U.S. GEOLOGICAL SURVEY CIRCULAR 1082

The Conterminous United States Mineral Assessment Program: Background Information to Accompany Folio of Geologic, Geochemical, Geophysical, and Mineral Resource Maps of the Ajo and Lukeville 1° by 2° Quadrangles, Arizona

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The Conterminous United States Mineral Assessment Program: Background Information to Accompany Folio of Geologic, Geochemical, Geophysical, and Mineral Resource Maps of the Ajo and Lukeville 1° by 2° Quadrangles, Arizona

By FLOYD GRAY, RICHARD M. TOSDAL, JOCELYN A. PETERSON, DENNIS P. COX, ROBERT J. MILLER, DOUGLAS P. KLEIN, PAUL K. THEOBALD, GORDON B. HAXEL, MICHAEL GRUBENSKY, GARY RAINES, HARLAN N. BARTON, DONALD A. SINGER, and ROBERT EPPINGER

U.S. GEOLOGICAL SURVEY CIRCULAR 1082

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MANUEL LUJAN, Jr., Secretary

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The Conterminous United States Mineral Assessment Program: Background Information to Accompany Folio of Geologic, Geochemical, Geophysical, and Mineral Resource Maps of the Ajo and Lukeville 1° by 2° Quadrangles, Arizona

By Floyd Gray, Richard M. Tosdal, Jocelyn A. Peterson, Dennis P. Cox, Robert J. Miller, Douglas P. Klein, Paul K. Theobald, Gordon B. Haxel, Michael Grubensky, Gary Raines, Harlan N. Barton, Donald A. Singer, *and* Robert Eppinger

ABSTRACT

Encompassing about 21,000 km^2 in southwestern Arizona, the Ajo and Lukeville 1° by 2° quadrangles have been the subject of mineral resource investigations utilizing field and laboratory studies in the disciplines of geology, geochemistry, geophysics, and Landsat imagery. The results of these studies are published as a folio of maps, figures, and tables, with accompanying discussions. Past mineral production has been limited to copper from the Ajo Mining District. In addition to copper, the quadrangles contain potentially significant resources of gold and silver; a few other commodities, including molybdenum and evaporites, may also exist in the area as appreciable resources. This circular provides background information on the mineral deposits and on the investigations and integrates the information presented in the folio. The bibliography cites references to the geology, geochemistry, geophysics, and mineral deposits of the two quadrangles.

INTRODUCTION

Purpose and Scope

This circular and the folio of maps published for the Ajo and Lukeville 1° by 2° quadrangles are part of a series of reports by the U.S. Geological Survey on the mineral resource potential of the conterminous United States. These studies are conducted under the Conterminous United States Mineral Assessment Program (CUSMAP), which provides regional mineral appraisal information to assist in the formulation of a long-range national minerals policy and to provide Federal, State, and local governments with information for land-use planning. CUSMAP studies include (1) compilations of published geoscience and mineral resource data; (2) regional geologic, geophysical, geochemical, and remote-sensing field investigations to obtain new data; and (3) interpretations and syntheses of data to produce systematic assessments of the mineral resource potential of selected areas. CUSMAP investigations also provide regional geological, geochemical, and geophysical information that is useful in a broad range of earth science studies of the conterminous United States; such information can be used in developing a framework for mineral exploration and in specific studies, such as the mineral resource assessment of wilderness areas.

Manuscript approved for publication March 2, 1992.

Location and Geography

The Ajo and Lukeville 1° by 2° quadrangles cover approximately 21,000 km^2 in southwestern Arizona (fig. 1). The eastern, northern, and western boundaries of these quadrangles lie, respectively, approximately 100 km west of Tucson, 50 km south of Phoenix, and 60 km east of Yuma, Arizona. The Ajo 1° by 2° quadrangle is located between latitude 32° and 33° N. and between longitude 112° and 114° W.; its southwest corner lies in Mexico. The Lukeville 1° by 2° quadrangle lies mostly in Mexico; only the triangular part of the northeast corner, from latitude 31°37' to 32° N. and from longitude 112° to 113°15' W., lies within Arizona, south of the Ajo quadrangle. Mexican lands were not evaluated (fig. 1).

The only major highways in the area are U.S. Interstate Highway 8, which crosses east-west along the entire northern part of the Ajo 1° by 2° quadrangle; Arizona

State Highway 85, from north of Gila Bend to Lukeville on the Mexican border; and Arizona State Highway 86, from Why east to the Santa Rosa Valley in the eastern part of the Ajo quadrangle. Major towns located within the study area are Ajo, Gila Bend, and Lukeville (fig. 1).

The quadrangles contain a system of northwest-trending mountains and valleys that are part of the Basin and Range physiographic province. The vegetation is part of the Sonoran Desertscrub biotic community, consisting of the Lower Colorado River and Arizona Upland subdivisions. The common vegetation consists of shrubs (dominantly creosote bush) and cacti, including saguaro, organ pipe, and cholla. Near washes, shrubs and trees such as acacia, mesquite, ironwood, and palo verde are common (Brown, 1982).

Land status

Most of the area within the Ajo and Lukeville 1° by 2° quadrangles is Federal and Indian Reservation land in which access has been limited for several decades (see fig. 2). The Barry M Goldwater Air Force Range covers the western, central, and southwestern parts of the Ajo quadrangle, and the southwestern part of the quadrangle also includes the Cabeza Prieta National Wildlife Refuge. The U.S. Army Yuma Proving Ground and the Kofa National Wildlife Refuge extend into the northwestern corner of the Ajo quadrangle. Also present in the quadrangle are the Organ Pipe Cactus National Monument, the western part of the Tohono O'odham (formerly Papago) Indian Reservation, and the southern part of the Ak Chin and Gila Bend Indian Reservations. Private- and State-owned land is in a strip along the north edge of the Ajo quadrangle and the area surrounding Ajo. Because of the many years of restricted access to much of the Ajo quadrangle, new exploration techniques and new deposit models have not been tested in the quadrangle.

Access Restrictions

At the time of this investigation, access to the great majority of the study area was restricted and required

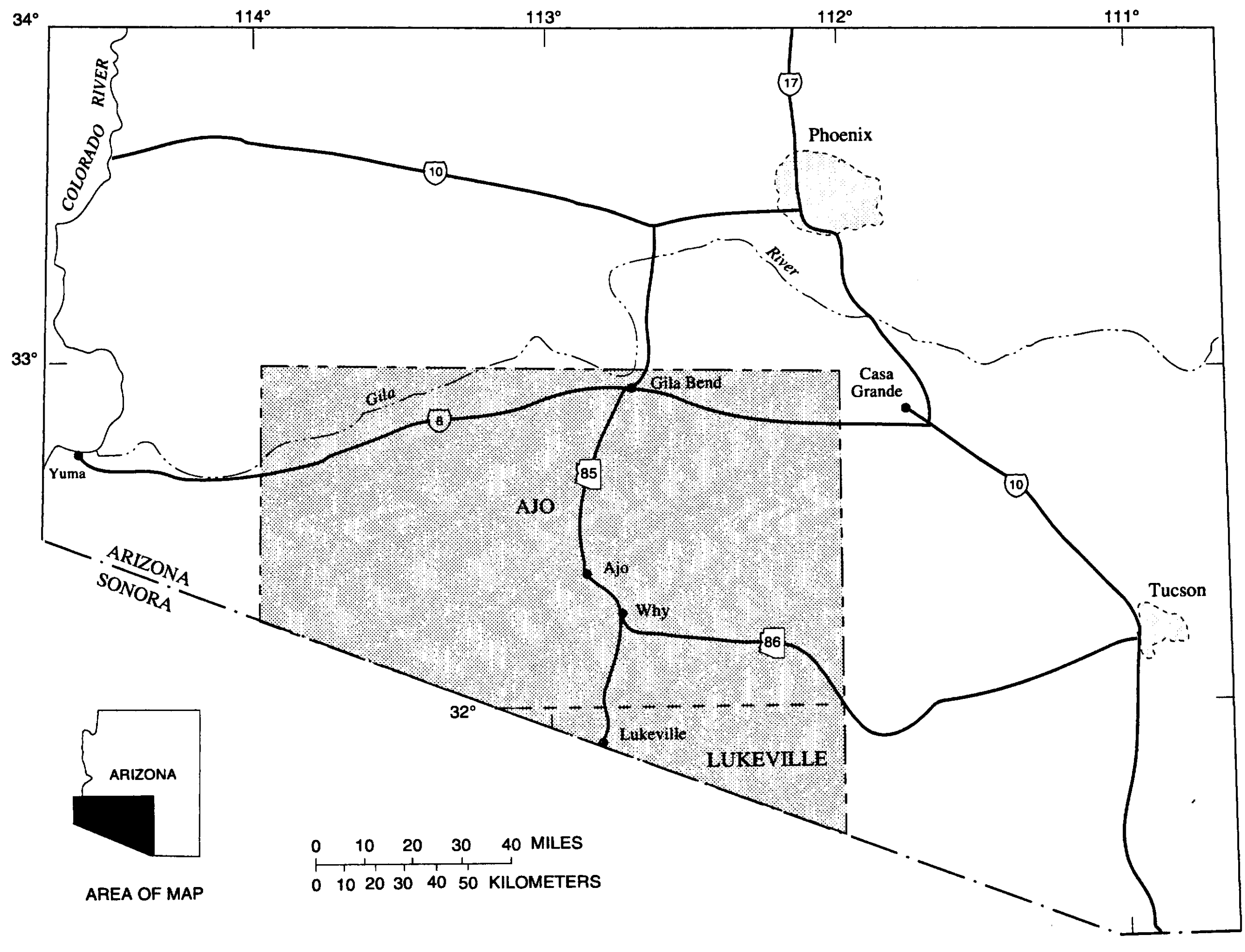

Figure 1. Location of Ajo and Lukeville 1° by 2° quadrangles and surrounding area in southwestern Arizona.

both approval several months in advance and day-to-day coordination with military authorities. The U.S. Air Force controls the Barry M. Goldwater Air Force Range (fig. 2), but operational control of the western part of the military range is by the U.S. Marine Corps based at Yuma. The U.S. Army restricts access to the Yuma Proving Ground in the northwest portion of the quadrangle. Access was also limited to the Kofa and Cabeza Prieta Game Ranges because both of these areas are within larger areas restricted by the military. Coordination with the U.S. Border Patrol offices in Yuma and Gila Bend was maintained for work near the international border. Access to most restricted areas was by helicopter.

Permission to sample within the Organ Pipe Cactus National Monument was obtained for the March and April 1979 and 1980 field seasons. Most site access was by helicopter based at Ajo. Sites closer than 2 km to roads were visited on foot.

Acknowledgments

Compilation of the Ajo and Lukeville CUSMAP reports would not have been possible without the contributions of many colleagues in the U.S. Geological Survey. We especially appreciate the consultation by A.K. Armstrong and the field assistance of Michael Cosca, Lottie Soll, Thomas Young, Richard L. LeVeque, and Katherine Kahle. John Rozelle, Jim Frisken, and Robert Turner facilitated much of the geochemical work. Competent commercial helicopter crews were essential in carrying out the geologic mapping, geochemical sampling, and geophysical observations. M.F. Hornberger, R.L. Ray, and K.A. Johnson helped with office compilation of the field data. E.H. McKee provided potassium-argon ages of rock samples collected in the initial phase of our study. W.D. Menzie discussed with us many aspects of the technique used in mineral resource assessment.

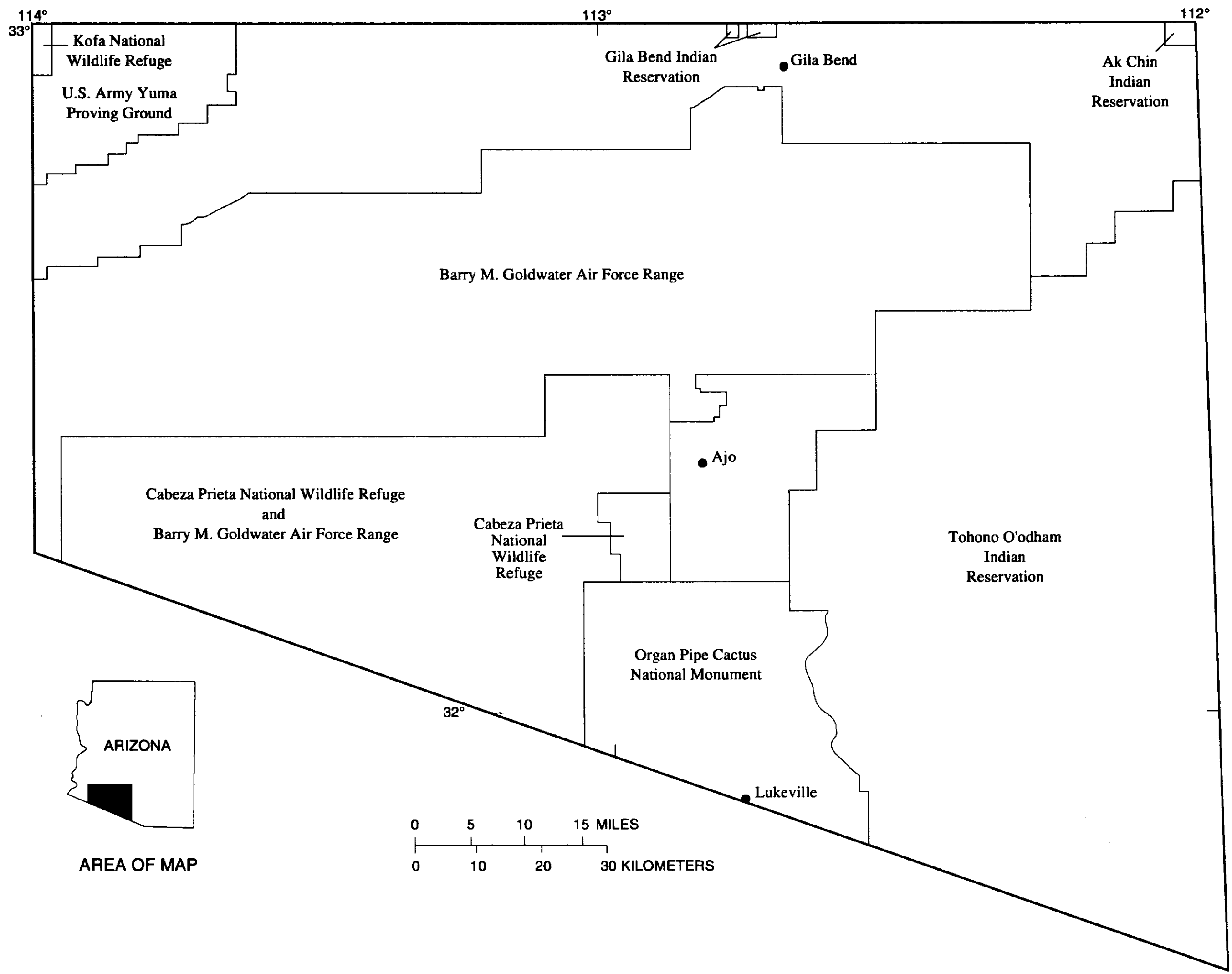

Figure 2. Status of land within Ajo and Lukeville 1° by 2° quadrangles. Undesignated areas are under State or private ownership.

A large part of the quadrangles is managed by the Luke Air Force Base. We wish to thank the commanding officer and other personnel for the help and courtesies they gave us during our study. Many thanks also go to the numerous dispatchers on duty, who maintained daily contacts with us regarding the scheduling of military exercises in the study area.

GEOLOGIC INVESTIGATIONS

Previous Work

Prior to the 1900's little was known about the geology of the Ajo and Lukeville 1° by 2° quadrangles, and most of the investigations were topical studies focused on specific mineralized areas, Paleozoic or Mesozoic stratigraphic sequences, water resources, or areas of special petrologic interest. The first published regional geologic studies conducted in the quadrangles were associated with water resource investigations by Bryan (1925), Heindl (1960), and Heindl and others (1962) of the U.S. Geological Survey. Proterozoic, Paleozoic, and Mesozoic stratigraphy in the northeastern part of the study area was studied by Carpenter (1947), McClymonds (1959), Hammer (1961), Heindl (1965a), and Chaffee (1974). The geology of the Ajo Mining District was detailed by Gilluly (1937, 1946). Neogene volcanic rocks in parts of the Ajo Range and Aguila Mountains were mapped, respectively, by Jones (1974) and Tucker (1980). Potassium-argon geochronology of southwestern Arizona is presented in Shafiqullah and others (1980). The status of mineral information for the Tohono O'odham Indian Reservation in the eastern part of the quadrangle is described by Johnson and others (1975). Summaries of geology, mineral deposits, and production for most mining properties in Pima County are given by Keith (1974).

Present Study

This study of the Ajo and Lukeville 1° by 2° quadrangles was conducted mostly between 1978 and 1983. An interdisciplinary team of earth scientists and technicians undertook systematic geologic mapping and made studies of the geochemistry, geophysics, Landsat imagery, and mineral deposits to produce a mineral assessment of the study area. These collateral field and laboratory studies were completed early in 1984. Specific topical and regional geologic and mineral resource investigations by team members during the CUSMAP study have been completed, and the results have been published in several reports (see table 1). The study originated as an outgrowth of investigations of the Tohono O'odham Indian Reservation and combines new geologic mapping with existing mapping to relate mineral resources, regional structure, and tectonostratigraphic units with ore deposit models. The project was incorporated into the CUSMAP program in 1980.

Extensive new geologic mapping, facilitated by helicopter support, of Tertiary volcanic sequences was done in the central and southern parts of the study area and in the metamorphic rocks of the Mohawk Mountains. Detailed studies of the Jurassic and older granitoids in the southeastern part of the study area, begun earlier, were continued during this project.

The geochemical survey consisted of (1) the collection and analysis of samples of stream sediment and of the nonmagnetic fractions of heavy-mineral concentrates from stream sediment, and (2) the identification of heavy minerals found in the nonmagnetic concentrates. Semiquantitative spectrographic analyses provided data on the abundance of 31 trace elements in each sample. Anomalously high concentrations of certain trace elements helped to identify mineralized areas. A review was made of available information on mines, quarries, and abandoned prospects. The existence and locations of many of the mines and prospects entered previously in the Mineral Resource Data System (MRDS) of the U.S. Geological Survey (Peterson, 1984) were confirmed during the field studies.

Maps showing mineral occurrences, geophysical information, areas of alteration (determined by Landsat imagery), and locations of geochemical samples containing anomalous concentrations of trace elements, were generated and used in conjunction with maps of favorable geologic units to infer the potential for various metallic commodities. Similar methods of combining data are also used to determine the potential for several nonmetallic commodities, except that geochemical data for such commodities are generally lacking, insufficient, or inappropriate. As a result, the inferred potential for these commodities is based largely on the combined information about mineral occurrences and the distribution of favorable geologic units. The potential for some industrial minerals is assessed only in broad terms. Such materials are available essentially throughout the area, and their usefulness may be as much a function of proximity to markets and variations in weathering as of bedrock geology. Geologic units from which resources of these construction materials have been obtained are accorded a somewhat greater potential for additional resources than are units that have not been exploited in the past.

The results of this study are presented in a series of U.S. Geological Survey Miscellaneous Field Studies Maps and Open-File Reports (table 1) and in the abstracts volume of a USGS-sponsored conference on the quadrangles (Gray, 1988). Other maps and reports related to the program are included in the bibliography at the end of this report.

Table 1. Component maps of the Ajo and Lukeville 1° by 2° quadrangle assessment

U.S. Geological Survey map	Author	Subject
MF-1834-A	(Peterson and Tosdal, 1987)	Mineral occurrences and tabulation of geologic, commodity, and production data
MF-1834-B	(Peterson and others, 1987)	Mineral resource assessment
MF-1834-C	(Theobald and Barton, 1987a)	Geochemical distribution and abundance of copper in geochemical samples
MF-1834-D	(Theobald and Barton, 1987b)	Geochemical distribution and abundance of lead, molybdenum, bismuth, and tungsten in geochemical samples
MF-1834-E	(Theobald and Barton, 1988)	Geochemical distribution and abundance of zinc, silver, antimony, manganese, barium, and strontium in geochemical samples
I-2139	(Klein and Kucks, 1990)	Gravity and aeromagnetic anomalies
Open-File Report 87-217	(Gray and others, 1987)	Geology

DESCRIPTION OF COMPONENT MAPS AND STUDIES OF THE AJO AND LUKEVILLE QUADRANGLES FOLIO

Geology

The bedrock geology of the Ajo and Lukeville 1° by 2° quadrangles can be divided into four broad terranes. The first, in the western part of the study area, consists of Proterozoic gneiss intruded by Late Cretaceous and (or) early Tertiary granite. The gneissic rocks have had a geologic history unlike similar-age rocks to the east, from which they are separated by a possible major tectonic break in the Growler and San Cristobal Valleys. This second terrane consists of Proterozoic, Paleozoic, and Mesozoic rocks and has a geologic history like that of much of southern and southeastern Arizona. This terrane has been referred to previously as the northern Papago terrane (Haxel and others, 1984). The third terrane, or southern Papago terrane of Haxel and others (1984), underlies the southeast one-third of the quadrangles and constitutes a region where Proterozoic and Paleozoic rocks are sparse to absent and, where exposed, are demonstrably allochthonous. The geology of this terrane is characterized by Late Cretaceous and (or) early Tertiary compressional deformation and early Tertiary plutonism. Rocks of the Jurassic magmatic arc are the oldest autochthonous rocks in this terrane. The boundary between the northern and southern Papago terranes is arcuate and gradational and passes through the southern Growler Mountains, the northern Gunsight Hills, and the Cimarron-Sheridan Mountains (fig. 3). The fourth terrane consists of Oligocene and younger volcanic rocks that unconformably overlie the early Tertiary and older metamorphic and plutonic rocks. A generalized geologic map of the quadrangles is shown in figure 4.

Proterozoic Rocks

The western Proterozoic terrane consists of gneissic rocks that crop out in the ranges to the west of the Growler Valley and the Agua Dulce Mountains. The gneisses can be subdivided into three facies. The most widespread facies consists of biotite-bearing quartzofeldspathic gneiss, orthogneiss, and amphibolite. These rocks are separated from the second gneiss facies by Tertiary detachment faults on the eastern side of the Mohawk Mountains (Mueller and others, 1982). The second gneiss facies of the western terrane consists of Early Proterozoic orthogneiss that is overlain by quartzite, quartz calcsilicate, and quartzofeldspathic metasedimentary rocks (L.T. Silver, oral commun., 1982). A sillimanite orthogneiss, interpreted to be a metamorphosed paleosol, separates the orthogneiss from the metasedimentary rocks. The second facies is found only on the east side of the Mohawk Mountains. The metamorphic grade and uranium-lead isotopic ages of the two gneiss facies are different from those of Proterozoic rocks in the northeast one-third of the Ajo quadrangle (L.T. Silver, oral commun., 1982). Postkinematic K-feldspar megacryst granites intrude the first gneiss facies in the southern Sierra Pinta Mountains and northern Agua Dulce Mountains. The third gneiss facies is found near Buck Peak in the northern Cabeza Prieta Mountains. These rocks contain a significant component of calcsilicate gneiss in addition to biotite and quartzofeldspathic gneiss. The age of this facies is uncertain and is constrained only as older than Late Cretaceous.

Proterozoic rocks in the northeast one-third of the Ajo quadrangle have had a geologic history similar to that of Proterozoic rocks elsewhere in southern Arizona. They consist of muscovite-biotite or muscovite-quartz feldspar schist and gneiss derived from supracrustal lithologies and are the oldest rocks in this terrane. These metamorphic rocks consist primarily of the unit known regionally as the Pinal Schist, but they also include a part of the Cardigan gneiss (Gilluly, 1946) near Ajo.

Several generations of Proterozoic granitoid rocks have intruded the supracrustal rocks. The older granitoids are deformed and crop out in the Maricopa and Little Ajo Mountains. Uranium-lead ages for these rocks indicate late Early Proterozoic emplacement ages (L.T. Silver, oral commun., 1982; J.L. Wooden and J.S. Stacey, oral commun., 1986). In several ranges, Middle Proterozoic K-feldspar megacryst granites intruded the deformed rocks. These granitoids are undeformed and are generally referred to as anorogenic granites (Silver, 1978). Limited uranium-lead and K-Ar dating indicates that these rocks have ages of about 1,400 Ma (Balla, 1972). Included in this suite are the Oracle Granite of Peterson (1938) and the Chico Shunie Quartz Monzonite (Gilluly,1946). In the northern Vekol Mountains and at Table Top Mountain, sedimentary rocks of the Middle Proterozoic Apache Group (Carpenter, 1947; Shride, 1967) unconformably overlie the older granitoids and gneissic rocks (Dockter and Keith, 1978; Peterson and others, 1987). The youngest Proterozoic rock in this terrane is diabase that occurs as sills and dikes. The diabase is considered correlative with the 1,100 Ma diabase that intruded the Apache Group in central and southeastern Arizona (Shride, 1967; Silver, 1978).

The boundary between the two Proterozoic terranes lies in the Growler and San Cristobal Valleys and corresponds approximately to the inferred trace of the

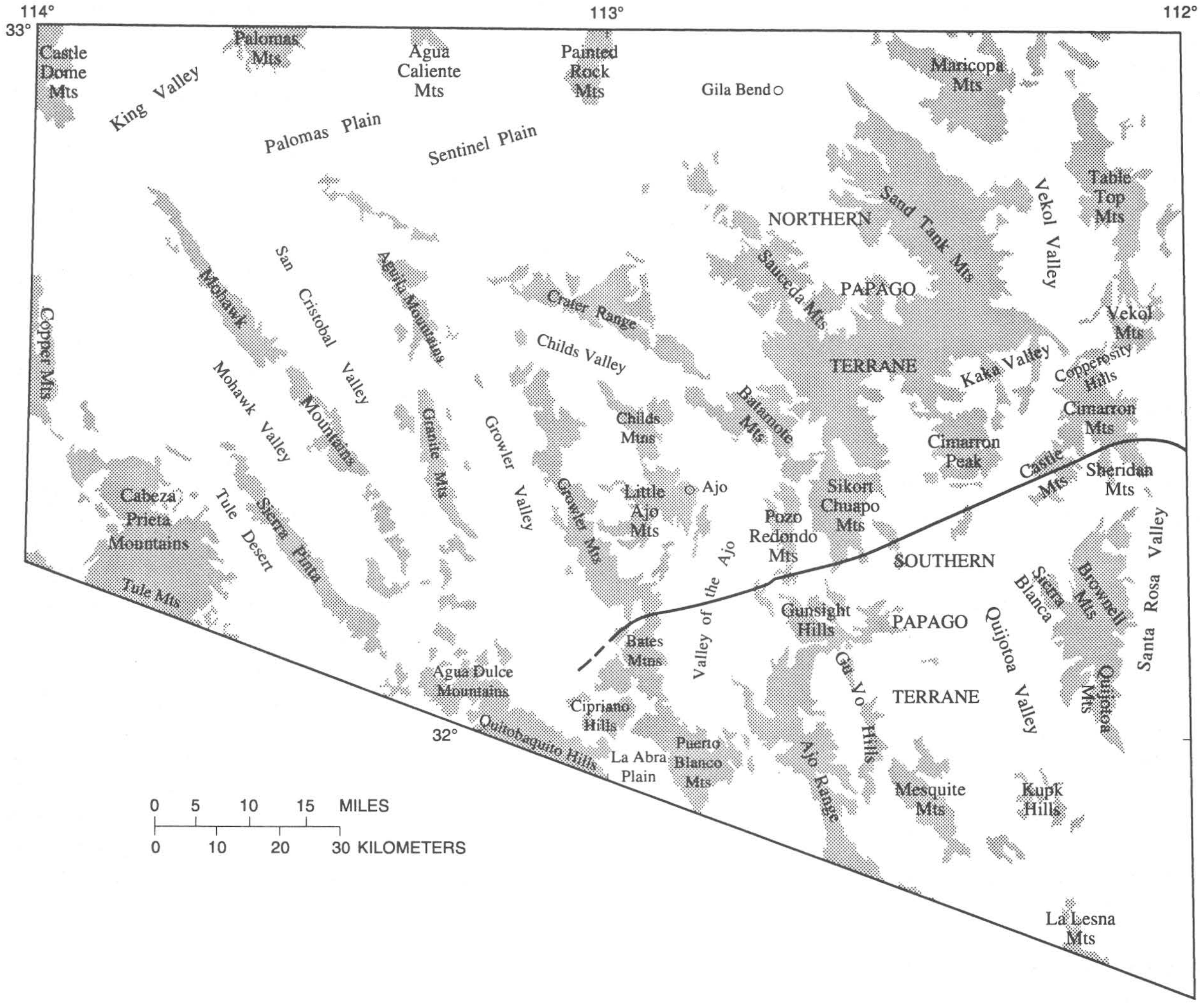

Figure 3. Location of approximate boundary (heavy line) between northern and southern Papago terranes and physiography of Ajo and Lukeville 1° by 2° quadrangles. Shaded areas indicate highlands.

Mojave-Sonora megashear of Silver and Anderson (1974, 1983; Anderson and Silver, 1979), a Late Jurassic sinistral strike-slip fault with as much as 800 km of displacement. If the boundary is the megashear, the two terranes could have been tectonically juxtaposed in the Mesozoic. However, Shafiqullah and others (1980) suggest that the juxtaposition of the Proterozoic terranes, which forms a part of the basis for the megashear, occurred during the Proterozoic.

Paleozoic Rocks

During the Paleozoic, at least the northeastern part of the area was part of a stable cratonic platform that was buried beneath about 2 km of carbonate and clastic sedimentary rocks (Wilson, 1962; Chaffee, 1974; Peirce, 1976). Stratigraphic sections that contain many of the Paleozoic formations known in southwestern Arizona crop out in the Vekol Mountains and near Lime Hill in the southeasternmost Growler Mountains. Smaller outcrops are scattered between these ranges, and many of them occur as roof pendants in Mesozoic granitoids. Rocks of Paleozoic age include the Cambrian Bolsa Quartzite, the Cambrian Abrigo Formation, the Devonian Martin Formation, and the Mississippian Escabrosa Limestone. The Pennsylvanian and Permian Naco Group, the uppermost unit of the southern Arizona cratonal sequence, does not outcrop within the quadrangles because it was removed by erosion prior to the deposition of Mesozoic volcanic and sedimentary rocks (Titley, 1976).

Mesozoic Rocks

The oldest Mesozoic rocks in the area are Jurassic in age and once were part of a through-going continental-margin magmatic arc. Cessation of arc magmatism was followed by uplift and erosion of the arc in the Cretaceous; magmatism during this time was sparse. In the Late Cretaceous, magmatism resumed as the arc swept eastward across southern Arizona. Near the end of the Cretaceous and continuing into the early Cenozoic, compressional deformation and intrusion of postkinematic, crustally derived plutons affected the rocks of the southern Papago terrane.

Jurassic Rocks

Most of the volcanic activity of the Jurassic magmatic arc was centered around dominantly explosive silicic and locally intermediate volcanic centers (Tosdal and others, 1989). Thick sections of locally derived clastic rocks filled intra-arc basins (Haxel and others, 1980). The silicic volcanic and associated sedimentary rocks of the intra-arc basins are known as the Lower and Middle Jurassic Fresnal Canyon sequence of Tosdal and others (1989), which includes rocks of the La Abra Plain in Organ Pipe Cactus National Monument. The principal rock type is rhyolitic metaporphyry that has conspicuous quartz phenocrysts and, locally, a relict volcanic texture. Quartzite, feldspathic phyllite, and semischist with subordinate arenaceous marble are minor supracrustal lithologies. Metagranite porphyry associated with quartz porphyry metarhyolite intrusive rocks of the intra-arc basins in the Quitobaquito Hills has a uranium-lead age of 175 Ma (Anderson and Roldan-Quintana, 1979).

In the Kupk Hills in the southeastern part of the area, a Middle Jurassic(?) granodiorite orthogneiss crops out. This pluton is lithologically correlated with the Middle Jurassic (informal) Kitt Peak-Trigo Peaks superunit (Tosdal and others, 1989) and is the only known exposure of these areally widespread plutonic rocks in the Ajo and Lukeville quadrangles. Haxel and others (1984) previously considered the granodiorite orthogneiss to be of Late Cretaceous or early Tertiary age. The regional significance of this isolated exposure is unknown, but its correlative granitoids are part of a compositionally expanded superunit of batholithic proportions that intruded the upper crust in Middle and Late Jurassic time.

The youngest supracrustal rocks of the magmatic arc are known regionally as the Middle(?) and Upper Jurassic Artesa sequence of Tosdal and others (1989). These rocks crop out in the Agua Dulce Mountains and the Quijotoa Mountains; in the latter range they were locally assigned to the Tertiary by Rytuba and others (1978). Volcanic rocks in the magmatic arc consist of approximately subequal amounts of trachyitic and rhyolitic rocks. Immature clastic rocks, many of which are reworked volcanic rocks, are also found. Late Jurassic subvolcanic granitoids called the (informal) Ko Vaya superunit (Tosdal and others, 1989) intrude the supracrustal rocks in the Quijotoa and Agua Dulce Mountains (Rytuba and others, 1978; Tosdal and others, 1989). Other outcrops of these granitoids are in the La Lesna Mountains, in the hills south of Cimarron Peak, and in the Puerto Blanco Mountains. In the latter range, the granites have intruded the silicic volcanic rocks of the Fresnal Canyon sequence. Detailed mapping in ranges to the east has shown the volcanic rocks of the Artesa sequence and the granitoids of the Ko Vaya superunit to be essentially comagmatic units that formed volcano-plutonic centers (Briskey and others, 1978; Haxel, 1978).

Upper Jurassic(?) and Cretaceous Rocks

Locally derived Upper Jurassic(?) and Cretaceous immature clastic rocks overlie Jurassic and older rocks

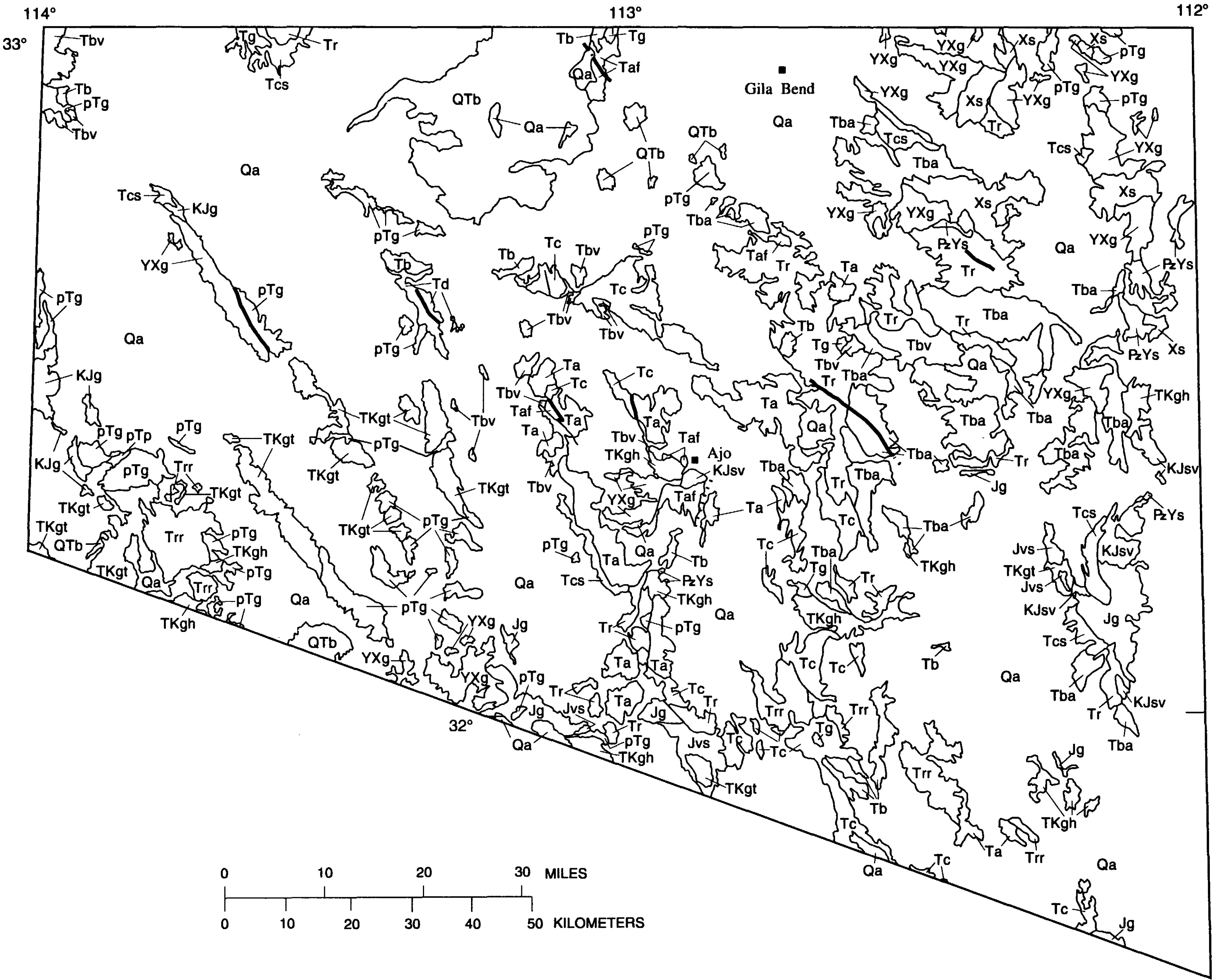

Figure 4. Generalized geologic map of Ajo and Lukeville 1° by 2° quadrangles, (modified from Gray and others, 1987).

DESCRIPTION OF MAP UNITS

Qa	Alluvium and landslide deposits (Quaternary)
QTb	Basalt of Sentinel Plain and Pinacate volcanic field (Quaternary and Tertiary)
Ta	Andesite of Batamote Mountains (Tertiary)
Trr	Rhyolite, rhyodacite, and dacite flows, tuffs, and plugs (Tertiary)
Tc	Childs Latite (Tertiary)
Tr	Rhyolite suite (Tertiary)
Tba	Basalt and basaltic andesite (Tertiary)
Tcs	Conglomerate and minor sandstone (Tertiary)
Tbv	Basal volcanic rocks (Tertiary)
Taf	Andesite, fanglomerate, and minor coarse arkosic sandstone (Tertiary)
Tg	Biotite-hornblende granitoids (Tertiary)
TKgt	Two-mica granite and biotite granite (Tertiary and Cretaceous)
TKgh	Hornblende-biotite-series granitoids (Tertiary and Cretaceous)
KJsv	Sedimentary and volcanic rocks (Cretaceous and (or) Jurassic)
KJg	Granitic rocks (Cretaceous or Jurassic)
Jg	Granitic and syenitic rocks (Jurassic)
Jvs	Volcanic and minor sedimentary rocks (Jurassic)
PzYs	Sedimentary rocks and minor diabase (Paleozoic to Middle Proterozoic)
YXg	Granite (Middle and Early Proterozoic)
Xs	Schist (Early Proterozoic)
pTg	Gneiss and schist, undivided (pre-Tertiary)
——	Contact
——····	Fault—Dotted where concealed

Figure 4.—Continued.

and include unnamed strata in the Vekol Mountains (Hayes, 1970), Sheridan Mountains, and Cimarron Mountains; thermally metamorphosed rocks in the southeasternmost Growler Mountains (Gray and others, 1987); and scattered outcrops in the low hills northwest of the Bates Mountains. Consisting of various combinations of arkosic and arenitic sandstone, conglomerate, and siltstone, and rare andesitic to rhyolitic volcanic and hypabyssal rocks, these Upper Jurassic(?) and Cretaceous sedimentary rocks record the unroofing and erosion of the Jurassic magmatic arc (Haxel and others, 1980; Tosdal and others, 1989). The conglomerate-rich outcrops in the northeastern part of the Ajo quadrangle have been tentatively correlated with the Lower Cretaceous Glance Conglomerate that forms the basal formation of the Bisbee Group (Hayes, 1970).

Late Mesozoic and Early Cenozoic Rocks

In the Late Cretaceous, magmatism in south-central Arizona resumed as the continental-margin magmatic arc swept eastward in response to events at the plate margin (Coney and Reynolds, 1977). In several ranges in the northern Papago terrane (fig. 3), andesitic to rhyolitic volcanic rocks were erupted. The best known of these is the Concentrator Volcanics (Gilluly, 1946) near Ajo. Compositionally expanded metaluminous granitoids intruded the upper crust and, locally, the Late Cretaceous volcanic rocks. The granitoids include the New Cornelia pluton of Gilluly (1946) (see also Cox and Ohta, 1984; Hagstrum and others, 1987), the granodiorite of Gunsight Hills (Tosdal and others, 1986), granite of Bandeja Well in the southeasternmost Growler Mountains (Gray and others, 1985), and unnamed granite bodies in the Cimarron Mountains (Briskey and others, 1978) and the Vekol Mountains. Porphyry copper deposits at Ajo and in the Vekol Mountains are associated with these granitoids. Uranium-lead ages and K-Ar minimum ages for these bodies range between about 68 and 64 Ma, confirming the Late Cretaceous ages for the granitoids (McDowell, 1971; J.E. Wright *in* Tosdal, 1979; Tosdal and others, 1986; Hagstrum and others, 1987).

West of Ajo, several granitoid plutons have intruded the western Proterozoic terrane. Most of these plutons are petrologically different from the Late Cretaceous plutons of the northern Papago terrane in that they are compositionally restricted to rocks of monzogranitic and granitic compositions; parts of the largest pluton contain, in addition to biotitite, the accessory minerals muscovite and garnet. The largest pluton outcrops in some five ranges from the Granite Mountains westward and was informally called the "Gunnery Range granite" by Shaffiqullah and others (1980). Other plutons compose much of the Copper Mountains and the northernmost Mohawk Mountains; a small part of a much larger granodiorite body south of the international boundary in northern Sonora crops out in the Tule Mountains. The granodiorite in the Tule Mountains is dated as Late Cretaceous (Anderson and Roldan-Quintana, 1979; R.M. Tosdal and R.J. Miller, 1982–86, unpub. data). Potassium-argon biotite and muscovite minimum ages from the other granitoids are early Tertiary and range from about 53 Ma on the west to about 40 Ma in the Granite Mountains (Shafiqullah and others, 1980; Tosdal and Miller, 1988). Arnold (1986) reported 53.40 ± 0.30 and 53.70 ± 0.20 Rb-Sr whole-rock isochron minimum ages for the "Gunnery Range granite." Late Cretaceous and (or) early Tertiary ages are presently tentatively assigned to these granitoids.

Mesozoic and early Tertiary orogenesis in the southern Papago terrane has involved a complex interplay between thrust faulting, regional metamorphism, and plutonism (Haxel and others, 1984). In the Quitobaquito Hills and adjacent Puerto Blanco Mountains, the Jurassic rocks are deformed in an imbricate stack of syn-metamorphic thrust faults. In the Gunsight Hills, a now-vertical ductile shear zone cuts one of the Late Cretaceous granitoids (Tosdal and others, 1986). The core of the Sierra Blanca is a window into the regionally subhorizontal Baboquivari-Window Mountain Well thrust of Haxel and others (1984). The Mesozoic rocks in the Copperosity Hills at the north end of the Cimarron Mountains are also folded and cut by south-dipping thrust faults (Dockter and Keith, 1978). Metamorphism in these ranges took place dominantly under greenschist-facies conditions, but mineral assemblages indicative of the lower amphibolite facies are found locally (Haxel and others, 1984; Tosdal and others, 1986; Reynolds and others, 1988). Late- to postkinematic peraluminous granites intruded the shortened terrane. In the quadrangles, the granite of Senita Basin exposed south of the Puerto Blanco Mountains and the granite of Sierra Blanca in the Sierra Blanca represent this suite of plutons. These garnet-bearing two-mica granites are crustally derived and are inferred to be of early Tertiary age based on correlation with similar granites of known age (Keith and others, 1980; Wright and Haxel, 1982; Farmer and DePaolo, 1983).

Cenozoic Rocks

Paleogene Rocks

After the cessation of magmatism and compressional deformation, the rocks of the Ajo and Lukeville quadrangles underwent a period of tectonic and magmatic quiescence. In general, K-Ar mica ages from west to east across the quadrangles become progressively younger; this age pattern does not apply to the northern Papago terrane, where the high-level granitoids cooled soon after they were intruded. Biotite and white mica minimum ages in the Cabeza Prieta Mountains are about 53 to 50 Ma (Shafiqullah and others, 1980; Tosdal and Miller, 1988) and decrease to between 40 and 30 Ma and, locally, between 30 and 20 Ma in the eastern part of the quadrangles. The general pattern of minimum ages decreasing from west to east is interpreted to result from the uplift and cooling of the terrane in the early Cenozoic. The pattern of K-Ar mica ages across the Gunsight Hills is a good example of the regional pattern. There, a Late Cretaceous and (or) earliest Tertiary (pre-59 Ma on hornblende) ductile shear zone has been tilted from an inferred originally subhorizontal attitude to its current near-vertical attitude in the latest Oligocene. From high structural levels to low levels, as inferred by the metamorphic mineral assemblages (Tosdal and others, 1986), the minimum ages of igneous and metamorphic biotite and vein alteration white mica decrease from between 47 and 40 Ma to 32 Ma (Shafiqullah and others, 1980; Tosdal and Miller, 1988). Latest Oligocene and early Miocene large-scale crustal extension, observed in the easternmost part of the quadrangles in the Sierra Blanca (Davis, 1980), disrupted and locally overprinted the cooling pattern.

Tertiary Volcanic Rocks

Tertiary volcanic rocks within the Ajo and Lukeville 1° by 2° quadrangles form a volcanic field composed of flows that comprise the entire compositional range from basalt to rhyolite. Parts of this field have been informally called the Ajo volcanic field. (May and others, 1981; Gray and others, 1983; Gray and Miller, 1984a, b; Gray and others, 1985; Tosdal and others, 1986). Tertiary volcanic rocks crop out over approximately 5,000 km^2, extending from the Mexican border on the south to just north of U.S. Interstate Highway 8 on the north, and from the Growler and Aguila Mountains on the west to the Vekol and Quijotoa Valleys on the east. Scattered Tertiary volcanic rocks in the Vekol Mountains and in the Palomas Mountains (Dockter and Keith, 1978; Rytuba and others, 1978; Briskey and others, 1978) are probably older than, but not related to, the Miocene rocks in the central part of the study area.

Conventional K-Ar geochronology has been used extensively in the Ajo and Lukeville quadrangles to establish the age of Tertiary volcanism and broadly contemporaneous tectonic activity. Sixty new K-Ar ages for volcanic rocks were produced during this study. Age data available prior to the inception of this study have been compiled by Tosdal (1979).

The Tertiary volcanic rocks in the central part of the study area are divided into three sequences that are each separated by angular unconformities: (1) the oldest sequence, of late Oligocene and early Miocene age, consists of red fanglomerate and coarse arkosic sandstone intercalated with andesite, rhyolite, rhyodacite, and local pyroclastic rocks; (2) the complex middle sequence consists of early and middle Miocene basalt, latite, silicic flows, and associated pyroclastic rocks; and (3) the youngest sequence, of middle Miocene age, is composed of basaltic andesite and andesite (Gray and Miller, 1984a, b). The angular discordance between the middle and youngest sequence is typically minor (less than 10°–15°).

The oldest sequence is exposed in scattered areas along the north and west edges of the field in the northwestern Sauceda, Little Ajo, and Growler Mountains. It is characterized by steeply tilted volcanic rocks intercalated with coarse clastic sedimentary strata. Initiation of volcanism coincided with local uplift and unroofing of crystalline basement rocks. In the Ajo area (Gilluly, 1946), the Growler Mountains (Gray and others, 1983), and the northwestern Sauceda Mountains, massively bedded coarse fanglomerate and coarse arkosic pebbly sandstone were locally derived from Proterozoic granite and gneiss. The coarse fanglomerate grades upward into coarse arkosic sandstone. Interbedded flows increase in abundance upward. An age of 23.8 ± 0.8 Ma was obtained from one of these flows near North Ajo Peak in the Little Ajo Mountains. Because this flow is near the top of the sequence, it provides a minimum age for the accumulation of the fanglomerates. A tuff lying nonconformably above the tilted andesite-fanglomerate sequence yielded an age of 22.0 ± 0.7 Ma (Gray and Miller, 1984a).

The middle sequence, the most widespread of the three, forms a heterogeneous assemblage of basaltic, andesitic, and rhyolitic rocks. The oldest rocks in the sequence are rhyolitic to rhyodacitic flows and tuffs. Silicic volcanism migrated southward from the Sand Tank Mountains into the Sikort Chuapo Mountains and the Ajo Range, eventually resulting in the eruption of rhyolitic flows and tuffs in the Ajo Range at approximately 17–16 Ma (R.M. Tosdal, unpub. data; R.J. Miller, unpub. data; Jones, 1974; May and others, 1981; Gray and others, 1985). Contemporaneous with silicic volcanism at approximately 21 Ma, basalt and basaltic andesite were erupted in the region extending from the northern Sauceda Mountains to the southern Sand Tank Mountains. The most distinctive rock type of the middle sequence is the coarsely porphyritic Childs Latite in the Ajo area (Gilluly, 1946; Gray and others, 1985).

Basaltic andesite was erupted between 16 and 14 Ma. The major source for flows in the western part of the Ajo volcanic field was Batamote Mountain, a dissected shield volcano. Minor vents and oxidized cinder cones are present in the Cipriano Hills and the Growler and Bates Mountains farther north.

The Sentinel and Pinacate basalt flows, adjacent to the northern and southwestern parts of the volcanic field, respectively, postdate most Basin and Range style block faulting. These basalts range in age from 5 to 1 Ma and are not considered part of the Tertiary volcanic field (Eberly and Stanley, 1978, Nos. 1–6; Gutmann, 1976).

Geochemical Studies

Geochemical maps included in the folio of the Ajo and Lukeville 1° by 2° quadrangles display the distribution and abundance of selected elements and delineate areas with anomalous concentrations of these elements.

The reconnaissance geochemical sampling was done during 1979 and 1980. The area covered includes all of the Ajo 1° by 2° quadrangle in the U.S., except the Tohono O'odham Indian Reservation, and includes part of the Lukeville 1° by 2° quadrangle, west of the Indian Reservation and north of the Mexican border. A total of 971 sample localities yielded 971 samples of stream sediment finer than 30 mesh and 952 samples of the nonmagnetic fraction of heavy-mineral concentrates from stream sediments. Sample localities were selected on first-order drainage channels, generally reflecting a drainage basin of less than 1 km^2. These localities represent the mountain ranges and their immediate flanks and disregard the 80 percent of the quadrangles underlain by a thick fill of young sediments in the basins. The average sampling density for the mountain ranges was one sample locality per 3.1 km^2. All samples were analyzed by optical emission spectroscopy for 31 elements (Ag, As, Au, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, La, Mg, Mn, Mo, Nb, Ni, Pb, Sb, Sc, Sn, Sr, Th, Ti, V, W, Y, Zn, and Zr) using a six-step semiquantitative emission spectrographic method (Grimes and Marranzino, 1968).

Geochemical data sets were merged and manipulated by computers located at the U.S. Geological Survey's computer center in Denver, Colorado. Collection, preparation, and analytical procedures are presented in Barton and others (1982); initial interpretations and statistical parameters for resource evaluation of geochemical data are given in Theobald and Barton (1983). Parts of the data have been used to produce the geochemical distribution and abundance plots incorporated into the geochemical maps. The elements shown on these maps were selected for their pertinence to the delineation of areas favorable for the occurrence of metalliferous mineral deposits.

Analyses of the distribution of eleven of these elements—considered singularly, in element groups, or in comparison with the other elements—are used to define 16 anomalous areas favorable for the occurrence of metalliferous deposits. The geochemical characteristics of each of these anomalous areas are summarized in table 2. Copper is considered both as a single element and as part of a suite of elements common in rock-forming minerals (Theobald and Barton, 1983, 1987a). Lead, molybdenum,

Table 2. Geochemically anomalous areas in parts of the Ajo and Lukeville 1° by 2° quadrangles

[Anomalous elements are listed by their chemical symbol; Ba+Sr, anomalous joint score for the two elements in heavy-mineral concentrates; –Sr, anomalously low strontium content in stream sediment]

Anomalous areas	Anomalous elements
1. Highway 84	Pb, W, Bi, Mn, –Sr
2. Booth Hills	Pb, Mo, W, Bi
3. Maricopa	Pb, W, Bi, Mn
4. Painted Rock	Pb, Mo, Mn, Ba+Sr
5. Sauceda	Cu, Sb, Mn, Ba+Sr
6. Batamote	Cu, Sb, Mn, Ba+Sr
7. Ajo	Cu
8. Ajo Range	Cu, Pb, Mo, W, Bi, Ba, –Sr
9. Growler Pass	Cu, Pb, Mo, W, Bi, Sb, –Sr
10. Sonoyta	Cu, Pb, Mo, W, Ag, Sb, Zn, –Sr
11. La Abra Plain	Pb, Mo, W
12. Agua Dulce	Pb, Mo, W, Bi
13. Mohawk	Pb, Mo, W, Bi
14. Mohawk Pass	Pb, Mo, W, Bi, Ba+Sr
15. Copper Mountains	Cu
16. Cabeza Prieta	Ag, Ba+Sr

tungsten, and bismuth are mutually sympathetic, and these four elements are interpreted singularly and as a group (Theobald and Barton, 1983, 1987b). Silver, antimony, and zinc were only occasionally detected, and their presence in measurable amounts is considered anomalous (Theobald and Barton, 1983, 1988).

Manganese, barium, and strontium provide both direct and indirect evidence of mineral potential. Manganese oxides, barite, and celestite have been produced from occurrences in the study area. These same minerals are often associated with the other metallic elements and can provide a larger geochemical halo than is seen for the metallic elements. Manganese oxides are the host for a variety of elements in the supergene environment; these elements, when hosted in this way, can be indicative of remobilized metal. This seems to be the situation for anomalies 5, 6, and 8. Strontium is often depleted in hydrothermally altered rocks surrounding a mineral deposit; thus, although high barium and (or) strontium in heavy-mineral concentrates indicates the presence of barite or celestite, abnormally low strontium in the stream sediments may also indicate areas of hydrothermal alteration.

The 16 anomalous areas all contain several anomalous sites. Most are complex, exhibiting anomalous characteristics for a variety of elements. The scale of the regional reconnaissance sampling is such that small, but significant, anomalies could easily be reflected by only a single site or even be missed. Any detailed evaluation of the area should consider individual anomalous sites as well as these anomalous areas. Furthermore, the scale of the reconnaissance leads to regional simplification of the anomalous patterns. Anomaly 13 (the Mohawk anomaly) consists in detail of three or four discrete anomalies that are merged in the regional synthesis (Eppinger and others, 1988). Similarly, anomalies 10 and 11 (the Sonoyta and La Abra Plain anomalies) overlap, yielding a complex assemblage of elements that is difficult to resolve at the regional scale.

Some of the anomalous areas reflect exposed mineralization; anomaly 7, at Ajo, is an obvious example. Other anomalous areas most likely reflect chemical leakage from concealed metal sources. Huston (Huston and Theobald, 1990) has demonstrated that anomaly 6, in the Batamote Mountains, is derived from metal incorporated in secondary iron and manganese oxides coating fractures adjacent to young faults cutting the Batamote andesite. Thus, the presence of an older metal source concealed beneath the andesite is a distinct possibility. Similar relations may be inferred for anomaly 5, in the Sauceda Mountains, where the surface chemical characteristics may reflect mineralization concealed at deeper levels of the rhyolitic volcanic sequence; for anomaly 8, in the Ajo Range, where the surface chemistry may reflect leakage along faults in the volcanic rocks from a concealed metal source beneath these rocks; and for anomaly 13, in the Mohawk Mountains, where at least one of the anomalies found by more detailed examination seems to reflect mineralization peripheral to a primary source concealed beneath the pediment gravels to the east of the Mohawk Mountains (Eppinger and others, 1988).

Geophysical Studies

Geophysical data acquired for the mineral resource assessment of the Ajo and Lukeville 1° by 2° quadrangles include quadrangle-wide gravity and aeromagnetic surveys and rock sampling to determine densities and magnetizations of rocks encountered in the survey area (Klein and Johnson, 1983). The latter provides information that aids in interpreting the origins of the anomalies.

Regional aeromagnetic and gravity maps in the quadrangles form the fundamental geophysical data. These maps are supplemented by more detailed aeromagnetic studies in the Ajo, Cimarron Mountains, Sauceda Mountains, and Crater Range areas, and by geoelectric studies in the Mohawk Mountains and Table Top Mountain areas. Synthesis of these data relates the geophysics to the geology and mineralization of the quadrangles. The locations of the detailed studies and of the regional anomalies mentioned below are shown in figure 5.

Gravity Maps

The regional gravity data consist of two maps: a complete Bouguer gravity anomaly map and a residual Bouguer gravity anomaly map. These maps are compiled

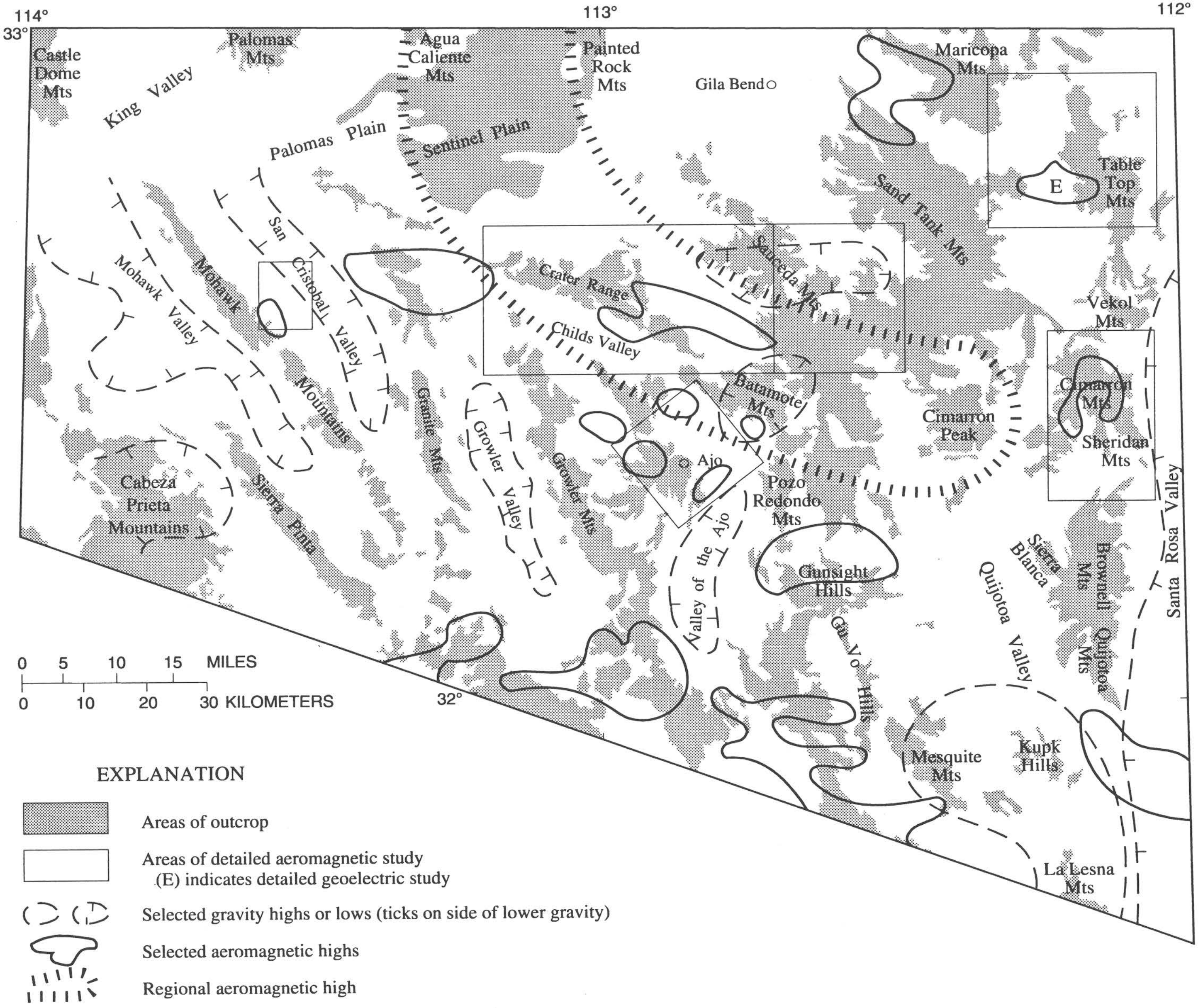

Figure 5. Areas of significant regional aeromagnetic and gravity features and locations of selected studies in Ajo and Lukeville 1° by 2° quadrangles.

from 4,157 gravity observations. Complete Bouguer anomalies contain information on the deep crust and mantle, which is not of critical importance to mineral investigations, whereas residual Bouguer anomalies are filtered to emphasize information in the mid- and upper-crust regions, which are important to the origin and mining of mineral resources.

The residual gravity anomaly map reflects lateral variations in the density of the crust from the surface to depths of a few tens of kilometers. Information on buried geological structures is the primary contribution of gravity interpretation. Mineral deposits are commonly associated with faults and intrusions that have a density contrast with their surrounding rocks; thus, gravity anomalies provide a means either to identify buried environments favorable to mineralization or to estimate the subsurface extent of mapped geologic features. Examples of gravity anomalies that are likely caused by crustal intrusion are the lows associated with the Batamote Mountains, the Sauceda Mountains, and the Cabeza Prieta Mountains (fig. 5). In these cases, plutonic intrusions of siliceous composition and (or) crustal brecciation associated with intrusion are probable causes of the low densities reflected in the gravity data.

A further result from the study of gravity maps is the distribution of deep basins, as opposed to areas that may have bedrock at relatively shallow depth and thus are amenable to mining. The Quijotoa Valley, particularly its more southern reaches, is an area where the lack of an intense gravity low suggests that a deep basin, which is typical in valleys of the southwest, either has not developed or has been modified by subsequent geologic events. The deepest basins are apparently restricted to the west half of the quadrangles, as indicated by the major gravity lows over the Growler, San Cristobal, and Mohawk Valleys. A few moderate gravity lows exist over valleys to the east, but the only major basin inferred east of Ajo is on the east boundary of the quadrangles beneath the Santa Rosa Valley. The depths of the basins in the Ajo and Lukeville 1° by 2° quadrangles have been previously studied by Oppenheimer and Sumner (1980).

Aeromagnetic Map

The aeromagnetic map was compiled from four surveys flown at 1.2 km above sea level along east-west lines at 1.6-km intervals. The map presents anomalies that reflect the lateral variations in the magnetic structure of the crust, which are due to the varying content of magnetized minerals in different rock types. These data are used in identifying geologic contrasts from the surface to depths of a few tens of kilometers. As with gravity anomalies, the main contribution of aeromagnetic interpretation is the identification of buried contrasts related to faulting and intrusion, both of which have a bearing on the distribution of mineralization. Inasmuch as the physical properties involved are different, the gravity and aeromagnetic anomalies show complementary but different aspects of crustal structure.

One result of the study of aeromagnetic anomalies is the delineation of geologic contrasts that are covered by alluvium or volcanic rocks. In addition to providing a degree of geologic mapping beyond outcrops, these contrasts may become targets for future exploration by other geophysical, geochemical, or drill-hole techniques that will aid in identifying the geologic source of the anomaly and in estimating its potential for mineralization. In the quadrangles, 102 aeromagnetic anomalies are identified that have the correct dimensions for near-surface (few hundred meters depth) intrusion or faulting. Although many of these anomalies are discarded as being insignificant to mineralization based on their association with identified or extrapolated geologic relations, others remain viable targets for future study. Several of the aeromagnetic anomalies that are under relatively shallow cover, or that are deeper but transverse to mapped geologic structure and thus indicative of anomalous conditions at depth, are indicated on figure 5.

Study of the aeromagnetic data has also identified a regional aeromagnetic high that extends from the Sentinal Plain to Cimarron Peak (fig. 5). This anomaly is not entirely explained by surface exposures of magnetized volcanic rocks, such as the outcrops of the Sentinel Plain. It probably represents a zone of crustal intrusion. This anomaly has importance in characterizing the tectonic setting of the area and may be significant in indicating a source of mineralizing magma (Klein, 1982a).

Landsat Imagery

As a part of this study, two types of analyses of Landsat Multispectral Scanner data were used to define mineralized areas. These two analyses are limonite mapping as a guide to hydrothermal alteration and lineament analysis as a guide to regional structural controls of mineralization. Digitally processed Multispectral Scanner data were used for all analyses.

Limonitic materials were identified using the color-ratio composite method (Rowan and others, 1974). This technique was used to map areas of hydrothermal alteration associated with limonitic materials and to help define mineralized areas. The term limonite is used as defined by Blanchard (1968)—that is, as a general term for iron oxides—but modified to include any material with the unique spectral reflectance properties of ferric oxide minerals such as hematite and goethite as defined by Hunt (1980). The minerals pyrite and (or) hematite are commonly associated with hydrothermal alteration that is possibly related to mineralization; these minerals weather to produce limonite, which is detected by this color-ratio composite technique. Areas of hydrothermal alteration that lack limonitic materials will not be detected by this technique; however, areas of this type are believed to be insignificant in the study area. Most areas defined as limonitic from the satellite analysis were visited briefly in 1979 and 1980 to determine if the limonite was associated with hydrothermal alteration.

A lineament analysis of southwestern Arizona was performed to define regional structural controls of mineralization. The techniques and philosophy of interpretation used for the lineament analysis are fully described in Sawatzsky and Raines (1981) and are a continuation of studies in Sonora, Mexico (Raines, 1978; Turner and others, 1982). Basically this lineament analysis identified regional lineaments and correlated these lineaments with known occurrences of mineralization in southwestern Arizona. This correlation was then used to identify areas with similar characteristics in the Ajo and Lukeville quadrangles.

Geologic Studies in the Ajo Mining District

As part of this resource assessment, a detailed study was made of the Ajo Mining District that resulted in a reevaluation of the geologic history and structure. The Ajo Mining District comprises the Ajo porphyry copper deposit and various small vein deposits in the Little Ajo Mountains of western Pima County. The New Cornelia Mine, developed on the Ajo deposit by Phelps Dodge Corporation, has produced 2.5 million tonnes of copper since it was opened in 1917. Ajo is the westernmost deposit of a large cluster of porphyry copper-molybdenum deposits in southeastern Arizona, and although molybdenum is recovered from parts of the deposit, it most closely matches the porphyry copper-gold model of Cox (1986a).

The geology of the Ajo 15' quadrangle and the New Cornelia Mine was described by Gilluly (1946). A geologic map of the Ajo Mining District, modified from Gilluly's work, is shown in figure 6. Proterozoic gneiss and granite and possible Mesozoic volcanic rocks of intermediate composition are intruded by quartz dioritic to monzogranitic rocks, which Gilluly named the Cornelia Quartz Monzonite. Copper mineralization is related to granodiorite porphyry phases of this latter unit in the eastern part of the district, and similar granitoid rocks are also exposed in a large pluton in the Cardigan Peak area. Gilluly mapped a major normal fault in Gibson Arroyo west of the mine and concluded that the copper deposit represented the down-faulted apex of the pluton of Cardigan Peak west of this fault. The Locomotive Fanglomerate lies unconformably on the Precambrian and Mesozoic(?) rocks and on the granodiorite porphyry in the mine area. No evidence indicates that the fanglomerate was cut by the Gibson Arroyo fault. Andesitic rocks referred to as the Ajo Volcanics lie within and at the top of the fanglomerate and form the oldest unit of the Ajo volcanic field of Miocene age.

Wadsworth (1968) subdivided intrusive phases in the Cornelia pluton and described textural features in support of Gilluly's idea that the Ajo deposit was the apex of the pluton. McDowell (1971) published K-Ar ages of 65–63 Ma for mineralized rocks in the New Cornelia Mine, and of 20 Ma for a sample from the pluton west of the Gibson Arroyo fault. He ascribed this difference in ages to a younger episode of hydrothermal alteration that influenced only the rocks west of the fault.

As a part of the Ajo and Lukeville 1° by 2° quadrangles mineral resource assessment, a study of the district was made to determine the relation between the pluton of Cardigan Peak and the Ajo deposit (fig. 6). Cox and others (1981) described fluid inclusions in igneous quartz from widely separated samples in the pluton that contain daughter minerals of Na, K, and Fe chlorides and Cu-Fe sulfides. These inclusions suggested that highly saline, metal-rich solutions were evolving from the pluton at the time of crystallization, consistent with the idea that the pluton was the root zone of the deposit. Cox and Ohta (1984) mapped the pluton at a scale of 1:25,000 and outlined areas of hydrothermal alteration that are cut by the Gibson Arroyo fault. This alteration, in which biotite and K-feldspar are replaced by actinolite and oligoclase, respectively, was also noted by Carten (1979) in the root zone of the Yerington porphyry copper deposit in Nevada.

The root-zone theory, however, has not survived the continuing work of geochronologists. Lee Silver (oral commun., 1985), R.M. Tosdal (written commun., 1987), and J.S. Stacey and J.L. Wooden (written commun., 1986) have reported incomplete uranium-lead ages that corroborate McDowell's (1971) middle Tertiary age for the pluton. Hagstrum and others (1987) reported K-Ar ages for the pluton ranging from 23.0 to 21.6 Ma and 25.3 to 23.8 Ma for the Ajo Volcanics. These ages confirm that the pluton is roughly 40 m.y. younger than the porphyry copper deposit and similar in age to the Ajo Volcanics interlayered with the upper part of the Locomotive Fanglomerate. Aside from the fluid inclusions and the alteration in the pluton, the only other hydrothermal features related to the middle Tertiary intrusion are small hematite-chalcopyrite veins with chloritic alteration that are distributed around the southwest margin of the pluton. Hagstrum and others (1987) geographically restricted the Cornelia Quartz Monzonite (informally called the Cornelia pluton) to intrusive rocks of Laramide age exposed in the New Cornelia Mine and on the ridge immediately northwest of the mine; they reassigned the intrusive rocks of middle Tertiary age west of

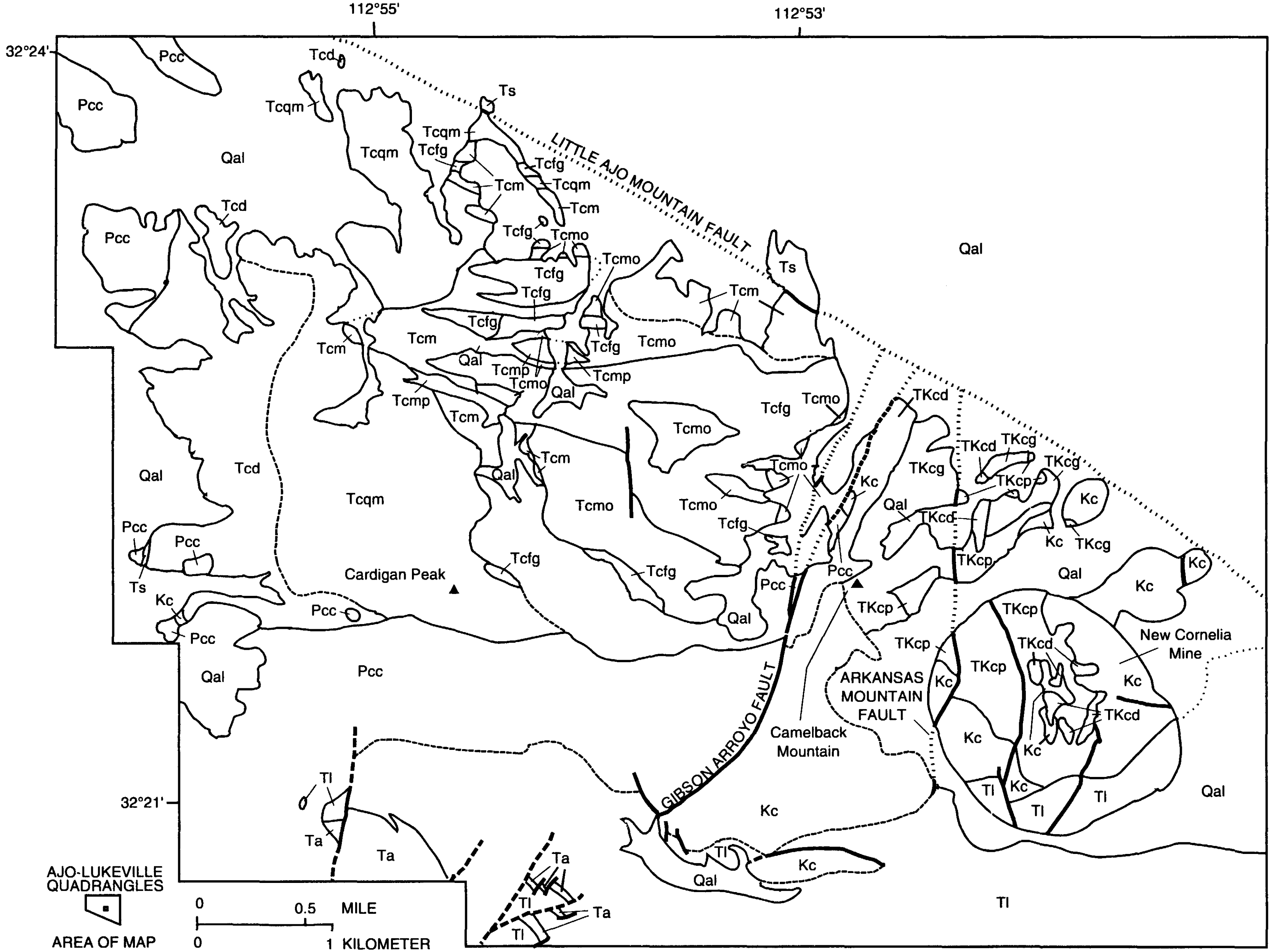

Figure 6. Geologic map of Ajo Mining District, southwestern Arizona.

EXPLANATION

- Qal — Alluvium and mine waste deposits (Quaternary)
- Ts — Sneed Andesite (Tertiary)
- Ta — Ajo Volcanics (Tertiary)
- Tl — Locomotive Fanglomerate (Tertiary)
- Cardigan Peak pluton (Tertiary)—Consists of:
  - Tcmp — Monzogranite porphyry
  - Tcfg — Fine-grained granite
  - Tcmo — Monzogranite with oikocrystic quartz and K-feldspar
  - Tcm — Monzogranite
  - Tcqm — Quartz monzodiorite
  - Tcd — Fine-grained diorite and quartz diorite (Tertiary?)
- Cornelia pluton (early Tertiary and Late Cretaceous)—Equivalent to the Cornelia Quartz Monzonite (see Hagstrum and others, 1987). Consists of:
  - TKcp — Granodiorite porphyry
  - TKcg — Granodiorite
  - TKcd — Fine-grained diorite and quartz diorite
- Kc — Concentrator Volcanics (Cretaceous?)
- Pcc — Cardigan Gneiss and Chico Shunie Quartz Monzonite, undivided (Proterozoic)
- Contact—Dotted where concealed
- Fault—Dashed where inferred; dotted where concealed

Figure 6.—Continued.

the Gibson Arroyo fault to the informally designated Cardigan Peak pluton.

Hagstrum and others (1987), with the cooperation of Ron Gibbs of Phelps Dodge Corporation, collected samples from the New Cornelia Mine area and from the Cardigan Peak pluton. Paleomagnetic analyses of these samples revealed that the Ajo deposit has been rotated approximately 120°, so that its apex plunges 30° to the south and its root zone is exposed near the town of Ajo. According to R. Gibbs (oral commun., 1986), drill holes that pass through the deposit encounter Proterozoic gneiss at depth. In the Cardigan Peak area, the only samples that gave reliable paleomagnetic orientations were from steeply dipping dikes cutting the pluton. These show consistent middle Tertiary poles, indicating that these rocks have not been rotated after their intrusion.

These new data on the Ajo district raise as many new questions as they answer. The similarity of ages between the Cardigan Peak pluton and the overlying Ajo Volcanics requires that the cooling, fracturing, and hydrothermal alteration of the pluton, the movement on the Gibson Arroyo Fault, and the deposition of most of the Locomotive Fanglomerate took place within a time span of about 4 m.y. (25.3 to 21.6 Ma). Although no major mineral deposits are known to be related to the Cardigan Peak pluton, its fluid inclusions and hydrothermal alteration suggest that hydrothermal processes were related to its crystallization. Plutons of middle Tertiary age should be considered prospective for hydrothermal deposits of unknown type in the Ajo region.

Mineral Occurrence Map (MF-1834-A)

Ore has been produced in the Ajo and Lukeville 1° by 2° quadrangles from the following types of mineral deposits: pegmatite, placer gold, porphyry copper (Cu-Au), manganese and polymetallic replacement, Cu-skarn, and various types of vein deposits. Additionally, one locality of chemically precipitated celestite and one gossan that contains base and precious metals have been discovered. The mineral occurrence map shows the locations of known mines and prospects with symbols representative of their deposit type. Small dots indicate prospects about which little is known. They are probably small veins, except for several possible placer-gold prospects in Growler Valley. A table that accompanies the map summarizes available published and unpublished data about location, geology, and resources at each deposit. Entries in the minerals column give representative minerals at the property, but they are not complete lists. A reference indicating where further information can be found is also given for each deposit. Generally, the unpublished reference materials of the Arizona Department of Mineral Resources are available in the U.S. Geological

Survey's Mineral Resource Data System (MRDS) file records. The table is arranged by 15' (or 7½') quadrangles from the northwest corner to the southeast corner of the 1° by 2° quadrangles to facilitate easy transition between the table and map.

The MRDS contains entries for most of the deposits listed in the table (Peterson, 1984). Inquiries about information stored in MRDS may be obtained from the Regional MRDS Representative at the U.S. Geological Survey, 12201 Sunrise Valley Drive, Reston, VA 22092, or at the U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025.

Vein deposits are widely scattered throughout the mountain ranges of the quadrangles. Other deposit types are more restricted geographically owing to geologic constraints. Skarn and replacement deposits are restricted to areas of Paleozoic carbonate rocks, which crop out primarily in the Vekol Mountains in the northeastern part of the quadrangles. Several Laramide-age hornblende-biotite granitoid plutons occur in the eastern half of the quadrangles, but only two areas are known to contain porphyry copper deposits. Two areas have confirmed accumulations of placer gold, and several propsects in Growler Valley are probably also placer prospects. Of numerous small pegmatite bodies in the metamorphic terranes in the western half of the quadrangles, only two have been prospected specifically for pegmatite minerals. Some of the pegmatites are spatially related to vein deposits that have been prospected for base and precious metals, but these pegmatites were neither the source of the mineralized rock nor the object of the prospecting. Except for the porphyry copper deposit at Ajo, the manganese replacement deposits in the Cimarron Mountains, and the placer-gold deposits in the Quijotoa Mountains, the known deposits in the quadrangles are small or nonproductive, although the Vekol Hills porphyry copper deposit in the Vekol Mountains could potentially yield significant amounts of copper.

Technique Used In Mineral Assessment

Introduction

Quadrangles that are 1° by 2° and other similarly large regions are assessed with the purpose of supplying information on mineral resources for use in making decisions on public land that will effect exploration and development and for decisions relating to national or regional resource planning. These decisions require consideration of undiscovered deposits (Richter and others, 1975; Singer, 1975; Hodges and others, 1984). The basic parts of the assessments are (1) the construction of grade/tonnage, or contained metal, models and the description of types of deposits that are known or suspected; (2) the delineation of tracts within which the occurrence of various types of deposits is geologically plausible; and (3) the estimation of the number of undiscovered deposits of each type that are likely to occur within the delineated tracts.

Information Needs for Resource Assessments

Requirements for the multistage assessment process can be divided into two broad categories: (1) information within the region being assessed; and (2) procedures to integrate this information in the assessment. The within-region information should include a buffer zone around the region to allow for interpolation.

The first requirement for information in the region is a geologic map at the same or a more detailed scale as that of the assessment. The map should emphasize lithologic units and ages rather than broadly grouped units. The geologic map is the primary basis for delineating tracts and identifying which are permissive for different deposit types.

The second requirement for information is an inventory of known deposits and prospects in and near the region being assessed. Because of incomplete deposit descriptions, it will not be possible to identify the deposit types for most prospects and some deposits, but those that can be identified will increase confidence in tracts delineated for the deposit type. Prospects may indicate possible deposit types and place limits on what is possible elsewhere. Because much of the older literature is based on rock and mineral deposit terminologies and genetic concepts not used today, older literature may require reinterpretation for proper deposit-type identification. Thus, field examination of at least some deposits in the assessment region is required.

Geophysics, particularly aeromagnetics, has in some cases indicated anomalous or mineralized areas, but its greatest contributions to assessing large regions have been in extending permissive rock units under covered areas and in identifying rock units in poorly mapped areas. Both stream-sediment and rock geochemistry have provided similar benefits to large regional assessments, providing direct evidence for the presence of elements or suites of elements associated with the processes of mineralization.

Another kind of information that can be useful is knowledge of the extent and efficiency of past exploration in the region. Where exploration has not taken place, large variability in the estimated number of deposits might be expected, but where there has been extensive and efficient exploration, there should be little uncertainty in the estimated number of deposits. Exploration information is often difficult to obtain and to evaluate.

The second stage in assessment is integration of all this information, diagrammed in the flow chart in figure 7. In Alaska, assessments have been performed mentally by several economic geologists (Richter and others, 1975). The key to this approach is a requirement that the geologist have many years of experience with a variety of deposit types and geologic settings. In the assessment of Colombia (Hodges and others, 1984) the large number of descriptive (Cox, 1983a, b) and associated grade-tonnage (Singer and Mosier, 1983a, b) models provided both guidance in the integration of information and a common set of standards. Although the process of delineating tracts by deposit type still requires mental integration of many variables, documentation of the characteristics of various types of deposits broadens the scope of the integration. Thus, deposit models, whether in the minds of experienced geologists, written on paper, or perhaps in a computer, provide a format for the integration of the information in the assessed region. After selecting the appropriate deposit models and delineating permissive tracts for them, an estimate of the number of undiscovered deposits was made (fig. 8). In the Ajo and Lukeville quadrangles, estimates were made for porphyry copper, skarn and polymetallic replacement, porphyry molybdenum, and evaporite deposits by a group of five geoscientists with diverse backgrounds who participated in the study. Estimates were made individually, but a Kendall rank correlation analysis showed that these estimates reached a consensus in most cases. Undiscovered deposits estimated for each deposit type have the same grade-tonnage distribution as the world-wide distribution for that deposit type. That is, half of the undiscovered deposits would be larger and half smaller than the median for that type.

The form of presentation of the assessment is critical. A map or maps showing the location of tracts with mineral potential is required and must be keyed to tables, organized by tract, in which deposit types, known deposits, geologic environment, and comments particular to each tract are presented. A short summary of the deposit types, exploration guides, and recommendations is useful. Graphical presentation of grade-tonnage models (fig. 9*A*, *B*) and of descriptive models has achieved wide acceptance. These descriptive and grade-tonnage models have been enlarged and republished as U.S. Geological Survey Bulletin 1693 (Cox and Singer, 1986).

Mineral Resource Assessment Maps (OF-85-527, MF-1834-B)

The mineral resource assessment for the Ajo and Lukeville 1° by 2° quadrangles consists of three maps that outline permissive tracts for 16 deposit types and a text that discusses the mineral resource assessment. The assessment, which follows the method of Singer (1975) wherever possible, estimates the number of undiscovered deposits of a given type that might occur within the tracts. This method was applied for several deposit types. Lacking good deposit models or adequate information on the tracts, some deposit types were discussed qualitatively. We delineated tracts within the quadrangles and organized the text according to deposit type, primarily using available deposit models (Cox and Singer, 1986). Each section of the text provides an in-

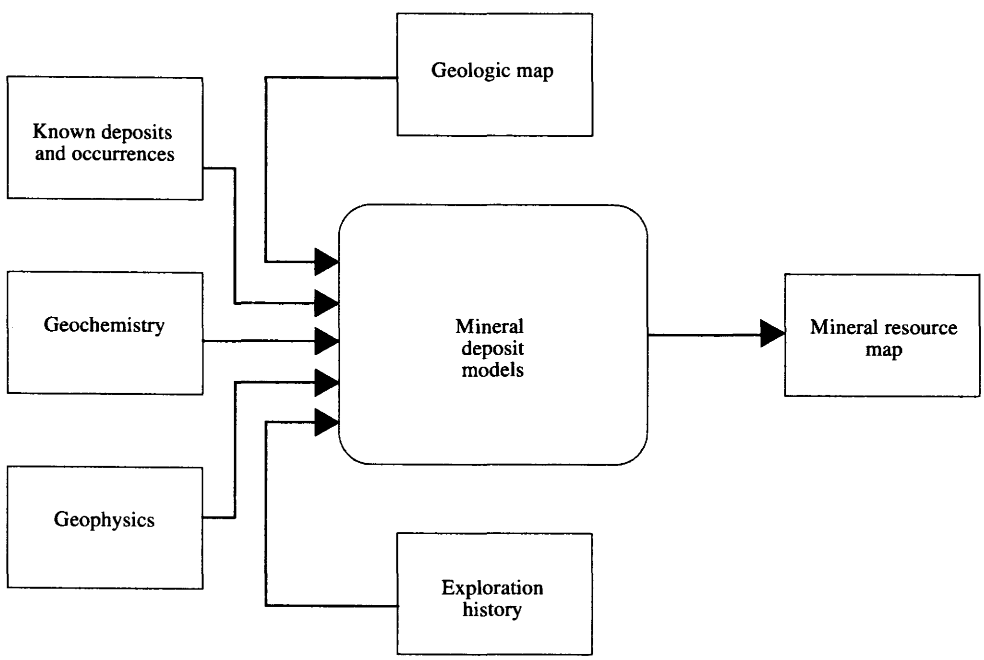

Figure 7. Diagram showing how flow of information from field studies is applied to selection of deposit models and delineation of tracts in mineral resource map.

troductory statement about the deposit type and explains why it was included. Criteria favorable for the presence of such a deposit are listed and are used to delineate the tracts. A brief description of known deposits in or near the quadrangle is given. The final section discusses the mineral resource assessment and includes probabilistic estimates for the number of undiscovered deposits, where appropriate.

Porphyry copper, skarn, and polymetallic replacement deposits are known in the quadrangles, and there is potential for additional discoveries elsewhere. Twelve tracts for porphyry copper are delineated in and near exposed, or possibly buried, Laramide-age plutons. Not enough information was available to delineate separately for the types (Mo- or Au-rich) of porphyry copper deposits. Ten tracts for porphyry copper-related skarn, skarn, and polymetallic replacement deposits are shown where Paleozoic limestone is known or likely to be present. There is a 50 percent chance of one or more undiscovered porphyry copper-molybdenum or porphyry copper-related skarn deposits and a 10 percent chance of

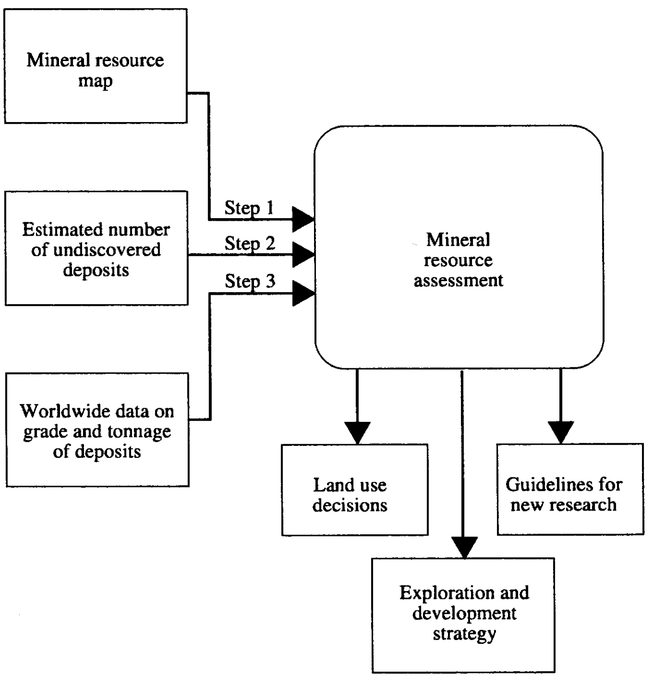

Figure 8. Diagram showing how resource assessment is derived from mineral resource map, estimates of number of undiscovered deposits, and worldwide grade-tonnage data. Applications of resource assessment are shown on lower right side.

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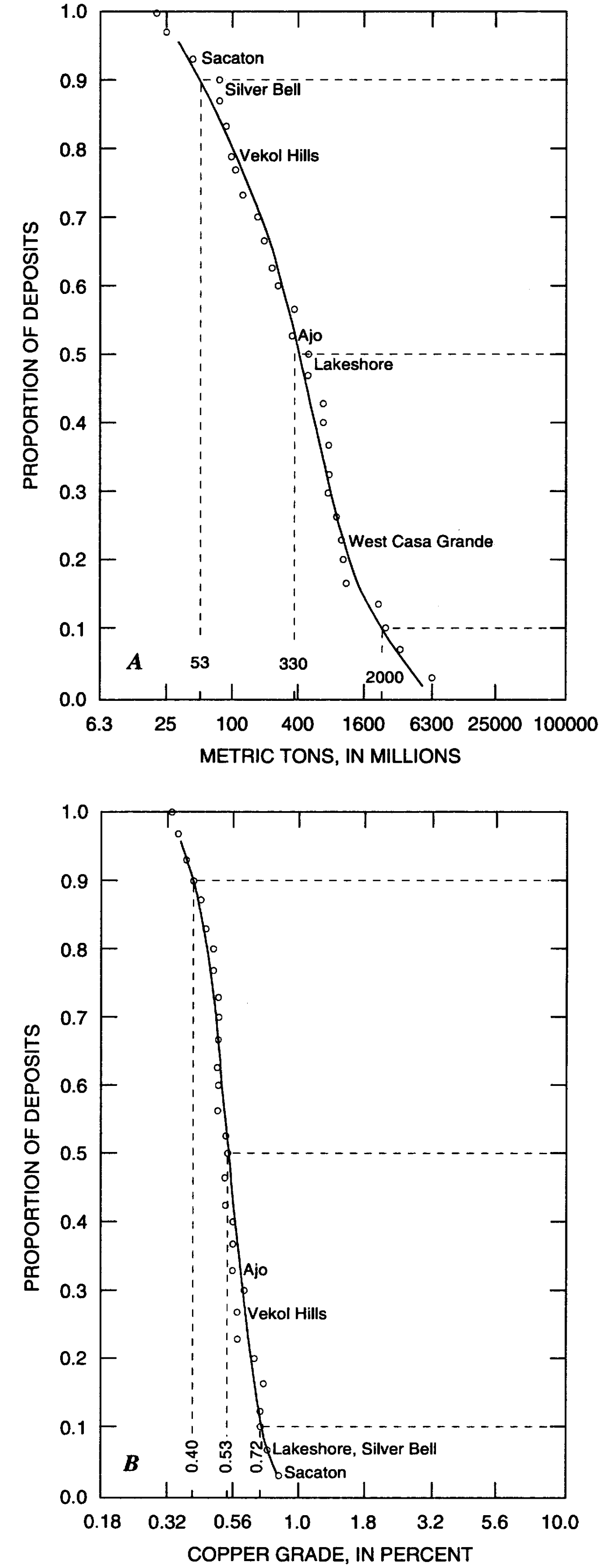

Figure 9. Inverse cumulative distribution of copper tonnage (*A*) and grade (*B*) in porphyry copper deposits in Arizona, showing tonnages and grades for deposits in and near Ajo and Lukeville 1° by 2° quadrangles. Tonnages and grades for these deposits are not significantly correlated.

four or more. There is also a 50 percent chance of one or more undiscovered Cu-skarn deposits and a 10 percent chance of four or more. There is a smaller probability that the quadrangles contain undiscovered replacement deposits.

Porphyry molybdenum deposits (low-fluorine type) have not previously been discovered in the quadrangles, but data suggest that 10 tracts contain some characteristics favorable for such deposits. There is a 50 percent chance of one or more undiscovered porphyry molybdenum deposits and a 10 percent chance of two or more.

Known vein deposits in the quadrangles include gold-silver-quartz veins that include low-sulfide gold-quartz veins, epithermal veins, vein-type iron deposits, and tungsten-bearing veins. Seven tracts with known gold-silver-quartz veins may contain additional deposits. Eight tracts show evidence for the existence of undiscovered epithermal vein deposits, and three tracts may have vein-type iron deposits. The undiscovered gold-silver-quartz veins and iron-bearing veins could contain uranium. Nine tracts show evidence for tungsten-bearing veins. If the known veins of these types in the quadrangles are representative, additional new deposits would likely be small.

There are numerous pegmatites, particularly in the western part of the quadrangles, but most are small and of simple mineralogy. Four tracts have potential for productive pegmatites based on known occurrences and geochemical data.

Undiscovered manganese replacement deposits would most likely be near the known deposits in the three designated tracts. Although limestone provides evidence for these deposits, there is no direct evidence for manganese in limestones outside the Cimarron Mountains.

Four tracts delineated for placer gold include known placer-gold localities and suspected placer localities based on evidence on the pediments or on the presence of suitable source terranes in the adjacent mountains.

Geological, geochemical, and (or) geophysical data suggest the possibility of several other deposit types. These include gneiss-hosted and volcanic-hosted disseminated gold mineralization, rhyolite-hosted tin deposits, evaporite deposits, various types of basin-hosted uranium deposits, perlite, and zeolites. In addition, warm-water wells suggest the possibility of geothermal resources.

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