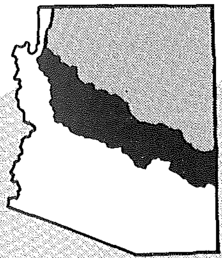

Arizona Geological Survey
# ARIZONA GEOLOGY
(formerly *Fieldnotes*)

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# Overview of the Geology and Mineral Resources of the Buckskin and Rawhide Mountains

*by Jon E. Spencer and Stephen J. Reynolds*
**Arizona Geological Survey**

The Arizona Geological Survey has made a major effort during the past 5 years to understand the geology and mineral resources of the Buckskin and Rawhide Mountains. The results of these studies and several studies by other geologists are presented in the Arizona Geological Survey Bulletin 198, from which the following text has been excerpted. This technical bulletin, which is now in press, represents a major addition to the geologic literature on the State and should be of interest to anyone concerned with the geology and mineral deposits of west-central Arizona.

## Introduction

Crustal extension and compression, involving large horizontal movements of the Earth's crust, are major processes that have shaped the crustal architecture of planet Earth. Compression has long been recognized as the chief architect of most mountain belts and is now moderately well understood. In contrast, the contribution of extension to the structure of the crust is less well understood because many extensional structures were only recently recognized and because areas affected by crustal extension are typically buried by sediments.

Cenozoic extension in western North America has left a geologic record that, for areas of extensional tectonism, is unsurpassed in its visibility. Geologic features related to Cenozoic extension are especially amenable to study in the arid southwestern United States where bedrock exposure approaches 100 percent. Approximately 25 mountain ranges or groups of ranges in western North America are characterized by a distinctive association of geologic features that defied interpretation until the early 1980's. These ranges or groups of ranges are commonly referred to as *metamorphic core complexes*. Distinguishing features include a major low-angle normal fault (referred to as a *detachment fault*) that separates brittlely distended and generally highly faulted rocks above the fault from crystalline rocks below the fault that commonly have a gently to moderately dipping mylonitic foliation. Most geologists now interpret such faults and foliations as products of large-magnitude crustal extension. These distinctive features have been recently recognized in parts of Greece, China, and New Guinea, which indicates that Cordilleran metamorphic core complexes are not idiosyncrasies of western North America geology, but are general products of extensional tectonism. The Buckskin and Rawhide Mountains, which are part of the Harcuvar metamorphic core complex in west-central Arizona (Rehrig and Reynolds, 1980), contain one of North America's most areally extensive exposures of a detachment fault and its mylonitic footwall.

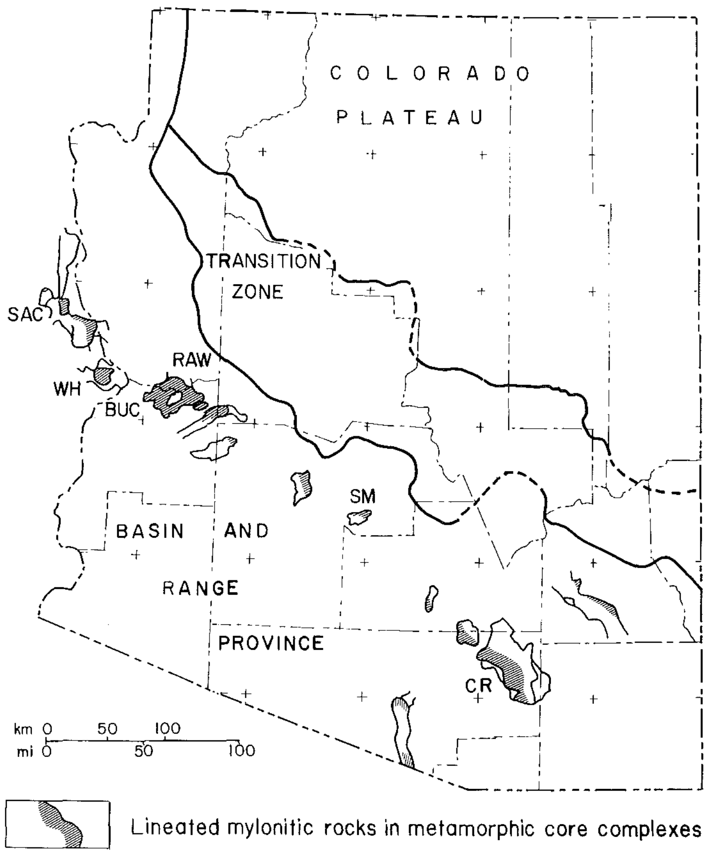



*Figure 1. Map of Arizona showing the three physiographic provinces in the State and the locations of lineated mylonitic rocks in metamorphic core complexes. BUC = Buckskin Mountains; CR = Santa Catalina - Rincon Mountains; RAW = Rawhide Mountains; SAC = Sacramento Mountains; SM = South Mountain; WH = Whipple Mountains.*

Evidence of mineralization is abundant along the Buckskin-Rawhide detachment fault, including economic deposits of copper and gold. Detachment-fault-related mineralization is nowhere better displayed in North America than in and around the Buckskin and Rawhide Mountains. This type of mineralization was first recognized in the southwestern United States in the late 1970's (Reynolds, 1980; Wilkins and Heidrick, 1982). The existence of geologically similar deposits has been proposed

*(continued on page 6)*

# The Nonfuel Mineral Industry: 1988 Summary

In 1988 the value of nonfuel mineral production in the Southwest reached $9.9 billion, a 30.5-percent increase from the 1987 value of $7.6 billion (Figure 1; Table 1). Production value in the Southwest accounted for 32.6 percent of the total value for the Nation, estimated to be $30.5 billion in 1988. For the purposes of this article, the Southwest includes Arizona, California, Colorado, Nevada, New Mexico, and Utah. In 1988 the Southwest boasted the three leading producers of nonfuel minerals in the Nation: California, Arizona, and Nevada. Two other States, New Mexico and Utah, held the 10th and 11th positions, respectively. Colorado ranked 27th in the Nation.

These preliminary figures were published by the U.S. Bureau of Mines (BOM), which has released State-by-State estimates of nonfuel mineral production for 1988. These estimates, based on 9 months of data, have been published for the first time in one volume: *State Mineral Summaries--1989*. This report is designed to be a companion volume to another BOM publication, *Mineral Commodity Summaries--1989*, which contains national statistics on the production of 82 nonfuel minerals. Excerpts from both volumes appear below. Single copies of each are free from the Publications Distribution Section, U.S. Bureau of Mines, Cochrans Mill Rd., P.O. Box 18070, Pittsburgh, PA 15236.

The State summaries were prepared by State mineral officers from the BOM, in cooperation with the respective State mineral agencies. Individual summaries are also published separately as State Mineral Industry Surveys. Copies are available from the respective State mineral officers: Michael N. Greeley, 201 E. 7th St., Tucson, AZ 85705 (Arizona, New Mexico, and Utah); Fred V. Carrillo, 1605 Evans Ave., Reno, NV 89512 (California and Nevada); and Jane P. Ohl, Bldg. 20, Denver Federal Center, Denver, CO 80225 (Colorado).

## U.S. Summary

The value of nonfuel mineral production in the United States increased 16 percent in 1988, from $26.3 billion to $30.5 billion, due to higher demand and prices. Metals and industrial minerals accounted for 34 and 66 percent of the total value, respectively. The value of metal production surged 40 percent in 1988, from $7.4 billion to $10.4 billion, whereas the production value of industrial minerals rose only 6 percent, from $18.9 billion to $20.0 billion.

Copper prices, driven by tight supply and record-low stock levels, averaged more than $1.00 per pound during 1988. Domestic mine production continued to increase, rising by an estimated 15 percent. Negotiating sessions to create an international forum for copper producers and consumers continued. Agreement was reached on a market-development role for the forum and on independence from the United Nations Conference on Trade and Development.

As in previous years, exploration for gold far outpaced that of other commodities both at home and abroad. About two dozen new gold mines began production in the United States during 1988, and several established producers expanded capacity. A number of domestic and international companies with gold-mining interests consolidated, merged, or spun off their mining operations into independent corporations devoted solely to mining gold. Domestic production of gold and silver increased. Although averaging slightly higher during most of the year, price levels for gold and other precious metals declined toward yearend.

Zinc mine production in 1988 rose for the second consecutive year after falling continuously in the prior 6-year period. The increase was partly due to a full-year's production of coproduct zinc at precious metal mines in the West.

The U.S. District Court of Appeals of the District of Columbia ordered the Environmental Protection Agency (EPA) to relist six wastes from the smelting and refining of aluminum, copper, ferro-alloys, lead, and zinc as hazardous under subtitle C of the Resources Conservation and Recovery Act (RCRA). The EPA was also ordered to reinterpret the Bevill amendment to the RCRA. This amendment excludes wastes from the "extraction, beneficiation, and processing of ores and minerals" from regulation under RCRA subtitle C until the need for such regulation is studied. Although the range of the amendment has been clearly understood, its application to processing ores and minerals has been less clear. Under the court order, the EPA proposed a list of wastes specifically excluded as Bevill wastes. Those that do not fall under the Bevill exclusion will be subject to regulation after the rule is finalized.

The EPA was also evaluating a stricter National Ambient Air Quality Standard that would lower the content of lead in air and impose additional costs on domestic lead smelters. The world's largest producer of secondary lead announced that it would convert its plants to a new electrowinning process, thus becoming the first U.S. lead firm to move toward pollution-free technology.

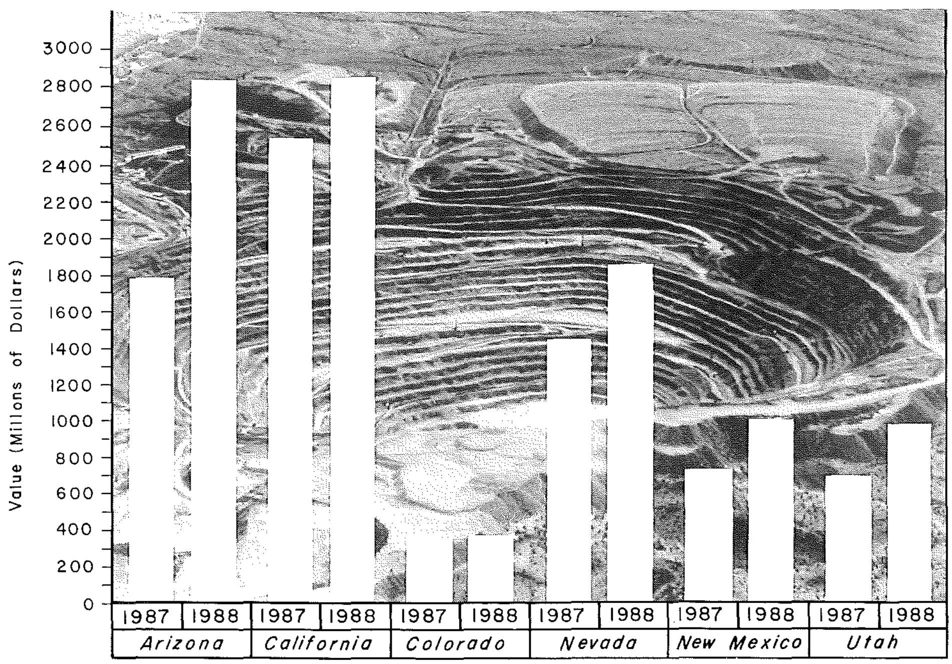



*Figure 1. Value of nonfuel mineral production in the Southwest, 1987 and 1988. Background photo: View of the New Cornelia open-pit copper mine near Ajo, Arizona. This currently inactive mine is within the Ajo mineral district, which produced from 1899 to 1979, 6 billion pounds of copper, 19.7 million ounces of silver, 1.6 million ounces of gold, 450,000 pounds of molybdenum, and 30,000 pounds of lead. Photo by Peter Kresan.*

The EPA's National Effluent Guidelines for gold-placer mining became effective on July 7, 1988. Studies by the U.S. Department of the Interior indicate that up to 75 percent of the small placer mines will close if these regulations are implemented.

Demand for building and construction materials, such as construction aggregate, gypsum, and cement, remained strong in 1988. Demand for cement nearly equaled that of the record established in 1987. Domestic production declined slightly while imports continued to make inroads into domestic markets. Imports of 17 million tons were slightly below the record level of 1987. Canada, Greece, Mexico, and Spain were the principal suppliers of the imported cement, accounting for 75 percent of the imports. Domestic cement-production capacity owned by foreign firms reached 62 percent in 1988 compared with 22 percent in 1981. For the first time, Japanese producers became owners of U.S. capacity by purchasing cement plants in Arizona and southern California.

The crushed stone industry, continuing the healthy growth trend that began in 1984, reported record production. The gypsum industry continued its strong performance, but because of reduction in new housing construction, output was slightly below the record high of 1987.

The EPA continued to analyze the impact of the proposed ban and phaseout of asbestos and asbestos products. In early 1988, the EPA released its regulatory impact analysis, an assessment of exposure to asbestos and nonasbestos fibers, and a profile of the nonasbestos fiber industry.

In September, the President signed a U.S.-Canadian free-trade agreement that will eliminate all tariffs and most nontariff barriers between the two countries by 1999, thereby creating the world's largest open market. In 1987 U.S.-Canadian bilateral trade totaled $161 billion. Trade expansion is expected to generate 5-percent higher growth for Canada and up to 1-percent higher growth for the United States by the end of the century. For the United States, that translates into 750,000 jobs and $2.4 billion in exports. Canadian parliamentary approval of the agreement is required before the treaty can take effect.

## Arizona

Arizona's mining industry rode a wave of prosperity during 1988. Its nonfuel mineral production rose sharply during the year to an estimated value of $2.83 billion (Table 2). This represents an increase of more than $1 billion, or about 58 percent, over the 1987 value. The bulk of this increase is due to the strong price received during the year for copper, which accounts for more than three-fourths of the State's nonfuel mineral value. The price of copper rose from an average of $0.825 per pound in 1987 to an average of $1.20 per pound in 1988. This price hike was attributed to diminished stocks and strong demand.

Ranking second nationally in the value of its nonfuel mineral production, Arizona continues to lead other States in the production of copper: in 1988 it produced nearly two-thirds of the Nation's copper. Copper was recovered at 12 principal operations. Copper producers, strengthened by a favorable market, continued to cut costs, expand capacity, and acquire future reserves.

In 1988 Arizona also gained the lead position in molybdenum production. In sharp contrast to the decline registered last year, production was greatly increased in 1988. Arizona's production of this coproduct and byproduct metal accounted for almost 50 percent of the Nation's domestic supply.

The State retained its place among the top producers of bentonite, cement, gem stones, lime, rhenium, sand and gravel, silver, and sulfuric acid. Most lead and silver were produced as byproducts of copper or flux ores. Gold production increased 64 percent.

The nonmetallic mineral industry is very diversified in Arizona. The 1988 production value of the largest component, construction sand and gravel, placed Arizona fifth in the Nation for this commodity. Cement and lime production contributed significantly to the total value of industrial minerals, which exceeded $297 million. There was also a considerable increase in the production of diatomite and salt.

Some 12,000 workers were employed in the Arizona mining industry in 1988. This figure, an increase over 1987, includes workers in the mineral fuels industry. About 75 percent of the total work force is in copper exploration and production.

Most exploration efforts in Arizona focused on precious metals and leachable copper. Claim-staking activity remained moderately strong during the year; Arizona ranked third among the States in the number of active claims for all commodities.

Construction began on a tailings recycling facility in Gila County. This

***Table 2.*** *Value of nonfuel mineral production in Arizona, measured by mine shipments, sales, or marketable production, including consumption by producers. All figures are from the U.S. Bureau of Mines; totals for 1988 are preliminary estimates.*

| Mineral | Value (thousands of dollars) 1987 | 1988 |
|---|---|---|
| Clays | 1,905 | 1,823 |
| Copper | 1,389,771 | 2,298,655 |
| Gem stones | 3,000 | 3,300 |
| Gold | 42,663 | 68,486 |
| Gypsum | W | W |
| Lime | 21,932 | 25,998 |
| Molybdenum | W | 144,069 |
| Perlite | 1,361 | W |
| Pumice | 7 | 7 |
| Sand and gravel (construction) | 141,300* | 136,200 |
| Silver | 25,706 | 20,832 |
| Stone (crushed) | 33,999 | 29,300 |
| Other** | 129,398 | 100,517 |
| TOTAL | 1,791,042 | 2,829,187 |

W Withheld to avoid disclosing company proprietary data; value included in "Other" figure.
* Estimated.
** Combined value of cement, diatomite (1988), pyrites (1987-88), salt, industrial sand and gravel, dimension stone (1988), and values indicated by symbol W.

***Table 1.*** *Value of nonfuel mineral production in the Southwest, measured by mine shipments, sales, or marketable production, including consumption by producers. All figures are from the U.S. Bureau of Mines; totals for 1988 are preliminary estimates.*

| State | Value (thousands of dollars) 1987 | 1988 | Percent of Total Value in 1988 Southwest | U.S. | Principal Minerals |
|---|---|---|---|---|---|
| Arizona | 1,791,042 | 2,829,187 | 28.5 | 9.3 | copper, sand/gravel, cement |
| California | 2,551,285 | 2,851,352 | 28.7 | 9.4 | cement, sand/gravel, boron |
| Colorado | 372,989 | 374,875 | 3.8 | 1.2 | molybdenum, cement, sand/gravel |
| Nevada | 1,446,814 | 1,866,865 | 18.8 | 6.1 | gold, sand/gravel, cement |
| New Mexico | 737,675 | 1,007,181 | 10.2 | 3.3 | copper, potassium salts, sand/gravel |
| Utah | 699,864 | 990,208 | 10.0 | 3.3 | magnesium metal, cement, gold |
| SOUTHWEST | 7,599,669 | 9,919,668 | 100.0 | 32.6 | |
| U.S. TOTAL | 26,346,000 | 30,461,000 | --- | 100.0 | |

solvent-extraction/electrowinning (SX-EW) plant is designed to wash down a pile containing 35 million short tons of copper-bearing mill tailings and recover approximately 125 million pounds of copper. The $20-million project, the first of its kind in the United States, will last about 8 years.

State officials and representatives of the mining community attempted to resolve the questions raised by the 1987 decision of the State Supreme Court, which declared that Arizona's land-leasing law was unconstitutional. During 1988, negotiations were underway between the State Land Commissioner and three major lessees. These companies operate mines on State Trust lands and make relatively large annual royalty payments to the State. Meanwhile all new applications for mineral leases were held in abeyance. Late in the year, the U.S. Supreme Court agreed to hear an appeal.

## California

California led the Nation in value of nonfuel mineral production for the fifth year in a row. The value of the commodities produced was estimated to be $2.85 billion, a 12 percent increase from 1987. California led all States in the production of asbestos, boron minerals, portland cement, diatomite, calcined gypsum, rare-earth metal concentrates, construction sand and gravel, and tungsten ore and concentrates. It was second in the production of natural calcium chloride, gold, byproduct gypsum, magnesium compounds from seawater, and sodium compounds. Gold exploration in the State increased as rising production encouraged further exploration. Several gold producers continued to expand their operations.

No-growth regulations and opposition to new mining permits impeded mining activities throughout the State. Gold-mining operations, sand-and-gravel quarries, and cement plants were among those whose operations were halted or delayed. Initiatives to prohibit surface-mining operations were proposed in El Dorado, Mariposa, and Tuolomne Counties. Mariposa County narrowly defeated this proposal in the fall election. The State of California, pursuant to AB No. 747, now requires that all existing surface-mining operations with vested rights must have an approved reclamation plan by July 1, 1990.

## Colorado

The estimated value of nonfuel minerals produced in Colorado in 1988 was $375 million, a 0.5-percent decline from 1987. Between 1985 and 1988, the reopening of several old precious-metal mines increased Colorado gold output by 313 percent. In 1988 gold production rose 21 percent to an estimated 215,000 troy ounces. Silver output at Colorado mines, however, was down an estimated 15 percent from 1987. Byproduct lead from gold and silver mining decreased nearly 18 percent from that of 1987.

Once again, Denver has become a gold capital. More than 50 percent of U.S. gold production is controlled by the two to three dozen companies of local, national, and international standing whose headquarters or major offices are in or moving to the Denver area.

Exploration continued around the historic mining camps of Creede, Cripple Creek, Leadville, Silverton, and Summitville. Old tailings piles are increasingly being considered as sources of metals.

On the Western Slope, seven uranium/vanadium mines were put back into production in 1987-88. Colorado's sole nuclear power plant, however, will be shut down before June 30, 1990 because of continuing technological problems since its opening in 1976.

Construction materials for the proposed new Denver airport, beltway E-470, and other projects have included an estimated 8 to 12 million short tons of fine and coarse aggregates and portland cement. Portland and masonry-cement production and value, however, declined slightly in 1988. Output of dimension stone rose an estimated 13 percent, and value 7 percent, over 1987.

Crude gypsum production fell 10 percent from that of 1987. The agricultural community and the U.S. Soil and Conservation Service have been using small gypsum blocks buried in the soil to measure moisture content and reduce ground-water pollution, soil erosion, and salt buildup. Such an inexpensive method of water conservation is claimed to be capable of raising water availability to a level higher than that expected from Denver's proposed Two Forks Dam and Reservoir.

The U.S. Congress approved a national charter for the National Mining Hall of Fame and Museum in Leadville, which will become a repository of mining artifacts and serve the industry in educating the public about mining.

## Nevada

Nevada's nonfuel mineral production was estimated to be valued at $1.87 billion in 1988, an increase of $420 million from 1987. The increase resulted from a 33-percent rise in gold production to 3.6 million troy ounces and a 35-percent rise in silver production to 16.5 million troy ounces. Nevada was the leading State in the Nation in the production of barite, gold, mercury, and silver and was the sole producer of mined magnesite. In 1988, Nevada ranked third in the United States in value of nonfuel mineral production.

Precious-metal production continued to increase with at least 10 additional mine openings. Extensive exploration for precious metals continued throughout Nevada, focusing on deeper deposits in the Carlin Trend area in the northwestern part of the State. Drilling and exploration projects were conducted in every county, with important discoveries reported in Elko, Eureka, Humboldt, Mineral, Nye, and White Pine Counties.

Byproduct production from several northern Nevada gold and silver mines was a major source of mercury. Nevada furnished almost all of the Nation's mercury output. The State's barite production continued to decline, with 1988 output estimated at 293,000 short tons, 5 percent lower than in 1987. Value also declined to $4.2 million, or 12 percent lower than in 1987. Despite the drop in production, Nevada remained the leading barite-producing State in the Nation.

At the end of August 1988, the U.S. Bureau of Land Management reported that 45,948 mining claims had been received in the Nevada office. Employment in the Nevada mining industry reached 11,000 by October 1988, compared to 8,700 in October 1987. By yearend, the industry had added 2,400 jobs statewide, a 28.2-percent increase.

## New Mexico

The value of nonfuel mineral production in New Mexico in 1988 was estimated at a record high of $1.01 billion, a 37-percent increase over 1987. Metals output accounted for more than two-thirds of the total value of the State's nonfuel mineral production, with copper being the principal contributor.

The State's leading commodities included copper, potash, construction sand and gravel, portland cement, silver, gold, perlite, and crushed stone. Nationally, New Mexico ranked first in production of perlite and potassium salts and second in copper, mica, pumice, and silver. Increases were posted for portland cement, copper, gold, lead, perlite, potassium salts, pumice, and silver.

The chief reason for the rise in the value of nonfuel mineral production was the 48-percent increase in the value of copper due to higher prices. In contrast, the quantity of copper produced rose only 2 percent. Another factor in the rise in production value was the more than 50-percent increase in the quantity and value of gold output. Gold prices

*(continued on page 12)*

# Theses and Dissertations, 1988

The following list includes theses and dissertations on Arizona geology, geological engineering, hydrology, and related subjects that were awarded in 1988 by Arizona State University, Northern Arizona University, and the University of Arizona. This list, however, is not a complete compilation of theses on such topics. Theses on the geology of other States that were awarded by these universities are not listed, nor are theses on the geology of Arizona that were awarded by out-of-State universities.

Most theses included here are not available in the library of the Arizona Geological Survey. Each thesis, however, may be examined at the main library of the university that awarded it. Information may also be obtained from the respective departments, which are indicated in parentheses after each citation using the codes listed below. (Theses from Northern Arizona University were awarded by the geology department.)

Arizona State University, Tempe, AZ 85287; (602) 965-9011. (Gg-Geography; Gl-Geology)

Northern Arizona University, Flagstaff, AZ 86011; (602) 523-9011.

University of Arizona, Tucson, AZ 85721; (602) 621-2211. (G-Geosciences; HWR-Hydrology and Water Resources; MGE-Mining and Geological Engineering; PS-Planetary Sciences; RNR-Renewable Natural Resources; SWS-Soil and Water Science)

### Arizona State University

Doorn, S.S., Theoretical energetics of the formation of iron-nickel alloy and magnetite in olivine: M.S. thesis, 116 p. (Gl)

Evans, K.E., Distribution of hourly rainfall intensities in the southwest United States summer monsoon: M.A. thesis, 80 p. (Gg)

Schuver, H.J., Modeling volcano morphology: M.S. thesis, 120 p. (Gl)

### Northern Arizona University

Darrach, M.E., A kinematic and geometric structural analysis on an Early Proterozoic crustal-scale shear zone; the evolution of the Shylock fault zone, central Arizona: M.S. thesis, 78 p.

Johns, M.E., Architectural element analysis and depositional history of the Upper Petrified Forest Member of the Chinle Formation, Petrified Forest National Park, Arizona: M.S. thesis, 163 p.

Muehlberger, E.W., The structure and general stratigraphy of the western half of the Payson basin, Gila County, Arizona: M.S. thesis, 86 p.

Shirley, D.H., Geochemical facies analysis of the Surprise Canyon Formation in Fern Glen channelway, central Grand Canyon, Arizona: M.S. thesis, 240 p.

Waters, J.P., A geophysical and geochemical investigation of selected collapse features on the Coconino Plateau in northern Arizona: M.S. thesis, 112 p.

### University of Arizona

Akman, H.H., Resistivity and induced polarization responses over two different earth geometries: M.S. thesis, 109 p. (G)

Asmerom, Yemane, Mesozoic igneous activity in the southern Cordillera of North America; implication for tectonics and magma genesis: Ph.D. dissertation, 232 p. (G)

Aubele, Jane, Crumpeler, J.S., and Elston, W.E., Vesicle zonation and vertical structure of basalt flows: M.S. thesis, 59 p. (PS)

Beer, K.E., A ground-water study and predictive model for the town of Florence, Arizona: M.S. thesis, 105 p. (HWR)

Brooks, S.J., A multidisciplinary analysis of the hydrogeology of the Maricopa Superconducting Super Collider (SSC) site, Maricopa County, Arizona: M.S. thesis, 85 p. (HWR)

Byrne, R.W., Ridge-transform-ride dynamics: M.S. prepublication manuscript, 23 p. (G)

Calderone, G.J., Paleomagnetism of Miocene volcanic rocks in the Mojave-Sonora Desert region, Arizona and California: Ph.D. dissertation, 163 p. (G)

Chen, Chuangming, Andisols of the San Francisco volcanic field, Arizona: M.S. thesis, 111 p. (SWS)

Chuang, Yuen, Solute transport measurement by ion-selective electrodes in fractured tuff: M.S. thesis. (HWR)

Colarullo, S.J., Identification of an optimal groundwater management strategy in a contaminated aquifer: M.S. thesis. (HWR)

Dolegowski, J.R., The hydrogeochemistry of strontium in the Ranegras Plain groundwater basin: M.S. thesis. (HWR)

Ekstrand, E.J., Paleomagnetim of the Moenave Formation: Implications for the Mesozoic North American apparent polar wander path: M.S. prepublication manuscript, 19 p. (G)

El-Ariss, S.R., A broad perspective of sand dune forms, wind regimes, and fixations: M.S. professional paper, 61 p. (RNR)

Elder, A.N., Neutron gauge calibration model for water content of geologic data: M.S. thesis. (HWR)

Fabryka-Martin, J.T., Production of radionuclides in the earth and their hydrogeologic significance with emphasis on chlorine-36 and iodine-129: Ph.D. dissertation, 399 p. (HWR)

Feldman, P.R., Hydrogeology of a contaminated industrial site on filled land: M.S. thesis, 127 p. (HWR)

Goering, T.J., Use of gamma-ray geotomography to measure dry bulk density and unsaturated flow through tuff: M.S. thesis. (HWR)

Haldeman, W.R., Water flow through variably saturated fractured tuff: A laboratory study: M.S. thesis. (HWR)

Hanson, R.T., Aquifer-system compaction, Tucson basin and Avra Valley, Arizona: M.S. thesis. (HWR)

Hartshorne, P.M., Paleoenvironmental analysis of a coral-rudist bioherm; Upper Mural Limestone (Lower Cretaceous), southeast Arizona: M.S. prepublication manuscript, 58 p. (G)

Hazlehurst, W.M., An estimation of the water resources for water planning and management in Fort Valley, Coconino County, Arizona: M.S. thesis, 138 p. (HWR)

Jeon, G.J., Innovative methods for long-term mineral forecasting: Ph.D. dissertation, 299 p. (MGE)

Karnieli, Arnon, Storm runoff forecasting model incorporating spatial data: Ph.D. dissertation, 249 p. (RNR)

Kebler, D.G., Coagulation of submicron aluminum hydroxide colloids by silica particles: M.S. thesis, 198 p. (HWR)

Lapham, W.W., Conductive and convective heat transfer in sediments near streams: Ph.D. dissertation, 318 p. (HWR)

Law, K.J., Dissolution of lead smelter dust compounds by humic acid: M.S. thesis, 30 p. (G)

Lawson, P.W., Sorption of fulvic acid on aluminum oxide and desert soil: M.S. thesis. (HWR)

Leo, T.P., Computer studies of heat tracer experiments in fractured rock: M.S. thesis. (HWR)

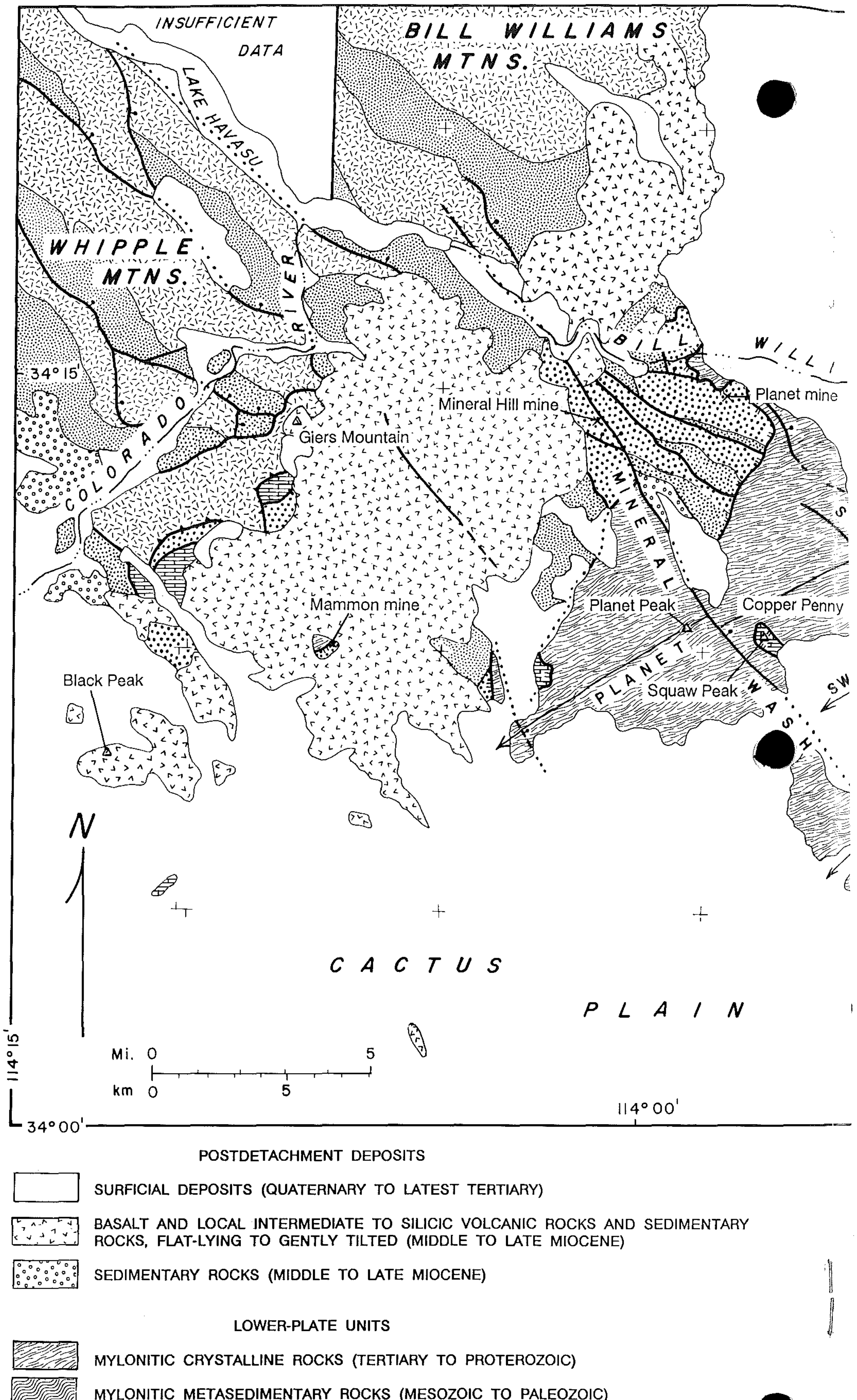
MacInnes, S.C., Lateral effects in controlled source audiomagnetotelurics: Ph.D. dissertation, 188 p. (G)

Maus, D.A., Ore controls at the Golden Rule mine, Cochise County, Arizona: M.S. thesis, 114 p. (G)

Page, D.I., Overland flow partitioning for rill and interrill erosion modeling: M.S.

*(continued on page 12)*

*Figure 2 (right). Simplified geologic map of the Buckskin and Rawhide Mountains showing the location of important mines and geographic features. The Buckskin Mountains include all areas of bedrock south of the Bill Williams River and east of the Colorado River, unless otherwise labeled (modified from Spencer, 1989).*



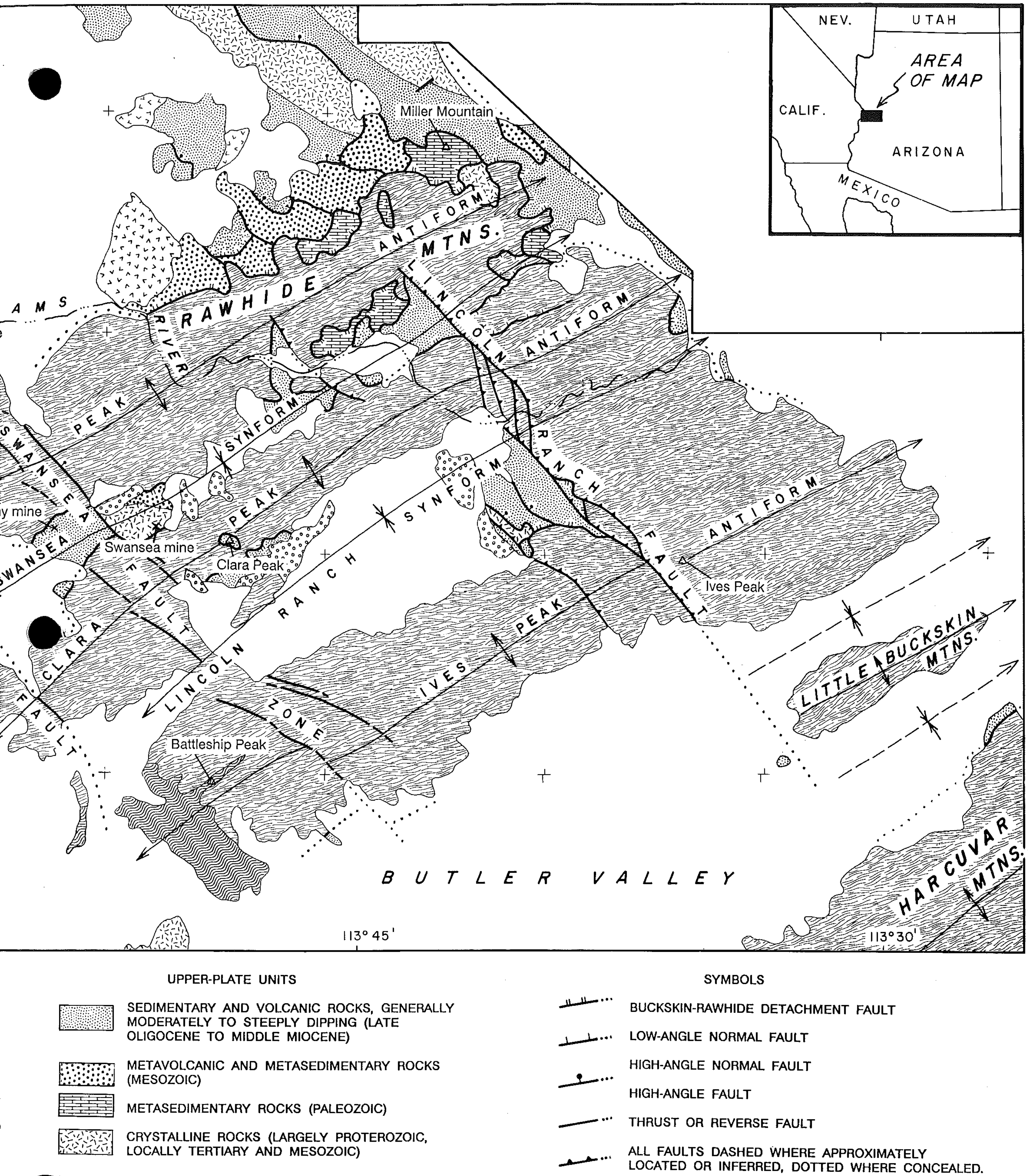

*(continued from page 1)*

for other areas in western North America, Spain, and New Guinea. The recently discovered Copperstone mine, Arizona's largest gold producer with annual production at approximately 60,000 ounces, is now known to be a detachment-fault-related deposit (Spencer and others, 1988). Recent recognition of these deposits as a distinct deposit type and their association with metamorphic core complexes, which are themselves recently recognized and incompletely understood features, have sparked much scientific interest. Discovery of the Copperstone mine has also generated exploration interest in these deposits. The largest domestic deposits of manganese, a strategic and critical mineral, are present in the Artillery Mountains, which are adjacent to the Buckskin and Rawhide Mountains, and may have originated by processes associated with detachment faulting. Because of these geologic and mineral-resource attributes, the Buckskin and Rawhide Mountains have attracted considerable attention from geologists during the past 15 years, beginning with the pioneering Ph.D. study of the geology of the Rawhide Mountains by Terry Shackelford (Shackelford, 1976, 1989a,b; Davis, G.A., 1989).

## Geology

The Buckskin and Rawhide Mountains are within the Basin and Range physiographic province of southwestern North America. This province, which includes southern and western Arizona, is characterized by numerous mountain ranges and intervening Cenozoic basins. The physiography of the Basin and Range Province is largely the product of middle and late Cenozoic low- and high-angle normal faulting, volcanism, and erosion. The significance and relative age of each of these processes vary greatly from range to range. Miocene low-angle normal faulting was the dominant process that determined the physiography of the Buckskin and Rawhide Mountains. Younger basaltic volcanism, erosion, and minor, postdetachment high-angle faulting were also important.

Cordilleran metamorphic core complexes are typically characterized by normal-faulted and extended hanging-wall rocks that overlie well-lineated, variably mylonitic footwall rocks along large-displacement, Tertiary low-angle normal faults (detachment faults). The Harcuvar metamorphic core complex, which includes the Buckskin and Rawhide Mountains, is one of the approx-




mately 10 such complexes that are discontinuously exposed in a belt extending diagonally across Arizona into southeastern California (Figure 1). Metamorphic core complexes have been intensively studied during the past 15 years. These once enigmatic associations of rocks and structures are now generally recognized as products of large-magnitude displacement on moderately to gently dipping normal faults and their down-dip continuations as ductile shear zones.

The subhorizontal Buckskin-Rawhide detachment fault is exposed discontinuously throughout the Buckskin and Rawhide Mountains (Figure 2). Hanging-wall rocks, collectively referred to as the *upper plate*, consist of a variety of complexly normal-faulted and tilted rocks that include syntectonic, mid-Tertiary sedimentary and volcanic rocks and variably deformed and metamorphosed, Mesozoic and Paleozoic sedimentary and volcanic rocks (Figure 3). The footwall block, commonly referred to as the *lower plate* (platelike form is not implied), is composed of variably mylonitic crystalline and metasedimentary rocks and is thought to be structurally continuous with similar lower-plate rocks in the nearby Harcuvar and Whipple Mountains. The mid-Tertiary age of some of the mylonitized rocks in the Whipple, Buckskin, and Rawhide Mountains has recently been established by U-Pb (zircon) geochronologic study (Wright and others, 1986; Bryant and Wooden, 1989). A northeastward direction of displacement of upper-plate rocks relative to the lower plate is inferred based on a number of criteria (e.g., Davis, G.A., and others, 1980; Reynolds and Spencer, 1985; Howard and John, 1987). The sense of displacement on the detachment fault is the same as that indicated for mylonitization by asymmetric petrofabrics in the mylonites (Davis, G.A., and others, 1986; Davis, G.A., and Lister, 1988; Marshak and Vander Muelen, 1989; Spencer and Reynolds, 1989b).

The detachment fault forms a corrugated surface defined by east-northeast-trending antiforms and synforms (Figure 4). Lower-plate foliation and lithologic layering broadly conform to the form of the detachment fault, at least in areas where exposure through the lower plate is good, such as the east face of Planet Peak and the west face of Ives Peak (Figure 2). The origin of these corrugations is unknown, but they are suspected to be related to detachment faulting and mylonitization because the direction of displacement on the detachment fault and mylonitic lineation are approximately parallel to antiform and synform axes.

Except for the corrugations, all of the basic Tertiary structural features in the Buckskin and Rawhide Mountains, and in metamophic core complexes in general, are accounted for by the shear-zone model. This model envisions that each metamorphic core complex originated by large displacement on a master low-angle normal fault that extended down dip into a zone of mylonitization (Figure 5). According to this model, rocks originally mylonitized at perhaps 8- to 15-kilometer depth rose isostatically and cooled as they were displaced from beneath a wedge of brittlely extending upper-plate rocks, and were overprinted successively by chloritic alteration and brecciation, microbrecciation, and fault-gouge formation along a narrow fault zone (Wernicke, 1981, 1985; Davis, G.H., 1983; Reynolds, 1985; Davis, G.A., and others, 1986). Arching and subareal exposure of the lower plate led to shedding of mylonitic debris into syntectonic sedimentary basins and to the distinctive physiography of many of the complexes (Rehrig and Reynolds, 1980; Howard and others, 1982; Spencer, 1984; Pain, 1985; Miller and John, 1988; Spencer and others, 1989a).

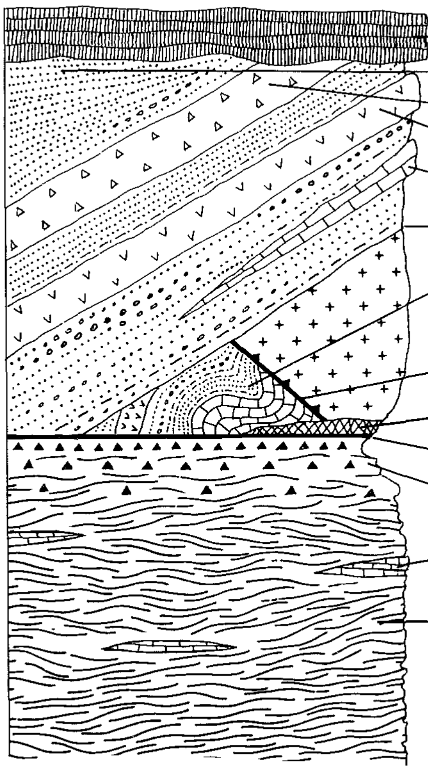



*Figure 3. Schematic structure-stratigraphy diagram for the Buckskin and Rawhide Mountains showing all important pre-Pliocene rock types and some of their contact relationships. Movement on rotational normal faults (not shown) caused tilting of upper-plate rocks.*

Upper-plate rocks in the Buckskin and Rawhide Mountains contain abundant evidence of compressional deformation and metamorphism of Mesozoic and Paleozoic sedimentary rocks. The stratigraphy of the pre-Tertiary rocks is recognizable in spite of variable but typically severe deformation and greenschist-grade metamorphism (Reynolds and others, 1987, 1989; Reynolds and Spencer, 1989; Spencer and others, 1989b). Deformation occurred in association with generally south-directed, late Mesozoic thrust faulting within the east-west-trending Maria fold-and-thrust belt (Reynolds and others, 1986).

Detachment faulting and related deformation and sedimentation were followed by dominantly basaltic volcanism with local associated felsic volcanism (Suneson and Lucchitta, 1983). Trachyte flows and interbedded pyroclastic rocks in the western Buckskin Mountains are the same age as, and may have evolved from, magmas associated with adjacent postdetachment basalts (Grubensky, 1989).

## Mineralization and Alteration

Mineral deposits are widely distributed in the Buckskin and Rawhide Mountains and, with a few notable exceptions, are along or within a few tens of meters of the detachment fault (Figure 6). Most of the deposits contain massive or fracture-filling specular hematite and younger fracture-filling chrysocolla. Early-formed copper and iron sulfides were probably common, but are largely obscured by later oxidation. Hydrothermal-carbonate replacements are also present along the fault and are commonly associated with copper-iron mineral deposits. These deposits have yielded approximately 52 million pounds of copper and 15,500 ounces of gold, with minor amounts of lead, zinc, and silver (Keith and others, 1983). All of the deposits formed at the same time that detachment faulting and related structural and sedimentary phenomena occurred. They are believed to have

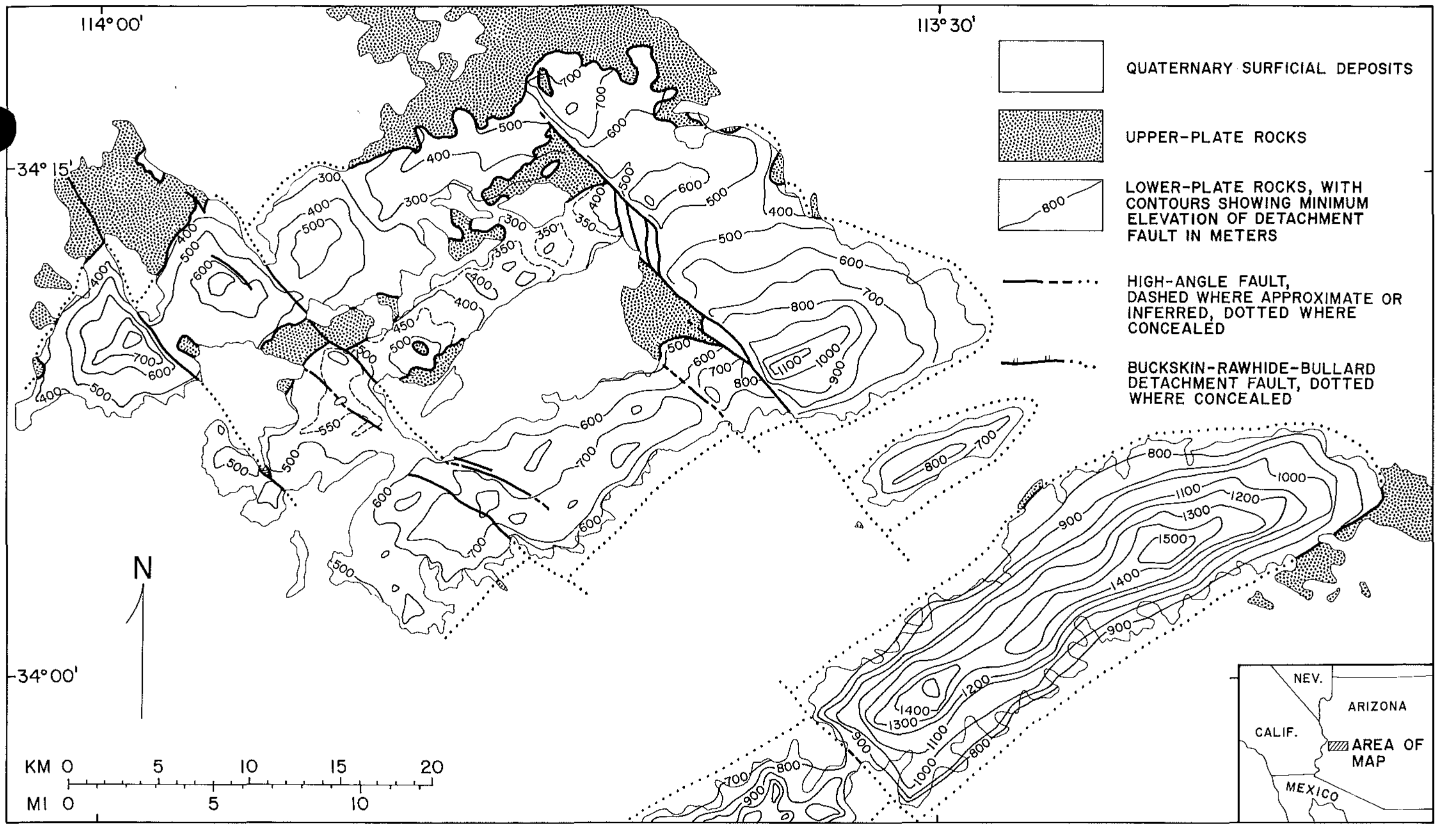
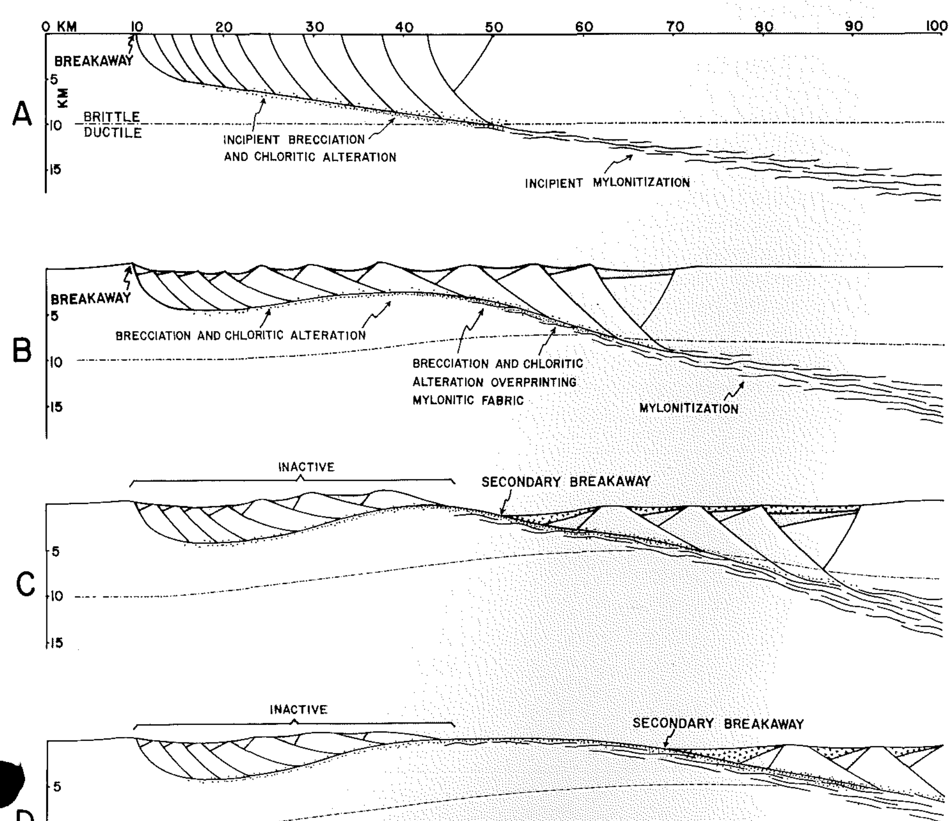



*Figure 4 (above). Minimum-relief contour map of the Buckskin-Rawhide detachment fault.*




formed from aqueous brines that leached metals from strata within extensional sedimentary basins (Wilkins and Heidrick, 1982; Spencer and Welty, 1986, 1989; Wilkins and others, 1986; Lehman and Spencer, 1989). The recent discovery of the Copperstone deposit in west-central Arizona, which is estimated to contain more than 500,000 ounces of gold and is related to the Moon Mountains detachment fault, has led to renewed interest in detachment-fault-related mineral deposits (Spencer and others, 1988).

Manganese deposits hosted in upper-plate, Miocene sedimentary rocks in the Buckskin and Rawhide Mountains have yielded approximately 24 million pounds of manganese. Similar manganese deposits in the nearby Artillery Mountains are the largest of such deposits in the United States (Lasky and Webber, 1949). Some of the deposits in the Artillery Mountains are younger than previously suspected and may postdate detachment faulting and related mid-Tertiary tectonism. These younger deposits formed from low-salinity fluids and thus were not derived directly from the saline aqueous fluids that caused detachment-fault-related mineralization (Spencer and others, 1989a).

*Figure 5 (left). Cross-section evolution diagram of Miocene extension in the Buckskin and Rawhide Mountains.*

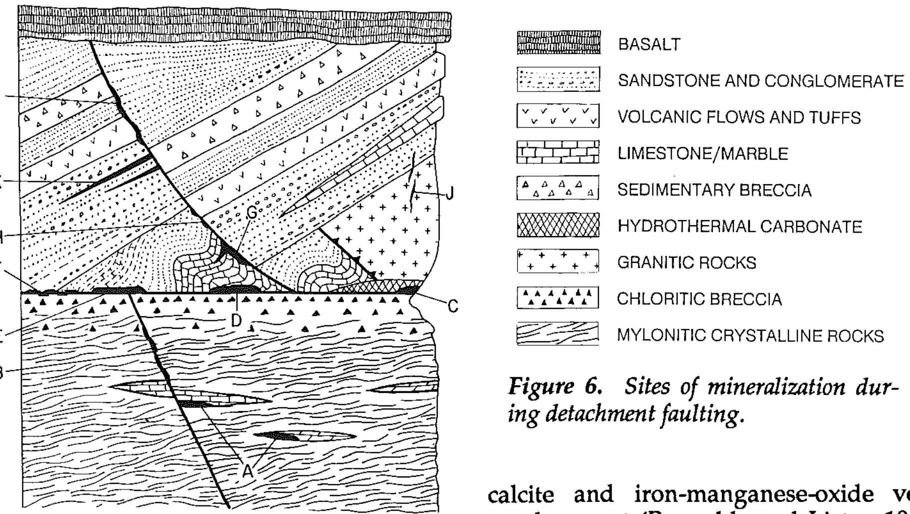



*Figure 6. Sites of mineralization during detachment faulting.*

In addition to manganese and detachment-fault-related mineralization, widespread potassium metasomatism of upper-plate rocks and chloritic alteration of brecciated rocks below the detachment fault attest to the pervasiveness of aqueous geochemical activity during detachment faulting (Figure 7). K metasomatism has been recognized elsewhere in association with detachment faults (Brooks, 1986, 1988) and is known to be older than detachment-fault-related mineralization in the eastern Harcuvar Mountains (Roddy and others, 1988). K metasomatism in the Buckskin Mountains has largely converted mafic volcanic flows, which may have originally been alkalic, to K-feldspar, calcite, and iron and manganese oxides (Kerrich and others, 1989). Plagioclase in K-metasomatized, upper-plate basalt flows in the Buckskin Mountains has been largely or entirely converted to K-feldspar; numerous K-Ar dates of feldspar concentrates from these rocks reveal a mid-Miocene age of K metasomatism (Spencer and others, 1989c). Chloritic alteration of lower-plate rocks, involving massive addition of iron, manganese, and magnesium and loss of silica, sodium, and potassium, occurred in a different fluid regime than that associated with later calcite and iron-manganese-oxide vein emplacement (Reynolds and Lister, 1987; Halfkenny and others, 1989).

The abundant evidence for widespread mid-Tertiary mineralization and alteration suggests that complex chemical and physical processes operated on a scale at least as large as the metamorphic core complex itelf. Genetic relationships between copper + iron ± gold mineralization and carbonate metasomatism along detachment faults, and K metasomatism and manganese mineralization in the upper plate, have not been established. All, however, were produced approximately synchronously in the same tectonic environment and are remarkably well developed in the Buckskin and Rawhide Mountains.

## Conclusion

Better understanding of the genesis of metamorphic core complexes, their relationship to older tectonic features, and their associated mineral deposits and igneous rocks could elucidate the nature of general processes that occur in extensional tectonic settings, including those related to the genesis of economic mineral deposits. The remarkably well-exposed and well-developed compressional and extensional structures and mineral deposits in the Buckskin and Rawhide Mountains present an exceptional opportunity to improve basic geologic understanding.

Although Bulletin 198 represents a major step forward in deciphering the complex geologic evolution of a major Cordilleran metamorphic core complex, it is clear that many questions remain unanswered. One can only hope that future investigators find these problems interesting and tractable and that the momentum established since Terry Shackelford's pivitol dissertation will continue to advance the geologic understanding of this remarkable area.

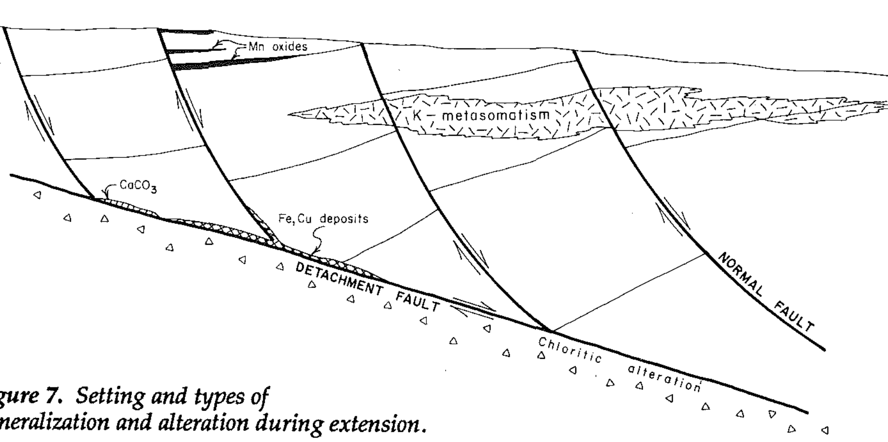



***Figure 7.** Setting and types of mineralization and alteration during extension.*

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## Bulletin 198 Ordering Information

Bulletin 198, titled *Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona,* contains 14 articles and 3 maps written or compiled by geologists from the Arizona Geological Survey and by non-Survey geologists who have researched this area. All 17 studies are cited in the reference list for this article. Bulletin 198 will be available by late July. To obtain a copy of this 280-page volume, send $35.50 ($30.00 plus a postage and handling fee of $5.50). All orders must be prepaid. Make the check or money order payable to the Arizona Geological Survey, 845 N. Park Ave., #100, Tucson, AZ 85719.

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*(continued from page 4)*

remained high, even though the average price slipped from $448 per troy ounce in 1987 to an estimated $439 in 1988. Although silver production rose nearly 30 percent in quantity, lower prices brought a slump in value. No molybdenum production was reported in 1988.

After several years of depressed prices in the potash industry, production stabilized and its value rose more than 46 percent. New Mexico producers claimed that dumping by Canadian producers had forced U.S. prices down, and in 1987 two companies filed an antidumping petition with the U.S. International Trade Commission. Early in January 1988, Canadian potash producers agreed to sell their product to U.S. farmers at a fair-market value and thereby avoid a final decision by the commission to impose heavy duties on the industry. As a result, New Mexico's potash industry improved throughout the year. Although several mines changed ownership, others started up and one announced an expansion.

## Utah

The value of nonfuel mineral production in Utah in 1988 increased 41 percent over that of 1987 and reached a record high of $990 million. Production exceeded the previous record achieved in 1981 when copper output peaked. Metals accounted for about four-fifths of the value of nonfuel mineral production, with copper, gold, and magnesium the principal contributors. Leading commodities included copper, gold, magnesium, portland cement, construction sand and gravel, salt, silver, crushed stone, phosphate, and potash.

The rise in the value of nonfuel mineral production was directly attributed to high prices for copper and gold and increased output at a recently reopened copper mine. Although silver output increased, lower prices brought a slump in value. Molybdenum production declined in quantity and value as prices and demand continued to slip. An increase in magnesium output also contributed to the rise in metal production. The declines posted for construction materials such as portland cement, gypsum, construction sand and gravel, and crushed stone were related, in part, to a depressed construction industry and the shutdown of several operations.

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Illustrators: Peter F. Corrao, Sherry F. Garner

**Arizona Geological Survey**
**845 N. Park Ave., #100**
**Tucson, AZ 85719**
**TEL: (602) 882-4795**