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THE CUSMAP PROGRAM IN THE AJO AND LUKEVILLE 1°x 2° QUADRANGLES

By Floyd Gray

The U.S. Geological Survey began the study of the geology and mineral resources of the Ajo and Lukeville 1° x 2° quadrangles in 1979 as part of the Conterminous United States Mineral Assessment Program. The project was initiated as a natural outgrowth of the Papago Indian Reservation mineral appraisal project. The Ajo/Lukeville project has utilized a multidisciplinary approach involving geology, geochemistry, geophysics, and studies of mineral deposits. It also included studies of granitic and metamorphic rocks, alteration, linear features, and isotopic dating. Results of these studies will be published in folio format as a series of 1:250,000-scale maps in Geological Survey Miscellaneous Field Studies Map MF-1877. Some larger scale geologic maps and topical studies will be prepared as Open-File Reports or other publications.

The Ajo and Lukeville 1° x 2° quadrangles cover about 21,000 km^2 in southwest Arizona between lat. 32 and 33 N. and long. 112 and 114 W. The quadrangle is within the Basin and Range physiographic province and the ranges constitute about 45 percent of the total area.

Pre-Tertiary rocks are exposed in the western, southern, and eastern part of the sheet while Tertiary age volcanic rocks are the predominate rock type in the central core of the quadrangle. the Tertiary rocks make up about 60 percent of the rocks exposed, and include intermediate and mafic flows, rhyolitic flows and intrusive bodies, and minor ash-flow tuff and tuffaceous sedimentary rocks. Quaternary basalt flows cover an area of approximate km^2 along the western edge of the quadrangle.

About 50 percent of the quadrangle was mapped at a scale of 1:62,500 or larger during the Ajo/Lukeville project. Areas selected for geologic mapping were chosen after an assessment of existing geologic maps and consideration of potential resources. Areas of new geologic mapping are the Ajo and Crater Range, Growler, Sauceda, Sand Tank, and Batamote Mountains.

Gravity and magnetic maps compiled for the Ajo/Lukeville CUSMAP Study combine new data with that from previous compilations. Maps prepared from the geochemical data show the distribution and abundance of selected elements, and summarize aspects of the regional geochemistry. Data from the LANDSAT Satellite Multispectral Scanner were used to compile maps showing the distribution of linear features and the generalized distribution of hydrothermally altered rocks.

Mineral deposits are widely distributed in the quadrangle and include gold and base metal deposits, skarn, low-sulfide quartz veins and replacement deposits. The mineral resource assessment indicates that the potential for discovery of precious-metal and base-metal deposits is high in various parts of the quadrangle.

MINERAL OCCURRENCES IN THE AJO AND LUKEVILLE 1° by 2° QUADRANGLES, ARIZONA

By R.M. Tosdal and Jocelyn Peterson

Numerous types of mineral occurrences are known within the Ajo and Lukeville 1° by 2° quadrangles, southwestern Arizona. These occurrences include base- and precious-metal deposits, minor radioactive and rare earth elements deposits, and deposits of manganese, silica, barite, and strontium. Of the wide variety of occurrences, only two are large ore deposits. Most of the mineral ore occurrences are small, with a maximum reported production of less than 15,000 tons.

The largest base metal deposit is the New Cornelia Mine, a porphyry copper deposit near Ajo from which 240 million tons of ore were produced as of 1975. Molybdenum and precious metals were also significant by-products of this mine. The undeveloped Vekol porphyry copper prospect in the Vekol Mountains is the other large tonnage deposit. Other base metal occurrences include skarn and vein deposits that are related genetically to the porphyry copper deposits, epithermal fissure veins, low-sulfide quartz veins, and replacement deposits. The porphyry copper and related deposits are genetically related to epizonal Late Cretaceous granites. Low-sulfide quartz veins are genetically related to Jurassic and Cretaceous granites, or they occur as widely distributed syn- or post-tectonic veins in metamorphic terranes of Proterozoic, Cretaceous, and early Tertiary age. Epithermal fissure veins are related to Oligocene epizonal granites.

Several types of precious metal deposits, with or without associated base metals, occur throughout the quadrangle, but are primarily concentrated in the southern and eastern parts of the quadrangle. Epithermal Pb-Zn-Ag-Au-Ba-F veins yield the largest tonnage of any vein type and occur in the Gunsight Hills, and in the Ajo, Cimar, Painted Rock, and Palomas Mountains. Other significant precious-metal deposits occur in the Quijotoa and Brownell Mountains where gold was recovered from low-sulfide quartz veins and from specularite or magnetite breccias that cut Jurassic volcanic and granitic rocks, and from placers on the fringing pediments. Gold and silver were also significant by-products of the New Cornelia Mine. Minor precious metal vein occurrences are common in many ranges. Rocks of all ages host the occurrences, although those in Jurassic and Oligocene plutonic rocks are larger.

Uranium, thorium, and some rare earth elements are present in pegmatites that cut Middle Proterozoic porphyritic granite near Chico Shunie Well southwest of Ajo, in the O'Neill Hills, and in the western Agua Dulce Mountains. Some uranium also occurs in low-sulfide quartz veins in the Quijotoa and Cabeza Prieta Mountains.

Non-metallic mineral occurrences are scattered throughout the quadrangle. Manganese is common in faults or as replacement deposits in the eastern part of the quadrangle. Barite and fluorite occurs in epithermal fissure veins that cut Oligocene volcanic and plutonic rocks in the Gunsight Hills and Painted Rock Mountains, and in Mesozoic granitic rocks and Proterozoic gneiss in the Mohawk Mountains. Quartzite, derived by thermal metamorphism of the Cambrian Bolsa Formation, has been mined for silica flux. Gypsum, strontianite, and celestite have been reported in the basin filling sediments to the north of the Sauceda Mountains.

Two general observations are made from the distribution of mineral occurrences in the quadrangle. First, the large base- and precious-metal deposits are related to Mesozoic and Oligocene epizonal plutons. Mesozoic and early Tertiary low-sulfide quartz veins are widespread in the quadrangle, but their significance as deposits is limited. Second, vast bedrock areas in the quadrangle lack known metallic mineral occurrences of any type or size. Gently dipping to subhorizontal volcanic rocks of the Miocene Ajo Volcanic Field cover these areas, and these unmineralized rocks may conceal mineral occurrences.

THERMO-TECTONIC TERRANES OF THE AJO AND LUKEVILLE 1° by 2° QUADRANGLES: K-AR GEOCHRONOLOGY OF EARLY TERTIARY AND OLDER ROCKS

By R.M. Tosdal, and R.J. Miller

The Ajo and Lukeville 1° by 2° quadrangles are divided into three thermo-tectonic terranes based on geologic criteria and K-Ar geochronology. Terrane 1 in the northeastern part of the quadrangle had a geologic and thermal history similar to that of adjoining southern Arizona. Here, K-Ar mineral dates from granitic rocks generally approximate their inferred emplacement age. Terrane 2, comprising the southeastern parts of the quadrangles, consists of Jurassic and Cretaceous supracrustal and plutonic rocks that were deformed and metamorphosed during a Late Cretaceous and early Tertiary orogenic episode. K-Ar mineral dates are minimum ages and either approximate the time of deformation or reflect cooling of the terrane. Terrane 3 constitutes the western half of the quadrangle, where a relatively simple Mesozoic and early Cenozoic geologic history is superimposed on several Proterozoic gneiss packages. K-Ar mica dates from this terrane decrease eastward due to the progressive cooling and uplift of mid-crustal rocks in the early Tertiary.

Terrane 1 occupies the region north of a diffuse boundary between the southern Growler Mountains on the west and the Cimar Mountains on the east. This region is also known informally as the northern Papago terrane of Haxel and others (1980). Here, a Proterozoic basement of metamorphic and granitic rocks is overlain unconformably by thin sequences of Upper Proterozoic and Paleozoic sedimentary rocks. The clastic rocks are overlain by Jurassic and Cretaceous volcanic and sedimentary rocks and intruded by epizonal granites of similar age. K-Ar muscovite and biotite dates from Middle Proterozoic megacryst granites and related pegmatites in the Little Ajo Mountains and in the Haley Hills agree or are only slightly younger than their inferred emplacement ages of about 1,400 Ma (Balla, 1972; this study). Similarly, biotite and locally hornblende K-Ar dates from Late Cretaceous epizonal granites near Ajo are inferred to approximate their emplacement ages, based on U-Pb isotopic data from the same or related granitic stocks (McDowell, 1971; J.E. Wright, in Tosdal, 1979; Anderson and others, 1980; R.M. Tosdal, 1986, unpub. data; Hagstrum and others, 1987).

Terrane 2 lies south of terrane 1, extends westward to the southeastern Agua Dulce Mountains, and is also known informally as the southern Papago terrane of Haxel and others (1980, 1984). Jurassic supracrustal and plutonic rocks and sparse Cretaceous plutonic rocks are the oldest autochthonous rocks in the terrane. Proterozoic and Paleozoic rocks are rare and are demonstrably allochthonous. In the Late Cretaceous and early Tertiary, the terrane underwent a complex deformation involving regional metamorphism and thrust faulting. Late- to post-kinematic peraluminous granite plutons intruded the region. Deformation affected Late Cretaceous plutons, and 72 and 70 Ma K-Ar dates are reported from low-grade metamorphic rocks (Haxel and others, 1984; Tosdal and others, 1986). Deformation ceased by about 58 Ma, based upon a K-Ar hornblende date of 59.1 Ma from an orthogneiss in the Gunsight Hills, 59-57 Ma K-Ar dates from mylonites in the Quitobaquito Hills Wright and Haxel, 1982; Haxel and others, 1984), and a 58 Ma U-Pb zircon age for the peraluminous Pan Tak granite located to the east of the quadrangle. A 49 Ma muscovite K-Ar dates from a peraluminous granite in the Sonoyta Mountains, K-Ar biotite K-Ar dates of 47-32 Ma from the Gunsight Hills, and 39-36 Ma whole-rock phyllite dates from the Sheridan Mountains (Shafiqullah and others, 1980; Haxel and others, 1984; Tosdal and others, 1986; this study) suggest that the terrane gradually cooled and was probably uplifted in the early Tertiary.

Terrane 3 lies west of the Growler Mountains and consists of several Proterozoic gneissic and granitic packages that were intruded by Cretaceous(?) mesozonal granites. The largest granite in the terrane crops out in four ranges and is known as the granite of Sierra Pinta (Gray and others, 1988) or informally as the "Gunnery Range Batholith" of Shafiqullah and others (1980). Igneous muscovite and biotite K-Ar dates from the granitic rocks decrease eastward across the terrane. For example, a biotite date of 53 Ma is reported from the southern Tinajas Altas Mountains southwest of the quadrangle, biotite dates in the Cabeza Prieta and Copper Mountains are 52 to 50 Ma, biotite dates in the Sierra Pinta Mountains 48-45 Ma, a biotite date in the Bryan Mountains is 40 Ma, and in the Granite Mountains biotite dates are between 40 and 38 Ma (Shafiqullah and others, 1980; this study). Muscovite dates similarly decrease eastward, with a 53 Ma age in the Tule Mountains, 53 to 50 Ma ages in the Sierra Pinta Mountains, and 45 Ma age in the Bryan Mountains. (No igneous muscovite dates are known from the Granite Mountains.) All muscovite and biotite dates from igneous rocks are interpreted as minimum ages, and any proposed emplacement ages for the granites based on K-Ar mica dates are suspect. The eastward younging of mica ages from Cretaceous(?) granitic rocks reflects the slow cooling of the terrane and probably its progressive uplift in the early Tertiary.

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TRACE-ELEMENT SYSTEMATICS OF PERALUMINOUS LEUCOGRANITES, BABOQUIVARI MOUNTAINS CHAIN, SOUTH-CENTRAL ARZIONA

By Gordon B. Haxel

The early Tertiary moderately peraluminous Pan Tak Granite, Coyote Mountains, and granite of Presumido Peak, southern Baboquivari Mountains, consist of two interspersed intrusive phases: older garnet-poor-leucocratic monzogranite (OPG) and younger garnet-bearing alaskitic monzogranite (YPG). The least-evolved of the OPG have 73 percent SiO^2; the highest percent of CaO, Fe^2O^3, MgO, Co, and Ba/Rb ratio (=7); and gently right-sloping chondrite-normalized (CN) REE spectra with CN La=80. CN HREE=15, and moderate Eu anomalies (Eu/Eu*=0.5). Relative to average upper continental crust (UCC), these primitive OPG are depleted to 0.5x or lower in all ferromagnesian elements (except Mn), Mo, W, and Sn; and enriched by >2x only in U. Ratios of most LILE and HFSE, including Nb/Ta=8-15, are similar (±50 percent) to UCC; but Sn/W and Ta/Sn are 2.5x those of UCC.

Differentiation of the peraluminous granites is unusual in certain aspects. Differentiation is marked by slight increase in SiO^2 (to 76 percent), sharp decline of Ba/Rb (to 0.5-0.05), development of flat to slightly concave-upward REE spectra (CN L&HREE=8-40) with deep Eu anomalies (Eu/Eu*=0.2-0.03), increase in Nb and Ta, and decrease of Nb/Ta to unusually low values (4-6). Ta and Th are negatively correlated. More than half of the YPG samples have high Nb (>60 ppm) and Ta (>10 ppm). Nearly all samples, of both phases, have low F (<0.08 percent), Cl (<0.01 percent), Sn (<5 ppm), W (<2 ppm), and Mo (<0.5 ppm). In both plutons, the most-evolved YPG are, relative to the least-evolved OPG, enriched in Sc, Ga, Rb, Y, Nb, Sn, Ta, and U; and depleted in H, Mg, Ca, Ti, Fe, Co, Sr, Zr, Sb, Ba, LREE, Eu, Hf, Pb, and Th. Na, Al, K, HREE, and W are only slightly (<15 percent) enriched or depleted. Be, Mn, Cu, and Cs behave differently in the two plutons. For most elements, these patterns of enrichment or depletion are similar to those reported from other high-silica magmatic systems. However, the Baboquivari peraluminous granites are unusual in that Sb and Th in both plutons, and Cs in one pluton, are strongly depleted during differentiation.

GEOLOGICAL, GEOCHEMICAL, AND GEOPHYSICAL STUDIES IN THE CENTRAL PORTION OF THE MOHAWK MOUNTAINS, SOUTHWESTERN ARIZONA, USA

By R.G. Eppinger, P.K. Theobald, D.P. Klein, and G.L. Raines

Reconnaissance geochemical studies at 1:250,000 scale in the Ajo 1°by 2° quadrangle delineated an area in the central portion of the Mohawk Mountains that is anomalous in the following metals:

1) minus-30 mesh stream sediments --weak high in Mo,
2) non-magnetic heavy mineral concentrates --high Pb, W, Bi, Mo.

Initially, we felt that this geochemical anomaly, discerned with 8 sediment samples, might reflect mineralization from a single large porphyry system.

Based on the above information, follow-up geochemical sampling, 1:24,000-scale geologic mapping, and detailed geophysical studies were undertaken in the 10 mi^2 study area. Results of these follow-up studies indicate that the single model for the geochemical anomaly is not appropriate; rather, several styles of mineralization, probably of different origins and ages, are more likely.

Geology

Several juxtaposed, lithologically distinct terranes are separated by faults that are generally expressed by gravel-filled topographic depressions. Terranes vary lithologically from massive to well-foliated meta-andesite and granite in the northern and western part of the area, to locally gneissic quartz monzonite and a variety of pelitic schists and gneisses in the southeast. Terranes could not be correlated across the major faults; radiometric dates are lacking. Extensive magnetite-tourmaline-allanite-bearing granitic pegmatites cut meta-andesite in the north. Pegmatite textures vary from fine-grained along borders to coarse-grained in the center and sericitization of enclosing rocks is locally intense. Sparse siliceous rhyolite dikes crop out along the southeastern edge of the area, locally exhibiting spherulitic silica and glass.

Phyllic alteration is common in the southeastern terrane, with intensity of alteration increasing eastward. Fluorite is pervasive and sericite, pyrite (or limonite after pyrite), silica, and quartz are common.

Geochemistry

Stream sediments and heavy-mineral concentrates from stream sediments (HMC) were collected at 139 sites, from intermittent first-order streams, generally at the interface of bedrock with basin gravel. Samples were analyzed for 31 elements by semiquantitative emission spectrography and HMC samples were analyzed mineralogically by optical methods.

Elements anomalous in stream sediments include Be, Cu, Mo, Pb, W, and Y. Single-site anomalies were more common than clustered groups of anomalous samples. HMC data were more useful, delineating four groups of samples with distinctive anomalous element suites: Cu-Mo-Pb±W in the western terrane, Cu-Mo-W±Pb-Bi in the northern terrane, Th-Mo-Pb±Sn in the east-central terrane, and Bi-Pb±Sn-Mo in the southeastern terrane.

Mineralogical data were useful in further characterizing the four groups of anomalous samples. Scheelite and molybdenian scheelite and tourmaline are most concentrated in the northern part of the area. Wulfenite, secondary Bi minerals (kettnerite, bismutite), galena, and abundant fluorite and barite, are found in the east-central and southeastern parts of the area. Specular hematite, chlorite, malachite, cuprite, and manganese oxides were observed in samples collected from the western half of the study area.

Geophysics

Reconnaissance aeromagnetic data revealed a magnetic high over the study area and pediment gravel immediately east of the study area. A detailed audio-magnetotelluric survey revealed high resistivities (300-1,000 ohm-m) beneath the eastern half of the study area, generally indicating areas of thin gravel cover over bedrock. Locally, low resistivity values (70-150 ohm-m) at depths less than 350 m in the southeastern terrane may reflect areas of concealed hydrothermal phyllic alteration.

Discussion

A mid-Tertiary detachment fault has been mapped in the Mohawk Mountains 9 mi north of the study area. The detachment trends along the eastern flank of the Mohawk Mountains, and has been postulated to extend 16 mi southward. If the detachment does extend into the study area, a possible hypothesis can be drawn to account for the complex geology and diverse types of mineralization observed.

The detachment fault is probably the major north-south-trending fault concealed along the western edge of the study area, possibly indicated by manganese oxides, copper oxides, and specular hematite in concentrates collected in the western half of the study area, and chlorite and manganese oxide identified in rocks collected near the concealed fault. Other faults in the area may be sympathetic/antithetic faults related to the detachment, or may be post-detachment, related to continued extension in the region. The juxtaposed, lithologically diverse terranes may have been brought together during the mid-Tertiary detachment-faulting event. Transport distances and sources of the terranes are unknown.

Mineralization preceded, was contemporaneous with, and may have followed the detachment-faulting event. The W-Mo mineralization in the northern terrane is probably related to the widespread pegmatites in this terrane, although scheelite has not been found in outcrop. No evidence for skarn or greissen was found in the area. Age of the pegmatites is uncertain; they could be Precambrian to Mesozoic. However, they are older than the Tertiary(?) extensional faults that cut them off to the south.

The Cu-Mo-Pb anomaly in the western terrane, as well as smaller Cu-Pb occurrences throughout the study area, may be related to the detachment-faulting event. Prospects in the western terrane contain abundant secondary Cu minerals, calcite, manganese oxides, and massive specular hematite as vein fillings along faults, shears, and fractures.

The Bi-Pb-Sn-Mo anomaly in the southeastern terrane is arcurate in shape, centered roughly aroung the aeromagnetic high in pediment gravels. Rhyolite dikes, fluorite, and extensive phyllic alteration are found in the area. These data may reflect a porphyry system (Mo?) concealed by gravels just east of the exposed crystalline rocks. This mineralization may be younger than the low-angle detachment-faulting event; the coherent aeromagnetic anomaly may indicate an intact cupola.

The Th-Mo-Pb-Sn anomaly in the east-central terrane is problematic. Thorium is widespread, although no Th mineral was found. The Mo and Pb values are highest in the western part of the terrane, near the proposed detachment fault, where argentiferous galena, fluorite, pyrite, malachite, hematite, and chlorite occur in prospects. Whether this anomaly is related to the detachment to the west, to the porphyry to the southeast, or to a combination of both is unclear.

Conclusion

This study documents a change-of-scale phenomenon, wherein an apparently simple geochemical anomaly discerned at the reconnaissance level is found to be much more complex at the detailed follow-up scale. Change in geochemical anomaly patterns with scale is a common feature of geochemical distributions, but is often overlooked or forgotten in geochemical exploration, as reflected by the scant mention of the subject in geochemical literature.

In this study, geologic mapping was fundamental in deciphering the complex geochemical patterns. The scenario for the complex geology and geochemical patterns is presented here as a working hypothesis. Only through continued detailed work in the area can the evidence be gathered to establish the true nature and significance of the mineralization responsible for the geochemical and geophysical anomalies.

STRATIGRAPHY, GEOCHRONOLOGY, AND GEOCHEMISTRY OF A CALC-ALKALINE VOLCANIC FIELD NEAR AJO, SOUTHWESTERN ARIZONA

By Floyd Gray, and Robert J. Miller

The Ajo volcanic field, in the Basin and Range province of SW Arizona, covers approximately 5,000 km^2 and consists of rock types ranging from basalt through andesite to rhyolite and interlayered sedimentary rocks. Ash-flow tuffs form a small part of the silicic volcanic rocks. Tertiary magmatism was probably initiated by subduction of the Farallon plate beneath western North American before subsequent sessation of the offshore Benioff zone in this region. The earliest flows, however, were affected by precursory Basin and Range extensional deformation, constrained at approximately 23 m.y. B.P. The volcanic section rests on an extensive erosional unconformity cut on granitic and metamorphic rocks of Proterozoic to Jurassic age. K-Ar ages show that the field consists of a distinct tripartite sequence: (1) an earliest Miocene (23.8-22 m.y. B.P.) steeply tilted sequence of red fanglomerate and coarse arkosic sandstone intercalated with andesite, rhyolite, rhyodacite, and scattered pyroclastic rocks; (2) an early and middle Miocene (22-15 m.y. B.P.) shallowly dipping sequence of basalt, trachyandesite (Childs Latite), silicic flows, and associated pyroclastic rocks; and (3) a middle Miocene (16-14 m.y. B.P.) relatively flat lying sequence of basaltic andesite and andesite.

Geochemical data suggest a calc-alkaline, high K differentiation trend with slight Fe enrichment for most of the volcanic rocks. The rocks are characterized by relatively high K_2O, Sr, Rb, and Ba, but low Ti, Ni, and Cr concentrations. However, major and trace element trends of trachyandesite lavas (Childs Latite) are distinct but parallel to the rest of the field, suggesting a heterogeneous source for the volcanic rocks of the Ajo field.

K-AR AGES OF VOLCANIC ROCKS NEAR AJO, PIMA, AND MARICOPA COUNTIES, SOUTHWESTERN ARIZONA

By Robert J. Miller, Floyd Gray, Richard M. Tosdal, and Edwin H. McKee

The volcanic field near Ajo, Arizona (fig. 1), is a tripartite constructional volcanic field composed predominantly of Tertiary lavas that include the entire compositional range between basalt and rhyolite. These rocks outcrop over an area of approximately 5,000 km^2 extending from the Mexican border to just north of U.S. Interstate Highway 8 and from the Growler and Aguila Mountains on the west to the Vekol-San Simon valleys on the east. Scattered Tertiary volcanic rocks farther east (Dockter and Keith, 1977; Rytuba and others, 1978; Briskey and others, 1979); are considered older than and apparently not related to those described here. Previous mapping in the area is of reconnaissance nature and is summarized on the Geologic Map of Arizona (Wilson and others, 1969). Much of the area lies within restricted access areas of Luke Air Force Range. A limited number of K-Ar ages of Tertiary rocks in the area have been published by Shafiquallah and others (1980), Eberly and Stanley (1978), Jones (1974), and Tosdal (1979).

We report here 13 new K-Ar ages from volcanic rocks of the Ajo volcanic field samples as part of the USGS Ajo 2° by 1° CUSMAP project. The dates are used in the study of the volcanic stratigraphy of the area and were selected because they define the age range of units within each of the tripartite sections. A more detailed compilation of isotopic age dates for the volcanic field is currently in progress (Miller and others, in prep.).

Geological Discussion

The Tertiary rocks of the Ajo volcanic field rest upon an extensive erosional unconformity cut on granitic and metamorphic rocks ranging in age from Proterozoic to early Tertiary (Haxel and others, 1980). Tertiary volcanic rocks in the area are divided into 3 sequences separated by angular unconformities: (1) the oldest sequence is late Oligocene to early Miocene in age and consists of red fanglomerate and coarse arkosic sandstone intercalated with andesite, rhyolite, rhyodacite, and local pyroclastic rocks; (2) a 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.

The oldest group is exposed in scattered areas along the western edge of the field, mainly northwest and southwest of the Sauceda Mountains. The unit is characterized by steeply tilted volcanic rocks intercalated with coarse clastic sedimentary strata. Initiation of volcanism was contemporaneous with local uplift and unroofing of crystalline basement rocks. In the Ajo area (Gilluly, 1946) and Growler Mountains (Gray and others, 1984) massively bedded coarse fanglomerate consists mostly of locally derived Proterozoic granite and gneiss. The coarse fanglomerate grades upward into coarse arkosic sandstone. Volcanic interbeds are increasingly abundant in the upper part of the unit. An age of 23.8±0.8 m.y. was obtained on the volcanic rocks near Ajo Peak (fig. 1, no. 81AM176). These flows are in the upper part of the tilted fanglomerate-andesite sequence and thus represent a minimum age for the accumulation of the fanglomerates. A tuff stratigraphically above the tilted andesite-fanglomerate sequence yielded an age of 22.0±0.7 m.y. (fig. 1, no. 81AM96).

The middle unit is the most widespread of the three and forms a heterogeneous assemblage of basalt, andesite, and rhyolitic rocks. The oldest rocks in the unit are rhyolitic to rhyodacitic flows and pyroclastic tuffs. Following eruption of these, volcanism progressed westward, then southward. An eroded rhyodacite dome in a composite volcano in the Sand Tank Mountains stands approximately 300 m high. A dacite flow from the flank of the dome yields a K-Ar age of 21.8±0.7 m.y. (no. AA1128). A lava flow in the vicinity of Hat Mountain and the adjacent Sauceda Mountains is dated at 20.7±0.6 m.y. (no. 81AG206). Silicic volcanism migrated southward into the Sikort Chuapo Mountains and the Ajo Range, eventually forming the tuffaceous rocks and the rhyolitic flows of the Mt. Ajo area at around 15.4 m.y. (Tosdal, unpub. data; Jones, 1974; May and others, 1981).

Contemporaneous with silicic volcanism approximately 21 m.y. ago basalt, olivine basalt, and basaltic andesite were extruded in the region from the northern Sauceda Mountains to the southern Sand Tank Mountains. An age of 18.4±0.9 m.y. (no. 82AM61) obtained on plagioclase from that sequence is considered to be too young based on geological evidence. The basalt flows occur in a composite volcano at Cimarron Peak and in fissure eruptions elsewhere. These basalts form prominent cliffs and plateaus throughout the eastern part of the volcanic field. The most distinctive rock type of the middle sequence is a coarsely porphyritic Childs Latite in the Ajo area (Gilluly, 1946). Its stratigraphic continuity makes it useful as a marker unit. The K-Ar age from the Childs Latite is 18.3±0.6 m.y. (no. 81AM57; see also Eberly and Stanley, 1978, no. 107).

Basaltic andesite extrusive rocks dated between 16 and 14 m.y. were the next materials to be erupted. 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-cone deposits are present in the Cipriano Hills and the Growler and Bates Mountains farther west.

The Sentinel and Pinacate basalt flows located adjacent to the northern and southwestern parts respectively, of the volcanic field, postdate most Basin and Range block faulting. These basalts range in age from 5 m.y. to recent and are not considered here as part of the Ajo Volcanic Field Tertiary sequence (Eberly and Stanley, 1978, no. 1-6).

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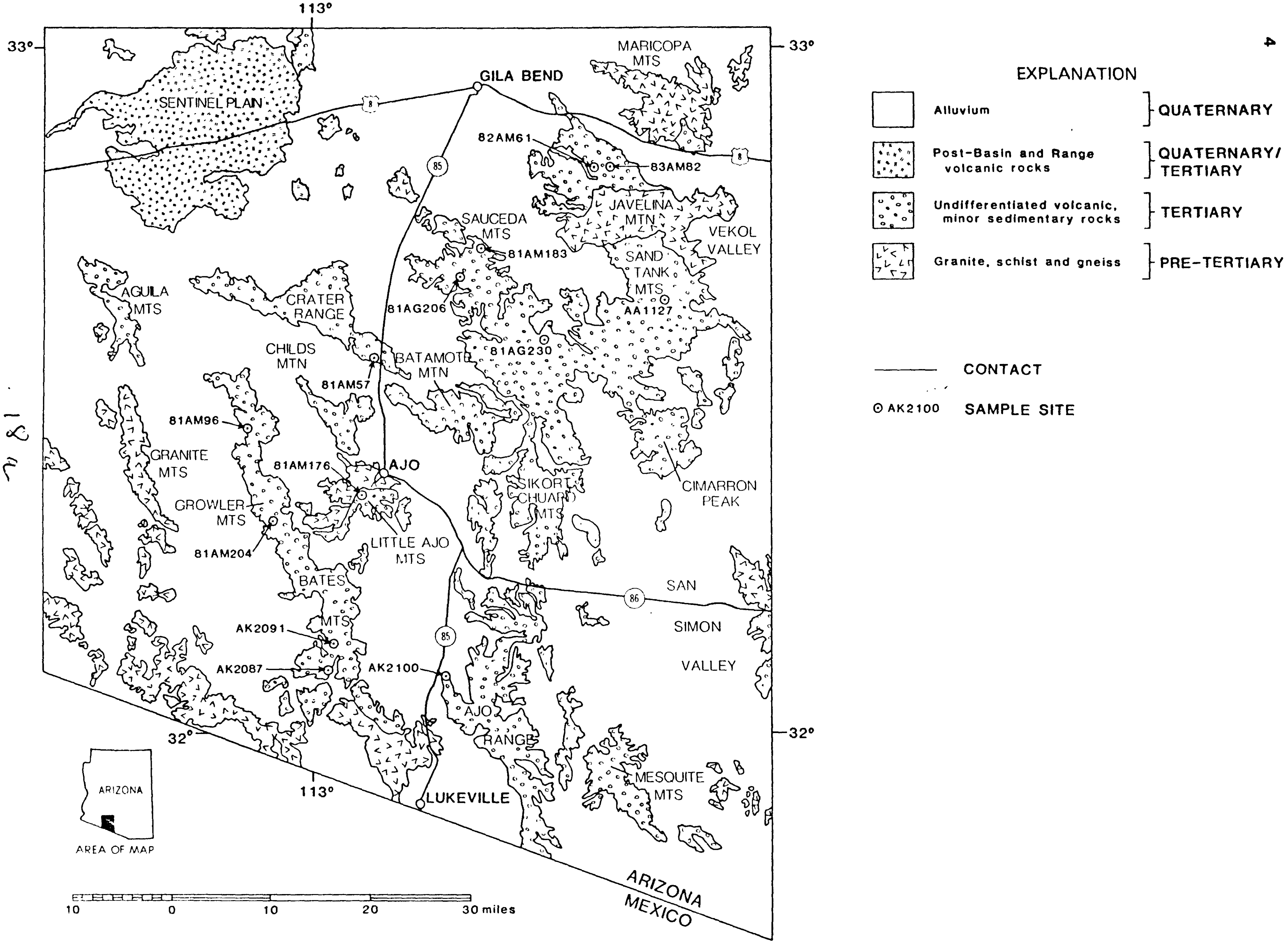

FIGURE 1. GENERALIZED GEOLOGIC MAP OF THE AJO AREA SHOWING SAMPLE LOCALITIES.

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STRUCTURAL REINTERPRETATION OF THE AJO MINING DISTRICT, PIMA COUNTY, ARIZONA, BASED ON PALEOMAGNETIC AND GEOCHRONOLOGIC STUDIES

By Dennis P. Cox, Jonathan T. Hagstrum, and Robert J. Miller

The Ajo mining district of southern Arizona is divided into two main structural blocks by the Gibson Arroyo fault. The eastern Camelback Mountain block contains the Late Cretaceous-early Tertiary porphyry copper deposit which has been previously thought to be associated with the displaced apex of a large intrusion exposed by deeper erosion in the western Cardigan Peak block. However, unpublished U-Pb data support a mid-Tertiary age for the western intrusion. Paleomagnetic and geologic evidence indicates that the ore deposit has been tilted to the south a total of approximately 120°: 68°before another 55° after emplacement of the overlying Locomotive Fanglomerate and Ajo Volcanics. The Ajo Volcanics have K-Ar ages (24-25 m.y.) slightly older than those from the large intrusion of the Cardigan Peak block (20-23 m.y.). Paleomagnetic directions are consistent with the southward tilting of the volcanic rocks, but they suggest that the remanent magnetization and perhaps the K-Ar dates of the western intrusion were reset by the emplacement of dikes younger than the Locomotive Fanglomerate and Ajo Volcanics. These and other geologic relations indicate the following sequence of mid-Tertiary events in the district: (1) emplacement of the western intrusion, (2) movement along the Gibson Arroyo fault, (3) unroofing and perhaps tilting of the pluton 70° to the south along with the Camelback Mountain block, (4) syntectonic depositions of the Locomotive Fanglomerate and the Ajo Volcanics, (5) continued uplift and tilting to the south totaling 40° to 60°, (6) intrusion of the youngest dikes with attendant alteration and remagnetization of the host rocks, and (7) minor(?) oblique movement along the Gibson Arroyo fault.

GEOLOGY, GEOCHEMISTRY, AND REGIONAL SIGNIFICANCE OF THE CHILDS LATITE: A MIOCENE INDEX UNIT IN THE AJO VOLCANIC FIELD

By Robert J. Miller

The Childs Latite is a distinctive plagioclase porphyritic volcanic formation exposed in several mountain ranges near the town of Ajo in southwestern Arizona. The unit represents greater than 50 km^3 of shoshonitic to latitic magma erupted approximately 18-18.5 Ma during the later stages of development of the Ajo volcanic field.

Geochronologic, chemical and petrologic data suggest that the unit was erupted from two shallow crustal chambers, one underlying the Crater Range and a second larger chamber underlying Organ Pipe Cactus National Monument and vicinity. Lavas exposed in the Crater Range are dominantly shoshonite whereas exposures to the south of the Crater Range are latite to high-K dacite.

The Childs latite has chemical characteristics similar to mildly alkaline suites. The bulk of the unit contains 53-60 wt% SiO^2 with minor differentiates reaching 65 percent. The unit is high in potassium (3.2-4.5 percent), Na_2O (3.7-4.1 percent), aluminum (18-19 percent) and phosphorous (0.5-0.8 percent) and depleted in MgO (1-3 percent). LILE and REE concentrations are high (200x chonderite) and show strong LREE enrichment (La/Yb=10). Evolution of the series represented by the Childs latite is consistent with simple crystal fractionation of phenocryst phases present in the mode. Fractionation of modal phases is not sufficient to explain the derivation of the Childs latite from the less potassic suite comprising the rest of the Ajo volcanic field.

K-Ar age determinations indicate that eruption of the unit occurred during the interval between 18 and 19 m.y. High K porphyritic basaltic andesites are dominantly older (19-22 m.y.) than the latite. The similarity in appearance of the porphyritic basaltic andesites with the latites in the Ajo area may be analougous to the confusion created by the use of the term Turkey Track andesite in the southeastern part of the state.

GEOCHEMICAL INVESTIGATIONS IN THE AJO AND LUKEVILLE 1° BY 2° QUADRANGLE TECHNIQUES AND RESULTS

By Harlan Barton and Paul K. Theobald

Regional geochemical studies were conducted during 1979 and 1980 in mountain areas of the U.S. portions of the Ajo and Lukeville 1° by 2° quadrangles except the Papago Indian Reservation. Nine hundred seventy-one localities were sampled for stream sediments within the 6,500 mi^2 study area. Quantities of heavy-mineral-concentrate samples sufficient for analysis were obtained from 952 of these. Sample sites were located on first- or second-order stream channels from drainage basins of less than half a square mile and generally were located on dry stream channels at points of emergence from the narrow linear mountain ranges. They, therefore, represented the mineralogy of the mountain ranges and their immediate flanks, rather than the portions of the study area underlain by alluvium-filled basins. For the mountain ranges the sampling density was one sample locality per 1.2 mi^2.

Stream sediments were analyzed for 31 elements by optical emission spectroscopy in field laboratories. Sufficient precision was obtained to distinguish major geochemical entities and recognize anomalies.

Maps are presented showing sample site localities and the locations of anomalous concentrations of ore and ore-related elements, antimony, bismuth, copper, lead, molybdenum, silver, tungsten, and zinc; of elements common to gangue minerals, barium manganese, and strontium; and of strontium depletion associated with hydrothermal alteration. Sixteen areas having anomalous element concentrations are identified (Ajo, Sonoyta Mountains, Mohawk Mountains, Painted Rock Mountains, Growler Pass, La Abra Plain, Agua Dulce Mountains, State Highway 84, Maricopa Mountains, Booth Mountains, Mohawk Pass, Ajo Range, Sauceda Mountains, Cabeza Prieta Mountains, Batamote Mountains, and Copper Mountains). The geological and geochemical characteristics of these areas are described.

REGIONAL GEOCHEMICAL STUDIES IN THE AJO AND LUKEVILLE 1° by 2° QUADRANGLES

By Paul K. Theobald and Harlan N. Barton

The regional geochemical data developed for the assessment of the Ajo and Lukeville quadrangles cover all of those quadrangles exclusive of the Papago Indian Reservation. The sampling design provides reasonable coverage of the ranges and shallowly covered pediments flanking the ranges. The broad, alluviated basins between ranges were largely ignored.

The choice of sample types was based on experience gained from previous work in adjacent areas of northern Mexico and from wilderness evaluations in adjacent parts of Arizona. The sample types were chosen to represent a reasonable composite of surficial material, weathered rocks, soils, etc., in a relatively small catchment area. They were chosen to enhance chemical variation among the catchment areas and to minimize the influence of material introduced by aeolian transport. The objectives were to define regional geochemical patterns, to identify all conspicuous anomalies, and to accentuate and identify as many of the more subtle anomalies as possible. To accomplish these goals, two samples were collected at each sample locality; 30-mesh stream sediment and the nonmagnetic fraction of a heavy-mineral concentrate from the stream sediment. Sample localities were on first- and second-order streams to minimize the variety of geologic units composited into each sample and to minimize the dilution of geochemical anomalies.

The analytical procedure was chosen to provide sufficient precision to distinguish among the major geochemical units of the quadrangles and to allow ready identification of geochemical anomalies. A broad spectrum of elements was required to evaluate a broad variety of possible anomalous situations and deposit types. Principal constraint on the analytical procedure was cost, capacity, and the need for rapid turnaround. The method best suited to fulfill these needs was a USGS mobile field laboratory equipped to produce 32-element, 6-step, semiquantitative optical emission spectrographic analyses. The overall precision of the analytical method was within 30 to 50 percent, whereas the natural variation measured for most of the elements spanned one to several orders of magnitude.

All of the analytical data were incorporated in an analysis of regional variation in the geochemical characteristics of quadrangles. Against this background, eight of the individual elements exhibit anomalous behavior that is likely to be related to metallic mineral-resource potential. These are copper, lead, molybdenum, zinc, silver, antimony, tungsten, and bismuth. In addition to these individual elements, five assemblages of elements can be identified as defining multi-element anomalies that may also reflect metallic mineral-resource potential. These are the assemblages of bismuth, tungsten, and lead; tungsten, molybdenum, and lead (there is an apparent antithetic between bismuth and molybdenum); barium and strontium (barite and celestite); strontium negative anomalies with anomalous values for other metals; and silver and antimony.

Anomalous levels were defined by analysis of individual elements and interrelations among the elements within these quadrangles and by experience in adjacent areas. No predetermined statistical method was employed for anomaly definition. For single elements such as copper or strontium, breaks or gaps in the frequency distributions often served to distinguish an anomalous population from the mass of the data. For the rarely detected elements such as silver or antimony, it is clear that any reported value above the limit of analytical sensitivity is anomalous. For element associations such as that of barium and strontium, the statistical technique of factor analysis applied to the entire data set clearly identifies a unique factor for these two variables. High scores for that factor identify the known barite and celestite deposits of the quadrangles and define additional areas of interest. In some instances, copper for example, the natural variation among the wide range of lithologies in the quadrangles is sufficient to obscure subtle anomalies. It was possible to compare the copper content with the scores of the dominant factor (a pseudo composite of the lithologies) to determine normalized-anomalous samples wherein the copper content exceeded that predicted by the lithology-related factor score.

A more complex scheme of anomaly definition was used to explain the unexpected correlation of thorium with vanadium. Analysis of the relations of these two elements with each other and to elements associated with thorium in "common" thorium minerals allowed definition of a thorite-rich anomaly.

The products of the geochemical reconnaissance that were used in conjunction with the geophysics, geology, and remote sensing to produce the mineral resource assessment include: (1) the basic data; (2) a statistical analysis of this data that was used to sort out the most pertinent geochemical parameters; and (3) a series of maps displaying the distribution of anomalous samples for a selected group of elements and element assemblages. Most of the anomalous localities for these selected parameters cluster in remarkably discrete areas. Relationships among the geochemical maps strengthen these anomalous areas and further amplify our understanding of the chemical characteristics of the anomalies.

REGIONAL GRAVITY AND MAGNETIC STUDIES IN THE AJO AND LUKEVILLE 1° by 2° QUADRANGLES, ARIZONA

By Douglas P. Klein

Gravity and magnetic anomaly maps reflect the distribution of mass and magnetization. Along with other geophysical data such as electrical conductivity and seismic velocity, these maps can help to infer geological structure and composition at depths where geological sampling is not feasible. Anomalies, either highs or lows in the mapped fields, usually indicate variations in the bedrock resulting from intrusions, mineral alteration or faulting. Primary contributions of these data to mineral resource assessment are in identifying bedrock structure beneath alluvium and volcanic rock and in locating anomalous mass or magnetization that may indicate favorable conditions for mineralization.

The map of the gravity field over the Ajo-Lukeville quadrangles is based on 4,157 measurements, with an average interval of about 2 km between observations for the approximately 21,000 km^2 of survey area. Intense gravity lows over alluvial areas on the map identifies the deepest parts of basins (bedrock at about 2 km or more beneath the surface). Deep basins include, from west to east, parts of the Mohawk Valley, the San Cristobal Valley, the Growler Valley, the Valley of the Ajo, and Quijotoa Valley (fig. 1). Besides helping to establish the structural framework of the area, such interpretations eliminate areas that are likely to be unproductive for further shallow mineral exploration. Similarly, alluvial covered areas that lack intense lows or show highs are inferred to be underlain by bedrock at depths less than about 1 km. Such areas are found south of the Mohawk and San Cristobal basins, south of the Growler Basin, surrounding the town of Gila Bend, north of the Cimarron Mountains, and in the southern part of the San Simon Valley (fig. 1). Other gravity lows over bedrock, such as the lows over the Cabeza Prieta, Batamote, and Sauceda Mountains (fig. 1), suggest silicic intrusion and related structural disruption at depth.

The magnetic anomaly map is based on airborne measurements along east-west lines spaced 1,600 m apart, at an altitude of 1,200 m above sea level; this altitude is typically about 700 m above the ground in the valley areas. A regional magnetic high extends across Sentinal Plain to Cimarron Peak (fig. 1). The anomaly is in part associated with a zone of volcanic rocks, but the width and gradients of the long-wavelength portion of the anomaly suggests that its main source lies at 5 km or more beneath the surface. Thus, the anomaly probably reflects a large scale zone of crustal intrusion. There are also about 100 anomalies whose smaller size and steeper gradients indicate shallow magnetic variations in the bedrock (within about 5,600 m of the surface). Many of these are over outcrop where geological relationships make it unlikely that they are related to mineralized intrusions or faults. Others (fig. 1), located over alluvium, or over outcrop but having features in conflict with exposed geology, indicate buried structures, intrusions, or alteration. These anomalies are candidates for further, more detailed geophysical exploration and drilling to investigate their origin and possible mineralization.

Figure 1. Location and generalized shape of regional aeromagnetic and gravity anomalies in the Ajo-Lukeville 1° by 2° quadrangles. Also shown are areas selected for more detailed geophysical studies.

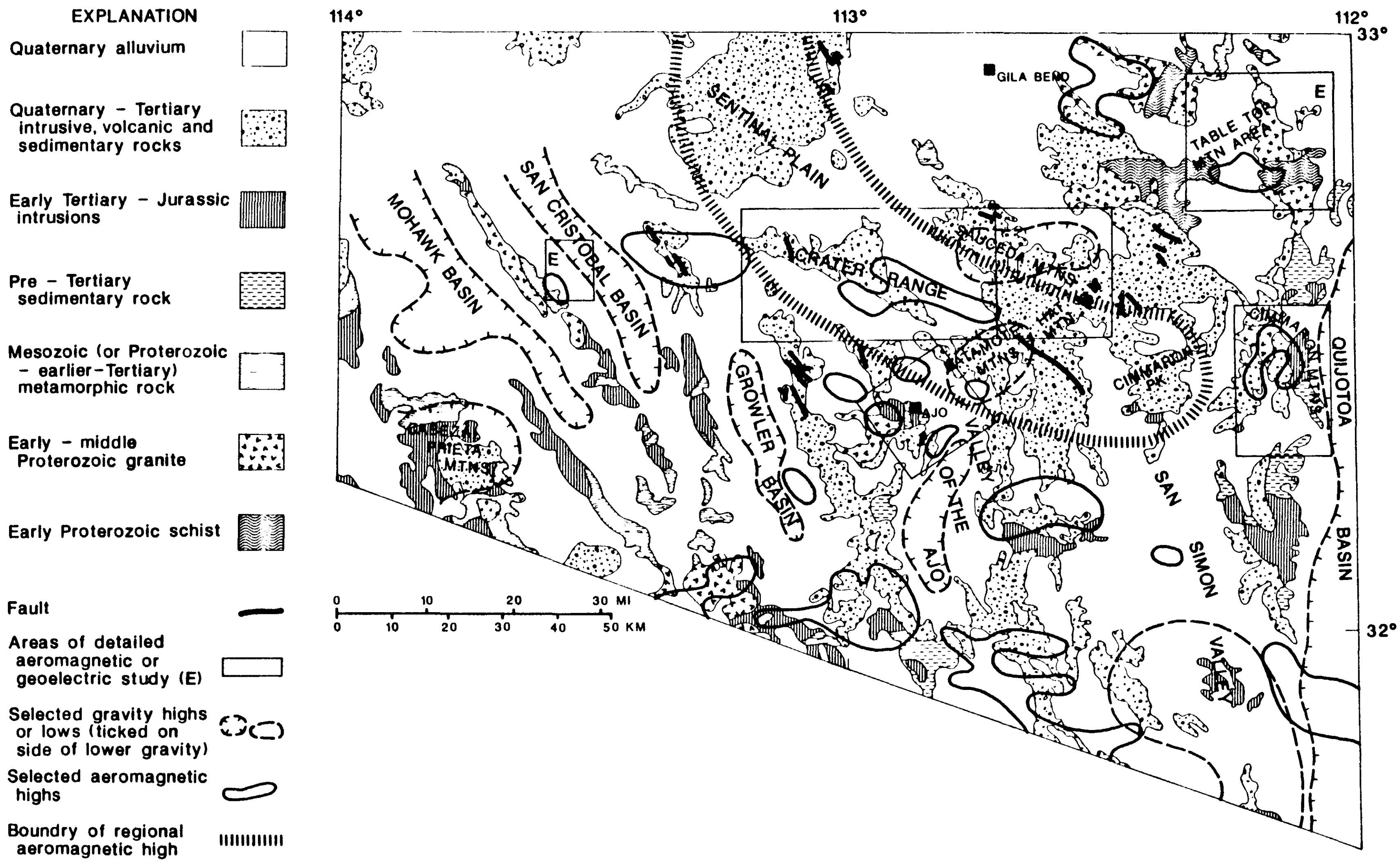

Figure 1. Location and generalized shape of regional aeromagnetic and gravity anomalies in the Ajo-Lukeville 1° x 2° quadrangle. Also shown are areas selected for more detailed geophysical studies.

REGIONAL STRUCTURAL AND HYDROTHERMAL ALTERATION STUDIES USING LANDSAT MULTISPECTRAL DATA, AJO AND LUKEVILLE QUADRANGLES, ARIZONA

By Gary L. Raines

As part of the Conterminous United States Mineral Assessment Program, Landsat images of the Ajo and Lukeville quadrangles were analyzed. The purpose was to identify areas of mineralized rock and regional structural controls of mineralization. Landsat data provide a regional view of both the structural elements and the altered rocks associated with mineralized areas. This regional perspective can provide new insights for exploration. The work described here was performed in 1977 through 1979. Thus Landsat Thematic Mapper data and analytical techniques commonly used in 1988 were not available.

Digital-image-processing techniques of Rowan and others (1974) and Raines and others (1978) were used to map limonitic materials to identify mineralized areas. Limonite is a field term for undifferentiated ferric oxide precipitates (Blanchard, 1968) and is identified with Landsat data by the typical spectral reflectance properties of the ferric oxide minerals such as hematite and goethite (Hunt and Ashley, 1979). Fifty-five areas of anomalous limonite were mapped. Field inspection of prominent limonitic areas defined 12 areas of limonite associated with hydrothermally altered or mineralized materials.

Interpretation of linear geomorphic features in relation to mineralized areas is the objective of lineament analysis. Sawatzsky and Raines (1981) fully describe the statistical method used in the lineament analysis. Statistical analysis of the Landsat data defined regional structural controls of mineralization. Raines (1978) and Turner and others (1982) have defined from lineament analysis a regional exploration model for northern Mexico, that is applied in this study to southern Arizona. The model is, in brief, as follows: within the northwest-trending porphyry-copper province, the major regional systematic control of mineralization was a set of northeast- to east-northeast-trending lineaments. Where these northeast- to east-northeast trending lineaments intersect regional northwest-trending structures, the plumbing allowing emplacement of hydrothermal systems was well developed. The spatial association between these lineaments and the major porphyry-copper deposits in southwestern Arizona and northern Mexico (Raines, 1978, and Turner and others, 1982) supports this exploration model. On the basis of findings in Peterson (1962), Shoemaker and other (1978), Raines (1978), Turner and others (1982), and Rehrig and Heidrick (1976), these northeast- to east-northeast-trending lineaments are interpreted to be basement shear zones of Precambrian origin. Six of these possible shear zones are identified in the Ajo and Lukeville quadrangles and seven areas of intersection of these shear zones with northwest-trending lineaments are identified.

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MINERAL RESOURCE ASSESSMENT OF THE AJO AND LUKEVILLE QUADRANGLES

By Jocelyn A. Peterson

A mineral resource assessment of the Ajo and Lukeville 1° by 2° quadrangles indicates that there is potential for the presence of undiscovered deposits of the types already known in the quadrangles. Geologic, geochemical, and geophysical data further indicate that the area has permissive localities for several other deposit types. Of tracts delineated for porphyry copper and skarn deposits, there is a 50 percent chance that there are one or more and a 10 percent chance that there are four or more undiscovered porphyry copper or related skarn deposits. In addition to porphyry copper-related skarns, the limestone in the area also contains small skarns and polymetallic replacement deposits unrelated to porphyry systems. There is a 50 percent chance that the area contains one or more and a 10 percent chance that there are four or more additional deposits of this type. Features in some localities suggest a permissive environment for Climax-type porphyry molybdenum deposits, while other areas are more likely to contain fluorine-deficient type deposits. Because of scant data we evaluated these two types of deposits together, realizing that there are significant differences between the grades and tonnages of the two types, and expecting that if there are undiscovered deposits in the quadrangles, they are more likely to be the lower tonnage, lower grade fluorine-deficient type. There is a 50 percent chance that the area contains one or more and a 10 percent chance that it contains two or more undiscovered porphyry molybdenum deposits. Several types of veins present in the area include gold-silver quartz veins, polymetallic epithermal veins, hematite-bearing veins, and uranium-bearing veins. The known veins of these types have very low tonnages. It is expected that undiscovered veins of these types would be in areas where such veins are already known and that they would also be small. Tungsten-bearing veins are not known within the quadrangles; however, geochemical data suggest that tungsten-bearing veins could be present, but they would probably be small similar to others in the United States. Simple pegmatites in granitic rocks in the area may contain limited quartz and feldspar resources, as well as niobium, lanthanum, and yttrium minerals. Gneissic terranes, similar to areas that contain disseminated gold along detachment faults near the Colorado River, are permissive for similar type gold deposits. Certain areas within volcanic terranes are permissive for volcanic-hosted disseminated gold deposits. Other volcanic localities, which have rocks similar to those in Mexico and New Mexico where rhyolite-hosted tin deposits are present, are permissive for such deposits. Limestones that contain manganese replacement deposits could have other deposits nearby. Small amounts of placer gold have been found adjacent to several of the mountain ranges, and the Quijotoa District produced an estimated 425,000 g of gold. Additional placer accumulations are likely to be found in known placer areas or in drainages near gold-silver quartz veins. Although the basins were not studied during this CUSMAP program, they are permissive for evaporite deposits and calcrete-type uranium deposits. There is a 50 percent chance that there are one or more and 10 percent chance that there are two or more undiscovered evaporites deposits in the area. Three areas of known warm-water wells and fairly recent volcanism are permissive for geothermal energy for local use. Because of the large amount of Tertiary volcanic rocks in the area, perlite and zeolite minerals could be present, although no significant accumulations were observed during field work in the area.