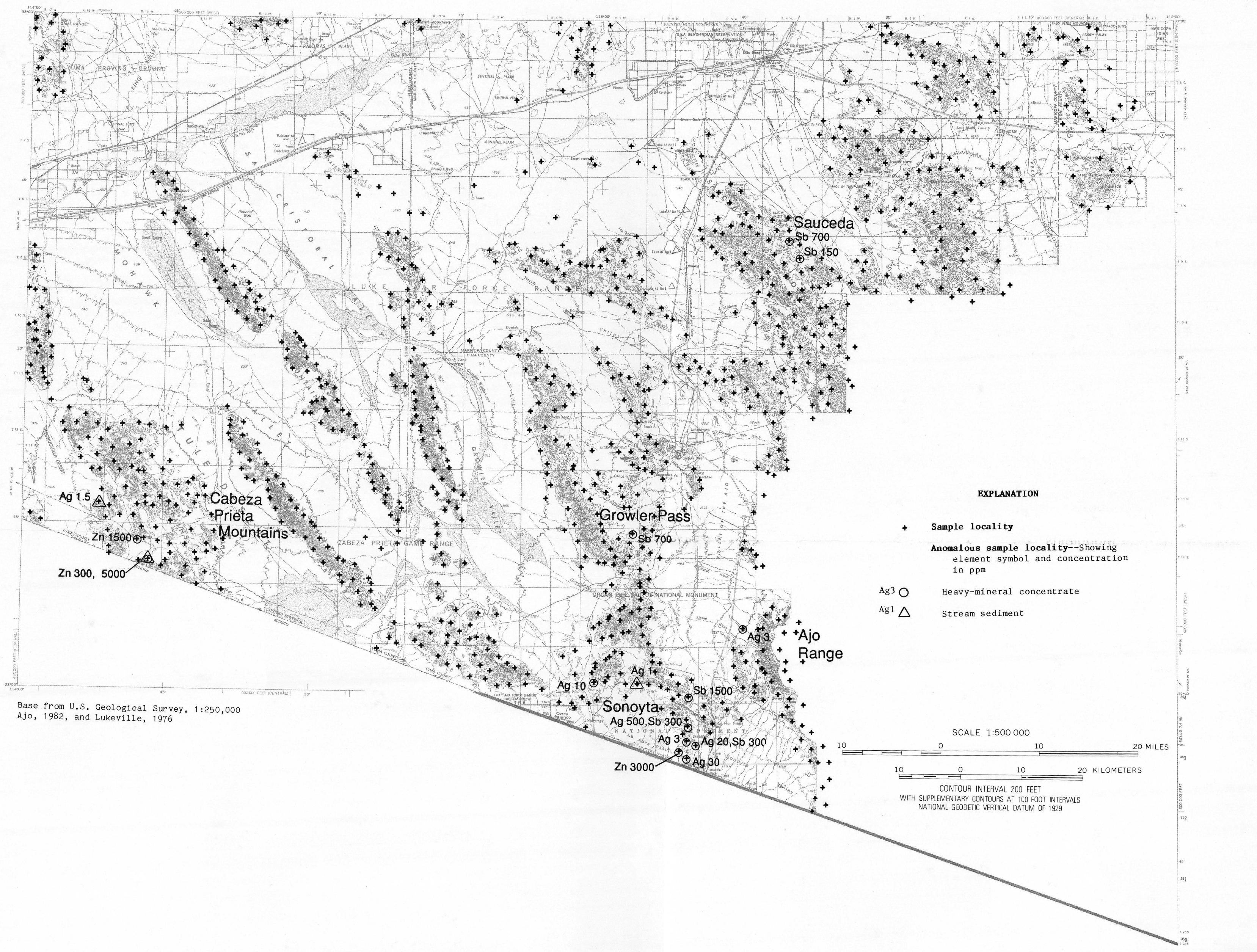
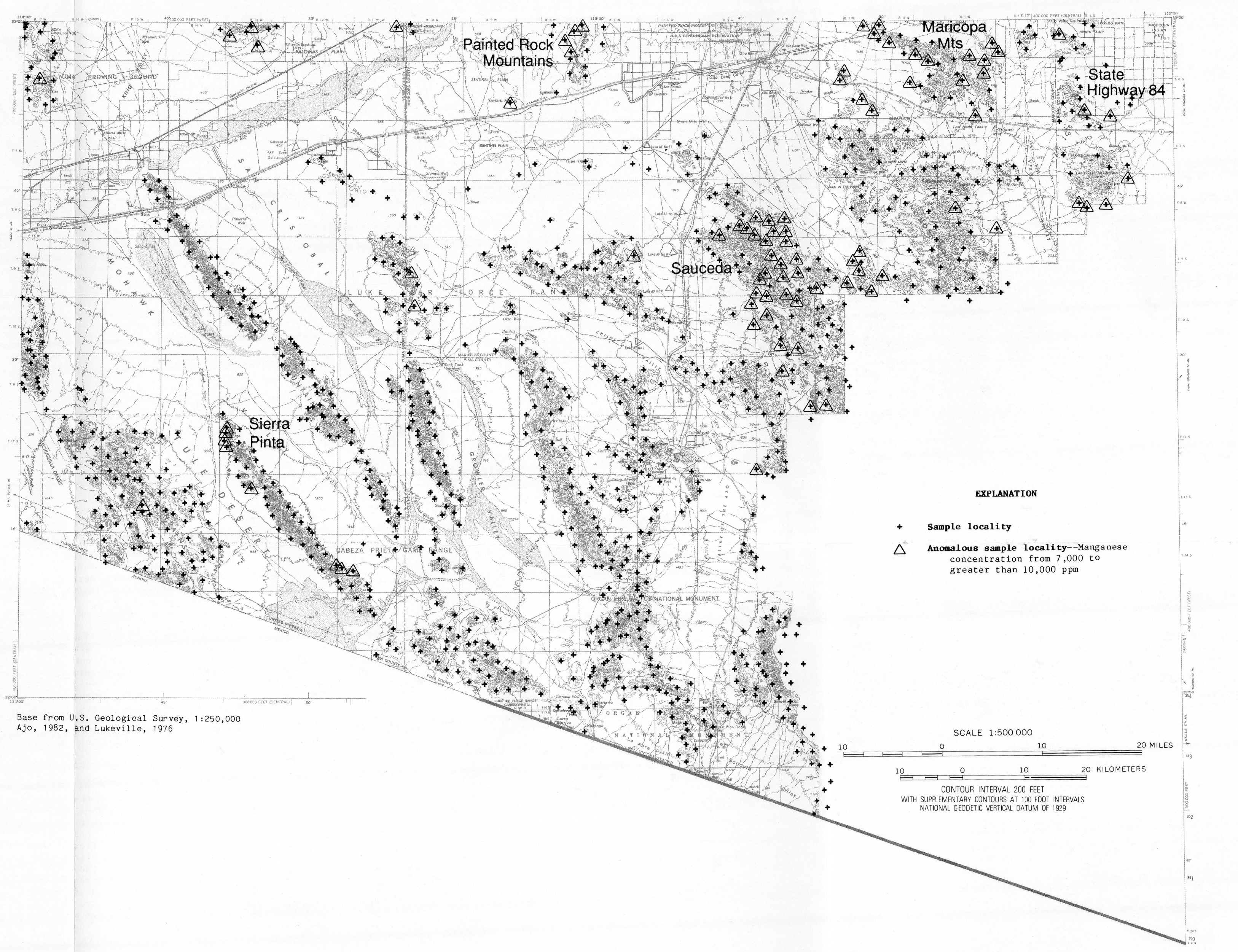
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

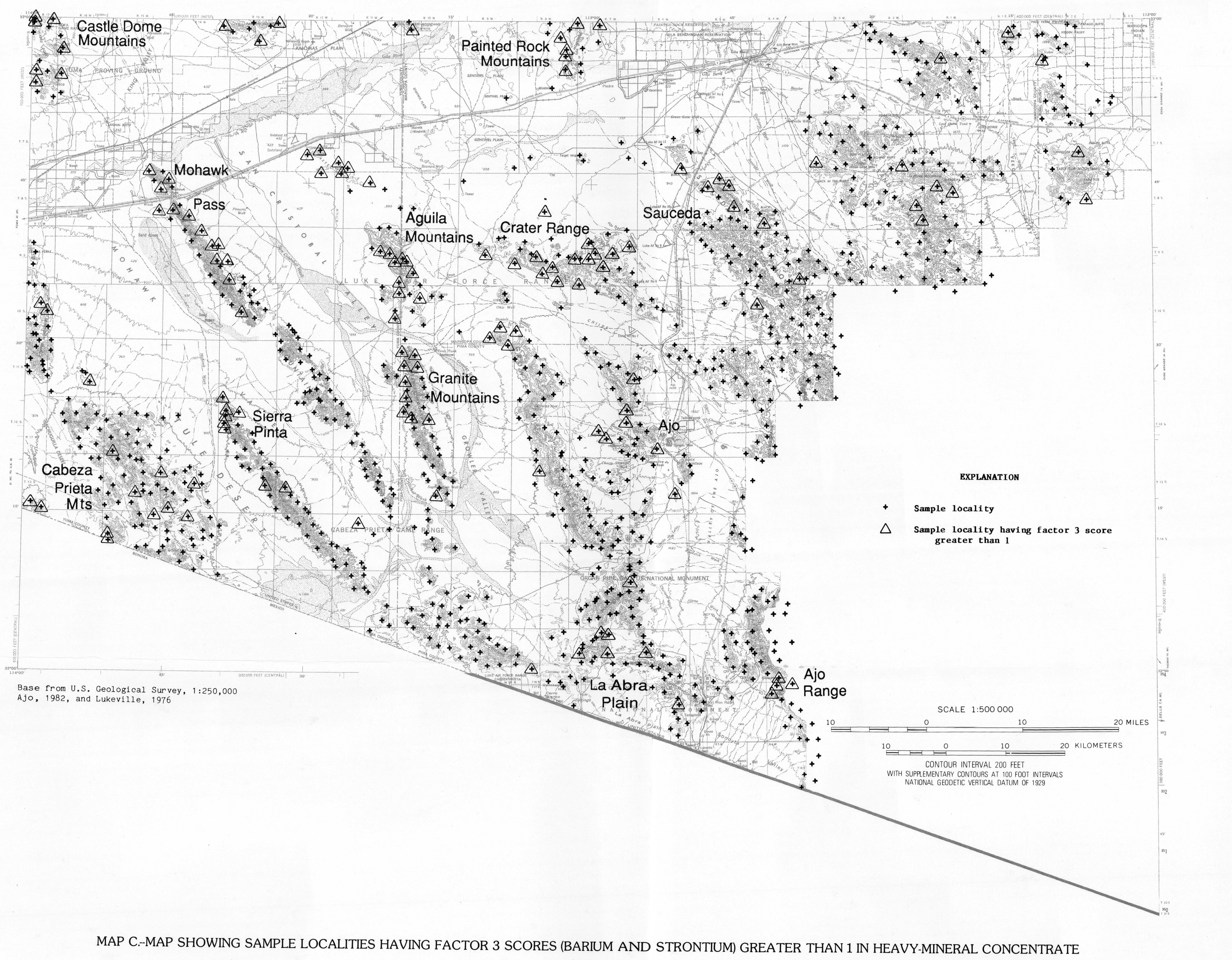
MISCELLANEOUS FIELD STUDIES
MAP MF-1834-E



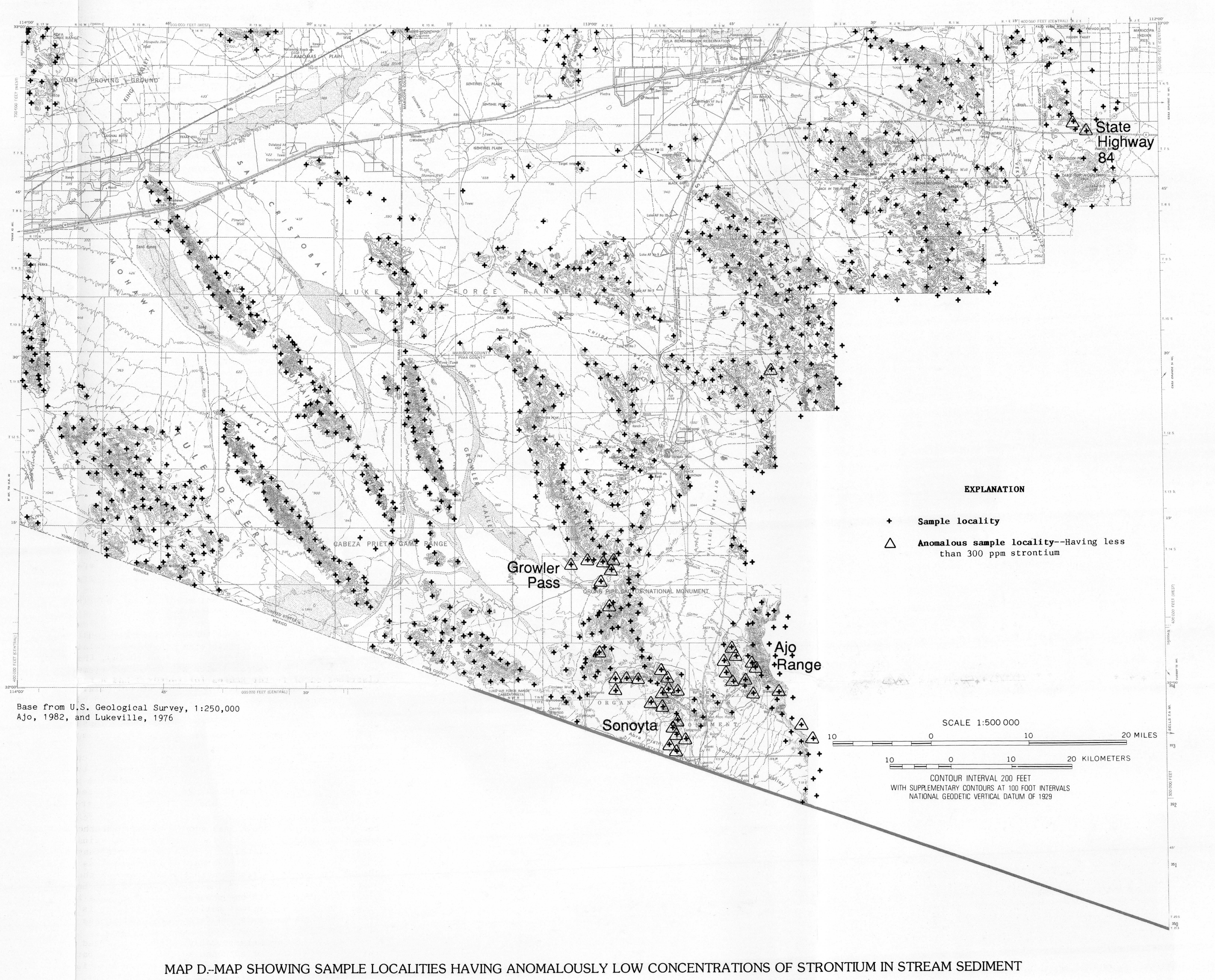
MAP A--MAP SHOWING ANOMALOUS CONCENTRATIONS OF ANTIMONY, SILVER, AND ZINC



MAP B--MAP SHOWING ANOMALOUS CONCENTRATIONS OF MANGANESE IN NONMAGNETIC HEAVY-MINERAL CONCENTRATE



MAP C--MAP SHOWING SAMPLE LOCALITIES HAVING FACTOR 3 SCORES (BARIUM AND STRONTIUM) GREATER THAN 1 IN HEAVY-MINERAL CONCENTRATE



MAP D--MAP SHOWING SAMPLE LOCALITIES HAVING ANOMALOUSLY LOW CONCENTRATIONS OF STRONTIUM IN STREAM SEDIMENT

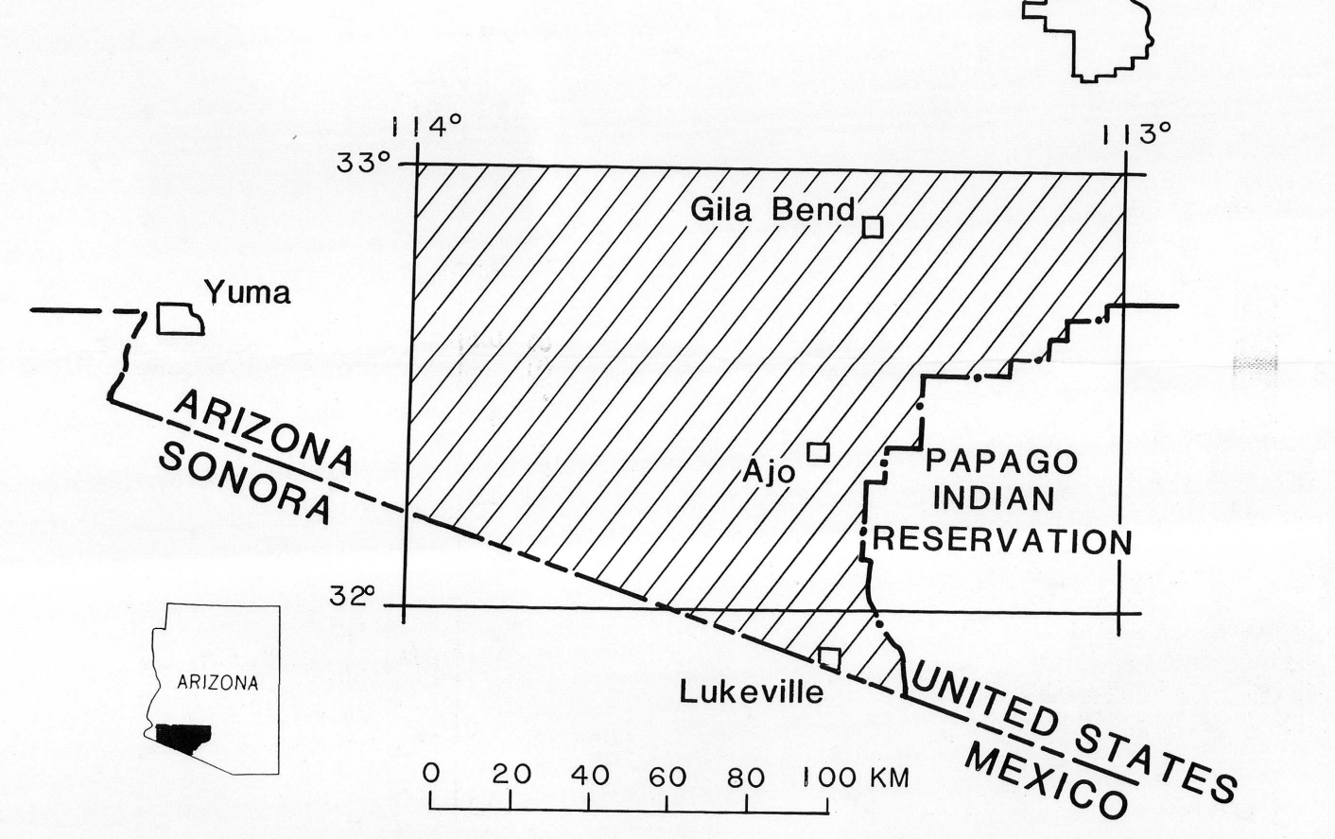


Figure 1.--Index map showing study area (ruled).

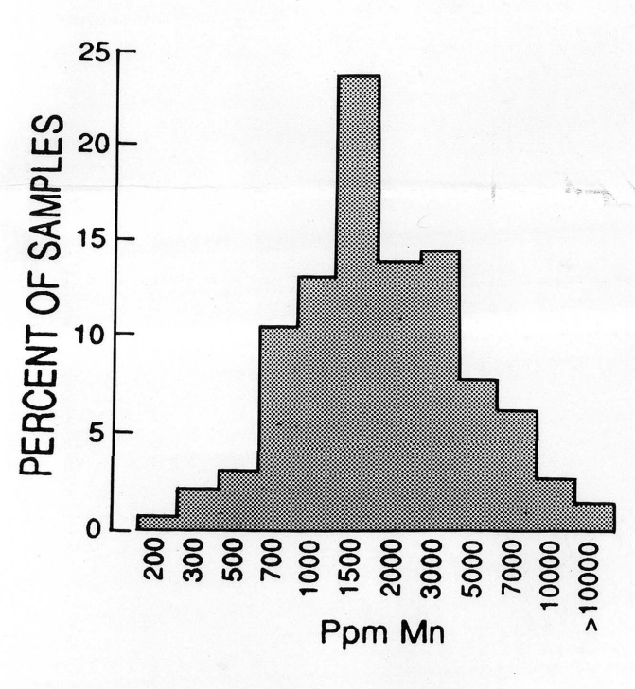


Figure 2.--Histogram showing distribution of manganese in nonmagnetic heavy-mineral concentrate.

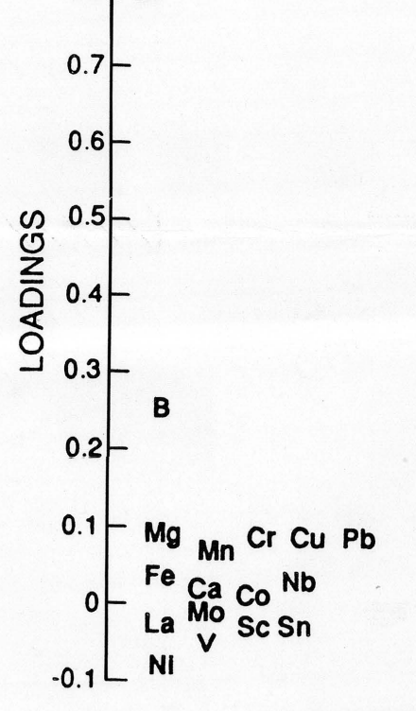


Figure 3.--Loadings for barium and strontium (which compose factor 3) in heavy-mineral concentrate.

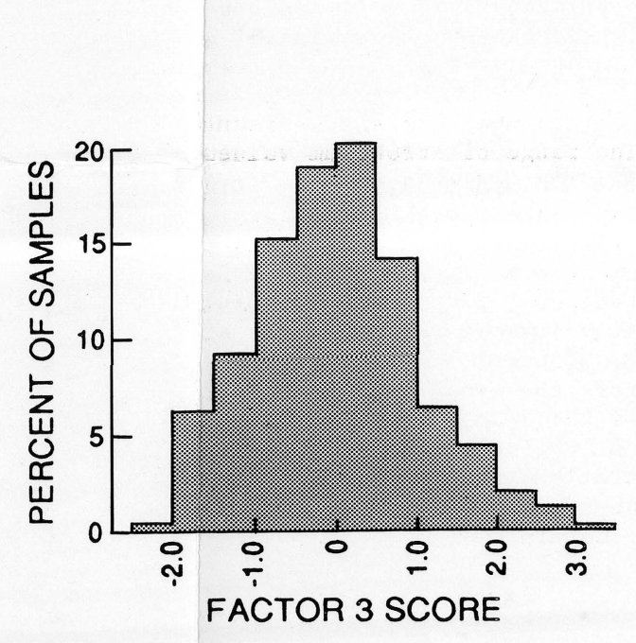


Figure 4.--Histogram showing distribution of factor scores for factor 3.

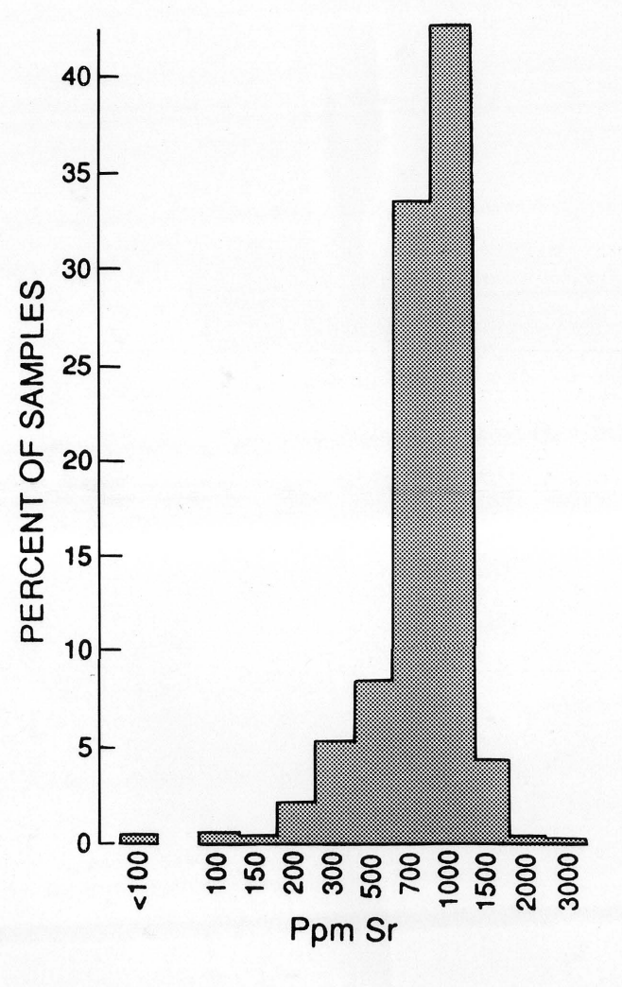


Figure 5.--Histogram showing distribution of strontium in stream sediment.

Table 1.--Frequency and range of detected values for zinc, silver, and antimony in stream sediment and heavy-mineral concentrate from the Ajo and Lukeville quadrangles, Arizona

| Element | Stream sediment | | Heavy-mineral concentrate | |
|---|---|---|---|---|
| | Frequency of detection (ppm) | Range of values | Frequency of detection (ppm) | Range of values |
| Zn | 1 | 300 | 3 | 1,500-5,000 |
| Ag | 2 | 1-1.5 | 6 | 3-500 |
| Sb | 0 | --- | 6 | 150-1,500 |

This map is part of a folio of maps of the Ajo and Lukeville 1° x 2° quadrangles, Arizona, prepared under the Conterminous United States Mineral Assessment Program. Other publications in this folio include U.S. Geological Survey Open-File Reports 82-419 (Barton and others, 1982), 82-599 (Klein, 1982), and 83-734 (Theobald and Barton, 1983), and Miscellaneous Field Studies Maps MF-1834-A (Peterson and Tosdal, 1986), MF-1834-B (Peterson and others, 1987), MF-1834-C (Theobald and Barton, 1987), and MF-1834-D (Theobald and Barton, 1988). Open-File Reports 82-419 and 83-734 constitute the basic data and initial interpretation on which this discussion is predicated. MF-1834-C and D show the distributions of anomalous concentrations of copper, lead, molybdenum, bismuth, and tungsten.

## INTRODUCTION

The geochemical reconnaissance sampling was done during 1979 and 1980. The area covered includes all of the Ajo 1° x 2° quadrangle in the United States, except the Tohono O'Odham (Papago) Indian Reservation, and part of the Lukeville 1° x 2° quadrangle, west of the Indian Reservation and north of the Mexican border (fig. 1). 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 concentrate from stream sediment. Sample localities were selected on first-order drainage channels, generally reflecting a drainage basin of less than 1 km$^2$. Sample localities were further selected to represent the mountain ranges and their immediate flanks, largely ignoring the 80 percent of the quadrangle underlain by a thick fill of young sediment 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. Collection, preparation, and analytical procedures are detailed in Barton and others (1982).

A number of geochemical anomalies suspected to reflect potential for metallic mineral resources have been defined on the basis of the distribution of copper, lead, molybdenum, bismuth, and tungsten (Theobald and Barton, 1987, 1988). In this report, the characteristics of these anomalies are further amplified by analysis of the geographic distribution of the rarely detected metals, zinc, silver, and antimony; of the elements common to gangue minerals, barium, strontium, and manganese in the heavy-mineral concentrate; and of an element commonly mobilized during hydrothermal alteration, strontium.

## ZINC, SILVER, AND ANTIMONY

The vast majority of the stream-sediment and the heavy-mineral-concentrate samples contain less zinc, silver, and antimony than can be detected by the spectrographic procedure used. These detection limits are, respectively, 200, 0.5, and 100 parts per million (ppm) in the stream sediment and 500, 1, and 200 ppm in the heavy-mineral concentrate. The few values above these detection limits are summarized in table 1, and are clearly anomalous (Theobald and Barton, 1983). All of these sample localities are plotted on map A where the anomalous stream-sediment sample localities are represented by triangles, the anomalous heavy-mineral-concentrate sample localities by circles, and the element present is identified by its chemical symbol followed by the concentration in ppm.

Only one of the three sample localities having anomalous concentrations of elements in the stream sediment also has anomalous concentrations of the same elements in the heavy-mineral concentrate. Though statistically not convincing, this fact does suggest that the host mineral of the elements is different in the two media. Stibnite has been identified in heavy-mineral concentrate from the Sonoyta Mountains, but the quantity of this mineral recovered in the bulk stream sediment would be insignificant. The host mineral for zinc and silver is not known, but we suspect that they are contained in secondary minerals such as smithsonite and native silver in the heavy-mineral concentrate and as more dispersed forms, such as secondary iron oxides in the stream sediment. Mass balance requires that the host minerals of these metals be different in the two media. For example, for the single sample locality in the Cabeza Prieta Mountains that has anomalous concentrations of zinc in both media, 5,000 ppm zinc in the heavy-mineral concentrate would be diluted to less than 1 ppm in the bulk stream sediment.

Most of the sample localities (10 of 18) where zinc, silver, and antimony were detected are in a large cluster in and near the Sonoyta Mountains. Included in this cluster are 6 of the 8 sample localities that contained anomalous concentrations of silver, 3 of the 6 that contained anomalous concentrations of antimony, and 1 of the 4 that contained anomalous concentrations of zinc. A trio of sample localities in the Cabeza Prieta Mountains contained anomalous concentrations of zinc and silver. One of these sample localities is the only one in which both the stream sediment and the heavy-mineral concentrate samples have anomalous concentrations of zinc. Two sample localities having anomalous concentrations of antimony are in the Sauceda Mountains and single sample localities have anomalous concentrations of antimony in the vicinity of Growler Pass and of silver on the northwest flank of the Ajo Range. All of these areas have anomalous concentrations of one or several other elements.

## MANGANESE IN HEAVY-MINERAL CONCENTRATE

Manganese concentrations range from 200 to greater than 10,000 ppm in nonmagnetic heavy-mineral concentrate (fig. 2). In figure 2, the distribution is remarkably symmetrical despite the two orders of magnitude in the concentration range, and there are no marked breaks to suggest an anomalous sample population. Thus, the values plotted on map B represent the upper part of a continuous distribution rather than a uniquely anomalous population. The values plotted are the upper 10 percent of the distribution and include values of 7,000 ppm or more. Intuitively, these would appear to be high values. In a similar data set in Sonora, southeast of the study area (Frisken and others, 1981), values in this range constitute only 2 percent of the distribution and are distinctly anomalous. The heavy-mineral concentrate from the study area is unusually rich in manganese, and the anomalous values likely overlap with the upper part of the high range for background values.

Map B shows several distinct clusters of manganese-rich localities and a scattering of manganese-rich single localities or smaller clusters. The most prominent of the clusters is that in the Sauceda Mountains, which includes nearly a third of the high values and nearly all of the samples collected from that range. Other clusters are in areas previously identified as anomalous (Theobald and Barton, 1987, 1988), such as the State Highway 84, Maricopa, and Painted Rock anomalies. There is a reasonable probability that the high manganese concentrations associated with these clusters are in relatively pure manganese oxides or in manganese and iron carbonates of hydrothermal origin. The relations of the manganese minerals to intermediate and shallow mineral deposits and the zonal arrangement of the manganese minerals in the outer or shallower environments relative to metal deposits is described by Hewett and Fleischer (1960).

The cluster of manganese-rich localities in the northern Sierra Pinta have no obvious relation to metallic mineralization. They are from streams draining a two-mica granite that is rich in niobium, thorium, and the rare-earth elements. The area is also reported to have a spectral signature attributed to hydrothermal iron oxides (Raines, oral commun., 1982).

## BARIUM AND STRONTIUM

The distribution of barium and strontium is related to several geologic features, such as potassium- or calcium-rich rocks, as described in Theobald and Barton (1983); however, only those features that may relate to mineral resource potential are emphasized here. In the heavy-mineral concentrate, the principal control for high concentrations of barium, and of strontium when associated with barium, is the presence of the mineral barite and it's isomorphous associate celestite. Both end members of this solid solution series are known in deposits at the north end of the Mohawk Mountains (barite, Wilson, 1933, p. 152-153) and north of the Sauceda Mountains (celestite, Moore, 1935). The geographic distribution of barium and strontium (map C) is displayed by the factor score dominated by these two elements.

High concentrations of barium and strontium in stream sediment are related to gross lithologic controls. The strontium distribution, in particular, reflects the abundance of calcium-rich rocks. During hydrothermal alteration, calcium is an unstable element often depleted in altered rocks. The depletion of strontium is a particularly sensitive indicator of the redistribution of calcium during alteration. The distribution of stream sediment abnormally poor in strontium (map D) thus provides an indirect indicator of hydrothermal alteration.

Displayed on map C are sample localities having varimax scores for factor 3 in excess of 1.0 for heavy-mineral concentrate. These scores are based on R-mode factor analysis (for a discussion of the statistical terms and techniques, the reader is referred to the chapter on multivariant analysis by Howarth and Sinding-Larsen in Howarth, 1983). The "factors" are based on the correlations among the elements and may be considered as groupings of related elements. "Loadings" provide a measure of the correlation of individual elements with the factors, and the "scores" provide a measure of the strength of the factor in the individual samples. As described in Theobald and Barton (1983), the factor model is based upon correlations among 18 elements. The correlations between the varimax scores and the elements (fig. 3) identify factor 3 as essentially a two-component factor consisting of barium and strontium. For both of these elements this correlation is greater than 0.8. Other than a weak correlation with boron (0.24), the correlation of the varimax scores for factor 3 with all the other elements is less than 0.1. The distribution of factor scores for factor 3 has a range of -2.2 to +3.4 and has a mean of 0.0 and a standard deviation of 1.0 (fig. 4). Thus the localities identified on map C are those more than one standard deviation above the mean for the whole data set, about 15 percent of the samples, and are those abnormally rich in barium and (or) strontium. These are generally samples with 1 percent or more of one or both of those elements and are usually samples containing barite and (or) celestite.

On map C, many of the barium-and strontium-rich sample localities form distinct clusters. At least four associations of these clusters of anomalous sample localities with other geologic features can be discerned. The clusters extending southeast from Mohawk Pass, in the Painted Rock area, the Aguila Mountains, surrounding Ajo, and in the Ajo Range are coincident with other evidence of hydrothermal mineralization. One association is particularly convincing in the Mohawk Pass anomaly where hydrothermal veins of barite have been mined (Wilson, 1933). These hydrothermal veins of barite have been interpreted to be related to a detachment fault that follows the east side of the Mohawk Mountains southeastward from Mohawk Pass (Mueller and others, 1982). The fault is repeated in the outcrops on the west side of the range southwest of Mohawk Pass. The association of the barium- and strontium-rich sample localities with the projected trace of this fault is remarkable and suggests that hydrothermal barite mineralization is a general characteristic of this detachment fault and is not confined to the small area in the vicinity of Mohawk Pass.

The Sauceda anomaly probably is not associated with hydrothermal-barite veins. Three lines of evidence suggest that the barium- and strontium-rich samples in this area may reflect a different association: (1) The evidence for hydrothermal activity in the Sauceda Mountains, for example the manganese distribution as shown on map B and the antimony distribution as shown on map A, is centered on the Tertiary rhyolite of the central part of the range. The principal cluster of barium- and strontium-rich sample localities is along the north edge of the range, outside of the rhyolite terrane. (2) There is five to ten times more strontium than barium in these samples. Celestite rather than barite is a more likely source of the anomaly, and in at least one of these samples celestite is the dominant mineral. (3) A small amount of celestite was produced from Tertiary evaporitic sedimentary rocks on the north flank of the range (Moore, 1935, and Phalen, 1912). Thus, the source for this anomaly is more likely from evaporitic rocks than a hydrothermal system.

A third association involves the La Abra Plain, Cabeza Prieta Mountains, Sierra Pinta, and Granite Mountains anomalies, which are spatially associated with pre-Tertiary granitic rocks. Barium exceeds strontium by a factor of 2 to 10, and barite is the predominate mineral.

The Crater Range and Castle Dome Mountains anomalies are probably associated with barium- and strontium-rich volcanic rocks. Although older granitic rocks are sparingly exposed in these two areas, both terranes are dominated by Tertiary volcanic rocks. Barite is present in the most barium-rich samples from Crater Range, but the strontium-rich samples in this area are dominated by apatite, perhaps a strontian apatite. The Castle Dome anomaly is predominately barium, but barite has not been confirmed in any of the samples. It seems likely that these anomalies simply reflect barium- and strontium-rich volcanic rocks with little or no resource potential in themselves.

Map D displays localities where stream sediment contains less than 300 ppm of strontium. The range of strontium values reported for stream sediment is from less than 100 ppm to 3,000 ppm (fig. 5). The distribution has high kurtosis (sharply peaked) with a mode at 1,000 ppm. The distribution is negatively skewed on the logarithmic scale, and the values used to plot anomalous sample localities on map D are the four percent of the data that forms the "tail" of low values. The geographic distribution of these sample localities having unusually low concentrations of strontium forms three prominent clusters in the Sonoyta Mountains, in the vicinity of Growler Pass, and in a narrow band across the Ajo Range. Two of three additional sample localities are in the low hills adjacent to State Highway 84 in the northeast corner of the map. All of the sample localities are in areas identified as having anomalous concentrations of several other metals. The patterns displayed here may define the extent of hydrothermal alteration associated with the introduction of metals.

## ANOMALOUS AREAS

The four maps define a series of discrete geochemical anomalies characterized by deposition of metals (map A), by the presence of elements characteristic of hydrothermally deposited gangue minerals (maps B and C), or by the loss of strontium accompanying hydrothermal alteration (map D). The geochemically anomalous areas are Ajo, Sonoyta, Painted Rock Mountains, Growler Pass, State Highway 84, Maricopa Mountains, Mohawk Pass, Ajo Range, Sauceda, and Cabeza Prieta Mountains. In addition to the probable hydrothermal systems represented, the granitic rocks of the central and southwestern part of the map area contribute to the presence of unusual amounts of manganese, barium, and strontium, and some of the volcanic rocks are barium rich.

The anomalies are all prominent, multi-component anomalies. Of the 10 anomalous areas identified on maps A-D, some are represented on 2 or more of the maps and all are associated with anomalous concentrations of other elements (Theobald and Barton, 1987 and 1988). All have been identified on the basis of clusters of anomalous sample localities; individual anomalous sample localities are shown but not discussed. The scale of the sampling for this compilation is such that moderate-size deposits could be indicated by only one sample locality, or perhaps even missed.

## AJO ANOMALY

The anomaly in the vicinity of Ajo is represented by a scattering of sample localities rich in barium and strontium, presumably derived from barite in veins peripheral to a major mineralized system. The majority of these veins are west of the Gibson Arroyo fault of Gilluly (1946) and peripheral to the Cardigan Peak stock. In this area, the barium- and strontium-rich sample localities are in the outer part of the prominent anomaly centered on the New Cornelia deposit, outside of the prominent copper and molybdenum anomalies and coincident with the outer part of the lead and bismuth anomaly (Theobald and Barton, 1987 and 1988).

This anomaly is of interest primarily for comparative purposes. It provides a measure of the composition, size, and intensity of anomalous values in the vicinity of the known deposit at the New Cornelia mine. Alternatively, the barium, strontium, bismuth, and some of the lead in this area may be related to the Cardigan Peak stock rather than to the mineralized cupola of the New Cornelia Mine area. These two igneous bodies are now believed to be separate and unrelated intrusives on the basis of their ages (Hagstrum and others, 1987).

## SONOYTA ANOMALY

The Sonoyta anomaly is strongly reflected in the distribution of antimony and silver, includes one of the few sample localities having anomalous concentrations of zinc, and has abnormally low concentrations of strontium, suggesting widespread strontium depletion during hydrothermal alteration. It is the most prominent and coherent of the anomalous areas as demonstrated by the distribution of these elements. In addition to these elements, the area has anomalous concentrations of tungsten, molybdenum, lead (Theobald and Barton, 1988), and copper (Theobald and Barton, 1987). A barium and strontium anomaly, peripheral to La Abra Plain (see map C), overlaps the Sonoyta anomaly. This overlap may contribute to the apparent intensity of the Sonoyta anomaly, but the distribution of silver, antimony, and zinc clearly identifies a separate anomaly in the Sonoyta Mountains.

The Mesozoic metasedimentary rocks of the Sonoyta Mountains are riddled with mines and prospects of the Montezuma mining district. Some production of copper ore was reported (Keith, 1974). However, the geochemical assemblage dominated by antimony and silver is more representative of an epithermal precious-metal system than of mesothermal base-metal veins described for the mines.

## PAINTED ROCK MOUNTAINS ANOMALY

The Painted Rock Mountains anomaly is reflected in the distribution of barium and strontium, barite, and manganese. The area is also rich in lead in stream sediment and heavy-mineral concentrate, molybdenum in stream sediment (Theobald and Barton, 1988), and, at one locality, copper in stream sediment (Theobald and Barton, 1987). Veins containing barite and a variety of lead and molybdenum minerals have been exploited in the Painted Rock mining district. The principal ore mineral in the best known locality of the district, the Rowley mine, is wulfenite, valued primarily as a collectors item (Wilson and Miller, 1974). The Rowley mine is a few miles north of the Ajo quadrangle, but similar occurrences probably produce the anomalies found in the southern Painted Rock Mountains. However, the subdued anomaly for lead and the absence of molybdenum in the heavy-mineral concentrate indicates that wulfenite is not the principal secondary mineral in these samples.

## GROWLER PASS ANOMALY

Stream sediment from the vicinity of Growler Pass is abnormally poor in strontium, and at one locality to the north of the pass, the heavy-mineral concentrate contains 700 ppm antimony. The size and configuration of this anomaly are particularly well displayed by anomalous concentrations of lead and molybdenum in heavy-mineral concentrate (Theobald and Barton, 1988). In addition to these elements, unusual concentrations of bismuth, tungsten, copper, and tin are present (Theobald and Barton, 1987 and 1988). The assemblage suggests erosion into the middle or upper levels of a hydrothermal system. The rocks exposed in the lower terrane flanking the pass are Mesozoic sedimentary rocks. They are overlain to the north by late Tertiary volcanic rocks of the Growler Mountains. The anomaly is confined to the Mesozoic rocks, which are suitable hosts for Tertiary mineralization. Small bodies of porphyritic, calc-alkaline, intrusive rocks, presumably in the roofs of early Tertiary cupolas, cut the Mesozoic rocks within the anomalous area (G. Haxel, oral commun., 1980). Small base- and precious-metal prospects and mines are in the vicinity.

## STATE HIGHWAY 84 ANOMALY

Heavy-mineral concentrate is manganese rich and stream sediment is strontium poor in samples from the low hills along State Highway 84 in the northeast corner of the Ajo quadrangle. The area has anomalous concentrations of lead, bismuth, thorium, lanthanum, yttrium, and locally tungsten (Theobald and Barton, 1988). The thorium, lanthanum, and yttrium association suggests a relation to Precambrian granite exposed in the area, whereas the other elements suggest late magmatic or hydrothermal concentration of selected elements. The abnormally low level of strontium could reflect alteration, thus providing some evidence of a hydrothermal event. No prospects are known in the area, possibly due to the subdued topography wherein only the most resistant granite knobs are exposed above the pediment surface. The source of the metals that contribute to this anomaly is most likely concealed.

## MARICOPA MOUNTAINS ANOMALY

Heavy-mineral concentrate from the Maricopa Mountains is anomalously rich in manganese. The area is also yttrium rich and a number of localities in the western part of the mountains have anomalous concentrations of tungsten, bismuth, and lead (Theobald and Barton, 1988). The anomaly is closely associated with the outcrop area of Precambrian granite and most likely reflects a hydrothermal event superimposed upon the granite. At least one manganese prospect is known at the west end of the Maricopa Mountains (Jones and Ransome, 1920).

## MOHAWK PASS ANOMALY

Heavy-mineral concentrate from the vicinity of Mohawk Pass is rich in barium and strontium. Barium is the dominant element, and barite is the mineral responsible for the anomaly. This barite-rich anomaly extends southward along the east side of the Mohawk Mountains nearly to the prominent gap and offset of the mountains 25 km south of the pass. At its southern end, the barite anomaly is adjacent to the Mohawk Mountains anomaly described by Theobald and Barton (1988), though the two anomalies appear to be distinct entities and no direct relation between them can be established with the information available. At its northern end, the Mohawk Pass anomaly includes sample localities rich in tungsten, bismuth, lead, molybdenum (Theobald and Barton, 1988), thorium, and copper (Theobald and Barton, 1987).

Small quantities of base and precious metals and barite have been produced from mines on vein deposits in the Mohawk mining district (Keith, 1978). These deposits are related to normal faults in the upper plate of a detachment-fault system (Mueller and others, 1982), and the extension of the barite anomaly to the south corresponds remarkably well to their extrapolation of the detachment fault in that direction.

## AJO RANGE ANOMALY

The Ajo Range anomaly is best defined by the long, northwest-trending cluster of sample localities where the stream sediment is anomalously poor in strontium. A cluster of barium- and strontium-rich heavy-mineral-concentrate sample localities is near the center of this anomaly, and a single heavy-mineral-concentrate sample locality in the northwest end of the anomaly is rich in silver. In addition to these elements, the area has anomalous concentrations of lead, molybdenum (Theobald and Barton, 1988), copper (Theobald and Barton, 1987), and tin. Most of this anomaly is underlain by Miocene volcanic rocks. Isolated outcrops of presumed early Tertiary, calc-alkaline, intrusive rocks are exposed through the pediment cover at the northwest end of the anomaly. The general nature of the anomaly suggests remobilization of metals from older rocks beneath the exposed volcanic rocks along a major northwest-trending structural zone. Only at the northeast end of the anomaly has erosion breached the capping rocks to allow direct measurement of metal concentrations in the underlying rocks.

## SAUCEDA ANOMALY

Heavy-mineral concentrate throughout the Sauceda Mountains is anomalously rich in manganese. Two localities have anomalous concentrations of antimony, and localities at the northwest end of the mountains have anomalous concentrations of barium and strontium; strontium is the dominant element. The area has the largest tin anomaly in the study area and also has anomalous concentrations of copper in stream sediment when normalized against the ferride factor (Theobald and Barton, 1987). The Sauceda Mountains are a complex of predominately Miocene intermediate to felsic extrusive rocks with remnants of several vents exposed at a very shallow level in the volcanic pile. The high intensity of the manganese and tin anomalies indicates a volcanic sequence in which metal redistribution and deposition were active. The low-level copper anomaly could reflect weak leakage to the upper levels of the volcanic system from a more copper-rich part of the system at depth. The strong strontium-rich anomaly can be attributed to celestite accumulations in the basin fill to the north and northwest of the mountains (Moore, 1935; Phalen, 1912).

## CABEZA PRIETA MOUNTAINS ANOMALY

Scattered localities in the Cabeza Prieta Mountains and the adjacent Tule Mountains are rich in zinc or silver. Several other localities have weakly anomalous concentrations of molybdenum or tungsten, molybdenum, and lead. A single locality is rich in both copper and zinc. Barium and strontium enrichment in the Cabeza Prieta Mountains is probably related to a granite intrusion rather than the hydrothermal mineral occurrences suggested by the presence of other elements. The strongest of the metal anomalies is near the Venegas prospect (Wilson, 1933). Peterson and Tosdal (1986) list several prospects, including the Venegas, on copper- and gold-bearing veins in the Cabeza Prieta and Tule Mountains, and the scattered nature of the geochemical anomalies is compatible with vein-type occurrences. Neither the geology nor the geochemistry of this remote part of the study area are well enough known to further evaluate the mineral occurrences.

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# MAPS SHOWING ANOMALOUS CONCENTRATIONS OF ZINC, SILVER, ANTIMONY, MANGANESE, BARIUM, AND STRONTIUM IN STREAM SEDIMENT AND HEAVY-MINERAL CONCENTRATE FROM PARTS OF THE AJO AND LUKEVILLE 1° x 2° QUADRANGLES, ARIZONA

By

P.K. Theobald and H.N. Barton

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