emission spectrography; gold was analyzed by atomic absorption.

Element	Sample	
	AJ100P	AJ101P
Ag-ppm	3.	0.7
Au-ppm	0.8	0.1
B-ppm	50.	>2,000.
Ba-ppm	<20.	50.
Be-ppm	<1.	1.5
Bi-ppm	500.	30.
Ca-percent	20.	20.
Co-ppm	<5.	5.
Cr-ppm	50.	70.
Cu-ppm	15,000.	2,000.
Fe-percent	7.	3.
La-ppm	N	50.
Mg-percent	0.7	2.
Mn-ppm	3,000.	1,000.
Ni-ppm	7.	15.
Pb-ppm	50.	150.
Sc-ppm	10.	10.
Sn-ppm	15.	N
Sr-ppm	200.	150.
Ti-percent	0.15	0.15
V-ppm	70.	50.
Y-ppm	20.	20.
Zn-ppm	N	300.
Zr-ppm	50.	100.

Table 5.--Relation of skarn tracts (pl. 1) to criteria for evaluation of undiscovered skarn deposits in the Ajo and Lukeville 1° by 2° quadrangles

[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element; blackened boxes, data that are proprietary to the Papago Indian Tribe]

	Tract										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S1
					Strongly favorable criteria						
Limestone or other calcareous rock	X	X	X	X	X	X	X		X	X	X
Nearby mafic to felsic pluton	X	X	X	X				X		X	X
Calc-silicate minerals and magnetite	X		Wollas-tonite								X
Potassic, phyllic, epidote-pyroxene-garnet alteration of pluton											
Geochemical anomalies	[redacted]	[redacted]	Cu	[redacted]	[redacted]		[redacted]			[redacted]	[redacted]
Primary or secondary sulfide minerals	X	X									
					Weakly favorable criteria						
Mesozoic to Tertiary pluton age	X	X	X	X				X			
Nearby porphyry copper, skarn, replacement deposits	X	X	X	X		X	X	X			
Gossan											
Remote sensing indication of hydro-thermal alteration	X	X		X		N of small anomaly			X		
Geophysical indication of buried pluton											
Upper Precambrian quartzite or diabase	X	X					X				
Remarka			1						2		

REMARKS:
[1]Pluton appears to be barren; aee table 4.
[2]Small limestone outcrop is adjacent pegmatite area and near geochemical anomaliea suggestive of stockwork molybdenum mineralization (P.K. Theobald, oral commun., 1984)

Table 6.--Relation of skarn tracts (pl. 1) to criteria for evaluation of undiscovered polymetallic replacement deposits in the Ajo and Lukeville 1° by 2° quadrangles

[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element; blackened boxes, data that are proprietary to the Papago Indian Tribe]

	Tract										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
					Strongly favorable criteria						
Limestone or calcareous sedimentary rocks	X	X	X	X	X	X	X		X	X	X
Sulfide minerals in limestone	X	X									
Lack of calc-silicate minerals	X										
Dolomitized or silicified limestone											
Mafic to felsic pluton near carbonte	X	X	X	X				X		X	X
Zoned geochemical anomalies	[redacted]	[redacted]	Cu	[redacted]	[redacted]		[redacted]			[redacted]	[redacted]
Argillic, silicic, calcic, potassic, barite alteration											
					Weakly favorable criteria						
Abundant fractures	X										
Widespread As, Sb, Bi geochemical anomalies											
Nearby skarn or replacement deposits	X	X									X
Upper Precambrian quartzite or diabase	X	X					X				
Geophysical evidence of buried pluton											
Remarks			1						2		

REMARKS:

[1]Pluton appears to be barren; see table 4

[2]Small limestone outcrop is adjacent pegmatite area and near geohcmeical anomalies suggestive of stockwork molybdenum mineralization (P.K. Theobald, oral commun., 1984)

known replacement deposits are less common than known skarn deposits there are probably fewer undiscovered replacement deposits within the quadrangle.

STOCKWORK MOLYBDENUM DEPOSITS

Stockwork molybdenum deposits share many characteristics with porphyry copper deposits, however, they differ enough to warrant separate consideration. Two distinct types of stockwork molybdenum systems have been identified: a granite porphyry system and a fluorine-deficient system which more closely resemble porphyry copper deposits (White and others, 1982; Mutchler and others, 1981; Westra and Keith, 1981). Presently, Arizona has no active stockwork molybdenum mines, but a geologic environment favorable for a molybdenum porphyry system has been identified previously in the Cimarron Mountains (Tosdal, 1981).

Granite Stockwork Molybdenum Deposits

The granite stockwork molybdenum deposits, also referred to as Climax-type deposits because of the well known deposit of this type in Colorado, are commonly associated with high-silica alkali granite or rhyolite porphyry plugs or dikes. Molybdenite occurs rarely as disseminations in the groundmass or more commonly as stockworks of quartz-molybdenite-fluorite veins surrounded by quartz-pyrite-huebnerite veins and a base-metal sulfide zone. Potassium silicate, quartz-sericite, argillic, and propylitic alteration and, in some deposits, a superimposed greisen alteration assemblage accompany Climax-type stockwork molybdenum systems (Mutchler and others, 1981). Some of these deposits contain economic concentrations of fluorite.

The following criteria provide guidelines for delineating tracts permissive for the discovery of Climax-type molybdenum deposits in the quadrangle (pl. 1). The criteria also were used to estimate the number of undiscovered stockwork molybdenum deposits. We evaluate the potential for undiscovered deposits within 1,000 m of the surface.

Strongly Favorable Criteria

1. High-silica alkali granite or rhyolite porphyry plugs or dikes containing high rubidium/strontium ratios and niobium (White and others, 1982; Mutchler and others, 1981; Westra and Keith, 1981). High-silica alkali granites which typically host or are associated genetically with Climax-type deposits are not exposed in the quadrangle. Such granites usually occur as stocks above batholiths in rift zones of continental cratons, but they may occur less commonly in a continental margin setting (Ludington, 1983) such as that of the quadrangle. Local differentiated intrusions related to such a batholith cause local geophysical anomalies near some deposits.
2. Greisen-like alteration assemblage. Also, potassium silicate and (or) quartz-sericite alteration (White and others, 1982; Mutchler and others, 1981; Westra and Keith, 1981)
3. Quartz-molybdenite stockworks or yellow ferrimolybdite staining of rocks (White and others, 1982; Mutchler and others, 1981)
4. Fluorite (White and others, 1982; Mutchler and others, 1981)
5. Anomalous Mo, F (greater than 1,000 ppm in rock samples), W relative to the country rock. Typically zoned from Mo in the core to W, Sn to Cu, Mn and finally to Pb, U, and rare-earth elements on the periphery. Cu content is

very low in core (White and others, 1982; Mutchler and others, 1981; Westra and Keith, 1981). The tungsten-tin zone which forms umbrella shaped mantles above the molybdenum mineralization is economic in some cases.

Weakly Favorable Criteria

6. Nearby fluorite deposits
7. Mesozoic to Tertiary age of pluton (White and others, 1982; Mutchler and others, 1981, Westra and Keith, 1981)
8. Nearby base- and precious-metal vein deposits
9. Anomalous Sn, U, Be, Li, rare-earth elements, Pb, Zn, Ag, Mn
10. Granites rich in Be, Cs, F, Li, Mo, Nb, Rb, Sn, Ta, Th, U, W
11. Circular gravity lows indicative of large siliceous batholith at depth (Mutchler and others, 1981, Steven, 1975)
12. Magnetic high or gravity high that may indicate a pluton buried in the pediment (D.P. Klein, oral commun., 1984)
13. Argillic and (or) propylitic alteration (White and others, 1982; Mutchler and others, 1981; Westra and Keith, 1981)

Description of a Possible Climax-type Stockwork Molybdenum Environment

Tosdal (1981) described an environment favorable for a Climax-type stockwork molybdenum system in the Cimarron Mountains (area M1, pl. 1), where there is evidence of a circular gravity low that indicates a low density mass of 2-4 km horizontal diameter. The system is centered on a mid-Tertiary dacite porphyry in a possible caldera complex, outlined by a series of ring fractures (Briskey and others, 1978; Dockter and Keith, 1978). The Pinal Schist, granitic intrusives, and some parts of the dacite porphyry have undergone widespread hydrothermal alteration that includes a potassium silicate-altered core in the dacite porphyry with superimposed phyllic and silicic alteration and more widespread propylitic and pyritic zones. Fluorite is present in veins in the Greenback Mine and in the surrounding area. The overall known vein mineralization in the Cimarron Mountains is weak and scattered, and is limited mostly to silver and gold rich zones (Keith, 1974). Secondary copper minerals and vein-associated galena occur there in epithermal veins at the Greenback Mine area. Molybdenite has not yet been found at this locality.

Fluorine-deficient Stockwork Molybdenum Deposits

Fluorine deficient stockwork molybdenum deposits commonly occur in geologic environments similar to those of porphyry copper deposits (White and others, 1982; Theodore, 1982; Westra and Keith, 1981). Additionally, some molybdenum mineralization has been recognized in two-mica granodiorites (Miller and Theodore, 1982) that are similar to two-mica granites in the quadrangle. The primary minerals molybdenite, pyrite, scheelite, and chalcopyrite (Theodore, 1983) may occur in the pluton, wall rock, or as skarn. Alteration assemblages resemble those of a porphyry copper deposit, but the volume of introduced silica, as quartz, generally is much greater (Theodore and Menzie, 1984). Cogenetic volcanic rocks are also missing, suggesting that stockwork molybdenum deposits form in a deeper geologic environment than is typical of porphyry copper systems.

The following sections list favorable criteria for delineating tracts permissive for the discovery of fluorine-deficient stockwork molybdenum deposits (pl. 1) within 1,000 m of the surface. We also used these criteria to estimate the number of undiscovered deposits.

Strongly Favorable Criteria

1. Hornblende-biotite felsic to intermediate plutons (calcalkaline) or garnet-two mica granites (peraluminous) (Miller and Theodore, 1982; White and others, 1982; Mutchler and others, 1981; Westra and Keith, 1981). Miller and Theodore (1982) described molybdenum mineralization in the Harvey Creek area, Wash., which occurs in a two-mica granodiorite pluton that may be similar to the two-mica granites within the Ajo quadrangle. Furthermore, trace-element geochemical data presented in Miller and Theodore (1982) is comparable to at least one geochemical anomaly associated with a two-mica granite in the quadrangle (table 7, tract M2).
2. Potassium silicate and widespread, pervasive phyllic and argillic alteration (Westra and Keith, 1981)
3. Widespread stockworks of quartz veinlets (White and others, 1982)
4. Anomalous Mo, W, F (much less than 1,000 ppm in rock samples) relative to the country rock. Usually zoned from Mo, Cu in the core, through Cu, Au and finally to Zn, Pb, Au, and Ag in the distal portion of the system (Westra and Keith, 1981). Fluorine-deficient deposits do not lack fluorine, but its concentrations rarely will be as much as 1,000 ppm in rock samples (S.D. Ludington, oral commun., 1984). Though some of these systems contain low levels of fluorine, overall they contain far less fluorine than Climax-type molybdenum deposits and typically do not occur near nor are they associated genetically with fluorite veins.
5. Associated tungsten minerals (scheelite) (White and others, 1982)

Weakly Favorable Criteria

6. Early Tertiary or older rocks
7. Mesozoic to Tertiary age of pluton (White and others, 1982)
8. Anomalous Cu, Ag, Au, Pb, Zn, As (Theodore, 1983)
9. Major local faulting (Blake and others, 1979)
10. Associated base- and precious-metal veins
11. Propylitic alteration, narrow zones of phyllic or argillic alteration (Westra and Keith, 1981)
12. Magnetic highs surrounded by magnetic lows caused by alteration of magnetite to pyrite (D.P. Klein, written commun., 1984)
13. Magnetic highs or gravity highs in pediment suggesting a possible buried pluton (D.P. Klein, oral commun., 1984)

Evaluation of Potential for Stockwork Molybdenum Deposits

Plate 1 shows 10 tracts that are permissive for a stockwork molybdenum deposit, and table 8 shows how each tract relates to the criteria listed above. Most of the tracts are probably more favorable for fluorine-deficient molybdenum mineralization; however, tracts M1 and M3 lie adjacent to areas of known fluorite mineralization and may have potential for Climax-type mineralization. Grade and tonnage values differ for Climax-type and fluorine-deficient stockwork molybdenum deposits in that Climax-type deposits usually are larger and have higher molybdenum grades (Singer and others, 1983, p. 28-

Table 7.--Ranges in detected values in stream-sediment-concentrate samples for selected elements collected in Senita Basin (7 samples) and Harvey Creek area, Washington (17 samples). Data from Harvey Creek was derived from Miller and Theodore (1982).
[Numbers in parentheses indicate number of samples with values above the lower limit of detection. Values are in parts per million]

Element	Senita Basin	Harvey Creek
Ag	3-500 (4)	1-50 (5)
As	no data	20-120 (3)
Bi	no data	30-2,000 (16)
Mo	70-700 (6)	10-50 (7)
Pb	50-7,000 (6)	no data
Sb	300 (2)	no data
Th	3,000->5,000 (5)	no data
V	150-1,500 (6)	no data
W	150-1,500 (6)	100-1,000 (12)
Zn	3,000 (1)	no data

Table 8.--Relation of stockwork molybdenum tracts (pl. 1) to criteria for evaluation of undiscovered deposits in the Ajo and Lukeville 1° by 2° quadrangles

[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element; blackened boxes, data that are proprietary to the Papago Indian Tribe]

	Tract									
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Strongly favorable criteria										
Climax-type										
High-silica alkali granite or rhyolite	X									
Greisen, potassic, quartz-sericite alteration	Potassic									
Quartz-Mo stockworks; ferrimolybdite stains										
Fluorite	X		X							
Mo, F, W; zoned anomalies	[redacted]	Mo, W	Mo, W			Mo, W	[redacted]			[redacted]
Fluorine-deficient										
Calc-alkaline or peraluminous granite		X			X	X	X			X
Potassic; widespread phyllic, argillic alteration			Phyllic							
Stockworks of quartz veinlets	X		X							
Mo, W; zoned anomalies	[redacted]	Mo, W	Mo, W			Mo, W	[redacted]			[redacted]
Associated W minerals			X							X
Weakly favorable criteria										
Climax-type										
Nearby fluorite deposits										
Be, Cs, Li, F, and so on rich granites										
Circular gravity lows	X				X					
Fluorine-deficient										
Lower Tertiary or older rocks		X	X	X	X	X				
Major faulting										
Magnetic high inside magnetic low			X							
Both (Climax-type and Fluorine-deficient)										
Mesozoic to Tertiary age of pluton	X	X	Rhyolite dikes		X	X				X
Nearby vein deposits	X	X	X		X	X				X
Geochemical anomalies	[redacted]	Ag, Pb, Sb, Zn	Bi, La Pb, Th			Th, Sn	[redacted]	Sn, Cu, Sb, Mn	Mn	[redacted]
Geophysical evidence of buried pluton				X						
Propylitic, argillic alteration	X									
Remarks		1	2	3	4			5	5	

REMARKS:

1 Two-mica granite; possible limonite anomaly determined by remote sensing

2 Remote sensing limonite anomaly nearby; an aeromagnetic high anomaly corresponds to geochemical anomaly

3 Geochemical data suggests that any potential buried pluton would likely be a two-mica granite (P.K. Theobald, written commun., 1984)

4 Geochemical data suggests that a two-mica granite underlies the area

5 Siliceous altered volcanic field possibly indicates a pluton at depth; geochemical evidence of mineralization at depth is more suggest ve of a stockwork molybdenum system than a porphyry copper system (P.K. Theobald, oral commun.,

30; Menzie and Theodore, 1983, p. 31-33) Thus, most of the tracts within the quadrangle would probably contain lower grade and tonnage fluorine-deficient deposits if they do contain a stockwork molybdenum-type deposit. In evaluating the potential for molybdenum deposits we combined all the molybdenum tracts because our data are insufficient to distinguish with certainty whether the tract might contain a Climax-type or fluorine-deficient stockwork molybdenum deposit. Considering the available information we believe there is a 50 percent chance that the quadrangle contains 1 or more undiscovered deposits and a 10 percent chance that it contains 2 or more undiscovered deposits.

VEIN DEPOSITS

The quadrangle contains several small tonnage polymetallic veins. Vein deposits can form in any terrane having extensive fracture, normal fault, or joint systems; those in the quadrangle occur in rocks of Tertiary age and older. Four types of vein systems have been identified in the quadrangle: gold-silver-bearing quartz veins, epithermal veins, vein-type iron deposits, and tungsten-bearing veins. A separate section will emphasize the characteristics of uranium mineralization in some quartz veins and vein-type iron deposits.

Gold-silver Quartz Vein Deposits

Regionally metamorphosed sedimentary terranes, perhaps best exemplified by the Mother Lode in California, commonly host low-sulfide quartz veins (Berger, 1983d). Gold, silver, copper, lead, zinc, molybdenum, and rarely vanadium and uranium may be concentrated in the quartz veins. The known quartz veins within the quadrangle, however, have a simple mineralogy and a consistently higher silver grade than is typical for low-sulfide quartz veins (Bliss, 1983) Thus, we are calling them gold-silver quartz veins. We believe that these veins formed in geologic environments similar to those in which typical low-sulfide quartz veins formed.

The presence of one or more characteristics outlined in the following criteria indicate areas permissive for gold-silver quartz vein deposits that occur at or near the surface (tracts Q1-Q7, pl. 2).

Strongly Favorable Criteria

1. Regionally metamorphosed sedimentary rocks (R.M. Tosdal, written commun., 1984; Berger, 1983d). Although other rocks could host gold-silver quartz veins, the known gold-silver quartz veins within the quadrangle occur in regionally metamorphosed rocks.
2. Secondary copper minerals in outcrops (R.M. Tosdal, written commun., 1984)
3. Banding and (or) brecciation in quartz veins (Boyle, 1979). Banding and brecciation is found in either gold-silver quartz veins or epithermal veins, but banding or brecciation without accompanying open space filling more likely indicates gold-silver quartz veins.
4. Areas of extensive fracturing, faulting, or jointing (Boyle, 1979)
5. Geochemical anomalies for silver, gold, arsenic (Berger, 1983d)

Weakly Favorable Criteria

6. Sericitic, pyritic, chloritic alteration (R.M. Tosdal, written commun., 1984). Sericitic alteration, the most prevalent type of alteration around gold-silver quartz veins in the quadrangle, forms weak to intense alteration envelopes (R.M. Tosdal, written commun., 1984).
7. Tertiary or ol*er rocks
8. Geochemical anomaly for Cu. A geochemical anomaly for copper without the presence of other criteria could indicate several deposit types, one of which is gold-silver quartz veins.
9. Proximity to known low-sulfide or gold-silver quartz veins

Description of Deposits

The quadrangle has three types of gold-silver quartz veins. One type consists of Late Cretaceous(?) to early Tertiary veins that are probably related to regional metamorphism in the eastern part of the quadrangle (Haxel and others, 1984; Tosdal, 1981). The second type is mesothermal veins that grade from pegmatites to quartz veins and are spatially, and perhaps genetically, related to Mesozoic plutons in the west and southwest parts of the quadrangle (tracts Q1-Q4, Q6-Q7, pl. 2). Gash and reef veins in Proterozoic Pinal Schist in the northeast corner of the quadrangle (tract Q5, pl. 2) comprise the third type; this type is of minor importance. All of these types of gold-silver quartz veins have simpler mineralogy than low-sulfide veins in other areas; the veins contain gold, chrysocolla, limonite, and sometimes malachite and pyrite. Most of the gangue consists of quartz, less abundant calcite, ankerite, and some white mica. Alteration adjacent to these veins ranges from absent to intense. Pyritic and (or) chloritic alteration locally accompanies the prevalent sericitic alteration. Chemical analyses of 6 selected vein samples showed concentrations of 1.1 to 1,900 ppm silver and 0.05 to 62 ppm gold (R.M. Tosdal, unpub. data, 1984). Reported gold and silver grades from mines in the quadrangle span a wide range (table 9). Reported gold grades for gold-silver quartz veins are fairly consistent with the available inverse cumulative grade curve for low-sulfide quartz veins; however, this is not so for silver grades (Bliss, 1983). All reported silver grades are higher than is typical for low-sulfide quartz veins. Also, silver is present in all of the gold-silver quartz veins in the quadrangle that have reported grade data, whereas the silver curve (Bliss, 1983) suggests that silver is normally present in only about 25 percent of low-sulfide quartz veins. Production from the mines in the quadrangle has been small (table 9). It falls below that of the production curve partly because the curve was constructed using deposits larger than 100 tonnes and because workings within 1 mi^2 were combined to define a deposit for the curves (Bliss, 1983). The gold grade and tonnage curves are reasonably approximate as long as the silver grade does not exceed 200 gm/tonne (J.D. Bliss, written commun., 1985), but the silver grade curve is inappropriate for use with gold-silver quartz veins in the quadrangle, based on the available information for these quartz veins.

Evaluation of Gold-silver Quartz Veins

Although gold-silver quartz vein deposits are widely distributed throughout the quadrangle, they are concentrated primarily in the southwest quarter and in the eastern part of the quadrangle. Seven tracts (Q1-Q7), all of which contain known gold-silver quartz veins, are the most likely places to

Table 9.--Reported gold and silver grades and tonnages of gold-silver quartz veins in the Ajo and Lukeville 1^{o} by 2^{o} quadrangles. Data from MRDS file
[NR, not reported]

Mine name	Gold grade (gm/tonne)	Silver grade (gm/tonne)	Tonnes of ore
Betty Lee	9.4	44	130
Brownell	NR	250	450
Cara Vaca	16	16	91
Cimarron	NR	130	1,000
Lilly	31	31	14
Lucky Strike	16	NR	14
Man's Dream	NR	NR	230
Monte Cristo	28	16	59
Oro Grande	110	250	4.5
St. Patrick	NR	31	660

discover new gold-silver quartz veins. Table 10 shows the relation between designated gold-silver quartz vein tracts and favorable criteria for finding such veins. The largest number of gold-silver quartz veins are concentrated in tracts Q1 and Q2 (pl. 2). Tracts Q3 through Q7 also contain minor deposits, although detailed descriptions are not always available for these deposits. Any undiscovered gold-silver quartz veins that exist in the designated tracts probably have small tonnages and variable grades like the known vein deposits, but could have tonnages comparable to those represented by the low-sulfide quartz vein tonnage curve (Bliss, 1983).

Epithermal Vein Deposits

Polymetallic epithermal vein deposits containing various combinations of Cu, Fe, Mn, Au, Ag, Mo, Pb, Zn, Ba, F, and W are present in the quadrangle. Areas satisfying the following criteria are permissive for near surface polymetallic epithermal vein deposits in the quadrangle (tracts V1-V8, pl. 2).

Strongly Favorable Criteria

1. Open-space filling textures in veins (Boyle, 1979, 1968)
2. A variety of sulfides and sulfosalts in veins (Buchanan, 1981; Boyle, 1979)
3. Distinct zoning of gangue and ore (Buchanan, 1981). Buchanan (1981) proposed that the zoning of ore and gangue minerals commonly seen in epithermal vein deposits resulted from boiling of the hydrothermal fluids that deposited the vein material. From top to bottom of the veins, the zoning is as follows: clay+agate, calcite, quartz+calcite, quartz+calcite+adularia+gold+silver, quartz+adularia+base metals. Every epithermal vein system need not have all of these zones.
4. Bleaching around and above veins (Buchanan, 1981)
5. Calc-alkaline extrusive rocks, mostly andesites (Buchanan, 1981)
6. Extensive fracturing, faulting, or jointing (Boyle, 1979)
7. Geochemical anomalies for Cu, Au, Ag, Pb, Zn, As, Sb, Hg (Berger, 1983b)

Weakly Favorable Criteria

8. Barite (Boyle, 1979, 1968). Barite is a common gangue mineral in epithermal vein deposits and in some deposits is sufficiently abundant to constitute ore.
9. Brecciation and (or) banding in veins (Boyle, 1979)
10. Tertiary or older rocks. Although epithermal mineralization may be of any age (Boyle, 1979), all the known epithermal vein deposits in the quadrangle are Tertiary (Tosdal, 1981).
11. Geochemical anomalies for iron, barium, fluorine, tungsten (Berger, 1983b; Boyle, 1979)
12. Nearby caldera structures (Buchanan, 1981)
13. Propylitic alteration extending hundreds of meters from veins. Also silicified, adularized, and albitized walls (Buchanan, 1981)
14. Proximity to known epithermal vein deposits

Description of Deposits

Epithermal veins are widely scattered throughout the quadrangle in Tertiary volcanic strata that range in composition from andesite to latite, but they are most abundant in the Cimarron Mountains, the Painted Rock

Table 10.--Relation of gold-silver-quartz-vein tracts (pl. 2) to criteria for evaluation of undiscovered gold-silver quartz veins in the Ajo and Lukeville 1° by 2° quadrangles
[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element]

	Tract						
	Q1	Q2	Q3	Q4	Q5	Q6	Q7
			Strongly favorable criteria				
Regionally metamorphosed sedimentary rocks	X	X	X	X	X	X	X
Secondary copper minerals	X	X	X	X		X	
Banding or brecciation in quartz veins	X	X	X				
Extensive fracturing, faulting, or jointing				X	X	X	
Ag, Au, As geochemical anomaly		Ag				Ag	
			Weakly favorable criteria				
Sericitic, pyritic chlorite alteration	Sericitic pyritic	Sericitic, chloritic, pyritic	Sericitic, pyritic	Sericitic		Chloritic sericitic	
Tertiary or older rocks	X	X	X	X	X	X	X
Cu geochemical anomaly				X			
Proximity to known deposits	X	X	X	X	X	X	X
Remarks	1						

REMARKS:
[1]This chart primarily documents conditions at known mines and prospects within the tracts, which provides a guide as to what might be expected elsewhere in the tracts

Mountains, and Gunsight Hills (tracts V1, V2, and V3, respectively, pl. 2) (Keith 1978, 1974; Wilson and others, 1934). Other known epithermal veins occur in tracts V4-V7. Most of these veins contain gold and (or) silver plus one or more base metals, which occur as sulfides or their oxidized derivatives. Gangue minerals include quartz, clays, iron oxides, calcite, chlorite, sericite, fluorite, and barite. The wallrock is weakly to intensely silicified, sericitized, and chloritized. Open-space filling characterizes all of these veins. Although adularia has not been identified in epithermal veins in the quadrangle, these veins more closely resemble those for the quartz-adularia model (Berger, 1983b) than those for the quartz-alunite model (Berger, 1983a).

At Ajo, several small veins in the Proterozoic Cardigan Gneiss, Tertiary Locomotive Fanglomerate, and Cretaceous Concentrator Volcanics (tract V7, pl. 2) consist of hematite, chrysocolla, copper oxides, and minor gangue of quartz, barite, epidote, and ankerite. These form a distinctive subset of the epithermal veins that occur within the quadrangle. Rare hematite-bearing veins in the southern Mohawk Mountains may be similar to those near Ajo.

Additionally, five barite prospects are known within the quadrangle: two near Quijotoa in the Papago Indian Reservation, one on the west side of the Mohawk Mountains, and two in the southern Painted Rock Mountains (Stewart and Pfister, 1960). In these prospects the barite occurs in coarse aggregates or massive veins in some places with fluorite, calcite, or metallic ore minerals.

Epithermal vein deposits are similar to the gold-silver quartz veins in the quadrangle in that gold and silver grades vary widely (figs. 9, 10) and production is usually small (fig. 11). The few copper and lead grades (table 11) reported (MRDS file data) are high (see grade curves in Mosier and Menzie, 1983a), probably due to the small size of the deposits. High grades due to small but rich pockets of ore average out in larger deposits.

Evaluation of Epithermal Vein Deposits

In the quadrangle the most likely setting for epithermal veins is in older rocks associated spatially with Tertiary volcanic and subvolcanic rocks. The lower sequence of the Tertiary volcanic field also contains epithermal veins in the Painted Rock Mountains (tract V2, pl. 2); other areas of the lower sequence are barren of epithermal veins based on field observations made during this study. We have designated eight tracts (V1-V8) as permissive for the discovery of new epithermal vein deposits. Table 12 shows how the known epithermal vein deposits in these tracts correlate with favorable criteria for epithermal vein deposits. Based primarily on geochemical data, tracts V2 and V8 may be particularly favorable for the discovery of new epithermal vein deposits. If the known deposits in the quadrangle are representative, any undiscovered deposits will also be small and variable in grade. However, larger tonnage deposits can not be ruled out.

Vein-type Iron Deposits

Iron-bearing veins are abundant in the Quijotoa Mountains area and one such vein is known farther north in the Copperosity Hills. A good deposit model for these iron-rich veins is unavailable.

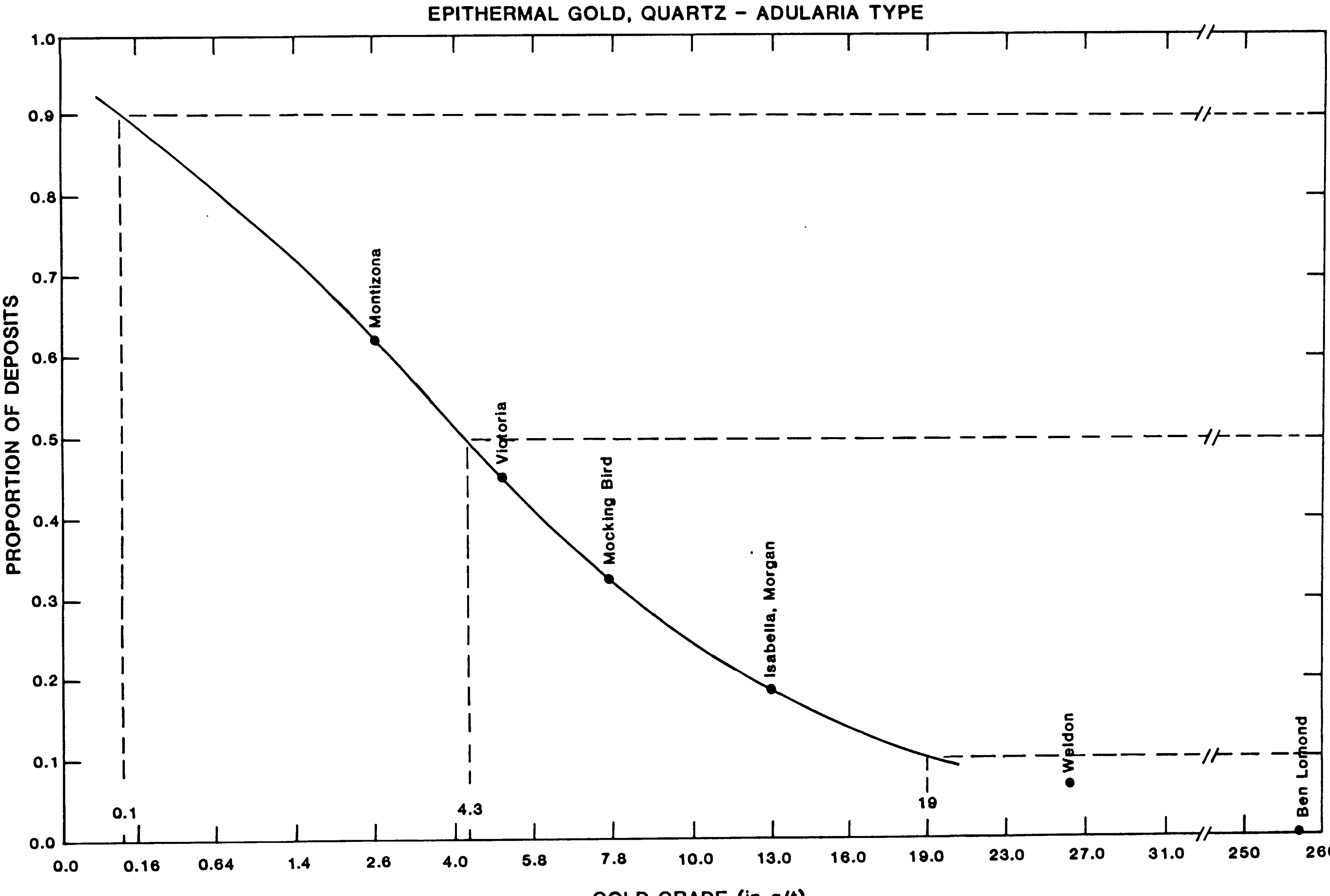

Figure 9. Inverse cumulative distribution of gold grade in epithermal vein deposits (modified from Mosier and Menzie, 1983a, p. 89) showing gold grades of deposits in the quadrangle (MRDS file). Gold grade is significantly correlated with tonnage and silver grade at 99 percent confidence.

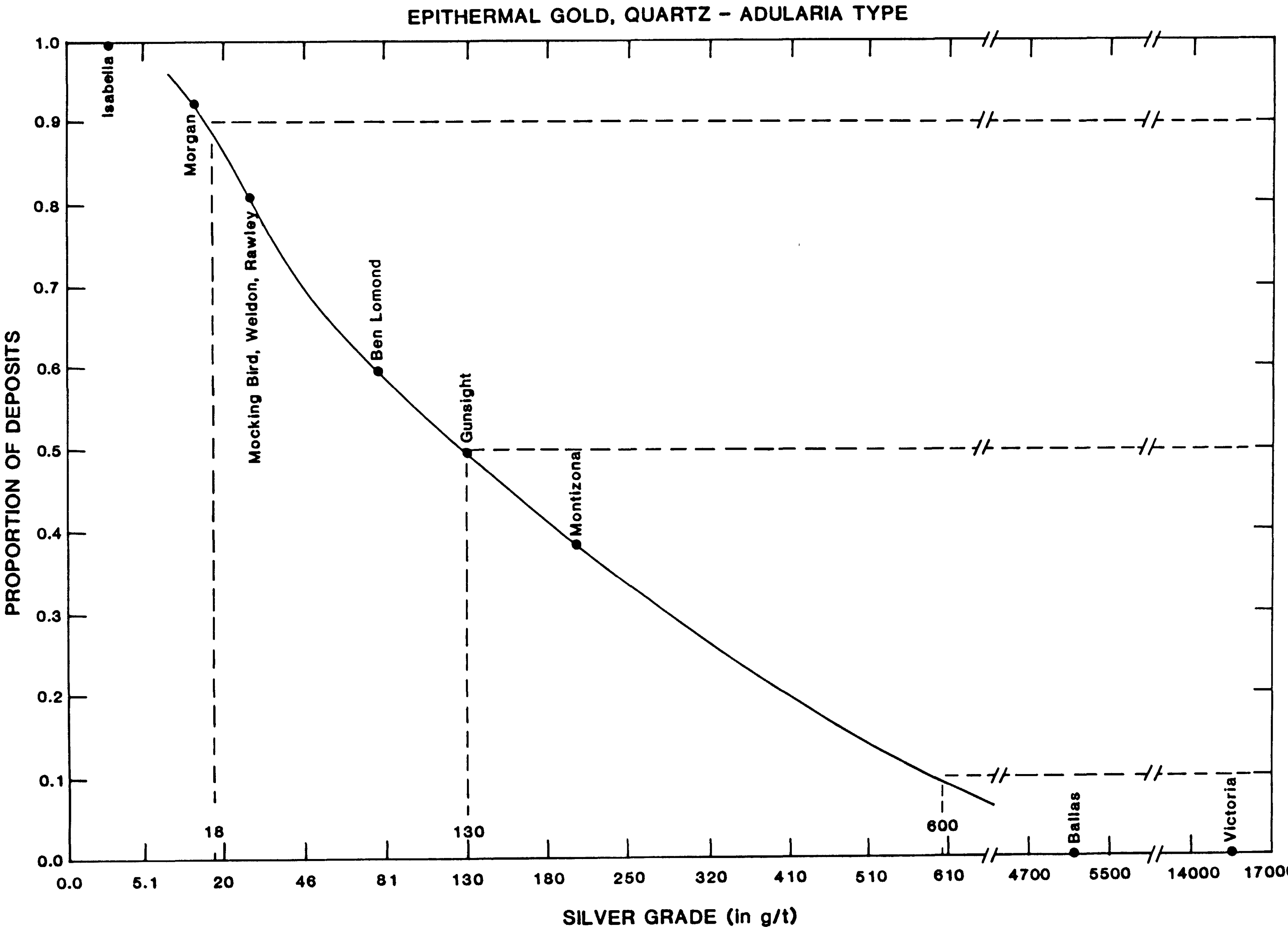

Figure 10. Inverse cumulative distribution of silver grade in epithermal vein deposits (modified from Mosier and Menzie, 1983a, p. 88) showing silver grade of deposits within the quadrangle (MRDS file).

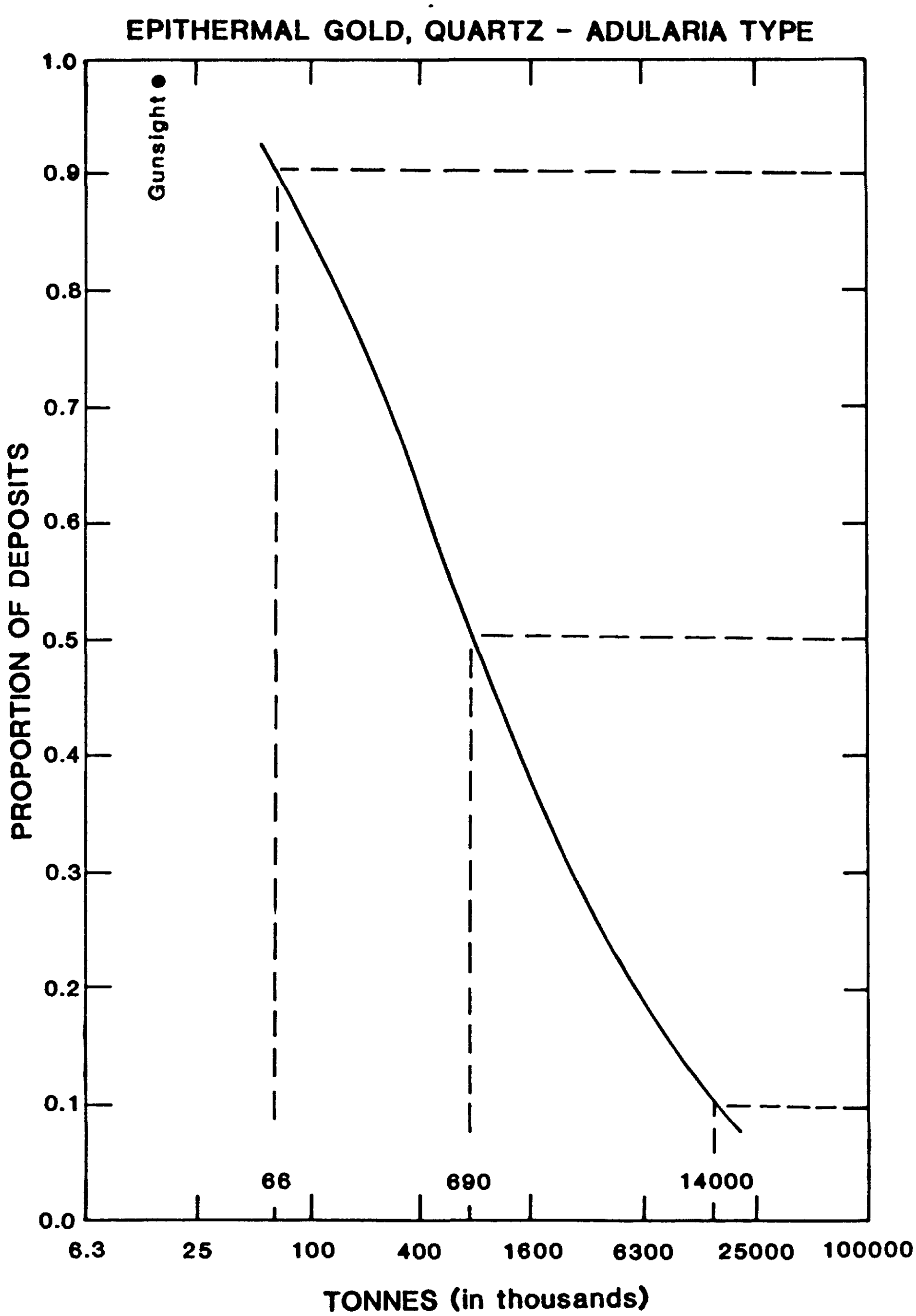

Figure 11. Inverse cumulative distribution of production tonnage in epithermal vein deposits (modified from Mosier and Menzie, 1983a, p. 84) showing production for the Gunsight Mine (MRDS file).

Table 11.--Reported copper and lead grades and tonnages of epithermal veins in the Ajo and Lukeville 1° by 2° quadrangles. Data from MRDS file.
[NR, not reported]

Mine name	Copper grade (percent)	Lead grade (percent)	Tonnes of ore
Ballas	1	8.5	91
Ben Lomond	NR	NR	270
Gunsight	NR	22	14,000
Isabella	NR	NR	18
Mocking Bird	NR	NR	410
Montizona	67	7	14
Morgan	NR	NR	540
Peer & Peerless	NR	NR	45
Pomona	NR	NR	0.9
Surprise	NR	NR	4.5
Victoria	4	58	45
Weldon	NR	NR	2,300

Table 12.—Relation of epithermal-vein tracts (pl. 2) to criteria for evaluation of undiscovered epithermal-vein deposits in the Ajo and Lukeville 1° by 2° quadrangles

[X's, indicate known presence of the criterion; element symbols indicate the presence of anomalous amounts of the given element; blackened boxes indicate data that are proprietary to the Papago Indian Tribe]

	Tract							
	V1	V2	V3	V4	V5	V6	V7	V8
				Strongly favorable criteria				
Open-space filling textures	X	X	X	X	X	X	X	X
Variety of sulfides and sulfosalts	X	X	X	X	X	X	X	X
Distinct zoning of gangue and ore		X						
Bleaching around and above veins					X			
Calc-alkaline extrusive rocks	X	X			X	X	X	
Extensive fracturing, faulting, jointing	X	X		X	X	X	X	
Cu, Au, Ag, Pb, Zn, As, Sb, Hg, geochemical anomaly	[redacted]	Cu, Ag, Au, Pb	[redacted]		Pb	Pb	Cu, Pb	Ag, Pb, Zn, Sb
				Weakly favorable criteria				
Barite		X		X				
Brecciation and (or) banding					X			
Tertiary or older rocks	X	X	X	X	X	X	X	X
Fe, Ba, F, W, geochemical anomaly	[redacted]		[redacted]		Ba	W	W	W
Nearby Caldera structure	Possibly							
Propylitic, silicic, adularia, albite alteration			Silicic, sericitic	Silicic, sericitic	Silicic			Sericitic
Proximity to known epithermal veins	X	X	X	X	X	X	X	X
Remarks	1						2	

REMARKS:

[1]This chart primarily documents conditions at known mines and prospects within the tracts, which provides a guide as to what might be expected elsewhere in the tracts.

[2]Copper geochemical anomalies are associated with the porphyry copper mineralization in the New Cornelia pluton rather than with vein mineralization.

Description of Deposits

Near Quijotoa (tract H1, pl. 2), iron prospects extend about 25 km from the Sierra Blanca Mountains south to Ben Nevis Mountain (Harrer, 1964). The largest of the prospects is as much as 90 m wide and can be traced intermittently for 5 km. There, individual iron veins vary between 1 and 9 m wide and extend down dip as much as 50 m. The iron mineralization consists of magnetite bands, which contain some hematite, ilmenite, and malachite (specularite breccia), in epidotized granitic rocks of probable Jurassic age (Gordon Haxel, written commun., 1985). Impurities in the ore include manganese, silica, phosphorous, sulfur, and titanium oxide (table 13). The magnetite bands alternate with silicate minerals. Abundant magnetite is found in the gold placers along the valley floors below the Quijotoa iron deposits.

Compared to vein-type iron deposits throughout the world, those in the quadrangle are very small. Production in the Quijotoa area was only 2,287 tonnes (Arizona MRDS file records), whereas some deposits (mostly in south America and Australia) have produced over a million tonnes and most produced more than 50,000 tonnes (D.L. Mosier, written commun., 1984).

Magnetic surveys, especially ground surveys, would be particularly useful in tracing shallow veins with high iron potential.

Evaluation of Vein-type Iron Deposits

We do not believe that any sizeable vein-type iron deposits will be found within the quadrangle. However, tracts H1 and H2 encompass the areas that contain known iron deposits, and tract H3 in the southern part of the Mohawk Mountains contains vein deposits of an unknown affinity that have magnetite and hematite. The latter deposits may be similar to the ones in tract H1 or to the epithermal deposits south of Ajo (see previous section).

Uranium-bearing vein deposits

The Basin and Range province of the western United States contains a significant number of productive uranium-bearing veins. Three uranium-bearing veins occur within the quadrangle and several others are known in Yuma and Pima Counties, Ariz., near the quadrangle (Finch, 1967). The criteria used in searching for uranium-bearing veins are similar to those used in searching for quartz or iron-bearing veins except that a radioactive anomaly should also be present. In addition, Mo, Be, W, V, Nb, and Zr may be useful geochemical indicator elements (Walker and Adams, 1963). A different type of uranium vein, currently known only from outside the quadrangle, occurs in the Dripping Spring Quartzite (Granger and Raup, 1959; Nutt, 1982).

Supergene alteration affects nearly all uranium-bearing veins to form zones of 6-valent uranium minerals outward from the primary 4-valent minerals (Walker, 1963b). This alteration is more important in quartz veins than in iron-bearing veins.

Discussion of Uranium-bearing Veins and Description of Deposits

Some quartz veins contain uranium minerals and minor amounts of metallic sulfides or iron oxides. The uranium minerals are either 4- or 6-valent compounds; autunite or metaautunite, torbernite or metatorbernite, uranophane, or sometimes pitchblende are the predominant uranium minerals (Walker and Osterwald, 1963), but locally, uranyl arsenates or vanadates may be present.

Table 13.--Analyses of iron ores from the Quijotoa area (Harrer, 1964)

Element or Compound	Range of Analytical Values (percent)
Fe	43.7 - 55.6
Mn	0.1 - 0.3
SiO_2	13.2 - 24.3
P	0.02 - 0.69
S	0.08 - 0.11
TiO_2	0.4 - 1.0

The veins contain siliceous gangue or no gangue at all. Most of these deposits are small (a few 10's or 100's of tonnes) and low grade (0.1 percent U). The McMillan prospect on the northwest flank of the Cabeza Prieta Mountains is such a deposit (Granger and Raup, 1962). The vein mineralization, which occurs in a 0.5 m wide (max.) fracture zone in biotite granite, is traceable for 65 m along a ridge crest where radioactivity is as much as five times background. The stockpile yielded 0.5 mr/hr and selected samples contained 0.034 percent uranium and 7.69 percent copper. Granger and Raup (1962) assessed the deposit as being a small local radioactive concentration that is below commercial grade.

Vein-type iron deposits locally contain stringers, veinlets, or pods of pitchblende and 6-valent uranium minerals (Walker and Osterwald, 1963). Most of these deposits are small (a few 100's to 1000's of tonnes) and low grade (a few hundredths of a percent uranium). The Linda Lee Claims (Walker, 1963a) and nearby Copper Squaw Mine in the Papago Indian Reservation near Quijotoa are of this type. At the Copper Squaw Mine uranophane and uraninite spatially associated with malachite, azurite, chalcocite, hematite, and limonite were removed from a 1-m-wide brecciated fault zone in altered Tertiary(?) andesite (Granger and Raup, 1962). Radioactivity in the stope is low but the stockpile contained 0.12 percent U_3O_8 and two chip samples from the ore body yielded 0.76 and 1.40 percent U_3O_8.

The Proterozoic Dripping Spring Quartzite, which crops out locally in the northeastern part of the quadrangle, hosts many uranium veins (Granger and Raup, 1959), most of which are in Gila County, Ariz., about 200 km northeast of the quadrangle. A recent study (Nutt, 1982) of the uranium mineralization in the Dripping Spring Quartzite indicates that primary diagenetic-sedimentary uranium concentrations were metamorphosed and altered. Previously, it had been thought that the deposits resulted from hydrothermal fluids that accompanied diabase intrusion (Granger and Raup, 1959). The upper member of the Dripping Spring Quartzite, host for the uranium mineralization, is a volcaniclastic sedimentary sequence that was deposited in a nearshore saline environment (Nutt, 1982). During diagenesis the uranium was released from the volcaniclastic sediments and transported to reducing zones where concentration and deposition occurred. Intrusion of the diabase remobilized the uranium into veins. In these veins, uraninite and coffinite are associated with minor base-metal-sulfide minerals, and secondary uranium phosphates and silicates are present. The deposits are commonly less than 1.5 m thick and less than 6 m wide but may be several hundred meters long parallel to joint sets.

Evaluation of Uranium-bearing Vein Deposits

Either the known or undiscovered quartz veins or iron-bearing veins in the quadrangle could contain minor amounts of uranium minerals. Uranium-bearing veins in the Dripping Spring Quartzite can occur only where there are exposures of Apache Group rocks, but because most of these veins occur many kilometers east of the quadrangle and because exposures of the Apache Group are limited, we do not expect this type of uranium vein in the quadrangle.

Tungsten-bearing Veins

Several small vein deposits with greisen-type alteration are located east of the Ajo quadrangle, and one area within the quadrangle that is not associated with a greisen assemblage contains scheelite. Although the United States is not a major producer of tungsten, these local occurrences warrant a discussion of this deposit type. Presence of the following criteria suggests areas permissive for the discovery of tungsten deposits at or near the surface (tracts W1-W8, pl. 1).

Strongly Favorable Criteria

1. Wolframite or scheelite in quartz veins (Bagby, 1983)
2. Wolframite or scheelite disseminated in two-mica granites (Bagby, 1983)
3. Geochemical anomalies for tungsten, arsenic, antimony (Bagby, 1983; Page and McAllister, 1944)
4. Greisen-like alteration (Bagby, 1983; Page and McAllister, 1944)
5. Mesozoic or younger two-mica granites (Bagby, 1983)
6. Metamorphosed country rock (Bagby, 1983; Page and McAllister, 1944). The parent pluton only rarely has quartz veins that contain tungsten minerals. Most of the veins occur in the country rock, whereas mineralization in the pluton is disseminated. Commonly the country rock has undergone regional metamorphism.

Weakly Favorable Criteria

7. Well developed joint system in metamorphic rocks (Page and McAllister, 1944)
8. Sericite-pyrite and calcite-pyrite alteration zones (Bagby, 1983). In some deposits, sericite-pyrite and calcite-pyrite alteration zones peripheral to the greisen assemblage indicate that a greisen is nearby.
9. Geochemical anomalies for beryllium, lead, zinc, copper (Bagby, 1983; Page and McAllister, 1944)
10. Intermediate to felsic calc-alkaline intrusive rocks. Tungsten mineralization and greisen assemblages most commonly are associated with two-mica granites, but rarely vein mineralization is found with other intermediate to felsic intrusive rocks, as at Gunsight Hills (see below).
11. Magnetic and gravity lows due to pyritic alteration and silicic nature of pluton

Description of Deposit

The known tungsten deposit within the Ajo quadrangle is located in the Gunsight Hills in the Papago Indian Reservation (tract W1, pl. 1), where one tonne of scheelite ore was produced by surface mining from a granitic pediment littered with quartz fragments. Shear zones 1 to 1.3 m wide contain lenticular, shattered, iron-stained, scheelite-bearing quartz veins (Wilson, 1941).

Sedimentary and volcanic rocks intruded by felsic to intermediate dikes host tungsten-bearing quartz veins in the Comobabi and Baboquivari Mountains, east of the quadrangle. These quartz veins contain wolframite, scheelite, and small amounts of barite and chalcopyrite. Wilson (1941) did not describe the alteration at these particular veins, but suggested in an introductory section that greisen and sericitic alteration occurred at most localities.

Evaluation of Tungsten-bearing Veins

Because the association of tungsten-bearing veins with either two-mica granites or hornblende-biotite granitoids permits large areas of the quadrangle to host such veins, criteria like geochemical data become important for focusing on particular areas. Most of the quadrangle's tungsten geochemical anomalies, however, are associated with Proterozoic granitic and metamorphic rocks, which probably indicates that these rocks have high background levels rather than mineralization. Also, plutons in the quadrangle apparently have not been altered to greisen assemblages. Nine areas (tracts W1-W9) are permissive for finding tungsten-bearing veins and table 14 shows how closely these tracts fit the favorable criteria. Grade and tonnage curves have not yet been developed for this deposit type. We believe that if other tungsten-bearing vein systems exist in the quadrangle, tonnages would be small like those that exist elsewhere in Arizona an the United States in general.

PEGMATITES

The Ajo quadrangle contains one productive pegmatite and numerous small unproductive pegmatites. Pegmatites are unusually coarse grained granitic to gabbroic rocks that are commonly spatially related to a pluton (Jahns, 1955). Simple pegmatites that contain quartz, feldspar, and mica are uniform from wall to wall, whereas complex pegmatites have two or more mineralogically and (or) texturally distinct zones and may be enriched in rare elements such as Ta, Nb, Be, Li, Mo, Sn, Ti, W, Cs, U, Ce, La, Th, and Y (Park and MacDiarmid, 1970; Jahns, 1955) that form complex, uncommon minerals which are locally of gem quality: topaz, garnet, spodumene, monazite, tourmaline, cassiterite, tantalite, columbite, beryl, and lepidolite, for example. In addition to supplying rare metals, pegmatites provide significant amounts of silica, feldspar, and mica. The following list outlines criteria used to delineate tracts (pl. 2) which are permissive for the discovery of near surface pegmatites in the quadrangle.

Strongly Favorable Criteria

1. Regionally metamorphosed terranes (Park and MacDiarmid, 1970; Cameron and others, 1954; Just, 1937)
2. Areas in metamorphic or igneous rocks that are unusually coarse grained (Jahns, 1955; Cameron and others, 1954)
3. Complex uncommon minerals (Park and MacDiarmid, 1970; Jahns, 1946; Just, 1937)
4. Geochemical anomalies for various rare elements (Park and MacDiarmid, 1970; Jahns, 1955)

Weakly Favorable Criteria

5. Nearby plutonic hypabyssal intrusives (Park and MacDiarmid, 1970; Jahns, 1946; Just, 1937). Most pegmatites form in regionally metamorphosed country rock rather than in the plutons that are the suspected source of the fluids. Pegmatites that do form in plutonic rocks are small.
6. Fracturing, faulting, brecciation, and other strongly developed linear features (Jahns, 1955; 1946; Cameron and others, 1954)
7. Metasomatic aureoles characterized by secondary foliation and a wide variety of minerals (Jahns, 1955, 1946). Not all pegmatites alter the country rock but, where present, alteration may indicate a nearby pegmatite. Minerals that develop in the alteration zones around some pegmatites include tourmaline, feldspar, apatite, beryl, biotite, muscovite, garnet, and others, depending upon the composition of the country rock (Jahns, 1955).

Table 14.—Relation of tungsten-bearing-vein tracts (pl. 1) to criteria for evaluation of undiscovered tungsten-bearing-vein deposits in the Ajo and Lukeville 1° by 2° quadrangles

[X's, known presence of the criterion; element symbols, presence of anomalous amounts of the given element; blackened boxes, data that are proprietary to the Papago Indian Tribe]

	Tract								
	W1	W2	W3	W4	W5	W6	W7	W8	W9
				Strongly favorable criteria					
Wolframite or scheelite in quartz veins	X								
Wolframite or scheelite disseminated in two-mica granites									
W, As, Sb geochemical anomalies	[redacted]	W, Sb	W	W		W	W	W	W
Greisen-like alteration									
Mesozoic or younger two-mica granites		X							
Regionally metamorphosed rocks	X	X	X	X	X	X		X	X
				Weakly favorable criteria					
Joint systems in metamorphic rocks									
Sericite-pyrite or calcite-pyrite alteration		X							
Be, Pb, Zn, Cu geochemical anomalies	[redacted]	Pb, Zn	Pb, Be	Be, Pb			Pb	Be, Pb	Be, Pb
Intermediate to felsic calc-alkaline intrusive rocks	X						X		
Magnetic or gravity lows			X		X				
Remarks		1	3		3		2		

REMARKS:

[1]This area may more likely have stockwork molybdenum mineralization with associated tungsten

[2]The tungsten geochemical anomaly in this tract may be skarn mineralization rather than vein mineralization

[3]Geophysical or geochemical data suggest a buried pluton

8. Mica impregnations in country rock (Jahns, 1946)

Description of Deposits

The Ajo quadrangle lies south of the main identified pegmatite region of Arizona, which is along the margin of the Colorado Plateau between Phoenix and Lake Mead (see Jahns, 1952). Pegmatites from that area have yielded feldspar, mica, beryl, tungsten, rare-earth elements, uranium, and lithium. In the Ajo quadrangle small pegmatites occur mainly in Jurassic and older granitic plutons, gneisses, and schists. Many of these pegmatites have locally abundant muscovite and biotite; others are spatially associated with small copper-bearing veins. At the San Antonio Mine (tract Pg1, pl. 2), the only productive pegmatite in the quadrangle, silica, feldspar, and scrap mica have been mined from pegmatitic dikes and irregular masses in the Proterozoic Chico Shuni Quartz Monzonite (Keith, 1974). Several tens of thousands of tonnes of silica flux have been shipped from this mine to the New Cornelia smelter. The pegmatite also contains a small amount of uranium. Unspecified rare-earth-element- and thorium-bearing minerals are present in the pegmatite at the Papago Mine in the Agua Dulce Mountains (tract Pg2, pl. 2), where gold-silver-copper veins transect the pegmatite (Keith, 1974). Pegmatites along the eastern flank of the central Mohawk Mountains (tract Pg3, pl. 2) vary from a few centimeters to 175 m wide and a few meters to nearly 1.5 km long (P.K. Theobald, written commun., 1984). These pegmatites locally contain large euhedral magnetite, euhedral but shattered tourmaline, and small allanite crystals. Geochemical anomalies around the pegmatites in the Mohawk Mountains include W, Sn, Bi, Y, La, Cu, Mo, and Pb.

Evaluation of Pegmatite Deposits

Known pegmatites within the quadrangle, both those containing rare elements and those composed mostly of quartz and feldspar, are located in the western half of the quadrangle in Proterozoic or inferred Proterozoic rocks that are near younger plutons. This suggests that the pegmatites are related genetically to the younger plutons. Based on this information, four tracts (Pg1- Pg4, pl. 2) are delineated for pegmatite deposits. Of these, tracts Pg1 and Pg2 contain known rare-element-bearing pegmatites. Possibly other small rare-element-bearing pegmatites exist in these tracts. Visual inspection of maps of the geochemical data (not included in this report) shows a clustering of anomalous niobium, lanthanum, and yttrium in tracts Pg2 and Pg3, which suggests a greater probability of discovering pegmatites in these tracts. Grade and tonnage data for pegmatites is not available but undiscovered pegmatites in the quadrangle are probably small and similar to those already known.

DISSEMINATED GOLD DEPOSITS

Gneiss-hosted Disseminated Gold Mineralization

A new type of disseminated gold deposit that is being found along the Colorado River in southeast California and southwest Arizona is receiving widespread attention. This type of deposit has informally been called a detachment fualt-type deposit (Wilkins, 1984a), although a strict genetic link has not been established in all cases. Two of these deposits are being mined. The Mesquite deposit, in the southern Chocolate Mountains in southeastern California, has ore reserves of 4 million tonnes at a gold grade of 1.96 gm/tonne. The nearby Picacho Mine has produced 544,000 tonnes of ore at an average grade of 7.8 gm/tonne gold and has projected reserves of 16 million tonnes at an average grade of 0.94 gm/tonne (Wilkins, 1984b; Harris and Van Nort, 1975a, b).

Possibly two types of deposits are included in this class of gold deposits. The first type are those that apparently can be related only to detachment faults and are hosted by mid-Tertiary volcanic rocks (Polovina, 1984; Cousins, 1984; Wilkins and Heidrick, 1982; Charlton and others, 1985). Gneisses host the second type. Deposits of this type include the Mesquite and Picacho deposits mentioned above and the Padre-Madre and Tumco properties in southeastern California (Henshaw, 1942; Morton, 1977; Harris and Van Nort, 1975a, b; Wilkins, 1984a). Because the gneiss hosted deposits have the largest reported reserves and (or) have had significant production, the following discussion deals only with these deposits. The discussion relies on unpublished field observations (R.M. Tosdal, written commun., 1984) and the little published information available.

Descriptive Model for Gneiss-hosted Disseminated Gold Deposits

This preliminary descriptive model is constructed largely from information about gold prospects and deposits in the Cargo Muchacho and Chocolate Mountains, southeast California.

The host gneisses are of both igneous and supracrustal derivation. In part, the orthogneisses are, metamorphosed equivalents of a Jurassic granitoid suite (Tosdal and others, 1985); other orthogneisses of uncertain Mesozoic or Proterozoic age may host some of the deposits (Picacho Mine in the Chocolate Mountains, for example). In the Cargo Muchacho Mountains, the pre-Middle Jurassic Tumco Formation, which hosts most, but not all, of the gold mineralization (Morton, 1977), is a metamorphosed supracrustal sequence similar to Early to Middle Jurassic silicic volcanic and volcaniclastic rocks and related hypabyssal porphyries (Tosdal and others, 1985). Thus, although there does not seem to be a unique protolith associated with this gold mineralization, the gold deposits are possibly associated with metamorphosed rocks of Jurassic age (Tosdal and others, 1985).

Two end-member deposit types comprise these gold deposits. The old Tumco Mine Group in the Cargo Muchacho Mountains, and the Picacho Mine in the Chocolate Mountains represent these end members. The Tumco Mine Group was developed along mesothermal veins in amphibolite facies gneiss (Dillon, 1976; Henshaw, 1942); the Picacho Mine is developed largely in intensely-brecciated, auriferous-pyrite-bearing amphibolite facies gneiss that has been flooded by limonite or hematite, clay, and carbonate minerals (Haxel, 1977; Harris and Van Nort, 1975a, b). Intermediate between these two extremes are the Padre-Madre prospect and the Mesquite deposits.

Ore minerals in the mesothermal veins are primarily free gold, but include auriferous pyrite, base-metal sulfides, and rarely scheelite (Morton, 1977; Henshaw, 1942). The dominant ore mineral in brecciated gneiss is assumed to be free gold, but minor amounts of auriferous pyrite are locally important (Harris and Van Nort, 1975a, b). Gangue rock and minerals include the gneiss, quartz, and fluorite in the mesothermal veins, and, quartz, calcite, chlorite, sericite, hematite, barite, and clay minerals in the brecciated gneiss. The wallrock adjacent to the mesothermal veins are not altered. The mineralized areas in brecciated gneiss have sericitic and chloritic alteration and clay and limonite flooding.

The mesothermal gold veins are associated with Mesozoic regional metamorphism (Dillon, 1976; Henshaw, 1942). Superposed intense mechanical brecciation, ferric alteration, and gold mineralization of uncertain origin or remobilization(?) at some deposits have been linked to mid-Tertiary regional extension and detachment faults (Wilkins, 1984a). Therefore, there are two or possibly more environments of gold mineralization.

Gneisses are the best exploration targets for this type of gold mineralization. The gneiss probably should have a Mesozoic protolith, although this criterion may not be necessary (Tosdal and others, 1985). Wilt and Keith (1984) argue that the deposits should be related spatially to early Tertiary peraluminous granite or to the regionally extensive Chocolate Mountains thrust (S.B. Keith, oral commun., 1985). Brecciated and altered gneiss should be examined closely. If the brecciation can be related to the mid-Tertiary detachment faults, then exposures of these faults and gneiss provide attractive exploration targets. Areas of known lode gold mining hosted by intensely brecciated rocks should also be examined.

Gold and perhaps base metals are the best geochemical indicator elements for gneiss-hosted gold deposits, but detailed geochemical data are not available.

Based on this discussion, evidence of the following criteria indicate possible areas in the quadrangle permissive for gneiss-hosted disseminated gold deposits.

Favorable Criteria

1. Gneiss of either igneous or supracrustal derivation (Tosdal and others, 1985; Morton, 1977; Dillon, 1976)
2. Geochemical anomaly for gold
3. Mesozoic regional metamorphism (Dillon, 1976; Henshaw, 1942)
4. Mid-Tertiary regional extension and associated low-angle normal faults (Tosdal and others, 1985)
5. Brecciated areas in gneiss (Haxel, 1977; Harris and Van Nort, 1975a, b)
6. Known gold-vein deposits (Dillon, 1976; Henshaw, 1942)
7. Mesozoic or Precambrian age of gneiss (R.M. Tosdal, written commun., 1984)
8. Veins having auriferous pyrite, base-metal sulfides, and scheelite (Morton, 1977; Harris and Van Nort, 1975a, b; Henshaw, 1942)
9. Either no alteration; or sericitic and chloritic alteration and (or) clay and limonite flooding (R.M. Tosdal, written commun., 1984)
10. Geochemical anomaly for base metals

Evaluation of Gneiss-hosted Gold Deposits

Evaluation of the potential for gneiss-hosted gold prospects in the Ajo quadrangle is, at best, tenuous. Extensively brecciated gneiss occurs in the northern Mohawk Mountains (J6, pl. 2) and Copper Mountains (J3, pl. 2). The brecciated rocks in the northern Mohawk Mountains contain some epithermal base-metal and barite veins that have been mined. These areas should be evaluated further.

Although regional metamorphism affected Jurassic and Proterozoic rocks exposed in the Quitobaquito Hills-Puerto Blanco Mountains (J5, pl. 2) and Quijotoa Mountains (J1, pl. 2), neither of these areas contain extensive tracts of intensively brecciated rocks. Both areas have been mined for precious- and base-metal veins, and disseminated gold could occur in halos that surround these veins.

Northwest of the quadrangle in the Castle Dome Mountains, numerous epithermal base- and precious-metal veins are exposed widely in mid-Mesozoic, weakly metamorphosed, clastic rocks that are part of a terrane extensively cut by low-angle normal faults. Whether this terrane can be extended into the quadrangle (J2, pl. 2) is unknown. Other exposures of detachment faults, such as in the Mohawk Mountains, should be evaluated for gneiss-hosted gold mineralization. Tracts J4, J7, and J8 (pl. 2) contain regionally metamorphosed rock that are permissible as suitable host rocks for these deposits.

Volcanic Hosted Disseminated Gold-silver Deposits

At several localities throughout the western United States Tertiary volcanic rocks contain low-grade disseminated gold and silver mineralization (Berger, 1983c). The ore bodies typically form large, irregular vein, stockwork, or breccia zones in rhyolitic volcanic centers and rhyolite domes. Alteration includes intense silicic alteration, development of adularia, and chloritic alteration which gives the rocks a bleached appearance (Berger, 1983c; Worthington, 1981). Environments permissive for such deposits occur in the quadrangle. We used the following criteria to indicate permissive areas for volcanic hosted disseminated gold-silver deposits.

Strongly Favorable Criteria

1. Rhyolitic volcanic centers and domes (Berger, 1983c; Worthington, 1981). Disseminated silver deposits may also be hosted by other siliceous volcanic rocks and intercalated sedimentary rocks (Graybeal, 1981). This is attributed to differences in the chemistry of the ore fluids, particularly oxygen and sulfur fugacities, and how these fluids react with wall rock.
2. Throughgoing fracture systems and brecciation (Worthington, 1981)
3. Geochemical anomalies for silver, antimony, arsenic, gold (P.K. Theobald, written commun., 1984)
4. Tertiary volcanic terrane (Worthington, 1981)
5. Sulfide, selenide, and telluride minerals (Berger, 1983c). Sulfide minerals include pyrite, stibnite, realgar, arsenoyrite, sphalerite, and chalcopyrite. Additionally, fluorite gangue may be present (Berger, 1983c). A single deposit would most likely not contain all of these minerals.

Weakly Favorable Criteria

6. Silicic and chloritic alteration, development of adularia, alunite, jarosite, hematite, or goethite (Berger, 1983c; Worthington, 1981)
7. Banded quartz veins, stockworks, and breccia pipes (Berger, 1983c)
8. Geochemical anomalies for Hg, Te, Tl, base metals, W (P.K. Theobald, written commun., 1984)
9. Gravity and magnetic lows resulting from high silica and low magentite content of host rocks
10. Quaternary volcanic terrane (Worthington, 1981)

Evaluation of Volcanic-hosted Gold-silver Deposits

Even though silicic volcanic sequences are common within the quadrangle, assessing their potential for disseminated gold mineralization is difficult because rock geochemical data for gold are lacking and because gold was not detected at 10 ppm in any stream-sediment samples or at 20 ppm in heavy nonmagnetic concentrates. Silicified rhyolite vent areas occur near Hat Mountain and elsewhere in the Sauceda Mountains (tract A1, pl. 2), in the northern part of the Ajo Range, in the southern part of the Growler Mountains, in the Aguila Mountains (tract A2, pl. 2), and in the southern part of the Sand Tank Mountains. However, the volcanic sequences in the quadrangle are flow dominated and anhydrous, whereas systems that form volcanic-hosted gold deposits typically contain hydrated silica minerals. The likelihood of such deposits occurring in the quadrangle is, hence, low. Of the identified vent complexes, those in the Sauceda Mountains and in the Aguila Mountains are more favorable because the vent complexes are larger and because geochemically anomalous tin, manganese, and lead (Barton and others, 1982) suggest that mineralization may have occurred in the area.

RHYOLITE-HOSTED TIN DEPOSITS

Low-grade, low-tonnage, rhyolite-hosted tin deposits occur in Mexico and New Mexico (Huspeni and others, 1984; Foshag and Fries, 1942; Fries, 1940). Tin geochemical anomalies from similar volcanic terranes within the Ajo quadrangle indicate that the rocks are permissive for such deposits. The following criteria for finding tin deposits are based on Mexican and New Mexican examples and were used to delineate areas permissible for this type of deposit.

Strongly Favorable Criteria

1. Metaluminous to slightly peraluminous rhyolite or latite (Huspeni and others, 1984). The host rhyolites in Mexico are commonly capped by ignimbrite that is more porphyritic than the host rock. Chemical data from the Mexican rhyolites suggest that they are differentiates of high-level magma chambers and possibly are related to caldera development (Huspeni and others, 1984). Some of these rhyolites contain topaz. Topaz was not found in rhyolites from the Ajo quadrangle, nor do cap rocks cover the silicic volcanic centers.
2. Proximity to eruptive centers (Huspeni and others, 1984)
3. Geochemical anomaly for tin (greater than or equal to 1,000 ppm in heavy-mineral concentrates)
4. Placer cassiterite

Weakly Favorable Criteria

5. Specularite as crusts on cavity walls (Huspeni and others, 1984). The cassiterite and specularite are usually intermixed (Huspeni and others, 1984; Smith and others, 1950).
6. Silica, zeolites, fluorite, or clay minerals (particularly smectite) (Huspeni and others, 1984)
7. Latite, andesite, volcanic breccia related to rhyolite (Huspeni and others, 1984)
8. Minor faults with little or no displacement (Huspeni and others, 1984)

9. Geochemical anomalies for Cu, Pb, Zn, Sb, Be, As (Huspeni and others, 1984; Grushkin and Vedernikov, 1978). Small amounts of these elements can occur in geochemical samples despite the apparent lack of sulfide minerals.
10. Low gravity and concentrically located aeromagnetic anomalies signifying major eruptive centers.

Evaluation of Rhyolite-hosted Tin Deposits

No tin prospects are known in the quadrangle, but nonmagnetic heavy-mineral concentrates from two areas contain visible cassiterite and yielded tin concentrations of greater than or equal to 500 ppm. These areas are the northern Sauceda Mountains (tract Sn1, pl. 2) and in the Crater Range (tract Sn2, pl. 2), where the most likely tin sources are rhyolite and Childs Latite, respectively. The only detected tin in stream-sediment samples (10 and 20 ppm) came from two samples in the Sauceda Mountains.

Because rhyolite-hosted tin deposits typically occur near eruptive centers, plate 2 shows the major eruptive centers in the quadrangle. A major eruptive center in the Sauceda Mountains that correlates with observed high tin concentrations is the most favorable area within the quadrangle to search for rhyolite-hosted tin deposits. This area is also marked by a significant gravity low over bedrock. Although tract Sn2 contains no eruptive centers, samples collected from the area have elevated tin concentrations and the area lies on the southeast flank of a gravity low. In a third tract south of Ajo (Sn3, pl. 2) three samples with anomalous tin concentrations correspond to a small rhyolite eruptive center. Geophysically, a gravity high that borders the east edge of a relative low over exposed bedrock characterizes this tract. Aeromagnetic data for all tracts do not fit the geophysical concept of an eruptive feature presented above, but actual geologic conditions can easily distort the idealized data presented in a model.

Unpublished grade-tonnage curves for rhyolite-hosted tin deposits based on 132 deposits in Mexico indicate that the median size and grade of these deposits is about 1,000 tonnes at 0.4 percent tin (D.A. Singer, written commun., 1985). Sizes of these deposits range from about 100 tonnes to about 10,000 tonnes and tin grades range from about 0.05 percent to about 3 percent. Therefore, if any rhyolite-hosted tin deposits are found in the quadrangle, they will probably be extremely small, low grade, and of questionable economic value.

MANGANESE REPLACEMENT DEPOSITS

Limestone and the breccia matrix of fracture zones in intrusive or young volcanic rocks host manganese replacement deposits within the quadrangle. The following criteria are important in delineating tracts permissive for the discovery of manganese replacement deposits at and near the surface.

Strongly Favorable Criteria

1. Carbonate rock (Mosier, 1983a; Farnham, 1961)
2. Abundant manganese oxide minerals (Mosier, 1983a; Farnham, 1961)
3. Fracture systems in potential host rock (Farnham, 1961)
4. Geochemical anomalies for manganese. Manganese geochemical anomalies indicate, in some places, nearby hydrothermal systems that contain stockwork molybdenum or copper porphyry mineralization as well as manganese replacement mineralization. Therefore, a manganese geochemical

anomaly alone does not necessarily suggest a manganese replacement deposit.

Weakly Favorable Criteria

5. Brecciated volcanic rocks (Farnham, 1961). Manganese deposits in both limestone and volcanic rocks commonly form as veinlets and stringers because they replace the host rocks along fractures. Nevertheless, they are considered to be replacement deposits. Major replacement deposits occur in sandstone near Artillery Peak in Mohave County, Ariz. Such deposits are not known in the quadrangle, because exposures of sandstone are limited.
6. Nearby intrusive complexes (Mosier, 1983a; Farnham, 1961)
7. Manganese carbonate minerals (Farnham, 1961)
8. Nearby skarn and replacement deposits
9. Lead-zinc mineralization or iron oxides (Farnham, 1961). Lead-zinc or iron-oxide minerals (magnetite or hematite) are commonly found in manganese replacement deposits in New Mexico (Farnham, 1961). Although known deposits in the quadrangle do not contain these minerals, undiscovered deposits could.

Description of Deposits

Cavity fillings, veins, and chemical replacement of the wallrock where the mineralizing fluids have spread away from fractures characterizes manganese replacement deposits in the quadrangle. Their simple mineralogy consists of manganese-oxide minerals, calcite, and, locally, hematite. Although Devonian to Tertiary rocks host the replacement deposits, the mineralization probably took place in the Tertiary (MRDS file data).

Four areas in the quadrangle contain manganese replacement deposits. Paleozoic carbonate rocks in the eastern foothills of the Cimarron Mountains in the Papago Reservation (area R1, pl. 2) hosts the largest deposits. There, several manganese claims are located in an area 600 by 300 m (Farnham and others, 1961). Bedding plane fractures contain most of the ore, but some mineralization extends into the limestone along cross fractures. In both marble and limestone, the manganese formed hard crystalline oxides and soft wad-like material that is mixed with abundant hematite locally. Gangue consists of the host rock and minor quantities of crystalline quartz. Approximately 14,300 tonnes of ore averaging 36 percent manganese was shipped from the area from World War I to the mid 1950's (figs. 12, 13). When combined, these deposits are smaller than about 55 percent of all manganese replacement deposits and are of median grade. Some of the world's low tonnage deposits contain small amounts of copper or phosphorus (Mosier, 1983b); the known deposits in the quadranlge are not reported to contain either.

The other known manganese deposits in the quadrangle (tracts R2-R3, pl. 2) are small replacements of breccia by manganese oxides and minor calcite (Farnham and others, 1961; Jones and Ransome, 1920). Two of these deposits yielded 34 and 109 tonnes of manganese ore at 15 to 20 percent manganese.

Evaluation of Manganese Replacement Deposits

The largest manganese replacement deposits in the quadrangle are hosted by carbonate rocks; small deposits occur in highly fractured volcanic or plutonic rocks. Areas containing manganese deposits are designated tracts R1-

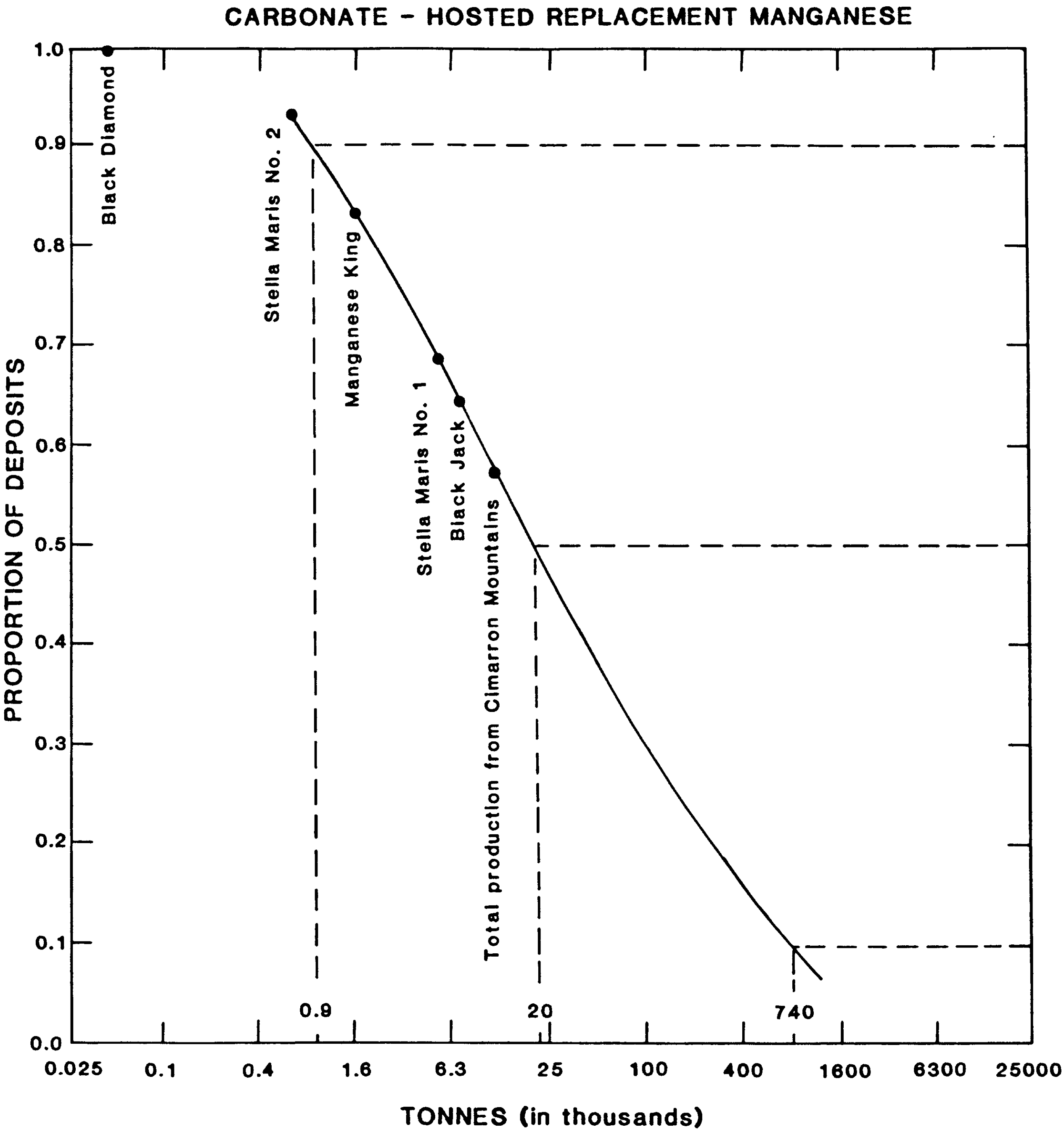

Figure 12. Inverse cumulative distribution of production in manganese replacement deposits (modified from Mosier, 1983b, p. 69) showing total production and production for individual claims in the Cimarron Mountains (MRDS file).

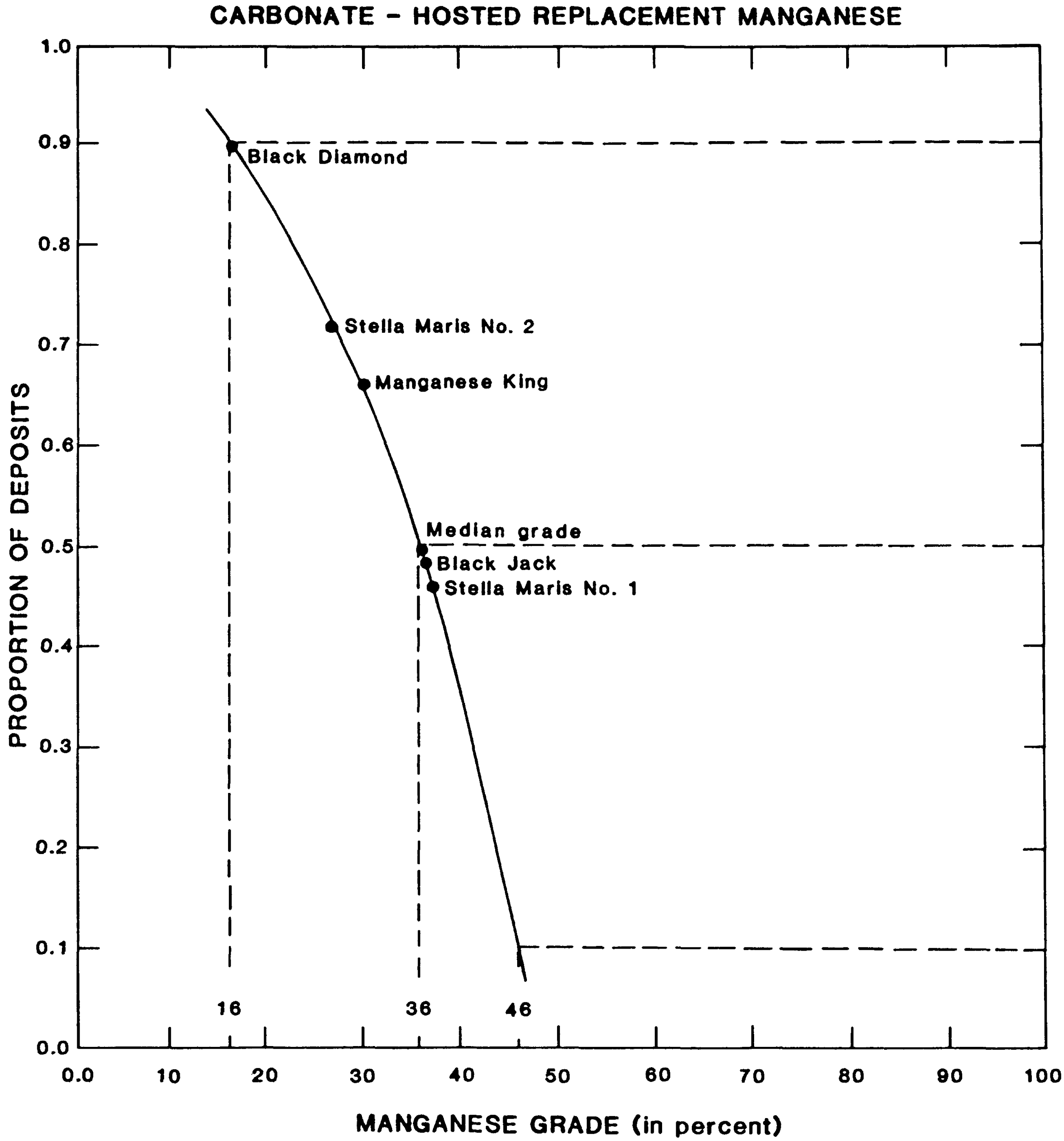

Figure 13. Inverse cumulative distribution of manganese grade in manganese replacement deposits (modified from Mosier, 1983b, p. 71) showing manganese grade of individual claims and approximate median grade for combined deposits in the Cimarron Mountains (MRDS file).

R3 on plate 2. We believe that any undiscovered manganese areas would most likely be near known deposits or in other limestone areas. Stream-sediment geochemical data indicate, however, that most of the high manganese concentrations correspond to exposed Tertiary volcanic rocks in the Sauceda, Painted Rock, and Sand Tank Mountains and in Proterozoic granitic rocks in the northeast corner of the quadrangle. These manganese anomalies probably reflect accumulation of manganese minerals in gold-silver quartz and (or) epithermal veins in those rocks. Although limestone (see pl. 2) provides the best target for manganese replacement deposits, there is no direct evidence that limestone outside of the Cimarron Mountains hosts manganese deposits. Two rock analyses from Lime Hill yielded low manganese values (table 4) and visual examination of other limestone areas does not suggest replacement deposits. If undiscovered deposits do occur in the quadrangle, we expect that they will be of low to medium grade and small to moderate tonnage as are the known deposits, because of the small and limited exposures of limestone and the lack of visual indications of manganese mineralization outside of the Cimarron Mountains Of the designated tracts, R1 in the Cimarron Mountains is the most favorable because of the known replacement bodies there. Limestone to the north in the Vekol Mountains is also favorable for replacement mineralization.

PLACER GOLD

Placer gold deposits form by a combination of mechanical and chemical processes. There are two types of placer deposits: eluvial deposits which occur above lode deposits and involve little transport and alluvial deposits which require transportation by water, usually a stream (Boyle, 1979). Ideally, to form alluvial deposits, gold is transported downstream from its source area and is concentrated where the stream has low gradients. The Basin and Range province provides this ideal topographic setting. Gold sources include auriferous quartz veins, porphyry copper deposits, auriferous polymetallic-sulfide deposits, auriferous conglomerates or quartzites, and old placers formed during an earlier erosion cycle. Typically, gold placer particles, which mostly are less than 2 mm long, collect near the bedrock or on a clay layer, compacted sands, or limonite-cemented sediments. In areas having a suitable source terrane, other heavy minerals may be concentrated with the gold.

The best indicator of placer gold deposits is the gold itself even though a whole suite of elements might be present. Placer deposits can be mined if they contain as little as 0.2 ppm gold (Boyle, 1979). Grade and contained metal data for 32 desert placer deposits in the western United States indicate that such plaers have a median grade of 0.96 gm/m^3 gold and a median of 55,000 gm gold. Table 15 shows the ranges in contained metal, size, and grade for desert placers. There is a highly significant inverse correlation between grade and volume of deposits (J.D. Bliss, oral commun., 1985). Arizona's known placer deposits are well represented by this data (Orris and Bliss, 1985).

Description of Deposits

Placer gold deposits are widely distributed throughout the Basin and Range part of Arizona. Three, or possibly four, placer areas have been prospected in the Ajo quadrangle. Of these placer areas the largest is the Quijotoa district (area P1, pl. 3) in the Papago Indian Reservation which had

Table 15.--Contained gold, volume, and grade data for desert placer deposits in the southwestern United States (J.D. Bliss, oral commun., 1985, based on data in Orris and Bliss, 1985).

	90 percentile	50 percentile	10 percentile
Contained gold	3,100 gm	55,000 gm	4,500,000 gm
Volume	2,300 m^3	76,000 m^3	17,000,000 m^3
Gold grade	0.28 gm/m^3	0.97 gm/m^3	2.8 gm/m^3

an estimated production of 425,000 gm of gold (Johnson, 1972; Wilson, 1961). This amount or greater production is typical for the largest 20 percent of placer gold deposits in desert regions. The placer gold occurrences extend southward into Mexico, but most of the gold was recovered near the old town of Quijotoa. Individuals have worked these placers on a small scale using drywash techniques since 1774. The gold was recovered from surface gravels and caliche-cemented gravels that averaged better than $1.05/m^3 at gold prices of $35/oz, or less (Wilson, 1961). This grade is nearly identical to the median for desert placers.

The Ajo placer district (area P2, pl. 3) produced an estimated 680 gm of gold from the Cornelia Arroyo during the early 1930's when the copper mine was closed. There has been no subsequent placering activity. The gold probably came from the oxidized portions of the copper ore body, where gold runs about 0.19 gm of gold per unit of copper (Johnson, 1972; Gilluly, 1946).

Thirty grams of gold were reportedly recovered near Mohawk in 1940 (Johnson, 1972), but its source is not known. It possibly came from the western flanks of the Mohawk Mountains (not delineated on pl. 3).

Several placer claims have been filed for property near the southern end of the Growler Valley (area P3, pl. 3) (Miller, 1979), but nothing is known about their production, if any. They are located in washes draining a pediment surface that contains small outcrops of granitic rocks which are cut by apparently barren quartz veins. Remote-sensing data shows a limonite anomaly 2 km southeast of the placer claims.

Evaluation of Placer Gold Deposits

Plate 3 outlines four tracts (P1-P4) for placer deposits. These include the three known placer areas plus an area northeast of the Agua Dulce Mountains which lies adjacent to rocks that are similar to those in the Quijotoa Mountains and that contain abundant gold-silver quartz veins. Most stream-sediment samples for this study were collected at the base of the mountain ranges, where a significant amount of any transported gold should be concentrated. Panned-concentrate samples, however, contained no detectable gold either by microscopic examination of the sample or by spectrographic analysis for gold at a detection limit of 20 ppm (P.K. Theobald, written commun., 1984). This suggests that the Ajo quadrangle lacks undiscovered placer deposits at the surface. Buried placers, if present, would likely have volumes and grades similar to other desert placers in the western United States.

BASIN-HOSTED DEPOSITS

During this CUSMAP program, an evaluation of the geology or geochemistry of the basins was not attempted because of fiscal restraints. Nevertheless, some mineral deposits may occur in basin environments, particularly evaporite and uranium deposits. The sections that follow present short descriptive models of these deposits and a discussion of the potential for finding such deposits within the quadrangle.

Continental Evaporites

Continental evaporites form in enclosed, structurally controlled basins, where water accumulates and evaporates for an extended timespan. The original water composition and complex equilibrium conditions in the brine as evaporation progresses determine whether or not an evaporite deposit forms under such conditions (Hardie and Eugster, 1970). A wide variety of sodium, potassium, boron, strontium, and calcium minerals may comprise an evaporite, but halite, gypsum (commonly dehydrated to anhydrite), and sylvite or carnallite are the most common minerals. Evaporite sequences vary in thickness and typically are interbedded with clastic material.

Numerous evaporite sequences exist in the Basin and Range province, which provides an ideal structural and climatological environment for evaporite formation. In Arizona, three thick evaporites were discovered during drilling for water. The Red Lake evaporite in Mohave County and the Luke evaporite in Maricopa County contain halite with anhydrite caps, whereas the Picacho evaporite in Pinal County is primarily anhydrite (Pierce, 1981, 1974). These three evaporites are probably late Tertiary and may have formed in a complex system of interconnected, rapidly subsiding basins. Thus, Tertiary lake beds that contain evaporites may be widespread throughout the Basin and Range portion Arizona. Two other evaporite sequences are suspected: one southeast of Phoenix near the northeast corner of the Ajo quadrangle and the other in the Safford Basin in eastern Arizona (Pierce, 1981). Detailed mineralogic information about Arizona's evaporites is unavailable, but halite in the Red Lake evaporite is usually coarsely crystalline.

All three known deposits have similar stratigraphic and structural relations. Most of the evaporite-bearing basins are filled by fine-grained continental claystone and sandstone, diatomite, marl, limestone, and gypsum which rapidly grade laterally into conglomeratic facies which include fanglomerates at the basin margin. Sedimentary rocks in many of Arizona's basins can be divided into two main units separated by a major unconformity which represents subsidence, block faulting, and erosion that occurred about 12 m.y. ago (see Eberly and Stanley, 1978). The lower unit is Eocene to Late Miocene. The evaporites formed in the lower part of the upper unit, above the unconformity. They are as thick as 2,000 m and their tops are several hundred meters below the surface. At least part of the Luke salt body forms a dome (compare Pierce, 1974 and Eaton and others, 1972). The Luke and Picacho evaporites and other small occurrences occupy a broad, northwest-trending structurally low area termed the Gila Low, which covers the extreme northeastern corner of the Ajo quadrangle including basin E4 on plate 3.

Extreme gravity lows may aid in the search for evaporite deposits within the basins. Basins typically have gravity lows but a large, low specific-gravity salt body exaggerates this geophysical signature.

Description of Evaporite Areas

A small celestite deposit containing minor strontianite and gypsum (Moore, 1935) that occurs north of the Sauceda Mountains formed as an evaporite (basin E10, pl. 3). The celestite is interbedded with steeply east-dipping Tertiary tuffaceous rocks that are unconformably overlain by basalt. Rocks adjacent to the celestite have been silicified. An estimated 8,100 tonnes of celestite are present at the deposit (Moore, 1935), but, if the celestite extends laterally into the basin to the north or east, this estimate is low.

A minor gypsum bed occurs in the Daniel's Conglomerate in the Growler Mountains.

Evaluation of Evaporite Deposits

Chemical analyses of water from warm-water wells within the quadrangle show a range in sodium concentrations between 33 and 2,320 mg/1 and in chloride concentrations between 0.7 and 2,504.4 mg/1 (Hollett, 1983; Swanberg and others, 1977). Water having a sum of the constituents greater than 1,000 ppm is considered saline (Krieger and others, 1957). Although this suggests that some ground water within the basins is in contact with saline deposits, groundwater of closed basins in arid regions can have high values of Na^+ and Cl^- due to normal cycling of groundwater through the alluvium (Krieger and others, 1957). However, analyses from areas where the water is known to be in contact with saline deposits are similar to the higher analytical values determined for water from the quadrangle (Hood and others, 1960; Hem, 1950).

Tracts for eleven basins with residual gravity values below zero mgals (El-E11, pl. 3) are delineated in the quadrangle as being permissive for evaporite deposits. The high-pass filtering technique used to construct the residual gravity data make it likely that gravity values of zero mgal approximate the edge of the pediment surface except in areas where there are extensive low-density volcanic rock (D.P. Klein, oral commun., 1983). Oppenheimer and Sumner (1981) estimated the depths to bedrock within Arizona's basins using gravity profiles and well-depth data. They estimated the depth of most if the delineated basins as 1,700 m or deeper; basins El and E2 may be close to 3,000 m deep. Basin E9 is probably less than 500 m deep. If any of the basins do contain evaporite deposits these estimated depths would be greater than the actual depths. Deep basins are more likely to contain evaporites than shallow ones (Eberly and Stanley, 1978). Of the eleven delineated basins, five are favored more by the gravity data. The southern half of basin E2 has gravity values of -24 mgals, the lowest in the quadrangle, which could imply either a very deep structural basin or an evaporite sequence. Oppenhiemer and Sumner (1981) showed this as a fairly deep basin that may be close to 3,000 m deep in the northwest part and 2,700 m deep in the southern part. Basins E4 and E8 both have gravity values of -20 mgals and E8 is probably deep (Oppenheimer and Sumner, 1981). Additionally, basin E4 lies within the Gila Low, as mentioned above, an area of known evaporite sequences. Two other basins, E5 and E7, show less pronounced gravity lows and are only moderately deep (Oppenheimer and Sumner, 1981) but are also permissive for evaporite sequences. The known celestite deposit in basin E10 lies at the edge of the pediment surface and may extend into an evaporite sequence at depth, particularly to the north where the basin is moderately deep.

Well logs from numerous shallow water wells (about 300 m maximum depth) drilled within the Papago Indian Reservation do not indicate evaporite minerals (Heindl and Cosner, 1961; Hollett, 1981; Hollett and Garrett, 1984); however, the large evaporites elsewhere is Arizona begin below the depth of these wells. Evaporites associated with lake-bed clay may exist in basin E11 because two water samples collected near the Mexican border yielded high sodium and chlorine values (Hollett, 1983).

We believe the available gravity data and information from the literature allow us to make a probabilistic estimate of the number of undiscovered evaporite deposits in the quadrangle. We think that there is a 50 percent chance that there are 1 or more undiscovered deposits and a 10 percent chance that there are 2 or more undiscovered deposits within the quadrangle.

No deep drilling has occurred anywhere in the quadrangle, thus the evaporite potential can not be further evaluated. Because large evaporite deposits should be highly resistive bodies, deep electrical sounding is recommended prior to drilling if this potential is to be evaluated further.

Uranium Occurrences in Basins

Davis and Hetland (1956), Bell (1956), and Carlisle (1978) summarized potential mechanisms for concentrating uranium in basin regions. Because the basins were examined only via aeromagnetic and gravity data, neither of which are diagnostic tools in uranium exploration, we can only speculate about the potential for such deposits in the quadrangle.

Several Tertiary lakebeds in Nevada and California contain small amounts of radioactive minerals, generally in small fractures in tuffaceous rocks (Davis and Hetland, 1956). In the Muggins Mountains, located about 45 km west of the northwest corner of the quadrangle, uranium exploration has focused on vitric tuff and tuffaceous lacustrine siltstone which form the lower member of the late Oligocene(?) to Early Miocene Kinter Formation (Smith and others, 1984; Scarborough, 1979; Scarborough and Wilt, 1979; Olmsted and others, 1973). The edge of area E10 in the quadrangle (pl. 3) contains tuffaceous sediments, suggesting that other basins could contain tuffs. However, the exposed Teritiary volcanic rocks are rarely tuffaceous, which indicates that tuff sequences in the basins are probably also uncommon.

Small amounts of uranium leached from uranium-bearing volcanic ash or other mineral bodies may precipitate in caliche (Bell, 1956). Such small, low-grade deposits are transient, moving about with the precipitation season. The uranium content of volcanic rocks in the quadrangle has not been determined, and high thorium values in stream-sediment samples are more closely associated with granitic and metamorphic terranes where uranium and thorium may be genetically related. In volcanic terranes it is difficult to assess uranium content based on thorium values derived from stream sediments because uranium and thorium are not necessarily related in volcanic environments. We conclude that uranium-bearing caliche derived from volcanic source terranes is not likely to be found in the quadrangle.

Uranium has been concentrated in calcrete, dolocrete, or gypcrete in western Australia and Namibia. Such concentrations may also be present in parts of the southwestern United States (Carlisle, 1978). Calcrete, which is distinct from caliche, is carbonate cemented alluvium that forms tabular masses tens of meters thick, several hundred meters to a few kilometers wide, and tens of kilometers long. The uranium, which is derived from granitoid rocks and transported laterally by ground water, is deposited as carnotite with authigenic carbonate in the trunks of subsurface drainages and in calcrete deltas where there is constricted flow or where the ground water is close to the surface. Reworking generally enriches the uranium prior to the stabilization of carnotite. Precipitation occurs in, adjacent to, or just below a calcrete mass close to the existing water table in an oxidizing environment.

Several environmental characteristics are required to form a calcrete uranium deposit. These include: a deeply weathered source terrane; anomalous uranium and vanadium in the ground water; large catchment area; low drainage gradient; limited runoff; non-pedogenic calcrete; absence of other uranium fixing processes in the catchment area; evaporative concentration of uranium, vanadium, and potassium down drainage; a constriction, shallowing, or upwelling of groundwater in the valley; reconcentration and stabilization of carnotite; and a moderate to low relief and tectonic stability in the area. Carlisle (1978) stated that the relatively recent tectonic history of the

Basin and Range could hinder the formation of such deposits. Several of these characteristics are, however, present in the Ajo quadrangle. A complete evaluation is impossible due to lack of detailed information about the basins. Carlisle (1978) indicated that the most favorable area for this type of uranium deposit in this country is in Clark County, Nev., and to a lesser degree south-central and western Arizona. Areas within basins that may be permissive for such deposits are designated tracts U1-U6 (pl. 3). These tracts were drawn at constrictions in the basins where calcrete might form.

Thorium and lanthanum values in stream-sediment samples are highest in samples collected near older granitic and metamorphic terranes in the western half and northeast corner of the quadrangle. These anomalous values and the identification of monazite in stream-sediment concentrates (P.K. Theobald, oral commun., 1984) indicates the possible incorporation of uranium into the monazite crystal structure (Overstreet, 1967). These areas may, therefore, shed uranium-bearing detritus into adjacent basins. The basins adjacent these older terranes have been designated U'1 through U'4 (pl. 3).

GEOTHERMAL RESOURCES

Thermal springs and wells are widespread in Arizona. Geothermal resources in Arizona would be used primarily for non-electrical purposes that include heating, argricultural processes, and industrial processes (Witcher and others, 1982).

Description of Geothermal Areas

Witcher and others (1982) designated three areas within the quadrangle that contain thermal wells as areas of geothermal potential. At Papago Farms (area G3, pl. 3), five irrigation wells that are 128 to 290 m deep contain 38°C to 51°C water that has a sodium bicarbonate composition. A mininum reservoir temperature of 80°C is predicted and geothermal resources of about 140°C may be present at depths greater than 2,000 meters (Witcher and others, 1982; Stone, 1980). Six warm-water wells near Gila Bend (east part of area G1, pl. 3) have temperatures ranging from 35°C to 49°C and are designated as having geothermal potential (Witcher and others, 1982). The part of the Agua Caliente-Hyder geothermal area that extends into the northern part of the quadrangle (west part of area G1, pl. 3) contains several warm-water wells and one hot spring. The wells range from 20 to 500 meters deep and have temperatures of 30°C to 45°C.

Evaluation of Geothermal Potential

The Agua Caliente-Hyder and the Gila Bend areas have been combined into area G1, which includes the Sentinel basalt flow located between the warm-well localities. Other warm-water localities may be present adjacent to this volcanic field, although basaltic terranes are less often associated with geothermal activity than more siliceous volcanic terranes. The Pinacate Volcanics in the southwestern part of the quadrangle (area G2, pl. 3), formed about 15,000 to 20,000 years ago (Wood, 1974) but has remained active into historic times. The volcanic field has no known associated warm-water wells but geologically resembles the Sentinel basalt flows. A spring at Quitobaquito, 25 km east of the Pinacate Volcanic field, has a temperature of 27°C (Wood, 1974), and heat-flow values increase towards the volcanic field which, at least, suggests a possibility for warm waters nearby. The Papago

Farms area constitutes area G3 (pl. 3). These three areas could possibly supply thermal waters for local use.

PERLITE AND ZEOLITES

Perlite is a relatively hydrous volcanic glass that can expand as much as 20 times on heating. It forms glassy zones in welded ash-flow tuffs, lava flows, and wall zones of felsic intrusive plugs and dikes (Meisinger, 1980) and is usually rhyolitic but may range to andesitic compositions. Perlite deposits, often a few hundred meters thick, extend over broad areas, but devitrified portions disrupt their continuity. Because glass devitrifies over time, rarely are perlite deposits older than Tertiary, and most commercial deposits are Eocene or Oligocene.

Much of the country's early perlite production came from Arizona, but, as deposits were discovered elsewhere, Arizona's production decreased. The best known perlite deposits in the state are near Superior in Pinal County and in the Black Mountains in Mohave County; smaller deposits are located in Gila, Yuma, and Maricopa Counties (Wilson and Roseveare, 1945). All of these deposits formed in thick volcanic piles. Because volcanic sequences in the quadrangle are flow dominanted and contain only small amounts of perlite, additional perlite occurrences in the quadrangle would also be scattered and small.

Zeolites fill cavities in igneous rocks or form authigenic minerals in sedimentary rocks, especially in silicic vitric tuffs (Sheppard, 1969). Zeolite deposits in silicic tuffs typically are the most extensive and of high purity. Deposits in Arizona occur in Cenozoic tuffs and tuffaceous sedimentary rocks in which the zeolites formed by reaction of the ash with interstitial water (Sheppard, 1969). West-central and southeastern Arizona contain most of the known bedded deposits, which occur in in beds of altered silicic tuff at least 0.3 m thick that contain 90 percent zeolites. Zeolites can form monomineralic beds but more commonly are associated with other zeolites, clays, silica, and (or) feldspars. Of the many zeolite minerals known, only six[1] have been found in Arizona.

We can only speculate about the zeolite potential in the quadrangle because of the lack of information about tuffaceous material in the basins. Tuffs are present at the celestite deposit mentioned previously, so zeolite-bearing tuff beds could possibly occur in the basins. As mentioned above, however, we do not expect extensive tuffaceous rocks to be found in the basins. Only small quantities of zeolites were seen during the field work in the flow dominated Tertiary volcanic sequences within the mountain ranges.

DISCUSSION OF ADDITIONAL AREAS

Several localities within the quadrangle have environments which suggest deposit types not discussed in this text, primarily due to a lack of information about the areas or to an uncertainty about what deposit types our information might imply.

Surrounding the La Abra Plain, geochemistry points to a thorium-niobium-vanadium rich, lanthanum-yttrium poor assemblage which is monazite deficient (P.K. Theobald, oral commun., 1984). There is a suspected, but unverified,

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1 Analcime, chabazite, clinoptilolite, erionite, mordenite, phillipsite

association of vanadium-bearing mica and thorite; thorite has been identified. We do not know if this geochemical signature has any significant relation to mineral potential, but its occurrence in an area of other significant geochemical anomalies indicates that the association should not be overlooked.

Proterozoic metavolcanic terranes north of the Ajo quadrangle distributed in a wide belt between Kingman and Payson, Ariz., contain massive-sulfide deposits in which the ores occur in rhyolite centers that are part of a basalt-andesite-rhyolite sequence (Anderson and Guilbert, 1979). Small areas of similar rocks that occur in the central part of the Mohawk Mountains may have a small, but at this point unknown, potential for massive sulfide.

Some hot-spring mercury deposits in Nevada formed near volcanic centers. No mercury mineralization was detected during field work in the quadrangle. Areas around siliceous volcanic centers, particularly in the Sauceda Mountains, may contain mercury minerals but the anhydrous lava that formed these rocks probably precludes such mineralization.

A geochemical anomaly for tin, tungsten, copper, and silver in the Ajo Range along the eastern edge of Organ Pipe Cactus National Monument suggests a hydrothermal system. The area contains a known hematite-bearing vein with associated copper mineralization.

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