Geology of the Vulture Gold Mine

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The Vulture mine in the Vulture Mountains of west-central Arizona is one of Arizona's largest historic gold mines. The mine yielded approximately 340,000 ounces of gold and 260,000 ounces of silver from 1863 to 1942 (White, 1988).

The approximately 1 million tons of ore mined had an average grade of 0.35 ounces per ton of gold and 0.25 ounces per ton of silver. In spite of significant gold production, the deposit has received little geologic study until recently (Reynolds and others, 1988; White, 1988). Recent geologic mapping and laboratory studies by the authors of this article, drilling, and deposit evaluations have led to a much better understanding of the geologic characteristics, age, origin, and evolution of the deposit.

New mapping in the Vulture Mountains was partially supported by the U.S. Geological Survey and Arizona Geological Survey Cooperative Geologic Mapping (COGEMAP) program. Results of these investigations have implications for exploration strategies in the Vulture mine area and in similar highly extended areas elsewhere in Arizona.

Geologic Setting

Rocks in the Vulture Mountains consist of a variety of Proterozoic metamorphic and igneous rocks, a Cretaceous granite or granodiorite pluton, and lower to middle Miocene volcanic and sedimentary rocks. Large-magnitude, middle Miocene extension, common to most of western Arizona, was accommodated in the Vulture Mountains by movement on numerous listric and planar normal faults. Normal faults and fault blocks were tilted to the east or northeast during extension. Miocene strata now typically dip steeply or are locally overturned to the east or northeast and faults dip gently to the west or southwest (Figure 1).

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Mineralization and alteration at the Vulture mine occurred primarily within and directly adjacent to a north-dipping quartz porphyry dike that extends eastward from a Late Cretaceous pluton and intrudes Proterozoic crystalline rocks (Figures 2 and 3). Moderate to severe alteration of the dike and wall rocks has converted feldspar and mafic miner-
Figure 2. Simplified geologic map of the Vulture mine area and fluid-inclusion sample locations.

Figure 3. Homogenization and liquid/vapor phase transitions in fluid inclusions from the Vulture mine.

Conceptual restoration of the rocks of the Vulture mine area to their pre-rotation orientation reveals the approximate geometry of the ore deposit at the time of mineralization. Mineralization and alteration originally occurred along a north-northeast-trending subvertical dike that projected upward from the structural top of a Cretaceous granitoid pluton (Figure 4A). The association of gold with the dike (Figure 3) and gradation of the dike into the granitic rocks of the pluton indicate that gold mineralization was intimately related to Cretaceous magmatism and dike emplacement. Later erosion and subsequent burial by lower Miocene volcanic rocks (Figure 4B) was followed by structural dismemberment and tilting (Figure 4C) and eventual uncovering by late Cenozoic erosion. The Astor fault (Figure 3), which is probably one of the youngest faults in the area, cuts the deposit and has displaced its down-dip continuation by an unknown amount (White, 1988).

Fluid-Inclusion Characteristics

Fluid inclusions are bubbles of liquid and gas that are trapped inside minerals during mineral formation. The composition of fluids in inclusions that were trapped in mineral deposits at the time of deposit formation reflects the composition of the aqueous fluids from which the deposits formed. One can determine the salinity of the inclusions by measuring the freezing temperature of the trapped fluid. The minimum temperature of the fluid at the time it was trapped can be determined by heating the sample until the two phases (liquid and gas) in the inclusion become one. (This is called the homogenization temperature.) Fluid inclusions that formed during precipitation of host minerals are called primary, whereas those that formed later along fracture planes are called secondary.

Quartz veins are numerous over a broad area around the Vulture mine. Samples of veins were collected from an area (Figure 2) that represents an originally vertical cross section through the Vulture mine and that includes more than 1 kilometer of paleodepth range. Homogenization temperatures of primary and secondary fluid inclusions vary from approximately 200°C to 320°C and calculated salinities vary from approximately 1 to 18 percent NaCl equivalent by weight. Homogenization temperatures and salinities generally decrease with decreasing paleodepth (Figure 5). These fluid-inclusion data reveal the temperatures and salinities of the hydrothermal fluids that were probably undergoing convective circulation above the Cretaceous intrusion and that were respon-
sible for much or all of the mineralization and alteration at the Vulture mine. Greater fluid temperatures at greater depths probably reflect heat from the magma intrusion (now the granitoid pluton) that lay beneath the Vulture mine deposit. Downward-increasing fluid salinities may reflect a downward increase in the proportion of aqueous fluid expelled by the magma during crystallization.

**Conclusion**

Recent geologic mapping of the Vulture Mountains and adjacent ranges has established that the area has undergone large-magnitude extension as a result of rotational normal faulting (Grubensky and others, 1987; Stimac and others, 1987; Grubensky and Reynolds, 1988; see also Rehrig and others, 1980). Geologic mapping in the Vulture mine area indicates that this area has been faulted and tilted like most of the range and that the Vulture mine gold deposit has been tilted approximately 80° (Reynolds and others, 1988). Drill-hole assay data show that mineralization is associated with a dike that extends from the structural top of a Cretaceous pluton (White, 1988). Fluid-inclusion studies indicate that mineralization at the Vulture mine deposit occurred within a larger system of circulating aqueous fluids in which temperature and salinity increased downward toward a crystallizing magma body.

**Figure 3 (below).** Geologic cross section through the Vulture mine (modified from White, 1988 and unpublished data). See Figure 2 for location.

Recognition of this type of ore-deposit tilting and possible structural dismemberment has implications for exploration strategies in extended areas. Specifically, mineral exploration in highly extended areas characterized by rotational normal faulting may be facilitated by the knowledge that mineral deposits may have been tilted 80° from their original orientation. Such rotation provides a natural laboratory for the study of mineral deposits because the
deposits are exposed in what was originally a near-vertical cross section. This type of extensional faulting may also cut an ore deposit into two or more pieces and leave them in shingel-like imbricate fault blocks separated from each other by several kilometers (e.g., Lowell, 1968).

References


State Geological Survey - U.S. Geological Survey Meeting Held in Tucson

The annual meeting of the directors of western State geological surveys and key U.S. Geological Survey (USGS) staff was held in Tucson October 22-25 at the Ghost Ranch Lodge. The purposes of the meeting were to improve communication between staff of the State and Federal surveys; learn about current activities, projects, and concerns (Figure 1); and explore ways of fulfilling the respective statutory mandates more effectively through improved coordination and cooperation. Ten of the 13 western State geological surveys were represented; approximately 20 USGS staff members, primarily from the Office of Mineral Resources, were also present.

Western State geologists held an all-day business meeting at the Arizona Geological Survey (AZGS) on October 21 (Figure 2). USGS geologists held a variety of postmeeting functions at their Arizona Field Office.

Two major discussion sessions were held at the joint meeting: (1) the Mineral Resources Data System (MRDS), a computerized database maintained by the USGS, and (2) outreach activities in earth science education. A half-day field trip was taken to observe detachment-fault geology and the impacts of groundwater withdrawal, subsidence, and earth fissures in the Picacho basin (Figure 3).

The 1990 meeting will be cohosted by the USGS and Idaho Geological Survey in Moscow, Idaho.
The Tucson CAP Tunnel:
A Lesson in Engineering Geology

by Brad Herbert
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In 1973 construction began on the Central Arizona Project (CAP) at Lake Havasu on the western Arizona border. Today, 16 years later and nearly 330 miles farther, the continuous ribbon of canals, pipelines, tunnels, and pumping plants is at Tucson's doorstep, with completion scheduled for 1991. The last leg of the project bringing potable water to Tucson is now under construction. This final phase involves the excavation of an 8,340-foot-long, 12-foot-diameter tunnel through the southern Tucson Mountains. The tunnel will convey treated water from Tucson Water's treatment plant on the west side of the mountains to the utility's distribution system on the east.

National Projects Inc. (NPI) from Boise, Idaho constructed the $12.6-million tunnel under contract with the U.S. Bureau of Reclamation (BOR). NPI excavated and supported the tunnel, which was completed on October 25, and is now constructing an 8-foot-inside-diameter pipeline within the excavation to carry the water under pressure to the outlet, just west of Star Pass Golf Course.

Conception and Siting

Originally, the treated water was to be pumped through a 5-mile-long buried pipeline that would run east along the Tucson-Ajo Highway to Robles Pass, where it would turn north and snake through the mountains to its terminus. When BOR geologists began investigations, however, they discovered problems with that location. A portion of the proposed pipeline traversed a steep colluvial slope. Water from a large wash had already eroded the toe of this slope and caused it to fail in one area. Constructing the pipeline across this slope would have been extremely difficult and assuring its stability would have been costly.

Another design problem uncovered during geologic investigations occurred where the pipeline was to pass through a small saddle within the Shorts Ranch Andesite. The design called for a cut approximately 40 feet deep through this saddle. When an exploration core hole was drilled in this area, geologists discovered that the condition of the rock was much worse than they expected. Less than 60 percent of the core was recovered, and what was recovered displayed evidence of extensive shearing and fracturing. Constructing a safe and usable excavation would have necessitated removing a hilltop on the west side and extending the cut on the east side nearly 100 feet up the mountain.

After these problems came to light, BOR designers examined several other construction-related problems more carefully. They realized that a less costly, more efficient, and more environmentally sound alternative was required. In 1986 they discussed the idea of a combination pipeline/tunnel. Initial cost analyses indicated that the tunnel option was economically feasible and geologic investigations were begun.

After initial reconnaissance and review of pertinent literature, BOR geologists began detailed geologic mapping in the fall of 1986 at a scale of 1:4,800 (1 inch equals 400 feet). The results of that mapping helped the geologists pinpoint areas that posed possible problems for tunnel excavation and stability. They conducted further investigations in these areas, including drilling six core holes on or near the alignment: two at both the inlet and outlet portals where stability could be a problem and two along a large fault that crossed the proposed tunnel. The drill holes along the fault revealed a 30-foot-thick clay gouge zone at tunnel level. This knowledge enabled BOR designers to plan for alternative support and excavation methods in this area.

Geologic mapping also revealed the possible existence of another, previously unmapped fault, which is a southwestern extension of a fault that Kinnison (1958) mapped. This fault closely paralleled a portion of the proposed tunnel alignment, a situation that could have made excavation and support difficult. Near-surface seismic refraction and resistivity surveys were conducted to confirm the existence of the fault. Although the results of the seismic survey were inconclusive, the resistivity survey revealed the existence of conductive ground at the suspected fault, indicating the presence of clay or moisture. These
As the excavation progressed, geologists prepared a descriptive log. On the TBM between the crown and side shields, a 4-inch "window" provided a view of the rock. From studying this window, geologists recorded the locations of significant geologic features. They also viewed the entire excavation for a short time just before a ring was constructed. Occasionally, they were allowed to examine the exposed cuts more thoroughly (Figure 3). Much of the exposed rock was completely covered with dust and mud; rock samples were, therefore, taken regularly for a detailed description of the lithology throughout the tunnel.

BOR geologists are compiling and analyzing all geologic data collected during tunneling for a final report. This report will include detailed descriptions of stratigraphy, structure, and lithologies in the tunnel, as well as how these parameters affected the excavation.

Constructions

Excavation of the tunnel proper began on March 17, 1989. NPI chose to advance the tunnel with a tunnel boring machine (TBM) rather than use a traditional drill-and-shoot (blast) method (Figures 1a and 1b). The TBM is designed with a slightly concave cutting head that turns up to 12 revolutions per minute and contains 24 separate roller cutters. Large "gripper" plates push against the sides of the tunnel to stabilize the machine while the cutting head is thrust forward at pressures of up to 4,000 pounds per square inch. Different types of cutters are typically needed for hard and soft rock. This TBM, however, was designed to run equally well with the same cutters in both rocks. This becomes advantageous when mixed faces are anticipated in a tunnel. A mixed face is encountered when two or more rock types are exposed at the face, or leading edge, of the tunnel. A TBM will generally deflect toward the softer rock, causing the tunnel to vary from proper line and grade. Mixed faces were expected in the Tucson tunnel throughout the megabreccia unit of the Cat Mountain Rhyolite sequence (Tucson Mountain Chaos). This TBM design was also advantageous when thick fault-gouge zones were encountered because the time-consuming process of changing cutters was eliminated.

Precast concrete ring segments, rather than more traditional steel sets and rock bolts, supported the tunnel walls and crown. Each ring was composed of four individual segments. The segments were 5 inches thick and 4 feet wide and were installed directly behind the TBM with a specially designed hydraulic erector arm (Figure 2). This system provided immediate and continuous support in all rock types. Unfortunately, this system also covered up the rock as fast as it was exposed, making geologic mapping difficult at best.

Figure 2. View from the rear of the TBM back through the trailing gear toward the inlet portal. The concrete segments in the foreground are ready to be set in place by the hydraulic erector arm (not pictured).

Figure 3. Folded sedimentary beds of the Cretaceous Amole Group seen between the concrete segments (left) and TBM shield (right). The top, or crown segment, is tightly secured in place with laminated wood blocks (upper left).

findings persuaded BOR designers to shift the alignment to the northwest to avoid the possible adverse effects of the fault.

BOR geologists analyzed and released the geologic data collected during the year-long study (U.S. Bureau of Reclamation, 1985). A copy of this report is available in the Arizona Geological Survey library.

References


PROFESSIONAL MEETINGS


(4) Geology and Ore Deposits of the Great Basin. Symposium, April 1-5, Reno, Nev. Contact Geological Society of Nevada, Box 12021, Reno, NV 89510; tel: (702) 786-0870.

The October 17, 1989 Loma Prieta (San Francisco) Earthquake

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At 5:04 p.m. on October 17, 1989, a magnitude 7.1 earthquake occurred along a section of the San Andreas fault in the Santa Cruz Mountains south of San Francisco. The earthquake, the largest to occur in the Bay area since 1906, caused more than $4 billion in damage and 66 deaths. During the 4 days that followed the earthquake, 19 aftershocks occurred with magnitudes larger than 4.0.

The U.S. Geological Survey (USGS) designated this earthquake the Loma Prieta earthquake. Aftershocks indicated that a 40-kilometer (km)-long area on or near the San Andreas fault ruptured during the earthquake (Figure 1). The event was very unusual for several reasons. First, the focus was at a depth of 17 km. Most of the previous San Andreas earthquakes had foci shallower than 12 km. Second, faulting during the Loma Prieta earthquake was not purely strike-slip. Typical San Andreas earthquakes have been the result of horizontal slip on a vertical fault; the Pacific plate moved northwest relative to the North American plate (right-lateral strike-slip). The Loma Prieta event was a mixture of right-lateral strike-slip and thrusting motion, during which the Pacific plate moved up and over the North American plate (Figure 2). The fault plane dipped about 70° to the west. Third, very little surface faulting associated with this earthquake has been detected, even though the aftershocks nearly reached the surface. Typical strike-slip earthquakes of this magnitude have had surface displacements of 1 to 3 meters.

The Loma Prieta earthquake occurred along a section of the San Andreas fault that had undergone no earthquakes larger than magnitude 5.0 since 1906. This section of the fault slipped during 1906, but the amount of slip was much smaller than that observed on the fault north of San Francisco. Based on the slip deficit during the 1906 earthquake, the USGS in 1988 identified this section of the fault as a likely candidate for a magnitude 7.0 earthquake during the following 5 years. The Loma Prieta earthquake has probably relieved the strain accumulation on a 40-km section of the San Andreas fault, but it has not decreased the chances for another magnitude 7.0 or larger event in the Bay area on the Calaveras or Hayward faults. Furthermore, a section of the San Andreas fault between San Francisco and Portola Valley (~30 km long) could rupture in a magnitude 6.5 to 7.0 event. The probability of a repeat of the great San Francisco earthquake of 1906 remains very low, however, and is not expected for 30 to 70 years.

The Loma Prieta earthquake was recorded at the Tucson seismic observatory (TUC). The seismic waves from the earthquake were so large that all the instruments were driven off scale for approximately 20 minutes. Ground shaking was recorded for nearly 3 1/2 hours at TUC. Based on the time it took for the ground shaking to return to normal background level, Tucson seismologists estimated that the magnitude of the earthquake was 6.8.

Reference

The records of the Anaconda Company's Geological Department (1895 to 1985) are available for public use at the University of Wyoming's American Heritage Center. The collection contains data from most of the major mining areas in the world and comprises prospect and mine evaluations, operating records, and regional studies. The records include 4,285 documents and 851 maps on the mineralogy and geology of Arizona.

The International Archive of Economic Geology (IAEG) at the American Heritage Center is a repository and research facility for original manuscripts from the field of economic geology. In addition to the Anaconda Collection, the IAEG contains files from more than 170 geologists and corporations. The collection has been described in a computer inventory that allows access to its 1.8 million documents and maps. Printouts tailored to specific inquiries are available for a fee.

For more information, contact Dr. Daniel N. Miller, Jr., Director, or Ms. Bridgid McGowan, International Archive of Economic Geology, University of Wyoming, Box 3924, Laramie, WY 82071; tel: (307) 766-3704.
The Most Significant Earthquakes in U.S. History

Before the Loma Prieta (San Francisco) earthquake occurred on October 17, 1989, the U.S. Geological Survey (USGS) compiled a list of the 15 most significant earthquakes in the history of the United States. Selection was based on a combination of magnitude, damage, and casualties. The magnitude 7.1 Loma Prieta earthquake, which caused an estimated $4 billion in damage and 66 deaths, would undoubtedly have been included in this list.

Earthquakes are measured in two basic ways: magnitude and intensity. Magnitude is an instrumental measure of the amount of energy released by an earthquake, as indicated by ground motion. It is determined from the logarithm of the amplitude of earthquake waves recorded by seismographs. The Richter magnitude scale, expressed in whole numbers and decimal fractions, theoretically has no upper limit; however, the largest earthquakes ever recorded had magnitudes of less than 10. The Modified Mercalli Scale (MMS) of intensity uses Roman numerals and is based on human judgment of the amount of damage and effects caused by earthquakes. It ranges from I (not felt) to XII (almost total destruction of manmade structures).

The 15 most significant earthquakes in U.S. history, listed in chronological order, are as follows:

(1) Cape Ann, Mass., Nov. 18, 1755—Estimated magnitude, 6.0; maximum MMS intensity, VIII. This earthquake was centered in the Atlantic Ocean, 200 miles east of Cape Ann. It was felt over 400,000 square miles, from Nova Scotia south to Chesapeake Bay and from Lake George, N.Y. east into the Atlantic. Damage was heaviest on Cape Ann and in Boston, with about 100 chimneys destroyed.

(2) New Madrid, Mo., 1811-12—Estimated magnitudes, 8.4 to 8.7; maximum MMS intensity, XI. In the most violent series of earthquakes in U.S. history, three earthquakes (counted here as one) hit the New Madrid seismic zone in southeastern Missouri and northeastern Arkansas on Dec. 16, 1811, and Jan. 23 and Feb. 7, 1812. Damage and casualties were not great because the area was sparsely populated. The earthquakes, however, were felt over the entire United States east of the Mississippi River and probably far to the west and caused extensive changes in the land surface.

(3) Virgin Islands, Nov. 18, 1867—Estimated magnitude, 7.5; maximum MMS intensity, VIII. This earthquake was felt from the Dominican Republic to the Leeward Islands. Property damage, which occurred in the Virgin Islands and Puerto Rico, was partly caused by 20-foot sea waves triggered by the earthquake.

(4) Charleston, S.C., Aug. 31, 1886—Estimated magnitude, 6.6; maximum MMS intensity, X. This earthquake killed 60 persons. Most buildings in the Charleston area were damaged or destroyed; losses totalled $20 million. It was felt in New York City; Boston; Milwaukee; Havana, Cuba; and Ontario, Canada.

(5) Charleston, Mo., Oct. 31, 1895—Estimated magnitude, 6.2; maximum MMS intensity, IX. This earthquake occurred near the junction of the Mississippi and Ohio Rivers and was the strongest shock in the New Madrid seismic zone since the earthquakes in 1811-12. It was felt over 1 million square miles in 23 states and Canada, caused considerable damage, and created a four-acre lake near Charleston.

(6) San Francisco, Calif., April 18, 1906—Estimated magnitude, 8.3; maximum MMS intensity, XI. Although known as the San Francisco earthquake, the 1906 shock actually ruptured the San Andreas fault along a 270-mile segment from San Benito County north to Humboldt County. Fault slip was up to 21 feet in Marin County. Damage was estimated at more than $24 million, from both the earthquake and fires that followed in San Francisco. More than 700 persons died.

(7) Mona Passage, Puerto Rico, Oct. 11, 1918—Estimated magnitude, 7.5; maximum MMS intensity, IX. This earthquake was one of the most violent recorded on Puerto Rico and was followed by a tsunami that drowned many persons. The death toll was 116; damage was estimated at $4 million.

(8) Long Beach, Calif., March 10, 1933—Estimated magnitude, 6.2; maximum MMS intensity, VIII. This earthquake was one of the most destructive in the United States because it was in a heavily settled area with many poorly constructed buildings, including schools. About 115 persons were killed and hundreds more were injured. Damage was estimated at $40 million. The earthquake led to stricter construction codes in California to mitigate earthquake damage.

(9) Olympia, Wash., April 13, 1949—Estimated magnitude, 7.1; maximum MMS intensity, VIII. This earthquake caused heavy damage in Washington and Oregon, killed eight persons, and injured many others. The earthquake was felt eastward to western Montana and south to Cape Blanco, Oregon.

(10) Hebgen Lake, Mont., Aug. 17, 1959—Estimated magnitude, 7.3; maximum MMS intensity, X. This was the strongest recorded earthquake in Montana. It was felt over 600,000 square miles, from Seattle to Banff, Canada and from Dickinson, N. Dak. to Provo, Utah. It caused massive waves on Hebgen Lake that did not subside for 12 hours. It also caused a massive landslide that blocked the Madison River canyon, creating a large lake. At least 28 persons were killed. Damage was extensive to summer homes and highways in the region.

(11) Prince William Sound, Alaska, March 27, 1964—Estimated magnitude, 8.4; maximum MMS intensity, X. This Good Friday earthquake is the second strongest in the world during the 20th century. It was topped by an 8.6-magnitude earthquake in Chile in 1960. The Alaska earthquake triggered extensive landslides and generated tsunamis. It caused an estimated $311 million in damage in Anchorage and south-central Alaska and killed 131 persons.

(12) Seattle, Wash., April 29, 1965—Estimated magnitude, 6.5; maximum MMS intensity, VIII. This earthquake was felt over 130,000 square miles of Washington, Oregon, Idaho, Montana, and British Columbia. Seven persons died; damage was estimated at $12.5 million.

(13) San Fernando, Calif., Feb. 9, 1971—Estimated magnitude, 6.6; maximum MMS intensity, XI. This earthquake killed 65 persons, injured many others, and caused $1 billion in damage in the Los Angeles area. As a result of this earthquake and the Alaskan tremor in 1964, the Federal government greatly expanded its earthquake research and reevaluated seismic design for hospitals, emergency clinics, and other critical facilities.

(14) Coalinga, Calif., May 2, 1983—Estimated magnitude, 6.7; maximum MMS intensity, VIII. This earthquake injured 45 persons and caused $31 million in damage, with the worst damage occurring in downtown Coalinga. The earthquake was felt from Los Angeles to Sacramento and from San Francisco to Reno, Nevada.

(15) Borah Peak, Idaho, Oct. 25, 1983—Estimated magnitude, 7.0; maximum MMS intensity, IX. This earthquake was the largest recorded in Idaho. It was felt over 330,000 square miles. Two children were killed and damage was estimated at $12.5 million.
The following publications may be purchased from the Arizona Geological Survey (AZGS), 845 N. Park Ave, #100, Tucson, AZ 85719. For price information on these and other publications, call the AZGS office at (602) 882-4795.

The Contributed Report series was created in January 1989 for reports written by non-AZGS geologists that are considered to be significant additions to the geologic literature on Arizona. This series title describes more accurately the source and status of these publications. Reports of this nature donated before 1989 were placed in the AZGS Open-File Report series. This latter series is now devoted to reports written by AZGS personnel. Many contributed reports are obscure and would not be readily available to the public if they were not placed in this series.


The northern Plomosa Mountains consist of a large fault block of dominantly crystalline rock that has been tilted to the south and is bounded on the east and north by a low-angle normal fault known as the Plomosa detachment fault. The hanging wall of the Plomosa fault comprises a variety of crystalline rocks, metamorphosed and multiply deformed Paleozoic and Mesozoic rocks, and Miocene volcanic and sedimentary rocks. Numerous Tertiary mineral deposits are associated with shear zones in the northern part of the range. This map is the only geologic map of the entire northern Plomosa Mountains.


This detailed geologic map covers the southern end of the Moore Gulch shear zone, a complex zone of Proterozoic deformation that separates contrasting Proterozoic rocks and represents an important tectonic feature. Tertiary sedimentary and volcanic rocks are also present in the range.


The exploration activities of the U.S. Atomic Energy Commission (AEC) during the 1950's are well documented in AEC reports. The program of constructing and improving access roads to exploration and mining areas, however, is less known. From 1951 to 1958, some 90 projects affecting 1,253 miles of road were undertaken in Arizona, Colorado, New Mexico, South Dakota, Utah, and Wyoming. These projects cost $17 million, $14 million of which the AEC provided. Seven projects, all totally funded by the AEC, were conducted in Arizona: two in Gila County and five on the Navajo Indian Reservation in Apache County. This report summarizes those projects.


Herbert E. Gregory, in his classic 1917 report on the Navajo Indian Reservation, mentions that silver and gold were discovered in the Carrizo Mountains. Gregory did not locate this deposit, nor is it referenced elsewhere in the literature. Some old mine workings, once thought to be related to uranium-vanadium prospecting, are believed to be the so-called Carrizo "gold" mine. Their history and geologic setting are summarized in this report.


The Salt Wash Member of the Jurassic Morrison Formation contains significant uranium-vanadium deposits in the Lukachukai Mountains in northeastern Apache County. North of there, smaller deposits have been mined near the Carrizo Mountains. During the uranium boom of the 1950's, some uranium was also mined from the Salt Wash near Rough Rock Trading Post. This report details the geologic setting and production history of these latter deposits.


During 1953 and 1954, the two primary authors, geologists with the U.S. Atomic Energy Commission, mapped the underground mine workings of the Monument No. 2 uranium-vanadium mine on the Navajo Indian Reservation. The maps are of historical value because the underground workings were later destroyed by open-pit mining. In addition to the maps, this report includes information on the geologic setting and production history of the mine.


The Granite Wash Mountains in west-central Arizona are part of the Maria fold-and-thrust belt, a belt of large folds and major thrust faults that trends east-west through west-central Arizona and southeastern California. In the Granite Wash Mountains, late Mesozoic deformation related to the Maria belt affected a diverse suite of rocks, including Proterozoic crystalline rocks, Paleozoic carbonate and quartzose clastic rocks, and Mesozoic sedimentary, volcanic, plutonic, and hypabyssal rocks. This deformation was mostly deep seated and produced an assortment of folds, cleavages, and ductile and brittle shear zones. Several discrete episodes of deformation occurred, resulting in re-folded folds, folded and refolded thrust faults, and complex repetition, attenuation, and truncation of stratigraphic sequences. Deformation and metamorphism were followed by emplacement of two Late Cretaceous intrusions and numerous dikes.

Mineralization includes gold deposits associated with quartz veins, shear zones, and silification; tungsten deposits associated with quartz veins and shear zones; and quartz-kyanite deposits similar to those in the southern Appalachian Mountains that are associated with large gold deposits.

The geology of the Granite Wash Mountains was mapped between 1982 and 1988 as part of the U.S. Geological Survey/AZGS Cooperative Geologic Mapping (COGEMAP) program. This report, which includes a 1:24,000-scale map, describes major findings about stratigraphy, structure, metamorphism, and mineral deposits in the area.


This report, which includes more than 4,500 references, is the first step toward an inclusive bibliography on the geology and mineral resources of Arizona. It was compiled from bibliographies that were previously published by or are currently available from the Arizona Geological Survey and the U.S. Geological Survey.

The AZGS was established on July 1, 1988. Its two most recent predecessors were the Arizona Bureau of Geology and Mineral Technology and the Arizona Bureau of Mines. Many of the publications of these antecedent agencies are out of print but available in the AZGS library. This report lists all the publications released by these agencies.


This map shows the distribution of alluvial deposits of different ages in the Phoenix South 30' x 60' quadrangle and provides a basis for evaluating the Quaternary geologic history of the area. The map was compiled from U2 high-altitude aerial photographs (scale 1:129,000), natural-color aerial photographs (scale 1:24,000), and field studies. The project was partially funded by the COGEO MAP program.


AZMIN is the result of a 10-year effort to develop a classification method, compile information, and create a digital database for Arizona's metallic mineral districts. In the mineral-district classification used for this database, known deposits are grouped according to geologic and metallogenic criteria rather than the geographic associations used in the traditional mining-district approach.

AZMIN databases and programs were developed on IBM-PC-compatible microcomputers through the use of dBase IV, a database-management program. AZMIN consists of 3 database files and 10 data-manipulation programs that allow the user to search data or display them in various formats. AZMIN includes mineral-district and mine locations, production data, and bibliographic information. This report, the first computer program, was developed on IBM-PC-compatible microcomputers through the use of dBase IV, a database-management program.

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Cooperative Geologic Mapping in Arizona:
1989 COGEOMAP Update

by Stephen J. Reynolds
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A major legislated responsibility of the Arizona Geological Survey (AZGS) is to characterize the geologic framework of Arizona. To help fulfill this responsibility, the AZGS has placed a high priority on geologic mapping, especially on producing high-quality, quadrangle-scale (1:24,000) geologic maps of previously unmapped areas. Such maps increase the understanding of the geologic framework, mineral potential, and geologic hazards of an area by helping to define the stratigraphy, structure, geologic history, and distribution and setting of mineralization and alteration. The quadrangle-scale maps may be used to compile intermediate-scale (e.g., 1:100,000 or 1:250,000) maps to define the regional distribution of mineral resources and geologic hazards and identify areas where additional mapping is needed. Maps at both scales will be used to produce a new 1:500,000-scale geologic map of Arizona.

Since 1984, the AZGS and U.S. Geological Survey (USGS) have participated in the Cooperative Geologic Mapping (COGEOMAP) program. As part of this cost-sharing program, AZGS geologists have concentrated their mapping in the Phoenix 1° x 2° quadrangle (Figure 1) and adjacent parts of west-central Arizona. This region is geologically complex and highly mineralized, but very poorly understood. The Phoenix quadrangle is also the site of rapid urban growth and major construction projects, such as the Palo Verde Nuclear Generating Station, Central Arizona Project, New Waddell Dam, and a hazardous and toxic waste repository.

During the past 9 years, AZGS geologists have completed 1:24,000-scale geologic maps of the Belmont, Big Horn, Granite Wash, Hieroglyphic, Little Harquahala, Maricopa, South, Vulture, and Wickenburg Mountains, Aguila Ridge-Bullard Peak area, and Merritt Hills (Figure 1). Parts of the Bouse Hills and Buckskin, Harcuvar, Harquahala, and White Tank Mountains have also been mapped. From this mapping, major geologic discoveries have been made, including (1) previously unknown Mesozoic sequences and an early Mesozoic uplift event; (2) the Maria fold-and-thrust belt, a previously unrecognized Mesozoic thrust belt; (3) a suite of quartz-kyanite rocks similar to those associated with gold on the Piedmont of the southeastern United States; (4) low-angle normal (detachment) faults that have regional tectonic and economic significance; and (5) previously undescribed areas of alteration and mineralization.

1984-88 COGEOMAP Projects

During the 1984-85 COGEOMAP project, AZGS geologists mapped the Bighorn and Belmont Mountains at a scale of 1:24,000 (AZGS Open-File Report 85-14) and prepared a report containing geologic, geochemical, and fluid-inclusion data on mineral deposits in the area (AZGS Open-File Report 85-17). The geologic maps depict numerous normal faults that cut moderately tilted Tertiary volcanic rocks and their underlying basement.

During 1986 and 1987, AZGS geologists completed 1:24,000-scale maps of the Hieroglyphic, Wickenburg, and northeastern Vulture Mountains (AZGS Open-File Reports 86-10, 87-9, 87-10, and 88-1). These maps show many previously unrecognized faults, Proterozoic banded-iron formations, a large Cretaceous granodioritic pluton, and a Miocene volcanic field. Some normal faults have several kilometers of displacement, which helped to accommodate 150 percent crustal extension. They are commonly the loci of middle Tertiary hydrothermal alteration and mineralization.

1988-90 COGEOMAP Projects

The 1988-89 COGEOMAP project produced a 1:24,000-scale geologic map of the southeastern Vulture Mountains (AZGS Open-File Report 88-9) and the Vulture mine, one of the premier gold deposits in Arizona. Geologic studies (AZGS Open-File Report 88-10 and this issue of Arizona Geology) documented that mineralization at the Vulture mine represents a midlevel, pluton-related Cretaceous granodioritic vein that has been turned on its side by Tertiary fault-block rotation. The top of the orebody was removed by pre-Miocene erosion rather than by faulting, as previous interpretations suggested.

The 1988-89 COGEOMAP project also resulted in the publication of a new, 1:4,000,000-scale, colored geologic map of Arizona (AZGS Map 26) and the release of three 1:100,000-scale maps of Quaternary deposits (AZGS Open-File Reports 88-4, 88-17, and 89-7). The 1989-90 COGEOMAP project, which began on May 1 of this year, has concentrated on completing a 1:24,000-scale geologic map of the southernmost part of the Phoenix 1° x 2° quadrangle.

Figure 1. Status of geologic mapping in the Phoenix 1° x 2° quadrangle.
Dikes associated with the younger suite commonly intrude along low-angle faults and are extensively K-metasomatized. A unique series of Sr- and U-bearing lacustrine rocks overlies the younger rhyolitic suite in the western end of the range. Even younger, largely post-tectonic basalts unconformably overlie tilted rocks in several parts of the range.

The AZGS recently released a 1:24,000-scale map of the Granite Wash Mountains, one of the most structurally complex mountain ranges in the western United States. This map is accompanied by a detailed description of rock units, structural evolution, and mineral deposits (AZGS Open-File Report 89-4). The range consists of a stack of imbricate, ductile thrust faults that juxtaposed Proterozoic and Jurassic crystalline rocks discordantly over an upturned section of Paleozoic and Mesozoic supracrustal rocks. The rocks show evidence of three episodes of thrusting, each with a different transport direction. The thrust sheets were later folded by two generations of large folds, some of which have amplitudes of 1 kilometer. Massive quartz-kyanite rocks were discovered in four areas; these rocks are similar to those associated with gold on the Piedmont of the southeastern United States.

AZGS geologists will spend the 1989-90 winter field season mapping the New River area and White Tank Mountains to complete the Phoenix North 1:100,000-scale quadrangle map (northeastern quarter of the Phoenix 10° x 20° quadrangle). Continued mapping in the western Harcuvar Mountains and Bouse Hills will complete the Salome 1:100,000-scale quadrangle map (northwestern quarter of the Phoenix 10° x 20° quadrangle). AZGS geologists will also start mapping the geology of the Little Horn Mountains in the southwestern quarter of the Phoenix 10° x 20° quadrangle. This range is an eastward continuation of the middle Tertiary Kofa volcanic field and contains several important areas of Tertiary precious-metal mineralization.

After the New River and Little Horn Mountains are mapped, the AZGS will have achieved one long-term goal: to produce a regional northeast-trending transect from the Kofa Mountains in southwestern Arizona to the edge of the Transition Zone. This transect, which includes the Kofa, Little Horn, Big Horn, Belmont, Vulture, Wickenburg, and Hieroglyphic Mountains and New River area, will enable AZGS and USGS geologists to address such fundamental issues as (1) the tectonic significance of the Basin and Range Province - Transition Zone boundary, (2) the magnitude of crustal extension in this part of the Basin and Range Province, and (3) the regional controls and timing of mineralization.